DURABILITY OF COMPRESSED AND CEMENT-STABILISED BUILDING BLOCKS

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DECLARATION

This declaration serves to confirm that this thesis is the original and exclusive work of the author alone. The thesis does not include either in part or in whole, any previous material submitted by any other researcher in any form not acknowledged as required by existing regulations. No material contained in this thesis has been used elsewhere for publication prior to the production of this work.

This declaration also formally affirms that this thesis is being submitted for the degree of Doctor of Philosophy of the University of Warwick only and not to any other similar institutions of higher learning for the same purposes.

DEDICATION

This thesis is especially dedicated to the following:

My father, Claudio, and mother, Sylvia	-	for their extraordinary foresight, devotion, and sacrifice in educating all their children.
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ABSTRACT

Adequate shelter is a basic human need, yet about 80% of the urban population in developing countries still live in spontaneous settlements as they cannot afford the high cost of building materials. The compressed and stabilised block (CSB) has been identified as a low-cost material with the potential to redress the problem and reverse the shelter backlog. While its other properties are well understood, the durability of the material remains enigmatic. The principal objective of this research was therefore to investigate the durability of CSBs, especially as used in the humid tropics.

The thesis examines the interplay between three main factors: constituent materials used (cement, soil, water); quality of block processing methods employed; and the effects of natural exposure conditions (physical, chemical, biological). Through a multi-pronged methodology involving literature reviews, laboratory experiments, petrographic analysis and an exposure condition survey, block properties and behaviour are rigorously investigated. The findings are presented under the two main division of the thesis: Part A and Part B.

Part A introduces a review of the literature on the main theoretical concepts of durability and cement-soil stabilisation. It discusses various deterioration modes, and examines in more detail mechanisms of stabilisation using Ordinary Portland cement. Part A also identifies and highlights critical stages of the CSB production cycle, and recommends a strict adherence to proper testing and processing procedures.

Part B presents the results of direct investigation methods used. Findings from the fieldwork confirmed that premature deterioration was widespread in exposed unrendered blocks, with defects exhibited mainly as surface erosion and cracking. Quality checks on site materials and practice established an urgent need for improvement through the provision of appropriate standards and codes. Laboratory experiments which compared the properties of traditional blocks (TDB) and blocks improved by the inclusion of microsilica (IPD), established that the latter significantly out-performed the former. A new quick predictive surface test, the slake durability test, which is more reliable and repeatable than existing tests, is proposed.

The thesis concludes that it is possible to significantly raise the strength, improve the dimensional stability and wear resistance of CSBs to the extent that they can be safely used in unrendered walls in the humid tropics. This improvement is achieved via better intergranular bonding, reduction in voids and lowered absorption. Using the slake durability test, it is now tenable to freely discriminate, classify, and compare not only blocks but other like materials of any category and storage history as well. New quantitative durability gradings are recommended for future incorporation into CSB standards. The findings are likely to contribute to the widespread use of CSBs. The research, however, also raises a number of new questions which are listed for further work.

ABBREVIATIONS

α	=	Degree of cement hydration in water
AAR	=	Alkali-aggregate reaction
ACR	=	Alkali-carbonate reaction
A_{CS}	=	Cross section area
ASL	=	Above sea level
ASR	=	Alkali-silica reaction
BDD	=	Block dry density
$C\bar{S}H_2$	=	Gypsum (C_aSO_4)
C_2S	=	Dicalcium silicate
C_3A	=	Tricalcium aluminate
C_3S	=	Tricalcium silicate
$C_4A\bar{S}H_{12}$	=	Monosulphoaluminate
C_4AF	=	Tetracalcium alumino ferrite
$C_a(OH)_2$	=	Calcium hydroxide
C_aCO_2	=	Calcium carbonate
C-A-H	=	Calcium aluminate hydrate
C_aO	=	Calcium oxide
CBS	=	Concrete block sample
cc	=	Cement content
CCD	=	Curing conditions
CLSB	=	Cement lime soil block
CO_2	=	Carbon dioxide

CP	=	Compaction pressure
CRM	=	Cement replacement material
CRS	=	Corner wall-section
CSB	=	Compressed and stabilised block
C-S-H	=	Calcium sulfate hydrate
CSSB	=	Cement stabilised soil block
DANIDA	=	Danish Agency for International Development
DCS	=	Dry compressive strength
DL	=	Design life
ECS	=	Exposure condition survey/humid tropics
EFF	=	East facing façade
FBS	=	Fired brick sample
GGBS	=	Ground granulated blast furnace slag
H_2O	=	Water (also 'H')
HBT	=	Hold back time
ILO	=	International Labour Organisation
IPD	=	Improved block
l_c	=	Lime content
L_R	=	Loading rate
LSF	=	Lime saturation factor
LST	=	Linear shrinkage test
LWS	=	Lower wall section
MCSB	=	Microsilica cement soil block
M_oWHUD	=	Ministry of Works Housing and Urban Development
MPa	=	Mega Pascal

MS	=	Microsilica
Mwc	=	Mix-water content
MWS	=	Mid wall section
NAB1	=	Namuwongo abandoned building 1 (8 years)
NAB2	=	Namuwongo abandoned building 2 (12 years)
NFF	=	North facing façade
OBS	=	Ordinary builders sand
OMC	=	Optimum moisture content
OPC	=	Ordinary Portland cement
PFA	=	Pulverised fuel ash
PSD	=	Particle size distribution
RBS	=	Rock block sample
RPC	=	Rapid hardening cement
S	=	Amorphous silica
SDI	=	Slake durability index (also I_d)
SDT	=	Slake durability test
SFF	=	South facing façade
SL	=	Service life
Soil 'S'	=	Artificial laboratory blended soil
SSA	=	Specific surface area
SSC	=	Soluble salts crystallisation
ST	=	Soil type
TDB	=	Traditional block
TVP	=	Total volume porosity
TWA	=	Total water absorption

UCR	=	Unhydrated cement residues
UWS	=	Upper wall section
w/c	=	Free water to cement ratio
WAD	=	Wetting abrasion and drying
WCS	=	Wet compressive strength
WFF	=	West facing facade

CHAPTER 1

INTRODUCTION

In Chapter 1, the background to the research, its aims and objectives, methodology used, and the structure of the thesis are described.

1.1 BACKGROUND TO THE RESEARCH

This section presents in outline form the general context in which the research is based, namely a brief history of compressed and stabilised blocks (CSB), their advantages, and the problems that have emerged since their introduction.

The majority of developing countries are today faced with an ever increasing problem of providing adequate yet affordable housing in sufficient numbers. In the last few decades, shelter conditions have been worsening: resources have remained scarce, housing demand has risen and the urgency to provide immediate practical solutions has become more acute. Adequate shelter is one of the most important basic human needs, yet 25% of the world's population does not have any fixed abode, while 50% of the urban population live in slums (ESCAP/RILEM, 1987; ILO, 1987). Indeed 80% of urban settlements in developing countries consist of slums and spontaneous settlements made of temporary materials (Keddi & Cleghorn, 1980; ILO/UNIDO, 1984). With the population in developing countries growing at rates of between 2% and 4% per year and the population in their major cities growing by double these figures, demand for low cost housing far outstrips the capacity to supply (UNCHS, 1981). No developing country without strategies for low cost materials is likely to meet its shelter targets (Webb, 1983; Hamdi, 1995).

Developing countries planning to expand their housing stock for the low-income groups will inevitably need to identify the lowest feasible unit housing costs. The main costs of shelter provision are for building materials (about 60%), machinery, manpower and loan interest repayments (BRE, 1980; Ashworth, 1994; Maclean & Scot, 1995). Strategies are therefore urgently needed to develop low-cost, readily available and durable building materials. A naturally abundant material such as soil that is found on most of the surface of the earth should be a significant resource for building in developing countries.

Research and development of stabilised soil as a building material is not new. The use of CSBs can be traced back 50 years (Fitzmaurice, 1958; Enteiche & Augusta, 1964; Fathy, 1973; Webb, 1988). From the early 1950s attempts were made to develop the material as an alternative walling unit to the modern and more expensive fired bricks and concrete blocks. The promotion of the material was originally introduced via the United Nations (UN Bulletin No. 4, 1950; Fitzmaurice, 1958). The idea of compacting earth to improve its quality and performance in the form of moulded blocks however dates back to the 18th Century (Houben & Guillaud, 1994). The addition of a binder to stabilise the soil is more recent.

Apart from the early work of the United Nations, the history of the spread of the CSB is not well documented. During the 1950s use of the material was widely disseminated worldwide. The 1960s and early 1970s were however stagnant years. This was to change with the 1976 Vancouver Assembly of the United Nations Conference on Human Settlements (UNHCS, 1976; UNIDO, 1980). Noting with concern that the worlds population was expected to double by the year 2000, and worse still, to quadruple by the year 2030 (representing the largest single population growth in human history), the conference resolved to focus on the development of low-cost housing. Further momentum was to be given 12 years later following the declaration of the year 1987 as the International Year of Shelter for the Homeless (UN/IYSH, 1987). Subsequent proclamations were to follow in 1988 under the theme 'Global Strategy for Housing by the Year 2000'. The key targets of these resolutions were the guaranteed access to decent and durable housing for all from the beginning of the new millennium. Renewed world-wide interest was soon to provide an immense impetus that has ensured the now vibrant spread of CSBs throughout the developing world. It was within this international context and drive that the author became involved with the material in 1987 following the donation to Uganda in that year of several block presses and ancillary materials by the International Labour Organisation (Okello, 1989; Schmetzer & Kerali, 1994; Kerali, 1996).

Continued interest in CSBs will in future evolve around the several merits and attractions associated with its use. Firstly, as the basic raw material is soil, its source will remain abundant. This facilitates direct site-to-service application, thereby lowering costs normally associated with acquisition, transportation and production. Home ownership can then be delivered at comparatively low costs. Secondly, the initial performance characteristics of the material such as the wet compressive strength (WCS), dimensional stability, total water absorption (TWA), block dry density (BDD) and durability are technically acceptable. They are also comparable to those of rival materials (ILO, 1987; Houben & Guillaud, 1994; Houben et al, 1996). Houses constructed of CSBs also uniquely proffer better internal climatic conditions than other modern materials (Fullerton, 1979; Hughes, 1983). Thirdly, promoting the use of CSBs generates more direct and indirect employment opportunities within the local populace than would be the case with other materials. Fourthly, use of the material contributes directly to the social, cultural and educational advancement of the population (Schumacher, 1973; Anderson et al, 1982; Aksa, 1984). Their use also contributes to the training and re-training of artisans and to the provision of new skills. Use of the material through the provision of local infrastructure such as schools, community centres, health centres and administrative units results in the promotion of human interactions and social development. Finally, use of the material is environmentally friendly, appropriate and correct since it utilises the otherwise unlimited natural resource in its natural state. Moreover, this is achieved with little resultant depletion of other resources, or pollution and requires no excessive energy consumption and wastage as is the case with clamp fired bricks. The elimination of the need for wood fuel resources is seen as a major attraction over such bricks. The use of CSBs is thus in keeping with current sustainable development strategies (VTA, 1977; Plinchy, 1982; Lawson, 1991; Perera, 1993; Norton, 1997).

Despite the above advantages however, as with most relatively new materials, shortcomings associated with their use have recently begun to emerge, especially in tropical environments. These regions are characterised by frequent and intense rainfall, high relative humidity and high diurnal temperature changes (Bilham, 1962; Atkinson, 1970; Eaton, 1981). CSBs are produced from soil as the bulk constituent (over 90%). Soil is known to have poor resistance to erosion and to disintegration in water, a low tensile strength, low resistance to abrasion, high water absorption and retention capacity, and is dimensionally unstable during cyclic wetting and drying (Ellison; 1944, Carter & Bently, 1971; BOR, 1974; Das, 1983). The vulnerability of soil has in turn led to blocks showing considerable defects over short periods under conditions of normal and severe exposure in the humid tropics (Lunt, 1980; Agarwal, 1981; Eaton, 1981; Tibbets, 1982; Spence & Cook, 1983). Whereas the initial building costs might be low, the subsequent high maintenance costs, or even early rebuilding costs are not acceptable to many. Some promoters have also done harm to the image of the material by claiming a high degree of long-term technical performance only to be contradicted by premature deterioration only a few years later (Hammond, 1973).

Although the problem is more acute in the humid tropics than in the arid zone, it nevertheless has not been seriously addressed by research. Interest in studying the durability of CSBs is therefore likely to remain a major research concern for the foreseeable future. It is the long-term durability of the block, rather than any other factor that will be the key to their widespread acceptance (Gooding, 1994). It is therefore the goal of this research to investigate the feasibility of producing a high intergranular strength block of low permeability, which is inert, dimensionally stable and durable, even under conditions of exposure to wetting, abrasion and drying.

1.2 AIMS AND OBJECTIVES

Following on from the discussions in the preceding section, the objectives of this thesis are threefold. Firstly, to investigate the main constituent materials and the block production process, secondly to examine the main block properties and their performance, and thirdly to make recommendations for improved specification, testing and protection of CSBs for the duration of their service lifetime.

The scope covered under each of the above objectives are summarised below:

1. *Constituent materials and block processing methods:*

   (a) to investigate all present theoretical and practical methods by which soil and cement are classified, selected, and tested for CSB production.

   (b) to closely examine the mechanisms by which cement and associated binders and additives effect stabilisation in soils by increasing strength, dimensional stability and durability.

(c) to investigate the block production process with a view to identifying the critical sub-processes that influence the quality and performance of the block as a product.

2. *Surface and bulk properties and performance:*

(a) to study experimentally the effect of altering important variables like: soil type, cement content, cement replacement materials, mix-water content, moulding pressure and curing conditions on the properties and performance of blocks.

(b) to compare the performance of traditional and improved blocks as defined by the absence and presence of partial cement replacement materials respectively in the mix composition of CSBs.

(c) to review the concepts of durability and identify the main deterioration mechanisms involved, understand their methods of progression and propose appropriate remedial action.

(d) to identify the key surface and bulk properties on which durability is thought to depend, and monitor the performance of block categories mentioned in (b) in conditions simulating the action of the main deteriorating agents using accelerated tests.

(e) to collect in-service performance data from condition surveys and other records in order to estimate the service life of blocks.

3. *Improved design and specification for durable blocks*

(a) to recommend, from data and evidence obtained from 1 and 2 above, new approaches for achieving more appropriate, affordable and durable blocks.

(b) to develop and specify new initial and accelerated predictive tests for blocks that can be conducted on site, in laboratories and under in-service conditions.

(c) to recommend alternative surface and bulk improvement and protective measures for use of blocks under severe exposure conditions.

(d) to suggest suitable minimum performance requirements and thresholds for incorporation into future standards.

(e) to disseminate findings and flag questions for further research through publications, seminars and conferences.

The achievement of the above objectives are evaluated in the concluding parts of this thesis.

1.3 METHODOLOGY

There is very limited information available on the long term behaviour of CSBs. This is partly because no prior research has been conducted in the area and partly because inspection and maintenance records on the performance of blocks are not available. In view of such circumstances, the use of a combination of various approaches was considered to be inevitable. These approaches included:

1. *Literature review*: to establish the level of current thinking and knowledge and to provide the intellectual context for the research.
2. *Laboratory experimentation and testing*: of key surface and bulk properties of blocks as well as monitoring their performance using accelerated tests. Two categories of blocks were evaluated: traditional and improved blocks.
3. *Petrographic examination of CSB microstructural features*: using thin sections
4. *Exposure condition survey in the humid tropics*: done through:

(a) Inventorisation of CSB buildings and characterising their exposure conditions.

(b) Visual inspection of buildings to identify defect types and their severity.

(c) In-service condition measurement of the main defect types.

(d) Quality tests on constituent materials: soils, cement and water.

(e) Visits to block production sites for preliminary work-study assessment.

(f) Questionnaires and interviews for opinions, experiences and knowledge from stakeholders.

1.4 STRUCTURE OF THE THESIS

The body of this thesis consists of eight chapters presented in two parts, A and B. The organisation of the chapters is as follows:

Chapter 1 provides an introduction to the whole thesis. It discusses the background to the research and the context in which it is based. This Chapter also summarises the main aims and objectives of the research and explains why the different methodologies listed had to be used for the research. Chapter 1 ends by providing guidelines on the organisation and structure of the thesis as a whole including the ordering of the main parts, chapters, references and appendices. These are now described each in turn.

Part A: *Concepts of Durability and Stabilisation*

Part A consists of two chapters, namely Chapter 2 and Chapter 3.

Chapter 2 introduces the fundamental theoretical concepts of durability and deterioration in CSBs. The Chapter emphasises the fact that understanding of the main concepts of durability and deterioration in blocks is both necessary and yet long overdue. This Chapter identifies the principal deterioration agents and their perceived effects and attempts to rank them according to their severity. It also discusses the various deterioration mechanisms related to water, temperature and chemical reaction respectively. The main significance of Chapter 2 is that concepts previously not recorded in CSB literature are developed. It further emphasises the multidisciplinary nature of the research topic and reviews the wide store of knowledge accumulated from recent advances in durability research of cementitious materials. By presenting the subject in this manner, a more comprehensive understanding of the concepts of durability and deterioration in CSBs is achieved. The main surface deterioration mechanism in blocks (water-related surface wetting, abrasion and drying) is identified for further direct experimental investigation in Part B of the thesis.

Chapter 3 reviews and builds on the current understanding of cement-soil stabilisation principles and practices. This Chapter also examines the properties of the main constituent materials that form blocks (soil, cement, water) and reviews the effects of varying their proportions on the performance of blocks. The nature of each of these constituent materials, the manner in which they are selected and proportioned to form mixes for CSBs are closely analysed. The Chapter examines the adequacy of the theories of cement hydration and hardening, and the effects of the various cement hydrates on the durability of the block. It also reviews the block production process and its influence on the initial performance characteristics of CSBs. The main feature of Chapter 3 is therefore the identification of the main production variables affecting the properties and performance of the CSB. These variables are examined experimentally in Part B of the thesis.

Part B: *Main Investigation Methods and Findings*

Part B of the thesis consists of Chapter 4, 5, 6 and 7.

Chapter 4 describes the fieldwork undertaken in Uganda and the results obtained. It presents findings from the following: inventory of the types and numbers of CSB buildings; characteristics of their exposure environment; visual inspection of defect types and severity; in-service measurement of the main defects; quality tests on soils, cement and water; work-study evaluation of block site production practices, and results from questionnaires and interviews. The significance of Chapter 4 is that the defect types reported on were a result of genuine weathering conditions. Since the full effects of the entire range and distribution of deterioration agents acting on the blocks in their full scale size and within the restraints of adjoining blocks and mortar could be observed and limited measurements taken, the results obtained were fairly reliable and useful for generalisations to be made. The same applies to findings from block production site and quality of the constituent materials examined. The results from interviews and interactions with stakeholders are also discussed in Chapter 4.

Chapter 5 describes the main experimental design and sample preparation methods used for laboratory tests. It explains why the experimental soil type was fixed for all types of tests while the stabiliser content and type, mix-water content, moulding pressure, curing conditions were varied for the different categories of block samples prepared. Chapter 5 also presents the two main categories of block types produced for further experimentation: improved blocks (containing cement and microsilica) and traditional blocks (containing cement only and cement plus lime). It is the comparison of the properties and performance of these two types of blocks that constitutes the core of the experimental work in this research. Chapter 5 also shows the main block sample sizes produced and provides test results on the laboratory experimental soil which was blended for the research. It was from the samples produced as described in Chapter 5 that further surface and bulk property tests were conducted.

Chapter 6 investigates block bulk properties and compares the performance of improved and traditional blocks. The properties examined experimentally include: wet compressive strength and dry compressive strength, total water absorption, block dry density, and total volume porosity. The effect of varying the main input variables on these properties are analysed. Chapter 6 records the main features of the standard tests used, and argues for the need to establish more appropriate calibrated tests for CSBs. Factors likely to affect the various test types are discussed. The implications of particular test results and their correlation to other block properties are discussed.

Chapter 7 reports on the microstructural features of block surfaces and discusses the main surface test method used and the results obtained. It explains how thin-section micrographs were obtained to identify the general surface features of CSBs. This Chapter also argues for the need for a more reliable surface test method and describes a new accelerated surface test method. The results of surface performance tests using this method on improved and traditional block samples, as well as those from comparable materials, are discussed. A new block classification system based on their index values is presented. Factors considered likely to influence the results such as equipment type, sample dimensions, pre-treatment, duration of slaking and nature of the slaking liquid are all described. Chapter 7 also discusses the correlation between different block properties based and their slake durability index.

Chapter 8 is the final chapter of the thesis, integrating and summarising the main conclusions and recommendations from Parts A and B. The Chapter also highlights the implications of the research findings and identifies areas for further research.

At the end of the thesis, references and appendices are presented. The appendices illustrate and support sections of the thesis that could not be included within the main body of the write-up. Summaries of experimental methodology and full tables of results are included in the appendices.

PART A:

LITERATURE REVIEW ON DURABILITY AND STABILISATION

CHAPTER 2

CONCEPT OF DURABILITY IN CSBs

2.1 INTRODUCTION

Cement based building materials like CSB's and concrete were originally promoted as having an indefinitely long service life, and that they would require only minimum maintenance. Many cement based materials have indeed given excellent service. However, as these structures continue to be left exposed, it is becoming evident over time that even normal exposure conditions are actually more deleterious than originally thought (Baker et al, 1991; Sjostrom et al, 1996). Occurrences of undesirable, unpredicted premature deterioration where defects are clearly visible even to the casual observer, are becoming common. Defects in CSB structures are mainly presented as surface erosion, volume reduction, cracking and crazing, surface pitting and roughening, and detachment of render. These deterioration phenomena have been predominantly witnessed in the wet humid tropical regions of the world. No similar adverse reports have been documented from the hotter and drier regions (Spence & Cook, 1983).

In this chapter, it is noted that while much research has been undertaken in the recent past on initial properties of CSBs, very little similar research has been done on its durability. Recent advances have however been made in the durability research of comparable materials such as concrete. These are now well documented, and moves to redress identified shortcomings are following. By contrast as mentioned before, no durability research work has been conducted for decades in the case of CSBs. Yet the urgency is even more acute. Interest in the durability of CSBs is likely to become a major concern in the foreseeable future given the potential of the material in alleviating shelter backlogs in developing countries (Gooding, 1993).

Durability research is a complex undertaking. This is because in practice several causes of deterioration will occur simultaneously. These are compounded by cumulative as well as synergistic actions. In recognition of such intricacies, the objectives of this chapter are several, namely to:

- identify the most critical deterioration agents, their effects, and severity ranking;
- understand the main mechanisms involved, their modes of progression and propagation;
- suggest measurement techniques to quantify the main outputs of deterioration;
- recommend selected remedial measures

Chapter 2 is presented in four main sections. After this introductory section, the main expressions of durability and deterioration are discussed. This is followed by a discussion of the main deterioration mechanisms likely to occur in CSBs. A brief conclusion then follows.

2.2 EXPRESSION OF DURABILITY AND DETERIORATION IN CSBs

The terms durability and deterioration are perhaps the two most commonly used words in the field of construction materials. This section attempts to describe the basis of these two terms, and examines their relevance to the performance of CSBs.

Durability

The word durability originates from the Latin word '*durabilis*' which means 'lasting' (Franklin & Chandra, 1972). It can be used in the context of most building materials to mean resistance to weakening and disintegration over time. The term has been described in various ways by different authors although the substance appears to remain the same in all cases. According to BS 7543 : 1992, durability is defined 'as the ability of a building and its parts to perform its required function over a period of time, and under the influence of agents'. But according to BSI CP3 1950, 'durability is a measure, albeit in an inverse sense, of the rate of deterioration of a material or component'. More recent definitions state that 'durability may be regarded as a measure of the ability of a material to sustain its distinctive characteristics, and resistance to weathering under conditions of use for the duration of the service lifetime of the structure of which it forms part' (Baker et al, 1991; Sjostrom et al, 1996; Glanville & Neville, 1997). These definitions are too general to be of any practical use with CSBs.

The author proposes that the definition and concept of durability be based on three key parameters, namely:

- intended function of the material,
- the standardised conditions of its use, and
- the time the material is required to fulfil its functions

The *intended function* of a CSB is as an internal and external walling unit. The primary desirable characteristics of walling units are strength, dimensional stability and resistance to weathering (ILO, 1987; Carroll, 1992). These properties are to a large extent governed by the choice of constituent materials, and by the quality of the manufacturing process used in their production (Webb, 1988). In terms of intended function therefore, the ability of a block to sustain its distinctive characteristics under service conditions for the service lifetime of the structure is very important. Unfortunately, the values of initial performance characteristics of a block are not likely to remain constant over time. Variations in properties can come about due to the evolution of the block fabric as it undergoes changes induced by the effects of its exposure conditions. The changes can lead to loss of performance, implying that every material has its durability limit. The durability limit is the point at which loss of performance leads to the end of the service life of a material (BS 7543, 1992). The threshold for satisfactory performance for CSBs is yet to be defined.

Standardised conditions of use ought to be included in the definition of durability. As walling units, CSBs are used on the exterior of buildings. They are therefore exposed to physical, chemical and biological elements. Some of these agents can have deleterious effects on blocks even under normal conditions of use. The fact that CSBs when used in the humid tropics (characterised by heavy and intense rainfall) are more vulnerable to surface erosion than similar blocks used in dry areas, supports the reasoning that conditions of use be included in the definition of durability (Fitzmaurice, 1958; Spence & Cook, 1983). Harsh conditions of use can lead to wear, cracking, dampness and undesirable dimensional changes. However, CSBs are still required to resist the effects of exposure conditions for the service lifetime of the building. The requirement for resistance will vary according to the different types of agents involved. For each of the different deterioration agents identified, it will be helpful to specify the particular aspect of durability required. For example 'abrasion-durability, slake durability, heat durability, chemical durability' etc., all require matching durability thresholds. The main reason is that the mechanisms for each deterioration agent are different. Moreover, not all types of agents are likely to be in operation in different parts of the world. As can be expected, different tests will also be required to measure the effects of the different deterioration agents.

The *time* the block is expected to fulfil its intended functions (in the definition of durability) should also be specified more clearly to meet the users requirements. In the case of building structures, the time ought to be expressed in terms of years of satisfactory life. Guidelines on building life categorisation are provided in BS 7543 : 1992. These range from 10 years in the case of temporary buildings to over 120 years in the case of high quality buildings. The effect of exposure conditions leading to loss of performance is likely to be gradual but not abrupt. The rate of loss of performance or quality of a block is also likely to depend primarily on the actual conditions of exposure: blocks left exposed in the humid tropics will be more vulnerable to rapid deterioration than similar blocks used in arid regions (Fitch & Branch, 1960). Since blocks are meant to be maintainable materials rather than replaceable materials, specification of expected performance limits over a certain period of time and under specified conditions of exposure, are long overdue.

Deterioration

Deterioration has been defined by several authors as 'the time-related loss of quality of a material, usually under the influence of environmental agents' (BS1 CP3 1950; BRE, 1980; Baker et al, 1991). Premature deterioration has also been defined as 'failure to achieve the predicted service life' (BS 7543, 1992). The predicted service life of a block can be obtained from recorded performance or from accelerated tests. Unfortunately, such records are not available.

Failure due to the inability of a newly made block to fulfil its functions has to be clearly distinguished from failure brought about by alterations in properties over the service lifetime of a block. Indeed most building materials will have some of their properties altered over time although their durability may not always be called to question. The durability of a block can therefore be regarded as its ability to resist deterioration. It can be treated as the reciprocal of deterioration under pre-defined conditions (Sjostrom et al, 1996).

Due to deterioration however, the durability of a block is unlikely to remain constant. It may in fact change considerably. The implication is that durability of a block and its deterioration are likely to influence each other mutually but negatively. As can be expected, the more a block deteriorates, the less durable it is likely to become over time. For example bulk properties of a block such as water absorption and permeability are related to the type of microstructure and density of the block. However, the microstructure and density of a block may alter appreciably due to weathering (deterioration). This alteration can in turn increase the water absorption and permeability of the block. Such increases are likely to accelerate the rate of deterioration due to softening and dissolution of any unbound soil particles in the block. Further loss of performance can then be expected. The limit at which the loss of performance can be considered unacceptable is not yet well defined in CSBs. Unfortunately, even if it was, the limit may not be easily applicable without further qualification. This is because depending on the constituent materials used in a block, and on the quality of the processing methods used, no two blocks might be easy to compare. Unacceptable deterioration will therefore vary from block to block, and from property to property. Block properties that diminish over time reflect the past history of the block, both during and after manufacture.

2.3 DETERIORATION MECHANISMS IN CSBs

As is the case with most other building materials, deterioration mechanisms in CSBs are varied and complex. From the literature and experience gained through the use of the material, laboratory tests, building inspection records and the exposure condition surveys, three main deterioration modes can be identified, namely:

- Water related deterioration
- Temperature related deterioration
- Chemical based deterioration

These are now discussed each in turn in the following sections.

2.3.1 WATER RELATED DETERIORATION IN CSBS

Water related deterioration mechanisms account for most of the observed premature deterioration defects in CSBs (Fiztmaurice, 1958; UN, 1964; Lunt, 1980; Agarwal, 1981; Spence & Cook, 1983; ILO, 1987; Norton, 1997). Water also serves as a common denominator for other deterioration mechanisms occurring in blocks. The main sources of water linked to such deterioration mechanisms are rain, rising damp and condensation. The action of water in causing deterioration in blocks can occur in any one or all of the following ways:

- solvent action
- abrasive action
- swelling action
- catalytic action

The first two in the above list, namely solvent action and abrasive action are discussed in this section. The last two, namely swelling action and catalytic action are discussed in Section 2.3.3 (chemically related deterioration). For each action, an attempt is made to describe its nature, where it occurs, when it occurs, why it occurs and how it is likely to occur in a block. Where possible, references to similarities and differences with associated mechanisms in concrete materials are examined.

The *solvent action* of water is mentioned in the literature as one of the most common deterioration mechanisms occurring in many building materials (Sjostrom et al, 1996). The ability of a block surface to easily get wet, and the capacity of the block to absorb and retain water for sufficiently long periods of time, are two properties likely to leave the material vulnerable to the solvent action of water. The composition of a block fabric itself might also contribute to its vulnerability. Over 90% of the block bulk consists of soil, with the other 10% or less consisting of cement. In a stabilised block matrix, the process of cement-stabilisation is known not to affect all the constituents in the block (Herzog & Mitchell, 1963; Houben & Guillaud, 1994). Moreover, the hydration reaction between OPC and water which is responsible for the binding action in the block also produces soluble by-products such as calcium hydroxide (Illston, 1994). The microstructure of a block consists of materials which are juxtaposed with capillary pores. The block is therefore able to attract water and retain it. As water permeates the block, any unstabilised soil fraction present, together with the freed calcium hydroxide from the hydration reaction of cement, can be expected to dissolve. Dispersal and subsequent leaching out of these substances can then follow. Repeated action of this nature over the years can lead to overall softening of a block fabric. Such action can also have the effect of weakening and altering the microstructure of the hardened cement matrix in a block. The microstructure of a block is therefore likely to continue evolving throughout its service lifetime. This is a detrimental trend since the softening and leaching action is irreversible. The severity of the action can be expected to increase during the rainy seasons, and to depend on the proportions of materials present in the block which are vulnerable to dissolution and softening. Unfortunately, as this form of deterioration progresses, it has the adverse potential of making the block more vulnerable to other forms of deterioration such as the erosive action of rainwater droplets. The solvent action of water in causing deterioration is not investigated experimentally in this thesis.

Surface abrasion by rainwater has been identified from literature sources as one of the most common deterioration mechanisms associated with water (Atkinson, 1970; Agarwal, 1981; Eaton, 1981; Fullerton, 1979; Ola & Mbata, 1990). Fortunately however, surface erosion only occurs in areas prone to frequent and intense rainfall such as obtains in the humid tropics. The mechanism of surface erosion in blocks might not yet be well understood but the phenomenon is thought to proceed as follows. When rainwater strikes an exposed block surface, it will directly impact on it, with part of it turning into a spray. While the effect of the impact can be likened to the removal of loose particles, the effect of the spray is more likely to first wet the block surface. It has been estimated that up to 75% of the energy of a raindrop is dissipated on impact (Ellison, 1944; Goldsmith et al, 1998). The erosivity of raindrops depend on the state of bonding of the block surface, and on the characteristics of the rain. The state of bonding of a block surface is discussed in Chapter 3. The main characteristics of rain are defined by the drop size, its distribution, fall velocity and impact kinetic energy (Gunn & Kinzer, 1949; Laws, 1941; Hudson, 1963; Wilson, 1993). It is therefore the interaction between the raindrop size, velocity and shape, storm duration and wind speed that is likely to control the erosive power of the raindrop. It would be reasonable to expect that the higher the impact velocity of a raindrop and the weaker the state of bonding at the block surface, the greater would be the effect of surface erosion. Conversely, the lower the impact velocity of a raindrop, the greater is the effect of the raindrop forming sprays on the surface of the block. Any detached soil particles, (usually assumed to be from the unstabilised fraction of the block surface fabric), can then be easily removed by the resulting wall surface flow. The effect of surface abrasion is irreversible. The defects linked to this process are discernible even to the casual observer. They include recessed wall surfaces and volume reduction caused by mass loss. Indirect effects of surface erosion include lowering of surface hardness, lowering of compressive strength, loss of rigidity, lowering of density and increase in permeability. The loss of mass from a block surface can have other more serious consequences. Given the mechanism of quasi-static compression used in forming blocks, their inside core is the part least affected by compaction (Gooding, 1994; Houben & Guillaud, 1994). This part is therefore considered to be its weakest link. As can be expected, exposure of the interior due to recessed surfaces can lead to the speeding up of the rate of deterioration. Extra measures are therefore needed to strengthen the block surface in order to protect its bulk from exposure.

Unlike in CSBs, the phenomenon of surface erosion (to the extent it occurs), has not been reported in concrete literature. Given the low amount of OPC used in CSBs (5-8% by weight) as compared to concrete products (12-14% by weight), weaker inter-particle bonding in the former can be expected. Moreover, even with the low amount of cement used, full hydration of the binder might not be fully achieved. This is because unlike in concrete where the water-cement ratio can be pre-determined accurately, the effective water-cement ratio in CSBs is still difficult to define. Moreover the water required for the hydration of cement is shared between the cement and the highly hydrophilic clay in the soil. The water is also required to be at an optimum level to fully lubricate the soil particles to achieve maximum densification. The equilibrium between these three requirements for the mix-water are not yet fully understood. Until this is done the incomplete hydration of OPC will continue to lead to weaker block fabrics. A denser, homogeneous and impermeable block surface would probably minimise the effect of surface erosion more than one which is not. In this thesis, the performance of block surfaces produced by changing input variables such as cement content, compaction pressure, cement replacement materials, etc., are investigated experimentally (Chapters 6 and 7). The severity of surface erosion is also investigated through a case study conducted in Uganda (Chapter 4).

2.3.2 TEMPERATURE-RELATED DETERIORATION IN CSBS

As CSBs form the exterior part of buildings, they will inevitably experience regular temperature variations. The daily maxima and minima, diurnal temperature differences and temperature levels will vary depending on the geographic location of the CSB building (BRE, 1980; Wilson, 1993). High ambient temperatures are common in tropical and sub-tropical regions of the world (Hammond, 1972; Spence & Cook, 1983; McIllveen, 1998). Maximum daily ambient temperatures averaging 40°C to 50°C occur in such areas especially between late mornings and early afternoons, often peaking at midday on cloudless days. At night, temperatures may drop to below 0°C. The diurnal temperature variation can therefore exceed 50°C (Anderson, 1982). Moreover, sunshine and night hours are long, typically averaging 12 hours each day most of the year. Such extremes provide contrasting settings for temperature related deterioration to occur in CSBs.

Temperature variations of such magnitude can cause both reversible and irreversible changes in the physical and chemical properties of blocks. These changes are likely to influence the durability of blocks in three main ways, namely:

- expansion and contraction of the block fabric
- shrinkage and drying (of clay and hardened cement paste)
- catalytic action (for chemical reactions)

Expansion and contraction of a CSB fabric due to temperature variations is likely to be detrimental to the properties of the material in the long run. Similar dimensional changes are also reported in concrete research (Baker et al, 1991; Glanville & Neville, 1997). Deterioration is likely to result from stress levels induced within the block. CSBs have a positive coefficient of thermal expansion, typically ranging between 0.010 mm/m°C and 0.015mm/m°C (Rigassi, 1995). It is the absorbed radiation which is responsible for the temperature rise in blocks. The amount of radiation absorbed depends on the specific heat (C) and the thermal conductivity (λ) of the block. Typical values for blocks range between 0.65 and 1.00 kj/kg for the former and between 0.23 and 1.04 W/m°C for the latter (Houben et al, 1996). The values vary from block to block depending on the moisture condition at the time of the temperature change and testing, and on the composition of each block. At high temperatures, a block can easily expand. But the expansion can be restrained by adjoining blocks as well as the embedding mortar. The expansion of a block can induce significant internal stresses (compressive and tensile). Since blocks are weaker in tension, such stresses can be expected to be more harmful to its fabric. Further, as stress and strain tend to occur together, any restraint of movement for the expanding block introduces a stress corresponding to the restrained strain (Neville, 1995; Case, Chilver & Ross, 1998). If this stress and the corresponding restrained strain within a block are allowed to develop to such an extent that they significantly exceed the bulk strength or its strain capacity, then interfacial bonds that bind and hold the soil particles within its fabric together can be weakened. In more extreme conditions, they might even be severed apart altogether. Cracks are then likely to appear and propagate on the surface of a block. Not only can such cracks facilitate entry of moisture, but they are also unsightly.

Conditions at night represent the complete reverse of the situation during the day. Contraction of a block can be expected to take place, at temperatures about or below zero degrees Celsius. This occurs in an attempt to revert to the pre-expansion order. The effect of cooling is rather late since irreversible damage to the block fabric is likely to have already occurred due to expansion. It is such continuous, cyclic and repeated phenomena of expansion and contraction that can eventually degrade the block (Torraca, 1988). The effect of expansion and contraction of blocks due to high temperatures are not investigated experimentally in this thesis. A case study to link various cracking patterns to this mode of deterioration was however undertaken (Chapter 4).

Shrinkage and drying of CSBs can also be associated with high ambient temperatures. According to literature sources, block surfaces left unprotected from direct sunlight can absorb considerable amounts of solar radiation, raising surface temperatures beyond that of the surrounding air temperatures (BRE, 1980). Surface temperatures as high as 100°C and shade temperatures as high as 60°C have been reported in parts of the humid tropics (BRE, 1980). Such high temperatures can cause dimensional changes to occur in a block resulting in a fractional reduction in its volume .

Two different mechanisms of shrinkage are believed to take place in a block (BRE, 1979). These are shrinkage due to the expulsion of water from its capillary pores, and shrinkage due to the withdrawal of moisture from the clay fraction and the hardened cement paste. While the former is considered to be a reversible process, the latter are irreversible. At high ambient temperatures, moisture can be lost from a block through evaporation. Unbound water filling the capillary pores in a block are expelled in the process. Any dimensional changes that follow are likely to be insignificant. This reversible process has been reported as not being harmful to the block fabric.

However, even after the expulsion of all capillary pore water, there can still remain some water within a block fabric. This can occur in the form of strongly adsorbed water within unstabilised clay platelets and the hardened cement gels. This water can only be gradually withdrawn at high temperatures over long periods of time. The withdrawal is a slow process, but more significantly an irreversible one in the case of the hardened cement paste (Van Olphen, 1997; Torraca, 1988; Glanville & Neville, 1997). The mechanisms of withdrawal for clay and hardened cement paste are different but are not discussed further in this thesis. The effects of shrinkage and drying in CSBs are not investigated experimentally in this thesis. Defects arising due to their action were however evaluated during the fieldwork (Chapter 4).

The *catalytic action* of temperature variations in initiating and propagating chemical reactions is a well known phenomenon in most cement based materials. The phenomenon is also widely reported in concrete literature (Baker et al, 1991; Bungay & Millard, 1996; Jackson & Dhir, 1996). Most chemical reactions that would not have occurred within a block at low ambient temperatures are more likely to take place at higher temperatures. As stated earlier, fluctuations of temperature can influence moisture movement within a block. The combination of the presence of moisture within a block, and high temperatures has been known to provide the catalytic setting responsible for reviving otherwise dormant chemical activity.

Temperature variations are associated with the control of the rate of chemical activity. Reactions facilitated by this type of mechanism include soluble salts crystallisation, oxidisation, leaching, etc. It is reported that an increase in temperature of only 10°C can double the rate of chemical reactions in most cement based materials (BRE, 1980). Increasing the rate of deleterious chemical activity can be potentially harmful to a block in the long run. The mechanisms of the various chemical reactions linked to temperature variation are discussed in Section 2.3.3.

In summary, temperature related deterioration in blocks are likely to affect the following block properties: shape, dimensions, strength, surface hardness, rigidity, permeability, brittleness and appearance. The severity of deterioration will depend on the degree of cloud cover, degree of shading from direct sunlight, geographic location, orientation of the building façade, moisture condition of a block and its texture, opacity and colour of the block (BRE, 1980). The influence of some of these factors were investigated during the fieldwork that formed part of this research (Chapter 4). To minimise the effects of temperature variations, surface protective measures ought to be adopted. These can include use of reflective coating, surface render, low roof overhangs, etc., which can all be specified whenever blocks are thought to be especially vulnerable to high ambient temperatures.

2.3.3 CHEMICAL-RELATED DETERIORATION

The deterioration of CSBs can also be linked to the effects of chemical activity. According to literature sources, mechanisms associated with chemical action in CSBs remain the least investigated (Houben & Guillaud, 1994). Yet sources of potentially reactive chemicals in a block are soil and cement. Soils which constitute most of the bulk of a block contain minerals as well as contaminants (Lunt, 1980). Some of these substances can remain dormant and stable when not in active contact with environmental elements (rainwater, high temperatures, relative humidity, gasses). Ordinary Portland cement as the main binder in blocks also contains potentially unstable chemical constituents even in the hardened cement paste phase. Contact with environmental agents can catalyse chemical reactions in cement hydrates (Illston, 1994).

The precondition for chemical reaction to start in most cement based materials is the presence of moisture (Lea, 1970; BS 7543, 1992). Due to seasonal moisture variations from heavy rainstorms and humid conditions in the tropics, chemical reactions can be expected to occur within a block during its service lifetime. The rate of such reactions is likely to be influenced by variations in ambient temperatures as discussed in Section 2.3.2. Environmental conditions found in the humid tropics therefore provide the best possible setting for chemical activity to occur in a block. Based on the nature of their action and resulting effects, deleterious mechanisms of chemical action can be broadly categorised into three groups, namely:

- leaching out effect (clay and calcium hydroxide)
- expanded product formation (internal stress generation)
- direct decomposition (of the cement binder)

These are now each briefly discussed in turn.

Leaching out effect

Leaching is a phenomenon that involves the washing out of soluble substances from a material (Jackson & Dhir, 1996). There are two key sources of soluble substances in blocks: the calcium hydroxide found in the hardened cement paste, and the clay fraction likely to be found in residual unstabilised or partially stabilised matrix of a block (Houben & Guillaud, 1994; Young, 1998).

Calcium hydroxide ($Ca(OH)_2$) is known to easily dissolve in water (Illston, 1994; Neville, 1995). The dissolution process is irreversible once started, and is known to be facilitated by high temperatures, and the presence of carbon dioxide. Moreover, block properties such as water absorption and permeability, are likely to ensure that adequate moisture is absorbed and circulated within a block. Dissolved calcium hydroxide can be removed out of a block in either of two ways. It may simply be washed out of a block through surface flow on saturation during rainstorms, or it may be expelled onto the block surface by evaporation due to high temperatures. The phenomenon of leaching out of calcium hydroxide is also widely reported in concrete literature (Baker et al, 1991; Illson, 1994; Lea, 1976; Taylor, 1998; Young, 1998). There is no justifiable reason to expect that similar occurrences would not occur in CSBs.

Residues of unstabilised soil (usually clay) have been found in a stabilised block fabric (Herzog & Mitchell, 1963; Houben & Guillaud, 1994). Even within the recommended limit of less than 30% by weight of a block which is generally tolerated, the presence of clay is a potential source of problems. Owing to its fineness and high specific surface area (Chapter 3), not only can clay grains obstruct the stabilisation process, but they are also likely to compete for the mix-water required for the hydration of cement (Van Olphen, 1977). Clay can also coat the surfaces of coarse soil fractions (fine gravel and sand). Such coatings can inhibit the binding effect of cement on these particles. During rainy seasons, a block can rapidly absorb rainwater. The attraction of water by clay minerals has been explained by various mechanisms but ion exchange appears to remain the dominant mechanism (Carter & Bently, 1971; Franklin & Chandra, 1972; Ingles & Metcalfe, 1972). The amount and type of clay in a block can affect the degree of dispersion or flocculation. Kaolinite clays whose structure comprises platelets at a fixed distance are more stable in water, but are still capable of being disrupted. Ilite and montmorolinite clays on the other hand, which mostly contain interlayer potassium favour hydration in their dispersal (Houben & Guillaud, 1994). The swelling of clay lattice is known to assist in the mechanism of dispersal. Dispersed clay in a block fabric can easily be washed out as moisture permeates and circulates within it during rainy seasons.

The combined effect of leaching out of both calcium hydroxide and dispersed clays from a block is likely to be more severe in CSBs than in concrete. Extensive leaching is known to increase the porosity of a material (Neville, 1995). This can cause a block to become progressively weaker, and more permeable. A weakened block surface is more vulnerable to the direct abrasive action associated with driving rains. Since these mechanisms are likely to occur for the duration of the service lifetime of a block, deterioration over time can be expected.

The effects of leaching can however be minimised in blocks if certain preventive measures are taken early enough. These include the following:

- the use of pozolans and lime in combination with OPC during stabilisation. Pozolans and lime have the ability to fix both the calcium hydroxide present in hydrated cement paste and in any excess clay respectively (Hilt & Davidson, 1960). This approach is investigated experimentally in this thesis (Chapters 6 and 7).
- use of denser and more homogenous blocks of low permeability (less than 1.10^{-5} mm/sec) and of low water absorption capacity (less than 15%).
- careful soil selection that avoids use of soil with excessive clay content (<30% when OPC is used as the sole stabiliser).

- adequate curing of blocks.

Expanded product formation

Certain categories of chemical activity that can influence the durability of CSBs are associated with the formation of expanded products within a block. According to literature sources, such expanded products can occupy a greater volume within the block than the compounds which they replaced. By forcibly trying to occupy space that is not readily available, internal stresses can be generated within a block. Reactions of this category are well documented in concrete literature (Lea, 1970; Lea, 1976; Neville & Brookes, 1994; Illston, 1994; Neville, 1995; Sjostrom et al, 1996; Taylor 1998; Young et al, 1998). Apart from the occasional mention of the harmful effects of organic matter and other soil contaminants, no similar documentation of this phenomenon is covered in CSB literature. Yet the potential for such effects may be even greater in CSBs.

The three main categories of reactions likely to affect the durability of CSBs through expanded product formation include:

- Sulfate attack (on cement hydrates)
- Alkali-aggregate reactions (involving silica and carbonates)
- Soluble salts crystallisation (within the voids in a block)

Sulphates occur widely in natural soils in most parts of the world (Scot, 1965; Ingles, 1962; Ingles & Metcalfe, 1972; Jackson & Dhir, 1994). The type of sulfates vary greatly. But the common ones in soil are calcium, sodium and magnesium sulfates. These are mostly found in clayey soils rather than in sandy soils. The inclusion of significant amounts of sulfates in CSBs cannot be ruled out since no tests have so far been devised for their detection during soil selection. In the presence of sufficient amounts of moisture, sulfates present in soil can readily dissolve in water and react with certain hydrated cement products namely, calcium hydroxide and calcium aluminate (Neville, 1995). The dissolution of sulfates in water can create a sulfate solution within a CSB fabric. The sulfate solution might then react with both the $Ca(OH)_2$ and the hydrated C_3A to form calcium sulfate (gypsum), and calcium sulphoaluminates compounds (ettringite) respectively (Neville, 1995). The volume of these two by-products is much greater than that of the original substrates in the block. As these products expand in order to occupy more space within a block, and when this expansion is restrained by adjacent particles and phases within the core of the block, significant internal stresses are generated. The generated stresses are capable of disrupting bonding within the block. This can in turn result in a weakened block of lower strength, rigidity and hardness. The reactions are irreversible and their deleterious effects are noticeable within only a few years of their occurrence. The damage in blocks is commonly presented as defective edges and corners. These can also be followed by spalling and cracking of the block surface.

The severity of sulfate attack on CSBs depends on a number of factors. They include: type and amount of sulfates present in the soil, type of cement used, and the bulk properties of a block. The effect of sulfate attack on CSBs is not investigated experimentally in this thesis.

Alkali-aggregate reactions (AAR) can also be expected to occur in CSBs. According to literature sources, the reaction is essentially an inter-constituent material reaction also with the potential to form expanded products in a block. The reaction can occur between the active silica and carbonate containing soils and the alkalis (Na_20 and K_20) present in minute quantities in OPC (Glanville & Neville, 1997). Alkalis may also be present in remote amounts in most soils (ILO, 1987). Two kinds of alkali-aggregate reactions, both potentially harmful to blocks, are distinguished:

- Alkali-silica reactions (ASR)
- Alkali-carbonate reactions(ACR)

These phenomena and the mechanisms involved are also widely reported in concrete (Neville, 1995).

Defects on blocks resulting from AAR reactions will most likely appear as map cracking and spalling, occurring mainly on the surface of the block. Cracking of the star shaped pattern is the most common, but not necessarily the only type (Palmers, 1988). Factors likely to influence AAR reactions in CSBs include the following:

- availability of moisture
- high temperature environments (10°C-40°C)
- concentration of alkalis in cement and soil
- concentration of active silica and carbonates in soil
- porosity and permeability of the block

From the above factors, the main preventive measures for AAR in CSBs should involve procedures that attempt to lower the alkali content in the cement while it is still in the plastic state. The addition of pozolans to the soil-cement-water mix at the time of stabilisation could be helpful. The main reason for using pozolans is that they easily combine with the alkali content of the cement and soil, thus effectively lowering the alkali content. AAR can therefore be avoided in CSBs by using low alkali cements, non-reactive soils and pozolans blended with OPC (Glanville & Neville, 1997).

Soluble salts crystallisation (SSC) can occur within the pores and voids spaces of a block. According to literature source, the crystallisation of salts results in expanded product formation (Neville & Brooks, 1994). As before, such products have the potential to generate significant internal stresses within the pores and void spaces in a block. The phenomenon is widely reported in concrete literature (Sjostrom et al, 1996). Soluble salts are commonly found in most soils especially sandy soils. Sandy soils won from rivers can also contain appreciable amounts of soluble salts. Amounts as little as 6% of the mass of the sand are enough to trigger off such reactions (Neville, 1995). The most common salts are usually sulfates and chlorides (Neville & Brookes, 1994). Although these salts could easily be removed by washing of sand, the procedure is rarely followed in most developing countries. Sand is normally imported from various sources to improve the particle grading of soils needed for stabilisation (ILO, 1987; Rigassi, 1995). The soluble salts are however not reactive in the solid form in which they are normally present in the sand. They will only become reactive in solution. The alternate wetting and drying of block surfaces provides an ideal setting for such reactions. The mechanism of SSC is thought to be as follows.

When soluble salts in solution are present in a block fabric, they are likely to permeate into its capillary pores. Due to high temperatures leading to evaporation, moisture is driven off from the solution causing the salts to crystallise within the pores and voids spaces of the block. The volume of the crystals increase as the pore spaces get filled. But any further increase can be resisted by the rigid block fabric. This leads to the creation of significant stresses within the pores in the block. The induced stresses can cause cracking and disintegration at the surface of the block. Progressive deterioration of the block surface can then take place as moisture and temperature variations occur over the service lifetime of the block. The deterioration mechanism is known to be unaffected by the type of cement used (Jackson & Dhir, 1994). Limits on the soluble salts content of soil (especially its sand component) should therefore be specified during soil selection for CSB production.

Due to the threat from SSC, use of CSBs below the foundation level is still prohibited (Rigassi, 1995). Moreover, even blocks used at short distances above ground level in the lower courses of a wall may also be vulnerable to deterioration from SSC. The lower layers of a wall can be plastered to minimise such incidences.

Direct decomposition of the cement binder

Direct decomposition of cement within a CSB can occur due to attack from acidic conditions. No OPC is known to be resistant to acid attack (Neville, 1995). The direct decomposition of OPC can lead to the progressive break up of the bonds that hold the CSB fabric together and progress towards the interior. The phenomenon is widely reported in concrete literature (Jackson & Dhir, 1994).

In summary, apart from attempts to attribute common defects in blocks under service conditions to each of the chemical actions described, no attempt was made in the thesis to experimentally investigate their deleterious effects on blocks. Defects assessment conducted during the fieldwork confirmed the occurrence of chemically induced deterioration in blocks (Chapter 4). Further future research is recommended in the area of chemically induced deterioration in CSBs.

2.4 CONCLUSION

From the preceding discussions in Chapter 2, it can be concluded that the concept of durability and its expression are not well covered in CSB literature. It is proposed that expressions of durability in CSBs should revolve around three factors, namely: intended function of a block, the expected service conditions, and the time taken to satisfactorily fulfil the functions.

It was established through literature reviews in Chapter 2 that even under normal service conditions, deterioration agents can still influence the durability of a block. Under more severe conditions of exposure such as in the humid tropics, the effects of deterioration agents can lead to the premature deterioration of blocks. The durability of a block can therefore be regarded as its ability to resist deterioration. It was noted that due to deterioration, the durability of a block is not likely to remain constant, but can vary over time. Performance characteristics which were initially deemed satisfactory at the time of production can alter appreciably for the worse over time. Durability and deterioration therefore influence each other mutually but negatively.

According to literature sources, it was noted in Chapter 2 that the principal agents likely to influence the performance of a block while in service include: rainwater, temperature, and chemical action. The exact mechanisms of these actions are not yet fully understood. Their combined and interdependent action in causing loss of quality in a block is thought to be highly likely. It was further noted that water and temperature related deterioration mechanisms represented the main forms of deterioration in CSBs in the humid tropics. Water-related action not only causes loss in mass on the block surface due to wetting and abrasion, but also contributes to the initiation and propagation of otherwise dormant chemical activity. Water related deterioration was found to occur in various forms: solvent action, abrasive action, swelling action, catalytic action and dampness. Temperature related deterioration on the other hand causes volume changes which lead to the creation of cracks and weakening of the block fabric. Various mechanisms involving expansion and contraction, shrinkage and drying, and catalytic action were discussed. It was noted that high temperatures are linked with the speeding up of harmful chemical reactions. The combined action of wetting-abrasion and drying are investigated experimentally in this thesis (Chapter 7). It can be concluded that the mechanisms of water and temperature related deterioration are neither well covered nor properly understood in current CSB literature.

It was discussed in Chapter 2 that chemical action related deterioration mechanisms in blocks remained the least investigated and documented of all deterioration modes. Yet such reactions are potentially possible in CSBs due to the various minerals found in soils and OPC hydrates. Three categories of potential chemical reactions with deleterious effects were identified: reactions resulting in expanded product formation (sulfate attack, alkali-aggregate reactions, soluble salts crystallisation), reactions resulting in the direct decomposition of the cement binder (acid attack), and reactions resulting in the leaching out of substrates ($Ca(OH)_2$ and clay minerals). It will not be possible to experimentally examine these chemical action related deterioration mechanisms during this research. However, defects arising from their effects are investigated through the field exposure condition survey described in Chapter 4. Further research is recommended on all aspects of chemically-related deterioration mechanisms.

From these brief conclusions, the objectives of Chapter 2 were met.

CHAPTER 3

CEMENT-SOIL STABILISATION

3.1 INTRODUCTION

In Chapter 3, current documented principles and practice of cement-soil stabilisation as applied to the production of CSBs are discussed. Soil requires to be stabilised because the material as found in its natural state is not durable for long-term use in buildings. By properly modifying the properties of soil, its long-term performance can be significantly improved (Bureau of Reclamation, 1975; Dunlap, 1975; Herzog & Mitchell, 1963). Soil stabilisation processes focus on altering its phase structure, namely the soil-water-air interphase. The general goal is to reduce the volume of interstitial voids, fill empty voids, and improve bonding between the soil grains. In this way better mechanical properties, reduced porosity, limited dimensional changes, and enhanced resistance to normal and severe exposure conditions can be achieved (Gooding & Thomas, 1995).

The objective of this chapter is to closely examine current methods of soil stabilisation in general, and their application to CSBs in particular. The chapter describes the fundamental theoretical background on which subsequent experimental investigations which follow in Part B of the thesis are based. The approach used in Chapter 3 is to first identify and examine each of the three main constituents of CSBs (soil, cement, water), then evaluate existing methods used for combining them during the block production process.

Chapter 3 is presented in five sections. After this introductory section, subsequent sections describe the following: main constituent materials, cement-soil stabilisation principles, the block production process, and conclusion.

3.2 MAIN CONSTITUENT MATERIALS USED IN THE PRODUCTION OF CSBs

The three main constituent materials used in the production of CSBs are:

- Ordinary Portland Cement (for binding the soil particles)
- Soil (for the skeletal structure of the block)
- Water (for the hydration of cement and lubrication of soil particles

These three materials each have unique properties. Before discussing how they are combined to form blocks, a description of their nature and properties is presented. This approach is considered relevant because in the past, the individual properties of these materials were more or less taken for granted, with unfortunate consequences for blocks. The quality of material used and their proportioning can significantly affect the durability of blocks. Each material is therefore discussed in turn in Sections 3.2.1, 3.2.2 and 3.2.3 that follow.

3.2.1 ORDINARY PORTLAND CEMENT AS THE MAIN BINDER

Ordinary Portland cement (OPC) plays such a critical role in the performance of CSBs that the following aspects of the binder are briefly examined:

- Function of OPC in CSBs
- Physical properties of OPC likely to affect its performance
- Basic chemical constituents of OPC
- Hydration reaction of OPC following the addition of water

- Properties and influence of the hydration products on the durability of blocks
- Use of cement replacement materials

Functions of OPC in CSBs

Ordinary Portland cement is an important ingredient and variable in a CSB. Without its inclusion, compressed blocks would be no different from common sun dried mud blocks and would simply disintegrate on contact with water, or when subjected to moderate impact loads. Compared with concrete products where 12-18% by weight of cement is used, only about half of that amount (5-8% by weight), is required in stabilised blocks (ILO, 1987; Webb & Lockwood, 1987; Houben & Guillaud, 1994). Though not commonly recommended, amounts as low as 3% and as high as 10%, have been used depending on the nature of the soil requiring stabilisation (Rigassi, 1995).

The function of OPC is to strongly bind the constituent materials (soil particles) together, in a dense, strong, dimensionally stable and durable unit. Other common binders currently in use include lime, gypsum, pozzolans, resins and bitumen (Apers, 1983; Stulz & Mukerji, 1988). Discussions in this thesis will be restricted to the use of OPC as specified in BS 12, 1971 and ASTM C 150-92. OPC has been selected for two reasons. Firstly it has a unique and superior binding capacity. Secondly, it is widely available in most parts of the world.

The uniqueness of OPC in comparison with other binders is based on its ability to achieve extremely high strengths in only a short period of time (about 28 days). OPC stabilised blocks remain dimensionally stable even when in contact with water in a manner not possible for comparable unstabilised blocks produced in a similar way. Uncontrolled swelling and shrinkage are appreciably contained when OPC is used.

For stabilised blocks, variations in OPC quality and amount can drastically affect its properties and behaviour more than any other input variable (Gooding, 1994). The effect of varying the amount of OPC on the performance of CSBs are investigated experimentally (Chapters 6 and 7).

Unfortunately the manner of current coverage of OPC in CSB literature leaves a lot to be desired. The coverage is so limited, scanty and routine that widespread and incorrect use of the binder is now becoming the order of the day (Fullerton, 1979; BRE, 1980; Spence & Cook, 1983). Problems associated with the misuse of OPC are also described in Chapter 4 (findings from the fieldwork). Due to poor coverage, critical phenomena in cement chemistry such as the need for adequate amounts of water to ensure complete hydration of cement, and proper conditions to ensure preservation of moisture within the block to facilitate completion of the hydration process, are overlooked. For these and other reasons to be mentioned later, this section attempts to redress the shortcomings brought about by the narrow coverage of the subject in CSB literature.

Physical properties of OPC

Two of the most important physical properties of OPC are its:

- Specific surface area (SSA), and
- Particle size distribution (PSD)

The SSA and PSD of cement are important to CSB production because they govern the manner in which the binder stabilises soils. These physical properties are directly related to the process of manufacture of the binder. The basic source materials for OPC are a mixture of about 75% limestone ($CaCO_2$) and about 25% clay (Lea, 1976). These are intimately mixed, then ground together. In the modern manufacture of

OPC, the ground mixture is fed into a rotary kiln against a counter flow of hot air, and heated to about 1450-1800K (Neville, 1995; Taylor, 1998). The resulting melts from the mixture coalesce to form clinker, of approximate dimensions 5-10 mm. After being allowed to cool, the clinker itself is then mixed with about 3-5% gypsum ($CaSO_4$) (Taylor, 1998; Young, 1998). The gypsum is added to control the otherwise spontaneous capacity for initial setting. The mix is finally finely ground to give the powdery form in which OPC is traded. There can be as many as 1.1 x 10^{12} particles or grains of OPC per kilogram after the grinding process (Neville & Brookes, 1994). It is the grinding process that determines the SSA and the PSD of OPC. These are now discussed each in turn, with implications for the stabilisation of soil emphasised in each case.

The *specific surface area* (SSA) of OPC is in the range 300-350 m^2kg^{-1} (Lea, 1976; Illston, 1994; Jackson & Dhir, 1996; Taylor, 1998). This is lower than that of rapid hardening cement (RPC) which falls in the range 400-450 m^2kg^{-1}. Since the hydration reaction of cement while stabilising soils starts from the surface of the grains and then proceeds inwards, the higher the SSA, the faster can the rate of reaction be expected. The hydration reaction proceeds uninhibited if the cement grain surfaces are free. However, due to the large range of particles of varied SSA in soil, the likelihood of surface blinding is high. Fine sand and medium silt have SSA between 0.02 and 0.23 m^2g^{-1}, while clay grains have between 10 and 1000 m^2g^{-1} (lowest in kaolinite, highest in montmorollinite) (Akroyd, 1962; Grimshaw, 1971; Head, 1980). Interference due to the blinding of cement grains by any of these substances, and thereby inhibiting hydration, is likely but undesirable. Moreover, the large SSA of clay present in soil ensures that they can attract water in the mix otherwise exclusively meant for the hydration of cement, thus reducing the amount of water going directly to hydrate cement. This can impair the hydration process, with negative implications for strength development in CSBs. For this reason for example, use of clay contaminated aggregates is prohibited in concrete production (Jackson & Dhir, 1996). It would however, be highly uneconomical and impractical to try to eliminate clay from its parent soil before use in CSB production.

The *particle size distribution* of OPC is characterised by an almost uniform type of grading (or packing characteristics). Cement grains do not contain every size fraction between the maximum and minimum particle sizes. Approximately 90% of the cement grains in OPC measure more than about 5μm, with only 1% measuring less than about 90 μm (Weideman et al, 1990; Glanville & Neville, 1997). The average size of most OPC cements is about 10 μm. This can be compared to the size of the very fine clay particles in soil with average size less than 2 μm (Houben & Guillaud, 1994). The detrimental effect of the presence of clay has been mentioned already. Despite the potential setback, the use of clay in CSBs is likely to continue to be tolerated.

Basic chemical constituents of OPC

Identification of the main constituents of OPC, and description of their role in influencing the hydration reaction leading to the stabilisation of CSBs has received no previous coverage in CSB literature. From concrete literature sources, the summary of the main constituents, together with their approximate quantities and role in the hydration reaction, are shown in Appendix A.

The listed constituents of OPC are impure reactive minerals which exist as multi-component solid solutions (Weidemann et al, 1990; Taylor, 1998). The implication is that the reactions of these ingredients following the addition of water, and mixing with soil particles, is likely to be quite complex. As can be expected, not only will each of the ingredients react separately with water, but they can also influence the manner in which the others (including raw soil minerals), react with each other. In view of this, the exact mechanism of cement stabilisation of soil remains poorly understood and is likely to become a subject of active research for years to come.

Hydration reaction of OPC on addition of water

The hydration reaction that ensues when water is added to unreacted OPC grains follows two distinct phases: setting, followed by hardening, to form a cement paste (Young et al, 1998). The mechanism of the reaction involving the main phases in unreacted cement (C_3S, C_2S, C_3A and C_4AF), occurs at different rates for each phase. The process is reported to evolve as follows (Lea, 1976; Weidemann et al, 1990).

When water is added to the OPC grains, the reaction begins from the surface of the grains, then progresses inwards. This results in the formation of gels and ettringite (Taylor, 1998). The C_3S and C_2S form gels, while the C_3A form ettringite. Due to the increased contact between the formed gels on adjoining grains, and due to the interlocking of the ettringite crystals, cohesion develops signifying the start of the setting period (initial setting). This occurs within about 45-60 minutes of water being added (Illston, 1994). The implication of this is that the soil-cement-water mix should be compacted before the initial setting begins. The water continues to diffuse into the gels, causing pressure to build up within, resulting in rupture of the gel. The ruptured gel peels away from the grain, forming gel foils and fibrils as wells tubules in the case of C_3A. This exposes the grain surface locally to further hydration. The process then repeats itself. As each grain sprouts a multitude of these fibres and as they continue to grow and multiply, they start to interlock even more closely and rigidly than before. This signifies the end of the setting period. The final set occurs approximately 12 hours after water was initially added (Illson, 1994). The paste is however, still weak and therefore of low compressive strength. The implication of this is that freshly demoulded green blocks will remain weak at this stage and should therefore be handled with extreme care.

The paste then starts to harden. The continued hardening of the paste is due to the further multiplication, growth and stronger interlocking of the gel fibres, ettringite and portlandite crystals. Hardening is effectively 'completed' about 28 days after the initial contact with water. Although further hardening takes place after this at a decelerating rate, the defining timing is specified as 28 days. At 28 days, the paste, and by implication the block, should be hard enough to be used. The chemical reactions involving the four phases in OPC are summarised as follows (Lea, 1970; Illston, 1994; Neville & Brookes, 1994; Young, 1998; Taylor, 1998):

<u>For C_3S</u>:

$$2\,C_3S \quad + \quad 7\,H_2O \longrightarrow C_3S_2H_8 \quad + \quad 3\,Ca(OH)_2 \quad \Delta H\ 500 J.g^{-1}$$

(tricalcium silicate) + (water) ⟶ (calcium silicate hydrate) + (calcium hydroxide) heat of hydration

<u>For C_2S</u>:

$$2\,C_3S \quad + \quad 5\,H_2O \longrightarrow C_3S_2H_8 \quad + \quad 3\,Ca(OH)_2 \quad \Delta H\ 250 J.g^{-1}$$

(dicalcium silicate) + (water) ⟶ (calcium silicate hydrate) + (calcium hydroxide) heat of hydration

The reaction is accompanied by a high rate of heat evolution (exorthermic reaction), silicate polymerisation, rapid increase in [OH^-], and a concomitant rise in pH number to 12.6 (Neville, 1995). Both silicates are reported to require approximately the same amount of water for their hydration. The C_3S silicates generate about twice the amount of $Ca(OH)_2$ than the C_2S silicate. The release of $Ca(OH)_2$ has direct implications on the durability of CSBs (Chapter 2). The calcium silicate hydrates are fine amorphous particles in a colloidal state, often represented simply as C-S-H to emphasise their indeterminate nature as no specific formula is considered to be that accurate (Taylor, 1998).

<u>For C_3A</u>:

The reaction involves not only water, but also gypsum and the extra ettringite produced as a result of the interaction. The two reactions are thought to proceed as follows:

1. $$C_2A \;+\; 3\,C\bar{S}H_2 \;+\; 26\,H_2O \longrightarrow C_6A\bar{S}_3H_{32} \qquad \Delta H = -1350\text{J.g}^{-1}$$

(tricalcium aluminate) + (gypsum) + (water) → (ettringite)

The excess ettringite formed reacts with more C_3A,

2. $$C_6A\bar{S}_3H_{32} \;+\; 2\,C_3A \;+\; 4\,H_2O \longrightarrow 3\,C_4A\bar{S}H_{12}$$

(ettringite) + (tricalcium aluminate) + (water) → (monosulphoaluminate)

Monosulphate aluminate is known to be the most stable phase in a mature cement paste (Young et al, 1998).

<u>For C_4AF</u>

The reaction involves both water and $Ca(OH)_2$ as produced before. Thus,

$$C_4AF \;+\; 2\,Ca(OH)_2 \;+\; 14\,H_2O \longrightarrow C_4(A,F)H_{13} \;+\; (A,F)H_3$$

(ferrite) + (calcium hydroxide) + (water) → (tetracalcium aluminate hydrate) + (ferric aluminium hydroxide)

The $C_4 (A,F) H_{13}$ is structurally related to the monosulfoaluminate, while the $(A,F) H_3$ remains amorphous (Taylor, 1998; Young et al, 1998)..

Properties and influence of the hydration products

As can be expected, the products of the hydration reaction of OPC can have major influences on the properties of the hardened cement paste and by implication, on the behaviour of CSBs. A summary of the hydration products and their likely impact on the durability of CSBs are shown in Appendix B. From this summary, various ways of improving the properties of hardened cement paste, and by implication the block, can be examined.

It is widely reported in concrete literature that the volume fraction of the cement hydrates, gel pores and capillary pores determine the properties of concrete (Baker et al, 1995; Sjostrom et al, 1996; Neville, 1995; Young et al, 1998). Given the similarities between concrete and CSBs, the same influence is likely to apply in the case of the latter. The role of hardened cement paste in both materials appears to be central to this hypothesis. The volume fraction of solids, gel and capillary pores are in turn determined by two factors : the water cement ratio (w/c) and the degree of hydration (α) (Illson, 1994; Taylor, 1998).

It is the w/c ratio that controls the porosity of hardened cement paste. Theoretically, the production of CSBs of high strength and of low permeability can therefore be achieved by:

- Lowering the water cement ratio
- Assuring a high degree of hydration

Low *w/c ratio* can be achieved by adequate proportioning of the main raw material ingredients; soil, cement and water. A particularly low w/c ratio can also be achieved in mixes by using partial cement replacement materials (CRM) (Neville, 1995). In situations where blocks are to be exposed to aggressive environmental conditions, such approaches are likely to be more beneficial than the short-term economics of increase in production costs. This is because mixes incorporating fine cement replacement materials are likely to result in high performance blocks which are more dense and more durable than blocks produced in the traditional manner. This theory is investigated experimentally in this thesis and the results are discussed in Chapters 6 and 7.

A *high degree of hydration* of cement paste in a block can be achieved by making sure that proper curing is done. The degree of hydration represents the fraction of the original cement grains which have hydrated. This requires that a sufficient length of time is dedicated for curing alone. During this time the green demoulded blocks should not be allowed to dry out quickly. This should help avoid causing the water still in the green blocks to evaporate, thus remaining available for the hydration reaction to continue. Adequate curing and low water/cement ratio are therefore potentially significant ways of improving the properties and performance of CSBs. The effect of varying curing conditions on the properties and performance of CSBs are investigated experimentally, with the results discussed in Chapters 6 and 7.

Modification of CSB properties using cement replacement materials

As discussed earlier, the properties of hardened cement paste can be improved by the partial replacement of OPC with CRMs. In this sub-section, the manner in which CRMs are able to modify properties of hardened cement paste, the types of CRMs available, their physical and chemical properties, and the mechanism of the reactions involved, are presented.

CRMs, sometimes referred to as mineral admixtures or additives, can be used as substitutes for some of the OPC in a block. CRMs modify properties of OPC by altering its setting and hardening behaviour (Neville, 1995). Improvements in strength and durability of the hardened cement paste is reported to be due to the pore-filling effect of the CRMs, which effectively lowers both the capillary and gel porosity in the resulting product (Young, 1998). Further, the transition zone between the sandy fraction of the soil and the cement paste, usually a major point of weakness, is likely to be considerably strengthened by the pozolanic reaction of CRMs. Amounts as low as 10% to 20% of the cement content are required. For blocks expected to be used in harsh environmental conditions, CRMs could be used only on the surface areas to reduce costs.

The *main types* of CRMs include the following (Jackson & Dhir, 1996; Neville & Brooks, 1994):

- Pulverised fuel ash (PFA), or fly ash
- Ground granulated blast furnace slag (GGBS)
- Microsilia, or condensed silica fume (CSF or MS)
- Natural pozolans, e.g. volcanic ash
- Calcined clay and shale
- Risk husk ash

The most commonly used of the above are the PFA, GGBS and CFS. They are all available as industrial materials, or as blends with OPC. The basic physical properties and chemical composition of PFA, GGBS and MS as compared to OPC are described in Illston (1994) and Neville (1995). The three CRMs contain a substantially greater amount of silica (SiO_2) than OPC (PFA, 48%; GGBS, 36%; MS, 97%; OPC, 20%).

Most importantly, most of the silica contained is in the active amorphous form (Neville, 1995) (a pozzolan by definition is a material that contains active silica, SiO_2). The silica is in its amorphous or glassy form in disordered structures. This is distinguished from the uniform crystalline structure form of silica found in sand. The latter is not chemically active and is therefore regarded as being dormant. It is only MS, with 97% SiO_2 and no CaO in its composition which entirely comprises active silica. For this reason, it is this CRM which is discussed further, and its effect on cement is investigated experimentally in Chapters 6 and 7.

The *physical properties* of MS make it one of the most effective CRMs. Firstly by having a significantly lower specific gravity than OPC (2.2 compared to 3.15), the substitution of the latter on a weight by weight basis with the former is likely to result in a greater volume for the resulting paste. This pore filling effect is just what is needed for surface layers of CSBs to prevent easy penetration of moisture. The pore filling effect is also known to enhance strength properties (Taylor, 1998). Secondly, by having a particle size range about three magnitudes of order below that of OPC (0.01-0.5 μm compared to 0.5-100 μm), the MS has the potential of ensuring more dense packing of the binder. Added to this, with its considerably higher specific surface area (15,000 compared to 350 m^2kg^{-1}), the speed of hydration is likely to be significantly higher. This is probably due to the small MS particles acting as nucleaic sites for the deposition of the C-S-H on the hardened cement paste. This can be quite useful in CSB production as it can effectively lower the water cement ratio in a damp mix. The lower the w/c ratio, the higher the strength (Webb & Lockwood, 1987; Baker et al, 1994; Taylor, 1999).

The *mechanism of the reaction* of the pozzolan mixed with OPC is as follows (Taylor, 1998). The pozzolan itself is not known to be cementitious on its own but in a finely divided form, and in the presence of moisture it can chemically react with the $Ca(OH)_2$ liberated during the reaction of the silicates in OPC. The reaction forms a fresh secondary set of calcium silicate hydrates whose properties are the same as those of the primary reactions. This represents one of the most significant reasons for partial substitution of OPC with CRMs. As was mentioned earlier, the $Ca(OH)_2$ liberated during the hydration reaction of OPC is a potential source of instability for the CSB. Being soluble in water, it can easily be leached out from the block, increasing its porosity and weakening the bond strength (Chapter 2).

The chemical equation representing the mechanism of the reaction is thought to be as follows (Illston, 1994):

$$\underset{\begin{bmatrix}\text{amorphous}\\ \text{silica}\end{bmatrix}}{S} + \underset{\begin{bmatrix}\text{Calcium}\\ \text{hydroxide}\end{bmatrix}}{Ca(OH)_2} + \underset{\text{(water)}}{H_2O} \longrightarrow \underset{\begin{bmatrix}\text{calcium silicate}\\ \text{hydrate}\end{bmatrix}}{\text{C-S-H}}$$

The C-S-H from the secondary reaction can contribute to further strength development, and by implication to the durability of the cement paste within a CSB fabric. The effect of MS on the properties and performance of CSBs are investigated experimentally in this thesis and the results discussed in Chapters 6 and 7. Blocks containing MS are referred to as improved blocks (IPD) (Chapter 5).

3.2.2 Characterisation of Soil for CSB Production

As stated earlier in the thesis, soil alone constitutes over 90 of the bulk of a CSB. Existing CSB literature appear to adequately cover fundamental theories of soil properties and behaviour.

According to BS 1377 Part 1: 1990, soil is an assemblage of discrete particles in the form of a deposit, usually of mineral composition, but sometimes of organic origin, which can be separated by gentle mechanical means, and which include variable amounts of water and air. Soil is also referred to as the loose material that results from the long-term transformation of the underlying parent rock by the simultaneous and evolutionary interaction of climatic factors and other physico-chemical and biological processes (Casagrande, 1947; Das, 1994; Houben & Guillaud, 1994; Craig, 1998). Most of soils consist of disintegrated rocks, decomposed organic matter and water soluble mineral salts. These descriptions confirm that soil is a highly variable and complex material in nature. Although soil properties can be modified to improve their performance, not all soils may be suitable for stabilisation as found. The decision on suitability requires the identification of the main constituents in the soil likely to have a direct bearing on its properties and behaviour (Head, 1980).

As the characteristics of a soil can affect the performance of a CSB, the review of literature discussed in this section will focus on the following:

- Composition of soils
- Classification of soil (to determine type and suitability)
- Current criteria for selection of suitable soils

Composition of Soils

Soil consists of three main phases, namely, solids, liquids and gasses (Das, 1994; Craig, 1998). The solids form the bulk of the material, while the liquids and gasses mainly fill the void spaces. The relative proportions of the three phases can have a significant influence on the behaviour of a soil. In this section only the composition of the solids fraction are discussed. Soils are made of varying proportions of four types of solids: gravel, sand, silt and clay (Fitzmaurice, 1958; Enteiche & Augusta, 1964; ILO 1987). Each of these different solids are briefly described in turn in the ensuing paragraphs.

Gravels are the larger granular particle sizes in a soil forming its skeletal structure. They range in size between 2mm and 20mm (BS 1377 Part 2: 1990). They are the cohesionless part of a soil resulting from the direct disintegration of underlying parent rocks and pebbles (Pettijohn, 1957). Gravels have a rough texture and may be found in almost all shapes, including rounded, angular, irregular, etc. (BS 1377 Part 2: 199). Due to their loose packing and stability, they are important for CSB production as they limit shrinkage and capillarity in a soil. Amounts of gravel in excess of 10% are not recommended for use in CSB production (Rigassi, 1995). The allowable maximum size fraction for gravel used for CSB production is not standardised. Some literature sources recommend 15 mm to 20 mm (Houben & Guilland, 1994), while others recommend 6mm (ILO, 1987). As will be shown later, the maximum size fraction has a considerable influence on the bonding properties of a soil-cement mix (PSD).

Sand particles in a soil range in size between about 0.06mm and 2mm (BS 1377 Part 2: 1990). The sandy fraction comprises granular grains of silica or quartz from the disintegration of sandstones and crystalline rocks. Sandy soils are very stable, lack cohesion, are non-sticky with a gritty texture. They also have a very high degree of internal friction and do not shrink. Because of these properties, they can provide the much needed mechanical strength to soil. Their pressure also limits swelling and shrinkage in a soil. According to literature sources, the specific bulk density of sands vary between 2500 kg/m^3 and 3000 kg/m^3, but their specific surface area is about 23 cm^2/g, and specific heat about 800 J/kgK (Jones, 1984; Houben & Guillaud, 1994). The recommended proportion of sand in soils for CSB production varies but is mainly between 70 and 80% (Lunt, 1980; Rigassi, 1995).

Silts are made up of particles whose size range varies between 0.002mm and 0.06mm (BS 1377 Part 2: 1990). Apart from the difference in size, silts are almost identical in nature to sandy particles. Their internal friction is however noticeably less than that of sand. Their specific surface area is about 454 cm^2/g and density between 1600 and 1800 kg/m^3 (Head, 1980; Houben & Guillaud, 1994). They have a smooth texture, are sticky and lightly cohesive, but their shrinkage capacity is not significant. Due to their lack of cohesion, gravels, sands and silts should not be used on their own for CSB production (reasons discussed under clay). According to literature sources, the recommended silty fraction in a soil for CSB production should be between 10 and 25% (Rigassi, 1995).

Clay particles form the finest fraction of soils with average sizes less than 2 μm (Scot, 1963). Their physical and chemical characteristics are not similar to those of the other three soil fractions. The specific surface area of clay is about 800 m^2/g, while their specific heat is about 965 J/kgK (Houben & Guillaud, 1994). Due to their fine grained nature, clays are cohesive and will form a coherent mass at suitable moisture contents (Vickers, 1983; BS 1377 Part 1: 1990). Clays are known to contribute to some of the important engineering properties in a CSB, and for this reason, are discussed in more detail. They are basically hydrated alumino-silicates of irregular but often hexagonal shapes (Torraca, 1988). Large clay molecules comprise a series of sheets or wafers of alumina and silica which are not electrically neutral (Van Olphen, 1977). The sheets have chemical make-up which varies according to the type of clay. Three major clay types exist; namely kaolinite, illites and montmorollinite (ILO, 1987; Houben & Guillaud, 1994). Within these three major types, there are about 20 different sub-groups of clay (Scot, 1963).

Kaolinite and montmorollinite represent the opposite extremes in the behaviour of clay when in contact with water. Kaolinite which is almost pure clay, is the most stable and therefore the least expansive of clay types. Since the two layer wafer has a fixed distance of about 7 A°, they are held together firmly. Its linear contraction is small, ranging between 3% and 10% only (Houben & Guillaud, 1994). Because of these properties, kaolinite clay was selected and used for blending the experimental soil type used for laboratory tests in this thesis (Chapter 5).

Illites and montmorollinites consist of type 2-1 structures which are more weakly held together. They are not stable in water and are highly vulnerable to swelling and shrinkage. Their linear contraction values are high, ranging between 4% and 11% and between 12% and 23% respectively (Das, 1994). The linear contraction value of the latter is more than twice that of kaolinite. No further tests are conducted in this thesis using these two clay types.

Generally, the presence of clay in moderate amounts in a soil is desirable (Smith & Smith, 1998). Being cohesive, they impart plasticity to the soil when under moist conditions. Plasticity is due to the thin film of absorbed water which adheres strongly to the clay layers thus linking the particles together (Grimshaw, 1971; RILEM, 1972). In this way, the clay minerals acts as natural binding agents for the cohesionless granular fractions of a soil (gravel, sand, and silt). This quality is particularly valuable during the production of CSBs. Green blocks after demoulding are still weak as the cement binder may not yet have had sufficient time to set. The presence of clay as a natural binder thus helps in the handleability of CSBs at this stage of the production process (Spence & Cook, 1983).

Clay minerals also have other properties which are unfortunately considered undesirable in a block. Being hydrophilic they have a very high affinity for water.

As the wafers attract water, clay particles can slide over each other resulting in an apparent increase in volume (due to dispersion). Conversely, as the clay wafers dry out, they shrink, causing cracks to appear in the clay mass, thus effectively irreversibly breaking their bond strength (Hilt & Davidson, 1960). Extreme swelling and shrinkage are not desirable properties in blocks. It is the uncontrollable swelling and shrinkage of clays which depend on moisture and temperature variations that makes them unique, and thus difficult to deal with. For this reason, most CSB literature sources recommend controlling the amount of clay in soils to be used for block production. Amounts of clay in excess of 40% is not recommended for soils for CSB production using OPC (Rigassi, 1995). In such cases, the use of lime is recommended due to its ability to fix the clay through a pozolanic reaction (Ingles, 1962; Spence & Cook, 1983; BS 1924, 1990).

Soil Classification

The classification of a soil is the first requirement needed to identify it. Knowledge of the soil type and properties can facilitate the optimisation of its use in CSB production. According to literature sources, soil classification is performed on particles nominally less than 60mm (Dunlap, 1975). Soils are classified in various ways depending on the prevailing local or regional standards in the particular part of the world. Whatever the geographic location, however, some common procedures are usually adopted in the classification of soils.

Soil classification methods are based on either one or a combination of the following: particle size distribution, plasticity, compactability, cohesion, and organic matter content (Casagrande, 1947; Fitzmaurice, 1958; Head, 1980; Vickers, 1983). Unfortunately, soil classification systems are not yet uniformly applied internationally. At the moment, the two classification systems widely used are based on the particle size distribution and on the plasticity of a soil (Lunt, 1980). According to these two methods, the soil size grading and its plasticity are divided into clearly defined ranges. For each range, a descriptive name and letter is assigned to the identified soil type to distinguish it from the others.

In the *particle size distribution* classification system, the term particle refers to an individual mineral grain within the disturbed soil mass. According to this system, the following size ranges are given (BS 1377: Part 2, 1990):

Name	Subdivision	Diameter of Particles (mm)	
Gravel	Course Medium Fine	60 20 6.0	20 6.0 2.0
Sand	Course Medium Fine	2.0 0.6 0.2	0.6 0.2 0.06
Silt	Course Medium Fine	0.06 0.02 0.006	0.02 0.006 0.002
Clay			<0.002

Table 1: Soil classification according to particle size distribution
(BS 1377 Part 2 1990; ILO, 1987)

In this system, each of the terms gravel, sand, silt and clay refers to a range of particles or grain sizes in a soil (table 1). In actual reality, soils are not found in this rigidly defined state. The normal natural state of soil is such that it is composed of grains from two or more particle size ranges. For example, a soil may be described as sandy CLAY, implying that the soil has significant amounts of sand and clay size ranges. In such a case, the size range with the higher percentage of particles is the last named range in the soil description (in capitals). The main terms used in this system are G for GRAVEL (60-2mm), and S for SAND (2-0.06mm). The qualifying terms are W for well graded and P for poorly graded (Pu, uniform; Pg, gap graded).

In the *soil plasticity* classification system, the soil is identified by its behaviour when in contact with water. The system is mostly used for the finer fraction of a soil, i.e. clays and silts smaller than the 425 μm sieve only (Houben & Guillaud, 1994). The soil is then classified using a soil plasticity chart (Stulz & Mukerji, 1988; Das, 1994). The advantage of this system is that it recognises the formation, and therefore the behaviour of soil groups can be predicted easily.

Use of both the particle size and plasticity based classification systems are recommended in analysing soils for CSB suitability. The crucial point is that either system should be able to describe the soil in a manner clearly understandable by engineers. The identification of a particular soil can be considered complete with the inclusion of its colour, particle shape and composition, soil name based on its grading and plasticity, and the soil group symbol. The approach is useful in that it clearly recognises the difference between the coarse and fine soil fractions.

Experience has also shown that within each class of soil, similar characteristics are displayed. With coarse grained soils (gravel and sand) for example, the similar characteristics are dependent not only upon the size of the particles, but also on the manner in which the sizes are distributed within the soil mass. With fine grained soils (silt and clay), it is the moisture content of the soil and the clay mineral type which play more significant roles in determining the behaviour of the soil (Ingles & Metcalf, 1972).

Current criteria for selection of suitable soils

The varied composition and properties of a soil in its natural state introduces difficulties during the selection of the material for stabilisation. As stated earlier, not all soils found in their natural state will necessarily be suitable for CSB production. In this sub-section the basic suitability requirements are outlined and the existing criteria for selection based on literature sources are summarised.

Basic suitability requirements are varied with a broad set of requirements proposed in CSB literature. For a soil to be suitable for stabilisation, its particle size distribution, plasticity and compressibility should be desirable. Existing suitability criteria require that the soil be:

- well graded with a continuous or dense gradation. It should be neither gap-graded nor uniformly graded. The size of the maximum soil particle should be less than 6 mm in diameter (ILO, 1987). Particle sizes greater than this size may easily get dislodged from the block fabric due to poor bonding. The gravel and sandy fraction should be densely packed not only to provide the skeletal structure of the block, but also to take up applied loads. The silt and clay fraction in a soil should be adequate enough to provide sufficient cohesion. As stated earlier, this is valuable when demoulding green blocks and when handling them during wet curing. In addition to the amount of clay in a soil, its type should also be ascertained. Not all clays have the same degree of shrinkage and swell. This property of clay is a potential source of disruption for the future performance of a block. Generally, when using OPC as the stabiliser, best results can be obtained with predominantly sandy soils. When using lime as the binder, best results can be obtained with predominantly clayey soils. It is however still possible to improve any poor gradation of a soil prior to stabilisation. This can be achieved by adding the missing fraction, or by removing the excessive fraction. The removal of excessive coarse fraction can be done by sieving the soil, while removal of fines from the coarse fraction can be done by washing it.

- of low plasticity index, thus able to exhibit low rather than high cohesion. Sandy soils of low clay content (about 10% or less) do not have an appreciable plastic limit. The clay content once again is the critical factor. Soils of high plasticity can have liquid limit in excess of 50% (Fitzmaurice, 1958; Houben & Guillaud, 1994). The corresponding clay content in such cases may be in excess of 40%. The plasticity index of a soil can be altered by modifying its particle size distribution. The plasticity index can be lowered by adding sand, and raised by adding clay (Rigassi, 1995). Adequate plasticity facilitates shaping a soil as it determines its ability to remain in close association, thus contributing to moulding and handling.
- compacted at its optimum moisture content for the maximum dry density to be attained (Guillaud et al, 1995). At the maximum dry density, the porosity of the soil is at its minimum. This increases both its shearing strength and compressive strength on loading. For every soil, reduction in porosity attained at maximum dry density will depend on the gradation of the soil, its optimum moisture content and on the compaction energy used (Ingles & Metcalf, 1972; Vickers, 1983).
- free of soluble salts and organic matter. These impurities can have harmful effects on OPC both during hydration and even after hardening. Presence of organic matter higher than about 1% represents a potential hazard (Houben & Guillaud, 1994). Organic matter is harmful because it contains nucleic acids,

tarturic acid and sometimes glucose. These substances can interfere with the proper setting of OPC, thus weakening the hardened cement paste (Neville, 1995). Soluble salts and sulfates can react with moisture in a soil and hardened cement past resulting in expanded product formation in a block (Chapter 2). Soils with soluble salts and sulfate contents higher than about 3% should not be used for CSB production (Rigassi, 1995). At the moment, there are no available tests specified in the literature to determine the presence of sulfates in soils to be used for CSB production. The criteria is also not well documented in most CSB literature.

Comparison of existing criteria for suitability is now possible because over the past few decades, several authors have published various recommendations. These have been successfully used in the past for the selection or rejection of soil for stabilisation. It is however noted that some of the suggested criteria, while based on similar properties, still differ from each other. Such dissimilarities only confirm the premise that the variability of a soil makes selecting a suitable soil a difficult exercise. Nevertheless, although the effect of climatic type and infinite variability of soils may influence some of the existing guidelines, most of the criteria still appear relevant to date. It is however, still rare to find authors recommending 'comprehensive' criteria based on all the four main soil properties, namely: particle size distribution, plasticity, compressibility, and chemical mineralogy. The summary of existing criteria for soil selection is shown in Appendix C.

The *adequacy of the criteria* for soil selection is still debateable, but the summary in Appendix C shows convergence on two main soil properties, namely: the particle size distribution and the plasticity of a soil. The guidelines are useful as basic criteria, but should not serve as rigid specifications for soil selection. This is because even soils that may fall out of the recommended ranges can, with modification, still be used to produce good blocks.

The size of the maximum size fraction (6 mm) and its distribution, and the clay content (and type) emerge as the major factors to consider in soil suitability selection. The chemical composition of a soil and its potential influence on the durability of the cement paste that bonds blocks, is likely to gain prominence as a new factor in the near future. Criteria limiting the presence of soluble salts and sulfates in soil samples are likely to become critical in light of recent scientific findings regarding their long-term harmful effects (Lea, 1976; Lunt, 1980; Neville, 1995). It is further noted that certain special soil types such as lateritic soils may not conform to these guidelines (Hammond, 1972; Ringsholt & Hansen, 1978; Stulz & Mukerji, 1988). Chemical tests for their composition is recommended in addition to the summarised criteria in Appendix C. The validity of the various criteria are not investigated further in this thesis.

3.2.3 QUALITY OF WATER FOR MIXING AND CURING

Water is required in CSB production at two critical stages: during the mixing of soil with cement and during the wet curing of green blocks. Existing CSB literature appear to place more emphasis on the quantity of water required, rather than on its quality (Webb & Lockwood, 1987). Water is basically needed for the hydration reaction leading to the gradual hardening of Portland cement. In the opinion of the author, both the quality and quantity of water ought to be given equal consideration. In most developing countries where CSBs are to be used, water is still a scarce resource, forcing many producers to use raw water from a variety of sources (Smith & Webb, 1987). The likelihood for the use of water with high levels of impurities cannot therefore be ruled out. Investigations during the fieldwork revealed widespread incidences of use of water of unknown quality (Chapter 4). In this section, the sources and suitability criteria for water are briefly discussed.

Sources

The main sources of raw water in developing countries include rainwater, rivers, lakes, swamps, groundwater, seawater, and rarely, tap water. Naturally occurring water may contain different substances such as dissolved solids, dissolved gases, suspended solids, bacteria, fungi, algae, protozoa (BRE, 1980). Apart from the few tap water sources where treatment works process the water (through screening, coagulation, aeration, flocculation, clarification and disinfection in that order, thus making the water potable), all other water sources in developing countries are unlikely to be treated. The quality of water used therefore remains unknown. High levels of impurities found in untreated water sources can be detrimental to the performance of a block (Parry, 1979). There use is likely to result in low strength, dimensionally unstable, and less durable blocks being produced (ILO, 1987). The effects of water of unknown service record on block properties are investigated experimentally in Chapter 4. Problems associated with use of water of unknown quality are also widely reported in concrete literature (Neville, 1995).

Suitability criteria

The suitability of water used for CSB production should be ascertained if good quality blocks are to be produced. Current specifications generally require that the water needed for the proper hydration of cement should be fit for drinking purposes (ILO, 1987; Rigassi, 1995). The criteria for potable water may not yet be absolute, but the following guidelines for quality are considered useful (BS 3148, 1980; ASTM C 94-

92a, 1992);

- Water with a high concentration of sodium or potassium should be considered unsuitable for use in cement hydration (due to dangers of AAR reactions)
- Water with pH of between 6.0-8.0, which does not taste saline or brackish, may be suitable for use in cement hydration
- Water containing humic acid or other organic acids should not be used (affects hardening of cement paste in the blocks)
- Use of sea water is not recommended (presence of chlorides >1000 ppm)
- Water with silt as suspended solids may be used even if concentration of 2000 ppm is found as long as the water is first left to stand in a settling basin or tank for at least 24 hours.

Since water sources are scarce in most developing countries, ways to comply with the above guidelines without rejecting the water should be sought. At the moment no known on-site test methods exist to determine the suitability of water for CSB production. Preliminary treatment methods for raw water of unknown sources could include screening, temporary storage, removal of algae, boiling and cooling.

3.3 CEMENT-SOIL STABILISATION PRINCIPLES

3.3.1 BACKGROUND

The stabilisation of soil to improve its properties for building purposes is an ancient practice. The procedures were passed on from generation to generation without necessarily understanding the main mechanisms involved. It was only from the 1920s that systematic scientific approaches were to emerge (Rigassi, 1995). Attempts were then made to replace the longstanding ad-hoc techniques previously adopted for soil stabilisation. Unfortunately, despite all the recent scientific advances made, soil stabilisation still remains an inexact science (Dunlap, 1975).

By soil stabilisation is meant the modification of soil properties by varying the soil-water-air interface (Fitzmaurice, 1958; UN, 1964; Ingles & Metcalfe, 1972). This is done to achieve more lasting characteristics than hitherto possible when the soil was still in its natural state. Some of the methods used to modify soil can result in irreversible changes, while others may result in reversible changes. The latter are likely to occur due to the lack of resistance offered by soil to environmental agents, especially water (PCA, 1970; Aksa, 1984). Evidence of poor resistance can be seen in most of the Third World where houses built of soil require to be regularly maintained during and after rainy seasons (Agarwal, 1981; Fullerton, 1979; BRE, 1980). Perennial problems of this type can be effectively overcome by stabilising the soil. Addition of a suitable stabiliser, especially a binder, can enable the soil retain its shape and dimensions. The soil will also gain in compressive strength and durability (Fitzmaurice, 1958).

As several input variables are involved, soil stabilisation is likely to remain a complex process. For effective stabilisation to be achieved the soil should be modified to give it the properties it lacks. There are several options for stabilising a soil, but the courses of action likely to be more effective should consider targeting its interstitial voids and improvement of bonding between its particles. Thus, it is generally accepted that:

- by reducing the volume of interstitial voids in a soil through mechanical compaction, direct action is taken to significantly reduce its porosity (Rigassi, 1995). Reduction in porosity is an effective way of increasing density and shear strength in a soil. By filling the voids in the soil which cannot be eliminated completely through compaction, direct action is also taken to reduce its permeability (Houben & Guillaud, 1994). Reduction in permeability has the positive effect of restricting circulation and retention of water within the soil fabric.

- by improving the cohesion and bonding in a soil, action is taken to cement and link the soil particles together. In this way dimensional stability, increase in compressive strength and improved durability can all be expected to be achieved. The method also ensures that changes in volume that would normally occur due to shrinkage and swelling are significantly reduced. Improved bonding also minimises the vulnerability of the soil to surface abrasion and erosions caused by rainwater and wind (DoHUD, 1979; Evans, 1980).

These two approaches are investigated experimentally in this thesis (Chapter 5).

3.3.2 CEMENT SOIL STABILISATION METHODS

Current soil stabilisation methods can be broadly categorised as follows:

- Mechanical stabilisation (by using a compressor)
- Physical stabilisation (by improving the soil grading)
- Chemical stabilisation (by using a binder to improve bonding between the soil particles)

Normally a combination of all three methods are used (Ingles & Metcalf, 1972). Each method is now discussed in turn to examine the degree of effectiveness in the stabilisation of soil.

Mechanical stabilisation involves compressing the soil particles together to increase density and reduce porosity. Compression leads to the redistribution and rearrangement of soil particles. It is the compaction energy used which forces the particles together and in the process most of the air is eliminated from the soil voids. Compaction is best achieved when the grain size distribution of a soil is continuous, not uniform or gap graded. The presence of grains of different sizes facilitates the occupation of voids left by other soil particles. Unfortunately, the effect of mechanical stabilisation when used alone is easily reversed, especially when the soil comes into contact with water (Jagadish et al, 1981). Water causes the lubrication the soil grains, forcing them to move about within the otherwise densified but still unbound fabric. It therefore follows that in addition to densification, the use of a binder will normally be required mainly to overcome the reversible effect of contact with water (Norton, 1986).

Physical stabilisation involves modification of soil properties by introducing the missing size fractions (Rigassi, 1995). The texture of a soil can be altered by calculated and controlled mixing of the different fractions together. When this is done, most of the voids that existed prior to physical stabilisation are closed due to closer packing of the grains. An anisotropic network is created limiting the movement of the grains in a soil (Ingles and Metcalf, 1972). Unfortunately, as was the case with mechanical stabilisation, the effect of physical stabilisation alone is not permanent (Rigassi, 1995). On saturation with water, soil grains are easily dispersed, or washed away. For better results, physical stabilisation of soil should therefore be combined with the other two methods (PCA, 1971).

Chemical stabilisation involves the addition of a binder or bonding agent to a soil. The binder modifies the soil properties through cementation or linkage of its particles (Houben & Guillaud, 1994). Both cementation and linkage are a result of chemical reactions involving the binder and water. Cementation creates a strong and inert matrix that can appreciably limit movement in a soil. The voids in the soil are also filled with insoluble by-products of the hydration reaction while some soil particles are coated and firmly held together by the binder (Ingles, 1962). The key binder that acts in this manner is Ordinary Portland cement. The full mechanism of the reaction as presently understood is discussed in the next section. It is generally reported in CSB literature that the effect of chemical stabilisation is more permanent, and may take several years or even decades to partially reverse. For this reason, chemical stabilisation of soil is so far considered to be the superior method of choice. It is also well established that the effect of chemical stabilisation is significantly increased by improving the soil grading and compacting the mix (Dunlap, 1975; Gooding, 1994). Combination of the three methods is therefore strongly recommended, and is used in the production of all experimental samples used in the research. The use of cement admixtures and lime in addition to OPC are also investigated experimentally (Chapters 5, 6 and 7). Other known chemical stabilisers include: pozzolanas, gypsum, bitumen, resins, whey, molasses, etc., (IIHT, 1972; Stulz & Mukerji, 1988; Houben & Guillaud, 1994). Use of these other binders are not discussed further in the thesis.

3.3.3 MECHANISM OF CEMENT-SOIL STABILISATION

The stabilisation reactions that follow from the addition of water to a soil-cement mix leads to the formation of a number of by-products (Ingles, 1962; PCI, 1970; BS 1924 Part 1, 1990). Since soil as the bulk constituent contains different fractions of gravel, sand, silt and clay, each of these fractions will respond to the reaction with cement in different ways. Moreover, as cement itself contains different minerals, each of them will also react differently. Not only will they interact amongst themselves, but they are also likely to affect the manner in which the others react (Weidemann et al, 1990). The main reactions involved and the nature of the resulting microstructure are described in the sub-sections which follow.

The Main Chemical Reactions

According to CSB literature sources, two main chemical reactions can be distinguished; a primary reaction involving the hydration of cement with water, and a secondary reaction involving the clay minerals and the liberated lime from the primary reaction (Houben & Guillaud, 1994). The hydration reaction between cement and water results in the formation of hydrated cement paste and conventional mortar (embedding gravel and sand fractions). The secondary reaction also results in the formation of a binder like by-product (Spence & Cook, 1983).

The mechanism of the reaction is thought to be as follows:

1. Primary reaction involving OPC constituents:

$$\left.\begin{matrix} C_3S \\ C_2S \\ C_4AF \end{matrix}\right\} + H_2O \longrightarrow C\text{-}S\text{-}H + C_4A\bar{S}H_{12} + Ca(OH)_2$$

$$\text{(Cement)} + \text{(Water)} \quad \left[\begin{matrix}\text{Calcium}\\ \text{silicate}\\ \text{hydrate}\end{matrix}\right] + \text{(monosulphoaluminate)} + \left[\begin{matrix}\text{Calcium}\\ \text{hydroxide}\end{matrix}\right]$$

The main products of the above reaction are: calcium silicate hydrates, monosulphoaluminates and calcium hydroxide. It is the first two, namely the C-S-H and $C_4A\bar{S}H_{12}$ that are responsible for strength development in a block (Ingles & Metcalf, 1972). It is the gravel and sandy fractions in the soil that are affected by this reaction. Both the C-S-H and $C_4A\bar{S}H_{12}$ are known to have high binding capacity. The binding forces they generate are responsible for intertwining and embedding the gravel and sand fractions creating a strong network within the soil fabric. This inert and anisotropic network introduces rigidity not previously present in the soil. Due to the network, movement of the coarse soil fraction is resisted and subsequently becomes highly limited. The net effect results in the development a particulate composite structure. As can be expected, the properties of the composite are influenced by the amount of cement used relative to the soil fraction, and by the nature of the bye-products resulting from the reaction. The reaction is known to liberate free lime which then sets off the secondary reaction with the clay component in the soil.

2. Secondary reaction involving freed lime and clay

A. S + $Ca(OH)_2$ ⟶ C-S-H + C-A-H

(Clay)	[Calcium hydroxide]		[Calcium silicate hydrate]	[Calcium alumate hydrate]

The two main products of this reaction (the C-S-H and the C-A-H) both have binding capacity not very different from the ones of the primary reaction. This reaction is mainly pozzolanic with the gelatinous amorphous hydrates equally contributing to hardening of the block. Following the reaction, a stable chemical bond develops between the clay crystals, through a mechanism known as linkage. The reaction proceeds slowly but is dependent on the quantity and quality of clay, and on the amount of free lime available (Spence and Cook, 1983; Houben and Guillaud, 1994). The amount of calcium hydroxide released is limited by the lime saturation factor (LSF) of the OPC. The LSF is fixed at the time of manufacture of the OPC, often ranging between 0.66 and 1.02 (Spence and Cook, 1983). Restriction of the upper limit is mainly done to control the amount of free lime in the cement paste which is otherwise associated with unsoundness and undesirable expansion.

The Resulting Particulate Composite Matrix

As a result of the preceding reactions, the particulate composite fabric that constitutes the block is thought to comprise the following matrices (Herzog & Mitchell, 1963; Ingles & Metcalf, 1972; Dunlap, 1975; Lea, 1976; Houben & Guillaud, 1994):

- cement hydrates (calcium silicates, calcium aluminates, sulphoaluminates, ferrites)
- conventional gravel-sand-cement mortar
- calcium hydroxide ($Ca(OH)_2$)
- unhydrated cement residues (UCR)
- stabilised clay
- unstablised soil (gravel, sand, silt, clay)
- capillary pores

The proportions of each of these matrices in the block and the strength of bonding between the cement hydrates and coarse soil fraction are thought to influence the compressive strength, dimensional stability and durability of a block (Mitchell & El Jack, 1978; Lunt, 1980; Rigassi, 1995). The various by-products are also summarised in Appendix B.

For better performance of a block, it is desirable that the cement hydrates coat a high proportion of the coarse soil fraction, as well as filling the spaces between the particles. For this to be achieved, an optimum proportion is needed between the sand and cement. It can generally be expected that the lower the cement content, the higher the resulting voids content in a block. A high voids content (porosity) is often associated with a weak block (Houben & Guillaud, 1994). This phenomenon is investigated experimentally in this thesis (Chapters 6 and 7). It is potentially possible that with the low amounts of cement used, the voids content of a block fabric is likely to remain high. Moreover, the low quantity of binder used can also result in the presence of a greater proportion of unstabilised soil in a block fabric. Such an outcome would be highly undesirable due to vulnerability to deleterious effects of water, temperature and relative humidity (Chapter 2).

The presence of the matrix of calcium hydroxide in a block is a potential source of instability. Calcium hydroxide is soluble in water and is therefore likely to be leached out during the service lifetime of a block (Chapter 2). Moreover, calcium hydroxide is also known to react readily with the CO_2 from air to form expansive products. Though the reaction is very slow, the expanded products formed can easily contribute to the disintegration of a block over time (Chapter 2). A means of eliminating the presence of $Ca(OH)_2$ in a block by providing a substance with which it can react (microsilica) to form a secondary binder is investigated experimentally in this thesis (Chapters 5, 6 and 7).

An attempt is also made to examine the microstructure of block samples in the course of this research. This is done using petrographic examination of thin sections (Chapter 7).

3.4 STABILISED BLOCK PRODUCTION PROCESS

3.4.1 BLOCK PRODUCTION CYCLE

The production process of CSBs is broadly similar to that of concrete blocks. Similarities exist between the products, manufacturing process and in the organisational control methods. The processing method represents a major input variable. It can significantly influence the quality and long term behaviour of a block (Rigassi, 1995). Yet most of the CSB literature sourced appear to take this variable for granted. For these reasons, the separate treatment of the processing method as is done in this section was thought to be necessary.

CSBs are produced by compressing a damp mix of soil and cement in a press mould. After demoulding, the green blocks are not used immediately, but are first allowed to cure. This is because the strength of a block, just as it the case with concrete blocks, increases with age (Apers, 1983; Ruskulis, 1997). The duration of curing is dictated by the specification for the type of stabiliser used; 28 days when OPC is used and 56 days when hydrated lime is used (BS 12, 1971; BS 890, 1972; Lea, 1976). The production of CSBs can be organised as a small scale cottage concern or as a much larger mechanised industrial unit. Whatever the approach adopted, the production cycle is likely to remain similar, and can be categorised into four basic stages, namely:

- Soil extraction (and preparation)
- Mixing (soil, cement and water)
- Moulding (of the block)
- Curing (of the green blocks)

The order of the production process stages is not commutative and should therefore follow one after the other. This is illustrated by the schematic shown in figure 1.

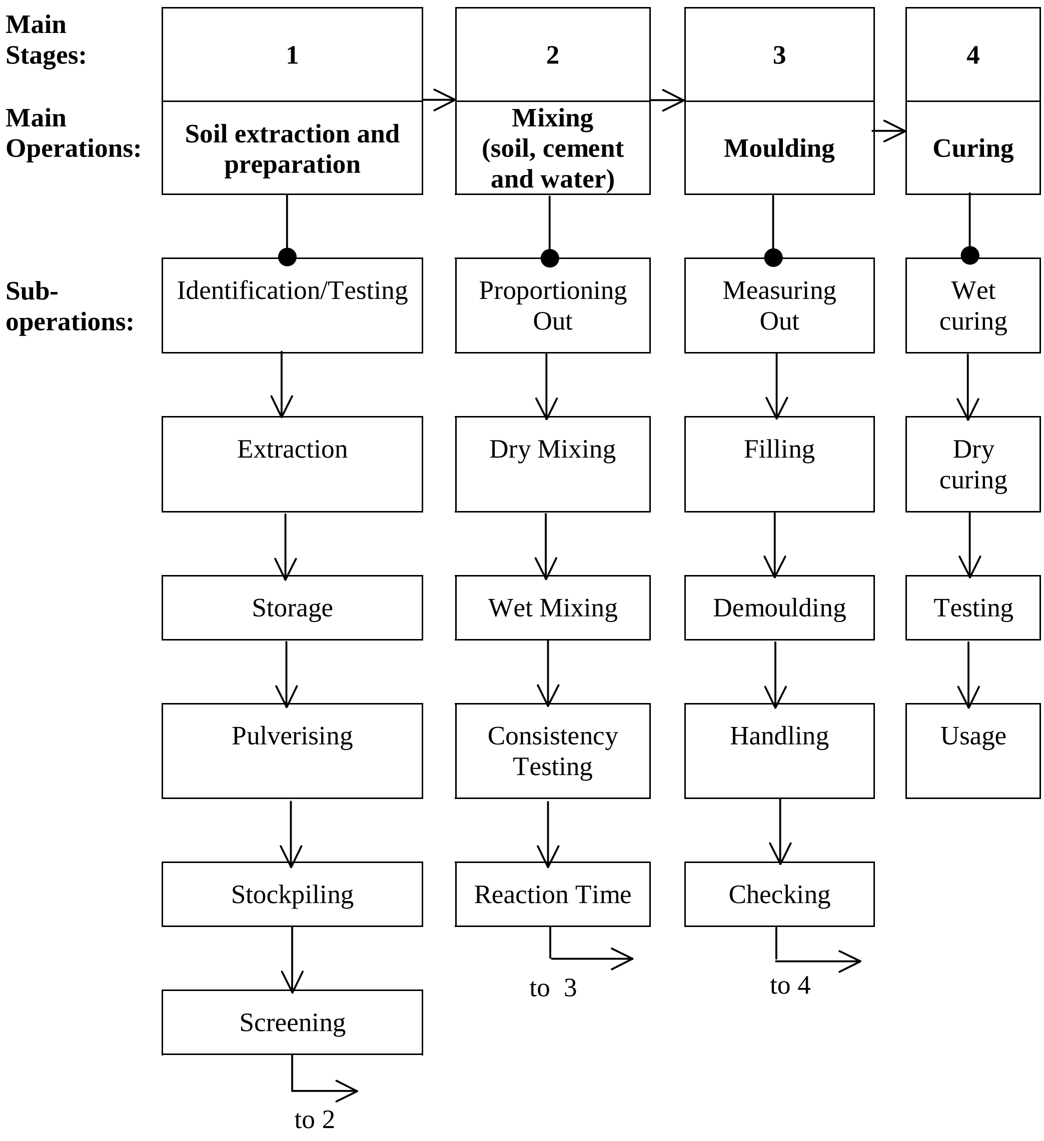


Figure 1: Schematic showing the main stages and operations of a CSB production cycle.

(Adapted from: Houben & Guillaud, 1994; Rigassi, 1995; Houben et al, 1996)

The schematic in figure 1 shows that within the four main production stages, there are several sub-operations. These operations are so interdependent that the sequencing adopted has to follow the order shown since each preceding operation must be completed before the next one can start (Webb & Lockwood, 1987). For efficient productivity, a block production site should be organised taking into account the unique nature of the various operations with a view to harmonising them. This has often been underrated with the result that key operations are missed or interfered with. In such cases both the quality of the block and the productivity of the site can be adversely affected.

As the properties and performance of a block are heavily dependent on the outcome of each of the production cycle processes, each stage is now discussed in turn. The experience gained by the author during the production of block samples for experimental investigations in the course of this thesis, and prior to this, during the manufacture of blocks for large CSB building projects in Uganda between the period 1987 and 1994, are also drawn upon. The discussions are presented in Sections 3.4.2 to 3.4.5 that follow.

3.4.2 Soil Extraction and Preparation

Soil to be used for CSB production should preferably be extracted from or near the proposed building site (Williams, 1980). Indeed this is one of the major attractions of using CSBs for building purposes (DoHUD, 1955; Fitzmaurice, 1958; Denyer, 1978; Agarwal, 1981). Sourcing the main raw material in this manner can significantly minimise expenses normally associated with transportation (Cinva-Ram, 1957; ILO, 1987). Prior to extraction however, the soil at the potential site has to be properly identified and classified (Norton, 1997). It is only after this has been done, with the results being acceptable, that subsequent procedures including extraction, may follow.

Identification of soil at the proposed extraction site may be facilitated if information on local soil types, or information based on experience can be obtained. Documented sources may include maps, previous construction records, etc. Even then, the soil will still need to be identified using field indicator tests followed by laboratory tests in that order (Akroyd, 1962; Stulz & Mukerji, 1988; BS 1377, 1990). Details regarding both types of soil tests are discussed in Chapter 4 and Chapter 5. As stated earlier, the soil needed for CSB production should contain some coarse fraction (fine gravel and sand), and some fines fraction (silt and clay). The clays in the fines fraction significantly contributes to binding the fine gravel, sand and silt together (Lunt, 1980). If the soil is deemed satisfactory either for direct use as it is, or following blending with the missing soil fractions, then the extraction process can commence.

The soil is best extracted from the sub-soil level and not from the top-soil level (from about 300 mm downwards from the surface) (Webb & Lockwood, 1987). Disregarding of top-soil layers ensures that undesirable inclusion of organic matter, normally dominant at this level, is avoided. Another important consideration before soil extraction can commence is whether the ground to be used as a pit can indeed supply enough soil for the particular size of the project. The pit should be located in an area large enough to generate and sustain the supply of sufficient raw material to satisfy the building requirements. In short, the process of soil extraction should only begin after it has been established that the soil is suitable, or can be modified to become suitable and that it is available in sufficient quantity (ESCAP/RILEM/CIP, 1987; ILO, 1987; Gwosdz & Sekivale, 1998).

The soil may then be extracted either manually or by mechanical means. Manual extraction involving labourers using basic hand tools such as shovels and picks has the disadvantage of low output. Experience of the author also showed that daily output in such cases rarely exceeded 3 m^3 per day per man. Yet when motorised mechanical means are used (excavators, bucket loaders), the output significantly can increase to about 100 m^3 per machine per hour. The high cost of hire or purchase of such equipment, coupled with the need to create jobs, might however continue to dictate that manual labour be used for the foreseeable future. Which ever approach is adopted, after the extraction of soil, further preparatory operations are still required. This is because freshly extracted soil is not immediately suitable in the natural state in which it is found (due to the presence of solid concretions in lumps or large pieces, or friable aggregations in powdery form). Further, the soil when freshly dug out, depending on its natural moisture content, may still be wet, moist, damp or even dry. It is not advisable therefore, to immediately use soil in any of these forms for block production without further preparations. The main objective of preparing the soil is to transform it into a more useable form of known moisture content and of the correct size functions (Cinva-Ram, 1957).

Soil preparation after extraction involves drying out, temporary storage, pulverisation, stockpiling and screening. Storing and stockpiling simply follow the key operations of drying and pulverisation. The just extracted soil can be dried out by spreading it out in thin layers on a hard level surface. By drying out the soil, an attempt is made to gradually free the soil particles from their entanglement and to obtain a material of almost even minimum moisture content. To achieve this fast enough, the thinly spread out soil should be regularly raked through in order to turn it over repeatedly. The same drying out operations were used for the ordinary builders sand used for manufacturing block samples for the experimental investigations in the course of this research (Chapter 5). The drying operation can be verified as satisfactorily completed through visual examination of any changes of colour of both the top and bottom layers. If the bottom soil is still of dark complexion even after several turning-over operations, it simply means the drying process has yet to be continued. When both the bottom and top layers of the spread out soil show a uniformly light colouration than when first obtained, then the soil can be considered to be dry enough. At this stage it should also be easy to break up any remaining soil lumps by hand. These should mostly be clay lumps, since it is such fines that are responsible for forming nodules. Nodules of diameter greater than 10 mm should not be allowed (Arrigone, 1986; Houben & Guillaud, 1994). Simple hand tools such as wooden hammers, hoes, pincers, etc., can be used to pulverise and break up soil lumps. Pulverisation and breaking up of lumps in this manner also helps speed up the drying process (by increasing the surface area). The pulverised soil can then be screened.

Screening of soil is a crucial process. Screening may be done by sieving using wire mesh sieve screens of agreed maximum aperture sizes. Recommended aperture sizes for sieves to allow the maximum size fraction of soil to be included in a block vary. Two recommended size ranges are reported in the literature: 5 to 6 mm (Webb & Lockwood, 1987; ILO, 1987), and 10-15 mm (Houben & Guillaud, 1994; Rigassi, 1995). The maximum soil size fraction used for block making in the course of this research was 5 mm (fine gravel and below). The process of sieving also serves to eliminate any undesirable materials still in the soil after the general preparations have been done. But the objective remains to rapidly ensure that only soil below the required maximum size fractions are the only ones obtained. The screen used may be a fixed one set at an oblique angle, or it may be a suspended one on top of a collecting bin. In the former case the soil is thrown at the screen while in the later case it is poured through it. When a fixed screen was used in Uganda, the rate of screening was about 1 m^3 per hour per person (Kerali, 1996). If no screen is available on site, it is still recommended that some form of removal, even by hand, be conducted. Large objects are usually easy to detect and to remove by hand.

After screening, the soil can then be stockpiled awaiting use. From this stage onwards, the soil should be covered in order to keep it dry and prevent clay lumps reforming once again. In the event that the soil obtained is predominantly of one type or size, then controlled mixing with other soil types and size fractions imported from nearby quarries should be done. This will improve the grading of the soil. For example, a predominantly sandy soil could be mixed with some clay (recommended minimum 10% and maximum 30%). Controlled mixing such as this will also help avoid unnecessary rejection and wastage of soil. During this research for example, the ordinary builders sand which was supplied, was mixed with pure Kaolin clay (15%) to form the soil of the desired design properties (Chapter 5).

In the preparation of soil samples for this thesis, it was not necessary to go through all the steps mentioned here. It was only necessary to dry out the soil on the laboratory floor, screen it through the 5 mm circular sieve screen, then store it in a well covered bin. The bins were kept in a dry area of the laboratory. Further discussions on the procedures are presented in Chapter 5.

3.4.3 MIXING OF SOIL, CEMENT AND WATER

This stage of the production process initially involves the dry mixing together of the main constituent materials (soil and cement), before wet mixing with water to hydrate the OPC. The sufficient distribution of OPC throughout the soil, and the homogeneity and uniformity of the resulting block, can be significantly affected by the procedures adopted at the mixing stage. Considering that over 90% of a block comprises soil, and that only less than 10% comprises cement, achieving an even distribution of the latter in the former is far from being straightforward. Yet the procedure is often underestimated, with severe implications for the quality of the resulting block. The main operations during the mixing stage include: proportioning out, dry mixing, wet mixing, consistency testing and hold-back time (retention time).

Proportioning out of soil and cement in their dry state is the first crucial step which requires care. The total volume of the separate dry ingredients to be mixed should be based on a practical criteria (Mukerji & Worner, 1991). From experience, the proportioning criteria is normally based on the hourly output of the press being used. This means blocks have to be produced in separate batches, requiring mixes to be prepared only in sufficient quantity to be consumed by the press within approximately one hours operation. Large batches are undesirable for several reasons. If larger batches are mixed without immediate compaction following, the water may evaporate causing the cement to set prematurely. This can easily be expected especially in hot tropical climates (Fullerton, 1979; BRE, 1980; Spence & Cook, 1983; Norton, 1986; Stulz & Mukerji, 1988). Moreover, with large batches, it is also very difficult to achieve an even and homogeneous mix. Use of large batches also increases the risk of moisture variations developing in a mix. OPC is known to set within about 45 minutes (Lea, 1972; Illston, 1994). If within this time the wet mix has not yet been compacted, then a significantly weakened block might be produced (Lunt, 1980). Moreover, as cement is usually scarce and therefore expensive in developing countries, wastage of the binder through premature setting should be foreseeable and avoidable. This can be done as stated earlier by proportioning materials based on batch sizes that can be compacted within the hour (Mukerji, 1994).

Proportioning out of dry soil and cement can be done either by weight, or by volume measurements (Webb & Lockwood, 1987). It is important that the materials being proportioned out remain in the same dry physical state. With volume measurement proportioning, either a single gauge box, or two different gauge boxes may be used. The use of a single gauge box which is meant to measure both soil and cement is common. The amount of cement and soil required for an hourly batch of blocks is then measured by filling, levelling and emptying the gauge box up to the required number of times for each separate material. This method is not without its failings. Apart from contamination, problems may arise if the moisture content of the soil will vary. When this happens, so will its specific surface area. Variation in specific surface area of a soil will result in different amounts of soil being measured out each time. This remains a major area of concern. Attempts should be made to ensure that the moisture content of the 'dry' soil remains constant. This is achievable through covering of the dry samples and avoiding humid environments. The mode in which the gauge boxes are filled is also a potential source of error. All loose material should ideally be filled in and tampered to avoid under-filling with the top also be levelled off to avoid over-filling. During the proportioning out of dry materials in the course of this research, proportioning was done by weight, not by volume (Chapter 5).

As stated earlier, following proportioning, the soil and cement should be mixed in two separate stages; first in a dry physical state, then in a wet state, in that order. Dry state mixing is best done by spreading the cement evenly over the spread out dry soil. The two are then mixed together thoroughly till a uniform homogeneous colour is observed. Samples of the mix can be scooped up and visually examined to certify that uniform colouration has approximately been achieved. Uniform colour of the mix is therefore the only useful control tool or indicator at this stage. Since no other obvious test exists, mixing of the two dry materials should therefore continue until a uniform colour is obtained. Mixing can be done manually or by mechanical means. For the experimental investigations during this research, dry mixing was done using mechanical means (Chapter 5). Mechanical mixing is preferable over manual mixing for several reasons. With hand mixing, the same high level of concentration that should be maintained throughout is not humanly possible all the time. It is not uncommon to find mixes produced earlier in the day being more uniform than those produced later in the clay by the same person(s). Exhaustion, familiarity, lack of concentration or interest, lack of knowledge of the implications, coupled with inadequate constant supervision, may all contribute to insufficient mixing.

After dry mixing to uniform colour, water can then be added to the still dry soil and cement mix. The purpose of the water is to hydrate the cement and to enable the mix to be compacted at optimum moisture content. Determination of the right amount of water to achieve both aims remains an area requiring more investigation in future. If mixing is to be done manually, then the determined amount of water should first be lightly sprinkled using a shower rose head container. This should be done in such a way that it just moistens the surface of the well spread dry mix. The water should not be poured onto the mix all at once, as was observed on some sites (Chapter 4). Neither should it be poured onto a heap of the mix as is also commonly and wrongfully done. This is to avoid creating particles of damp soil that may roll down the side of the heap while growing even larger in size. Contact with water should be made uniform and widespread. The mix is then turned over before more water is added to the soil and cement mix. The wet mixing operation has to be done repeatedly until two things happen: the damp mix achieves a uniform colour and it also passes the 'drop test'. Even on achieving uniform colour, any lumps still in the mix should be broken down. Lumps can form if the mixing time is too long, the moisture content is too high, or when incorrect mixing procedures were followed. Both dry and wet mixing should ideally be done within 3 to 4 minutes (Houben & Guillaud, 1994; Rigassi, 1995). For clayey soils, the moisture content of the mix should preferable be slightly higher than the OMC: for sandy soils, it should preferably be slightly lower than the OMC (Houben & Guillaud, 1994). In the absence of any other consistency test similar to the slump test used for concrete products, the drop test remains the only satisfactory indicator for approximating the OMC of the damp soil and cement mix (ILO, 1987). The slump test as used in concrete production may not work as a consistency test for CSB production due to the near-dry mix state required for the latter.

Unfortunately, passing the drop-test may not necessarily mean that further control measures be set aside. During the production of blocks in the course of this research, it was noted that in some of the mixes which had passed the drop test, excess water was observed dripping on the sides of the mould during compression. Similar experiences were recorded in Webb & Lockwood (1987). The amount of water in the mix had to be reduced as mentioned earlier. In the experiments conducted during the thesis, the blocks made from mixes where the water dripped by the side of the mould were not rejected. They were kept aside and labelled accordingly. The surprising outcome when these blocks were tested for wet compressive strength twenty-eight days later, was that values obtained were 25 to 30% higher than for the blocks made from the reduced water content mixes. The difference between the mean dry and wet compressive strength were also reduced. The only feasible explanation of this unexpected outcome was that the excess water in the mix contributed to the maximum hydration of cement. The issue of OMC and the sufficiency of water for hydration of cement is recommended for further future research (Chapter 8).

The time between wet mixing and compaction in the mould should be as short as possible when OPC is used as the stabiliser. A period of between 5 and 10 minutes has been suggested (Houben & Guillaud, 1994). For this reason, water should only be added for wet mixing precisely before the start of the moulding process. If any delay between dry mixing and moulding is anticipated, then wet mixing should be deferred.

The dry mix should be covered with a polythene sheet or similar protective cover. Delays of more than two hours due to lunch breaks or other human needs should not be allowed. The effect of hold-back time on the performance of blocks is investigated experimentally (Chapter 6).

3.4.4 Compressing the Damp Soil and Cement Mix

Compressing the damp soil and cement mix is a key stage in the production of CSBs. The effect of cement stabilisation of soil is significantly enhanced by compressing it (Ingles & Metcalf, 1972; Gooding & Thomas, 1995). Compression reduces voids by driving off air (compaction) and any excess water (consolidation) from the damp soil and cement mix. The combined expulsion of air and water, and the squeezing of the solid particles together increases the density of the mix. Uncompressed soil-cement mix of the same mass prior to moulding may have density ranging between 1000 kg/m^3 and 1400 kg/m^3 (Norton, 1997). After compression, the increase in density for the same mass of mix is between 30% and 120%, commonly ranging between 1700 kg/m^3 and 2200 kg/m^3 (Houben & Guillaud, 1994; Rigassi, 1995). Higher densities are associated with improved durability (Spence, 1975). Compression of the mix should be done as soon as it has passed the drop test. The compression stage involves five distinct steps, namely: measuring out, mould filling, moulding, demoulding, and handling of the green blocks (Rigassi, 1995). Underestimation of any of these five steps can lead to the production of inferior blocks of low compressive strength and durability.

The damp soil-cement mix has to be correctly measured out before filling the mould. Any slight variations in the amount of mix fed into the mould can result in blocks of differing density and sizes. Cases of differences in density are normally associated with fixed-volume type of compression machines while size variations with fixed-pressure ones (Lunt, 1980). The two types of errors are cumulative and should be minimised or avoided completely. To do this, the amount of damp soil-cement mix to be filled into the mould should be strictly controlled. This can be achieved by measuring out the exact amount of mix to be placed into the mould each time using either a graduated bucket, scoop, or measuring box of fixed volume. Measurement by weight, though considerably slower, can also be done. Presses equipped with adjustable measuring devices which either use sliding valves or tipping boxes are extremely rare. Whichever method is adopted, the important point is to ensure that the correct amount of mix, and of even moisture content, is fed into the mould each time. The moisture content of the mix matters a great deal, and variations should preferably be avoided. Variations can lead to changes in specific volume causing differing amounts of mix to be placed each time. During the manufacture of block samples for experiments in the course of this research, measuring out was done exclusively by weight (Chapter 5).

Filling of the mould with the measured out mix should then follow promptly. Before the actual filling of the mould box, its interior should be cleaned. Although mould types vary, they are generally designed to be completely filled with the mix. After filling the mould, the top of the last layer should be scraped off level with the sides of the mould. The filling is best done in two or three equal layers. The filling operation for each layer should be checked each time, with the fingers being used to press the mix into the corners after each layer has been placed. Pressing the corners is necessary because the bottom corners of the mould are the most difficult part of the mould to fill. In addition to this topping up, removing excess material and any lumps of soil or stones, etc., should all be done for the top layer at this stage. After the mould has been filled and checked, it can then be covered with the mould lid. The lid itself has to be correctly positioned ensuring that no mix is left entrapped between the lid and the edges of the mould. There is yet no known device to indicate that the mould has been correctly filled (Mukerji, 1988; Rigassi, 1995).

The mix can then be compressed. As machines vary widely, the operations needed to compress the block will differ according to the specified characteristics and operating manual for each press. Block making presses will vary by:

- Compression type (static compression, dynamic, or kneading)
- Moulding pressure (low < 3 MPa; moderate 4-6 MPa; high > 7 MPa)
- Compression ratio (1:1.65 to 1:2)
- Productivity (maximum daily or hourly output)
- Mould size and type (fixed, adjustable: solid, hollow, frogged, interlocking)

In most manual presses, the force applied to the compression lever will depend on how much mix has been placed in the mould. This force should neither be too high, nor too low. If the force required is too high, either the machine will gradually get damaged, or the operators will tire out quickly. If the force is too low, the block will be insufficiently compressed (Norton, 1997). Such difficulties are experienced even with motorised press units. As the compression force remains uniform, it becomes impossible to check during compression if the mould has been correctly filled. If the correct amount of mix is at its OMC is placed each time and the same moulding pressure is applied, it can be expected that blocks of constant density are produced. Such blocks will also tend to be of uniform dimensions. For the Brepack machine used to produce samples in this research, an attached pressure gauge provided the needed indication of the pressure exerted (6 MPa and 10 MPa). The transmission of energy to the mix was through an hydraulic system. The main advantages of this compression machine were that the number of operations needed were few, thickness of the block could be controlled, and laminations usually associated with other compression methods avoidable. Laminations will tend to occur if the speed of compaction is below 1-2 seconds (Houben & Guillaud, 1994). A further advantage was that the sides of the blocks were well compacted. This should be expected as the internal friction of the soil-cement mix increases, so does the pressure on the surface of the mould. The mix closer to the mould surface is more thoroughly compressed than that further from it. Which is why the least compacted soil-cement mix is likely to be found at the middle of the block which is subjected to the least shear (Houben & Guillaud, 1994). This has clear implications for the durability of a block. It explains why block surfaces should be protected at all costs and not allowed to deteriorate prematurely. If allowed to recede inwards, it will expose the core of the block which is its least compacted part. The rate of deterioration is then likely to increase significantly from then on (Chapter 2).

After moulding, the green blocks have to be ejected usually through the same piston that compressed the block (in most presses). On ejection, the block should be carefully removed and handled. Since the green block is still weak and fragile, great care should be taken during the handling operation. The surface area of contact between the block and the mechanism of removal (hands, block pincers, wooden pieces) should be as large as possible to reduce any unreasonably high pressures on the green blocks to a minimum. Special precautions should be taken while removing blocks from certain types of moulds. Removal of solid blocks is easier than removal of hollow, frogged and interlocking blocks of a similar size. Non-solid blocks will tend to have several points of vulnerability, such as protrusions, indentations and thin sections. Areas of the block such as edges and corners still remain particularly vulnerable and should not be touched. These considerations are often underrated with the result that blocks with broken edges and chipped corners are commonly produced. On removal from the mould, green blocks should undergo certain quality control checks. Between 5 and 10 blocks per batch can be selected at random for such tests (Rigassi,1995).

Details of the tests conducted at this stage and findings are presented in Chapter 5. These tests were done to identify variations in blocks produced and their possible reasons. For example, any variations in the direction of compaction (height) could easily be attributed to irregular filling, which could then be corrected. Density variations can be detected by weighing the samples and taking their dimensions. Low density for the same mix could then be attributed to insufficient mould filling. These quality control tests are useful since they contribute to reduction in wastage and early detection of poor procedures which would otherwise lead to the production of inferior quality blocks, of low compressive strength and durability (Chapter 4).

For quality output to be sustained, regular maintenance of the press should be conducted. After each day, or even on brief stoppage of work, the press should be thoroughly cleaned and left in a state ready for the next production to begin. Maintenance procedures normally included in the manual for each press should be strictly adhered to. Supervisors can assign one person the responsibility to do the daily maintenance. Each inspection and maintenance conducted should be verified and a record of what was done and when should be kept.

3.4.5 CURING OF GREEN BLOCKS

Curing of green blocks may be the last stage in the production process but remains one of the most consequential. As stated earlier, the strength of CSBs, as with almost all concrete products in which OPC is used, increases with age (ILO, 1987; Lea, 1970). The hardening of OPC takes time, and so will the development of strength in a block. For the OPC to harden normally, it requires the continued presence of moisture in a block which enables it to complete the hydration process. Insufficient w/c ratio, and low degree of hydration can result in considerably weak blocks. If the green block is not allowed to retain sufficient moisture, then the hydration process will have been interfered with. This can result in unsatisfactory blocks of low strength and poor performance (Enteiche & Augusta, 1964; Odul, 1984).

The objective of the curing stage is therefore to ensure that moisture still in the block is allowed to facilitate the hydration process and to come out gradually and evenly. The two variables during curing that can affect this objective are the duration (time) and conditions (wet, dry, temperature, relative humidity, wind). The curing duration is often dictated by the specifications for the type of binder used and is based on the time needed to achieve the maximum degree of hydration. For OPC the recommended length of time is usually 28 days (BS 12, 1971; Spence, 1980; ILO, 1987; Taylor, 1998). Curing conditions specifically refer to the microenvironment in which the green block is placed. Normally the conditions are such that wet curing is followed by dry curing. During this research, the effect of varying curing conditions and time were investigated. The results are discussed in Chapters 6 and 7.

The curing process normally consists of two phases (ILO, 1987; Neville & Brookes, 1994):

- Primary curing phase (3-5 days)
- Secondary curing phase (up to 28 days for OPC, up to 56 days for lime)

The *primary curing phase* follows immediately after the demoulding of green blocks. During this phase, emphasis is placed on ensuring the retention of moisture within the block. The green blocks should be shielded from direct sunlight and strong winds. The process usually takes three to five days with seven days being the maximum possible (ILO, 1987). If the green block is not shielded, then rapid evaporation is likely to take place, promoting the undesirable loss and uneven distribution of moisture in the block. This can result in surface shrinkage cracking. For this reason, the surface of green blocks should be well protected using light coverings such as polythene sheeting, tarpaulins, or other suitable light materials. Polythene sheets are quite useful since they allow the temperature to rise, while at the same time ensuring that approximately 100% relative humidity is achieved (Rigassi, 1995). During the curing of samples for this research, green blocks were superficially covered on the first day, then placed inside sealed polythene sheeting 24 hours later. The blocks were then laid next to one another in a designated primary curing area within the laboratory.

Current indicators of sufficient primary curing are based on colour changes of the block, and sometimes on the degree of evaporated moisture trapped beneath the covering polythene sheeting. Freshly demoulded blocks, due to the relatively high moisture content still in them, tend to be of dark complexion. As the moisture is used up for hydration, with some escaping, the complexion of the demoulded block begins to adopt a much lighter colour. When sustained light colouration is attained then primary curing can be considered complete. Generally, the moisture content of the block should not be allowed to vary by more than 1-2% during the primary curing period (Houben & Guillaud, 1994; Rigassi, 1995).

The *secondary curing phase* follows on from the previous phase, with the objective this time being to allow any moisture still in the block to evaporate out gradually and evenly. The gradual evaporation of moisture out of a block affects both the OPC hydrates and the clay minerals in the block. Secondary curing also allows the semi-cured blocks to be conveniently stacked nearer to the actual building site proper. Even then, the blocks have not yet fully developed the required compressive strength. They should therefore be stacked not more than 10 blocks high on a hard, flat and level surface (Rigassi, 1995). The stacked blocks should continue to be protected from direct sunlight, wind and rain. This can be done by dry stacking the blocks under a covered shed or shelter for 2 to 3 weeks in the case of OPC stabilised blocks. After 28 days from the date of demoulding, the blocks are deemed to have achieved sufficient strength. After this period, there will be no further noticeable significant increase in strength for the OPC hydrates that bind the blocks particles together (Fitzmaurice, 1958; PCA, 1970). For lime stabilised blocks, twice the time recommended for OPC should be provided for during both primary and secondary curing (BS 890, 1972; Bessey, 1975; Coad, 1979; Apers, 1983; Webb & Lockwood, 1987).

The fully cured blocks can then be placed on wooden pallets, or stacked in easily counted lots. Initial performance tests can then be conducted on randomly selected samples from each batch (ILO, 1987). These are then compared with local acceptable minimum standards for buildings (Houben et al, 1996). Results of initial performance tests for blocks produced during this research are presented in Chapters 6 and 7.

3.5 CONCLUSION

From the preceding sections, a number of important conclusions can be made. These are summarised below, presented in the order of coverage in Chapter 3.

Main constituent materials (cement, soil, water)

CSBs will perform well for the service life of the structure of which they form part if sufficient attention is paid to the choice of materials and their proportioning. A thorough knowledge of the nature and properties of the three main materials (cement, soil and water) is thus required.

Cement constitutes between 5 and 8% by weight of a block. It was noted in Chapter 3 that the main function of OPC is to bind the soil particles in the block together, thus forming a composite structure with increased compressive strength (both wet and dry), limited dimensional movement and improved durability. For this to be attained, the mechanism of cement hydration and the properties of the resulting cement hydrates that can influence the durability of the block, should be well minded. It was established from literature sources that present approaches in the use of the binder appear to take these factors for granted. Yet for OPC to have maximum effect in binding the soil particles together, and for the block to develop high strength, the water-cement ratio used should be low and a maximum degree of hydration has to be achieved. The former can be facilitated by use of cement replacement materials, while the latter can be achieved by proper curing. These two considerations rarely feature in current CSB manuals. The effect of these two factors on the durability of blocks are investigated experimentally in Chapters 6 and 7.

Soil constitutes the bulk of CSBs. Amounts as high as between 90 and 95% by weight of the block are normally used. Soil is composed of fine gravel, sand, silt and clay. In natural soils, the proportions of these four main soil constituents can vary infinitely, and with each variation, so do the properties of the soil. Not all soils can therefore be considered suitable as found for CSB production. To assess the suitability of a particular soil, the soil will first need to be identified and classified. It was established from literature sources that the most important basis for soil classification are through its particle size distribution and its plasticity. Current suitability criteria for soil requires that they be well graded. The soil has to contain almost every soil size fraction between the maximum (usually gravel less than 20 mm, or 6 mm), and the minimum particle size (usually clay less than 0.002 mm). In a well graded soil, the packing of the soil particles is considered to be in its most dense state. The plasticity of soils on the other hand is associated with the presence of fines, usually clay. According to literature sources the desirable plasticity index of soil suitable for stabilisation should vary between 5% and 30%.

Clay types vary immensely, though three main groups are identifiable (kaolin, illite and montmorolinite). It was widely reported in the literature that the clay type and amount is a major factor in determining the suitability of soil for stabilisation. Soils with clay content below 30% can be stabilised using OPC, while those with more than 30% using lime. Lime is known to have the capacity to fix the clay, through a pozzolanic reaction.

Water is added to the dry soil-cement mix to hydrate the cement and to lubricate the soil to attain maximum densification. Unfortunately the literature reveals that current emphasis is generally placed on the required quantity of water, but not on its quality. Due to the scarcity of water in most developing countries, all kinds of sources are likely to be used for CSB production. Water of unknown service record may contain contaminants that may adversely affect the hydration reaction of OPC. Such water may contain suspended solids and soluble substances in excess of current limits for drinking water. The effect of the use of water of unknown service record is investigated and discussed in Chapter 4.

Soil-Cement Stabilisation

Chemical stabilisation of soil using OPC as the binder of choice was the main stabilisation method described. It was noted that the effect of cement stabilisation is more long lasting than pure mechanical or physical means of stabilisation used alone. It was also reported in the literature that the combination of all the three methods is more effective. It was noted in Chapter 3 that in the mechanism of stabilisation using OPC, the binder joins the soil particles together by forming strong interlocking bonds with the fine gravel and sand fractions of the soil. The lime that is released from the hydration reaction of OPC then reacts with the clay to form a secondary binder, with similar binding effects.

The composite matrix that results contains cement hydrates, conventional mortar, calcium hydroxide, unhydrated OPC residues, unstabilised soils, and capillary pores. According to CSB literature sources the exact proportions of each of these matrices in the block fabric is still unknown. The proportions of each of these matrices is likely to influence the durability of blocks significantly. Attempts are made in this thesis to identify some of these matrices using the petrographic analysis of thin sections (Chapter 7).

Block Production Cycle

It was established from literature sources that the CSB production cycle comprises four main stages, each with several sub-processes. The main stages include soil winning and preparation, soil-cement-water mixing, moulding and curing. It was noted that the processes were so interdependent and interrelated that they require to be conducted in a proper sequence. Omission of any of the stages is likely to adversely affect the properties of the final block.

With the preceding conclusions, the objectives of Chapter 3 were met. The key issues identified in Chapter 3 are to serve as the theoretical background for the experimental investigations described in Part B of this thesis.

PART B:

MAIN INVESTIGATIONS AND FINDINGS

CHAPTER 4

EXPOSURE CONDITION SURVEY OF CSB BUILDINGS

4.1 INTRODUCTION

The performance of CSBs can be better understood through a combination of theoretical knowledge, study of precedents and assessment of the experience of its users. This chapter reports on methods and findings from a study of the last two approaches.

As part of the research, a fieldwork was undertaken in Uganda between January and March 2000. Uganda was selected for two main reasons: firstly, its geographic location within the humid tropics, and secondly due to the large stock of CSB buildings found in the country. The exposure conditions were considered to be representative of similar conditions in most of the humid tropics. Further, CSBs were first officially introduced in the country for low cost housing in high density urban areas in 1987 (Okello, 1989). Since then, several hundred CSB structures were built mostly under the auspices of donor agencies like the ILO. During this period (1987 to 1995) the author, apart from involvement in similar projects in other parts of the country, directly supervised the construction of a number of residential buildings using CSBs (Kerali & Schmetser, 1995). At the time of the fieldwork visit, the use of CSBs for low-cost housing had been extended to other large urban municipalities in the country.

The objective of Chapter 4 is to report on the main methods and key findings from the fieldwork. Four methods were used during the fieldwork, namely:

- Collection of documented data on the inventory of CSB buildings and environmental exposure conditions in Uganda.
- Conduct of exposure condition survey of CSB structures of various ages and stages of completion. This involved: random inspection of existing buildings, in-service testing, scrutiny of maintenance records and other test records. Photographic records of inspected structures were then kept.
- Observation of methods of work on current CSB production sites including the conduct of suitability tests on soils and quality test checks on cement and water used.
- Interviews and questionnaires to gauge the opinions and experiences of randomly selected respondents.

The scope of coverage of Chapter 4 therefore focuses on the discussion of findings resulting from using the above methods. The chapter is divided into six sections. After this introductory section, the rest of the chapter covers background documentation, condition survey methods and findings, block production site visits, interviews and questionnaires, and conclusion.

4.2 BACKGROUND DOCUMENTATION

In this section, the inventory of CSB structures in Uganda and the characterisation of the exposure environment are presented.

4.2.1 Inventory of Existing CSB Buildings

The purpose of seeking information on the inventory of CSB buildings in the country was to obtain an indication of the overall total number of existing CSB structures. The same exercise was also used to get information on current building programmes and future plans.

Since the introduction of CSB structures in the country in the late 1980s, over 400 buildings have been constructed. As mentioned earlier, CSB structures were introduced officially under the auspices of the International Labour Organisation (ILO). The ILO was implementing an earlier resolution of the United Nations Conference on Shelter Strategy that had been held in Vancouver, Canada in 1978 (DoH, 1992). At the time, the projected housing backlog in Uganda by the year 2006 was estimated at 3 million dwellings. CSB structures were targeted at the high density, low income urban areas (Davidson & Payne, 1983; Taylor & Cotton, 1994).

Other CSB structures were built in rural areas in the form of public buildings such as health centres, schools, community centres, etc. These were initially built in the central region districts of Kampala, Luweero, Mpigi and Kiboga. The largest single housing estate in which CSBs were used remains at Namuwongo (in Kampala)where over 100 residential buildings were erected. At the time of the fieldwork visit, the project site consisted of buildings in various stages of completion (completed, on-going, abandoned, etc.). Also at the time of the visit, another large CSB project site had been initiated at Malukhu, in Mbale Municipality. Over 80 structures had been erected, with plans to construct at least 100 buildings annually over the next few years. This latter project was being funded by the Danish Agency for International Development (DANIDA). These two sites therefore represent the largest single concentrations of CSB structures in the country. Both sites were extensively inspected by the author and in-service tests conducted on buildings as well as on green blocks being produced. Photographs of some of the main features at the two sites were taken.

The findings are discussed in Sections 4.3, 4.4 and 4.5 of this Chapter.

Even with these promising developments, the housing deficit in the country, as is the case with many other developing countries, remains acute (Hamdi, 1995). The demand for CSB structures is therefore likely to remain very high in the foreseeable future.

4.2.2 CHARACTERISTICS OF THE NATURAL EXPOSURE CONDITIONS IN UGANDA

Characterisation of the exposure environment in which CSBs were being used was considered to be a crucial undertaking during the fieldwork. The objective was to identify the main naturally occurring agents whose effects were likely to remain deleterious to the block structure over its service lifetime. The approach which led to the listing of the different types and ranges of deterioration agents was based on the deterioration mechanisms discussed in Chapter 2. The highlights of the mode of occurrence of the main deterioration agents (rain, temperature, relative humidity) and the results of the visual inspection of defects were used to produce a provisional severity ranking of deterioration mechanisms (Appendix D).

The type of agent acting on a block and the severity of its actions are closely correlated to the geographic location of the CSB building structure (BS 7543, 1992; Sjostrom et al, 1996). Moreover, local topography and geographic features are known to modify climate. Before presenting the average climatic conditions in Uganda therefore, it is necessary to first of all describe some of the main geographic characteristics of the country.

Uganda is located astride the Equator, lying between latitudes 4°12N and 1°29S, and within longitudes 29°34E and 35°0E. Although the total land area is 241,000 square kilometres, about 20% of it is covered by water, and about 30% by forests (Briggs, 1994; Hood, 1996; Tetley, 1998). Located at the highest altitude in Africa, the elevation above sea level (ASL) varies between 620 metres ASL and 5110 metres ASL. About 85% of the country lies between 900-1500 metres ASL. As can be expected, these geographic features (water bodies, forest cover, elevation ASL) do have a considerable influence in modifying the climatic conditions in the country. The use of CSBs under such unique climatic conditions can therefore be expected to present special problems. The description of the average climatic conditions in the country would not have been complete without mentioning these geographic features. In terms of macro-climatic and global weather classification, Uganda falls within the Equatorial belt. This humid, tropical belt stretches between 6°N and 6°S (BRE, 1980; Webb, 1988). The climatic characteristics of interest to this research are rainfall and temperature.

The *mean annual rainfall* in Uganda is about 1500 mm per annum (Hood, 1996). The rainfall, which is seasonal, is fairly well distributed throughout the country. Two distinguishable rainfall seasons are the long rains of March to May and the short rains of September to November. In analysing the potential deleterious effects of rainfall on CSB structures, it is the mode of occurrence of the rain within the immediate proximity of the block which is critical (intensity and duration of the rain) (Ola & Mbata, 1990). The intensity of rainfall in the country, a measure of the quantity of rain falling in a given time, is reported as being greater than 7.5 mm/hr. This falls within the classification for heavy rains (> 7.5 mm/hr) as opposed to light rains (< 2.5 mm/hr) or moderate rains (2.5 – 7.5 mm/hr) (Linsey et al, 1975; Wilson, 1993). The maximum fall of rain in any 24 hours was recorded as 300 mm in Ssesse Islands. The average drop size was reported to vary between 0.5mm and 6.0 mm (Wischmeier &

Smith, 1958; Kirkby & Morgan, 1980). The duration of rainfall in the country, a measure of the period of time in which it falls, also varies a great deal. Periods of between less than one hour and six hours are reported as being typical (Newman, 1986; McIllveen, 1998). It is well documented that the higher the intensity of rainfall in the country, the shorter is the duration in which it occurs. It is this intensity-duration relationship that can considerably influence the erosive potential of rain (Blanchard, 1948; Bilham, 1962). The erosivity of rain can also be determined by the rain drop-size, its distribution, fall velocity and impact kinetic energy (Ellison, 1944). As can be expected, an erosive threshold below which no surface erosion will take place ought to exist. A similar approach has been successfully used in soil erosion sciences. It was established that the erosive threshold for loose soil in terms of rainfall intensity was about 25 mm/hr (Kirkby & Morgan, 1980). This is a theoretical cut-off point above which erosion of soil can take place. Since CSBs are much denser, stronger and more structurally stable than natural soils, the erosive threshold is likely to be several times higher than the 25 mm/hr suggested for loose and weakly bonded natural soils. Intense rainfall on a CSB surface is more likely to initially wet the surface and generate surface flow than immediately dislodge material from the block surface. The mechanism of water-related deterioration was discussed in detail in Chapter 2. The rainfall characteristics in the country suggest that water-related deterioration of exposed block surfaces is likely to take place during the service lifetime of the block. Defects associated with this mechanism of deterioration are described in Section 4.3 of this Chapter.

The *ambient temperature* in the country is quite high. The average daily ambient temperature is 25°C. The highest mean daily temperature recorded in the country was 35°C (Karamoja region in the dry north east). The lowest mean temperature recorded was -5°C (at the peak of the Rumenzori Mountains in the west of the country). The sunshine hours in the country average between 8 and 10 hours. The mean total evaporation is reported as 1950 mm (Hood, 1996; Tetley, 1998). As can be expected these temperature conditions provide the basic setting for temperature-related deterioration to occur in blocks. Mechanisms of temperature-related deterioration were discussed in Chapter 2. The presence of large, fresh water bodies in the country such as lakes and rivers and the high temperatures ensure that the level of humidity in the country is also high. Typical ranges for relative humidity are reported as lying between 30 and 90% depending on the cloud cover.

The data presented in this section was considered to be adequate enough to provide sufficient information to link the deterioration of CSB structures to the most common deterioration agents known. The condition survey that follows describes in more detail the common types of defects found on exposed CSB wall structures.

4.3 CONDITION SURVEY METHODS AND FINDINGS

The condition survey of exposed CSB structures was perhaps the most important undertaking during the research. Three methods were used for the survey, namely:

- Visual inspection (of CSB buildings)
- In-service condition measurement (of defects)
- Field indicator soil testing (at the major CSB project sites)

These are now discussed each in turn, in the following sections, 4.3.1, 4.3.2 and 4.3.3.

4.3.1 VISUAL INSPECTION OF EXPOSED CSB STRUCTURES

As with most building materials, the initial detection of their exposure performance is initially based on visual inspection (BRE, 1982; Bungay & Millard, 1996). Visual inspection is therefore the first phase of any in-service evaluation of a material such as a CSB. In this section, the following are discussed:

- Reasons for choosing visual inspection as a method for evaluating the performance of CSBs
- The number of types of CSB buildings inspected
- The type and range of defects observed

Visual inspection as a way of assessing the performance of CSBs under natural exposure conditions was selected for several reasons. They include the following:

- the CSB specimens being inspected within the exposed wall structure are at their 'full scale' during the assessment. This makes it possible to closely examine their current condition on a full scale basis. Any defects due to dimensional changes and the effects of the restraining action of adjacent blocks and mortar, can be observed directly. The effect of such restraint is very difficult to accurately simulate experimentally.
- the weathering conditions under which the defects were caused are genuine. Because of this, the full effects of the entire range and distribution of deterioration agents acting on the wall surface can be directly observed. A cause-effect link between defect and action of agent(s) can be deduced.
- through visual inspection, more severe cases of deterioration can be distinguished from less severe ones. Using the severity ranking (defects, agents), further in-service tests and measurements can be recommended based on visual observations. The selection of test types can only follow on from the visual inspection report. This is time and cost saving (BS 8210, 1986).
- it is possible to use a number of non-destructive measurement techniques and instruments. Some of the instruments used included: depth gauges, electronic

callipers, crack gauges, hand-held microscopes, rulers, set-squares, etc.

- the in-use conditions of the buildings being inspected are genuine. All user induced influences on the normal wear and tear of the CSB structure can be assessed.
- through the use of a sufficient number of samples, it is possible to reach fairly reliable results and therefore generalise. In this way the interpretation of findings from visual inspection can be considerably facilitated.

With the above reasons in mind, a systematic inspection was made of several CSB buildings in Uganda.

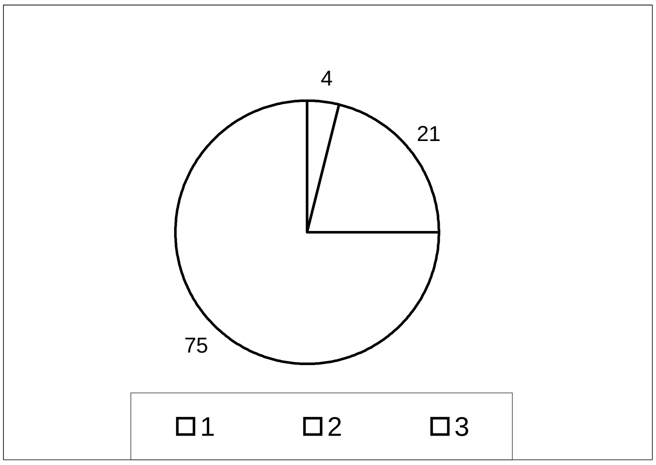
The *number and types* of CSB buildings inspected were varied, all chosen at random. Seven out of the thirty five districts where CSBs had been used for building were visited. In this way a total of 58 CSB buildings were inspected, representing a sample size of about 15% of the officially recorded number of CSB buildings in the country (above the 10% minimum normally required statistically for reliable inferences to be made). Using a checklist of all possible types of defects, the average time taken to inspect each structure was about 45 minutes. The inspected buildings were of different periods of exposure ranging from one month following substantial completion to those with over twelve years of exposure. The buildings were also in various stages of completion: completed, on-going construction and abandoned structures. Buildings found abandoned at wall-plate level and below without roofing appeared to be the most severely damaged (equitable to normal experimental exposure situations). It is from such structures that further in-service measurements (recessed volume of block, width of cracks, degree of pitting and roughening, etc.) were made. These are discussed in Section 4.3.2 that follows.

The line Ministry of Works and Housing provided background information on the period of exposure of each building, types of constituent materials used and the processing method employed to make the blocks. By compiling the list of defects and comparing the findings with the information obtained on each building, a number of useful conclusions were made.

The *type and range* of defects observed from the fifty-eight CSB buildings inspected are summarised in Appendix E. Also shown are the type of defects, façade and section of wall in which they occur, likely causes, age of structure and frequency with which the defects were observed. Comments on some of the features observed by the author, together with information from the users and co-inspectors, are also included.

From the information summarised in Appendix E, it is noted that:

- Surface erosion (resulting in mass loss, or volume reduction) and surface cracking (resulting in bond breakage and segregation) are the two most common defects observed in CSB structures left exposed to the elements. In the tally of number of buildings inspected and frequency with which a particular defect was observed, surface erosion (including roughening and pitting) occurred in 75% of all the cases. Surface and bulk cracking occurred in 21% of all cases. Other defects all counted together only occurred in 4% of the buildings observed. The above results are shown in the form of a pie chart in figure 2.



Key:

1: Others (4%)
2: Surface and bulk cracking (including crazing) (21%)
3: Surface erosion (including pitting and roughening (75%)

Figure 2: Relative frequency of observed common defects in CSB buildings in Uganda (January-March 2000)

- Surface erosion occurs more severely on the lower sections of a wall, rather than on the middle and upper sections. The combined effect of direct abrasive action of rainwater, surface run-off and splash from the ground is thought be account for this difference (Chapter 2).
- Surface cracking and crazing occur more on the east-west facades than on the north-south facades. With the country located astride the Equator, the effect of the direction and period of sustained solar radiation from the east (sunrise) and west (sunset) ought to be taken into account when explaining the difference.
- Cracking of the bulk mostly occurs within the framework of the wall rather than in the corners. The unusually thick and non-uniform mortars used (10mm to 20mm) is believed to be responsible for some of the cracking in the bulk. Mortars are designed to be weaker than the block to allow for flexibility due to dimensional changes. Where the mortar is unnecessarily thick, the restraint on movement can result in enhanced cracking (Neville & Brooks, 1994; Walton,

1995).

- The corners of walls were the worst affected. A likely explanation is that at wall corners, rain is able to strike the block from all directions. Moreover, wind velocities are highest at corners. The level of erosion is therefore likely to be higher in such parts of the wall than in others.
- Defects due to causes other than environmental factors can also occur in CSBs. These include defects due to overall foundation settlement, biological agents and impact from users. Also observed were defects related to improper material design, workmanship and processing methods (Odul, 1984).

The results of the visual inspection of exposed CSB buildings confirm that premature deterioration of CSBs can occur in humid tropical environments. In Section 4.3.2, the extent of surface erosion and cracking, being the two most common defects observed, are determined by direct measurement for the most severely affected units.

4.3.2 IN-SERVICE MEASUREMENT OF VOLUME REDUCTION, DEPTH OF PITTING AND CRACK WIDTHS

As mentioned in the previous section, the two most common defect types (surface erosion and cracking) were identified for further direct measurement. The measurements were conducted on two of the oldest exposed structures located at the Namuwongo Urban Slum Upgrading project site in Kampala City. Both CSB structures had been left abandoned at wall-plate level without roofing. A third building, also abandoned at a similar level, that had also been selected for similar assessment, was inaccessible (recently fenced off for rebuilding). The two structures were taken as being representative of the worst case of severe deterioration from long-term exposure. The walls could be equated to similar walls built on normal experimental exposure test sites (BRE, 1980). Lack of protection from environmental elements due to the absence of roof cover and external render meant that the full extent of deterioration from weathering agents could be said to have reached its maximum during the eight and twelve years of exposure respectively. Moreover, the weathering conditions (normal and severe) under which the defects were caused were all genuine.

The direct measurements involved assessment of the following:

- Volume reduction (including pitting depth) to estimate the extent of surface erosion
- Crack width measurements

The methods and results obtained for each defect type are now described.

Estimates of Surface Erosion (by volume reduction)

Surface erosion leads to irrecoverable mass loss. This in turn results in the reduction of the volume of a block. By measuring the overall depth, width and length of surface material lost due to erosion, the volume of the recessed block surface can be determined. By deducting the recessed volume of the block from the original volume (determined from original block dimensions), a volume reduction percentage for each block can be obtained.

The procedure adopted to obtain the recessed volume for blocks in each of the two abandoned buildings was the same. For each building, thirty six blocks per building were measured. This total number was arrived at as follows. For each abandoned building, the nine most severely affected blocks per façade (north, east, south, west) were identified for measurement. The nine blocks on each façade comprised three blocks each from the upper, middle and lower courses of the wall. In this way, not only would any differences in defect severity per façade be obtained, but also differences per section of the wall in which the block was embedded. Where the degree of recession was high, the determination of the recessed volume was easy to measure and calculate. Where loss of mass was spread out on the block, the block surface was divided into four sectors. In each sector, the dimensions of recession were measured, and the total recessed volume obtained by adding up. All measurements were done using an electronic calliper complete with a depth guage (Mitutoyo brand). This light, hand-held calliper displayed the depth, width and length of eroded surface zones directly on its mini-screen. From the results, the histogram shown in figure 3 was obtained for each building. They show the volume reduction percent (%) for each wall façade and sector.

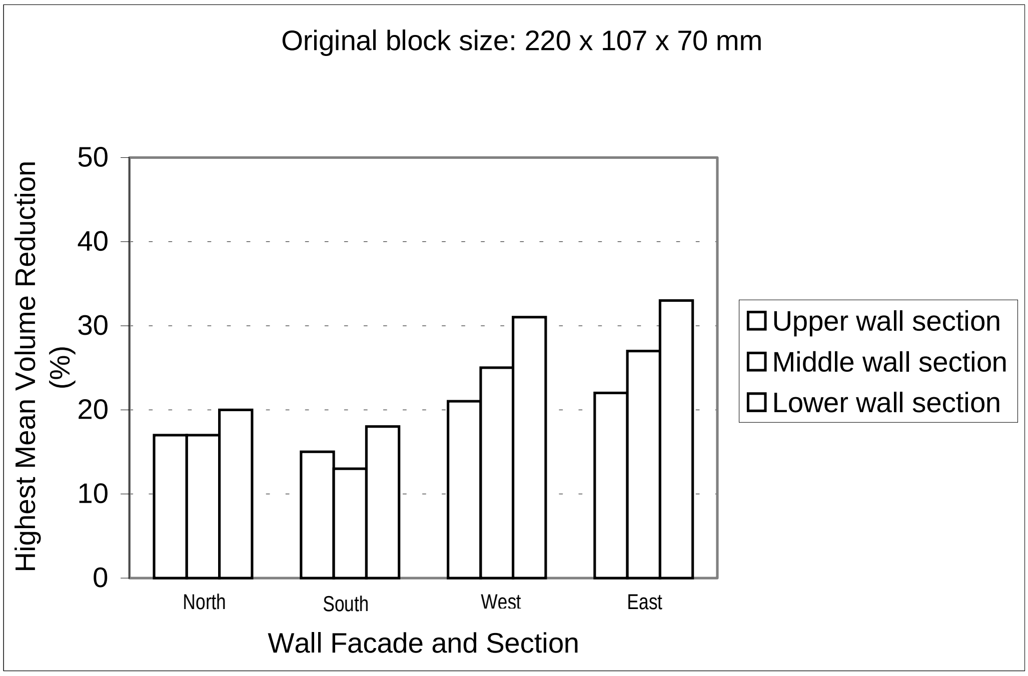


Figure 3(a): Abandoned building (NAB1: 8 years exposure)

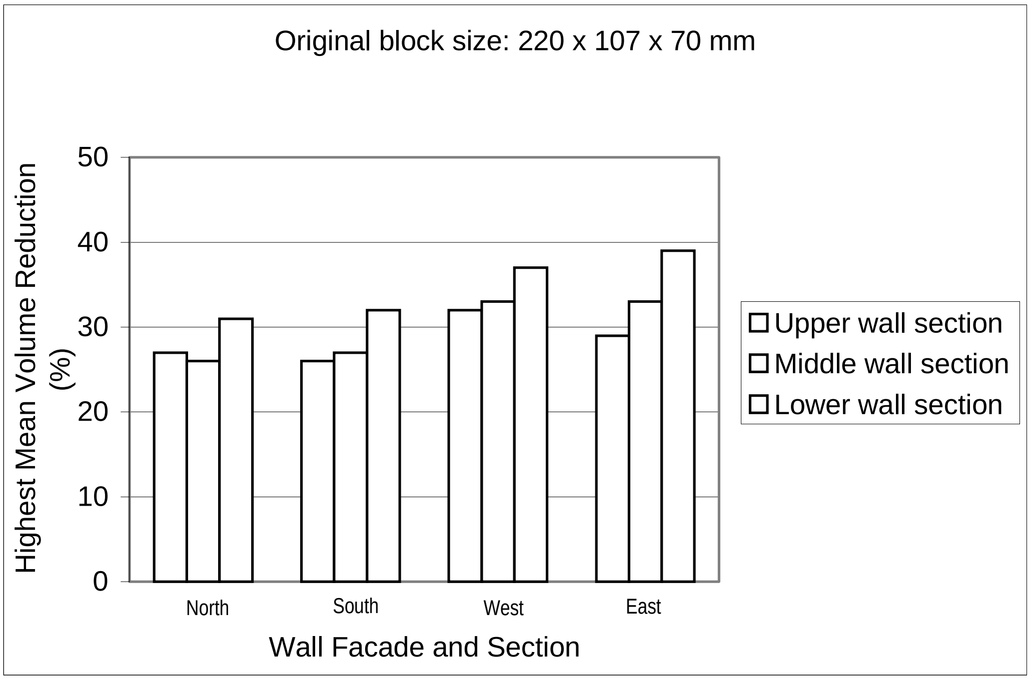


Figure 3(b): Abandoned building (NAB2: 12 years exposure)

Histograms showing the highest mean volume reduction percentage for each wall façade and sector for NAB1 and NAB2 (Uganda, January – March 2000)

From the histograms in figure 3, it can be confirmed that mass loss resulting in volume reduction does occur when CSBs are left exposed and unprotected in a humid, tropical environment. The reduction in volume is however not the same for all facades and levels in a wall. The results show that surface erosion varies according to the:

- elevation of the block within the wall (upper, middle and lower sections)
- orientation of the façade (north-south and east-west)
- age of the building (period of exposure under similar conditions)

The explanation for the above variations are likely to be several as discussed in the following sections.

The *elevation of a block* within the upper, middle or lower section of a wall can influence the rate of deterioration for several reasons. To begin with, the author was advised by the users and technical staff that most of the surface erosion appeared during the rainy seasons. Very little surface erosion if any occurred during the dry seasons. The main mechanism for surface erosion is therefore rainwater related. In each wall sector, although the amount and intensity of rain striking the wall might be about the same, the overall effect varies.

The histograms show that the reduction in volume is greater at the lower courses of a wall than at the higher ones. For the lower courses in both structures, volume reduction percentage for the most severely deteriorated blocks varied between 18% and 34% in NAB1, and between 30% and 38% in NAB2. Similar values for the upper sections were between 15% and 22% in NAB1, and between 26% and 28% in NAB2.

The amount of surface run-off created by raindrop splash from the upper section of a wall, and from the ground appear to contribute to the higher erosion at the lower wall sections. At the upper wall sector, whereas raindrops may strike the block surface, the surface might not begin to erode immediately. The raindrop striking the surface expends some of its energy in striking the wall and some in creating a splash (Chapter 2). It is the splash which then wets the block surface and may also progressively soften it. Erosion is likely to take place after a period of wetting and softening of the surface fabric. Meantime, the accumulation of rain splash transformed into surface run-off will flow downwards along the vertical profile of a wall. In the process, the middle and lower sections of the wall, in addition to being struck directly by rain drops from the same storm, will have to contend with the surface flow from the upper sections. The surface flow can increase in momentum and volume, washing away any loose soil particles from the blocks along its path. It is unfortunate that for the lower course blocks, surface erosion can be further increased by back-splash from raindrops striking the apron or ground immediately below it. The combination of direct raindrop impact, spray surface run-off and ground back splash appear to account for the increased severity of surface erosion in the lower courses of a wall than in the higher ones. As can be expected, the effect of raindrop erosion can be considerably increased in storms accompanied by strong winds (> 20 m/s). Despite these theories, the mechanism of rain erosion on CSB structures is not yet well understood. A considerable scope for reappraisal and review still remains.

Another observation made was that the lower corners of walls appeared to be more severely eroded that similar blocks at the same level. The fact that it is only at the corners that rain from all directions can strike the block is thought to account for this variation. More research is needed into this and other phenomena associated with raindrop erosion of block surfaces.

The *orientation of a wall façade* (north-south and east-west) appears to affect the extent of volume reduction. The highest average volume reduction percentage for east-west facing walls for NAB1 and NAB2 were 27% and 34% respectively. The highest average volume reduction percent for north-south facing facades were 17% and 28% for the former and latter buildings respectively. Corresponding volumes for roofed buildings can be expected to be lower. Whereas several explanations to account for the differences may exist, the most plausible one is likely to be connected to the direction of sunrise (east) and sunset (west). While all facades may experience similar amounts and intensity of rain abrasion, the east-west facades may dry up much faster on the reappearance of the sun soon after the rains stop. The duration of most storms in the humid tropics as mentioned earlier in the thesis is short (between 2-6 hours at a time). After such short periods of wetting, the reappearance of the sun can ensure that the wet block surfaces absorb considerable amounts of solar radiation. Absorption of solar radiation causes temperatures of the block surfaces to rise. This warming up effect can cause the block surface to dry up more quickly on the east-west facades than on the north-south facades. This can happen within a matter of only a few hours, causing moisture to evaporate from the wall surface, thus changing the moisture profile in the block.

The absorbed radiation can raise the temperature of the block by an amount depending on the specific heat of the block (on average between 0.65 and 1.00 kJ/kg), and on the thermal conductivity of the block (on average between 0.23 and 1.04 W/m°C) (Houben et al, 1994). As both values are positive for CSBs, thermal expansion and contraction of a block surface can therefore occur with changes in temperature. This is likely to lead to both temporary and permanent alterations in the physical and chemical properties of the block. Surfaces of blocks experiencing such cyclic changes in temperature can ultimately crack. Cracking can then expose the block surface to easy entry of moisture. Moisture within a block is likely to initiate otherwise dormant chemical activity between the constituent materials which make up the material. The range of chemical actions likely to occur were discussed in Chapter 2.

This phenomenon is also likely to occur in the reverse order of heating and cooling. Before the rainy seasons, sunlight can heat the block surfaces very fast (more on the east-west facades than on the north-south facades). Raindrops striking the already hot block surfaces can apply a severe quenching shock to it. The bonds between the soil particles and OPC hydrates can thus experience their first disruptive action (Baker et al, 1991). This can lead to weakening of the surface fabric thus exposing it to further abrasive attacks from raindrops. Surfaces which are weak can be easier to erode than those which are more intact. The combined cyclic action of wetting-and-drying can progressively lead not only to mass loss, but also to loss of strength, loss of hardness, rigidity and stiffness, as well as loss of appearance (pitting, roughening, cracking, etc.)

(ASTM D 559-55, 1975).

The *period of exposure* corresponding to the age of a CSB structure also appears to affect the amount of deterioration in the block. For the two buildings (NAB1 and NAB2) which were made from like materials and exposed under similar natural conditions in the same locality, the amount of deterioration varied according to the period of exposure. NAB1 had been left exposed for eight years, while NAB2 exposed for 12 years. The amount of deterioration in NAB1 was markedly less than that in NAB2 for each façade and at all wall levels. The highest average volume reduction percentage in NAB1 within the eight year period was 22%, while the corresponding amount for NAB2 within 12 years was 31%. Other factors being constant, the highest estimated annual volume reduction rate for NAB1 was 2.75% per annum, while that for NAB2 was 2.58% per annum. The difference in the two rates was only 0.17%. This result shows a certain degree of convergence. It can be interpreted to mean that, on the basis of the measurements taken, the highest average rate of volume reduction percent in CSB structures exposed under similar circumstances can be expected to be less than about 3% per annum.

The rate of volume reduction is likely to be influenced by the degree of resistance to surface abrasion that the block can offer. A block surface that is smooth, impermeable, non-reactive and of high inter-granular strength, is likely to offer more resistance to surface erosion than one which is not. The abrasion resistance of block surfaces can be increased in a number of ways. These include the use of surface render, surface coating and surface layering with mixes of higher inter-granular strength. These protective procedures can transform the block surface into a layer of significantly greater wearing resistance. As mentioned earlier in the thesis, protection of block surface should remain the main strategy in enhancing its durability. If the block surface is eroded, exposure of its core to similar deleterious action can prove to be more severe since the bulk is its least compacted zone (Houben & Guillaud, 1994; Gooding, 1994). Ways of improving the durability of blocks through the use of CRMs are investigated experimentally in Chapters 6 and 7.

Crack dimension measurements

Cracking on CSB surfaces, sometimes extending deep into the bulk, were commonly observed defects. Classification of the main crack patterns and direct measurement of the most extensive crack widths were done in order to link them to likely deterioration mechanisms and to assess the severity of the phenomena. It is the width of a crack, rather than its length or depth, that is commonly measured in like building materials (Neville, 1995). Moreover, maximum permissible crack dimensions are normally specified strictly according to limits based on crack widths.

The procedure adopted involved visual identification of three of the most badly affected blocks on each wall façade then measuring their crack widths. The average of the greatest crack widths from each of the three blocks were then determined. To make the measurements, two hand-held crack width measuring instruments were used, namely: an optical crack microscope and a crack comparator scale (Baker et al, 1991; Sjostrom et al, 1996). Both instruments were originally developed for measuring similar cracks in concrete structures, and the author had used them several times before. Use of the two instruments side by side did not present any difficulties. The crack microscope used was of the 'ULTRA LOMARA' Mess-Mikroskop make. The instrument powered by a battery, was held against each block surface right over the crack to be measured. The surface was then illuminated by the small internal bulb within the instrument and the magnitude of the crack width measured directly by comparing it against the internal graduated scale that was clearly visible through the eyepiece.

To complement the measurement, the simple hand-held (unmagnified) comparator scale was also used for estimating the same crack width (sometimes referred to as the crack calculator). The type used was the Colebrand/Abbot Brown crack calculator. The procedure involved is slightly different. To estimate the crack width using this instrument, the comparator was placed directly against the targeted crack on the block. By sliding it upwards or downwards until a comparable thickness was determined, the crack width could then be estimated accordingly. The range of crack widths on the comparator ranged from 0.100 mm to 2.0 mm. Crack widths wider than this maximum value had to be estimated using an electronic calliper whose double tips were inserted between the cracks and extended in opposite directions till firm contact was made. The use of these instruments was found to be necessary because, allowing for human eye variations, the minimum crack width that can be seen by the naked human eye is about 0.13 mm (Neville, 1995). As the procedure was laborious and time limited, measurements were only done on NAB2. The summary of the widest average dimensions of crack widths measured are shown in the histogram in figure 4.

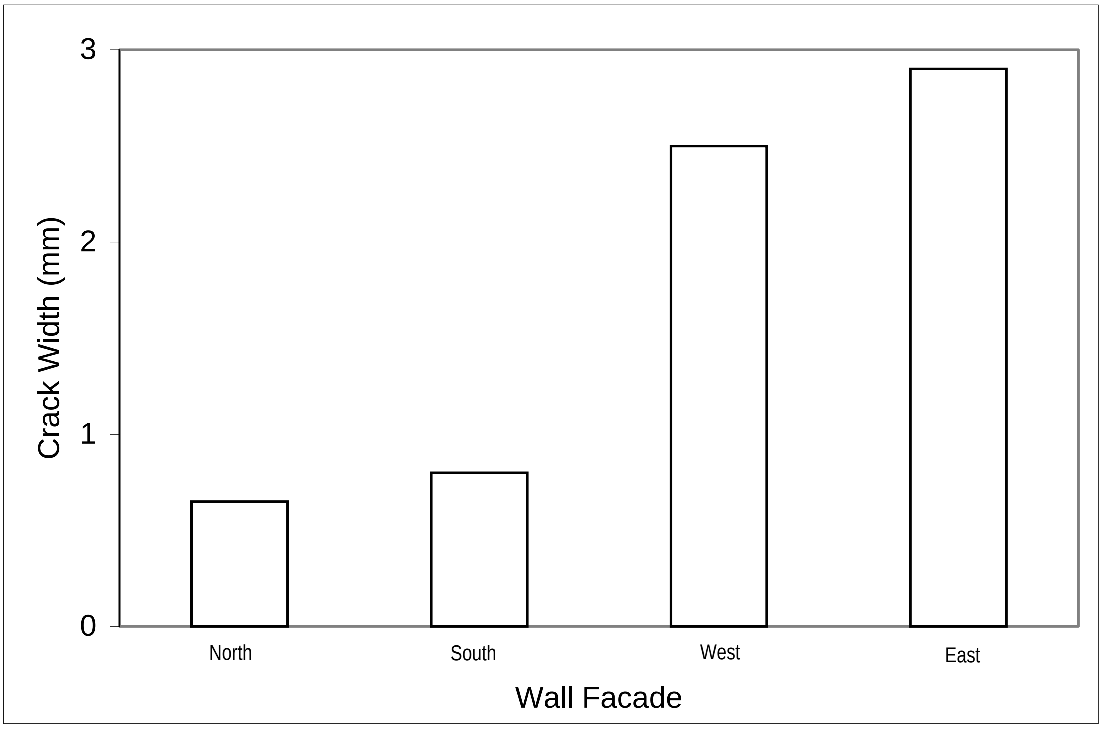


Figure 4: Histogram showing the mean crack width of three of the worst affected blocks on each wall façade for NAB2 (Uganda, January-March, 2000)

From the histogram shown in figure 4, it can be seen that the phenomenon of cracking occurs on all the wall facades of an exposed CSB structure. The highest mean maximum size crack width measured was 2.9 mm on the east façade of the building. The corresponding lowest mean crack width was 0.65 mm on the north façade. These results compare unfavourably with the maximum permissible crack width limits normally specified for concrete structures (Neville, 1995). The permissible crack width for exterior wall concrete used in normal, and under severe conditions of exposure are given as 0.25 mm and 0.15 mm respectively. The values obtained from the measurements of exposed CSB walling units (0.65 mm to 2.9 mm) are much higher than the permissible limits for concrete. The comparison will however need to take into account the presence of clay in CSBs as opposed to concret where its presence is not allowed. The presence of clay (amount and type) is likely to severely affect the magnitude of cracking in CSBs (Spence & Cook, 1983).

The results also show that cracking is more pronounced on the east-west facades than on the north-south facades. The reasons for the differences were discussed earlier. It should be mentioned here that whereas the kind of cracks measured on a block may simply be symptoms of many causes, the common feature is that they all result from the restraint made on strains. Since stress and strain are supposed to occur together, any restrain of movement can introduce a stress corresponding to the restrained strain. If these stresses and the restrained strain are allowed to develop to the extent that they exceed the strength or strain capacity of the block, then cracking can occur. The diagnosis of the exact cause of cracks in a block might therefore not always be that straightforward. Indeed, cracks can be a result of several causes such as: plastic shrinkage, drying shrinkage (clay and OPC hydrates), chemical action resulting in expanded product formation within the block fabric, settlement of the foundation, improper curing and thermal movement. Some of the mechanisms involved were discussed in Chapter 2.

In summary, whereas a particular cause within or outside the block might be responsible for initiating a crack, its subsequent development and propagation may be due to other causes. The types of cracks observed on CSB structures (star shaped, linear, interconnected) could therefore have been a result of more than just one cause. Further research is recommended to link particular crack patterns in CSBs to specific deterioration mechanisms. Limits such as have been specified for concrete should also be set for CSBs. Such limits should however take into account the presence of clay in CSBs. The limits can be specified as maximum permissible crack widths for use of CSBs under normal and severe exposure conditions.

4.3.3 FIELD INDICATOR SOIL TEST RESULTS

In this section, field indicator soil tests conducted during the fieldwork, together with the results obtained, are described. The results are compared with available laboratory test results for the same soils at the two major CSB project sites in the country (Namuwongo in Kampala and Malukhu in Mbale). This section covers the following:

- Need for field indicator tests
- Types of indicator soil tests available
- Results of conducted indicator soil tests

Need for field indicator tests for soils

In order to classify a particular soil, two types of tests can be done: indicator (or field tests) and laboratory tests (Webb, 1988; Norton, 1997). Only the former will be described in this section since the latter are presented in Chapter 5. The two test categories should normally be done together with the one following the other (indicator, then laboratory testing). It is normal to conduct indicator soil tests first since it is from the results obtained that justification for further laboratory testing is usually based.

Although field indicator testing might be regarded as being preliminary, it is only through such tests that the rapid evaluation of important soil properties can be made. The tests might also appear empirical but they enable the general suitability and acceptability of a soil for CSB production to be determined quickly. As can be expected, there are now many types of indicator soil tests. The common factor in all the tests remains their relative simplicity and speed of execution. These tests are also quite inexpensive to conduct given that they require little or no equipment. The only drawback (according to the experience of the author) is that these tests over-rely on the competence and judgement of the operator. The veracity of interpretation by the operator is often taken for granted despite errors likely to be caused either by human weakness or lack of competence. With better experience and training however, such problems should be easy to overcome. Soil indicator testing is likely to continue to be highly regarded as they help avoid unplanned and premature laboratory testing. At the moment, there can be no serious alternative to soil indicator testing as a precursor to laboratory testing.

Types of indicator soil tests available

There are currently several soil indicator test types to choose from. Over the years, a multitude of test types have been put forward by various authors and researchers. Despite the numbers, the common objective remains the identification of the presence and predominance of the main soil fractions (gravel, sand, silt and clay). After the various types of field indicator tests have been done, further laboratory testing may follow to determine the precise proportions of each soil fraction, and perhaps more importantly, the overall behaviour of the soil type when in contact with water.

In order to make the comprehensive review of current available field indicator test types easier, a tabulated summary listing the test methods has been drawn up. According to literature sources, up to 15 different types of soil indicator field tests are currently available for preliminary use in determining the suitability of a soil for CSB production. The different types of tests and the various authors who have reported them, are presented in Appendix F.

Not all authors managed to describe all the available tests with the exception of Houben & Guillaud (1994) and Stulz & Mukerji (1988). Although some of the authors attempted to combine some of the tests, or tried to use different names for the same test, the summary list was compiled to show separate distinct tests. Tests with similar names are shown in brackets. During the fieldwork, all the listed tests with the exception of number 10 (Dry Strength) and number 14 (Decantation), were done. The tests were done on soils taken from the sub-soil level after removal of the top soil (varying in depth between 150-300 mm). This was done to ensure that the presence of organic matter (normally found at the top-soil level), was avoided. Apart from trying to ascertain the suitability of soils used at the two largest CSB project sites, the tests were also conducted to get a feel of the operational difficulties and levels of accuracy and convergence expected. The main procedural steps involved in each test can be found in the references shown. The results are presented in Appendix G.

Summary results of soil indicator tests done in Uganda

From the summary of the results shown in Appendix G, it is noted that:

- there was no significant presence of organic matter (the soil is likely to be suitable for CSB production)
- the fines content (silt and clay) in both soils are high enough (24-35%) (the soil is likely to be suitable for CSB production)
- the coarse soil fraction content (fine gravel and sand) is above 60% in both soils (falls within the recommended limits) (Chapter 3).

With these preliminary results, the soils at the two project sites were found to be suitable for CSB production. The soil indicator test results were later compared to earlier documented laboratory test results from the Namuwongo project site which had been done in 1986 (Okello, 1989). For comparison purposes, extracts from the laboratory test results showing particle size distribution, linear shrinkage, sedimentation, natural moisture content, as well some of the test results form the initial performance testing of cured blocks, are presented in Appendix H.

The laboratory test results in Appendix H confirm that the soil used for CSB production at Namuwongo:

- was well-graded, with adequate percentage of fines and course soil fractions
- had moderate shrinkage levels, confirming a low to medium proportion of clay in the fines
- was found to contain almost similar levels of fines and coarse fractions using both the sedimentation test (soil indicator test) and the particle size distribution test (laboratory test)
- had a moderate natural moisture content.

The records from the initial performance tests done on blocks produced from the above soil showed that the blocks compared well with most minimum requirements of performance. The average wet compressive strength was above the minimum recommended values of between 1.2 MPa and 2.8 MPa (Lunt, 1980; ILO, 1987; Houben & Guillaud, 1994). The mean total water absorption capacity for the blocks were lower than the maximum permitted value of 15% (ILO, 1987). These results confirm that, in any post mortem diagnosis of possible causes of premature deterioration of exposed CSBs within the area, the inclusion of non-suitability of the soil used may not make sense. Any premature deterioration will therefore have come from factors other than soil selection and suitability.

The near convergence of field indicator test results and those obtained from laboratory records for the same soil further confirms that the former can be a very useful indicator of soil suitability. The field indicator tests should however be done following a logical order to ensure a coherent approach to testing. Use of soil indicator tests are especially recommended for CSB production sites in rural areas where no sophisticated equipment exists and where the cost of direct laboratory testing might be quite prohibitive. On very large CSB project sites, however, both field and laboratory tests should be conducted so that results from each category can be used to compliment the other. Moreover for large project sites, especially in areas known to be underlain by special soil types such as laterites, additional laboratory tests will need to be done. From Appendix H, it can be seen that this consideration was overlooked. Additional laboratory tests should have been done to provide information on the following:

- the plasticity index of the soil (using Atterberg limit tests)
- the acidity of the soil (using pH value tests)
- chemical composition of the soil minerals (using chemical analysis tests)

4.4 INSPECTION OF CSB PRODUCTION SITES

In Chapter 3, it was stated that the block production process was one of the three major influencing variables that can affect the properties and long-term performance of CSBs. The other two major variables of equally significant influence were identified as constituent material quality and action of environmental agents. In the CSB production process, any departure from widely accepted good site practice is likely to adversely affect the quality of the block produced (Guillaud et al, 1996).

In this section, results from the following investigation methods are presented and discussed:

- visits to block production sites (at two on-going CSB project locations in Uganda)
- quality checks on OPC and water used on CSB production sites.

Each of the above are discussed separately in Sections 4.4.1 and 4.4.2, that follow.

4.4.1 EVALUATION OF BLOCK PRODUCTION PROCESSES AND PRACTICE

The objective of inspecting production sites was to assess the organisational set-up of the site, and to compare individual production sub-processes against a pre-prepared checklist of good practice. Departures from the norm were carefully noted.

Two on-going project sites were visited: the large CSB building site at Malukhu (as before) and the smaller, single residential building site at Temangalo (farm in Mpigi district). While the former is an extensive project site with over 80 CSB structures built and another 200 or more planned, the latter is a single residential unit. At both locations however, the same type of machine was being used to produce blocks. The description of the machine is as below:

- Make: Hydraform block making machine (from South Africa)
- Type: Motorised diesel engine 10 kW air cooled
- Dimensions: 1000 l x 1400 w x 1300 h
- Weight: 750 kg
- Output: + 130 blocks per hour
- Mould: various (including interlocking dry stacking blocks)
- Block size: 240 x 220 x 115 mm; and 200 x 220 x 115 mm

At both locations, there was no centralised yard for mixing, proportioning, etc., as was described in Chapter 3. Details of the observations made are summarised in Appendix I.

From the summary findings shown in Appendix I, the following are deduced:

- Pre-extraction soil test records are not kept on site or nearby where they can be referred to. While manual extraction may be suitable for a small site (output about 1-3 m^3/day/man), mechanical extraction would be preferable on the larger project sites (output about 100 m^3/hour). The extracted soils are not prepared well before further use. They should be properly dried out and pulverised. Soils that have been dried out and screened ought to be stored in a protected area to preserve their moisture state and avoid changes in moisture content.

- The concept of batching is not closely followed so wastage and misuse of the stabiliser is likely. While proportioning is done by volume, checking that the gauge containers are properly levelled off each time is not strictly enforced. The stabiliser is mixed with the soil irrespective of the latter's moisture condition. As no obvious mix indicator such as the achievement of uniform colouration of mix is used, insufficient and uneven distribution of the stabiliser and water in the soil are possible. Moreover both water and stabiliser are poured down on the heaped soil instead of on a spread out soil. As no drop test is used to check the consistency of the mix, compression of blocks will take place below or way above the optimum moisture content of the soil. This will result in poor compaction of the soil, with blocks of low density being obtained. Moreover, the mixing process is also not closely supervised.
- Measuring out of the soil mix fed into the mould is not strictly done. This can result in variation in density and sizes of blocks produced. The filling of the mould is not done in layers and corners of the mix in the mould are not pressed by hand. Moreover, in motorised units as the compression force remains the same, it is important to check each time if correct filling is done.
- Demoulded green blocks are removed by hand, without use of pincers or

wooden pieces that could ensure that a large surface area is placed in contact with the yet weak block. No special attention was being given to the corners and edges of green blocks. Random quality checks normally conducted at this stage for each batch of blocks produced, were not being done as required. These shortcomings are likely to compromise the quality of blocks produced.

- Curing conditions appear not to be clearly categorised into wet and dry stages. Curing was being done under light cover under direct sunshine. Blocks were apparently being used earlier than the specified curing periods for the OPC and lime (28 and 56 days respectively). Due to high evaporation rates and pre-mature use of blocks, the likelihood of low quality blocks being used cannot be ruled out. Moreover, the blocks being cured are not separated according to batches and are poorly stockpiled at random. This could lead to the use of improperly cured blocks.

It was not possible to immediately evaluate the affects of these variables on the performance of the blocks produced. The observations do confirm that poor site practice and bad workmanship do take place (constituting significant variables likely to affect the quality and properties of a block). There is clearly a big difference between block production under strict laboratory procedures and field practice. The above problems can be attributed directly to the absence of codes of practice and checklists that should normally accompany trade standards. The findings also confirm earlier fears that variations in processing methods, especially due to inadvertent departures from the norms, could severely influence the durability of the block. Block production processes should be properly executed under close supervision if good quality and durable blocks are to be produced. It is recommended that all current impediments to the dissemination of standards and codes of practice for the production and use of CSBs be identified and resolved (Lowe, 1998; Schildermann, 1998). The above findings and their implications were brought to the attention of the supervisors found at the project sites at the time. It was clear that they had not received any prior briefing on good site practice, and could not therefore appreciate the adverse implications of their actions.

4.4.2 FINDINGS FROM QUALITY CHECKS ON OPC AND WATER

In Chapter 3, the importance of the quality of each of the three constituent materials used in the production of CSBs (soil, cement, water) were emphasised. The quality of soil used on CSB production sites has already been reported on (4.3.3). In this section, attention is focused on the basic quality checks conducted on OPC and water found being used on CSB building sites.

Although the objective of the tests at the time was to routinely ascertain the quality of OPC being used, the results obtained were rather surprising. Broadly it was found that both cement and water quality were poor, so the study was extended to cover why this was so. Although the quality of these ingredients were examined from a CSB production standpoint, the findings also have implications for all the cement-using activities in Uganda. Most of the OPC used in East Africa is expected to conform to the requirements of BS 12: 1991. It is also normally included in bills of quantities and specifications that contractors, users and consultants carry out periodic quality checks on any products in which OPC has been used. Despite the existence of this requirement, it is the normal practice in countries like Uganda to take the quality of OPC supplied (in sealed 25 kg bags) for granted. In addition, although the quality of water used for mixing of soil and cement and for wet curing of CSBs is required to be high, the normal practice on block production sites appears to disregard this consideration. It is not yet clear whether this is due to scarcity of water or other reasons such as lack of awareness of the dangers involved in using poor quality water (Chapter 3). The highlights of the procedures used for the quality checks are described next.

There are several forms of quality checks that can be done on OPC: comparing setting times, strength, or even chemical composition with standard requirements (BS 4550: Part 2, 1970; ASTM c 114-88). Tests involving the analysis of the chemical composition of OPC were considered to be beyond the scope of this research. Instead, the quality checks used were based on the comparison of the values of the wet compressive strength and tensile strength of prisms made from the OPC in question and the specified values from prevailing standards.

In the wet compressive strength test, three 50 x 50 x 50 mm cement and sand mortar prisms were cast. The prisms were made from a cement-sand mix proportion of 1 : 2.75 with a water-cement ratio of 0.49. They were cured under controlled conditions for 28 days (in water at temperatures of about 23°C). After 28 days, the cubes were tested and the value of the mean wet compressive strength of the prism made from the OPC in question, obtained. The results were compared to those specified for the type of OPC that was being used on site. The results are shown in table 2. To check the quality of water used, the same procedure was followed but this time using the water of unknown service record (found being used on the block production site) (BS 3148, 1980). The results from prisms made with clean tap water and those made from the site water were then compared. The results are also shown in table 2.

For the avoidance of doubt, an additional test was simultaneously done on both the OPC and water. In this tensile strength test, nine small prisms of dimensions 175 x 25 x 6 mm were cast (Rigassi, 1995). The sand-cement mortar prisms were cast using the ration of 1 : 3 (cement : sand) and water cement ratio of 0.49 as before. Some of the bars were wet cured for only 24 hours, while the rest were similarly cured for 28 days. For each test, three bars were tested for direct tensile strength by subjecting them to available loads of up to 100 g (24 hour cured prisms) and of up to 500 g (28 day cured prisms). To conduct the test, a simply supported prism bar of the material was loaded at the end span. The load at which the bar snapped was noted. The results are all shown in table 2.

S/N	TEST	SAMPLE AGE (days)	UNITS	COMPARISON OF RESULTS	
				Obtained Value	Recommended standard Class 32.5N OPC
	A: Cement	28	MPa	27.4	32.5
1	Mean wet compressive strength (50 x 50 x 50 prism): clean water				
2	Mean tensile load (175 x 25 x 6 mm prism) "	28	g	350	500
3	Mean tensile load (175 x 25 x 6 mm prism) "	1	g	75	100
	B: Water	28	MPa	21.2	24.76
4	Mean wet compressive strength (Same prism but site water used)				
5	Mean tensile load (Same prism but site water used)	28	g	245	500
6	Mean tensile load (same prism but site water used)	1	g	55	100

Table 2: Results of site quality checks on OPC and water (Uganda, March 2000)

OPC quality test results

The results in table 2 show that the mean wet compressive strength value of the site cement-sand prisms was 27.4 MPa. This is less than the 32.5 MPa value specified as the minimum for the same grade of OPC (class 32.5N OPC, or equivalent). The difference was even higher (15%) than the allowable difference in strength of 10% due to errors. Some variation was expected but the result obtained was rather surprising. Similar trends were shown in the results from the prisms tested for tensile load. The values obtained were between about 25% and 30% lower than the recommended load values at 1 day and 28 days respectively. Since the bags in which the OPC found on site were examined (to conform to BS 12, 1990), the only conclusion that can be reached at this stage is that the contents could have been adulterated. Recent press reports from the country confirm the widespread contamination of OPC with clay before the bags are resealed (New Vision Newspaper, June 2001).

In the experience of the author as a practising civil engineer, incidences of this nature were not uncommon even on large concrete production sites. The problem is therefore a long standing one, and is more widespread than was originally thought. As can be expected, use of low quality OPC is likely to adversely affect the properties and performance of CSBs. Due to the above findings, the author decided to find out more about use of OPC in the country. From other site visits and interactions with users, stakeholders, suppliers, contractors and consultants it was established that OPC related problems were varied. These ranged from supply problems, unsuitability, incomplete hydration and misuse.

Water quality test results

The results of water quality tests show that the sand-cement mortar prisms cast using the dirty site water were of low strength. The wet compressive strength value of 21.2 MPa was 23% lower than the equivalent value for the cube cast using clean tap water (27.4 MPa). The allowable difference should not have been more than 10%. Tensile load tests also showed that prisms cast using the site water were about 43% lower in tensile strength than similar cubes cast using clean water. As stated earlier, water quality checks had not been planned for before (had it not been for the unusual appearance of the water being used on site). These results confirm that the quality of CSBs can be compromised when water of unknown quality is used for the hydration of OPC. The quality of water being used should therefore not be taken for granted. Water is scarce in most parts of the world. Even where available, clean piped water is inaccessible to most. Use of unsuitable water for hydrating OPC can therefore not be ruled out.

4.5 FINDINGS FROM QUESTIONNAIRES AND INTERVIEWS

As part of the research, a direct survey of the personal experiences of various stakeholders with respect to the production and use of CSBs was conducted in Uganda (January-March, 2000). In this section, highlights of the methodology used and results of the main findings are presented.

Methodology

At the start of the survey, two separate contact methods were planned, namely: interviews and questionnaires. It was later decided that a combination of the two methods into one would be more cost-effective and time saving. Face-to-face interviews using pre-structured questions facilitated the process making it more systematic and relevant to the situation on the ground. Moreover in a country where telephone, postal and communication systems were all undergoing major rehabilitation, there was no alternative to direct contact with respondents. By combining the contact method, problems associated with illiteracy, need for reminders, clarifications etc., were overcome. Respondents were also able to make suggestions and to raise other simpler or more complex questions associated with the production and use of CSBs in the country.

A sample size of 35 respondents from all walks of life was used. This was considered large enough for the purposes for which the survey was intended. The respondents were chosen at random from amongst the stakeholders: users of CSBs, government officials, private contractors and consultants, potential clients and funding agency representatives. It was assumed that the contacted respondents represented an unbiased sample of the population. Other highlights of the procedure were as follows:

- Interviews were conducted at various locations. These included dwellings where CSBs had been used, work locations, block production sites, on-going CSB building sites, and on substantially completed building sites.
- All respondents were assured of future confidentiality before the start of each interview. This was done to obtain their consent and ensure that their views would be freely expressed. In this way respondents answered questions put to them while at ease, and freely shared their experiences with the author. It was made clear to all of them that the results would be used purely for research purposes only.
- Each interview took approximately 20 to 30 minutes from start to finish. With the exception of interviews conducted on block production sites and on building sites where the respondents wanted to show the author further items,

the above time frame was maintained throughout the survey process.

- The response rate was 100%. All stakeholders directly contacted as above were willing to participate freely. This led the author to conclude that the survey method adopted was the right one under the prevailing circumstances in the country. Helpful inferences could then be made from the experiences of the respondents.

Findings from the Survey

The results of the findings which were manually tallied, coded and categorised relate to the type of questions put to the respondents, namely:

(a) : current walling material of preference

(b) : reasons for making the particular materials choice

(c) : preferred block types

(d) : common defect types encountered

(e) : preferred method of protection for blocks

(f) : suggestions on ways to improve CSBs.

The results of the findings are shown in the form of pie charts in figure 5.

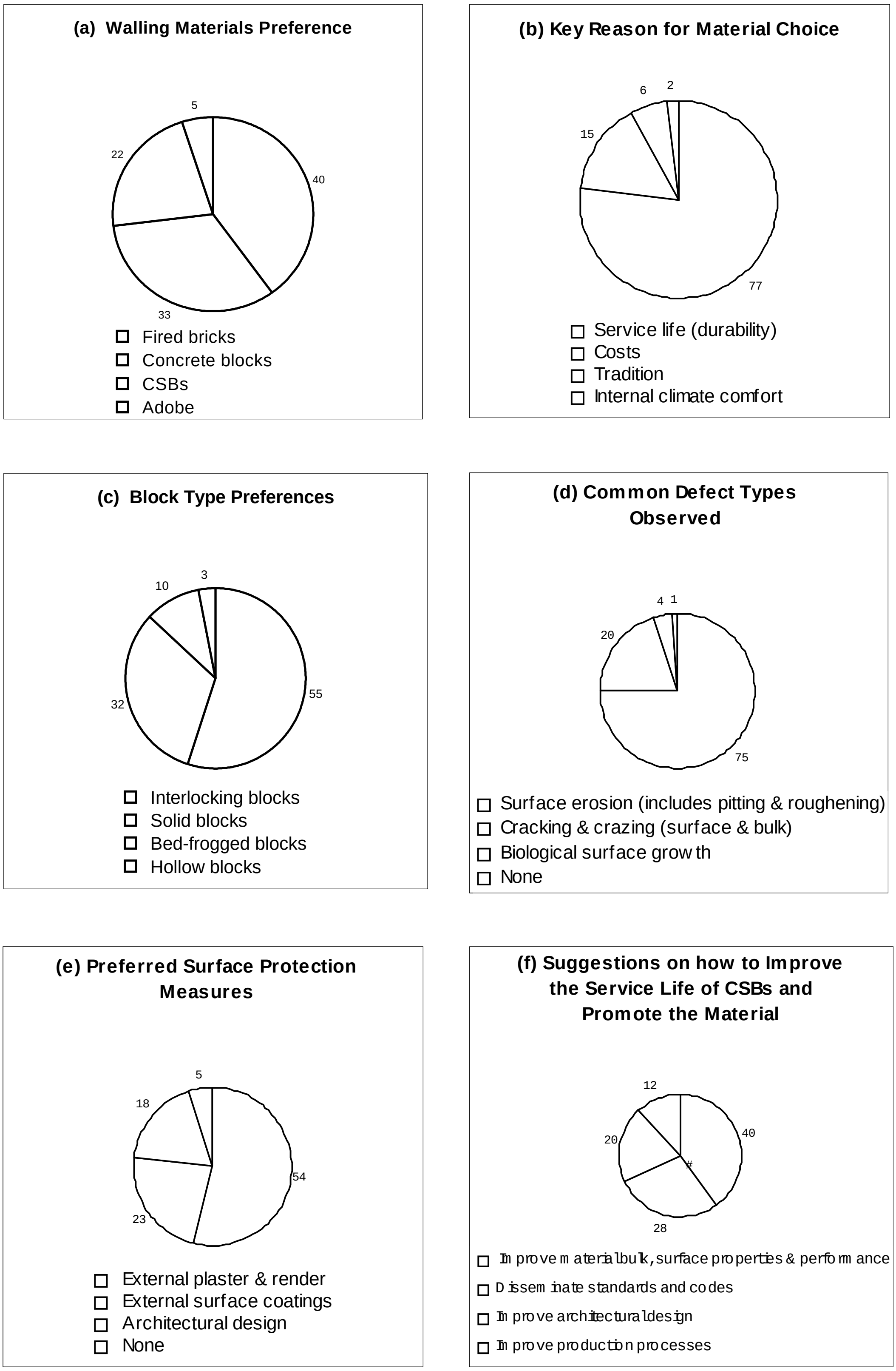


Figure 5: Results of findings from interview and questionnaire surveys conducted in Uganda (January – March, 2000)

Each of the outcomes shown in figure 5 (a) to (f) are now discussed in turn.

Preferences of walling materials to use were almost equally divided between fired bricks, concrete blocks and CSBs. However, fired bricks remain the material of first choice for most of the respondents (40%). This is followed by concrete blocks (33%). These two materials have been in use for generations and most respondents still have a high regard for them. The results for CSBs are encouraging. Having been introduced in the country only as recently as 1987, the fact that up to 22% of the respondents preferred the material over the otherwise cost free adobes (5%) represents a major sign of approval. The substantially better performance of CSBs as compared to adobes appears to account for the immediate popularity of the former over the latter (Games, 1981).

Key reasons for materials choice reveals the main basis for the selection of a particular walling unit. The key reason given by up to 77% of the respondents for choosing a particular walling unit is its in-service record (durability of the material). Only 23% of the respondents considered issues such as costs, tradition and internal climate as being more important. At the time of the survey, fired bricks were the most highly regarded walling units mainly due to their long service records requiring minimum or no maintenance. In future however, as fuel resources for firing bricks get depleted, the use of CSBs is likely to overtake that of fired bricks. According to the respondents interviewed, CSBs have gained prominence in a relatively short time because the material does not require to be fired, or burnt. Moreover, since the soil can be obtained on or near the site, where processing of the block is taking place, transportation costs are significantly reduced.

Block type preferences by respondents reveal a significant shift from solid blocks (33%) to interlocking blocks (55%). While solid blocks have been used since the introduction of CSBs in the country, interlocking blocks have only recently appeared on the scene (late 1990s). The dry-stacked-interlocking blocks have gained prominence over other types of blocks mainly because the use of mortar is not required. Other advantages mentioned are that walls from interlocking blocks are quick to build and are easy to align. Moreover, even if plaster is to be applied, the straight walls achieved require much less render than the traditional mortar bedded blocks (Van Den Branden & Hartsell, 1971). The production of interlocking blocks however, requires very sophisticated presses. At the time of the survey, these blocks were being produced by communally hired and donor subsidised motorised presses (Hydraform press, M 5 Mark I & II from South Africa). The quality of the green blocks appeared to be very high indeed (in terms of surface appearance, parallelism, edge straightness, etc.).

The *most common defects types* observed by respondents were surface erosion (75%) and cracking and crazing (20%). According to the respondents, not only were these two defect types common, but they were also clearly visible and discernible even by the casual observer. The older the building the more visible the defects became. No similar symptoms were observed in walls made from fired bricks and concrete blocks. It was therefore not surprising that 75% of the respondents had detected premature deterioration on unprotected CSB walling in the form of surface erosion (including pitting and roughening). Only 4% of the respondents had observed other, less common defect types like the peeling off of render, plant and surface growth, insect boring, etc. The majority of the respondents interviewed did not find any difficulty in linking some of the major defect types to seasonal variations. The author was informed that it was generally observed that most of the surface erosion in CSB walls occurred during the two main rainy seasons in the country (March-May and

September-November). The symptoms were reportedly similar to those that occurred on adobe walls at the same seasons of the year. The only difference was in the degree of severity. Cracking of exposed CSB walls was also a phenomena more noticeable during the long-dry seasons than during the rainy seasons. A casual link between environmental action and deterioration in blocks was therefore being strongly suggested. The author could not see any reason to disagree with the general hypothesis. When asked why they thought surface deterioration of CSBs occurred too prematurely, most of the respondents were of the view that use of low amounts of cement (4-6%) might be responsible. The reasoning was that due to the low stabiliser levels, poorly bonded soil particles at the surface of the block could easily be dislodged by the mechanical energy from rainfall impact (Laws, 1941, Herbert, 1974). The premature appearance of such defects when no similar defects could be observed in like materials of the same age serving under similar conditions was seen by many as a major cause for concern. It partly explains why fired bricks and concrete blocks, despite their higher costs, still remain preferable to most of the respondents.

Preferred surface protection measures for exterior wall faces were varied. Up to 95% of the respondents considered one form of exterior wall surface protection method or another. The most preferred option was external surface render (54%), followed by surface coating (23%) and architectural design (low roof overhang) (18%). Only 5% of the respondents were not bothered and preferred to let events take their course. Part of this latter group thought external render was expensive since it involved remedial surface repairs being done first on the walls before application of the render proper could follow. Some even considered replacing defective CSBs with equivalent sized fired bricks. Where surface render was used, incidences of plaster peeling off from the blocks were also observed. The reason for this could be attributed to inadequate curing, improper workmanship during rendering, poor choice of soils (too much clay), or even poor choice of stabilisers (high clay content, lime is preferable; low clay content, OPC is preferable). Most respondents preferred to use higher amounts of OPC to improve the overall quality and durability of the block than to have to use lower amounts and still plaster the wall in addition. They thought the former option would work out to be cheaper than the latter in terms of overall costs. The findings appear to support strategies based on enrichment of block surface layers to offer additional resistance to deleterious environmental actions. Use of enriched surface layered material is investigated experimentally in Chapters 6 and 7 of this thesis.

Proposals on *quality and durability improvement* strategies for CSBs came in many forms. The strategy that emerged as the most prominent was the improvement in the overall bulk and surface properties and performance of CSBs (40%). This was followed by the need to disseminate and comply with written standards and codes of practice on the production and use of CSBs (28%). Improved architectural design of CSB buildings and improved block production processing methods were considered by 20% and 12% respectively of the respondents as being the best ways of protecting blocks and achieving higher quality. As stated earlier in the thesis, it is the considered opinion of the author, now confirmed by these findings, that it is the durability of the block, rather than any other consideration, which will ensure its widespread demand and use in developing countries. Current research into the durability of the material therefore appears to be timely. Even where research findings may lead to the production of improved blocks, codes of practice and standards are still needed to ensure that compliance with minimum standards and better methods of work are upheld. At the time of the survey, no approved CSB standards were available in the country yet over 400 CSB structures had been built. And more CSB buildings are being planned for (DoH, 1992).

4.6 CONCLUSION

From the results and findings discussed in this Chapter, the following conclusions can be made.

CSBs are likely to remain in high demand in developing countries such as Uganda where the housing backlog is still very high. The increased use of CSBs for walling in high density, low income urban areas appears to represent the best way forward in redressing the imbalance. The current approach using community hired or centrally used motorised block presses also appears to be the best practical housing delivery method.

In humid tropical areas, rainfall and temperature variations can adversely affect the performance of a block exposed to the elements. These variations can also catalyse chemical reactions between the constituent materials forming the block. More research is needed to understand the mechanisms involved, and to explain how individual rainfall parameters such as drop size, drop size distribution, fall velocity and impact kinetic energy, etc., affect the rate of surface deterioration in blocks.

Visual inspection of a sample population of officially documented CSB structures revealed that in the absence of protective render, premature deterioration can take place. The most common defects observed included: surface erosion, surface roughening, surface pitting, surface cracking, surface crazing, bulk cracking, chipped edges and corners, and loose material residuals. Since weathering conditions were genuine and since the blocks were inspected at full scale, a direct link can be said to exist between the symptoms observed and the exposure conditions. Moreover, as a fairly sufficient number of CSB structures were inspected (more than 10% of the total number), this conclusion is likely to be fairly reliable (cause and effect link).

The amount of loose material lost from the original mass of a block was estimated by directly measuring the recessed volume of the material. The loss in volume from unroofed and unrendered blocks over a period of 12 years was about 38%. Losses were higher on the east-west facades than on the north-south facades. Lower courses of walls also experienced more losses than the middle and upper courses of the same wall (about 8-15% more). The increased amount of rainwater and splash experienced by the lower courses, and the increased amount of solar radiation absorbed by east-west facades appear to be responsible for the differences. Surface protection measures are strongly recommended for blocks that are to be used under similar conditions.

It was also found that crack patterns and dimensions followed the above trends. The widest cracks recorded (2.9 mm) were found on the east-west facades of CSB walls. These cracks are much wider than the normal permissible crack widths in concrete structures. Cracking is undesirable as it makes the block vulnerable to ingress of moisture. The crack patterns observed indicate that drying shrinkage, expanded product formation, thermal expansion and contraction and improper curing can all lead to disruption in bonding. More research is still required to explain the mechanism involved in each of these phenomena.

It was found that field indicator soil testing was a valuable tool for early identification and selection of soils for CSB production. Although at the time of the fieldwork no clear order for conducting the several available tests existed, a more planned approach is recommended. Since the results of the field indicator tests showed considerable convergence with documented laboratory test records for the soils in the same location, the former are recommended as the first step in determining the suitability of a soil for CSB production. For large CSB production sites, laboratory tests should be extended to analyse the chemical composition of the soil to be used. This should be done even after the soils have passed all basic suitability tests.

Findings from the observation of site practice at block production sites visited confirmed that the level of process management can indeed influence the quality of the block produced. Shortcomings were observed right through the production process from soil extraction and preparation to curing of green blocks. Most of the shortcomings could be corrected by better supervision and proper guidance. A balance of emphasis is therefore required between design quality of blocks and their actual quality.

Impromptu quality checks conducted on OPC and water used for production of CSBs confirmed that significant differences can exist between the required minimum standards for each material and the values obtained on site. The wet compressive strength of a sand-cement mortar cube tested at 28 days using the OPC found on site was about 15% lower than the minimum recommended value for the same brand of cement. Tensile force tests also showed similar trends. Similar cubes made and tested in exactly the same way as before but this time using the site water of unknown quality was found to be about 23% lower, well outside the allowable variation. These two findings further confirm that CSBs are likely to be adversely affected not only by variations in the processing methods or exposure to environmental agents, but also by the quality of each of the constituents used in producing them. It is therefore strongly recommended that regular quality checks, inspections, tests and certification be introduced at all key stages in the block production process.

Surveys conducted using interviews and questionnaires revealed a number of wide ranging issues. It was found that a good service record (durability) of a material would ensure its widespread use (as underlined by 77% of the respondents contacted). It was noted that interlocking blocks that do not require use of mortar were the most highly demanded block type. These blocks were considered to require less time and money to use for building than comparable solid, hollow and frog-bedded blocks. It was established that most respondents were quite familiar with causes of premature defects in CSBs, citing surface erosion and cracking as the two most common defect types. To improve the service life of CSBs, various surface protection measures were regarded as the most economic way of achieving the goal (by 90% of the respondents). Other approaches considered included improved intergranular strength (40%), dissemination of standards and codes (28%), better architectural design (20%) and better processing methods.

With the preceding conclusions, the objectives of Chapter 4 were met.

CHAPTER 5

EXPERIMENTAL DESIGN AND PREPARATION OF SAMPLES

5.1 INTRODUCTION

In this Chapter, experimental design for the main laboratory based tests are described. The preparation of CSB specimen samples for further tests are also described. Laboratory based experiments were planned for in the research methodology mainly to test ideas, theories and designs that had been formulated. The scope of this Chapter is limited to the description of the experimental design adopted and the methods used to produce CSB specimen samples. Surface and bulk property tests for which the specimens are fabricated are discussed separately in Chapters 6 and 7.

The objectives for which CSB specimen samples were produced were:

- to obtain a sufficient number of CSB samples from which statistical generalisations can be made.
- to obtain quantitative experimental results from samples with various input variables (response experiment).
- to monitor the effects of the main input variables in CSB production.
- to compare the experimental data obtained with theoretical predictions and with other available data on CSBs.
- to facilitate the explanation of discrepancies between predicted and measured performance.

The laboratory tests had to be completed within a limited period of time. For this reason, the samples produced as described in this Chapter were meant to satisfy only a limited number of tests. For all laboratory tests attempts were made to ensure that the results obtained satisfied three basic conditions: accuracy, reliability and reproducibility. Only standard methods were used in the production of CSB samples. This chapter only describes the measurements made on green blocks and just cured blocks. Measurement on block samples were limited to: dimensions, weight, shape and appearance. The specimens were then marked and labelled for further extensive tests (reported in Chapters 6 and 7).

The rest of this Chapter is presented in four sections, namely: experimental design, results of soil classification tests, preparation of CSB specimen samples, and conclusion.

5.2 EXPERIMENTAL DESIGN

Variation of any of the several production input variables can influence the quality and performance of blocks (Chapter 3). These variables include:

- Soil (type and proportions of main fractions)
- Stabiliser (type and content)
- Mix-water (amount)
- Compaction pressure
- Curing conditions

For any meaningful experiment, it is unhelpful to vary all the input variables at the same time. The experimental design was therefore based on fixing some of the variables while varying others. The control (independent) variables were taken as the composition variables (soil type, stabiliser, water) and process variables (compaction pressure, curing conditions). The main variable fixed was the soil type. All block samples were made using soil of a fixed composition. In this way the effect of varying the stabiliser type and content, compaction pressure, mix-water content and curing conditions on the properties (response) of the block could then be easily monitored. It was also considered necessary to specify the number of observations, the values of the control variables at every observation and the order of observations (Ray, 1992; Greenfield et al, 1996).

The main approach adopted was to compare the properties and performance of two categories of blocks, namely: traditional blocks (TDB) and improved blocks (IPD). While the former were made in the conventional way using OPC and/or lime as the stabiliser, the latter were made using partial replacement of OPC with condensed silica fume (microsilica). The amount used was fixed at 10% of the OPC content (Neville, 1995). The blocks were regarded as being improved because of the theoretical expectation of enhanced performance due to the inclusion of microsilica (Chapter 3).

The stabiliser type and content, rather than any other variable, was used as the main categorisation parameter for several reasons. To start with, it is the stabiliser content which is responsible for most of the improvement in CSB strength, dimensional stability and durability (Spence & Cook, 1983). Compaction pressure could have also been used as the main parameter for categorising block types. Unfortunately, although compaction pressure contributes towards reducing voids and thereby increasing density in blocks, its effects can be easily reversed in the absence of a stabiliser (Chapter 3). It is the stabiliser content alone which is responsible for binding the block particles together on a more permanent basis. It was reported in Chapter 3 that densification alone without the addition of a chemical stabiliser has no permanent effect on soils. However, the effect of varying the compaction pressure, mix water content and curing conditions were also investigated for both improved and traditional blocks. The summary of the actual input variables used in the design of the experimental samples are shown in table 3.

S/N	INPUT VARIABLE	UNITS	AMOUNT	EXPERIMENTAL DESIGN	
				FIXED	VARIED
A	SOIL 'S' (Laboratory soil)			•	
	Gravel	%	2	•	
	Sand	%	75	•	
	Silt	%	8	•	
	Clay	%	15	•	
B	STABILISER				
	OPC	%	3,5,7,9,11		•
	Lime	%	5	•	
	Microsilica	%	10 (of OPC)		•
C	MIX-WATER				
	Highest	%	9.0		•
	Medium	%	8.5		•
	Lowest	%	7.0		•
D	COMPACTION PRESSURE				
	High	MPa	10		•
	Medium/Normal	MPa	6		•
E	CURING				
	Time	Days	28, 56	•	
	Humidity	%	0, 100		•
	Temperature	°C	22-24	•	

Table 3: Summary list of the main constituent materials and input variables used in the production of block specimens.

Each of the variables listed in table 3 are discussed in turn.

The *soil type* was kept fixed, with approximate composition: gravel (2%), sand (75%), silt (8%) and clay (15%). As several block types of nominal dimensions 290 x 140 x 100 mm were required for the experiments, keeping the soil type the same for all specimens would help increase reliability in the tests. It was from the full block sizes that smaller specimen samples were obtained for further experimentation. By keeping the soil type the same at all times for all specimens, better consistency, repeatability and controllability could be achieved. The selected soil composition had to comply with the suitability criteria earlier discussed for soils for CSB production. An optimum composition of soil fractions for more effective stabilisation with OPC rather than lime was chosen. The criteria used for soil classification was particle size distribution. According to literature sources, an ideal soil for effective stabilisation with OPC has the following composition: coarse fraction (gravel and sand) 75% and fines fraction (silt and clay) 25% (Fitzmaurice 1958; United Nations, 1964; Houben & Guillaud, 1994). Following from this, an artificial soil was blended in the laboratory for repeatable use.

The mock soil was made by controlled mixing of ordinary buildings sand (OBS) and ordinary potters clay. The soil was from then on referred to as soil 'S'. The clay type was of the Kaolinite group, chosen due to its known stability and non-expansive nature when in contact with water (Scot, 1963; ILO, 1987; Webb, 1988). The importation of representative soils from the humid tropics was considered not to be necessary. Even if this had been done, not much would have been achieved. This is because soil remains a highly variable material even within each country and moreover, even within regions of the same country. A further advantage in using the artificial laboratory blended soil was that soil properties such as particle size distribution, plasticity, bulk density, moisture content, etc., could all be easily controlled. These soil properties could be kept consistent for all block samples. Any variations in soil properties would not only influence the choice of stabiliser, but also the properties of the blocks produced from it. By keeping the soil type consistent, a more logical interpretation of the effects of other production variables on the performance of the block could be achieved. Further, any variations detected in the performance of blocks could be linked to the method of investigation used instead of attributing it to variations in soil composition. For the soil 'S', key soil properties such as particle size distribution, linear shrinkage, moisture content, etc., were tested using standard test methods. Test methods are described in Webb (1988) and in Webb and Lockwood (1987). The key test results are presented and discussed in Section 5.3 of this Chapter.

The *stabiliser type and amounts* were varied as discussed earlier (table 3). The predominant stabiliser type used was OPC of class 42.5N, supplied from Rugby Cement (BS 12, 1996). The other stabilisers used in combination with OPC were lime (BS 890: 1995) and condensed silica fume (Illston, 1994; Neville, 1995). OPC was selected as the main stabiliser for a number of reasons (Chapter 3). Of all the common stabilisers OPC is widely available in most parts of the world. Lime was also used in combination with OPC for a limited number of specimens. The objective of such combinations was to evaluate the effect of lime on the clay fraction of the soil (Hilt & Davidson, 1960). The lime type used belonged to the Limbux brand, a high quality hydrated lime of typical assay 96.5% calcium hydroxide. The neutralising value was 7.4% CaO. Each required amount of lime was accurately weighed in self-sealing bags on an electronic scale. Microsilica (non-combustible amorphous S_1O_2: CA_5 No. 69012-64-2) in controlled amounts of 10% of the OPC content, was added to a selected number of blocks. The microsilica used was grade 940-4 (Elkem microsilica from Norway). The objective was to assess the effect of such partial cement replacement materials on the improvement of strength and quality in blocks. The material was known to have been employed in the production of high-strength concrete (Neville, 1995). By progressively altering the stabiliser content and type, variations in the performance of blocks produced under each category were monitored. The extent and significance of changes in properties were of great interest to the research. The amounts of OPC used is shown in table 3. OPC content varied from 3% to 11% by weight in increments of 2%.

Theoretically, when OPC is partially replaced with a CRM such as microsilica, the latter acts as a nucleic centre, thus reducing the water-cement ratio (Chapter 3). With proper wet curing, a maximum degree of hydration can also be achieved. Moreover, the microsilica also reacts with the lime that is released during the hydration of OPC to create a secondary binder in the block. Under such circumstances, it can be expected that such a block would have a much higher inter-granular strength, higher density and more resistance to surface abrasion. It is for this reason that such blocks have been referred to here as 'improved blocks' (IPD).

Mix-water content was varied (from 7% to 9%) for a select number of blocks (those made with 5% OPC content). For all other blocks, the mix water content was maintained at 8.5% by weight of the soil plus stabiliser mix. Variation of mix-water content was not originally planned. After accidentally adding more water than was originally intended and obtaining a much higher value of wet compressive strength for the block, it was decided that the variable be investigated further experimentally. The effect of changing the mix-water type was also investigated: ordinary laboratory tap water and distilled water. The results from three samples showed that there was no significant difference in the performance of blocks made from either type of water. Consequently, Coventry tap water was used to produce all block specimen samples used in the experiments. The water temperature was approximately 23°C.

Compaction pressure was maintained at 6 MPa, but only varied to 10 MPa for a select number of blocks. The latter was used purely for comparison purposes only since such high values are rarely used in practice. It is common to compact CSBs at compaction pressures between 4 MPa and 8 MPa (Houben & Guillaud, 1994). The BREPAK press that was used to make all the blocks was equipped with a pressure monitoring gauge (Webb & Lockwood, 1987).

Curing conditions were maintained for all blocks according to the specifications for the binder type used. For a select number of blocks, curing conditions were varied by curing the blocks under exposed and wet conditions throughout (immersion after 24 hours of demoulding). Otherwise normal curing conditions were applied to the majority of blocks produced. Primary curing taking 3-7 days, followed by secondary curing for 28 days was the general format adopted. Where lime was included in a block, the above periods were doubled. After curing, the blocks were then cut to the required sizes (Section 5.4).

5.3 CHARACTERISATION OF SOIL 'S'

Soil classification tests were performed on soil 'S' in order to confirm its category amongst other soils. The main tests conducted included the following:

- Particle size distribution test (Vickers, 1983; BS 1377: Parts 1 and 2, 1990)
- Sedimentation test (Appendix J)
- Linear shrinkage test (Appendix K)
- Moisture content test (BS 1377: Parts 1 and 2, 1990)

The procedures involved in each of the above tests are described in the references shown while some are discussed in Appendices J and K. The soil tests were conducted before and after the manufacture of the several specimens. These showed that no significant changes in soil composition had occurred during the entire testing period. Summary of the average values obtained in the above tests are presented in table 4.

S/N	TEST	UNITS	TEST RESULTS	RECOMMENDED VALUES
1	PARTICLE SIZE DISTRIBUTION			
	Gravel	%	1.3	< 40
	Sand	%	75.4	25-80
	Silt	%	8.1	10-25
	Clay	%	15.2	8-30
2	SEDIMENTATION (JAR)			
	Gravel and sand	%	73.9	75
	Silt and clay	%	26.1	25
3	LINEAR SHRINKAGE	mm	17.6	15-30
4	MOISTURE CONTENT	%	0.9	<3
	SOIL TYPE		SANDY SOIL	

Table 4: Summary of soil classification test results for soil 'S'. (Recommended values: ILO, 1987; Houben & Guillaud, 1994; Rigassi, 1995)

The *particle size distribution* test results for soil 'S' show that the soil type is predominantly sandy (Appendix L). The proportions of the main soil fractions present fall within the recommended ranges. Soil 'S' was therefore found to be suitable for stabilisation with OPC. The soil has sufficient proportions of coarse fraction (fine gravel and sand) for the skeletal frame and body of the block, as well as an adequate proportion of fines (silt and clay). The test method used is fully described in Vickers (1983) and in BS 1377: Part 2 (1990).

The *sedimentation (jar)* test results also confirm the presence of sufficient quantities of coarse soil fraction and fines. This result also shows convergence with the previous test. According to the results, the amount of coarse soil fraction was about 73.9% and fines fraction about 26.1%. As explained in the earlier parts of the thesis, the main advantage of having a sufficient amount of fines is to make sure that the block remains intact on demoulding. On ejecting a block, the hydration reaction of OPC is still at a very early stage and the cement will require more time before it begins to set and harden. The presence of a natural binder like clay in the block is therefore advantageous. The sedimentation test is however, quite slow (over 48 hours) and of medium accuracy. The values of silt and clay can be slightly distorted due to swelling and expansion in water. It was also found difficult to differentiate the silt from the clay as both appeared to be well intertwined. The test method is described in Appendix J.

The *linear shrinkage test* (LST) result of 17.6 mm (mean value) confirmed that soil 'S' had just enough clay in its composition (Webb & Lockwood, 1997). There is therefore no need to add more clay than the amount already added (15%). The results also confirm that the use of OPC, rather than lime for stabilisation would be more effective in this case. Lime would have been required if the shrinkage value had been higher, signifying a high clay content in the soil. The LST method is described in Appendix K.

The *moisture content* value of 0.9% shows that soil 'S' is in a near dry state. The term 'dry' as used here might not be strictly accurate since there is still some water present in the soil in the form of adsorbed water which surrounds the solid soil particles (Chapter 3). The term 'dry' has been used here to indicate that soil 'S' attained constant weight on being heated to 105°C - 110°C (BS 1377: Part 2: 1990). The dry state of soil 'S' is quite important since mixing of the soil with the stabiliser has to be done with both materials in a similar state. If the soil had been wet, then its specific surface area would have varied unnecessarily. The size and density of blocks obtained would not have remained consistent (Chapter 3). By determining the dry state moisture content, it was also then possible to determine the total amount of water added to achieve the optimum moisture content of the soil. The test for the optimum moisture content in this case is done using the drop test. Soils are compacted at the optimum moisture content because it is difficult to compact them at lower moisture contents. An increase in moisture content lubricates the soil, making it more workable. Dry density increases and air voids are reduced. The optimum moisture content of the soil is however, not a parameter dependent on the soil type alone. It also depends on the type of grading and on the compaction effort used (ILO, 1987). The test method used to obtain the moisture content value for soil 'S' is based on BS 1377: Part 2: 1990.

5.4 PREPARATION OF CSB SPECIMENS

In this Section, the design and production of CSB specimen samples used for subsequent tests and experiments are described. The summary list of the total number of samples made during the experimental stages is also provided. The sample size for each test was based on earlier exploratory tests where the coefficient of variability for each test type was determined (5.4.2).

5.4.1 LABORATORY PRODUCTION OF CSBs

The planned experiments demanded a large number of specimens prepared to a high degree of accuracy, reliability and consistency. Extra care had to be taken at all stages of the block production process: soil preparation, mixing, compression, and curing of the samples. After curing, the block specimens were cut to conform with the sizes required for each test. Apart from the mix-proportioning stage that distinguished the block types by amount and type of stabiliser used (improved and traditional blocks), the rest of the procedures remained the same. Specimen design and preparation describes the procedures adopted and the precautions taken to produce the required number of block specimens for the various tests planned. The description is based on the four main stages of CSB production:

- Soil preparation
- Mixing
- Moulding
- Curing (and sizing)

Soil preparation involved the mixing and storing of soil 'S'. Before this was done however, the ordinary builders sand (OBS) was dried and screened prior to mixing with clay. The sand was supplied in 500 kg bags and placed in bins outside the laboratory. The sand had been supplied clean, i.e. after washing out the clay fraction from the sand. To dry out the material, the sand was removed from the yard bins and spread out on the hard, flat concrete laboratory floor. About 100 kg of the OBS was weighed and spread out each time. The weighing was done using the Avery Weighing Scale: type 3202/CLE No. B672521 (capable of weighing up to 50 kg at a time). The objective of drying out the sand was to ensure that a material of an almost even moisture content was obtained. The spread out sand was regularly and repeatedly raked to turn it over every four hours for about three days. When both the bottom and top layers achieved uniform light colouration, the sand was considered to be dry enough. The dry sand was then screened by pouring portions of it at a time onto a circular framed screen placed tightly over a laboratory soil storage bin. The square sieve aperture used was 5 mm (BS 410) to allow only fine gravels and sand to pass through (sieves made by Endcotts Test Sieves Limited). In this way all medium to coarse gravel present in the supplied sand was eliminated. Even then, it was still found necessary to use the hand to occasionally remove soil fraction sizes larger than 5 mm that may have accidentally gone through. The screened material was then stored in sealed bins within dry areas of the laboratory.

Mixing was then done to improve the grading of the sand. Controlled mixing was done by adding about 15% by weight pure grade E Kaolin clay. The characteristics of the clay used were: ECC International Grade E potters pure clay (quality China clay made in England); specific gravity 2.6; specific surface area 8.0 m^2/g; water soluble salts 0.15%; silica (S_iO_2) 50%; alumina (Al_2O_3) 35%; and pH 5± 0.5. The Kaolin clay was supplied in 25 kg bags. The OBS and clay were mixed mechanically using the Hobart machine mixer. Mixing was done for each batch of about 30 kg for about 4 to five minutes till a uniform colouration was achieved each time. After a homogeneous mix was obtained, soil classification tests were performed for every other five batches (Section 5.3). Soil 'S' was then stored in laboratory bins, covered and sealed. Covering of soil 'S' was done to minimise risks of contamination and to ensure that the moisture content remained uniform throughout. This procedure was repeated until enough soil to make about 60 blocks of nominal dimensions 290 x 140 x 100 mm was obtained. Each block required about 8.0 kg of soil 'S'. The amount of OBS and clay supplied was sufficient for the required number of experimental samples.

Mixing of soil 'S' with stabilisers (OPC, lime and microsilica) and water, was done in four stages for each batch. Proportions for the various stabilisers and soil 'S' used are shown in Appendix M. The key objective during the mixing stage was to ensure a good distribution of the stabiliser and water throughout the mix. Consistent proportioning out, dry mixing and wet mixing were required to obtain proper samples.

The proportioning out of soil and stabiliser was done by weight, not by volume. An electronic weighing scale capable of weighing up to 20 kg to an accuracy of 0.05 grams was used each time. All materials were weighed inside a plastic bag which was then sealed and clearly marked. The bags were carefully labelled to show the exact weight, type of material and date of weighing. By sealing the bags, variations of moisture content and contamination of the weighed out material were avoided. In all cases, dry mixing was done first before wet mixing with water. All mixing (wet and dry) was done in the Hobart Machine mixer as described earlier. Dry mixing was done for about three to four minutes. After this, water was then uniformly added to the dry soil and stabiliser mix and the process repeated. Amounts of water varied between 7.0% and 9.0%. The amount used was determined to give the soil its approximate optimum moisture content. The water was also meant to be sufficient for hydration of the stabiliser(s).

After uniform colouration was achieved, a consistency test was done for each mix (Chapter 3). Soil and stabiliser mixes which passed the drop test were immediately separated into three equal amounts sealed in polythene bags. Separation was necessary in order to ensure that mould filling could be done in three equal layers. Except where it was done deliberately, no delay between mixing and moulding was allowed.

Compression of the damp soil and stabiliser mix was done using the pre-installed BREPAK block making machine (SN BQ 038074, originating from Bristol, United Kingdom). The block making machine was designed on the quasi-static compression principle. The same machine was used for all block specimens produced. The main characteristics of the machine were: maximum nominal block size: 240 x 140 x 100 mm; maximum daily output, 300 blocks; maximum moulding pressure, 2 to 10 MPa.

Instructions contained in the operators manual for the machine were followed while making blocks (Webb & Lockwood, 1987). The compression procedures were done in three stages: mould filling, moulding, and demoulding. Mould filling was done after first cleaning the mould using release oils. This was repeated after every four to six blocks were made. Filling was done in three equal layers as described before, using the pre-weighed and separated mixes. By accurately weighing the mixes, it could then be expected that blocks of the same size and of consistent density could be produced. On placing each layer into the mould, the operation was checked by using fingers to press the mix into the corners of the mould. After the last layer was levelled, the mould cover was turned into position to cover the mix. The pressure monitoring gauge attached to the machine was used to determine the amount of force applied as required. The procedures were repeated till the required number of blocks were produced. Three blocks were produced for each specific mix type.

After the blocks were made, demoulding and handling followed, (done with great care as the blocks were still weak). Plywood sheets of about 20 mm thickness were used to remove the blocks from the elevated mould base plate. The sheets over which the green blocks were carried were each pre-weighed. The removal procedure was the same for all green blocks demoulded. While holding the pre-weighed plywood sheet level with the top of the elevated mould base plate, the green block was gently moved onto it using a second plywood sheet. The removed green block was then weighed together with the plywood sheet on which it was carried. Weighing was done using the electronic scale described earlier. External dimensions of the demoulded blocks were also taken. Dimensions were taken using a Mitutoyo shockproof dial calliper accurate to 0.05 mm. Measurements were taken at several locations on the block edges and mid-sections as specified in BS 6073: Parts 1 and 2, 1981 and BS 3921,

1985. The blocks were then carefully labelled using a soft-nib permanent marker. This was done to identify each block by date of manufacture, serial number, stabiliser content and moulding pressure used. The blocks were then covered with polythene sheets, which were also marked externally as before.

Curing of green blocks was done according to the specifications for each type of stabiliser used. A selected number of blocks were however cured under different conditions to evaluate the effect of varying this parameter on the properties of the block. For all other blocks, normal curing procedures were followed. Primary curing periods varying between three and seven days, followed by secondary curing periods lasting up to 28 days for OPC stabilised blocks, were maintained. Where lime was included in the mix, these periods were doubled. Secondary curing temperatures were maintained at the laboratory levels (22-24°C). After curing, the blocks were again marked to indicate the time and curing conditions followed for each block. The blocks were then cut down to smaller sizes as required for each test category (Section 5.4.2).

5.4.2 NUMBER OF SPECIMENS PRODUCED

A sufficient number of CSB specimens were required for all the planned laboratory experiments. Initial performance tests and accelerated tests for surface and bulk properties of blocks required specimens of different sizes. For these reasons, the CSBs that had been produced in full scale had to be cut to smaller dimensions.

Blocks were cut mechanically using a concrete lathe machine (masonry saw machine: Clipper, model EN 2-40-3). The lathe was driven electrically with a powered circular saw complete with a water sprinkler. Each block was accurately pre-demarcated with the required dimensions before the lathe was used to cut through. The machine was so effective that the cut surfaces were neat and straight. In this manner, blocks of nominal dimension 290 x 140 x 100 mm were cut down to the following major sizes: 100 x 100 x 100 mm (two per block); 100 x 100 x 40 mm (two per block); 100 x 100 x 90 mm (one per block); 100 x 90 x 40 mm (one per block). Even during the cutting, differences in the resistance of the block bulk to cutting could be felt. The blocks made using partial replacement of OPC by microsilica were the hardest to cut while blocks made with lime inclusion were the weakest to cut. Blocks compacted at 10 MPa were also harder to cut than blocks compacted at 6 MPa but consisting of the same stabiliser and soil mix.

For each test, three specimen samples made in exactly the same manner and composition were required (reasons explained later in this section). The total number of full size blocks made in this way were three per stabiliser and soil mix. The grand total number of blocks made was 51. From this grand total, over 306 smaller specimen samples of different dimensions were obtained. The specimens were then used for various bulk and surface property tests as described in Chapters 6 and 7. Appendix N shows the list of the various types of blocks produced as well as the different specimen samples obtained from them. Specimen samples for comparable materials such as concrete blocks (CBS), fired brick samples (FBS) and rock block samples (RBS) were obtained from the laboratory. These materials were used for the TWA and SDI tests only.

The reasons for testing three specimen samples for each test (then using the mean for interpretation) were based on the following considerations:

- as it is well known that all test results vary, preliminary tests using six specimen samples composed of 5% OPC and compressed at 6 MPa (cured for 28 days) showed the estimated variation from the mean in each case (properly tested) to be consistently low: WCS, 2.49 MPa (variance 0.027): BDD, 2127kg/m^3 (variance 0.023): TWA, 9.8% (variance 0.135) and SDI, 81.4% (variance 0.118). A 95% confidence interval was used in each case. There was no reason to expect that other mixes of differing OPC content would not show similar consistency and trends.

- previous findings by other researchers had arrived at the same conclusion (Webb, 1958; Fitzmaurice, 1958; Gooding, 1994)
- composition variables (soil type, stabiliser content, mix-water-content) and processing variables (moulding pressure, curing conditions) were determined using precision instruments and standard processing methods respectively. The specimens were therefore produced with a high degree of consistency. It is unlikely that the methods used in the laboratory can be repeated in field practice without major departures (Chapter 4).

Moreover, even if more specimens than the determined number of three for each case had been produced, other research constraints such as cost, time and space, had to be taken into account. Time constraints at planning, design and implementation showed that mandatory delays due to curing periods meant that the number of specimens required had to be limited. The time for the actual experimental work and for recording, computation and analysis of the results were also important considerations. Cost considerations relating to ordering of materials, delivery, wages, electricity, water, etc., were other important constraints. From the degree of accuracy, reliability and repeatability achieved in each case, it was later found that the decision made to use three specimens per test was justifiable.

5.5 CONCLUSION

From the preceding discussions in Chapter 5, a number of conclusions can be made regarding the following: experimental design, soil 'S' test results, CSB specimen production, and the total number of specimens provided.

The *experimental design* was based on identifying the main composition and processing variables involved in the production of CSBs: soil type, stabiliser type and content, mix-water content, compaction pressure, and curing conditions. In the experimental design for sample production, the soil type was fixed. Soil 'S' was composed of about 75% fine gravel and sand, and about 25% silt and clay. This was done to ensure that consistent use of the same soil would be possible throughout the testing period.

Stabiliser type and content were varied: cement content was varied from 3% in increments of 2% to 11%. Microsilica amount was fixed at 10% of the cement content. The amount of lime was fixed at 5% by weight of the soil when used in combination with cement. Blocks made using a mixture comprising microsilica and cement were designated as 'improved blocks'. Blocks where microsilica was not used were regarded as 'traditional blocks'. The categorisation was based on the stabiliser type because it is this variable that remains the single most influential factor that can affect the performance of blocks.

The mix-water content, compaction pressure and curing conditions were maintained at similar levels for the majority of blocks produced. For a select few numbers of blocks, these parameters were varied. The majority of blocks were made with a mix-water content of 8.5%, while the select few referred to were made using 7.0% and 9.0% by weight respectively. Blocks made using the 9.0% mix-water content were later found to perform better than those made using 8.5%. Compaction pressure was fixed at 6 MPa for most blocks. A few blocks were produced using a compaction pressure of 10 MPa mainly for comparison purposes only. Curing time and conditions were maintained at the specified levels required for each stabiliser type. All wet curing (100% humidity) was done for a select number of blocks to evaluate the effects of such conditions on the performance of blocks. The effects of these variables on the bulk and surface properties and performance of blocks are discussed in Chapters 6 and 7 respectively.

The *artificial experimental soil* blended in the laboratory (soil 'S') was found to meet critical requirements for suitability for stabilisation with OPC. The mean linear shrinkage value of 17.6 mm was within the range (15-30 mm) indicating the presence of a sufficient amount of clay. If the shrinkage value had been less than 15 mm, then the soil would have been regarded as having an insufficient amount of clay in it. The glass jar sedimentation test results confirmed that the coarse soil fraction (fine gravel and sand) was about 73.9%, while the fines fraction (silt and clay) was about 26.1%. Both values are within the recommended ranges for soils suitable for stabilisation with OPC. The laboratory dry moisture content value of 0.9% showed that the soil used was in a near-dry state, and of uniform moisture distribution. Most soils have moisture content well above 3% in the 'dry' natural state. The particle size distribution test results confirmed that soil 'S' was composed of all the four main soil fractions: fine gravel (1.3%), sand (75.4%), silt (8.1%), and clay (15.2%). The amount of silt was however lower than the recommended minimum of 10%. The values obtained still fall within the range for suitable soils for CSB production.

Specimen design and production of CSBs for further testing were done with the main objective of obtaining an adequate number of samples for all the planned experiments.

For each mix type, at least three blocks were obtained. From these blocks, smaller specimen sizes were cut. A total of 51 blocks of nominal dimension 290 x 140 x 100 mm were produced. Out of this number of blocks, over 306 smaller specimen sizes were obtained. This number was considered to be adequate for all the bulk and surface property tests planned for. The decision to use three specimens per test was based on earlier findings by other researchers, and the low variance calculated during preliminary tests. Careful attention was paid to the block production process: preparation, mixing, compression, and curing. The blocks produced were all found to be of high quality and fit for further testing. Each of the block samples produced and specimens obtained were carefully labelled for easy identification.

From the preceding conclusions, the objectives of Chapter 5 were fully met.

CHAPTER 6

BULK PROPERTIES AND PERFORMANCE

6.1 INTRODUCTION

As mentioned earlier in this thesis, CSB bulk properties can be influenced by the proportions of the main constituents that form the block and by the processing methods used to produce them (moulding pressure, curing conditions, etc.). The objectives of this chapter are twofold, namely: firstly, to identify the main bulk properties likely to affect the durability of a block, and secondly, to test experimentally the performance of blocks made using differing input variables (stabiliser content, mix-water content, moulding pressure, curing conditions, etc.). The bulk properties identified as likely to influence its durability include (Lunt, 1980; Baker et al, 1991; Illston, 1994; Rigassi, 1995):

- Wet compressive strength (WCS)
- Block dry density (BDD)
- Total water absorption (TWA)
- Total volume porosity (TVP)

For each of these properties, the effect of varying some of the input variables described before are investigated (Chapter 3). The results obtained from the tests are analysed with a view to identifying general trends as well as comparing the performance of traditional blocks and improved blocks. Current standards and initial performance characteristics of like materials such as fired bricks and concrete blocks are also compared. Finally, the results are used to validate or query theoretical assumptions made in the earlier chapters of the thesis. The implications of the findings on future methods of design and production are discussed.

The coverage in Chapter 6 is limited to the discussion of experimental findings related to the above properties. All experiments were conducted following standard procedures to ensure accuracy, repeatability and reproducibility. Chapter 6 is presented in six sections. After this introductory section, the others include discussions of the findings relating to compressive strength, dry density, water absorption, volume porosity, and conclusion.

6.2 THE COMPRESSIVE STRENGTH OF BLOCKS

The compressive strength of a block is perhaps one of its most important engineering properties. It was established from the literature that the durability of CSBs increases with increase in its strength (Stulz & Mukerji 1988; Houben & Guillaud, 1994). Indeed a stronger block which has been well cured is usually better resistant to deleterious environmental agents (Chapter 2 and 3).

It is on the basis of the value of the strength of a block that its mechanical and other valuable qualities are judged (Rigassi, 1995; Young, 1998). Knowledge of the compressive strength value of a block can be used in a number of ways. They include:

- to check the uniformity of block quality
- to compare a given block sample with a specified requirement
- to approximate the degree of hydration achieved by OPC (through the strength of bonding)

- to classify a block in terms of its resistance to abrasive durability

Just as is the case with concrete, CSBs are composite materials. Such materials are known to be brittle and are therefore more accommodating of compressive stresses than tensile ones. The tensile strength of a block is about 90% lower than its compressive strength (Fitzmaurice, 1958). For this reason, the discussion in this section is confined to the behaviour of a block under compression only. The discussion is presented under the following three sub-headings:

- Type of inter-particle bonding in CSBs
- Factors influencing strength in CSBs
- Test methods used to investigate the compressive strength in blocks

Type of inter-particle bonding in CSBs

As a heterogeneous mixture of fine gravel, sand, silt, clay and stabiliser, the type of bonding between the different particles in a CSB is believed to be complex (Ingles, 1962; PCA, 1971). The nature of the bond is known to greatly influence its compressive strength. Unfortunately, determination of the quality of bonding is difficult to assess as no accepted test exists at the moment. However, most of the strength of a block is said to depend on the bond between the cementitious matrix and the coarse soil fraction (fine gravel and sand) (Houben & Guillaud, 1994). Physical mechanical interlock takes place between OPC hydrates and the mainly sandy fraction of a soil, with the bond strength varying from point to point (Mitchell & El Jack, 1978). The bond strength also varies according to the type and texture of the coarse soil fraction. It is generally held that characteristics of sand which do not permit penetration of its surface by the hardened cement paste cannot be conducive to good bonding. Soft, porous and mineralogically heterogeneous sand particles are likely to result in better bonding with cement paste. This consideration is often mentioned in concrete research (Glanville & Neville, 1997; Young, 1998).

As sand particles form the bulk of a block, by preserving their own integrity through their own high internal bonds, they constitute the strongest component within the block. Such high internal strength surrounded by 'weaker' contact strength can influence the path lines of failure in a block (cracks). The compressive strength of a block cannot therefore be expected to exceed that of its constituent sand particles. This theory is easier to assume than to test experimentally.

The cement hydrates that intertwine sand particles in a block are known to be porous aggregation of interlocking fibres (Hertzog & Mitchell, 1963). Bundles of these fibres form a cross-linked anisotropic network that effectively limits and opposes movement within the block fabric. The bonds between OPC hydrates are reported to be of the van der Waal type (Weidemann et al, 1990; Young, 1998). Such bonds are known to be physical in nature arising from the large energy available at the surface of gel particles. The forces at the surface of these gels can be large in comparison with their body forces. The bonds within OPC hydrate fibres are however chemical in nature (of the ionic and covalent types) (Taylor, 1998). Such bonds are stronger than the physical ones. These bonds are strong enough to resist any unlimited thixotropic expansion that might normally occur. Lastly, the bond between clay particles in a soil and the OPC hydrates is thought to be of the chemical type (Herzog & Mitchell, 1963; Ingles & Metcalfe, 1972). Through linkage due to the presence of water, a fairly stable chemical bond occurs between the clay minerals and the freed lime from the hydration reaction of cement.

In summary therefore, the strength of a block is governed by the strength of its cement paste, the strength of bonding between the cement paste and sand particles, and the internal strength of the sand particles (Uzomaka, 1978).

Factors likely to influence the strength of CSBs

The strength of CSBs can be influenced by a number of factors (BRE, 1980; Hughes, 1983). The main ones are the:

- water-cement ratio and degree of hydration
- degree of compaction
- state of moisture in a block
- temperature of a block
- age of a block
- type of coarse fraction present

The above factors are briefly discussed each in turn.

The *water-cement ratio and the degree of hydration* are known to determine the strength of a cement matrix (Neville, 1995). It can be expected that the lower the effective water cement ratio and the higher the degree of hydration, the lower the capillary porosity and the stronger the block. This can be achieved through accurate determination of the water cement ratio (proportioning and consistency testing) and proper curing (to maximise the degree of hydration). The degree of hydration can increase as long as moisture continues to be available for hydration. Wet curing of green blocks soon after demoulding is therefore a critical factor in this respect. This phenomenon is investigated experimentally in this research. The total volume porosity of a block and its correlation to strength are also investigated experimentally in this thesis (Section 6.5).

The *degree of compaction* can also affect block strength (Chapter 3). Compression reduces the amount of voids and increases inter-particle contact within a block.

Higher density has always been associated with higher strength (Spence, 1975; Gooding, 1993). This phenomenon is also investigated experimentally in this thesis.

The *moisture state* of a block can also influence its strength. Saturated blocks are weaker than dry blocks (Fitzmaurice, 1948; Houben et al, 1996). The difference in strength can be explained in a number of ways. Firstly, the presence of moisture in a block lowers the weak van der Waals bonds between the surfaces of the cement hydrates and the surface of the sand particles in the material. Secondly, since CSBs contain clay minerals, their high affinity for water leads to absorption and subsequent dispersal of any unstabilised grains. This can have the undesirable effect of weakening the state of bonding in the block. Thirdly, in a saturated state, as a block is subjected to loading, internal pore pressures can build up within it. Such pressure build-up can lead to the type of stress relief normally associated with disruption of inter-particle and inter-phase bonding in cement-based materials (Lea, 1970; Newman, 1986). The difference between the wet and dry compressive strength of a block is likely to be a valuable indicator of the strength of bonding achieved within it. The smaller the gap between the two, the higher can the bond strength be expected to be. This difference is also investigated experimentally in this thesis (Section 6.2.2).

The *temperature* of a block can also influence its strength, and by implication its durability. The effect on strength is likely to be more pronounced during the early age of a green block. It is known that the hydration reaction between OPC and water depends on temperature (Weidemann et al, 1990; Illston, 1994; Young, 1998). The rate of hydration increases as the temperature increases. At later periods in the life of a block, higher temperatures can still be counterproductive. A higher temperature maintained during the service life of a block is likely to result in short-term strength gains but, lower long-term strengths. This phenomenon is not investigated experimentally in this thesis.

The *age* of a green block influences its strength since the degree of hydration of the OPC stabiliser is known to increase with time. During the early stages of production, the degree of hydration within a block increases with curing age, and so does its strength. This phenomenon is investigated experimentally in this thesis. It is also possible that the hydration reaction of OPC might never really become complete (Taylor, 1998). CSBs are therefore likely to continue to gain strength for many years. The rate of increase in strength is however known to decrease after some years.

The *type of the coarse-soil fraction* (fine gravel and sand particles) used to produce blocks can also influence their strength. Increased surface roughness of sand particles is thought to be beneficial in improving bonding, mainly due to improved mechanical interlock between the sand particles and the OPC hydrates. Moreover, improved grading of sand particles can also improve the degree of interlocking due to closer packing of the grains within a block (Chapter 3). Conversely, the use of larger soil grain particles is likely to be disadvantageous. This is because larger soil fractions have a lower overall surface area with a corresponding weaker transition zone. Limits on the size and proportion of the maximum soil fraction can therefore lead to improved bonding, and thus strength of blocks. During the block production stage for this research, the maximum allowable coarse fraction size was limited to 5 mm (by screening with a 5 mm aperture sieve, Chapter 5).

Compressive strength test methods and factors considered

In this sub-section, highlights of the test method and factors considered during compressive strength evaluation of CSB specimens are discussed. Block specimens were produced as discussed in Chapter 5.

The compressive strength of a block is the failure stress measured normal to its face. For all CSB specimens tested, standard methods of test were used throughout (BS 6073: Parts 1 and 2: 1981; BS 3921: 1985). For research purposes only, some similar block specimens were tested both in their wet and dry state. Current standards only recommend testing of samples in the wet state. The reason why dry state testing was also done was explained earlier in this section.

Standard procedures which were consistently followed with no departures allowed are presented in Appendix O. This was done because even with standard procedures, a slight variation in one of a number of test conditions can easily affect the outcome. The most important test factors considered included the:

- block specimen size
- sample moisture condition
- specimen curing age
- specimen end-surface preparation
- rate of application of loading
- rigidity of the testing machine

Each of the above factors are now briefly discussed in turn.

The *block specimen size* was kept uniform as 100 mm cubes for all samples tested. Although standards permit use of cylinders as well, it was found to be a lot more convenient to use cube prisms. The decision was mainly dictated by the method of manufacture used to produce full-scale block samples. Cutting out smaller specimens from the full-scale sizes had several advantages. The 100 mm cube specimens were:

- easy to cut out
- expedient to protect from damage

- cheaper to make
- convenient to test with a lower capacity machine
- economic to test as less material was wasted (the test was destructive)
- small enough to be less likely to contain elements of weak points

It is well established that the strength of a cement based specimen decreases with size (Neville & Brooks, 1994). So does the *variability* in strength of geometrically similar block specimens, because smaller specimens are more homogenous. The results obtained were satisfactory with a high degree of consistency (Section 6.2.1).

The choice of *moisture condition* in the test samples was considered an important factor. Testing in the 'wet' state is advantageous in that it is more reproducible than testing in the 'dry' state. Testing in the latter state can be unhelpful since it includes a widely fluctuating degree of dryness in a block sample used. The outcome from such a test would really not be that accurate to compare. Testing in the dry state can also lead to higher strength values being recorded (Fitzmaurice, 1958). This can be misleading when related to actual service conditions where blocks are likely to be continually subjected to moist conditions. Testing in a wet condition therefore relates better to real life applications of the block. For purely research purposes, compressive strength tests on a select few number of blocks were conducted in both states.

The choice of *specimen curing age* was based on the specifications of the stabiliser type used. As stated earlier, curing is associated with the rate of hydration of the stabiliser used. Indeed it is with age of hydration that OPC gains strength, especially at the early stages of the process (Weidemann et al, 1990). For practical purposes the hydration of OPC is generally regarded as being substantially complete at 28 days (Illston, 1994). Compressive strength test values obtained around this time ought to reflect the full strength of a cured block. No significant increase in strength is likely to be recorded after 28 days (Lea, 1970). For these reasons, all cement based block specimens were tested at 28 days. Lime based blocks were tested at 56 days (BS 890, 1972; Bessey, 1975; Coad, 1979).

The *end surface preparation* for each test specimen was considered a critical factor likely to affect the results. As during the test two dissimilar types of surfaces (block surface and testing machine platen) would be coming into intimate contact with one another a special precaution was required. While the surface of the end platen of the machine might be smooth, the surface of the CSB specimen is rougher, uneven and not really plane (ILO, 1987). Such dissimilarities can give rise to undesirable stress concentrations on the block specimen. This effect can lead to variations in test results to the extent that the outward compressive strength of a block specimen would appear to be diminished (Bungey & Millard, 1996). In order to overcome this problem, the surfaces of all block specimens tested were capped using plywood pieces of dimensions 105 x 105 x 12 mm (BS 6073: Part 1 and 2, 1981). The size was chosen to be about the same as the top of the block specimen. In this way, the influence of any surface defects in planeness that could have created significant variations in test results were removed, or at the very least minimised. The narrow scatter of test results later showed that this decision had been the correct one (Section 6.2.1).

The *rate of application of loading* (compression testing machine) was also regarded as an important factor likely to affect the seeming strength of test specimens. It is well established that the lower the rate at which the stress is increased onto the block, the lower will the eventual recorded compressive strength be (BS 6073: Parts 1 and 2, 1981). Conversely, if the load is applied rapidly, higher strength values can be recorded. The reasons behind such outcomes is based on the rate of increase in strain over time. It is widely reported in concrete studies that when the limiting strain is reached too soon, failure also takes place prematurely (Lea, 1970; Neville & Brookes, 1994; Jackson & Dhir, 1995). It is therefore important that the stress on block specimens is applied at a uniform and consistent rate for all samples tested. In this way comparable results can be obtained. The selected rate of loading applied gradually without shock for all specimens tested was 15 KN/minute (BS 6073: Parts 1 and 2, 1981; BS 3921: 1985; ILO, 1987). It was generally observed that stronger blocks (higher stabiliser content 7%-11%) exhibited lower severity to the strain rate. The required rate of loading was selected using an electronic input board attached to the testing machine. Failure in most blocks samples occurred within about 2 to 4 minutes.

The *rigidity of the testing machine* was the last factor considered. A less rigid testing machine can store up energy leading to explosive fractures occurring in the test specimen. The machine used for the tests had just been serviced and recalibrated only a few months earlier. This problem cannot therefore be a source of errors for the tests conducted during that period.

After failure was achieved, the crushing strength of each block specimen was calculated by dividing the maximum recorded load carried (in KN) by the cross-section area of the specimen (mm^2). The crushing strength was expressed to the nearest 0.05 KN/mm^2 (MPa). The results are discussed in Sections 6.2.1 to 6.2.4.

6.2.1 EFFECT OF VARYING THE STABILISER CONTENT AND MOULDING PRESSURE ON THE WCS OF CSBs

The values of the 28-day mean wet compressive strength for both traditional and improved blocks are shown in Appendix P(1) to P(5). A plot of these values against the range of cement contents used is given in figure 6. Each of the data points shown plotted in figure 6 is an average of three separate experimental results (Chapter 5). The key to the symbols used on the graph is also given. All subsequent graphs are presented following the same format.

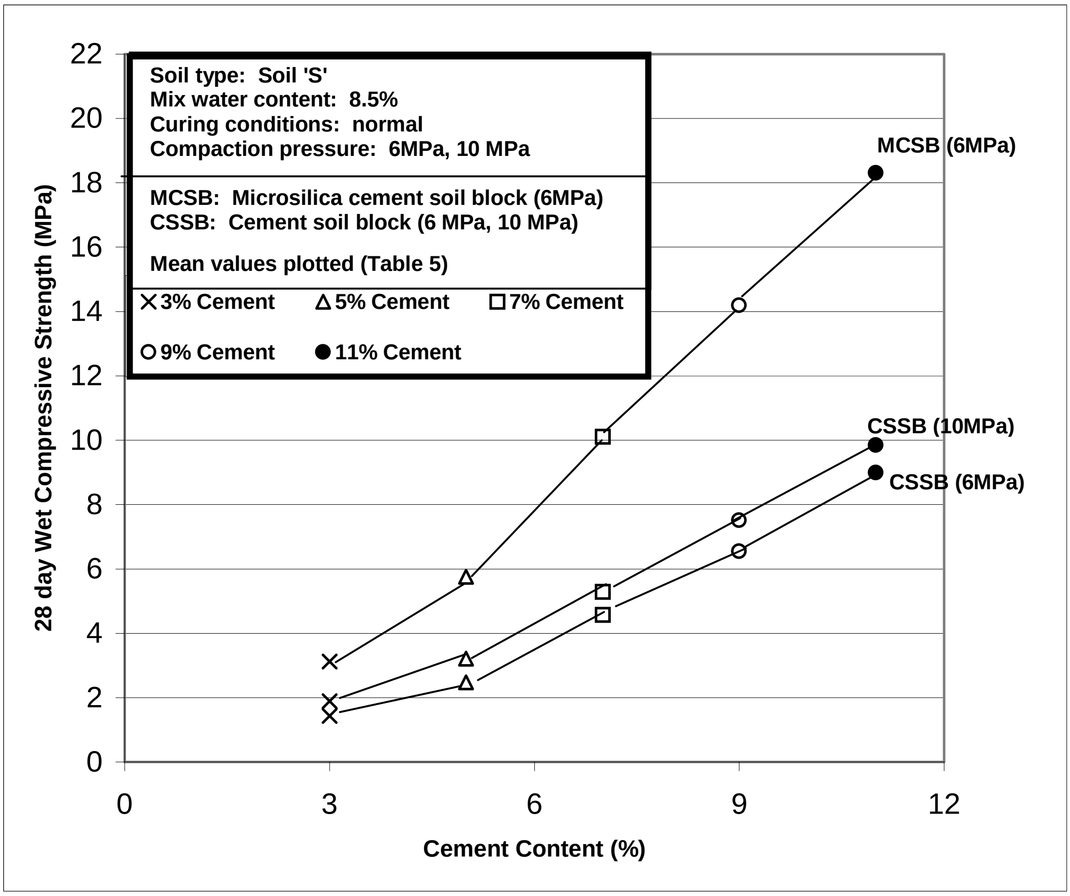


Figure 6: Effect of varying the stabiliser content and compaction pressure on the wet compressive strength of CSBs. (University of Warwick, 2000)

The discussion of figure 6 is conducted along three lines: the range of values obtained, comparison of these values to existing standards, and analysis of the trends shown by the results. This approach is used for all other subsequent results presented in this thesis.

Table 5 shows a summary of the plotted values in figure 6.

Cement content	28-day Wet Compressive Strength		
%	MPa		
	MCSB (6MPa)	CSSB (10MPa)	CSSB (6 MPa)
3	3.12	1.89	1.43
5	5.76	3.21	2.48
7	10.11	5.29	4.57
9	14.19	7.51	6.54
11	18.3	9.84	8.99

Table 5. Mean wet compressive strength values (28-day) for MCSB and CSSBs.

The values of the average 28-day wet compressive strength for both traditional (CSSB) and improved blocks (MCSB) were satisfactory. The values ranged between 1.43 MPa and 8.99 MPa in the case of the former and between 3.12 MPa and 18.3 MPa in the case of the latter. The lower values in either case correspond to the cement content of 3%, while the higher ones to 11%. As can be seen, the WCS values in improved blocks were found to be considerably higher than in traditional blocks made in exactly the same manner but without the addition of microsilica. On average the addition of microsilica resulted in the doubling of strength in blocks. Although some improvement had been expected, the magnitude of the strength gain achieved was surprising. Such high values had not been previously obtained with the corresponding amounts of OPC according to current CSB literature (Rigassi, 1995). The inclusion of a partial cement replacement materials (CRM) such as microsilica therefore appears to be an effective way of increasing the WCS of blocks. These results also confirm the earlier theoretical assumptions described in Chapter 3. This approach represents a new way forward in terms of strengthening CSB fabrics for wider engineering applications. It is also likely to be particularly useful for blocks exposed to severe environmental conditions.

According to literature sources, recommended WCS values for CSBs are quite wide-ranging, varying from country to country, and from author to author. The experimental values obtained here however, compare well with most current CSB standards. Some recommended minimum values are: 1.2 MPa (Lunt, 1980),1.4 MPa (Fitzmaurice, 1958) and 2.8 MPa (ILO, 1987). The value of 1.2 MPa is now more widely used (Houben & Guillaud, 1994). The lowest experimental value obtained for traditional blocks (1.43 MPa), is about 20% higher than this. For improved blocks the 3.12 MPa value is about 62% higher. Both values correspond to blocks stabilised with 3% OPC. The blocks made with OPC contents of 5-7% were all significantly stronger than the 1.2 MPa standard (5 to 8 fold stronger). Moreover, by interpolating the plotted values for IPD blocks below the 3% cement content point, it can be estimated that only about 1% of the binder content would be required to achieve the minimum recommended WCS value of 1.2 MPa. The approach established from these results constitutes a significant new finding.

The preceding discussions concerned variation in stabiliser content only. The results of varying compaction pressure from 6 MPa to 10 MPa over the same range of cement contents for TDB blocks are also shown in figure 6. No improved block samples were subjected to similar variations in compaction pressure. The results show that for the same stabiliser content, increase in compaction pressure leads to an increase in WCS. It was found that at lower cement contents, increase in compaction pressure from 6 MPa to 10 MPa (about 70%) resulted in increase in WCS of about 32%. A similar increase in compaction pressure resulted in a corresponding increase of only 9% at the higher cement contents (11%). Within the range of interest (5-7% cement content), the increase in WCS was between 16 and 30%.

These values are much lower than the dramatic increases witnessed by varying the stabiliser content. The findings confirm earlier work by other researchers that increase in stabiliser content is a more economic way of increasing the wet compressive strength in blocks (Lunt, 1980). Blocks stabilised at high stabiliser contents but compacted at low compaction pressures were found to perform satisfactorily. The final wet strength of a block appears to be more sensitive to changes in cement content than compaction pressure. The results also show that although improved performance can be achieved by increasing compaction pressure, the degree of improvement diminishes as this pressure is increased. Block making machines operating within the range of 4 to 8 MPa should therefore be adequate to give satisfactory results (Houben & Guillaud, 1994).

6.2.2 Comparison of the ratio between Mean dry and wet Compressive Strength

The effect of varying the stabiliser type and content on the gap between mean dry and wet compressive strength was investigated experimentally. The values obtained are plotted as shown in figure 7.

The range of the plotted values shown in figure 7 are summarised in table 6.

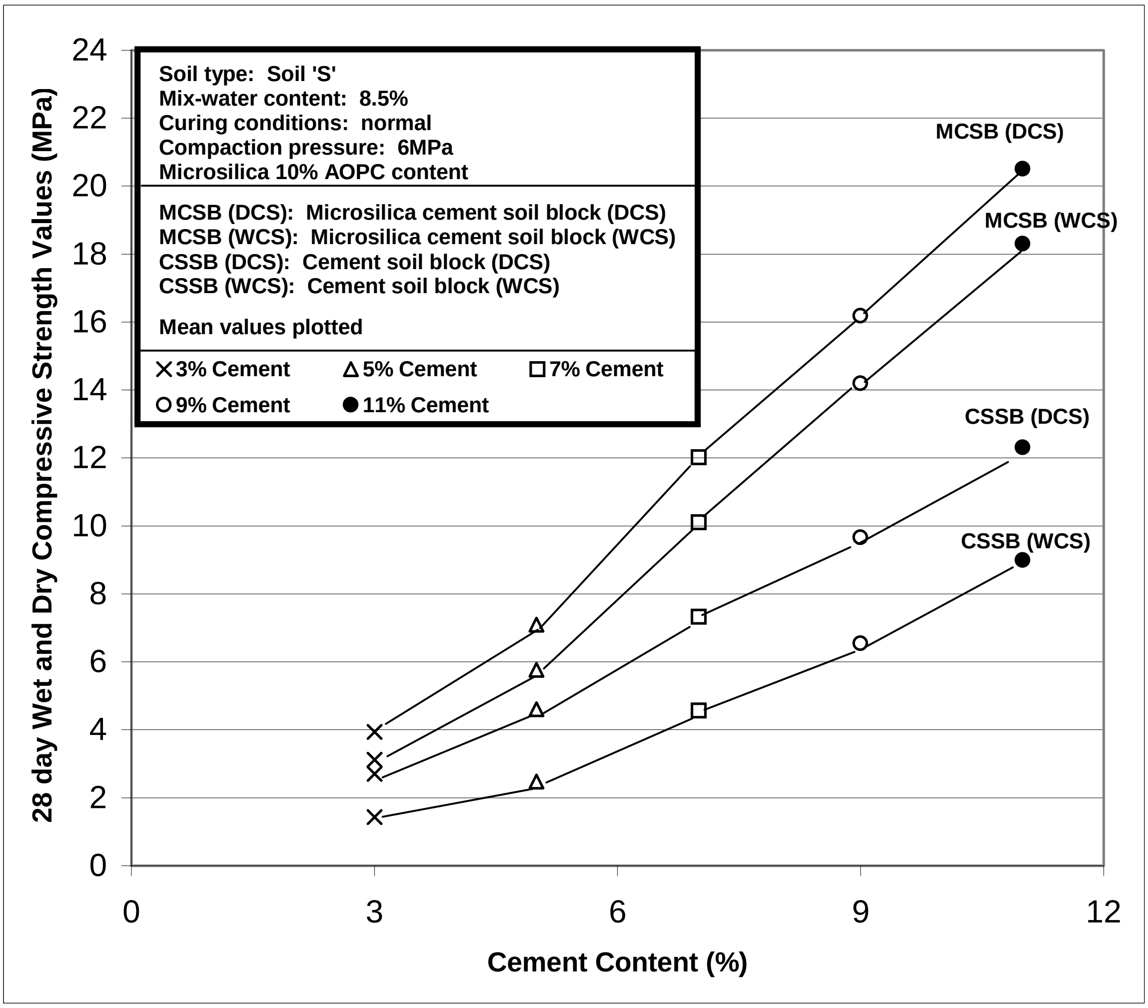


Figure 7: Comparison of the mean wet and dry compressive strengths in both traditional and improved blocks (University of Warwick, 2000).

Cement content	Mean Compressive Strengths					
%	MPa					
	MCSB			CSSB		
	WCS	DCS	Ratio	WCS	DCS	Ratio
3	3.12	3.94	1.3	1.43	2.70	1.9
5	5.76	7.09	1.2	2.48	4.61	1.9
7	10.11	12.02	1.2	4.57	7.33	1.6
9	14.19	16.18	1.1	6.54	9.66	1.5
11	18.30	20.50	1.1	8.99	12.30	1.3

Table 6. Values of the 28-day mean WCS and DCS of TDB and IPD blocks: Ratio (DCS/WCS).

The values of the mean WCS in traditional blocks ranged between 1.43 MPa and 8.99 MPa. The equivalent values of their dry compressive strengths ranged between 2.70 MPa and 12.3 MPa. The difference between mean DCS and WCS ranged between about 40% (for 11% cc) and 90% (for 3% cc). This shows that the higher the cement content, the lower the fractional difference between mean wet and dry strength in a block.

A similar trend emerged with results obtained for improved blocks. The mean WCS in these blocks ranged between 3.12 MPa and 18.3 MPa, while the matching dry strength ranged between 3.94 MPa and 20.5 MPa. Apart from the inclusion of microsilica (10% of the cement content), all other production variables remained the same. As before, the magnitude of the gap ranged between 12% and 26% only (for 11% and 3% cc blocks respectively).

The results for improved blocks compare well with values reported in concrete research where the difference between mean wet and dry compressive strength ranges between 9% and 21% (Neville, 1995). The results for traditional blocks similarly compare well with results obtained by earlier researchers. It was found that the difference between the two strength values in stabilised blocks varied between 35% and 120% (Fitzmaurice, 1958). It has also recently been recommended that the ratio of the mean dry and wet compressive strength in CSBs should not be greater than 2 (Houben et al, 1996). The experimental results obtained here for both traditional and improved blocks fall well within this limit. However, the ratio in improved blocks (1.1 to 1.3) is much lower than in corresponding traditional blocks (1.3-1.9). The variation in ratios for IPD blocks is also less wide-ranging than the case with TDB blocks. The considerable reduction in the gap between the mean dry and wet compressive strengths achieved in improved block represents a major breakthrough in

CSB development. It is well established that the higher the gap between the two, the lower can the strength of bonding between the particles and phases in a block be expected to be (Houben et al, 1996).

The marked increase in strength witnessed in improved blocks as opposed to traditional blocks can be linked to an increase in the degree of bonding within the block. In this case, the improvement can solely be attributed to the inclusion of microsilica in the mix (Chapter 3). The use of this CRM in moderate amounts (5 to 10% of the OPC content) for particular applications is recommended in preference over OPC-only mixes. The general pattern of improvement in strength and other properties of the block are undeniable. The upturn in strength is a consequence of its pozzolanic reaction with the freed lime from the hydration reaction of OPC with water, and also due to its ability to effectively 'fit in' between the OPC grains (Weidemann et al, 1990; Illston, 1994; Young, 1998; Taylor, 1998).

According to cement literature, in traditional blocks, the cement hydrates produced from the hydration reaction grow away from the OPC grains (Weidemann et al, 1990; Taylor, 1998). Even when hydration is deemed complete, the extended hydrate structure is likely to remain sparse, weak and permeable, given the low amounts of OPC used. When microsilica is added, the situation is markedly different. Being an almost pure silicon dioxide, when well dispersed in the cement/block, it can surround every OPC grain with about 100,000 microspheres (surface area 15,000 m^2/kg compared to 350 m^2/kg in OPC) (Illston, 1994). Finer and stronger hydrates can then grow from both the OPC and the 'nucleation centres' of the well dispersed CRM. As can be expected, this action can transform the relatively weak and porous structure into a far denser, more homogenous and impermeable matrix than hitherto possible. As the results in this thesis have shown, dramatic improvement in block properties are evident. Higher strength, density and hardness, as well as effective abrasion resistance and possibly longer service life, are some of the beneficial outcomes. The fact that the block attains superstrength in a matter of weeks shows that improved blocks are likely to outlast traditional blocks in whatever condition they are used in. The wear resistance of both categories of blocks are investigated experimentally in Chapter 7.

In summary, the inclusion of a CRM such as microsilica can be expected to have the following beneficial effects on CSBs:

- Rapid strength development
- Rapid surface drying (to below 75% relative humidity in one to five days)
- No bleeding or segregation at the surface
- Very low surface permeability
- Higher wear and abrasion resistance
- Extreme durability
- Reduced life cycle maintenance costs
- High strengths (compressive, tensile, flexural)
- Very low bulk permeability and sorptivity
- Lower shrinkage and creep
- Extended use of CSBs for flooring, foundations, pathways, underwater applications, etc.

It has also been reported in the literature that concrete materials achieve about 80 to 90% of their ultimate strength within 28 days of production (Neville, 1995). The comparable value attained by CSBs within the same period is lower, about 60-70% (Houben & Guillaud, 1994). The use of a rapid strength developing material such as microsilica is therefore a major advantage where early high strength is required. The problem of increased costs due to its inclusion can be overcome in either of a number of ways. These include the use of hollow blocks, thin surface layered blocks, frog-bedded blocks and interlocking blocks. All these simple measures can effectively reduce the amount of microsilica actually used and thus enable cost reduction to be achieved at no extra expense. The use of microsilica in improving block strength, dimensional stability and durability is therefore highly recommended.

6.2.3 THE EFFECT OF MIX HOLD-BACK TIME ON THE WET COMPRESSIVE STRENGTH OF BLOCKS

The ultimate cured wet strength of a block can be affected by the manner in which it is produced. At stated earlier in the thesis, despite its importance this is an area which has previously received very little attention in CSB literature. The effect of mix hold-back time was investigated experimentally to establish the extent to which WCS can be affected when this variable is introduced. The investigation was limited to traditional blocks stabilised with 5% OPC and compressed at 6 MPa. A similar effect is likely to apply in the case of improved blocks. The phenomenon was also investigated experimentally because it was found during the fieldwork (Chapter 4) that batches too large to be moulded within the hour were being widely used. Very little concern was being shown in the field regarding the potential adverse effects of this variable on the quality of blocks produced.

The mean values of the experimental results obtained are shown in table 7 and figure 8. Each point represents the average of three block specimen samples.

Time	WCS 28-day	Ratio
minutes	MPa	
5	2.53	1.0
30	2.08	1.2
60	1.73	1.5
90	1.58	1.6
120	1.49	1.7

Table 7. Wet compressive strength values (28-day) of CSSBs compacted at various hold-back times.

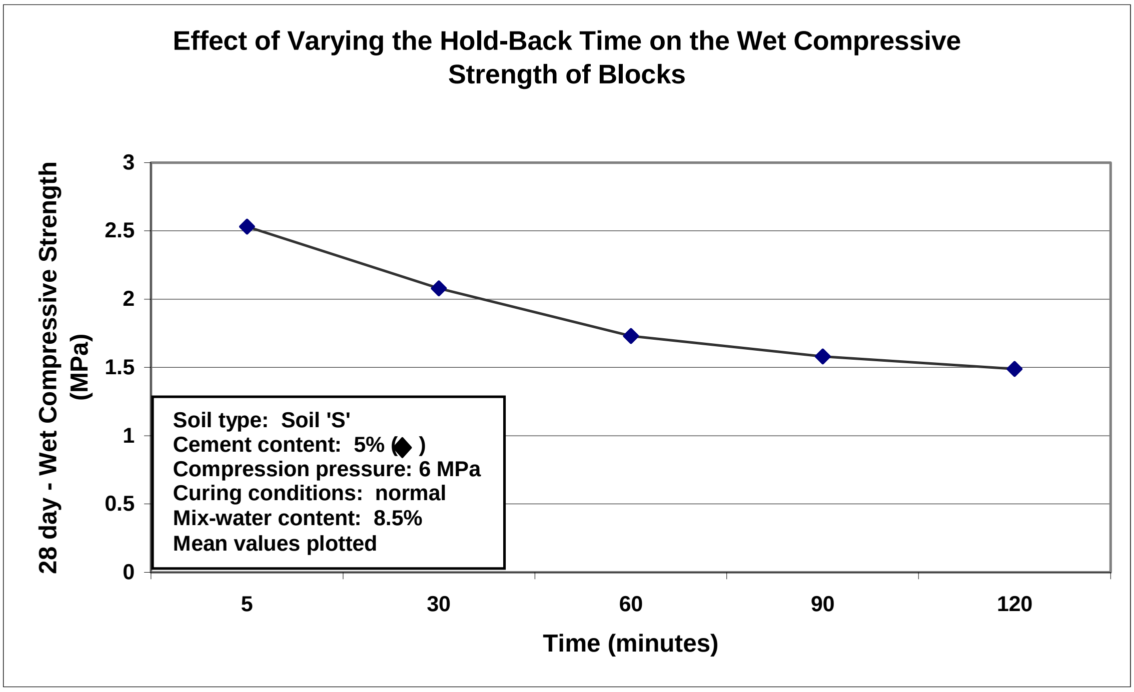


Figure 8. Effect of mix-hold back time on the 28-day WCS of CSSBs (University of Warwick, 2001)

Figure 8 and table 7 show that the average 28-day wet compressive strength fell from 2.53 MPa to 1.49 MPa as the hold-back time was increased from 5 to 120 minutes (a 41% loss).

It was found that blocks compacted within 20 minutes after damp mixing were about 27% stronger than those compacted after 45 minutes of delay. These findings confirm earlier results by other researchers. For example, it was found by Rigassi (1995) that loss of strength after two hours delay was about 50%. It was also found that blocks moulded within 20 minutes of damp mixing were between about 30 and 40% stronger than those compacted after 45 minutes (Houben & Guillaud, 1994). The time of 45 minutes is used as a yardstick because it approximates the early setting time of OPC (Weidemann et al, 1990). The findings here confirm that a general downward trend of loss of strength due to long hold-back times should be expected when OPC is used as the stabiliser. The opposite is true for lime (Bessey, 1975; Coad, 1979). OPC stabilised blocks should therefore be compacted within 20 minutes of mixing, but certainly not after 45 minutes. It is still common field practice to mix batches for hourly production which end up not being used up within the hour (Chapter 4). This discussion confirms earlier statements made in this thesis that the processing method employed during production can significantly affect the ultimate quality of a block (Chapter 3). It is therefore recommended that all CSB production stages should be treated with the same level of skill, competence and supervision.

6.2.4 The Effect of Varying Curing Conditions on the Wet Compressive Strength of Blocks

The effect of varying curing conditions on block strength was investigated experimentally for a limited range of blocks (Chapter 3). CSB specimens stabilised with 5% OPC and compacted at 6 MPa were used. As the test was meant to be indicative only, the OPC content was not varied as before. The investigation was also restricted to traditional blocks only on the assumption that similar effects would be applicable in improved blocks of matching cement content. The curing conditions were varied to approximate common practice in the field on the one hand, and to test theoretical predictions that full moist curing would be beneficial on the other. Curing time of 28 days was maintained for all blocks. The conditions were varied as follows:

Condition A: Open exposure (within a well lit area in the laboratory)

Condition B: Normal curing (7 days wet curing, 21 days dry curing)

Condition C: Complete cover (with polythene sheeting material)

Condition D: Wet curing throughout (by immersion in water 24 hours after moulding until testing time)

After 28 days, three specimen samples from each curing condition category were tested as before. The results are shown in table 8 and are also plotted in the form of a histogram (figure 9).

Condition	28-day WCS	Ratio
	MPa	-
A	1.13	1.0
B	2.54	2.3
C	3.28	2.9
D	6.85	6.1

Table 8. 28-day WCS values of CSSBs cured under varied conditions

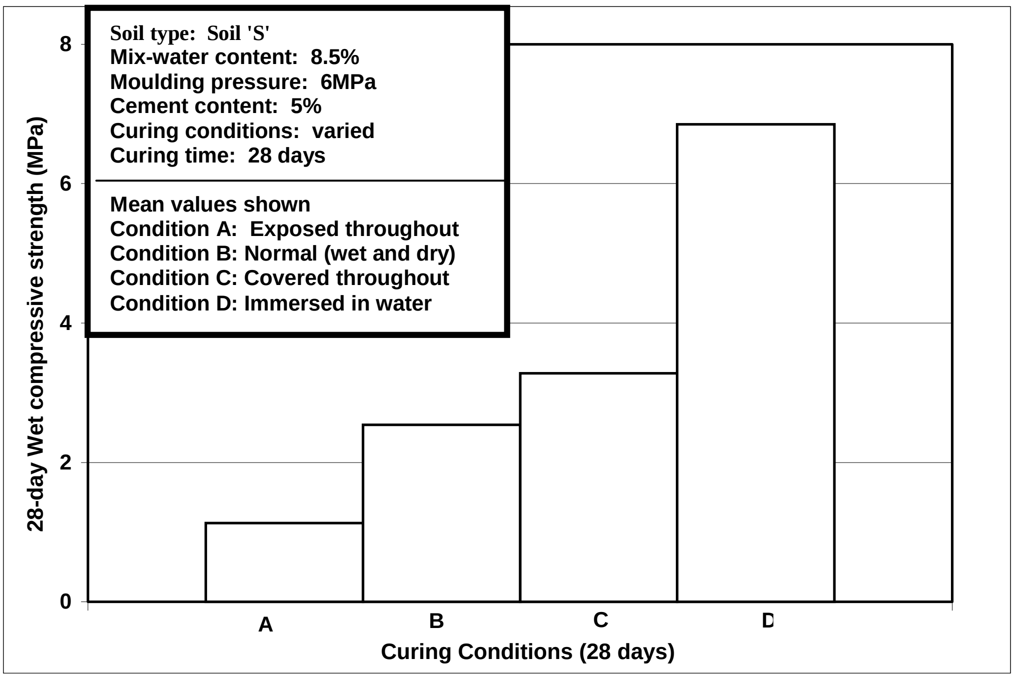


Figure 9: Histogram showing the effects of varying curing conditions on the wet compressive strength of CSBs (University of Warwick, 2001)

When condition A blocks are compared with the other blocks, the differences in strength found are considerable. Normal cured blocks were about twice stronger than exposed blocks. If these blocks had been left exposed in the sun, it is likely that the difference in strength could have been even higher. The case actually approximates actual practice on most CSB production sites (Chapter 4). The belief in such places is that the faster the loss of moisture, the stronger the block becomes and thus the faster it can be used. It is a mistaken concept since prolonged retention of moisture can be beneficial in ensuring that the hydration process continues till maximum hydration is achieved (Chapter 3). This finding partly explains the poor performance of CSBs as observed during the fieldwork.

The results also show that block samples covered throughout are about three fold stronger than those cured under exposed conditions. Blocks cured fully immersed in water for 28 days were about six fold stronger than similar ones cured exposed. The immersion in water was done 24 hours after demoulding since initial attempts to immerse them immediately proved futile. The blocks were then left in water till testing time. The difference in wet strength between the fully immersed cured blocks and the exposed blocks is about 506%. This should be a cause for concern since the latter simulates field practice in most developing countries (ILO, 1987). The recommendation here is that CSB standards covering specifications and workmanship during production should lay more emphasis on the need for proper curing. The procedures to be followed should be clear, simple and easy to understand and execute (Lowe, 1998; Schildermann, 1998). A checklist system spelling out all the necessary steps during production ought to be beneficial in this regard. The main emphasis should be on keeping green block surfaces moist for as long as possible. Exposure of green blocks to rainy conditions, direct sunlight and wind conditions should be avoided especially during the first few days of production (Chapters 3 and 4).

6.3 BLOCK DRY DENSITY (BDD)

The density of a block is a valuable indicator of its quality. It can be expressed in a number of different ways, depending on the pre-existing moisture state of the block, thus:

- Block dry density (BDD) (usually indicating the oven-dried value when desiccated to 105 ± 5°C for 26 hours)
- Block bulk density (BBD) (based on the pre-existing state of moisture, e.g. soon after demoulding)
- Saturated block density (SBD) (when soaked in water for between 24 and 48 hours after oven drying as before)

It is the dry density that is commonly used in building specifications (BS 6073: Part 2, 1981) and is the one discussed in this thesis. In addition to the solid phases that exist in a block, the material also contains pore spaces filled partly with air and partly with water (Jackson & Dhir, 1996). The amount of either phase depends on the moisture state of the block (varies from block to block). When both air and water are driven out (by oven drying to constant mass), the block dry density value is obtained. Apart from the state of moisture in a block, its density also depends on the following:

- the degree of compaction used (normally between 4 and 8 MPa)
- the density of the constituent materials (especially the coarse sand fraction) Sand has a dry density value of about 2,200 kg/m^3 while that for clay is about 2000 kg/m^3 (Houben & Guillaud, 1994)
- the size and grading of the soil particles
- the form of the block (solid, hollow, frogged)

Since the structural strength of a block is the result of the friction between the constituent cement hydrates and soil grains, the closer the packing of these solids, the stronger the block can be expected to be. Densification following the stabilisation of soil with OPC can ensure that the close packing achieved is maintained through the mechanical interlock of the grains. It is this interlock which limits excessive movements more than would have been possible if the stabiliser had not been used. Without the binder, either through omission or due to progressive decay, a block is likely to become weak. In such cases, the effects of densification can be progressively reversed (Lola, 1981; Minke, 1983).

The density of a block can have implications on most of its other bulk properties (Markus, 1979). These include compressive strength, permeability, water absorption, porosity, thermal capacity, sound insulation, hardness and durability (Lunt, 1980;

BRE, 1980; Spence & Cook, 1983). The higher the density of a block, the better can its performance be expected to be. For example, density has commonly been closely associated with the strength of a block (UN, 1964; Spence, 1975). The relationship between strength and density is investigated experimentally in this thesis to determine whether density can be a surrogate for the strength of a block. The correlation between density and water absorption and porosity are also investigated experimentally. Similarly, the correlation between density and durability is discussed in Chapter 7.

Determination of the density value of a block is provided for in most standards. The test method used in this thesis is based on the one described in BS 6073: Part 2, 1981. For all block specimens, three samples were tested in each category and the mean value used for subsequent analysis (Chapter 5). The density obtained in each case was expressed to the nearest 10 kg/m^3 (BS 6073: Part 2, 1981; BS 3921, 1985). The full summary list of the results are shown in Appendix Q(1) to Q(4). The findings are discussed in Sections 6.3.1 and 6.3.2. References to the same values obtained are also made in subsequent sections of this chapter as well as in Chapter 7.

6.3.1 EFFECT OF VARYING THE STABILISER CONTENT AND COMPACTION PRESSURE ON DENSITY

The effect of changing the above variables on density were investigated experimentally. The number and type of samples tested were as before. The compaction pressure was varied from 6 MPa to 10 MPa for a limited number of traditional blocks. The plotted results are shown in figure 10.

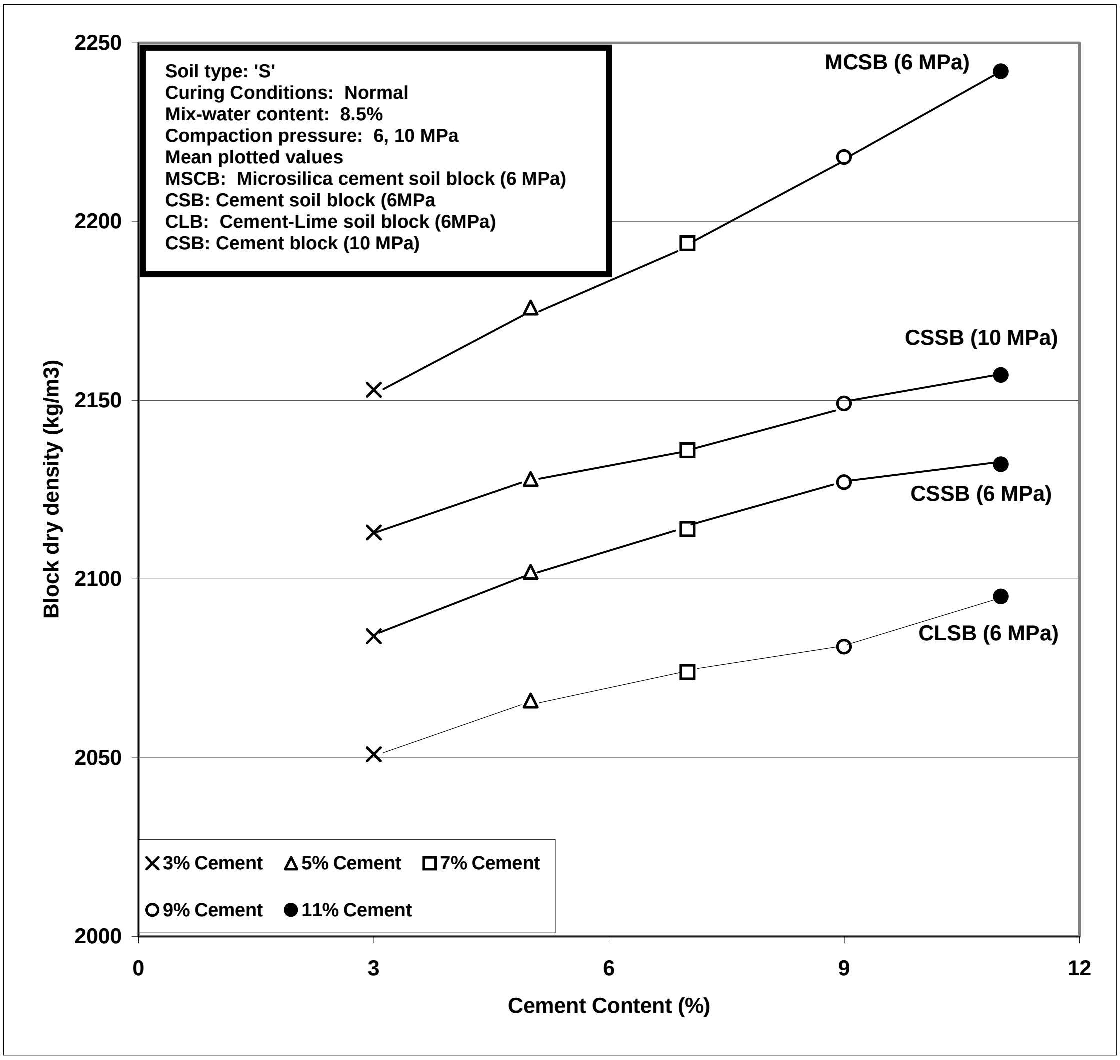


Figure 10: Effect of varying the stabiliser content and compression pressure on BDD

The range of BDD values obtained for both improved and traditional blocks are presented in table 9.

Block type / stabiliser	Compaction Pressure used	Range of BDD values	Density increase with increase in OPC from 3% to 11%
	MPa	Kg/m^3	%
Improved OPC + Microsilica	6	2153 - 2242	4.1
Traditional OPC + Lime	6	2051 – 2095	2.1
Traditional OPC only	6	2084 – 2132	2.3
Traditional OPC only	10	2113 – 2157	2.0

Table 9: Range of BDD values obtained for improved and traditional blocks

The two density values shown in table 9 correspond to blocks stabilised with 3% and 11% OPC respectively. Although the overall increase in density in improved blocks was marginally higher than in traditional blocks, the difference does not appear to be dramatic. However, for matching amounts of OPC content, improved block density was about 4% higher than in traditional blocks. The increase was directly proportional to the increase in cement contact. While the part substitution of OPC by lime resulted in less dense blocks, the partial substitution of OPC by microsilica produced the opposite effect.

Increase in density was also found to occur when compaction pressure was increased. For the OPC only stabilised blocks, increase in moulding pressure from 6 MPa to 10 MPa resulted in a corresponding increase in density of about 1.3% only. So for an increase in compaction of about 70%, increase in density of less than about 2% was achieved. This is considerably lower than the equivalent increase in density due to the inclusion of microsilica (between 3.3% and 5.2%). The addition of a partial cement replacement material appears to be an economic way of achieving higher densities in blocks. The marked increase in density witnessed in improved blocks could have been due to four factors associated with the inclusion of microsilica:

- Pore filling effects
- Increased homogeneity
- Improved bonding
- Reduced voids

The results further confirm the beneficial effects of using a partial cement replacement material such as microsilica (Chapter 3).

6.3.2 Correlation Between Density and Wet Compressive Strength

In this section, the correlation between density and strength is discussed. It was stated earlier that for better performance, a denser block would be required. Density was also mentioned as a valuable indicator of strength and durability in a block. The experimental results obtained for BDD are plotted against those for 28-day WCS (shown in figure 11).

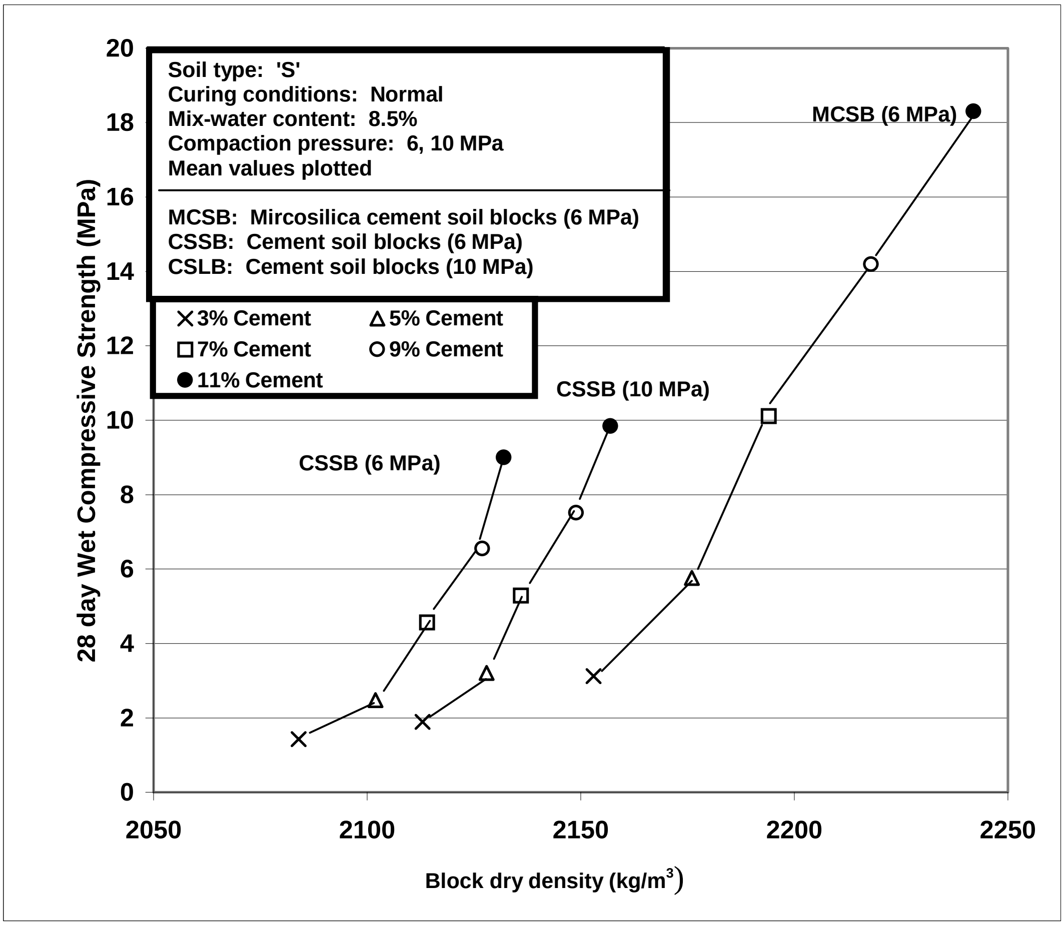


Figure 11: Correlation between BDD and 28-day WCS in CSBs (University of Warwick, 2001)

Figure 11 shows that a general positive correlation exists between BDD and WCS for all the different types of blocks tested. The graph shows that an increase in density is accompanied by a corresponding increase in strength. The coefficient of correlation and P-values are as follows: traditional block (0.971; 0.006), improved block (0.996; 0.000). A strong correlation therefore exists between BDD and WCS.

The correlation between density and strength has also been widely reported in comparable materials (Jackson & Dhir, 1996; Ruskulis, 1997). The dry density values for some like materials are:

- Fired clay bricks: 2250-2800 kg/m^3 (usually 2600 kg/m^3)
- Calcium silicate bricks: 1700-2100 kg/m^3
- Concrete blocks: 500-2100 kg/m^3

These values compare favourably with those obtained experimentally for CSBs. It is widely known that fired clay bricks are the most popular building material in most parts of the world (Parry, 1979; Agarwal, 1981; Spence & Cook, 1983). These blocks are denser, stronger and more durable than comparable materials. The average density of 2,600 kg/m^3 is probably a major contributor to the strength of fired bricks. The comparable density values also show that improved blocks were denser than concrete blocks by about 5%. The only drawbacks likely to result from higher densities are ease of handling and transportation. Blocks which are very heavy can be difficult to lay, and are normally expensive to transport (NASA, 1971; ILO, 1987).

6.4 TOTAL WATER ABSORPTION IN CSBs

Almost all bricks and blocks can absorb water by capillarity (Keddi & Cleghorn, 1980). The existence of pores of varying magnitudes in these materials confers marked capillarity in them. The total amount of water absorbed is a useful measure of bulk quality. The reason for this is that the total volume of voids (or pore space) in a block can be estimated by the amount of water it can absorb. This property is clearly distinct from the ease with which water can penetrate a block and permeate through it (Neville, 1995).

Knowledge of the value of the total water absorption (TWA) of a block is important because it can be used for:

- routine quality checks on blocks (surrogate test for quality)
- comparison purposes with set standards and values for other like materials
- the classification of blocks according to required durability and structural use
- approximation of the voids content of a block (Section 6.5)

Generally, the less water a block absorbs and retains, the better is its performance likely to be (ILO, 1987). Reducing the TWA capacity of a block has often been considered as one of the ways of improving its quality. The deleterious effects of moisture on block properties were discussed in Chapter 2. A block that readily absorbs water is likely to be vulnerable to repeated swelling and shrinkage as moisture and temperature variations take place. Repeated swelling and shrinkage is likely to progressively lead to the weakening of a block fabric (either directly or indirectly). A block that contains absorbed water is often weaker with a less hard surface than when it is dry. The presence of absorbed water can also lead to the creation of conditions suitable for the resumption and acceleration of otherwise dormant chemical activity (BSI, 1950; BS 7543, 1992). The lower the water absorption capacity of a block therefore, the more likely it is to be more durable.

Test methods used

The TWA capacity of a block can usually be measured by determining the amount of water it can take in (ILO, 1987). Since the amount absorbed is influenced by the pre-existing moisture condition of a block, it is advisable that it be first dried to constant mass before further testing (BS 3921, 1985). For this particular research, attainment of constant mass was determined using an electronic weighing scale accurate to 0.01% of the sample mass. Simple immersion of the specimen without prior evacuation can lead to incomplete absorption and saturation. Moreover, the suction exerted by a dry block is usually much higher (PCA, 1970).

Various procedures can be used to determine the TWA capacity of a block (BS 3921: 1985):

- Cold immersion in water (24 to 48 hours) after oven drying to constant mass
- Boiling test method (5 hours)
- Absorption under vacuum test

With the above methods, widely differing results can still be obtained (Bungey & Millard, 1996). It is reported that none of the three methods above can show any precise convergence (BS 3921, 1985). The results obtained from each of the three methods can be different, and neither proportional nor equivalent to one another (Neville, 1995). For this thesis, oven-drying followed by cold-immersion in water was found to be the most convenient (and easy one) to conduct. The method was also found to be fairly accurate and repeatable. It was therefore the only method used throughout for determination of the TWA capacity of both traditional and improved blocks. For comparison purposes, tests were also conducted on samples of other like materials found in the laboratory (fired clay bricks and concrete blocks). Brief details of the test method are described in Appendix R. For each test however, three specimen samples of each material under test were examined (Chapter 5). The TWA was calculated by taking the amount of water absorbed by a dried sample that had been immersed in water for a specified period of time (24 to 48 hours). Mean values obtained were taken as the total water absorption (TWA) of the sample. The result was expressed as a percentage of the original dry mass of the specimen to the nearest 0.1% of the dry mass. Details of all individual measurements recorded are presented in Appendix T(1) to T(5).

6.4.1 EFFECT OF VARYING THE STABILISER CONTENT AND COMPACTION PRESSURE ON THE TWA IN BLOCKS

Both traditional and improved blocks were examined. The mean values obtained are shown in figure 12 and in table 10. The latter shows the range of the extreme values found.

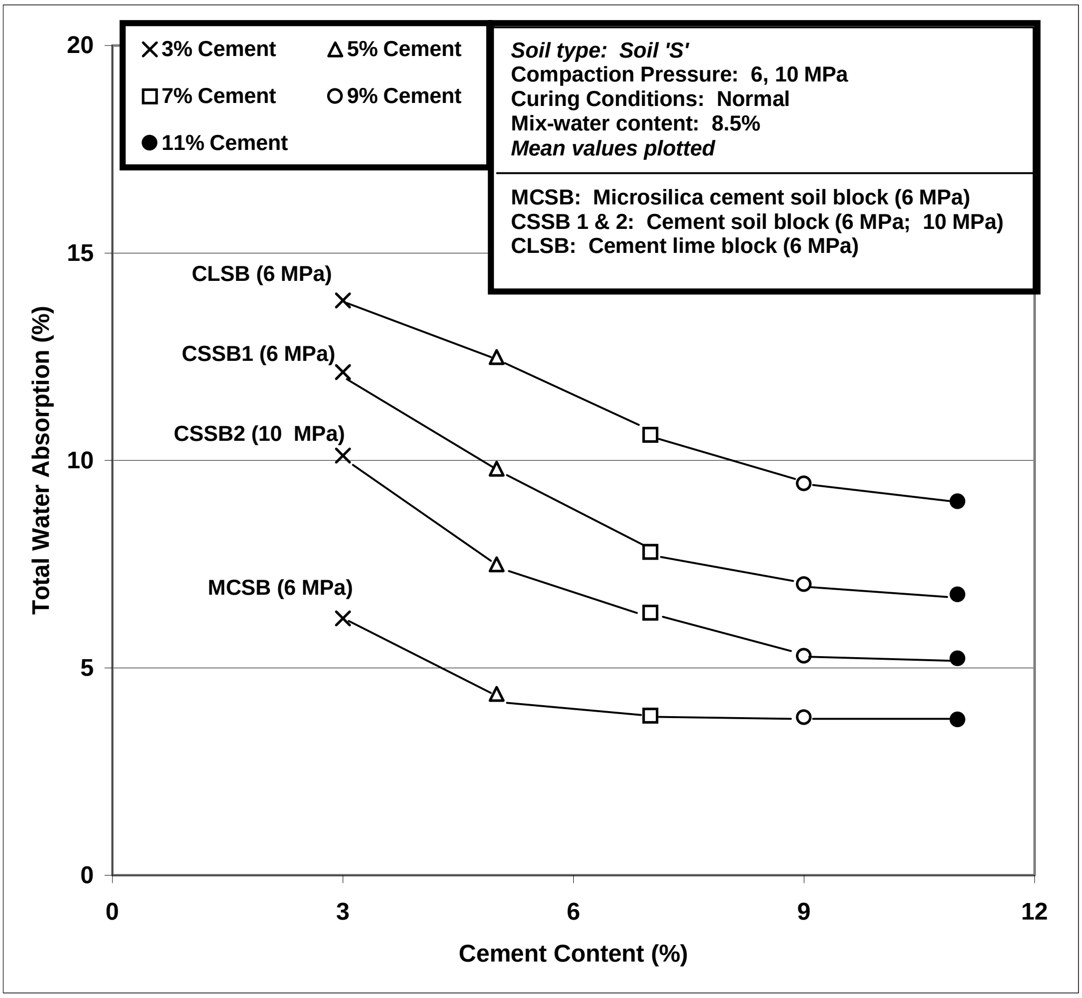


Figure 12: Effect of varying the stabiliser content and type, and compaction pressure on the TWA in CSBs. (University of Warwick, 2001)

Block Type	Compaction	Range of TWA Values		Comparison of values with those for improved blocks		Overall decrease in TWA
		OPC 3%	OPC 11%	OPC 3%	OPC 11%	
	MPa	%	%	%	%	%
Improved (OPC + microsilica)	6	6.19	3.75	-	-	40
Traditional (OPC + lime)	6	13.86	9.01	124	140	35
Traditional (OPC only)	6	12.13	6.76	96	80	44
Traditional (OPC only)	10	10.11	5.22	63	39	48

Table 10: Range of TWA values obtained

Figure 12 shows that a negative correlation exists between increase in cement content and total water absorption: coefficient of correlation values were -0.947 (P = 0.014) for traditional blocks, and -0.832 (P = 0.080) for improved blocks. From both figure 12 and table 10, improved blocks had the narrowest band of TWA results. They also absorbed considerably less water than traditional blocks. Generally, traditional blocks compacted at the same level absorbed about twice the amount of water absorbed by improved blocks.

There was a general decrease in water absorption with increase in cement content (and compaction pressure). The decrease was generally about 42% with variation in cement content from 3% to 11% (table 10). The trend was the same for all categories of blocks. Blocks of lower stabiliser contents were however found to absorb more water than those with higher ones. The reduction in absorption with increase in stabiliser content is progressive but diminishes. The absorption effectively ceases to reduce any further beyond certain cement content values in both traditional and improved blocks. These limits are 9% and 7% respectively. Beyond these limits, increase in OPC content does not result in any appreciable reduction in TWA. It is also worth noting that the limit of 9% appears to apply to all types of traditional blocks regardless of the moulding pressure used. The lowering of the limit to 7% from 9% in improved blocks can only be attributed to the inclusion of microsilica. Even beyond these points however, the block can still continue to absorb water.

The results also show that the TWA values obtained compare well with those of other like materials and with current recommended maximum values for CSBs. The recommended maximum is 15% (ILO, 1987). Although this value is neither absolute nor widely adopted by other researchers, it still serves a useful purpose. The experimental TWA values for improved blocks were on average considerably lower than this recommended value. The values obtained were favourable when compared with those of like materials (clay bricks 0 to 30%; concrete blocks 4 to 25%; calcium silicate bricks 6 to 16% (Jackson & Dhir, 1996)). According to BS 5628 Part 1, TWA values below 7% are regarded as being low, while those above 12% as high. All improved blocks tested would therefore be regarded as having low TWA values. The values for traditional blocks fall in between the two limits and would therefore be regarded as moderate.

The above results confirm that CSBs have the potential to absorb appreciable amounts of water and possibly retain it too. They also show that the use of CRMs can be a effective way of reducing water absorption. Moreover, they confirm earlier findings that improvement in the quality of a block is easily achieved by variation in stabiliser content and type. The correlation of TWA and other bulk properties are discussed in subsequent sections.

6.4.2 *Correlation Between Total Water Absorption and Density*

The correlation between water absorption and dry density was examined. Figure 13 shows the plotted values from the measured points for both properties.

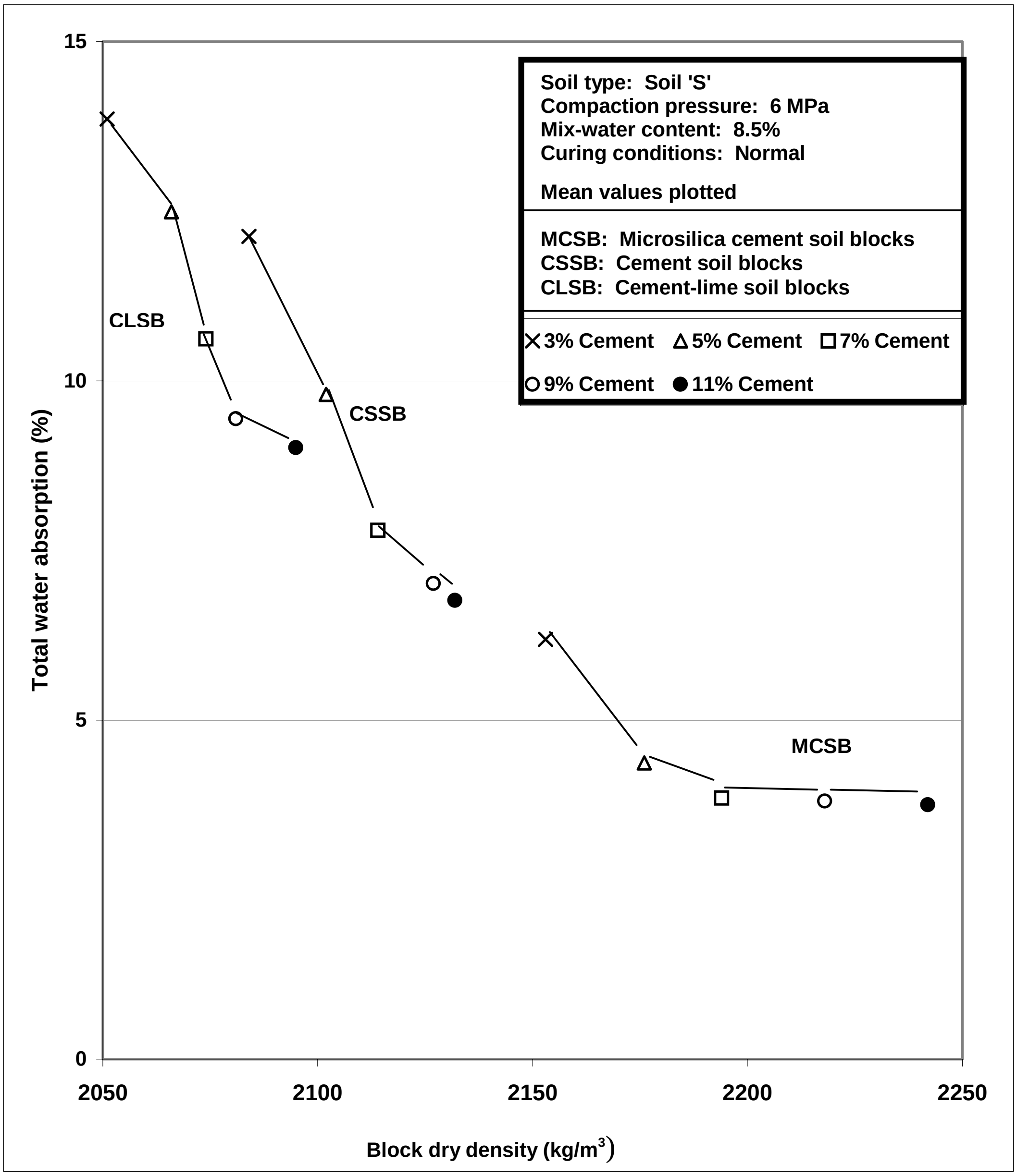


Figure 13: Correlation of TWA and BDD (University of Warwick, 2001)

As shown in figure 13, a negative correlation exists between TWA and BDD. The coefficient of correlation and P-values for both traditional and improved blocks were: -0.985 (P = 0.002) and –0.820 (P = 0.089) respectively. These values confirm that a strong negative correlation exists between the two bulk properties. Increase in the latter is likely to result in a decrease in the former. For example, in traditional OPC only stabilised blocks, increase in density from 2084 kg/m^3 to 2132 kg/m^3 (2.3% increase), resulted in an overall reduction in water absorption by 44%. Similar increase in density over the same range of cement contents in improved blocks resulted in a decrease in TWA of about 39%.

The results also show that for the samples tested, beyond a certain density value, no appreciable reduction in TWA can be found. The limiting density values correspond to matching cement contents beyond which a similar occurrence was noted in Section 6.4.1. The implication here is that no further increase in BDD would necessarily lead to continued reduction in TWA. The blocks can still be able to absorb water but at almost uniform amounts. Similar correlation was also found between WCS and TWA. Generally, the more a block was found to absorb water, the lower was its strength.

6.5 VOLUME FRACTION POROSITY

In this Section, the term porosity refers to the total amount of voids and pore structure within a block fabric (sand pores, gel pores, capillarity pores, entrapped air, entrained air, etc.) (Young, 1998). The concept of porosity has neither been well researched nor reported in CSB literature. Yet most bulk properties including strength and water absorption are believed to be a function of the total porosity of cement-based materials (Weidemann et al, 1990). The general link between porosity and quality has been widely reported in concrete literature (Neville, 1995). There is no good reason to expect that similar findings would not obtain in CSBs.

In addition to their volume, the shape and size of pores within a block can determine its bulk performance. The capillary porosity which is often the most predominant is believed to be a function of the water-cement ratio and the degree of hydration achieved (Sjostrom et al, 1996). The value of the latter can only increase as long as moisture is available to ensure the completion of hydration. Proper moist curing can therefore be a vital factor in influencing the volume fraction porosity of a block.

The total volume fraction porosity (TVP) in a CSB can be determined directly. This can be done by measuring the weight gain on saturation with water of an initially dry block after evacuation to remove air from the pore network (Jackson & Dhir, 1996). The water absorption is expressed as before in weight percent. The value of the water absorption may be converted to a volume basis porosity by using the following relationship:

$$n = \frac{(WA)\,\rho}{100\ \rho_w}$$

where n = volume fraction porosity
ρ = dry block density (kg/m^3)
ρ_w = density of water kg/m^3)
WA = water absorption (%)

A summary of the calculated total volume fraction porosity of CSB samples are shown in Appendix T. The relationship between these results and other bulk properties are discussed in the following sections.

6.5.1 *CORRELATION BETWEEN STRENGTH AND POROSITY*

The correlation between wet compressive strength and total volume porosity was examined. The mean values plotted are as shown in figure 14.

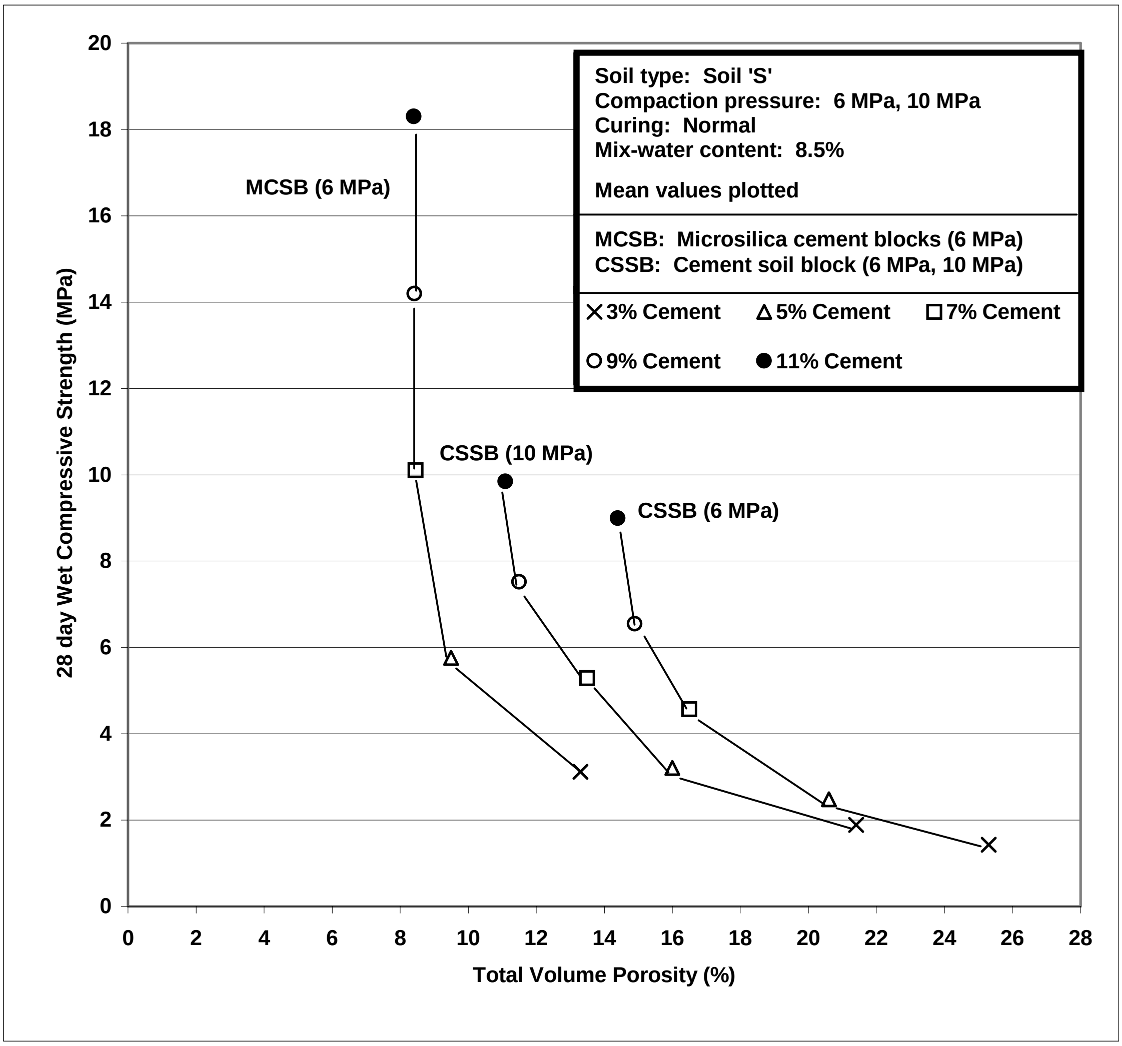


Figure 14: Correlation of WCS and TVP in CSBs (University of Warwick, 2001)

According figure 14, WCS and TVP are negatively correlated. Increase in porosity is accompanied by a decrease in strength. The coefficient of correlation and P values for traditional and improved blocks were: –0.905 (P = 0.035) and –0.771 (P = 0.127) respectively. A strong negative correlation therefore exists between the two bulk properties.

The total volume porosity values are lower in improved blocks than in their traditional counterparts (8.4% to 13.3% as compared to 14.4% to 25.3%). The pore filling effect of microsilica is likely to account for some of the difference between the two types of blocks. The lime plus OPC stabilised blocks exhibited the highest porosity (between 18.9% and 28.4%). The values for both categories of blocks however compare well with those of like materials. Materials with TVP above 30% are considered to be of high porosity (Jackson & Dhir, 1996). All the blocks examined during this research can therefore be considered to be of low porosity.

The decrease in compressive strength with increase in porosity can be partly explained as follows. The compressive strength of a block is limited by brittle fracture. It is therefore sensitive to individual flaws in the block sample under test. Discontinuities between solid phases in a block (due to the presence of voids and pore structure) constitute flaws in it. The higher the amount of voids, the weaker the block is likely to be. Large coarse soil fractions in a block can also create flaws in it. The combination of such large particles and voids in a block can make it more susceptible to brittle fracture failure.

6.5.2 CORRELATION BETWEEN DENSITY AND POROSITY

The above relationship was examined using the results obtained as before (shown plotted in figure 15).

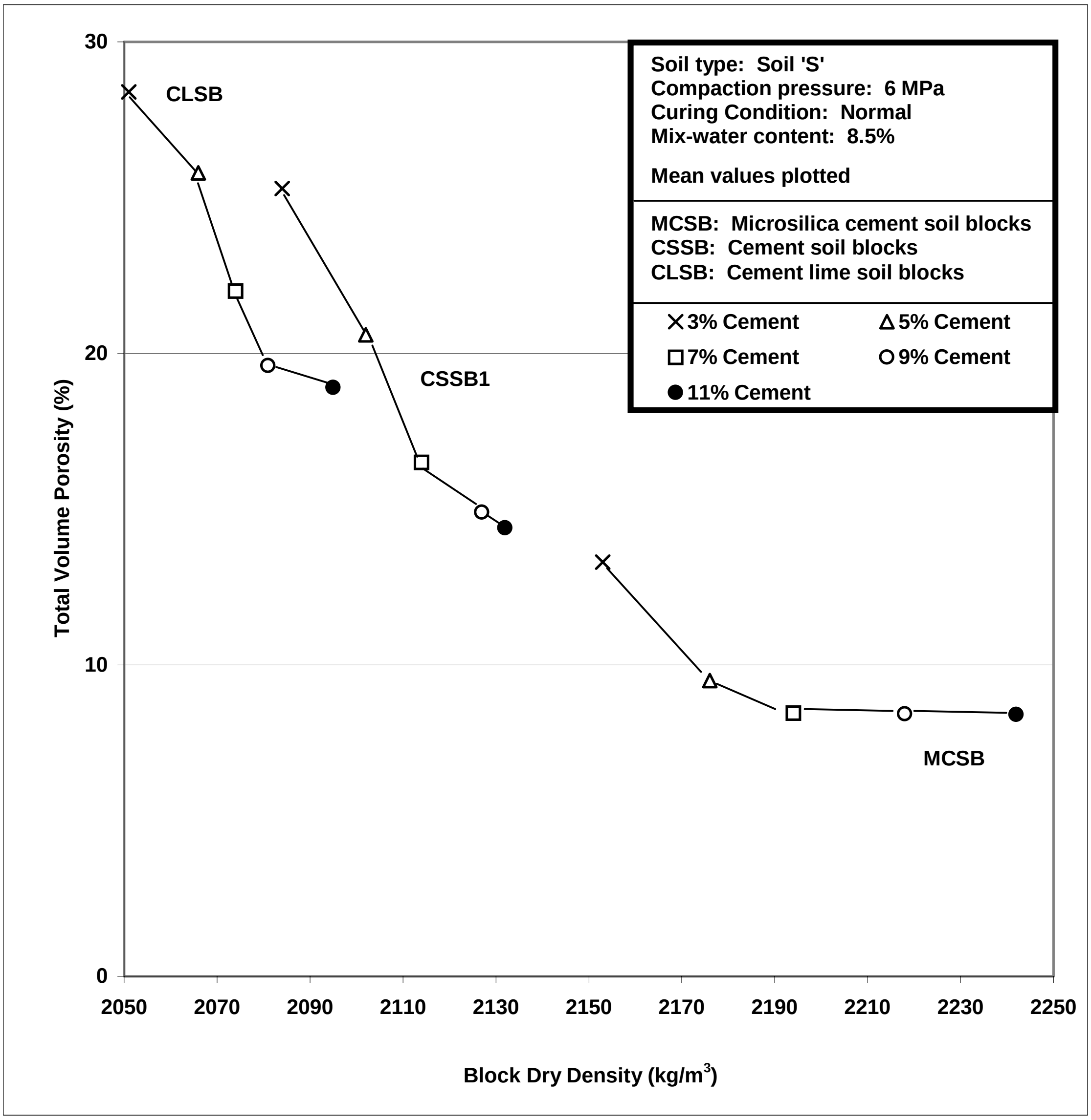


Figure 15: Correlation of BDD and TVP (University of Warwick, 2001)

Figure 15 shows the general correlation existing between the two bulk properties. The coefficient of correlation and P-values are as follows: –0.984 (P = 0.002) for traditional blocks, and –0.935 (P = 0.020) for improved blocks. These statistical values confirm that a very strong negative correlation exists between the two bulk properties. Increase in dry density is associated with a decrease in porosity for all blocks examined.

For example, in traditional cement only stabilised blocks, increase in density from 2084 kg/m^3 to 2132 kg/m^3 (3% and 11% cement contents respectively), resulted in an overall reduction in porosity of about 43%. Similar trends were shown in the improved blocks examined. Reduction in porosity by 37% was found to result from an overall increase in density of 4.1%. These blocks were generally denser than their traditional counterparts. Increased density is accompanied by closer packing of the solids in a block. The closer the packing, the less the amount of voids in a block. It was however also found that further increase in density beyond a certain value did not result in any appreciable reduction in porosity.

6.6 CONCLUSION

From the results discussed in Chapter 6, a number of conclusions can be reached.

The *wet compressive strength* of a block is one of its most valuable properties. It is influenced by the following factors: cementitious matrix (water cement ratio and degree of hydration), degree of compaction, state of moisture, temperature, age and type of coarse soil fraction present. The strength of the cement hydrates, and the bond between them and the coarse soil fraction accounts for most of the strength in CSBs.

It was found in Chapter 6 that the WCS of both traditional and improved blocks increased with increase in cement content and compaction pressure. The inclusion of microsilica in improved blocks was found to significantly improve their strength. The use of microsilica was also found to reduce the gap between the mean WCS and the DCS in blocks. The reduced gap of between 12% and 26% in IPD blocks is comparable to those obtaining in concrete products (9% to 25%). Hitherto, the same gap in CSBs was between 40% and 120%. The considerable reduction in the gap can be associated with an increase in bonding strength between the phases and particles in the block. Use of microsilica is therefore beneficial for improvement in CSB strength and by implication its durability.

It was also found that delays in compaction after wet mixing of soil and cement resulted in an appreciable reduction in the strength of a block. Delays of up to two hours resulted in loss of strength of about 41% in traditional blocks. Blocks compacted within 20 minutes of wet mixing were about 27% stronger than blocks compacted after 45 minutes of delay. Similar trends are expected to occur in improved blocks. These findings confirm earlier work by other researchers. It is therefore recommended that smaller batches of wet mixes that can be compacted within 30 minutes (instead of one hour) be planned for. Compaction of wet mixes more than 60 minutes old are not recommended.

It was also found in Chapter 6 that the WCS of a block can be affected by the method of curing used. Blocks cured under normal conditions were about twice stronger than those cured under open exposure in the laboratory. Those cured under continued moist cover were about three times stronger than exposed blocks. Moreover, blocks cured by full immersion in water (100% relative humidity) were about six fold stronger than those cured exposed. Improved curing conditions were found to be linked to higher strengths in CSBs. This can be partly due to the higher degree of hydration achieved by the OPC in the block (continued presence of moisture). Proper curing conditions are therefore critical if CSBs are to achieve high strength. It is recommended that proper curing guidelines be included in CSB production codes.

The *density* of a block is another valuable indicator of its bulk quality. Its value depends on the degree of compaction used, the form of the block, and the size, grading and density of its individual constituent materials. The higher the density of a block, the better is its overall performance expected to be. It was generally found that traditional blocks were less dense that their improved counterparts. Increase in cement content resulted into increase in density for both categories of blocks by about 3%. Increase in density due to increase in compaction pressure of about 70% only resulted in an increase in density of about 1.2%. The use of CRMs, and increase in cement content appear to be more economic ways of achieving higher densities in CSBs. The experimental density values obtained were also found to be above the recommended minimum of 2000 kg/m^3 (by about 9%). The pore filling effect, increased homogeneity, improved bonding and reduced voids due to the use of CRM was thought to be responsible for the marked increase in density of improved blocks.

The BDD was also found to be strongly correlated to other properties such as WCS, TWA and TVP. Generally, more denser blocks were found to perform better in all the complimentary tests done. Blocks which are too dense might however prove difficult to lay, and costly to transport. It is recommended that the maximum weight of a block should not exceed about 8,500 kg.

The *total water absorption* in CSBs is also an important bulk property that can be used for routine quality checks as well as for their classification. It was found that the TWA of traditional blocks ranged between 6.76% and 12.13%. Comparable figures for improved blocks were considerably lower than these values. The use of CRMs therefore results into a marked reduction in TWA. It was also found that the TWA decreases with increase in cement content and compaction pressure. However, the decrease is gradual and more pronounced at the lower cement contents than at the higher ones. Beyond a certain cement content however (7% in improved blocks and 9% in traditional blocks), increase in cement content did not result into any further appreciable decrease in TWA. All blocks made for experimental tests in the course of this thesis were found to have TWA values below the recommended maximum value of 15%. It was also found that TWA was strongly correlated with BDD, WCS and TVP.

The *total volume porosity* of a block also represents an important bulk property. It was found that porosity of block samples decreases with increase in cement content. Porosity values for traditional blocks ranged between 14.4% and 28.8%, while those for improved blocks between 8.4% and 13.3%. It was found that traditional blocks were generally more porous than their improved counterparts. Porosity was also found to be negatively correlated to strength and density, but positively correlated to water absorption. High porosity in a block is thought to reduce strength due to the presence of flaws and discontinuities in its fabric. All blocks made were found to be of low porosity, i.e. less than 30%.

From the preceding conclusions, the objectives of Chapter 6 were fully met.

CHAPTER 7

SURFACE FEATURES AND PERFORMANCE

7.1 INTRODUCTION

The surface of any building material is one of its most important features. For materials such as CSBs, the quality of their surfaces can affect their durability (Hughes, 1983). The block surface forms its first line of defence against deterioration agents likely to come into contact with the material during its service lifetime. As mentioned earlier in the thesis, the bulk of a block is its least compacted zone and is therefore in need of protection provided by a denser surface.

The deterioration mechanisms that can erode the surface of a block and expose its bulk are likely to lead to accelerated damage (Chapter 3 and 4). A good surface is therefore required if a block is to remain durable for the duration of its service lifetime. How a block surface can influence its performance depends on its surface properties. Properties thought to be affected by the quality of the outer part of a block include: surface wetting, adsorption, adhesion, abrasion, hardness and capillary effects (Young et al, 1998).

The objectives of this Chapter are to:

- identify microstructural features of block surfaces
- monitor the overall performance of the surface in conditions which simulate the main cause of surface deterioration. It was mentioned in Chapter 2 and

found in Chapter 4, that surface erosion was the most serious form of surface deterioration. The softening and abrasive action of water and the heating effects of high temperatures, are thought to combine to contribute to much of the mass loss from the surface of a block. The test method used in this Chapter is the Slake Durability Test. Its pioneering use for CSBs was found to be appropriate for laboratory testing owing to the rapid acceleration of surface erosion (ISRM, 1971).

The rest of this Chapter is presented in three sections, namely: thin-section microstructural features of block surfaces, monitoring the performance of block surfaces using the slake durability test, and conclusion.

7.2 THIN SECTION MICROSTRUCTURAL FEATURES OF CSB SURFACES

The performance of a block is closely linked to its microstructure (Houben & Guillaud, 1994). Awareness of such links has led to several recent advances being made in concrete research (Baker et al, 1991; Taylor, 1998). It was with this in mind that a similar approach was adopted for this research. After all, the two materials both develop their microstructure by solidification from solution formed as the cement particles in either material dissolve in water (Young et al, 1998). In concrete studies it has been found that the resulting microstructure controls most of its key properties, especially those associated with its durability, and it would be reasonable to expect that a similar happening would occur in CSBs.

Investigation method used

The scope of microstructural investigations were limited to the identification and description of the main surface features of blocks. Although other petrographic methods exist, two microscopic methods were considered, namely: examination of a prepared block surface specimen using reflected light and examination using light transmitted through a 'thin section' (Brandon & Kaplan 1999). The latter method was selected for use in this research. Its advantage is that it is also widely used in concrete research to identify mix components, defects types and even causes of defects (Taylor, 1998). To the knowledge of the author, this represents the first published petrological study of CSB like materials..

The CSB samples for microscopic examination were prepared as described earlier in Chapter 5. Several six month old samples, some made using 5% cement and the other using 9% cement plus 2.25% microsilica, were examined. The blocks were compacted at 6MPa and cured under normal conditions (wet followed by laboratory dry curing). Samples of dimensions 100 x 90 x 40 mm were thin-sectioned. Slices of these samples (and others not described here) were cut using diamond saws preceded by vacuum resin impregnation. The slices were then dried and again impregnated using low viscosity epoxy resins. The samples were then ground using standard petrographic procedures to a 30 μm thickness. Oil lubrication was used to avoid the dissolution of water soluble materials in the block. The thin-surface sections were then examined with a petrographic microscope. The examination was done under both plain polarised light and cross-polar light. Micrographs of the thin sections were then produced for analysis and interpretation. Appendix U shows the three sets of micrographs discussed in this thesis. Additional comments are also shown on the same Appendix.

Interpretation of the Results

The interpretation of micrographs remains a highly specialised field. What is described in this Section are key features discernible even by the casual observer. The main object was to identify the following phases and defects:

- general features
- calcium hydroxide (portlandite)
- unreacted cement residues
- cement hydrate phases
- free sand, silt and clay residues
- gross porosity
- microdefects
- possible causal links to surface properties

In terms of general features, the micrographs in Appendix U reveal the existence of an amorphous particulate composite structure of predominantly short range order. As would be expected, the spatial pattern seen throughout is not rotationally repeated symmetrically over the long range (like in concrete). The precipitates look like a collection of individual particles and phases that are fairly well agglomerated. Given the low amount of cement used (5%), it was not expected to find a continuous interlocking phase of OPC hydrates and embedded sand particles. However, such a continuity has been reported in fired bricks mainly due to the resulting mulite structure, and partly explains the marked difference in performance between such bricks and other comparable materials (Jackson & Dhir, 1996). Continuity is known to confer marked improvement in the properties of bricks. By using microsilica in improved blocks, an attempt was made to improve packing and continuity in the block microstructure. Although this does not come out quite clearly in the micrographs (only 2.25% by weight used), evidence from other tests suggest that considerable improvement in performance was achieved (Chapter 6 and Section 7.3 that follows). Nevertheless, the groundmass was far more detailed than in an OPC mortar.

CSBs contain more varied particles and phases than concrete. Distinguishable features observed in the micrographs were: fine gravel, sandy fraction, clay agglomerations, and cement hydrates phases (Appendix U(1) and U(2)). The amorphous but homogenous areas seen in the micrograph resemble C-S-H gels. However, with so little (5%) OPC present, one would indeed be hard pushed to find any technique that could detect the individual cement hydrate products. The micrographs also reveal evidence of portlandite in the sample (Appendix U(3)). Fewer than expected platelets of portlandite, characteristic of hydrated cement paste were present. Appendix U(3) shows a relatively large portlandite crystal, approximately 30μm across, embedded in the matrix. Modification of CBSs using microsilica is therefore justifiable to encourage pozzolanicity.

Normally, it should have been easy to detect unhydrated cement residues. These were however conspicuous by their absence. Despite this surprising finding, conglomerations of unreacted cement-like collections were evident during processing even though the block materials had undergone careful mechanical damp mixing. Similar collections were also observed on new surfaces of blocks that had been subjected to the slake durability test (Section 7.3).

Microdefects which should normally have been detectable at the cement hydrate and sand interface zone were not discernible in the micrographs. Instead, the micrographs show that the cement hydrates and coarse soil fractions are satisfactorily intertwined. Gross porosity was lower than expected, suggesting good compaction. It is unlikely that CSB surfaces obtained from field production sites would have had similar quality finish (Chapter 4). Instead, inclusions, cracks, point defects and production defects would have been more prominent. Overall the findings are encouraging as they indicate no fundamental defects in the material.

From the above findings it can be expected that the microstructure of a block can mediate some of its properties. Block properties likely to be sensitive to the nature of their microstructure can be referred to as being 'structure sensitive'. They are structure sensitive because of their dependence on gross porosity, grain size and level of bonding of the composite structure. Properties such as strength, dimensional stability, water absorption, permeability and durability are likely to be structure-sensitive (Young et al, 1998). Future research should be able to reveal causal links between a particular microstructural feature and a particular block property. Conversely, block properties such as thermal expansion, elastic moduli, specific gravity, etc., are likely to be structure-insensitive. This is because such properties vary only slowly with structural composition, particle sizes and microstructural variations.

The desirable qualities at the surface of a block are impermeability, non-reactivity and high-intergranular strength. These features are likely to be linked to the microstructure of the block surface, which is in turn determined by the processing methods used. By reducing voids in the fabric (microstructure) for example, pores can be reduced. By improving bonding (microsilica, high degree of hydration), contact can be improved. Such procedures could result in considerable surface resistance being offered by the block. An attempt to achieve such a surface is investigated experimentally in the next Section.

7.3 MONITORING THE PERFORMANCE OF CSB SURFACES USING THE SLAKE DURABILITY TEST

In this Section, the need for a new accelerated surface test for CSBs and the main features of the proposed test are discussed. The proposed test is the slake durability test (SDT) which was originally developed for evaluating the resistance of clay-bearing rocks to slaking, abrasion and heating (Eigenbrod, 1969; Chandra, 1970; Franklin et al, 1971; Gamble, 1971; ISRM, 1971; Franklin et al, 1971; Goodman, 1980). In the subsequent sections that follow (Section 7.3.1 to 7.3.5), the results of the application of the test to block samples made as described in Chapter 5 are presented.

Need for a new accelerated surface test for CSBs

Surface erosion has been identified as a major problem for CSBs (Chapter 2 and 4). Yet it has always been difficult to monitor the performance of CSB surfaces when they are subjected to wetting and the abrasive action of water (Ola & Mbata, 1990). Selection of experimental methods to evaluate the integrity of cured block surfaces have proved difficult in the past (Webb, 1988; Gooding, 1994). Of the current surface monitoring test methods documented (drip test, water spray test, brushing test, abrasion test, wet-and-dry cycling test, etc.), none has been without criticism (Houben & Guillaud, 1994). Further, none has gained universal acceptance and application. Current tests have been found to be simplistic, misleading, of no relevance to the main mode of surface erosion, or over-dependant on the competence of the operator. These tests have failed to be predictive enough, with the unfortunate result that substandard blocks were passed. Moreover, after the full curing period is reached, the tests become largely inappropriate. A method of test is required that can monitor the performance of a block irrespective of its pre-cured and post-cured age. An accelerated durability test that can be conducted from a few weeks of production to several weeks or years after production would be quite helpful (Baker et al, 1991).

CSBs like most other building materials are characterised by a wide variation in their surface and bulk properties. The most important surface property of a block is its ability to resist short and long-term deterioration due to wetting, abrasion and drying (Chapter 2). For example it was found in Chapter 4 that CSB surfaces that were satisfactorily protected survived the deleterious effects of rains, humidity and high temperatures. Where similar surfaces were left unprotected in similar conditions, premature defects in the form of surface roughening, pitting, cracking and erosion were found to occur. The defects were more excessive than those observed on the surfaces of comparable materials used under similar conditions. It was further found that the clearly distinguishable surface defects had negatively influenced the attitudes of many users (Chapter 4). CSBs were therefore regarded as being sub-grade and of lower durability than comparable materials.

Under normal conditions, a durable block would be required for walling for the service lifetime of a building. While some surface deterioration might be expected, the deterioration should not be so excessive that the functional requirements of the wall are adversely affected (normal load bearing, resistance to weathering, etc.). Where such phenomenon are expected, the block surface ought to be protected. Surface protection is unfortunately considered to be expensive since more costs are incurred. The erosion of block surfaces should therefore be more accurately and reliably forecasted early enough. This can only be done by using more appropriate and suitable accelerated tests than was hitherto possible. The key specification is that the required test should simulate more accurately the main mechanism of surface erosion as identified in Chapter 2 and Chapter 4. Such a test would be an invaluable asset for site and laboratory use. The author describes in this thesis one such pioneering test which was successfully used to monitor the surface performance of block samples made as described in Chapter 5. The surface monitoring test described is the slake durability test (SDT). Since both clay-bearing rocks and CSBs contain clay and rocky residues (sand, silt, fine gravel), use of the test for the latter was found to be quite appropriate. As will be discussed in subsequent Sections, use of the test was further extended to evaluate the performance of like materials such as fired bricks, concrete blocks and rock samples.

The Slake Durability Test

In this subsection, the main features of the test, the factors likely to influence the results, merits of the test and classification systems for evaluating the test results are discussed.

The *main features* of the SDT are briefly described here (full details are provided in Appendix V). The main test equipment used consists of a standard cylindrical drum 140 mm in diameter and 100 mm long (ISRM, 1971). The drum frame is enclosed by a standard 2 mm aperture sieve mesh which forms its wall. Four to five oven-dried prism block samples (about 30 x 30 x 30 mm) with a combined total weight of between 450 and 550 grams, are loaded into the drum. The drum is closed and the whole system rotated using an electrically operated motor at 20 revolutions per minute. The rotation is continued for 10 minutes through a bath filled to an assigned mark with ordinary tap water at 20°C. In the apparatus used, four drums all attached to the same motor were rotated simultaneously. Due to internal contact between the samples within the block, mixing and softening in water, attrition and abrasion from the mesh sieve walls, the surfaces of the block samples are continuously eroded. After 10 minutes of the generally slow rotation, the eroded block sample materials can be seen partly suspended in water, and partly settled at the bottom of each bath. The state of the slaking water, owing to the presence of suspended material, is clearly distinguishable by the amount and degree of discoloration observed. The partially eroded block samples are then removed from the drum, then re-weighed. The drying, wetting, abrasion and redrying cycles attempts to simulate the most severe environmental conditions that a block sample can be expected to endure in real service life.

The slake durability index is then defined as the percentage ratio of final to initial dry mass of the block samples (ISRM, 1971). The SDI for each sample to the nearest 0.1% was calculated using the formula:

$$SDI = \frac{M_f \times 100}{M_i}$$

where: SDI or (I_d) = slake durability index (%)
M_f = final mass (g)
M_i = initial mass (g)

The SDI value can be used to assess the degree of resistance offered by each block surface. Samples of traditional and improved blocks, concrete blocks, fired bricks and various rock samples were all tested in the same manner. Comprehensive results for all samples tested are shown in Appendix W(1) to W(7). The results are discussed in Sections 7.3.1 to 7.3.5.

The *factors considered likely to influence the results* were noted as: the equipment; sample dimensions; sample pre-treatment; duration of slaking; and chemistry of the slaking fluid. These are briefly discussed below.

- The *equipment or apparatus* used was the standard one. Its sieve mesh size (2 mm), drum size (140 x 100 mm) and speed of rotation (20 revolutions per minute) remained the same for all categories of blocks and other materials tested. If any of these had been varied, then comparison of the results would have been misleading.
- The *sample dimensions* selected were such that they would be approximately the same for all samples tested. The sample dimensions used were about 30 x 30 x 30 mm with a combined weight of between 450g and 550g. About four to five pieces of the same material were placed in the drum each time.
- *Sample pre-treatment* was kept uniform for all samples. They were all pre-oven dried, cooled under cover, and stored under cover. A similar procedure was followed after each test. In this way, a controlled and reproducible condition of moisture was ensured for all categories of samples tested. In a way, this could be equated to the intense drying of a block by the sun in the humid tropics. Drying has been though to accelerate the suction rate of blocks (Jackson & Dhir, 1996). In this test therefore, the very worst scenario has been applied to block samples since drying accentuates the deterioration process. Since SDI is based on the comparison of weights, before and after the test, oven drying was found to be essential for accuracy and repeatability. No similar durability test has been able to achieve this level of reproducibility (variance 0.118). Clearly, comparison of dry weights is more meaningful than comparison of wet weights. The latter would give varying inaccuracies since there is no known way of controlling initial and final water contents in the samples. Moreover, by drying, the moisture history of a block sample can be rendered useless so that previous storage conditions do not become an issue.

All samples can then be reduced to nearly the same level of zero moisture content at the start and finish of the test regime. Weighing of all cooled oven-dried samples were done using an electronic weighing scale with a display.

- *Duration of slaking* was maintained for all samples at 10 minutes (± 1%) without exception. A stop clock was used in addition to an electronic wrist alarm watch. The duration used is also the standard recommended period. If shorter durations had been opted for, the potential for errors was likely to be high. It would have for example been difficult to discriminate between any two highly durable blocks within a much shorter time. Even in actual service conditions, deterioration requires a period of initiation, followed by progression. Errors associated with timing of the test would have also contributed to poor results. Longer durations on the other hand, would have caused weaker or less durable blocks to show a 100% mass loss (or zero durability). This would have defeated the primary purpose for the test which was simply comparative and predictive.
- *Chemistry and nature* of the slaking fluid were also considered. It was found that use of distilled water and Coventry laboratory tap water at 20°C did not produce significantly dissimilar results. The use of cold tap water was therefore adopted for all test samples. Use of fluids other than water would most likely affect the results. Since it is the effects of rainwater that were being simulated, it was found not to be necessary to pursue this factor any further.

All the above factors were kept the same for all samples tested. These specifications are recommended for future similar tests.

The *merits* of using the SDT are associated with its extreme severity on the one hand,

and its simplicity on the other. The slake durability test aims at accelerating weathering to a maximum by combining the processes of slaking, abrasion and drying. During the test, as block surfaces are eroded, the new surfaces which emerge are exposed to further similar treatment. The test can therefore be said to be a very severe accelerated surface test. The more severe the test, the better even if such a test might appear to exceed the worst possible weathering conditions which a block is likely to get exposed to in actual practice. The SDT is likely to give a reasonable indication of future service behaviour of a block over time. The test measures within a much shorter time the durability behaviour of a block sample by attempting to reproduce outdoor conditions. This enables the durability of a block to be assessed within a much shorter time than would have been possible under actual conditions of use. Some short term significance can be derived from the ensuing results.

The SDT was also adopted as the main surface test due to its other several attractions over existing methods (rain erosion test, abrasion test, wet and dry cycling test, brushing test, etc.). In any case all these current tests, as mentioned earlier, still remain non-standardised and fragmented. The strong points in favour of the SDT over other durability evaluation methods can be summarised as follows:

- Simplicity
- Controllability
- Reproducibility
- Accuracy
- Reliability
- High speed and practicality
- Timeless capacity (blocks of any age)

Moreover, the SDT was found to be capable of causing significant mass loss from block surfaces of any age. All other current test methods are valid only for blocks of a certain pre-cured age. Through the SDT it was also possible to deduce the degree of alterability of a block surface. This was found to be linked to a quantitative index. As an index test, the method was found to be helpful in comparing not only one block with another, but also CSBs with other like materials. A test similar to this was not available in the past for use with CSBs. While the SDT test might not yet be able predict the rate of surface deterioration, it is nevertheless more indicative than other existing methods. In any case, the prediction of the rate of surface deterioration has to take into account all factors other than slaking, abrasion and drying that the test attempts to simulate. Further, as an index test, the SDT represents a compromise between simplicity and precision (Gamble, 1971). Most current durability tests are so complicated and delinked from the main surface deterioration mechanism that the interpretation of results is difficult. For each mechanism or group of similar mechanisms, other durability tests should be devised. Use of the test to compare the performance of traditional and improved blocks are discussed in subsequent Sections of this Chapter. It is recommended at the end of the this Chapter that a modified hand operated version of the SDT apparatus be devised for field use.

The *classification and grading* of SDT results is based on existing standards for rocks. In the present classification system, six classes of durability are provided for. These, together with the proposed recommended classes and grades for CSBs, are shown in table 11. Unequal subdivisions have been used. This might be more useful particularly for the more durable blocks. Most well made blocks might have 'extremely high' SDI (i.e. they slake to a negligible extent). In such cases, smaller subdivisions are more helpful in reflecting the slight differences in resistance to breakdown.

S/N	Author (Year)				Proposed Classification for CSBs		
	Gamble (1971)		Franklin & Chandra (1972)				
	Classification	SDI(%)	Classification	SDI(%)	Classification	SDI(%)	Grade
1	Very high durability	> 99	Extremely high	95-100	Extremely high	95-100	A
2	High durability	98-99	Very high	90-95	Very high	90-94	B
3	Medium high durability	95-98	High	75-90	High	75-89	C
4	Medium durability	85-95	Medium	50-75	Medium	50-74	D
5	Low durability	60-85	Low	25-50	Low	25-49	E
6	Very low durability	60 <	Very low	0-25	Very low	0-24	F

Table 11: Current classification systems for slake durability index in clay-bearing rocks and proposed standards for CSBs
(Adapted from Gamble, 1971; Franklin & Chandra, 1972)

The test results for all samples tested are shown in Appendix W(1) to W(7). The results when compared to the range of classes shown in table 11 represent a valuable indication of their resistance to surface erosion. Blocks giving low durability index should be investigated further to determine whether adequate processing safeguards were followed. The test results can be used in several ways:

- as an aid to block classification
- for selection of blocks for particular applications
- for quality control during production
- for prediction of the surface performance of a block

- for selecting suitable production equipment

The SDT therefore offers a new possible quantitative method of discriminating between various types of blocks. The proposed boundaries shown in table 11 are tentative and can be reviewed on the basis of results from future research or from those based on service record and experience. The use of the SDT is likely to ensure that block durability is no longer neglected in favour of other properties such as strength, whose values can be determined quantitatively (Lunt, 1980; ILO, 1987; Rigassi, 1995).

7.3.1 Effect of Varying the Stabiliser Type on the Slake Durability Index of CSBs

The effect of varying the cement content on the slake durability index of CSBs were investigated experimentally. All CSB samples were prepared in accordance with the descriptions given in Chapter 5. The mean values of the test results for blocks compacted at 6 MPa are shown in figure 16.

The mean values used for plotting the graph shown in figure 16 are tabulated for comparison purposes and for durability classification (table 12).

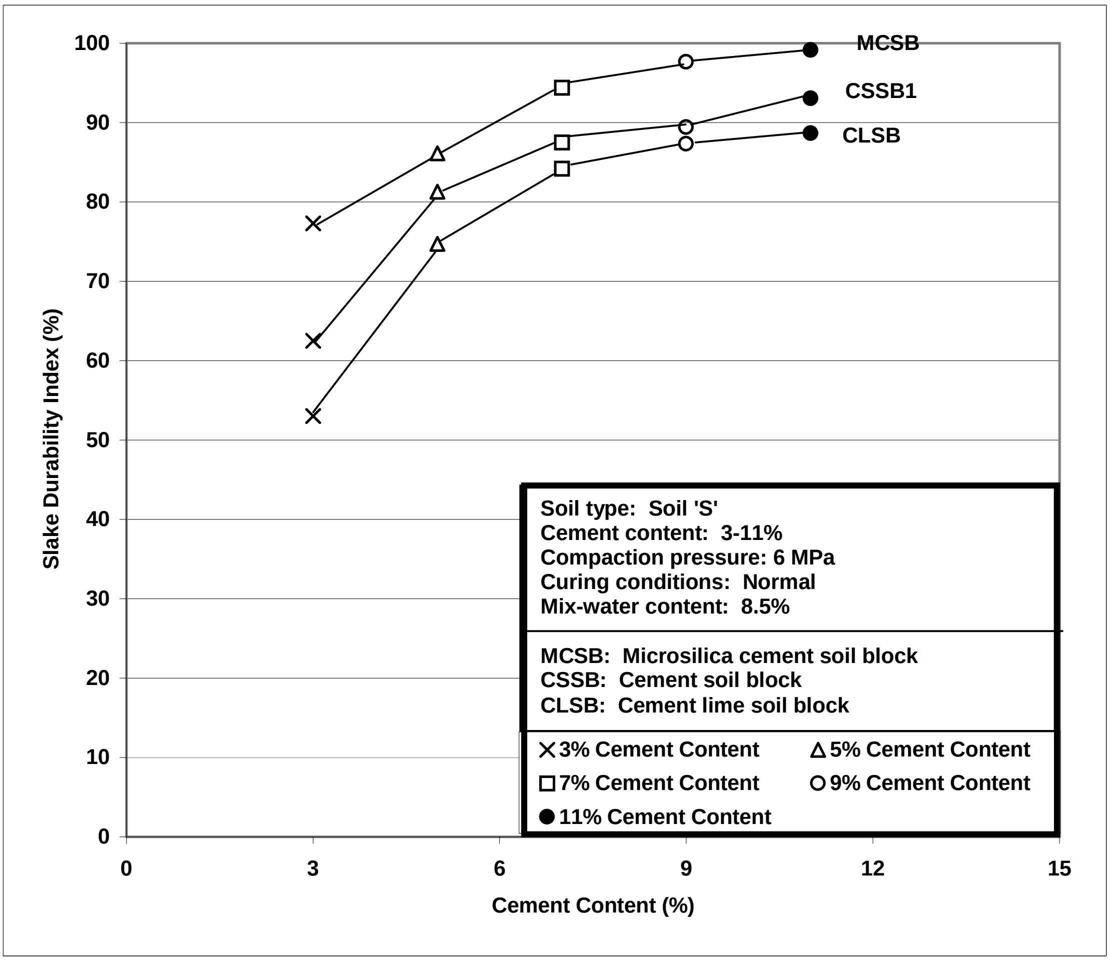


Figure 16: Effect of varying the cement content on the SDI values of improved and traditional blocks (University of Warwick, 2001)

SN	Material	cc (%)	Mass Loss (%)	SDI (%)	Durability Classification		
					Existing (Franklin & Chandra, 1972)	Proposed	Grading
1	MCSB	11	0.9	99.1	Extremely high	Extremely high	A
2	MCSB	9	2.4	97.6	Extremely high	Extremely high	A
3	MSCS	7	5.6	94.4	Very high	Very high	B
4	MCSB	5	13.9	86.1	High	High	C
5	MCSB	3	22.7	77.3	High	High	C
6	CSSB	11	7.0	93.0	Very high	Very high	B
7	CSSB	9	10.6	89.4	High	High	C
8	CSSB	7	12.5	87.5	High	High	C
9	CSSB	5	18.7	81.3	High	High	C
10	CSSB	3	37.5	62.5	High	High	D
11	CLSB	11	11.4	88.6	High	High	C
12	CLSB	9	12.7	87.3	High	High	C
13	CLSB	7	15.8	84.2	High	High	C
14	CLSB	5	25.3	74.7	Medium	Medium	D
15	CLSB	3	47.0	53.0	Medium	Medium	D
16	FBS	-	0.2	99.8	Extremely high	Extremely high	A
17	RBS	-	1.7	98.3	Extremely high	Extremely high	A
18	CBS	12-18	3.4	96.6	Extremely high	Extremely high	A

Table 12: SDI results for various samples tested and their durability classifications (University of Warwick, 2001). Abbreviations as before.

The results confirm that mass losses occur in CSBs when they are subjected to continued wetting, abrasion and drying. It was found that loss in mass in traditional blocks were higher than those in improved blocks. Table 12 shows the SDI values of the various materials tested and the range of values obtained. As can be seen, improved blocks with 7% and more cement content performed almost as well as FBS, RBS and CBS (all grade A). At the 9% cement level and above, improved blocks performed better than concrete blocks. During the test, it was found that one of the three test results from both fired brick samples and improved block with 11% cement content achieved 100% SDI values (Appendix W(1) – (7)).

According to the tentative classification system shown in Table 12, traditional blocks with cement content 5% and above can be regarded as having high durability (grade C and better). Improved blocks of similar cement content can be regarded as having high durability, although the SDI value was tending towards the very high durability classification levels. Even the 3% cement content improved blocks were found to be of high durability (grade C). This SDI surface test has been successful in grading blocks according to their degree of resistance to weakening. The findings clearly confirm that the test can be used for classification of blocks, irrespective of their storage and production history.

The graph in Figure 16 also shows that a strong correlation exists between increase in cement content and the slake durability index of blocks. For all block samples tested, it was found that increase in SDI due to increase in cement content was more pronounced at the lower stabiliser content levels than at higher ones. For example, in the traditional (OPC only) blocks, increase in cement content from 3% to 7% was accompanied by a matching increase in SDI of about 40%. Further increase in cement content from 7% to 11% resulted into a lower increase in SDI of about 6%. A similar trend was found with improved blocks where the corresponding increases over the same ranges of cement contents were 22% and 4.9% respectively. In both cases a further increase in cement content beyond the 7% level did not result in any appreciable increase in SDI.

The test results also show that most improved blocks were comparable to rocks. Rocks are known to be almost impermeable and are of high inter-granular strength. The fact that improved blocks were found to be comparable to rocks confirms that the use of microsilica can considerably improve bonding in blocks. The loss in mass as evidenced in all blocks implies that under certain environmental conditions, surface protection measures should be considered. As mentioned earlier, this could take the form of external render, low-roof overhangs, skirting plaster, thin-surface coating and thin-surface enriched layering of blocks. Where enriched surface layering is considered, costs could be saved by either using interlocking blocks, frog-bedded blocks, or hollow blocks.

7.3.2 EVOLUTION OF DURABILITY WITH CURING AGE

The SDT was also used to monitor the development of surface resistance with curing age in CSBs. The samples tested were all stabilised with 5% cement and compacted at 6 MPa. They were tested at 7, 14, 21, 28 and 56 days. The mean values of the results obtained are shown in Figure 17.

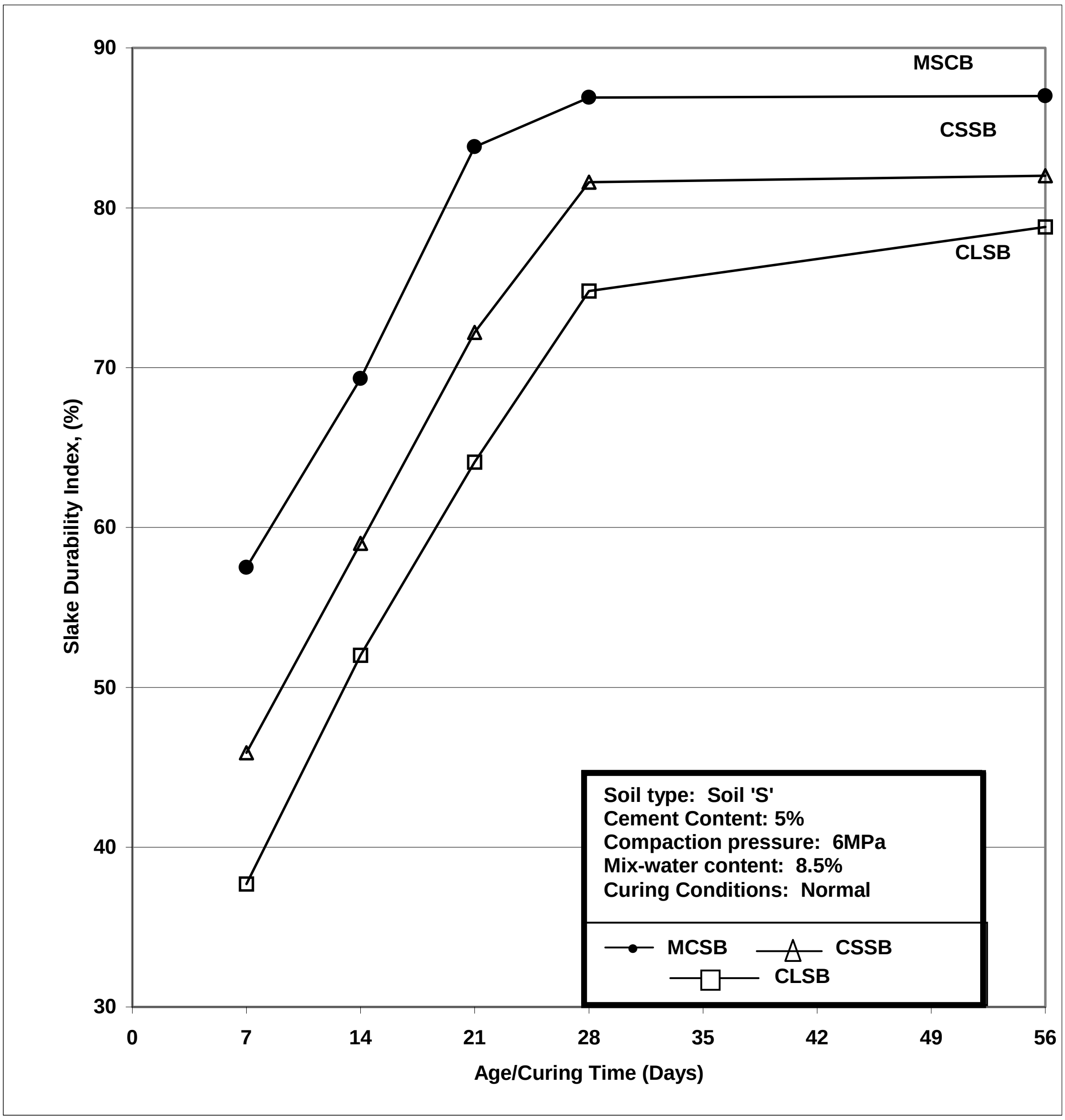


Figure 17: Evolution of SDI with curing age in traditional and improved blocks. (University of Warwick, 2001)

As expected, the results in figure 17 show that for both categories of blocks, increase in curing age is accompanied by an increase in the SDI value of a block. The increase in all cases is more pronounced before the 28th day after production than later. Except for blocks stabilised with both cement and lime, the increase in SDI value after 28 days was not appreciable. Table 13 shows a summary of the values obtained.

Age/Time	Slake Durability Index					
days	%					
	MCSB	R	CSSB	R	CLSB	R
7	57.5	1.0	45.9	1.0	39.7	1.0
14	69.3	1.2	59.0	1.3	52.0	1.3
21	83.8	1.4	72.2	1.6	64.1	1.6
28	86.9	1.5	81.6	1.8	74.8	1.9
56	87.0	1.5	82.0	1.8	78.8	2.0

Key: R = ratio (Age (SDI/7 days value)

Table 13: SDI values for various CSBs at different curing periods (all 5% cc, compacted at 6MPa).

The SDI values at 28 days for traditional blocks were about 1.8 times those at 7 days. The comparable ratio for improved blocks was only 1.5. Improved blocks were found to have gained strength more rapidly than traditional counterparts. Other ratios are also shown in table 13. These results show that SDI can also be used as a quick predictive test for gain in strength over time during curing. This can be a very useful surrogate test to identify quality problems in blocks at a very early age after production. To the knowledge of the author, this is the first published finding of such results.

7.3.3 *CORRELATION OF SLAKE DURABILITY INDEX AND WET COMPRESSIVE STRENGTH IN CSBS*

The above relationship was investigated from the results discussed earlier (Chapter 6). The mean values for SDI and WCS are shown in Figure 18.

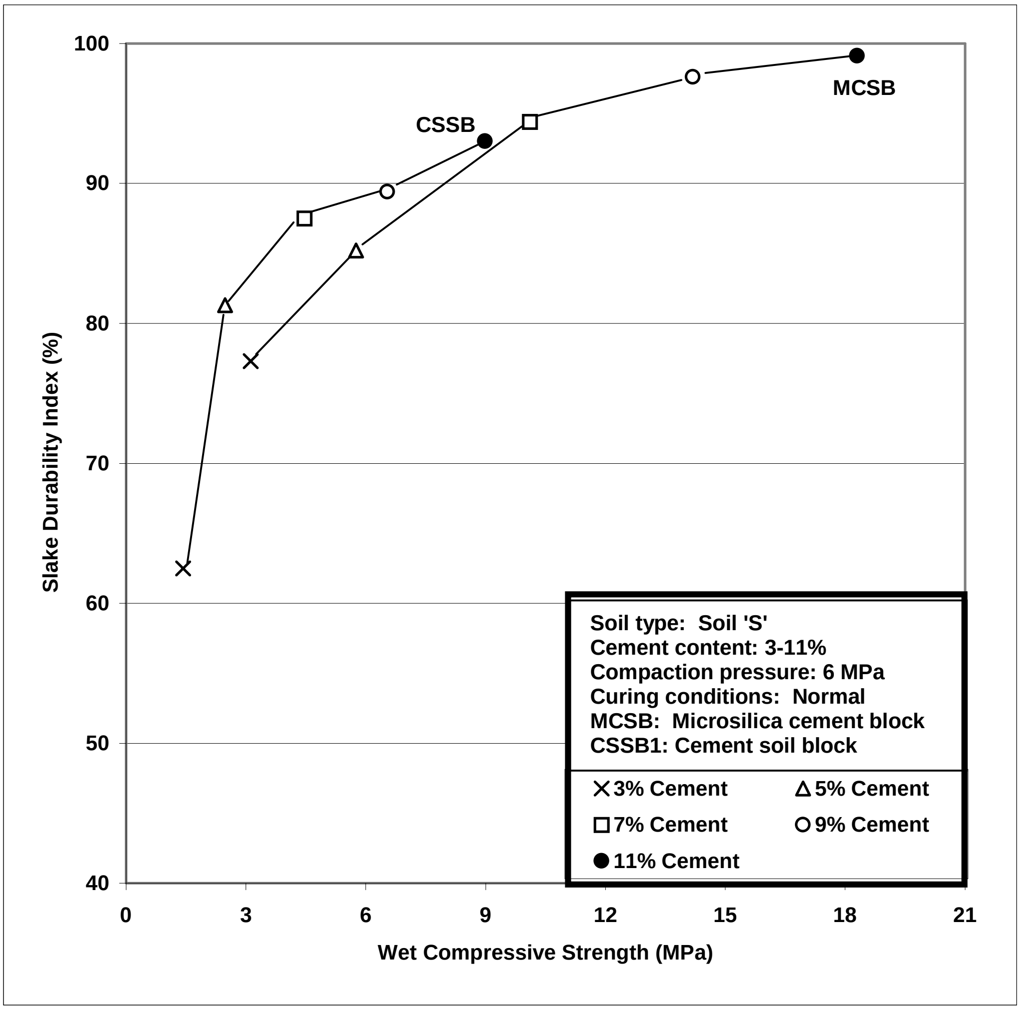


Figure 18: Correlation of slake durability index and wet compressive strength in CSBs (University of Warwick)

The graph in figure 18 shows a general positive correlation existing between SDI and WCS in both categories of blocks. The correlation coefficient for traditional blocks is

0.846 (with a two tailed significance of 0.71). The equivalent correlation coefficient for improved blocks is 0.938 (significant at the 0.05 level (2-tailed)). These non-parametric correlation coefficient values are all above 0.5 and approaching 1. They confirm that a very strong correlation exists between SDI and WCS (28-day) in stabilised blocks. The correlation is stronger in improved blocks than in traditional ones. If all points were to lie on the same curve, then WCS and SDI are surrogates for each other. The correlation is likely to remain valid only for homogenous blocks and not (for example) surface enhanced blocks. The SDT is a better test since it is more related to the surface resistance of a block, and is much easier to perform than the WCS test.

7.3.4 CORRELATION OF SLAKE DURABILITY INDEX AND TOTAL WATER ABSORPTION

The association between SDI and TWA in both categories of blocks were examined. The mean values are shown plotted in figure 19.

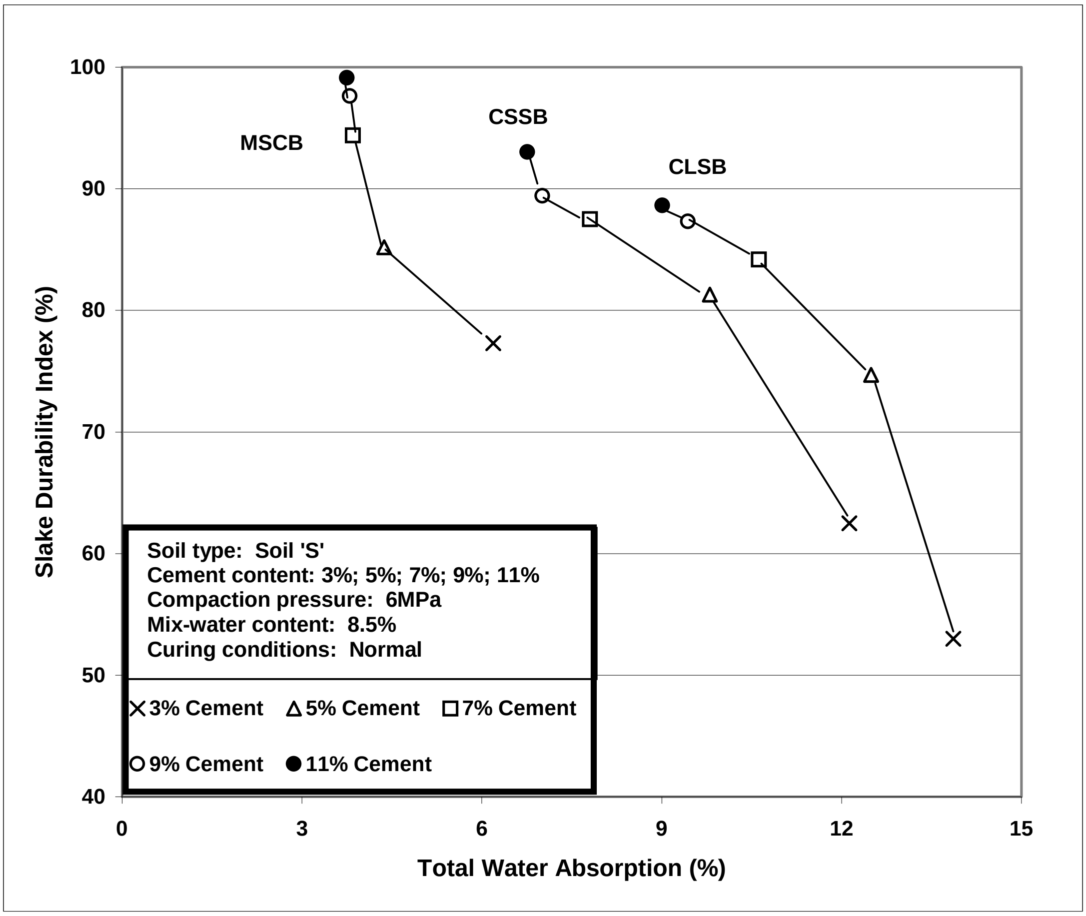


Figure 19: Correlation of Total Water Absorption and Slake Durability Index in CSBs (University of Warwick, 2001)

The results in figure 19 show that a general negative correlation exists between SDI and TWA in the blocks tested. The correlation coefficient for traditional blocks is -0.975 (with a two-tailed significance of 0.005). The correlation between SDI and TWA is significant at the 0.01 level (2-tailed). Similarly, the matching correlation coefficients for improved blocks is –0.939 (with a two tailed significance of 0.018).

Again the correlation is significant at the 0.01 level (2-tailed). These confirm a strong negative correlation between SDI and TWA. The finding implies that the higher the surface resistance, the lower the water absorption. This is a very desirable relationship in CSBs. The results show that both SDI and TWA can valuable indicators of the durability of a block.

7.3.5 CORRELATION OF SLAKE DURABILITY INDEX AND DENSITY

A plot of the mean values of SDI and BDD for the two categories of blocks are shown in figure 20.

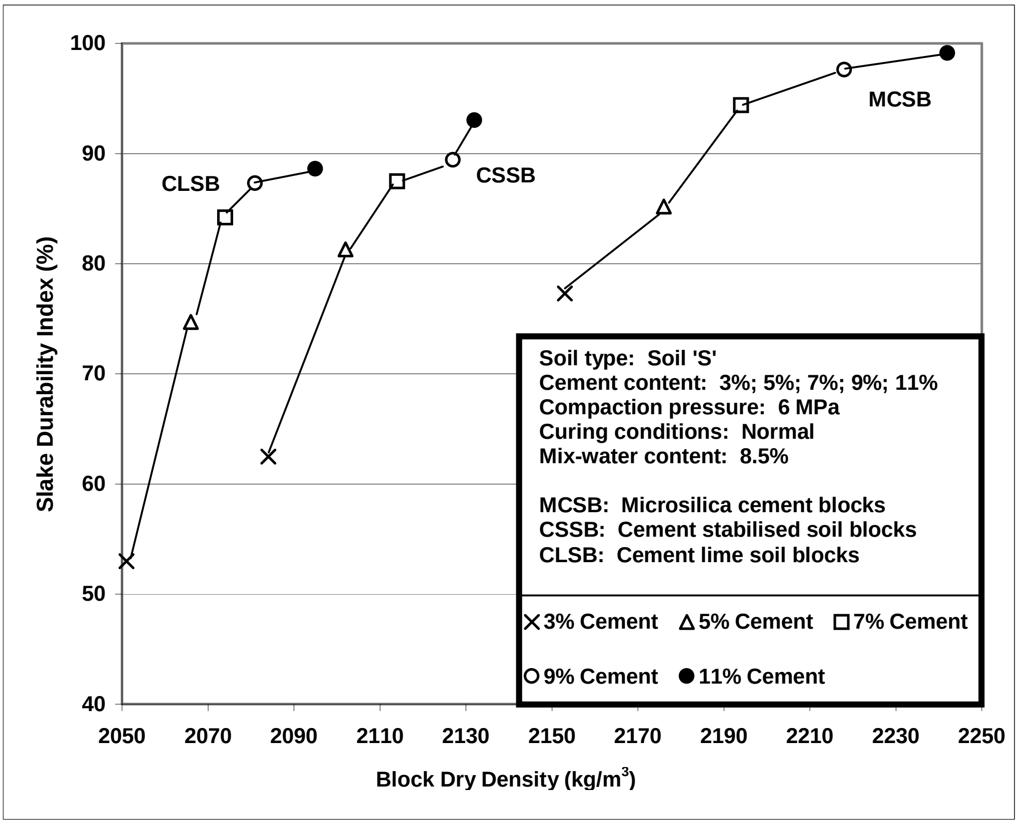


Figure 20: Correlation of Slake Durability Index and Block Dry Density (University of Warwick, 2001)

The graph in figure 20 shows a general positive correlation existing between SDI and

BDD. The correlation coefficients for traditional blocks is 0.953 with a (2-tailed significance value of 0.005). The correlation between the two properties is significant at the 0.05 level (2-tailed). The equivalent correlation coefficient for improved blocks is 0.944 (with a two-tailed significance of 0.016). The correlation is significant at the 0.05 level (2 tailed). Both values confirm a strong correlation between SDI and BDD. An increase in density can be expected to be accompanied by an increase in the durability of a block. The denser the packing of particles and phases in a block, the stronger and therefore more durable it is likely to be. Density is therefore a valuable indicator not only of strength but also of durability in blocks.

Increase in SDI with increase in density appears to be greater in traditional blocks than in the improved ones. Increase in density of about 2.3% is accompanied by an increase in SDI of about 49%. While increase in density of 4% over the same range of increase in cement content in improved blocks results into an increase in SDI of only 28%. So the denser the block, the less is the increase in SDI, but the higher is its resistance to surface abrasion.

7.4 CONCLUSION

From the discussions in the preceding Sections of Chapter 7, a number of general conclusions regarding the following key areas can be made .

The *surface microstructural features* of block samples as observed confirm the existence of an amorphous particulate composite, of predominantly short range order. The matrix shows sand and silt in a highly textured groundmass. The porosity was lower than expected indicating good packing possibly due to the compaction used. The groundmass was homogeneous, with some clayey inclusions seen in the 100 μm range. There was hardly any difference between the microstructure of the surface and bulk. Fewer than expected platelets of calcium hydroxide were present, with no CH precipitation in voids. Their presence justifies use of microsilica to promote pozzolanicity, and thus development of a secondary binding product. Generally no fundamental defects were observed in the material. It can be concluded that the method used is promising, and should be extended to examine samples from CSB production sites in future.

The *slake durability test* was found to have great potential in evaluating surface performance of various block samples. The test procedure was found to be more simple, controllable, reproducible, accurate, reliable and speedy. Moreover, it can be applicable to blocks of any age or stage of curing. The SDI values obtained could be satisfactorily compared with values from other like materials (rocks, concrete, fired bricks, etc.).

From the discussions in Chapter 7, a tentative classification and grading system for potential use in discriminating CSB samples is recommended. The classification is based on six levels of slake durability index SDI, namely: A = extremely high (95-100%); B = very high (90-94%); C = high (75-89%); D = medium (50-74%); E = low (25-49%); and very low (0-24%). While grade A represents blocks of extremely high durability, grade F represents blocks of very low durability (equivalent to unstabilised blocks). Blocks of low and medium durability can be investigated further to identify any production inadequacies.

While all previous tests relied on the veracity of an operative, and were clearly delinked from simulating the main mechanism of surface deterioration in CSBs, the SDI test is independent, and accurately approximates surface deterioration by wetting, abrasion and drying. The test is therefore strongly recommended for adoption and use in testing CSB samples of all backgrounds and ages. Its modification for manual use on block production sites is highly recommended.

It was found in Chapter 7 that increase in cement content resulted into a similar increase in the SDI value of all block categories. It was also found that all stabilised blocks and most comparable materials, were vulnerable to mass loss when subjected to continued wetting, abrasion and drying. Traditional blocks were found to be less resistant than matching improved blocks. The former lost between 12% and 45% more mass than the latter when both were tested under similar conditions.

At the range of interest (5% cement content), traditional blocks were found to have SDI values above 75%, and can therefore be classified as having high durability (grade C). Improved blocks of the same category were found to have very high durability (SDI above 90%). Unstabilised blocks were found to be of very low durability classification (0-24%). These are not recommended for use in building. The results also showed that the majority of improved blocks were comparable to rocks, concrete blocks and fired bricks (SDI > 90%). It can be concluded that the inclusion of microsilica in these blocks effectively increased the bond strength between the particles in the block. The approach therefore offers great potential for strengthening block surfaces and increasing their resistance against rain erosion.

It was also found that SDI values were positively correlated to compressive strength and density, but negatively correlated to water absorption in blocks. The SDI value is therefore a valuable indicator and surrogate measure of strength, density and water absorption in blocks. Use of the index can be favourably extended to compare the performance of other like materials.

Lastly, it was also found in Chapter 7 that with increase in curing age, a corresponding increase in SDI value of the block was recorded. The increase was uniform but more pronounced before the 28th day than after. The SDI value at 28 days was higher than that at 7 days by 51% in improved blocks, and by 88% in traditional blocks. Similar levels of change in strength with curing age have been reported in the literature. The SDI can therefore be used as a quick predictive test for gain in strength over time during and after curing.

With the preceding conclusions, the objectives of Chapter 7 were fully met.

CHAPTER 8

CONCLUSION

The principal objective of this thesis was to investigate the durability of CSBs, especially when used in conditions similar to those found in the humid tropics. Interest in the durability of CSBs is likely to remain a major concern for the foreseeable future given the potential the material has for reducing the enormous shelter backlog in developing countries (1.1). The figure in brackets relates to the section where the issue was discussed in this thesis. The adequate performance of a CSB throughout its service lifetime depends primarily on the interplay between three factors: choosing the right constituent materials, using the correct processing methods, and properly counteracting the effects of the exposure environment (1.2).

At the time of commencing this research, there was hardly any documented record of previous research in the same field. For this reason, a multi-pronged methodology was adopted involving: literature review (Part A of the thesis), laboratory experimentation, and an exposure condition survey (Part B of the thesis) (1.3). In this final Chapter, summary recommendations and conclusions are presented in three separate sections covering Part A, Part B and the highlights of the implications of the findings on further areas of research.

8.1 RECOMMENDATIONS AND CONCLUSIONS: PART A

The aim of the literature review conducted as part of the research was to provide the intellectual context for the work and to determine how far other researchers had reached. It was also meant to determine whether the literature on durability and stabilisation were accessible.

Chapter 2 explored the concept of durability and deterioration in CSBs (2.2). It was found that CSB literature on the subject was scarce and inaccessible. Since both concrete and CSBs develop their microstructure from the precipitation of solids from solution following the hydration of cement, documented findings on the former were used to try to understand related phenomenon in the latter. It is recommended that this approach be pursued further.

From the literature survey conducted, it was found that no uniformly accepted expression for durability existed. It is therefore recommended that the durability of a CSB be regarded as "a measure of its ability to sustain its distinctive characteristics of strength, dimensional stability and resistance to weathering under conditions of use for the duration of the service lifetime of the wall of which it forms part". This concept of durability is based on three important parameters: intended function of the block (for walling); conditions of exposure (weathering elements); and age of exposure (time in years). Due to the effects of exposure conditions, the properties of a block can be altered over time, and so their durability will not remain constant. Durability is therefore more dependent on exposure conditions than just time.

According to the literature surveyed, the time-related loss of quality of a block is its deterioration (2.2). It implies that the durability of a block can be regarded as its ability to resist deterioration. Due to deterioration however, the durability of a block can fall with time. The more a block deteriorates, the less durable it is, and will become over time. An assumed progressive deterioration model characterised by a gradual loss of performance (typified by a deterioration gradient) would be more applicable to the durability-time relationship. The service life of a block can be regarded as the actual period of time during which no excessive expenditure is required on its maintenance or repair in actual use (2.2.). The design life of a block is the period set by the designer of the building of which the block forms part. A gap exists in CSB literature on the concepts of service and design life. Further research is recommended with a view to reducing the gap between the two.

Chapter 2 also discussed various deterioration agents and their likely mechanisms (2.3). Three categories of deterioration modes were identified: water, temperature, and chemical related actions. Water-related deterioration was categorised as occurring in four different forms: abrasive action, solvent action, swelling action, and catalytic action (2.3.1). The most prominent of these was the direct abrasive action of rain on the surface of blocks leading to surface erosion. The exact mechanism and rate of surface deterioration is not yet well understood. Further research is recommended in this area.

Temperature-related deterioration was reported to cause both reversible and irreversible changes in block properties, occurring in three main ways: expansion and contraction, shrinkage and drying, and catalytic action. The main defect types associated with this mechanism of deterioration were surface and bulk cracking and crazing (2.3.2).

It was found through the literature survey that chemically-related deterioration was the least covered in CSB literature (2.3.3). Yet both soil and cement contain sources of potentially reactive minerals. Three categories of chemically related deterioration were identified: leaching-out effect (of clay and calcium hydroxide), expanded product formation (due to action of sulfates, soluble salts crystallisation and alkali-aggregate reactions leading to internal stress generation), and direct decomposition of the OPC hydrate binder (from acidic conditions). Leaching out effect and expanded product formation were regarded as being the most common. It is recommended that use of lime and pozolans in combination with OPC be considered in vulnerable materials. The two help in stabilising both clay and the freed calcium hydroxide from the reaction of OPC and water. It is further recommended that careful soil selection that avoids use of soils with an excess of clay (> 30%), and proper curing that ensures a maximum degree of hydration, be considered as ways of minimising some of the effects of chemically related deterioration. Limits should also be set on the amounts of sulfates (< 2.5%), active silica and carbonates, soluble salts (< 6%) and organic matter (< 3%) found in soils to be used for CSB production. At the moment, there are no such limits. The limits shown in brackets are from recommendations found in concrete literature. Despite these findings, the objectives of Chapter 2 were fully met.

Chapter 3 reviewed from literature sources current methods used to select the main constituent materials in CSBs, the mechanisms of cement-soil stabilisation, and processing methods for blocks (3.1).

The main constituent materials in CSB production were identified as: cement, soil and water (3.2). Coverage of these three materials varied a great deal in the literature reviewed, with quality of cement and water being the least documented. The function of OPC in a CSB is to bind and hold the soil particles together in a dimensionally stable unit (3.2.1). Coverage of OPC in CSB literature was very scant. No mention was made of the main desirable OPC physical properties such as specific surface area (300-350 m^2 kg^{-1}) and particle size distribution (90% more than 5 μ : 1% < 90 μm). These two properties govern the manner in which OPC effectively stabilises soil. Moreover, the implications of the different rates of reaction and influence of the several OPC constituents on the stabilisation mechanism were not covered in CSB literature. Neither were the effects of the various hydrates formed following the reaction of OPC and water covered. These hydrates have implications on the durability of CSBs. By discussing issues such as these in Chapter 3, an attempt was made to fill the existing CSB gap in literature. Capillary porosity for example is closely associated with strength, and is controlled by the water cement ratio and the degree of hydration. While the former can be reduced by the use of very fine pozzolans (e.g. microsilica), the latter can be attained by ensuring that a high degree of hydration is achieved (by proper wet curing). It was this finding from the literature on cement chemistry that led to the successful manufacture for the first time of improved blocks of superior strength and durability than comparable conventional blocks (Chapters 6 and 7). The approach used is strongly recommended for CSBs meant for use in severe climatic conditions such as the humid tropics.

Chapter 3 also discussed findings from the literature review conducted on the characterisation and selection of soil for CSB production (3.2.2). It was found that soil classification and selection criteria were generally well covered in most CSB literature. Classification by particle size distribution is the most commonly used method. It is recommended that other methods based on plasticity, compactability, cohesion and chemical content also be investigated further for future use. The current soil selection criteria recommends the use of a well graded soil containing adequate proportions of coarse soil fraction (fine gravel and sand) and sufficient fines (silt and clay) for cohesion. The soil should ideally have about 75% coarse fraction and about 25% fines content (of which at least 25% is clay). As soils are highly variable and complex materials even in nature, it is recommended that even where soils on site do not conform to the above specifications, they be not rejected but modified. A dense, well graded soil requires less cement to bind its particles together due to the increase in specific surface area. The effect is even greater when a limit is set for maximum size fraction (< 6 mm). At the time of the research, it was established that various authors recommended different maximum size fraction sizes (5 mm, 6 mm, 15 mm, 20 mm). A limit of 6 mm is recommended.

The quality of water for mixing and curing is poorly covered in CSB literature (3.2.3). Due to the scarcity of water in most developing countries, the sources are varied and so is the quality. It was noted that the use of untreated water of no known service record cannot be ruled out.

Chapter 3 also reviewed current cement-soil stabilisation principles (3.3). The conclusion that emerges from the review is that, despite the recent scientific advances made, cement-soil stabilisation still remains an inexact science. Soil properties can be modified by mechanisms that vary the soil-water-air interphase through minimising the volume of interstitial voids and improvement of cohesion and bonding between its particles (3.3.1). The literature documents three theoretical and practical methods of achieving this: mechanical (compaction), physical (improvement of soil grading), and chemical (using a stabiliser such as OPC). The effect of chemical stabilisation mechanisms are widely documented as being more permanent. It is therefore recommended that chemical stabilisation of soil be done even when the other two methods have been used (3.3.3).

Further research is required to determine the proportions of the final CSB matrix known to comprise the following: cement hydrates, conventional cement-sand mortar, calcium hydroxide, unstabilised clay and sand, and unhydrated cement residues. According to literature sources, the predominance of any one of these products in a CSB fabric can influence its durability.

In Chapter 3, the block production process was described as being a major input variable that can affect the properties and behaviour of a block (3.4.1). The main processing stages identified from the literature were: soil preparation, mixing, moulding, and curing. The sequencing is so dependent that one stage must be completed before the next one can begin. The importance of each of the sub-stages in the block production process has often been underrated. Underestimation of the above steps can lead to the production of blocks of low strength and durability (3.4.1, 3.4.2, 3.4.3, 3.4.5). Generally, as the findings described in this section show, the objectives of Part A of the thesis were fully met.

8.2 RECOMMENDATIONS AND CONCLUSIONS: PART B

Part B of the thesis was devoted to direct investigations incorporating an exposure condition survey in a humid tropical environment and laboratory experimental work. The findings were reported in Chapters 4, 5, 6 and 7.

Chapter 4 described methods and findings from the exposure condition survey conducted in Uganda where CSBs have been in use since the late 1980s (4.1). Uganda is a humid tropical country, where deterioration agents occur naturally. The exposure conditions were considered to be sufficiently representative of similar conditions in most of the humid tropics. Four methods were used during the fieldwork: (i) collection of data on the inventory of CSB structures and the exposure condition, (ii) condition survey of existing buildings (random inspection, in-service testing, maintenance records), (iii) observation of methods of work at CSB production sites, including field indicator testing for soils and quality test checks of OPC and water, and (iv) interviews and questionnaires (4.1).

From the provisional inventory of CSB buildings in the country, it was found that a large stock of over 400 buildings had been built since 1987 (4.2.1). This however represents a very small fraction of the total number of buildings constructed over the

13 year period. The buildings were constructed in an attempt to reduce the enormous housing backlog (estimated at 3 million by the year 2006). Up to 90% of the CSB buildings were found in high density, low income urban areas (Namuwongo in Kampala, and Malukku in Mbale). The general conclusion made was that the rate of construction was not yet able to meet the enormous demand for low cost housing. The demand for CSB buildings is therefore likely to remain high for the foreseeable future.

Chapter 4 also described the characteristics of the natural exposure environment in Uganda (4.2.2). This was done to identify the main naturally occurring agents whose effects were likely to prove deleterious to CSB structures during their service lifetime. The main agents identified were rain, temperature and relative humidity. It was found from records that the average rainfall intensity was above 7.5 mm/hr (i.e. heavy rainfall), with drop sizes varying from 0.5 mm to 6 mm. The duration of rains varied between one and six hours. With a frequency of two rainy seasons lasting about 6 months, it can be concluded that water-related deterioration of CSBs is likely to occur during the service lifetime of such buildings. It is recommended that more research be done on erositivity of rain including the contribution of the interactions of rain drop size, drop size distribution, fall velocity and impact kinetic energy to the deterioration process.

It was also found from records that ambient temperatures averaged about 25°C, with surface temperatures in the shade reaching about 100°C. It can be concluded that under such conditions, temperature related deterioration will occur within the service lifetime of a block. Moreover, with the presence of large water bodies (lakes, rivers, swamps) throughout the country, high temperatures ensure that there is a high relative humidity (30-90%). These conditions can serve as catalysts to chemical and biologically related deterioration mechanisms. The conclusion made was that as characterised, the exposure conditions in the country provide an ideal setting for most deterioration mechanisms discussed in Chapter 2.

Chapter 4 described several reasons why visual inspection as a way of evaluating defect types and their severity on exposed block surfaces had been selected (4.3.1). All 58 buildings inspected (representing about 15% of the total CSB building stock) were all chosen at random. Their ages ranged from one month to 12 years. It was found that defect types were wide ranging: surface erosion, spaling, pitting and roughening (due to rain); surface and bulk cracking and crazing (due to temperature variations); surface and plant growth (due to biological action); disintegrated loose material residues (due to chemical action); and interblock and mortar cracks (due to settlement). The predominant defect types were surface erosion (75%) and cracking (25%). These findings confirmed that premature deterioration of CSBs can occur in the humid tropics. It was also found that like materials used under similar conditions for the same period of exposure did not show similar defects.

Chapter 4 also described findings from in-service measurements done to determine the amount of volume reduction that had occurred due to mass loss, and the dimensions of cracks (4.3.2). It was established that surface erosion can lead to irrecoverable loss of volume in a block. It was found that the reduction in volume varied with the elevation of a block within a wall, the orientation of the wall façade, and the age of exposure. For the 12-year old building, volume reduction at the higher and lower levels of its walls averaged about 28% and 35% respectively. The mean volume reduction for the east-west façade was about 34%, while that for the north-south one was about 28%. The mean volume reduction for all facades in the 8-year old structure was about 22%, while that for the 12-year old building was 31%. The average estimated rate of annual mass loss for both structures was below 3%. The rate of mass loss can be influenced by the degree of resistance offered by a block surface. It is recommended that CSB surfaces used under similar exposure conditions be made more denser, smoother and of higher intergranular strength. Other surface protection measures should also be considered, such as: rendering, surface coating and layering with higher intergranular strength mixes at the surface. Adequate surface protection is likely to remain the most economic way of increasing the durability and thus extending the service life of a block.

The severity of cracking on CSB surfaces was found to follow the same trend as surface erosion (4.3.2). It was established that while cracks occurred on all wall facades, their widths on the east-west facades (2.5 mm to 2.9 mm) were markedly greater than on the north-south facades (0.65 mm to 0.80 mm). The measured values were found to exceed the maximum permissible crack widths specified for concrete (0.25 mm for severe exposure, and 0.15 mm for normal exposure conditions). Such comparisons do not take into account the fact that CSBs contain clay, while concrete does not. It is recommended that similar permissible maximum crack widths, higher than those given for concrete, be set for CSBs. It was also found that exceptionally thick mortar was widely used for bedding blocks (15-20 mm thickness). Such mortar thickness can prevent flexible movement on expansion of blocks encouraging cracking and is therefore not recommended. It can be concluded that while a particular cause within or outside a block might initiate cracking, its subsequent development can be due to other causes. The different types of cracks observed (star shaped, linear, interconnected and penetrating) indicated that there were more than just one cause of cracking in CSBs. The linking of particular crack patterns to likely causes is recommended for further research.

Findings from preliminary field indicator tests showed that the test methods used can be valuable indicators of soil properties and behaviour (4.3.3). The conclusion made was that although the tests were largely empirical, they could still enable the general suitability and acceptability of a soil to be determined rapidly and at lower costs. It is recommended that of the 15 different indicator soil tests described, the linear shrinkage test and the sedimentation test be made compulsory. This is because they are less vulnerable to operator errors than all the other tests. The tests should also be done in the order in which they were presented in this thesis. It is further recommended that the outright rejection of soils as being unsuitable as advocated for by previous authors be avoided. It should only be done when laboratory tests show that it will prove too costly to modify the soil by improving its grading (removal of the excess fraction or inclusion of the missing fraction through controlled mixing).

It was found from visits to block production sites that no proper processing procedures were being followed (4.4.1). Yet the production process represents a major input variable that can influence the properties and performance of a block. The observations of shortcomings noted during soil extraction and preparation, mixing, moulding and curing confirmed fears that poor site practice, bad workmanship, lack of supervision and codes of practice can affect the final quality of a block. It is recommended that appropriate codes of practice, preferably based on a checklist system of good practice, be made available on block production sites. It can be concluded that without proper standards and codes, even skilled supervisors and foremen might not be able to appreciate the consequences of bad methods of work.

The results of quality checks on OPC and water used on sites showed that variations from standard specifications can significantly affect the properties and performance of a block (4.4.2). Quality checks on prisms made using the cement on site showed that the wet compressive strength (28-day) was about 15% lower than the specified minimum of 32.5 MPa for the class of OPC used (class 32 N OPC; BS 12, 1990). The prisms tested for tensile load were between about 25% and 30% lower in capacity than the recommended load values at one day and at 28 days respectively. The conclusion here is that the OPC found being used on site was not of the same quality as the specified one. It must have been contaminated at some stage (purchase, storage, mixing). Press reports seen more than one year later confirmed that malpractices involving the adulteration of OPC with clay was rampant. It can be concluded that use of low grade OPC will affect the properties and thus performance of a block. It is recommended that regular quality checks be conducted on OPC found on CSB production sites.

It was also established that use of water of unknown service record can result in blocks of lower wet compressive strength (4.4.2). The difference in strength from the specified minimum was about 23%. Tensile load tests using the same mix water source showed that the prisms were about 43% lower in wet compressive strength than the specified minimum. The conclusion here is that use of water of unknown service record can affect the strength and by implication, other properties of a block. However, since water is scarce in developing countries, the continued use of such water sources cannot be ruled out. It is therefore recommended that simple water purification and quality improvement methods be adopted (3.2.3). It was also noted that use of pre-treated tap water was taken for granted by most CSB authors.

Results of interviews and questionnaires conducted revealed a number of wide ranging issues (4.5). The number of respondents contacted was 35 (stakeholders including users, professionals, government officials, project managers, etc., all chosen at random), and the response rate was 100%. A number of conclusions can be drawn from the results.

It was found that the walling materials of choice based on previous experience and tradition were fired bricks (40%), followed by concrete blocks (33%) and CSBs (22%). Adobes were the least preferred, being considered materials of the last resort. The main reason given for preferences was the durability of the material as evidenced by its service life record (77%), followed by costs (15%) and tradition (2%). Preferred block types were found to be dry stacked interlocking blocks (55%), followed by solid blocks (32%), and bed frogged blocks (10%). Hollow blocks, despite their cost saving potential, were the least preferred (3%). The most common defect types observed by respondents over the years were surface erosion (including pitting and roughening) (75%), followed by surface and bulk cracking and crazing (20%). These findings are in agreement with earlier findings reported after the visual inspection was done. Preferred surface protection methods were external plaster and render (54%), followed by surface coatings (23%), and architectural design that incorporated a low roof overhang (18%).

According to these respondents, suggested ways of improving the service life of blocks and thus promoting their image amongst potential users include improvement of bulk strength and bonding (40%), dissemination of standards and codes (28%) and improved architectural design (20%). It can be assumed that the views of the stakeholders interviewed as summarised here represents the broad opinion and experiences of other users in developing countries. The above findings show that the objectives of Chapter 4 were fully met.

In the experimental design described in *Chapter 5*, all the input variables that can influence the quality and performance of a block were identified (5.2). They include constituent materials and processing methods (5.2 to 5.4). The soil type was fixed for all blocks, while the stabiliser type and amount, moulding pressure and curing conditions were varied. The main objective was to compare the properties and performance of improved blocks (with 10% of the cement content comprising microsilica) and traditional blocks (OPC only stabilised and OPC plus lime stabilised). Bulk and surface properties of both categories of blocks were extensively tested. The number of specimens produced for each test was three. The decision to use three specimens was based on earlier preliminary tests which concluded that the variability for the major tests were quite low (5.4.2). With the above findings, the objectives of Chapter 5 were fully met.

Chapter 6 described findings from bulk property tests which included wet compressive strength, block dry density, total water absorption and volume fraction porosity The mean WCS of improved blocks were found to be more than double those for matching traditional blocks (6.2.1). Although some improvement in strength had been expected, the order of magnitude achieved was surprisingly greater than predicted. The conclusion here is that the use of a partial cement replacement material (such as microsilica) can be an effective way of increasing strength, and by implication the durability of a block.

It was also found in the case of improved blocks, that the WCS value at the 5% cement content level (range of interest) was about five times greater than the recommended minimum value of 1.2 MPa (6.2.1). Even at the lower cement content of 3% (generally not used), the WCS value attained was surprisingly about three times higher than the minimum recommended value. The trend of the graph showed that where microsilica is used, only 1% of OPC would be required to achieve the minimum wet compressive strength of 1.2 MPa. There is no previous record prior to this thesis to show that similar spectacular gains in strength have ever been achieved in CSBs. The use of microsilica in enhancing strength in blocks is therefore strongly recommended.

The effect of increase in cement content with strength in blocks was found to closely correspond in all cases (6.2.1). Overall increase in strength in both traditional and improved blocks with increase in cement content from 3% to 11% was about six-fold. It was generally found that the increase in WCS was higher at the lower cement content levels than at the higher ones (220% compared to 97% respectively). It can therefore be concluded that use of cement contents beyond 7% is not an economic way of achieving further strength in CSBs.

It was also established that increase in compaction pressure resulted in an increase in WCS. A 70% increase in compaction pressure resulted in a 32% increase in WCS (6.2.1). The increase in WCS is however considerably lower than that achieved through a similar increase in cement content. It can be concluded that increase in cement content is a more effective way of increasing the WCS in blocks. Even where blocks of high cement content were compacted at lower moulding pressures, they were found to perform satisfactorily. The opposite was not found to be the case. This confirms earlier conclusions that the ultimate cured wet strength of a block is more sensitive to changes in cement content than compaction pressure. Moreover, it was also found that the degree of increase in WCS with increase in compaction pressure diminishes as the pressure increased. It can therefore be concluded that block presses operating within the range 2 MPa to 8MPa can be adequate to produce blocks of sufficient WCS.

It was also found in Chapter 6 that the ratio between mean dry and wet compressive strength was much lower in improved blocks than in the traditional ones (6.2.2). The ratio ranged between 1.4 and 1.9 in traditional blocks, but only between 1.1 and 1.3 in improved blocks. The ratios for the improved blocks were found to compare well with those for concrete blocks (between 1.09 and 1.21). The findings show that the higher and broader the ratio between mean DCS and WCS, the lower can the degree of intergranular bonding be expected to be. It can be concluded that the reduction in ratio for improved blocks is directly attributed to the inclusion of microsilica. This must have transformed the weaker and more porous CSB fabric into a far denser, more homogeneous and more impermeable matrix, than was hitherto possible. The use of CRMs in improving CSB properties such as strength is therefore strongly recommended. It is further recommended that use of the value of the ratio between the mean DCS and WCS be adopted as a tool for assessing the quality of bonding achieved in CSBs. Where CRMs are used, it is recommended that various cost reduction measures be considered: use of thin surface layered blocks, hollow blocks, frog-bedded blocks, and interlocking blocks.

It was shown in Chapter 6 that the effects of processing variables such as hold-back time on the WCS of blocks can be adverse (6.2.3). A progressive loss of quality was found to occur on delay in compaction of a damp soil cement mix. It was established that blocks compacted within 20 minutes of delay after damp mixing were about 27% stronger than those compacted after 45 minutes. Blocks compacted within two hours of delay were about 41% weaker. These findings compare well with those of earlier researchers. Similar effects can be expected to occur in improved blocks. It is therefore recommended that only batches that can be compacted within 30 minutes, instead of the currently used one hour, be mixed and used up in that time. The findings also confirm earlier ones which noted that poor site practice can result in the production of low quality grade blocks. It is strongly recommended that all CSB production processes be treated with the same high level of skill, competence and supervision. This should be reinforced through standards, codes, checklist systems and certification requirements.

The effect of varying curing conditions on the performance of was blocks was investigated in Chapter 6 (6.2.4). Blocks cured under exposed conditions were found to be about two-fold weaker than blocks cured under standard conditions. Had they been left exposed directly under the sun (as is commonly the practice on block production sites), the loss in WCS would have been even higher (4.4). Blocks cured by prolonged covering throughout were found to be about 29% stronger than their standard cured counterparts. Blocks cured fully immersed in water were about three times stronger than standard cured blocks, and about six-fold stronger than those cured in open exposure in the laboratory. Variation in curing conditions affects the state of moisture in a green block. It can be concluded that the fully immersed blocks emerged strongest because hydration was allowed to continue until a maximum degree of hydration was achieved. It is therefore recommended that the curing of blocks be done in such a manner as to allow the continued presence of moisture to complete the hydration reaction of OPC. Wet curing should be extended to longer periods than currently allowed for. These results also confirm the urgent need for proper codes of practice to be observed during the manufacture of blocks.

From investigation into the effects of varying the stabiliser type and content on the block dry density, it was found that the latter varied markedly with changes in the former (6.3). For matching OPC content, it was found that the density in improved blocks was between 3.3% and 5.2% higher than in corresponding traditional blocks (6.3.1). The conclusion here is that inclusion of microsilica in improved blocks had a pore filling effect, and resulted in increased homogeneity, improved bonding and reduced voids content in the block. Dry density can be a valuable indicator of quality in a block. Density however also depends on the degree of compaction used, the density of the constituent materials, the size and grading of soil particles and on the form of a block (solid, hollow, etc.). It was also established that no uniform standard exists for the determination of dry density in CSBs. It is recommended that the method requiring oven pre-drying to constant mass be adopted.

It was found in Chapter 6 that a strong positive correlation exists between density and the 28 day WCS in both categories of blocks (coefficient of correlation was 0.971 for traditional blocks and 0.996 for improved blocks) (6.3.2). It can be concluded that increase in density can result into an increase in WCS. The increase was however found not to be uniform throughout, being more pronounced at the lower cement contents than at higher ones. However, very high densities could prove disadvantageous during block laying and transportation. It is recommended that production of blocks heavier than 8.5 kg be avoided.

It was also found in Chapter 6 that due to the existence of pores within their fabric, all categories of blocks absorbed water (6.4). Increase in stabiliser content resulted into a decrease in TWA (6.4.1). Traditional blocks absorbed more water than their improved counterparts (more by 120%). The overall decrease in TWA with increase in cement content from 3% to 11% was around 40%. Generally, the less water a block absorbs, the better is its performance expected to be. It can be concluded that TWA is a valuable indicator of quality of a block as it can be used to estimate the total volume of pore space (voids).

The results showed that beyond a certain stabiliser content, water absorption by a block ceases to decrease any further, becoming almost uniform instead. The limiting value was found to be 9% in traditional blocks, but only 7% in improved blocks. It can be seen that lowering of the limit to 7% in improved blocks must have been due to the pore filling effect of microsilica.

It was also established from the results that the TWA values obtained were much lower than the recommended maximum value of 15%. Values for improved blocks were the lowest (3% to 6%). The conclusion here is that use of microsilica in improved blocks was an effective way of lowering TWA (than increase in compaction pressure). It is recommended that TWA values in blocks be used for routine quality checks, for comparison with set standards, for approximation of the voids content, and for classification of blocks according to required durability, and structural use. It is also further recommended that existing TWA test methods be standardised. Current tests do not take into account the need to oven pre-dry blocks to constant mass in order to expel air and water from the pores before immersion in water.

In Chapter 6 a strong correlation was found to exist between TWA and density (correlation coefficients were –0.985 and –0.820 for traditional and improved blocks respectively). It can therefore be inferred that increase in BDD will result in a decrease in TWA (6.4.2). For example, increase in density of 2.3% resulted into a decrease in TWA of 44% in traditional blocks (39% in improved blocks). The results also showed that beyond a certain density value (corresponding to the limiting OPC contents described earlier), no further appreciable reduction in TWA could be expected.

A general link between TVP and the performance of blocks was established in Chapter 6 (6.5). It was shown that a very strong negative correlation exists between TVP and WCS (coefficients –0.905 for traditional blocks, and –0.771 for improved blocks) (6.5.1). The conclusion here is that the greater the pores, the higher the number of flaws and localised faults within a block fabric, and so the weaker it is. The TVP was lower in improved blocks (8.4% to 13.3%) than in corresponding traditional blocks (14.4% to 25.3%). This can be attributed to the pore filling effect of microsilica. It is recommended that use of microsilica be considered in future as an economic way of reducing the TVP in CSBs.

It was also found in Chapter 6 that the correlation between BDD and TVP was strong and negative (correlation coefficients –0.984 in traditional blocks, and –0.935 in improved blocks) (6.5.2). Increase in density of about 4.1% was found to result in the lowering of the TVP by about 37% in improved blocks. It can be concluded that increased densification can be an effective way of reducing the TVP in blocks. The TVP is however also a function of water-cement ratio and of the degree of hydration achieved. The value of the latter can be increased only when moisture is available to complete the hydration process. It is therefore recommended that proper moist curing be used as a way of reducing the TVP in CSBs. The general link established between TVP and other block bulk properties are similar to those reported in concrete literature. The TVP approach has not been used before in quality evaluation of CSBs. It is recommended that TVP be included as a quality check parameter for CSBs. With the preceding findings in Chapter 6, it can be concluded that improved blocks performed significantly better than their traditional counterparts in terms of all properties for which they were tested (WCS, DCS, BDD, TWA, TVP). The objectives of Chapter 6 were fully met.

Chapter 7 described findings from petrographic analysis and surface performance monitoring tests done on improved and traditional block samples. It was noted that as the outermost boundary of a block, the surface represents its first line of defence against deterioration agents and is therefore an important feature for a block (7.1). It was also noted that any erosion of the block surface that exposes the bulk would most likely lead to an accelerated rate of deterioration.

From the thin-section micrographs of block surfaces examined it was found that the general features revealed the existence of an amorphous particulate composite structure of predominantly short range order (7.2). This was expected since particulate regularity in such a composite material is difficult to attain. Moreover since CSBs like concrete are formed from the rapid precipitation of solids from solution, random packing such as was observed should be expected. This contrasts with the distinctly continuous interlocking phases reported in fired bricks (due to mulite formed from firing). No previous publication of similar petrographic analysis exists for CSBs.

The most distinguishable features noted were coarse soil grains (fine gravel, sand), gross porosity, calcium hydroxide, clay inclusions and aggregations of OPC hydrates in the groundmass. At the resolution used, the micrographs could not resolve sub-micron phases such as individual clay or microsilica grains. The presence of calcium hydroxide justifies the use of microsilica to promote pozzolanicity in CSBs. It was however difficult to detect any micro-defects in these particular samples. It is very unlikely that similar micrographs of samples made in the field would have yielded the same results. The conclusion here is that the samples were well mixed. The micrographs confirm the release of calcium hydroxide which when left in a block fabric can be detrimental to its durability (Chapter 2). The surprisingly low gross porosity detected in improved blocks also vindicates the use of microsilica in CSBs.

The conclusion here is that by reducing voids through densification or inclusion of CRMs, pores can be reduced, hence lowering water absorption and permeability properties of a block. Further, by improving bonding through the use of CRMs and proper wet curing, closer and more rigid contacts can be attained, hence improving the surface resistance of a block. Use of microsilica in CSBs is therefore strongly recommended. Use of petrographic examination of CSBs should be extended to examine samples from various production sites.

It was discussed in Chapter 7 that no proper accelerated surface test is currently available for monitoring the performance of CSBs (7.3). Existing methods (the water drip test, water spray test, brushing test, hardness test, absorption test and the wet-dry-cycling test) all lack reliability, repeatability and accuracy. These tests were found to be operator dependent and difficult to conduct. This explains why blocks were in the past passed as durable only to prematurely succumb to normal or severe exposure conditions. The slake durability test (SDT) was therefore proposed and used as a quick predictive accelerated test for monitoring the performance of CSB surfaces of various categories (7.3). It is recommended that the standard procedures used for the test be maintained for all future tests on CSBs. It is also recommended that further research be undertaken to modify the test apparatus to make it convenient to use on a block production site (e.g. manual operation instead of mechanical).

Using the SDT, the effect of varying the stabiliser type and content on the quality of block surfaces were monitored (7.3.1). It can be concluded that more rapid mass loss will occur from the surfaces of traditional CSB samples, than from those of like materials such as fired bricks, concrete blocks and rocks. It was found that mass loss was markedly higher in traditional blocks than in improved blocks of matching cement contents.

Improved blocks of cement content above 9% were found to have mean SDI value of about 99.1%, performing as well as fired bricks and concrete block samples (mean SDI values of 99.8% and 96.6% respectively). According to current and proposed SDI classification system, improved blocks of 5% cement content and above could be categorised as being of "very high durability" or grade B and better blocks. Comparable traditional blocks of the same cement content if carefully made would be classified as being of "high durability". It can be concluded that the use of microsilica reduces the loss in mass in blocks, by considerably increasing its surface resistance to cyclic wetting, abrasion and drying. Use of microsilica (or other similar CRM) is therefore highly recommended as a way of improving the surface resistance of a block.

A strong correlation was found to exist between increase in cement content and the SDI value of all categories of blocks tested (7.3.1). It was established that increase in SDI with increase in cement content was higher at the lower cement content levels (less than 7%) than at higher ones (40% compared to 6% in traditional blocks and 22% compared to 4.9% in improved blocks). In both cases, increase in OPC content beyond 7% did not result into any further appreciable increase in SDI values. This phenomenon of diminished increase in performance with increase in OPC content beyond about 7% has featured in almost all the properties evaluated. It can be concluded that at 7% cement content, CSBs will perform better in most respects than at the current lower recommended level of 5%. The elevation of the minimum amount of OPC used (5% to 7%) is strongly recommended for CSBs meant to be used in the humid tropics. Ways of reducing costs such as bed-frogging of blocks or use of interlocking blocks that do not require use of mortar or render could be investigated. Since rapid loss in mass was detected in most block samples, it is recommended that surface protection measures be used for CSBs as described earlier (especially blocks with 5% cement content and below).

It was also found in Chapter 7 that the SDI value was strongly correlated with the evolution of strength in blocks during curing (7.3.2). Increase in curing age was found to correspond to increase in SDI values. The increase was more phenomenal before the 28th day (for OPC stabilised blocks) and on the 56th day (for OPC plus lime stabilised blocks). No appreciable increase in SDI with curing age was recorded after these periods. The SDI value for improved blocks at 28 days was about 85% higher than at seven days. The comparable figures for traditional blocks was about 51%. It can be concluded that improved blocks gained strength, and thus surface resistance, more rapidly than their traditional counterparts. The results further indicate that SDI values can be used as a surrogate test for quality in CSBs irrespective of the pre- and post-curing periods. The pattern was similar to that found with increase in strength over time during curing. Moreover, the SDT test was found to be applicable even six months and after the prescribed curing periods. The conclusion is that a new test that can reliably test the evolution of strength similar to wet compressive strength has been found for CSBs. A further conclusion is that the SDT can be used to evaluate and classify blocks irrespective of their curing age and storage history. This was not possible prior to these findings.

The correlation between SDI and WCS was found to be very strong and positive, thus confirming the preceding conclusions (7.3.3). The conclusion here is that the higher the value of the 28 day WCS, the greater is the resistance offered to surface erosion due to wetting, abrasion and drying. It was however also established that there was a diminished increase in SDI with increase in WCS. The SDI is therefore a valuable indicator of both strength and surface resistance in CSBs.

A strong correlation was also found to exist between SDI and TWA (coefficients were –0.975 and –0.939 for traditional and improved blocks respectively) (7.3.4). The higher the SDI value, the lower the TWA. The inference here is that higher surface resistance corresponds to lower water absorption. Both properties are therefore valuable indicators of surface and bulk quality respectively.

It was also established in Chapter 7 that a strong positive correlation exists between

SDI and the BDD (7.4.4) (correlation coefficients were 0.944 and 0.953 for improved blocks and traditional blocks respectively). Both were significant at the 95% confidence level using the 2-tailed test. The conclusion made is that increase in density can be associated with increase in the SDI value of a block. The denser the packing of particles and phases within a block (i.e. lesser voids), the stronger and therefore more durable it can be expected to be. Increase in SDI with increase in density was higher in traditional blocks than in the improved ones (2.3% increase in density resulting into a 49% increase in SDI, as compared to 4% increase in density resulting into a 28% increase in SDI in improved blocks). The conclusion here is that the denser the block, the less is the increase in SDI value, but the higher is the resistance to surface erosion. Increase in density is therefore an economic way of increasing the SDI value in blocks.

As the preceding findings have shown, use of the SDT as a new surface quality test is strongly recommended. Use of the procedure was found to be simple, controllable, fast, practical, accurate and of timeless value. The test method was also found to be an excellent accelerated test procedure since loss in mass occurred with significant short term value for research. The test also simulated the main deterioration mechanisms on block surfaces (erosion due to repeated wetting, abrasion and drying). Further research is recommended into the test method with a view to having the results calibrated with those obtained from natural exposure condition surveys. It is possible that the test results could one day be used to estimate the rate of surface erosion due to this particular mode of deterioration.

It is further recommended that the proposed SDI classification system be adopted for use with CSBs. The SDI test results can be used in several ways: as an aid to block classification, for selection of blocks for particular applications, for quality control during production (and delivery to site), for prediction of the rate of surface material loss, and for selection of suitable presses. The use of the SDT is likely to ensure that the durability of CSBs can for once be quantitatively determined in a more uniform and independent manner than before. Minimum required values can be specified and included amongst initial performance characteristics of CSBs. This is likely to bring an end to widespread attempts to characterise CSBs qualitatively as being of low or high durability without any standardised method of quantitative determination. From the preceding findings and conclusions, the objectives of Chapter 7 and Part B of this thesis were fully met.

8.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The main objectives of this thesis have been fully met (8.1, 8.2). The findings have however flagged up a number of new questions for further future research. It was not possible to undertake the identified new research areas within the current study. The areas for further research include the following:

- Durability concepts should be developed further so that a proper expression for the term (that extends what was described in this thesis) can be documented in CSB literature. This should be based on the intended function of a block, its conditions of use, and time in years.
- Deterioration agents should be ranked according to their severity as attempted in this thesis, and the mechanisms of their action investigated further with a view to understanding them better (surface versus bulk phenomenon).
- Surface protection methods should be researched into with a view to reducing costs. The cost and applicability of high durability blocks which are not rendered could be compared with those of low durability blocks which are

rendered. The use of surface enriched thin layers, hollow blocks, interlocking blocks and bed frogged blocks should be investigated as ways of reducing costs while maintaining adequate surface properties.

- The role of the various OPC hydrates in determining the durability of blocks requires further research. Ways of lowering the water-cement ratio and increasing the degree of hydration also require further work.
- In-service performance data of CSBs should continue to be collected and documented. Data banks could be established where such information can be centrally collected and sourced. Of particular interest to further research should be information on volume reduction due to mass loss, and crack formation in CSBs.
- Accelerated test methods for block surface evaluation and monitoring require further research. The SDT or similar tests that are not operator dependent, easy to conduct, and to interpret results, should be researched into. The test method should simulate the main modes of deterioration for the particular type of surface resistance required and should be convenient to use on site.

Finally, the use of CSBs as a cheaper alternative walling material is likely to increase in the foreseeable future. It is the improved durability of a block, rather than of any other property, that is likely to ensure its widespread acceptance in developing countries.

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APPENDIX A

BASIC CHEMICAL CONSTITUENTS OF OPC

S/N	Compound Name	Shorthand Nomenclature	Mineral Name	Density Kg/m^3	Typical Quantity by Weight %	Role
1	Tricalcium silicate	C_3S	Alite	3150	55	The major constituent in OPC; involved in the initial gel formation contributing to setting; hydration products are C-S-H fibres and $Ca(OH)_2$ crystals; contribute to strength in the early stages of hardening.
2	Dicalcium silicate	C_2S	Belite	3280	20	Same hydration products as above; contributes to increase in strength at later stages of hardening due to its slower rate of hydration.
3	Tricalcium aluminate	C_3A	Aluminate	3030	12	Contributes to setting through gel and ettringite formation due to its fast rate of hydration, but little to hardening.
4	Tretracalcium alumino ferrite	C_4AF	Ferrite	3770	8	Contributes to colour of cement, but plays little part in setting and hardening
5	Hydrated calcium sulfate	$C\bar{S}H_2$	Gypsum	2320	3.5	Controls hydration rate of C_3A; own rate of hydration very fast
6	Alkali oxides, other impurities	K_2O, Na_2O, CaO	-	-	1.5	May affect the crystal structure and reactivity or both of 1-5 above; Na_2O and K_2O may react with soils containing silica to cause ASR

(Adapted from: Weidemann et al, 1990; Young et al, 1998; Lea, 1976; Taylor, 1998)

APPENDIX B

PROPERTIES OF HYDRATION PRODUCTS OF OPC AND THEIR POTENTIAL INFLUENCES ON THE DURABILITY OF CSBs

S/N	Product		Volume Fraction	Density	Particle Size		Specific Surface Area	Morphology and Crystallinity	Strength	Impact on durability of CSBs
	Symbol	Name	%	Kg/m^3	Across µm	Thick µm	m^2g^{-1}			
1	C-S-H	Calcium sulphate hydrate	65	2000	<1	0.01	400	Irregular foils Amorphous Microporous	Provides major cohesive force but is weak due to its microporosity. This is why dry blocks will be stronger than wet blocks (stronger van der Waal forces)	Very insoluble. Water loss from its micropores will cause shrinkage or drying and creep on loading even at room temperature. Responsible for drying shrinkage in CSBs and creep respectively.
2	$Ca(OH)_2$	Calcium hydroxide	20	2250	100	10	~ 0.5	Thick hexagonal plates which cleave easily and are crystalline	Contributes to strength in CSBs reducing porosity. Cleavage tends to limit levels of high strength pastes. Is dimensionally stable and will restrain C-S-H deformations.	Blocks capillary pores hence lowering permeability in blocks. Very soluble in water, especially in presence of CO_2. It is slowly leached out by water causing increase in porosity, permeability and reduction in strength.
3	$C_4A\bar{S}H_{12}$	Monosulpho-aluminate	10	1950	~ 2	~ 0.1	~ 2	Thin irregular plates and farily crystalline	Reduces porosity but not significantly. Has minimum effect on deformation	Responsible for causing sulphate attack by reforming ettringite and causing expansion.
4	UCR	Unhydrated cement residues	5	3150	~ 1	-	~ 0.1	Remnants of original cement grains	Not very significant but may restrain C-S-H deformation	Renewed hydration may cause autogeneous healing of internal micropores
5	CP GP	Capillary pores; Gel pores	-	-	-	-	-	Openings	Total porosity is the major factor influencing strength. Fine pores contribute to shrinkage and creep	Porosity influences permeability. Large interconnected pores facilitate circulation of moisture in blocks. These can catalyse chemical reactions.

(Adapted from: Young et al, 1998)

APPENDIX C

COMPARISON OF EXISTING SOIL SUITABILITY CRITERIA

S/N	Author	Year	Basis of Criteria	Details
1	Fitzmaurice	1958	Particle size distribution	Recommendation: 33-40% sand (min.) 20-30% clay (max.) Limit: not ≮ 5% clay OPC: 5-10%
			Plasticity	Liquid limit: 40-50% Plasticity index: Less than 22% and more than 2.5%
			Compactability	Optimum moisture content: 10-14% (urban) 7-16% (rural)
			Simplified particle size distribution test	Limits: not >30% silt and clay not < 70% gravel and sand
2	United Nations	1964	Particle size distribution	Optimum: 75% sand 25% silt and clay clay not < 10% Limits: 45% sand (min.) 55% silt and clay (min.) 80% sand (max.) 20% silt and clay (max.) OPC: 4-12% by volume
3	Spence and Cook	1983	Particle size distribution	Range: Sand 60-90% Silt 10-40% Clay 0-30%
			Plasticity	Range: Liquid limit 7-40% Plasticity index 0-20%
4	Webb and Lockwood	1987	Linear Shrinkage (Alcocks Mould)	Shrinkage limits: < 15 mm not recommended 15-30 mm recommended (use 1:20/C:S) 30-45 mm recommended (use 1:15 C:S or 1:7 L.S) 45-60 mm recommended (use 1:12 C:S or 1:6 L:S) > 60 mm not recommended. Insufficient sand Advantage: • Various soil combinations can be tested for shrinkage • Guidelines for stabiliser content given
5	ILO	1987	Particle size distribution	Limits: None specificed Recommendation: Well graded soil of max. size < 6 mm

6	Stulz and Mukerji	1988	Particle size distribution	Optimum: Gravel 7% Sand 53% Silt 20% Clay 20%
			Plasticity	Plasticity index 7-29% Liquid limit 25-50% Caution: Lateritic soils may not conform to these limits
7	Houben and Guillaud	1994	Particle size distribution Plasticity Compactability Cohesion	Range: Clay 5-20% Silt 5-40% Sand 40-90% Limits: Plasticity index 3-30% Liquid limit 24-37% Dry density 1700-2400 kg/m^3 Corresponding moulding moisture content: 4-10% Maximum acceptable load 0.3-0.6 MPa Cohesion 15,000-36,000 Pa
8	Rigassi	1995	Particle size distribution Plasticity	Recommended: Gravel 0-40% Sand 25-80% Silt 10-25% Clay 8-30% Stabiliser: OPC 4-8% not < 3% For clay content 30-70% use lime Plasticity index 15-20%
9	Houben et al	1996	Particle size distribution	Range: Gravel 0-40% Sand 25-80% Silt 10-25% Clay 8-30% Recommended: Other tests be done as well OPC: Optimum 5-6% Maximum 8% Minimum 2% Caution: Clay not > 30%
10	Norton	1997	Particle size distribution Plasticity	Recommended: Gravel/sand 45-70% Silt 15-30% Clay 10-30% OPC: 5-10% not > 10% Plasticity index 10-25% Liquid limit 25-42%

APPENDIX D

DETERIORATION AGENTS AND THEIR SEVERITY RANKING (UGANDA)

S/N	Category	No	Agent	Severity Ranking	Source	Type of Action	Effect	Affected Property		Speed	Common Defect Type
								Surface	Bulk		
A	Environmental	1	Water Liquid Rain	*I*	Rain	Abrasion Wetting Penetration Solvent Catalytic	Erosive wear and tear Dampness Swelling Softening Dissolution Chemical reactions	•	•	Fast	Pitting, Roughening Mass loss Volume Reduction Moulding Volume Change
			Rising damp	*III*	Ground water	Wetting Solvent Catalytic	Dampness Swelling Softening Chemical reactions				"
			Condensation	*III*	Users	Wetting Solvent Catalytic	Dampness Chemical reactions				"
			Vapour Humidity	*II*	Atmosphere	Wetting Catalytic	Creation of moisture gradient				"
		2	Temperature	*I*	Atmosphere	Reversible Warming Cooling Irreversible Catalytic Drying	Volumetric expansion and contraction Contraction Chemical Reaction Shrinkage	•		Fast	Cracks
		3	Radiation Solar Thermal	*III*	Sun CSB	Heat absorption (heating) Heat emission (cooling)	Volumetric expansion Lowering temperature	• •	•	Fast	Cracks
		4	Wind	*II*	Atmosphere	Driving rains and particles Differential pressure	Rain penetration Loosening particles	• •		Fast	Pitting, Roughening
		5	Air Carbon dioxide	*III*	Atmosphere	Acid solution formation Alkalinity Neutralisation Catalytic (leaching)	Bond weakening	•	•	Slow	Porous residues Mass loss
			Oxygen	*III*	Atmosphere	Catalytic Oxidisation	Bond weakening				
			Gases Nitrogen oxide & Sulphur dioxide	*III*	Atmosphere	Dissolution in H_2O to form acidic conditions	Bond weakening				
			Particulates dust/grit	*IV*	Atmosphere	Accumulation in pores Other chem. reactions Deposition	Bond weakening				

B	Chemical	6	Sulfates	*II*	Soil	Expanded product formation within cement paste	Build-up of internal stresses Bond weakening Disintegration	•	•	Slow	Cracks Mass loss Disintegration Porous residues
		7	AAR ASR ACR	*III*	 Sand Clay	 Gel formation, swelling in presence of H_2O "	 Build up of expansive forces Bond weakening "				
		8	Soluble Salts	II	Soil	Crystallisation within pores	Volume changes of salt crystals induce internal stresses				
		9	Acids	*I*	Soil Groundwater	Dissolution of hydrated cement and $Ca(OH)_2$	Bond weakening				
		10	Calcium Hydroxide	*II*	Cement paste	Dissolution in water followed by leaching out	Segregation Porosity increase				
		11	Clay	*II*	Soil	Hydrophilic attraction of water	Swelling Loss of bonding				
C	Biological	12	Plants	*III*	Seeds	Penetration	Bond weakening Disintegration	•	•	Slow	Surface cracks Deep cracks & crevices
		13	Insects	*III*	Larvae	Boring	Bond weakening Disintegration	•	•	Slow	Deep holes

LEGEND:	Speed		Severity Ranking
	Fast: 1-3 years	I	Very severe
	Moderate: 3-5 years	II	Severe
	Slow: >5 years	III	Low severity

RESULTS OF THE VISUAL OBSERVATION RECORD OF DEFECTS IN CSB BUILDINGS AND DIAGNOSIS OF LIKELY CAUSES (UGANDA, JANUARY-MARCH, 2000)

S/N	DEFECT TYPE	Fraction of buildings (%)	CAUSE										WALL						AGE OF BUILDING		REMARKS
			Rain abrasion	Rain softening	Temperature	Relative humidity	Chemical action	Biological action	Handling	Workmanship	Curing	Settlement	FACADE		SECTION				YEARS		
													N-S	E-W	U	M	L	C	1-5	5-12	
1	Surface erosion	75	•										***	***	*	**	***	***	•	•	Mostly in the rainy season
2	Surface pitting	72	•										***	***	*	**	***	***	•	•	"
3	Surface roughening	74	•	•									***	***	*	**	***	***	•	•	"
4	Surface spalling	16		•			•				•		***	***	*	**	***		•	•	"
5	Surface growth	3				•		•					*	*	*	*	*			•	"
6	Surface cracking	21			•		•	•			•	•	**	***	*	**	`**		•	•	All seasons
7	Surface crazing	17			•		•				•		**	***	*	**	**		•	•	"
8	Bulk cracking	21			•		•	•			•	•	*	***	*	*	*			•	"
9	Chipped edges	25							•	•			*	*	*	*	*	***	•	•	Due to handling or transportation
10	Loose material residue	16		•			•	•					*	*			***	***		•	All seasons
11	Plant growth	1				•		•					*	*	*	*	*	*		•	"
12	Peeled off plaster	9				•					•		*	*			***	***		•	"
13	Inter block/mortar cracking	2										•	*	*	*	*	*	*		•	Foundation settlement
14	Other	1																			

KEY: Denotes defect observed •
Severity ranking: * low ** medium *** high

Façade:
N-S North-South
E-W East-West

Wall section:
U Upper
M Middle
L Lower
C Corner

APPENDIX F

COMPREHENSIVE SUMMARY LIST OF CURRENTLY AVAILABLE SOIL INDICATOR TEST TYPES

S/N	TEST NAME	AUTHOR AND YEAR OF PUBLICATION										
		1	2	3	4	5	6	7	8	9	10	11
		DoUHD 1955	Fitzmaurice 1958	United Nations 1964	ILO 1987	Webb & Lockwood 1987	Webb 1988	Stulz & Mukerji 1988	Gooding 1994	Houben & Guillaud 1994	Rigassi 1995	Norton 1997
1	Visual	•	•	•				•	•	•		•
2	Odour (smell)	•			•		•	•	•	•	•	•
3	Touch	•	•					•	•	•	•	•
4	Nibble							•		•		
5	Washing	•						•		•	•	
6	Cube (disc)				•	•		•		•	•	
7	Lustre (shine)	•		•	•			•	•	•		•
8	Adhesion	•						•		•		
9	Water retention (surface water)	•		•	•		•	•	•	•		
10	Dry strength	•		•				•	•	•		•
11	Thread (rolling/consistency)	•			•	•	•	•	•	•	•	•
12	Ribbon (cohesion)	•	•	•			•	•	•	•	•	•
13	Sedimentation (jar/bottle)		•	•	•	•	•	•	•	•	•	•
14	Decantation						•		•	•		
15	Linear Shrinkage		•	•	•	•	•	•	•	•		•

Key: • indicates that the test was described by the author

APPENDIX G

SUMMARY OF FIELD INDICATOR SOIL TEST RESULTS FOR TWO CSB PROJECT SITES IN UGANDA (JANUARY-MARCH, 2000)

S/N	TEST NAME	UNITS	RESULTS		INTERPRETATION	
			NAMUWONGO (B)	MALUKHO	NAMUWONGO (B)	MALUKHU
1	Visual test	-	Dark red-brown soil Large sand content	Dark brown-grey soil Moderate sand content	Silty sand	Clayey sand
2	Smell test	-	Non-musty smell (even on wetting)	Non-musty smell (even on wetting)	No significant presence of organic matter	No significant presence of organic matter
3	Touch test	-	Rough sensation felt on rubbing Moderate cohesion	Rough sensation felt on rubbing More cohesive: lumps sticky when moist	Silty sand	clayey sand
4	Nibble test	-	Gritty sensation	Gritty and floury sensation	Silty sand	Clayey sand
5	Washing test	-	Hands easy to rinse, but powdery sensation felt	Hand difficult to rinse clean Soapy sensation	Silty sand	Clayey sand
6	Cube test	-	Forms cube on moulding Breaks easily on drying	Forms cube on moulding Breaks with difficulty on drying	Silty sand	Clayey sand
7	Lustre test	-	Freshly cut surface of ball sphere is dull	Freshly cut surface of ball sphere is shiny	Silty sand	Clayey sand
8	Adhesion test	-	Easy penetration by knife No sticking on to knife on withdrawal	Penetration of knife with difficulty. Soil sticks on to knife on withdrawal	Silty sand	Clayey sand
9	Water retention test	taps	5-10 Ball partially crumbles	20-30 Ball flattens on pressing	Fine sand and silt present	Silt and clay present
10	Thread test	-	Medium hard thread. Reconstituted ball tends to crack and crumble	Hard thread. Reconstituted ball difficult to crush. Does not crumble	Low clay content	High clay content
11	Ribbon test	cm	5-10 Short ribbon	24-30 Long ribbon	Low to medium clay content	High clay content
12	Sedimentation test	% % %	6 (gravel) 70 (sand) 24 (silt and clay)	14 (Gravel) 61 (sand) 35 (silt and clay)	Low gravel content High sand content Medium fines content	Low gravel content Moderate sand content High fines content
13	Linear shrinkage test	mm	23	45	Soil suitable for CSB production. Recommended: 1:20 cement: soil	Soil suitable for CSB production. Recommendation: 1:12 cement : soil, or 1:6 lime : soil

LABORATORY TEST RESULTS FOR NAMUWONGO CSB SLUM UPGRADING PROJECT (UGA 186/005)

S/N	TEST TYPE	UNITS	NAMUWONGO SITE		
			A	**B**	**C**
	A. Laboratory Soil Test Results				
1	Particle size distribution				
	Gravel	%	8	2	5
	Sand	%	68	70	70
	Silt	%	12	13	3
	Clay (+ fine silt)	%	12	15	22
2	Linear shrinkage (mean)	mm	21	13	10
3	Sedimentation (Bottle test)				
	Gravel	%	10	15	5
	Sand	%	60	60	75
	Silt and Clay	%	30	25	20
4	Natural moisture content	%	14	16	16
5	Soil type	-	Lateritic soil (or dark grey coffee soil	Silty sand (murrum)	Silty sand (sand)
	B. Stabiliser Selection				
1	Cement (only)	%	6	5	4
2	Lime (only)	%	5	5	5
	C. Initial Performance Tests				
1	Block sizes (mean)	mm mm	290 x 140 x 88 220 x 107 x 70	290 x 140 x 88 220 x 107 x 70	290 x 140 x 88 220 x 107 x 70
2	Wet compressive strength (mean) R_c28				
	Cement blocks	MPa	5.1	3.9	4.1
	Lime blocks	MPa	3.0	2.9	1.5
3	Water absorption (mean)				
	Cement blocks	%	12.0	8.0	10.3
	Lime blocks	%	10.2	12.3	-

(Source: Okello, 1989; MoWHUD, 1992)

APPENDIX I

SUMMARY OF FINDINGS FROM VISITS TO BLOCK PRODUCTION SITES IN UGANDA

S/N	PROCESS and SUB PROCESSES	OBSERVATIONS / NOTES	
		MALUKHU	TEMANGALO
1	Soil Extraction and Preparation		
	Extraction		
	Adequacy of soil pre-determined	x	x
	Soil test records available (field and laboratory)	x	x
	On-site soil used	●	●
	Sub-soil extraction	●	●
	Top-soil extraction	x	x
	Manual extraction	●	●
	Mechanical extraction	●	x
	Drying		
	In sheltered area	x	x
	In the open yard	●	●
	Spreading out in thin layers	x	x
	Turning over	x	x
	Uniform colour check for drying	x	x
	Supervision	x	x
	Storage		
	In open yard	●	●
	In sheltered area (ventilated)	x	x
	Pulverising		
	Manual (wooden hammers)	x	x
	Mechanised	x	x
	Screening		
	Fixed inclined screen (5-20 mm)	●	●
	Suspended screen (5-20 mm)	x	x
	Extra removal check by hand	x	x
	Stockpiling		
	Sheltered area	x	x
	Open area	●	●
	Controlled mixing to modify	x	x
2	Mixing (soil, stabiliser, water)		
	Proportioning out		
	By mass	x	x
	By volume	●	●
	Batching (per day)	●	●
	Batching (per hour)	x	x
	Levelling off	x	x
	Dry physical state (soil, stabiliser)	x	x
	Dry mixing		
	On clean/hard ground surface	x	x
	On the open yard (grass, soil)	●	●

	Mechanical	x	x
	Manual	●	●
	Spread out soil (plus stabiliser)	x	x
	Heaped soil (plus stabiliser)	●	●
	Supervision	x	x
	Wet mixing	x	x
	On clean/hard ground surface	x	x
	On open yard (grass, soil)	●	●
	Mechanical	x	x
	Manual	●	●
	Water added by spray	x	x
	Water added by pouring	●	●
	Uniform mix colour check done	x	x
	Drop test check (OMC)	x	x
	Supervision	x	x
	Reaction time		
	Moulded within 45 minutes (OPC)	x	●
	Moulded within 24 hours (lime)	●	x
	Supervision	x	x
3	Compression		
	Measuring out		
	Controlled amount pre-measured	x	x
	Fixed volume box used	x	x
	Protected mix	x	x
	Unprotected mix	●	●
	Supervision	x	x
	Filling		
	Mould interior cleaning	x	x
	By hand	●	●
	By spade	●	x
	In layers	x	x
	Corners checked, pressed	x	x
	Topping up, removal	x	x
	Levelling off	x	x
	Correct filling check	x	x
	Periodic repeat cleaning	x	x
	Supervision	x	x
	Moulding		
	Manual press	x	x
	Motorised press	●	●
	Mould pressure check	x	x
	Solid blocks	x	x
	Hollow blocks	x	x
	Bed frogged blocks	x	x
	Interlocking blocks	●	●
	Output > 2000 per day	●	x
	Output < 2000 per day	x	●
	Same day moulding	●	●
	Supervision	x	x

	Demoulding / handling		
	Automatic	x	x
	By hand removal	•	•
	By timber pieces removal	x	x
	By pincer removal	x	x
	Curing area close by	•	•
	Supervision	x	x
	Quality checks		
	By batch	x	x
	All blocks	x	x
	None	•	•
	Appearance	x	x
	Weight	x	x
	Dimensions	x	x
	Bulk density	x	x
	Surface penetration	x	x
	Parallelism	x	x
	Corners and edges	x	x
	Supervision	x	x
4	Curing		
	Wet curing		
	Close to mould site	•	•
	On hard surface	x	x
	Polythene sheet cover	x	x
	Elephant grass cover	•	•
	Sheltered area	x	x
	By stabiliser specification	x	x
	In separated batches	x	x
	Marking	x	x
	Dry curing		
	On open yard	•	•
	In sheltered area	x	x
	Duration check	x	x
	Supervision	x	x
	Stockpiling		
	Near machine side	•	•
	Near building side	x	x
	Covered	x	x
	Uncovered	•	•
	Testing		
	WCS, BDD, TWA	x	x
	Use		
	Walling with render	•	•
	Without render	•	•
	Without mortar	•	•
	Surface coating	x	•

Key: • process observed/noted
x process not observed/noted

FIELD AND LABORATORY TESTING

SEDIMENTATION TEST (BOTTLE)

TEST TITLE: **Sedimentation (jar or bottle) Test**

Standard: Stulz and Mukerji (1988), Houben and Guillaud (1994).

Objective: To determine quantitatively the approximate relative proportions of the main fractions in a soil sample.

Precision: Low to medium accuracy.

Limitations: It is difficult to precisely discriminate the boundaries of the grain layers, which may not always be linear. The resettling movement of sand, but more especially silt and clay can affect the results if they are taken too early. The volume of the silt and clay is slightly increased due to swelling and expansion of the particles in water. They will therefore appear to be larger than they really are.

Duration: 3 to 24 hours

APPARATUS

1. Transparent cylindrical glass jar (65 mm diameter, of flat bottom with the top sealable by the palm of the hand).
2. Clock or stopwatch.
3. Centimetre scale.
4. Clean drinking water.

TEST PROCEDURE

(i) Take a representative sample of the soil and place it into the glass jar until it is about one quarter full. Fill some of the remaining three-quarters of the jar with clean drinking water, leaving just enough space at the top to allow agitation.

(ii) Leave the bottle and its soil and water content standing undisturbed so that the soil can soak in the water for about 60 minutes.

(iii) After 60 minutes have elapsed, firmly cover the top opening of the jar and shake vigorously for between 1 and 3 minutes, then replace the bottle and its contents on a flat horizontal surface. Repeat the process again an hour later, then leave the jar standing undisturbed for at least 45 minutes. After this time, the soil fractions should begin to segregate with the heavier fraction (fine gravel and sand) settling at the bottom of the bottle. The silt, clay and organic matter fractions will settle at the top of each other in that order of lightness. Organic matter will float at the surface of the water, while the finer colloids will remain in suspension in the water.

(iv) Allow up to 8 hours before measuring the precipitated height of the segregated layers using an accurate centimetre scale. First measure the overall depth of the sediments (100%) without including the depth of the clear water covering them. Then measure the height of each fraction layer separately and record it as a percentage of the total depth. Take three measurements for each layer and record the average for the sand, silt and clay.

Results are discussed in Chapter 4 and 5.

INTERPRETATION AND RECOMMENDATIONS

The depth of each separated layer provides an indication of the relative proportions of each of the main soil constituents in the sample tested. If the results show an even distribution of sand, silt and clay, then the soil is suitable for CSB production. If the results reveal an excess or absence of either sand, silt or clay, then the soil is unlikely to be suitable for stabilisation without further modification as before. The separation of the soil fractions can be further facilitated by using a suitable dispersant or deflocculant (ILO, 1987; Houben and Guillaud, 1994). Sodium hexametaphosphate (tannic acid) is commonly used. The use of ordinary salt is not recommended as it is a known flocculant causing the agglomeration of clay particles in water (Grimshaw, 1971).

FIELD AND LABORATORY TESTING

LINEAR SHRINKAGE TEST

TEST TITLE: **Linear Shrinkage Test (LST)**

Standard: Webb and Lockwood, 1987; ILO, 1987; Webb, 1988; Stulz and Mukerji, 1988.

Objective: To estimate the proportion of the clay fraction in a soil from its linear shrinkage value and by implication, the stabiliser type and amount.

Precision: Medium to high accuracy.

Duration: 7 to 10 days.

Limitations: Requires at least one week before results can be obtained.

APPARATUS

1. Sieve of aperture opening 6 mm (or 5 mm)..
2. Alcocks wooden mould: internal dimensions 600 x 40 x 40 mm open at the tope with formica lined walling.
3. Wooden spatula (small).
4. Accurate measuring scale (vernier calliper or rule to 0.5 mm).
5. Lubricant: mould release oil, vaseline or silicone grease.
6. Clean drinking water.

TEST PROCEDURE

(i) Take about 1.5 kg to 2.0 kg of the representative soil sample that has passed through the 6 mm sieve and moisten it. Make the soil wet enough to form a paste which when tapped brings water to the surface, thus indicating proximity to the OMC. Confirm the proximity to OMC by squeezing the damp soil lump in the hand and checking if it can retain its shape without soiling the hands. Also drop the lump from about one metre height and check if it does not break into several smaller lumps.

(ii) Measure and record the internal dimensions of the mould and lightly smear the inside with a suitable lubricant. This is done to prevent the soil adhering to the surface of the internal walls of the mould which would interfere with the movement while shrinking.

(iii) Fill the soil into the mould in three equal layers while tapping and lightly pressing it in all four corners using a wooden spatula. This is done to eliminate any trapped air pockets from the soil. Smoothen the top of the final layer using the spatula so that the soil exactly fills the mould box. This ensures that any soil that would have extended over is removed. It would have otherwise increased the drag as the sample dries out and begins to shrink.

(iv) Leave the filled box with its contents in the sun for a period of 5 to 7 days, or in a shaded area for 7 to 10 days. During this period, the mould and its contents should not be rewet, e.g. by rain or addition of more water.

(v) After the above period in (iv), the soil should have dried out and shrunk either as: a single piece, several pieces with cracks across the width; or hogged up and out of the mould in a crescent shape. If the soil dried out in several pieces, gently elevate the box to about 45° on one end and tap it to move all the cracked pieces to one end of the mould. If hogging is the result, then take the dry length as the average length of the upper and lower faces lengthwise.

(vi) Calculate the linear shrinkage by determining the shrinkage gap by deducting the length of the dry soil sample from that of the mould cavity box. The shrinkage is expressed as a percentage of the original mould cavity length, or simply in millimetres.

$$LS = \frac{L_W - L_d}{L_W} \times 100 \ (\%)$$

Where LS = linear shrinkage (%)

L_W = length of the wet bar (mm)

L_d = length of the dry bar (mm)

Results are discussed in Chapters 4 and 5.

RESULTS AND RECOMMENDATIONS

Shrinkage and severe cracking across the width of a soil is an indication of high sand content soils of low clay and silt contents. Shrinkage with hogging up and out is an indication of a high clay content soil.

Soil for CSB production should shrink or swell as little as possible. The more the clay content of the soil, the more it will tend to shrink. Such soils can be modified by controlled mixing with sand, in which case the test has to be repeated using the blended soil. The amount of linear shrinkage in soils have been used to suggest the type and amount of stabiliser to be used (Webb and Lockwood, 1987). Low shrinkage soils (high sand content) are better stabilised with OPC, while high shrinkage soils (high clay content) are better stabilised using lime.

PARTICLE SIZE DISTRIBUTION CHART FOR SOIL 'S'

APPENDIX M

LABORATORY RECORDING SHEET

MIX COMPOSITION USED FOR MCSB, CSSB AND CLSB

A. Microsilica-Cement Soil Blocks (MSCB)

SN	STABILISER PERCENTAGE USED		ACTUAL MASS IN GRAMS				
	cc	Microsilica	Fine gravel + sand + silt	Clay	Cement	Microsilica	Total
	%	%	g	g	g	g	g
1	3	0.3	6986.6	1232.9	255.0	25.5	8500.0
2	5	0.5	6827.6	1204.9	425.0	42.5	8500.0
3	7	0.7	6668.7	1176.8	595.0	59.5	8500.0
4	9	0.9	6509.7	1148.8	765.0	76.5	8500.0
5	11	1.1	6350.8	1120.7	935.0	93.5	8500.0

B. Cement-Stabilised Soil Blocks (CSSB)

SN	STABILISER PERCENTAGE USED		ACTUAL MASS IN GRAMS				
	cc	Other	Fine gravel + sand + silt	Clay	Cement	Other	Total
	%	%	g	g	g	g	g
1	3	-	7008.2	1236.8	255.0	-	8500.0
2	5	-	6863.7	1211.3	425.0	-	8500.0
3	7	-	6719.2	1185.8	595.0	-	8500.0
4	9	-	6574.7	1160.3	765.0	-	8500.0
5	11	-	6430.2	1134.8	935.0	-	8500.0

C. Cement-Lime Soil Blocks (CLSB)

SN	STABILISER PERCENTAGE USED		ACTUAL MASS IN GRAMS				
	cc	Lc	Fine gravel sand + silt	Clay	Cement	Lime	Total
	%	%	g	g	g	g	g
1	3	5`	6647.0	1173.0	255.0	425.0	8500.0
2	5	5	6502.5	1147.5	425.0	425.0	8500.0
3	7	5	6358.0	1122.0	595.0	425.0	8500.0
4	9	5	6213.5	1096.5	765.0	425.0	8500.0
5	11	5	6069.0	1071.0	935.0	425.0	8500.0

APPENDIX N

SUMMARY LIST OF CSBs PRODUCED

S/N	SPECIMEN REFERENCE	CEMENT CONTENT	NUMBER OF BLOCKS	NUMBER OF THE DIFFERENT SPECIMEN SIZES OBTAINED			
			290 X 140 X 100 mm	100 x 100 x 100 mm	100 x 100 x 90 mm	100 x 100 x 40 mm	100 x 90 x 40 mm
		%	No.	No.	No.	No.	No.
A	COMPACTED AT 6 MPa						
1	MCSB 116	11	3	6	3	6	3
2	MCSB 096	9	3	6	3	6	3
3	MCSB 076	7	3	6	3	6	3
4	MCSB 056	5	3	6	3	6	3
5	MCSB 036	3	3	6	3	6	3
6	CSSB 116	11	3	6	3	6	3
7	CSSB 096	9	3	6	3	6	3
8	CSSB 076	7	3	6	3	6	3
9	CSSB 056	5	3	6	3	6	3
10	CSSB 036	3	3	6	3	6	3
11	CLSB 556	5	3	6	3	6	3
12	CLSB 356	3	3	6	3	6	3
	SUBTOTAL A	**-**	**36**	**72**	**36**	**72**	**36**
B	COMPACTED AT 10 MPa						
13	CSSB 1110	11	3	6	3	6	3
14	CSSB 0910	9	3	6	3	6	3
15	CSSB 0710	7	3	6	3	6	3
16	CSSB 0510	5	3	6	3	6	3
17	CSSB 0310	3	3	6	3	6	3
	SUBTOTAL B	-	15	30	15	30	15
	GRAND TOTAL (A + B)	**-**	**51**	**102**	**51**	**102**	**51**
C	COMPARABLE MATERIALS						
18	CBS	12-18	-	6	-	-	-
19	FBS	-	-	6	-	-	-
20	RBS	-	-	6	-	-	-
	TOTAL C			**18**			

Reference key: MCSB 116 = Microsilica cement soil block compacted at 6 MPa (11% cement)
CSSB 116 = Cement stabilised soil block compacted at 6 MPa (11% cement)
CLSB 556 = Cement lime soil block compacted at 6 MPa (5% cement, 5% lime)
CBS = Concrete block sample
FBS = Fired brick sample
RBS = Rock block sample

Note: Includes list of comparable materials obtained from the laboratory.

WET COMPRESSIVE STRENGTH TESTING

TEST TITLE: **Wet Compressive Strength Test (WCS)**

Standard:	BS 3921: 1985; BS 6071: Parts 1 & 2: 1981; Neville 1995
Objective:	To determine the wet compressive strength of various categories of blocks
Precision:	High accuracy (BS 1610: 1964 Grade A or B)
Delimitations:	Results can be affected by the sample size, moisture condition, curing age, the rigidity of the testing machine, type of end preparation used, and the rate of application of the load.
Duration:	2 to 5 minutes per test
Specimen description:	Various CSB categories: MCSB, CSSB, CLSB cut to cube size 100 x 100 x 100 mm, 28 days old, pre-immersed in water for 24 hours prior to testing.

APPARATUS

1. Compression Testing Machine: Denison 7231, machine number T91080/ES 8171, calibration certificate number 04818 (re-calibrated December 1998, 1999, 2000). The machine has the means of providing the rate of loading, capacity 100-300 KN. Accuracy complies with BS 1610 grade A and B. The upper platen of the machine is able to align freely with the specimen as contact is made. The lower platen bearing the sample is plain and non-tilting.
2. Plywood packing 105 x 105 x 20 mm; free from knots and new for each sample tested.
3. Masonry saw machine (concrete lathe cutting machine); trademark Clipper, model (t W 2-40-3), MS 27, serial number 606726, 4Kw 50Hz T/M 2900 (Luxembourg). Used to reduce blocks of 290 x 140 x 100 mm to 100 x 100 x 100 mm prisms.
4. Water tank 2000 x 1000 x 600 mm with provision for free circulation of water at bottom of samples (to immerse and soak blocks overnight)
5. Laboratory balance: accuracy up to 0.1% of the mass of the specimen.

TEST PROCEDURE

(i) Take three samples each cut from the various categories of block types; measure and record their area and volume individually.

(ii) Immerse the samples in a water filled tank (temperature 10-25°C) provided with a free circulation frame at the bottom for 24 hours.

(iii) Remove and leave to drain on a stillage or damp sacking until the blocks stop dripping (about 30 minutes).

(iv) Wipe clean the bearing surface of the platens to remove any loose grit. Place the specimen between two new 4 to 20 mm plywood sheets with an over-hang allowance of 5 mm along each edge. Make sure the centre of the mass of the specimen coincides with the axis of the machine.

(v) Make a final check of the correct positioning and packing, then apply the load without shock at a rate of 15 KN/min. Maintain the load up to failure (1 to 5 minutes).

(vi) Record the maximum load at failure and as well as the rate of loading (these were recorded automatically by the machine and a printout obtained).

(vii) Note the type of failure mode and calculate the crushing strength as below:

$$WCS = \frac{M_L \quad (KN)}{A_S \quad (mm^2)}$$

Where: WCS = wet compressive strength (MPa)

M_L = maximum load (KN)

A_S = cross section area (mm^2)

(viii) Calculate the average of 3 tests done on each category of material from the same mix batch and processing method.

Repeat the same procedure to determine the dry compressive strength (DCS) value, except that the samples do not need to be soaked in water for 24 hours as before. Instead they are oven-dried till constant mass and tested as described above. Results are discussed in Chapter 6.

LABORATORY RECORDING SHEET: WET COMPRESSIVE STRENGTH

SN	SPECIMEN REFERENCE A_{CS} = 10,000 mm^2 L_R = 15 KN/min	CC	MAXIMUM LOAD	WCS (28 DAY)	MEAN WCS (28 DAY)
		%	KN	MPa	MPa
1	CSSB 361	3	14.7	1.47	
2	CSSB 362	3	14.4	1.44	1.43
3	CSSB 363	3	14.1	1.41	
4	CSSB 561	5	22.5	2.25	
5	CSSB 562	5	27.7	2.77	2.48
6	CSSB 563	5	24.2	2.42	
7	CSSB 761	7	45.4	4.54	
8	CSSB 762	7	43.3	4.33	4.57
9	CSSB 763	7	48.4	4.84	
10	CSSB 961	9	64.2	6.42	
11	CSSB 962	9	62.9	6.29	6.54
12	CSSB 963	9	69.1	6.91	
13	CSSB 1161	11	90.6	9.06	
14	CSSB 1162	11	88.8	8.88	8.99
15	CSSB 1163	11	90.3	9.03	

Key: CSSB 363 = Cement stabilised soil block / 3% cc / 6 MPa / sample no. 3
A_{CS} = Cross-section area
L_R = Loading rate
CC = Cement-content

LABORATORY RECORDING SHEET: WET COMPRESSIVE STRENGTH

SN	SPECIMEN REFERENCE A_{CS} = 10,000 mm^2 L_R = 15 KN/min	CC	MAXIMUM LOAD	WCS (28 DAY)	MEAN WCS (28 DAY)
		%	KN	MPa	MPa
1	MCSB 361	3	31.9	3.19	
2	MCSB 362	3	30.7	3.07	3.12
3	MCSB 363	3	31.0	3.10	
4	MCSB 561	5	53.3	5.33	
5	MCSB 562	5	61.5	6.15	5.76
6	MCSB 563	5	58.0	5.80	
7	MCSB 761	7	96.8	9.68	
8	MCSB 762	7	106.7	10.67	10.11
9	MCSB 763	7	99.8	9.98	
10	MCSB 961	9	143.6	14.36	
11	MCSB 962	9	140.1	14.01	14.19
12	MCSB 963	9	142.0	14.20	
13	MCSB 1161	11	181.0	18.10	
14	MCSB 1162	11	181.3	18.13	18.30
15	MCSB 1163	11	186.7	18.67	

Key: MCSB 761 = Microsilica-cement soil block / 11% cc / 6 MPa / sample no. 1
A_{CS} = Cross-section area
L_R = Loading rate
CC = Cement-content

LABORATORY RECORDING SHEET: WET COMPRESSIVE STRENGTH

SN	SPECIMEN REFERENCE A_{CS} = 10,000 mm^2 L_R = 15 KN/min	CC	MAXIMUM LOAD	WCS (28 DAY)	MEAN WCS (28 DAY)
		%	KN	MPa	MPa
1	CSSB 3101	3	19.8	1.98	
2	CSSB 3102	3	18.7	1.87	1.89
3	CSSB 3103	3	18.2	1.82	
4	CSSB 5101	5	31.5	3.15	
5	CSSB 5102	5	32.9	3.29	3.21
6	CSSB 5103	5	31.9	3.19	
7	CSSB 7101	7	52.4	5.24	
8	CSSB 7102	7	53.3	5.33	5.29
9	CSSB 7103	7	53.0	5.30	
10	CSSB 9101	9	74.8	7.48	
11	CSSB 9102	9	75.0	7.50	7.51
12	CSSB 9103	9	75.5	7.55	
13	CSSB 11101	11	98.1	9.81	
14	CSSB 11102	11	98.4	9.84	9.84
15	CSSB 11103	11	98.7	9.87	

Key: CSSB 9102 = Cement stabilised soil block / 9% cc / 10 MPa / sample no. 2
A_{CS} = Cross-section area
L_R = Loading rate
CC = Cement-content

LABORATORY RECORDING SHEET: DRY COMPRESSIVE STRENGTH

SN	SPECIMEN REFERENCE A_{CS} = 10,000 mm^2 L_R = 15 KN/min	CC	MAXIMUM LOAD	DCS (28 DAY)	MEAN DCS (28 DAY)
		%	KN	MPa	MPa
1	CSSB 361	3	27.3	2.73	
2	CSSB 362	3	26.9	2.69	2.70
3	CSSB 363	3	26.8	2.68	
4	CSSB 561	5	46.6	4.66	
5	CSSB 562	5	45.7	4.57	4.61
6	CSSB 563	5	46.0	4.60	
7	CSSB 761	7	73.1	7.31	
8	CSSB 762	7	73.0	7.30	7.33
9	CSSB 763	7	73.8	7.38	
10	CSSB 961	9	96.9	9.69	
11	CSSB 962	9	96.4	9.64	9.66
12	CSSB 963	9	96.5	9.65	
13	CSSB 1161	11	122.5	12.25	
14	CSSB 1162	11	123.6	12.36	12.3
15	CSSB 1163	11	122.9	12.29	

Key: CSSB 562 = Cement stabilised soil block / 5% cc / 6 MPa / sample no. 2
DCS = Dry compressive strength
A_{CS} = Cross-section area
L_R = Loading rate
CC = Cement-content

LABORATORY RECORDING SHEET: DRY COMPRESSIVE STRENGTH

SN	SPECIMEN REFERENCE A_{CS} = 10,000 mm^2 L_R = 15 KN/min	CC	MAXIMUM LOAD	DCS (28 DAY)	MEAN DCS (28 DAY)
		%	KN	MPa	MPa
1	MCSB 361	3	39.8	3.98	
2	MCSB 362	3	39.1	3.91	3.94
3	MCSB 363	3	39.3	3.93	
4	MCSB 561	5	70.0	7.00	
5	MCSB 562	5	71.0	7.10	7.09
6	MCSB 563	5	71.7	7.17	
7	MCSB 761	7	121.5	12.15	
8	MCSB 762	7	119.7	11.97	12.02
9	MCSB 763	7	119.4	11.94	
10	MCSB 961	9	162.2	16.22	
11	MCSB 962	9	161.2	16.12	16.18
12	MCSB 963	9	162.0	16.20	
13	MCSB 1161	11	206.0	20.6	
14	MCSB 1162	11	207.0	20.7	20.5
15	MCSB 1163	11	202.0	20.2	

Key: MCSB 761 = Microsilica-cement soil block / 7% cc / 6 MPa / sample no. 1
A_{CS} = Cross-section area
L_R = Loading rate
CC = Cement-content

LABORATORY RECORDING SHEET: BLOCK DRY DENSITY (BDD)

(CSSB Specimens)

SN	Sample Ref.	cc	Dimensions				Oven dry mass			Block dry density	
			L	W	H	Gross volume	1	2	3	Gross	Mean
		%	mm	mm	mm	m^3 (x 10^{-3})	g	g	g	Kg/m^3	Kg/m^3
1	CSSB 361	3	101.2	99.5	101.1	1.01802	2120.1	2118.6	2118.5	2081	
2	CSSB 362	3	101.3	99.6	101.2	1.02106	2130.3	2130.0	2129.9	2085	2084
3	CSSB 363	3	101.4	99.8	101.1	1.02310	2134.0	2133.4	2133.2	2085	
4	CSSB 561	5	101.1	99.6	101.4	1.02105	2153.9	2153.4	2153.4	2109	
5	CSSB 562	5	101.2	99.6	101.4	1.02206	2146.8	2146.3	2146.3	2100	2102
6	CSSB 563	5	101.4	99.7	101.3	1.02410	2147.9	2147.6	2147.5	2097	
7	CSSB 761	7	101.1	99.7	101.1	1.01905	2153.1	2152.3	2152.2	2112	
8	CSSB 762	7	101.0	99.6	101.0	1.01602	2149.6	5149.2	2148.9	2115	2114
9	CSSB 763	7	101.0	99.8	101.0	1.01806	2153.4	2153.2	2153.2	2115	
10	CSSB 961	9	101.3	99.5	101.1	1.01902	2172.8	2172.6	2172.6	2132	
11	CSSB 962	9	101.2	99.7	101.1	1.02006	2167.9	2167.6	2167.6	2125	2127
12	CSSB 963	9	101.2	99.5	101.3	1.02003	2167.8	2166.8	2166.5	2124	
13	CSSB 1161	11	101.1	99.9	101.2	1.02211	2179.2	2178.2	2178.1	2131	
14	CSSB 1162	11	101.4	99.8	101.1	1.02310	2185.8	2185.3	2185.3	2135	2132
15	CSSB 1163	11	101.3	99.9	101.1	1.02312	2178.6	2178.2	2178.2	2129	

Key: CSSB 361 = Cement stabilised soil block (3% cc / 6 MPa / sample no. 1)
L = Length
W = Width
H = Height

LABORATORY RECORDING SHEET: BLOCK DRY DENSITY (BDD)

(CSSB Specimens)

SN	Sample Ref.	cc	Dimensions				Oven dry mass			Block dry density	
			L	W	H	Gross volume	1	2	3	Gross	Mean
		%	mm	mm	mm	m^3 (x 10^{-3})	g	g	g	Kg/m^3	Kg/m^3
1	CSSB 3101	3	101.0	99.8	101.1	1.0191	21525.5	2152.3	2152.3	2112	
2	CSSB 3102	3	101.1	99.9	101.2	1.0221	2164.9	2164.9	2164.8	2118	2113
3	CSSB 3103	3	101.0	99.8	101.2	1.0201	2151.3	2151.3	2151.3	2109	
4	CSSB 5101	5	101.2	99.5	101.3	1.0200	2171.7	2171.6	2171.6	2129	
5	CSSB 5102	5	101.1	99.7	101.3	1.0211	2168.9	2168.9	5168.8	2124	2128
6	CSSB 5103	5	101.2	99.7	101.4	1.0231	2180.3	2180.3	2180.2	2131	
7	CSSB 7101	7	100.9	99.6	101.3	1.0180	2170.6	2170.5	2170.4	2132	
8	CSSB 7102	7	101.0	99.5	101.3	1.0170	2174.5	2174.4	2174.4	2138	2136
9	CSSB 7103	7	101.1	99.6	101.2	1.0190	2178.9	2178.8	2178.8	2138	
10	CSSB 9101	9	101.3	99.7	101.1	1.0211	2193.4	2193.3	2193.3	2148	
11	CSSB 9102	9	101.3	100.1	101.0	1.0242	2201.9	2201.9	2201.9	2150	2149
12	CSSB 9103	9	101.1	99.9	101.2	1.0221	2196.8	2196.6	2196.5	2149	
13	CSSB 11101	11	101.2	99.8	101.3	1.0231	2205.9	2205.8	2205.8	2156	
14	CSSB 11102	11	101.2	99.6	101.4	1.0221	2202.8	2202.5	2202.5	2155	2157
15	CSSB 11103	11	101.3	99.9	101.2	1.0241	2212.4	2212.2	2212.1	2160	

Key: CSSB 3101 = Cement stabilised soil block (3% cc / 10 MPa / sample no. 1)
L = Length
W = Width
H = Height

LABORATORY RECORDING SHEET: BLOCK DRY DENSITY (BDD)

(MCSB SPECIMENS)

SN	Sample Ref.	cc	Dimensions				Oven dry mass			Block dry density	
			L	W	H	Gross volume	1	2	3	Gross	Mean
		%	mm	mm	mm	m^3 (x 10^{-3})	g	g	g	Kg/m^3	Kg/m^3
1	MCSB 361	3	101.2	99.6	101.1	1.01904	2197.5	2197.0	2197.0	2156	
2	MCSB 362	3	101.1	99.6	101.2	1.02211	2199.8	2199.6	2199.6	2152	2153
3	MCSB 363	3	101.0	99.7	101.3	1.02006	2194.3	2194.2	2194.2	2151	
4	MCSB 561	5	101.1	99.8	101.2	1.02109	2221.3	2221.0	2220.9	2175	
5	MCSB 562	5	101.3	99.7	101.3	1.02309	2230.5	2230.3	2230.0	2180	2176
6	MCSB 563	5	101.2	99.6	101.2	1.02005	2216.7	2216.7	2216.6	2173	
7	MCSB 761	7	101.2	99.6	101.4	1.02514	2247.3	2247.2	2247.1	21912	
8	MCSB 762	7	101.1	99.8	101.3	1.02209	2247.9	2247.8	2247.6	2199	2194
9	MCSB 763	7	101.4	99.8	101.4	1.02614	2248.5	2248.4	2248.3	2191	
10	MCSB 961	9	101.3	99.5	101.1	1.01902	2255.8	2251.1	2255.1	2213	
11	MCSB 962	9	101.4	99.7	101.0	1.02107	2267.2	2266.9	2266.8	2220	2218
12	MCSB 963	9	101.1	99.6	101.3	1.02005	2265.7	2265.6	2265.5	2221	
13	MCSB 1161	11	101.2	99.8	101.0	1.02008	2284.4	2283.9	2283.9	2239	
14	MCSB 1162	11	101.2	99.8	101.0	1.02008	2297.7	2292.2	2292.1	2247	2242
15	MCSB 1163	11	101.3	99.6	101.1	1.02005	2285.3	2284.9	2284.9	2240	

Key: MCSB 361 = Microsilica-cement soil block (3% cc / 6 MPa / sample no. 1)
L = Length
W = Width
H = Height

LABORATORY RECORDING SHEET: BLOCK DRY DENSITY (BDD)

(CLSB SPECIMENS)

SN	Sample Ref.	cc	Dimensions				Oven dry mass			Block dry density	
			L	W	H	Gross volume	1	2	3	Gross	Mean
		%	mm	mm	mm	m^3 (x 10^{-3})	g	g	g	Kg/m^3	Kg/m^3
1	CLSB 3561	3	101.2	99.5	101.1	1.01802	2085.3	2084.9	2084.9	2048	
2	CLSB 3562	3	101.0	99.6	101.0	1.01602	2089.1	2088.9	2088.9	2056	2051
3	CLSB 3563	3	101.3	99.6	101.2	1.02106	2092.4	2092.2	2092.1	2049	
4	CLSB 5561	5	101.1	99.8	101.3	1.02209	2109.8	2109.6	2109.6	2064	
5	CLSB 5562	5	101.1	99.8	101.1	1.02008	2109.9	2109.6	2109.5	2068	2066
6	CLSB 5563	5	101.3	99.8	101.2	1.02311	2113.8	2113.8	2113.7	2066	
7	CLSB 761	7	101.0	99.9	101.1	1.02009	2113.9	2113.7	2113.6	2072	
8	CLSB 762	7	101.4	99.9	101.1	1.02413	2127.3	2127.2	2127.1	2077	2074
9	CLSB 763	7	101.1	99.7	101.2	1.02006	2114.8	2114.6	2114.6	2073	
10	CLSB 961	9	101.2	99.5	101.3	1.02003	2121.9	2121.8	2121.7	2080	
11	CLSB 962	9	101.2	99.8	101.3	1.02311	2126.2	2126.1	2126.0	2078	2081
12	CLSB 963	9	101.3	99.6	101.2	1.02106	2129.4	2128.9	2128.9	2085	
13	CLSB 1161	11	101.4	99.9	101.1	1.02413	2147.9	2147.6	2147.6	2097	
14	CLSB 1162	11	101.2	99.8	101.0	1.02008	2132.5	2131.9	2131.9	2090	2095
15	CLSB 1163	11	101.3	99.9	101.0	1.02211	2144.7	2144.5	2144.4	2098	

Key: CLSB 3561 = Cement-lime stabilised soil block (3% cc / 5% lc / 6 MPa / sample no. 1)
L = Length
W = Width
H = Height

TOTAL WATER ABSORPTION AND VOLUME FRACTION POROSITY

TEST TITLE: **Total Water Absorption Test (TWA)**
Total Volume Porosity (TVP)

Standard: BS 3921: 1985; BS 1881: Part 122: 1983; ASTM C 642 90

Objective: To determine the water absorption values of blocks and to calculate the total volume porosity.

Precision: Medium to high accuracy

Delimitations: By using the cold immersion method, some air may still remain entrapped in the pores.

Duration: 24 hours

Specimen description: Various CSB categories (as before); fired brick samples and concrete block samples.

APPARATUS

1. Ventilated drying oven (BS 2648).
2. Tank with bottom grid to ensure free circulation of water.
3. Electronic weighing scale (accurate to 0.1% of the specimen mass).

TEST PROCEDURE

(i) Dry the specimens from each category of blocks to constant mass in the oven at temperatures between 110°C and 115°C.

(ii) When cool, weigh each specimen to an accuracy of 0.1% of the specimen mass.

(iii) Immerse the specimens in a single layer tank immediately after weighing so that water can circulate freely on all sides and bottom of the sample. Leave a space of about 10 mm between adjacent samples in the tank.

(iv) After 24 hours, remove the specimens, wipe off the surface water while shaking lightly with a damp cloth and reweigh each specimen within 2 minutes of removal from the water tank.

(v) Calculate the water absorbed by each sample (TWA) expressed as a percentage of the dry mass using the equation:

$$TWA = \frac{(M_W - M_D)}{M_D} \times 100$$

Where: TWA = total water absorption (%)
M_W = wet mass (g)
M_D = dry mass (g)

Obtain the mean of three samples of the same mix and processing category (Chapter 5).

(vi) Calculate the total volume porosity using the formula.

$$n = \frac{(TWA)\,\rho}{100\,\rho_W}$$

Where: n = porosity (fraction)
ρ = block dry density (kg/m^3)
ρ_W = density of water (kg/m^3)
TWA = total water absorption (%)

The results obtained are discussed in Chapter 6.

APPENDIX T (1)

LABORATORY RECORDING SHEET: TOTAL WATER ABSORPTION AND TOTAL VOLUME POROSITY

			SAMPLE TYPE														
			Cement stabilised soil block (CSSB) : 6 MPa block samples														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	ITEM	UNITS	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	Pre-test dry mass (1)	g	724.7	704.1	711.3	722.9	722.5	731.7	740.8	741.3	742.5	770.4	761.7	763.9	781.8	782.6	796.9
2	Pre-test dry mass (2)	g	724.5	703.9	710.6	722.8	722.2	721.6	739.9	741.0	742.3	770.1	761.5	763.5	781.7	782.4	796.9
3	Pre-test dry mass (3)	g	724.5	703.8	710.6	722.8	722.2	731.6	739.8	740.9	742.3	770.1	761.5	763.4	781.7	782.4	796.8
4	Post-test wet mass	g	818.7	784.7	794.5	792.2	791.5	806.2	801.2	800.2	795.0	827.1	812.5	816.1	835.6	838.0	847.8
5	Total water absorption	%	13.0	11.5	11.8	9.6	9.6	10.2	8.3	8.0	7.1	7.4	6.7	6.9	6.9	7.1	6.4
6	Mean TWA	%	12.1			9.8			7.8			7.0			6.8		
7	Volume fraction porosity	%	25.3			20.6			16.5			14.9			14.4		

LABORATORY RECORDING SHEET: TOTAL WATER ABSORPTION AND TOTAL VOLUME POROSITY

			SAMPLE TYPE														
			Cement stabilised soil blocks (CSSB) : 10 MPa block samples														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	ITEM	UNITS	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	Pre-test dry mass (1)	g	721.3	722.8	726.9	750.6	744.8	754.4	775.7	763.9	760.9	781.3	776.7	782.7	789.3	793.6	796.0
2	Pre-test dry mass (2)	g	720.9	721.7	726.5	749.9	744.7	753.4	775.5	763.9	760.8	781.3	776.6	782.4	788.9	793.4	795.2
3	Pre-test dry mass (3)	g	720.8	721.7	726.4	749.8	744.6	753.3	775.5	763.9	760.8	781.1	776.5	782.4	788.9	793.4	795.1
4	Post-test wet mass	g	795.8	793.1	799.0	807.5	801.9	806.8	823.6	809.0	812.5	820.9	821.5	821.5	827.6	837.0	836.4
5	Total water absorption	%	10.4	9.9	10.0	7.7	7.7	7.1	6.2	5.9	6.8	5.1	5.8	5.0	4.9	5.5	5.2
6	Mean TWA	%	10.1			7.5			6.3			5.3			5.2		
7	Volume fraction porosity	%	21.4			16.0			13.5			11.5			11.1		

LABORATORY RECORDING SHEET: TOTAL WATER ABSORPTION AND TOTAL VOLUME POROSITY

			SAMPLE TYPE														
			Microsilica cement soil block (MCSB) : 6 MPa block samples														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	ITEM	UNITS	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	Pre-test dry mass (1)	g	741.6	743.3	757.1	760.4	765.3	763.5	770.6	769.9	772.5	788.4	786.5	786.5	791.8	795.7	799.9
2	Pre-test dry mass (2)	g	740.8	742.9	755.9	760.1	764.8	763.5	770.4	769.7	771.8	787.9	786.5	786.1	791.5	795.6	799.5
3	Pre-test dry mass (3)	g	740.7	742.8	755.9	760.1	764.8	763.4	770.3	769.5	771.8	787.9	786.3	786.0	791.5	795.6	799.4
4	Post-test wet mass	g	794.8	782.2	801.3	789.0	803.0	796.2	801.9	797.2	801.1	817.1	818.5	814.3	821.6	824.2	830.6
5	Total water absorption	%	7.3	5.3	6.0	3.8	5.0	4.3	4.1	3.6	3.8	3.7	4.1	3.6	3.8	3.6	3.9
6	Mean TWA	%	6.2			4.4			3.9			3.8			3.8		
7	Volume fraction porosity	%	13.3			9.5			8.5			8.4			8.4		

APPENDIX T (4)

LABORATORY RECORDING SHEET: TOTAL WATER ABSORPTION AND TOTAL VOLUME POROSITY

			SAMPLE TYPE														
			Cement-lime soil blocks (CLSB) : 6 MPa block samples (5% cc)														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	ITEM	UNITS	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	Pre-test dry mass (1)	g	674.9	699.6	693.8	707.2	713.7	725.9	731.3	727.6	728.7	738.6	740.9	741.8	764.6	756.8	772.5
2	Pre-test dry mass (2)	g	674.7	699.1	693.5	706.8	713.5	725.2	731.1	726.9	728.5	738.5	740.8	741.7	764.1	756.7	772.3
3	Pre-test dry mass (3)	g	674.6	699.1	693.5	706.8	713.4	725.2	731.1	726.9	728.4	738.5	740.8	741.6	763.9	756.7	772.3
4	Post-test wet mass	g	767.0	792.8	794.8	801.5	799.0	812.9	817.4	789.7	802.0	810.1	810.4	809.1	828.8	826.3	844.1
5	Total water absorption	%	13.7	13.4	14.6	13.4	12.0	12.1	11.8	9.9	10.1	9.7	9.4	9.1	8.5	9.2	9.3
6	Mean TWA	%	13.9			12.5			10.6			9.4			9.0		
7	Volume fraction porosity	%	28.4			25.8			22.0			19.6			18.9		

LABORATORY RECORDING SHEET: TOTAL WATER ABSORPTION AND TOTAL VOLUME POROSITY

			SAMPLE TYPE														
			Fired bricks (FB); Concrete blocks (CBS); and Rock block samples														
			FB			CBS			RBS (sandstone)								
SN	ITEM	UNITS	1	2	3	1	2	3	1	2	3						
1	Pre-test dry mass (1)	g	163.9	188.6	207.1	229.7	216.9	212.3	236.8	224.5	241.9						
2	Pre-test dry mass (2)	g	163.6	188.3	207.1	229.4	216.9	211.9	236.5	223.9	241.7						
3	Pre-test dry mass (3)	g	163.6	188.3	207.1	229.4	216.8	211.8	236.5	223.9	241.7						
4	Post-test wet mass	g	179.3	204.7	225.7	237.0	227.0	219.6	247.1	235.5	252.3						
5	Total water absorption	%	9.6	8.7	9.0	3.3	4.7	3.7	4.5	5.2	4.4						
6	Mean TWA	%	9.1			3.9			4.7								
7	Volume fraction porosity	%	-			-			-								

THIN SECTION MICROGRAPH OF CSB SURFACES

EVALUATION OF SURFACE PERFORMANCE

SLAKE DURABILITY TEST

TEST TITLE:	**Slake Durability Test (SDT)**
Standard:	ISO (1967); ISRM (1971); Gamble (1971); Franklin and Chandra (1972).
Objective:	To monitor the performance of surfaces of various block samples when subjected to wetting, abrasion and drying.
Precision:	Very high accuracy
Delimitations:	Results can be affected by sample shape, size, weight and number; sieve mesh size, drum size and speed of rotation; state of sample moisture condition; duration of slaking; chemistry of the slaking liquid.
Duration:	10 minutes
Sample description:	Soil type (soil 'S'); sample types (IPD and TDB of varied cc 3% to 11% compressed at 6 MPa and 10 MPa; curing age (7 days, 14 days, 28 days, 56 days). FBS, CBS and RBS also tested

APPARATUS

1. Slake durability test equipment: sieve mesh opening 2mm, drum size (140 mm diameter), 100 mm (long); speed of rotation (20 revolutions per minute); electrically operated.
2. Electronic weighing scale.
3. Standard laboratory oven (105°C)
4. Timer (clock).
5. China clay dish containers (90g to 300g).
6. Laboratory tap water (Coventry).
7. Hand-held magnifying glass.

TEST PROCEDURE

(i) To represent each specimen sample, select 4 or 5 pre-cut samples each weighing between 115g and 125g with a total mass of between 450g and 550g. Oven dry the samples overnight to constant mass.

(ii) Weigh and mark the dish containers separately and then together with their contents from (i) above.

(iii) Place the pre-weighed and oven-dried samples into the drums. Couple the drums to the mortar drive, making sure they are connected in the correct order.

(iv) Fill the tanks with laboratory tap water (about 20°C) to the level indicated on the side of the tanks and immediately set the test in motion using the switch. Run and time the test for 10 minutes.

(v) At the end of 10 minutes, switch off the drive, remove the drums and record the state of the water in each bath and the type of sediments deposited at the bottom of each one. Examine the worn samples using a hand-held magnifying glass.

(vi) Place the removed specimens into their respective china containers and dry them to constant mass using the oven set at 105°C. When successive weighings yield the same result, record the dry mass.

(vii) The slake durability index (SDI or I_d) is then given in percent terms by the ratio of the final to original mass:

$$SDI = \frac{M_f}{M_O} \times 100$$

Where: SDI = slake durability index (%)

M_f = final mass (g)

M_O = original mass (g)

The container mass should be deducted before determining the SDI in all cases.

(viii) Repeat steps (i) to (vii) for all other samples to be tested.

CLASSIFICATION OF RESULTS

Existing and proposed classifications and grading are described in Chapter 7, the results obtained are also discussed in Chapter 7.

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Cement-Stabilised Soil Blocks (CSSB) – 28 days (6 MPa)														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	Container Reference	-	CSS31	CSS32	CSS33	CSS51	CSS52	CSS53	CSS71	CSS72	CSS73	CSS91	CSS92	CS593	CS111	CS112	CSS113
2	Container mass	g	274.5	257.3	296.7	136.2	136.0	155.5	156.7	155.8	157.9	171.4	157.5	157.9	257.3	274.5	182.4
3	Container + pre-test dry mass (1)	g	717.8	712.9	789.7	624.3	611.5	633.0	644.1	657.3	668.6	679.9	681.7	696.9	798.8	821.3	721.7
4	Container + pre-test dry mass (2)	g	716.2	711.2	789.4	622.9	611.3	631.7	643.5	655.4	666.3	679.4	681.1	696.8	798.4	820.6	721.3
5	Container + pre-test dry mass (3)	g	716.2	711.2	789.1	622.8	611.0	631.3	643.4	655.2	666.1	678.9	681.0	696.8	797.7	820.4	721.3
6	Container + pre-test dry mass (4)	g	716.1	711.2	789.1	622.5	611.1	631.3	643.3	655.2	666.0	678.9	680.9	696.7	797.7	820.4	721.0
7	Pre-test dry mass less container mass	g	441.6	453.9	492.2	486.3	475.1	475.8	486.6	499.4	508.1	507.5	523.4	538.8	540.4	545.9	538.6
8	Container + post-test dry mass (1)	g	551.6	549.7	597.4	549.1	515.5	534.9	587.3	600.7	592.4	632.2	617.5	642.8	755.5	778.1	693.7

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W (1)

			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
9	Container + post-test dry mass (2)	g	551.2	548.2	596.5	547.6	514.9	534.6	586.4	600.2	590.9	630.8	617.1	642.5	755.3	778.5	692.2
10	Container + post-test dry mass (3)	g	551.2	548.2	596.3	547.6	514.8	534.4	586.4	600.2	590.8	630.6	617.1	642.3	755.0	778.5	691.9
11	Container + post-test dry mass (4)	g	550.9	548.2	596.2	547.6	514.7	534.2	586.4	600.3	590.8	630.7	617.0	642.3	755.0	778.4	691.9
12	Post-test dry mass less container mass	g	276.4	290.9	299.3	411.4	378.7	378.7	429.7	444.5	432.9	459.3	459.5	484.4	497.7	503.9	509.5
13	Slake durability Index	%	62.6	64.1	60.8	84.6	79.7	79.6	88.3	89.0	85.2	90.5	87.8	89.9	92.1	92.3	94.6
14	Mean SDI	%		62.5			81.3			87.5			89.4			93.0	
15	Mean total mass loss	%		37.5			18.7			12.5			10.6			7.0	

CSSB (28-days, 6MPa)

APPENDIX W (2)

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Cement-lime Soil Blocks (CLSB) – 28 days (6 MPa)														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	Container Reference	-	C31	C32	C33	C51	C52	C53	C71	C72	C73	C91	C92	C93	C111	C112	C113
2	Container mass	g	157.5	156.8	136.0	296.9	257.3	274.5	155.5	171.4	136.2	182.4	157.5	156.7	155.8	157.9	155.7
3	Container + pre-test dry mass (1)	g	613.8	618.6	595.9	774.7	759.4	771.6	662.5	667.8	588.1	707.9	623.0	631.8	662.7	695.5	615.3
4	Container + pre-test dry mass (2)	g	613.3	617.9	595.1	773.9	758.3	770.5	661.9	667.3	587.5	707.8	622.7	630.9	662.3	694.8	614.6
5	Container + pre-test dry mass (3)	g	612.8	617.4	594.7	772.0	757.3	769.8	661.4	667.3	587.3	707.8	622.7	630.6	662.3	694.6	614.5
6	Container + pre-test dry mass (4)	g	612.8	617.4	594.7	772.0	757.3	769.8	661.4	667.2	587.2	707.7	622.7	630.6	662.2	694.6	614.5
7	Pre-test dry mass less container mass	g	455.3	460.6	458.7	475.1	500.0	495.3	505.9	495.8	451.0	525.3	465.2	473.9	506.4	536.7	458.8
8	Container + post-test dry mass (1)	g	411.6	391.1	379.6	650.0	637.8	642.9	592.8	584.7	513.3	638.5	573.9	566.2	607.6	635.4	559.4

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W (2)

SN	Item	Units	3% cc			5% cc			7% cc			9% cc			11% cc		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
9	Container + post-test dry mass (2)	g	410.9	390.3	378.7	648.8	636.4	642.6	592.5	584.1	512.1	636.9	573.7	565.5	607.1	635.3	558.7
10	Container + post-test dry mass (3)	g	410.7	389.4	378.7	648.5	636.4	642.5	591.2	584.0	512.1	636.8	573.4	564.3	607.1	635.2	558.5
11	Container + post-test dry mass (4)	g	410.7	389.4	378.7	648.5	636.3	642.5	591.1	583.9	511.9	636.8	573.4	564.3	607.0	635.0	558.5
12	Post-test dry mass less container mass	g	253.2	232.6	242.7	351.6	379	368.0	435.6	412.5	375.7	454.4	415.9	407.6	451.2	477.1	402.8
13	Slake durability Index	%	55.6	50.5	52.9	74.0	75.8	74.3	86.1	83.2	83.3	86.5	89.4	86.0	89.1	88.9	87.8
14	Mean SDI	%		53.0			74.7			84.2			87.3			88.6	
15	Mean total mass loss	%		47.0			25.3			15.8			12.7			11.4	

CLSB (28 days, 6 MPa)

APPENDIX W (3)

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Microsilica-cement soil blocks (MCSB) – 28 days (6 MPa)														
			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	Container Reference	-	MC31	MC32	MC33	MC51	MC52	MC53	MC71	MC72	MC73	MC91	MC92	MC93	MC111	MC112	MC113
2	Container mass	g	136.0	157.9	155.6	136.1	155.8	156.7	156.8	296.9	274.5	157.5	156.8	155.5	171.4	182.4	257.3
3	Container + pre-test dry mass (1)	g	623.3	619.6	634.7	643.9	683.8	735.4	657.5	810.6	810.8	650.1	647.7	649.9	695.5	729.8	803.6
4	Container + pre-test dry mass (2)	g	622.2	617.8	633.3	643.7	682.6	735.1	656.9	810.4	809.9	649.7	647.3	649.2	694.5	729.7	802.7
5	Container + pre-test dry mass (3)	g	622.2	617.8	633.3	643.5	682.3	735.1	656.7	810.3	809.9	649.6	647.2	649.2	694.3	729.6	802.7
6	Container + pre-test dry mass (4)	g	622.1	617.8	633.2	643.5	682.3	735.1	656.6	810.2	809.9	649.4	647.0	649.2	694.0	729.6	802.4
7	Pre-test dry mass less container mass	g	486.1	459.9	477.6	507.4	526.5	578.4	499.8	513.3	535.4	491.9	490.2	493.7	522.6	547.2	545.1
8	Container + post-test dry mass (1)	g	513.7	512.5	526.6	577.7	599.4	647.1	628.7	789.6	775.0	643.5	626.6	644.7	693.9	725.1	796.5

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			3% cc			5% cc			7% cc			9% cc			11% cc		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
9	Container + post-test dry mass (2)	g	512.8	511.3	526.4	576.6	598.8	647.0	628.3	788.4	771.3	642.3	625.8	643.5	692.6	723.9	795.8
10	Container + post-test dry mass (3)	g	512.8	511.1	526.4	576.5	598.7	646.6	628.2	788.1	773.7	642.1	625.0	643.3	692.5	723.6	795.4
11	Container + post-test dry mass (4)	g	512.7	511.1	526.2	576.5	598.6	646.6	628.1	788.1	773.5	642.0	624.9	643.3	692.4	723.6	795.3
12	Post-test dry mass less container mass	g	376.7	353.2	370.6	440.4	442.8	489.9	471.3	491.2	499.0	484.5	468.1	487.8	521.0	541.2	538.0
13	Slake durability Index	%	77.5	76.8	77.6	86.8	84.1	84.7	94.3	95.7	93.2	98.5	95.5	98.8	99.7	98.9	98.7
14	Mean SDI	%		77.3			85.2			94.4			97.6			99.1	
15	Mean total mass loss	%		22.7			14.8			5.6			2.4			0.9	

MCSB (28 days, 6 MPa)

APPENDIX W (4)

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Fired brick samples (FBS); Concrete block sample (CBS); Rock block sample (RBS)														
			FBS (0% cc)			CBS (12-18% cc)			RBS (sandstone)								
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**						
1	Container Reference	-	Fb1	Fb2	Fb3	Cb1	Cb2	Cb3	Rb1	Rb2	Rb3						
2	Container mass	g	136.1	155.7	155.5	296.9	257.3	274.5	156.7	157.9	136.2						
3	Container + pre-test dry mass (1)	g	587.8	619.4	437.5	821.6	783.7	789.7	594.4	598.1	582.7						
4	Container + pre-test dry mass (2)	g	587.3	618.1	436.6	821.4	783.2	789.7	593.3	597.5	581.9						
5	Container + pre-test dry mass (3)	g	587.3	618.1	436.6	821.3	783.2	789.5	593.3	596.9	581.8						
6	Container + pre-test dry mass (4)	g	587.2	618.1	436.5	821.3	783.2	789.3	593.3	596.9	581.7						
7	Pre-test mass less container mass	g	451.1	462.4	481.0	524.4	525.9	514.8	436.6	439.0	445.5						
8	Container + post-test dry mass (1)	g	587.9	618.3	635.9	802.6	771.1	768.9	590.9	587.3	571.7						

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W (4)

			FBS (0% cc)			CBS (12-18% cc)			RBS (sandstone)								
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**						
9	Container + post-test dry mass (2)	g	587.4	617.2	635.6	802.2	770.5	768.8	590.8	587.1	571.5						
10	Container + post-test dry mass (3)	g	587.2	616.9	635.1	801.9	770.2	768.8	590.8	587.1	571.6						
11	Container + post-test dry mass (4)	g	587.2	616.7	635.1	801.9	770.1	768.7	590.7	587.2	571.5						
12	Post-test dry mass less container mass	g	451.1	461.0	479.6	505.0	512.8	494.2	434.0	429.3	435.3						
13	Slake durability Index	%	100	99.7	99.7	96.3	97.5	96.0	99.4	97.8	97.7						
14	Mean SDI	%		99.8			96.6			98.3							
15	Mean total mass loss	%		0.2			3.4			1.7							

FBS; CBS; RBS

APPENDIX W (5)

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Cement Stabilised Soil Blocks (CSSBs): 6 MPa; 5% cc														
			7 days			14 days			21 days			28 days			56 days		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	Container Reference	-	CS571	CS572	CS573	CS5141	CS5142	CS5143	CS5211	CS5212	CS5213	CS5281	CS5282	CS5283	CS5561	CS5562	CS5563
2	Container mass	g	136.0	155.5	136.2	297.6	296.9	297.0	257.3	297.6	275.1	274.5	313.9	257.4	171.4	157.5	156.8
3	Container + pre-test dry mass (1)	g	640.7	673.5	659.0	791.5	786.9	793.4	790.5	836.6	815.9	732.4	776.8	730.5	683.5	677.8	683.7
4	Container + pre-test dry mass (2)	g	640.1	671.8	658.1	791.3	786.7	791.6	789.6	836.3	815.3	731.2	775.1	730.2	683.2	677.6	683.3
5	Container + pre-test dry mass (3)	g	639.9	671.7	658.2	790.9	786.7	791.6	789.6	836.2	815.1	730.1	774.6	730.2	683.2	677.4	683.3
6	Container + pre-test dry mass (4)	g	639.8	671.7	658.1	790.9	786.7	791.5	789.6	836.2	815.1	730.1	774.6	730.2	683.2	677.4	683.2
7	Pre-test dry mass less container mass	g	503.8	516.2	521.9	493.3	489.8	494.5	532.3	538.6	540.0	455.6	460.7	472.8	511.8	519.9	526.4
8	Container + post-test dry mass (1)	g	372.3	386.4	378.8	586.5	583.7	594.5	635.9	686.1	672.8	641.5	695.5	644.7	587.8	591.6	585.3

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W (5)

			7 days			14 days			21 days			28 days			56 days		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
9	Container + post-test dry mass (2)	g	371.9	385.9	378.4	585.9	583.4	594.3	635.8	685.5	672.1	640.3	695.3	644.3	587.5	591.2	584.9
10	Container + post-test dry mass (3)	g	371.8	385.8	377.9	585.7	583.4	594.3	635.7	685.4	672.1	640.3	694.9	644.1	587.5	591.1	584.8
11	Container + post-test dry mass (4)	g	371.8	385.7	377.8	585.7	583.4	594.2	635.8	685.4	672.1	640.3	694.9	644.2	587.5	591.1	584.8
12	Post-test dry mass less container mass	g	235.8	230.2	241.6	288.1	286.5	297.2	378.5	387.8	396.9	365.8	381.0	386.8	416.1	433.6	428.0
13	Slake durability Index	%	46.8	44.6	46.3	58.4	58.5	60.1	71.1	72.0	73.5	80.3	82.7	81.8	81.3	83.4	81.3
14	Mean SDI	%		45.9			59.0			72.2			81.6			82.0	
15	Mean total mass loss	%		54.1			41.0			27.8			18.4			18.0	

CSSB (6 MPa)

APPENDIX W (6)

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Microsilica-cement Soil Blocks: 6 MPa: 5% cc														
			7 days			14 days			21 days			28 days			56 days		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	Container Reference	-	MS571	MS572	MS573	MS5141	MS5142	MS5143	MS5211	MS5212	MS5213	MS5281	MS5282	MS5283	MS5561	MS5562	MS5563
2	Container mass	g	171.4	156.8	157.5	313.8	257.3	274.5	136.0	136.2	155.5	297.6	296.9	297.0	157.8	155.7	158.0
3	Container + pre-test dry mass (1)	g	633.0	626.9	611.3	864.3	808.4	811.4	630.8	627.5	644.7	834.6	834.5	822.9	649.8	646.7	654.6
4	Container + pre-test dry mass (2)	g	632.7	626.7	611.2	864.2	807.2	809.1	629.9	627.3	644.4	834.2	833.8	822.8	649.7	646.4	654.5
5	Container + pre-test dry mass (3)	g	632.5	626.7	611.2	863.9	807.2	809.1	629.8	627.3	644.3	834.1	833.9	822.7	649.7	646.3	654.4
6	Container + pre-test dry mass (4)	g	632.5	626.6	611.1	863.9	807.2	809.1	629.8	627.3	644.3	834.1	833.8	822.7	649.7	646.2	654.4
7	Pre-test dry mass less container mass	g	461.1	469.8	453.6	550.1	549.9	534.5	493.8	491.1	488.8	536.5	536.9	525.7	491.9	490.5	496.4
8	Container + post-test dry mass (1)	g	440.4	430.1	414.8	696.9	634.5	647.9	546.7	548.8	569.4	761.5	765.8	755.7	592.3	577.9	589.5

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W (6)

			7 days			14 days			21 days			28 days			56 days		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
9	Container + post-test dry mass (2)	g	439.9	429.8	414.5	696.8	634.1	647.7	546.3	548.3	568.6	761.3	765.2	755.6	592.2	577.1	588.9
10	Container + post-test dry mass (3)	g	439.8	429.8	414.4	696.7	634.0	647.6	545.9	548.1	568.5	761.2	765.1	754.9	592.2	577.1	588.9
11	Container + post-test dry mass (4)	g	439.8	429.8	412.4	696.7	634.0	647.6	545.9	548.2	568.5	761.1	765.1	754.9	592.1	577.0	588.9
12	Post-test dry mass less container mass	g	268.4	273.0	254.9	382.9	376.7	373.1	409.9	412.0	413.0	463.5	468.2	457.9	434.3	421.3	430.9
13	Slake durability Index	%	58.2	58.1	56.2	69.6	68.5	69.8	83.0	83.9	84.5	86.4	87.2	87.1	88.3	85.9	86.8
14	Mean SDI	%		57.5			69.3			83.8			86.9			87.0	
15	Mean total mass loss	%		42.5			30.7			16.2			13.1			13.0	

MCSB (6 MPa)

LABORATORY RECORDING SHEET: SLAKE DURABILITY TEST

			SAMPLE TYPE														
			Cement-Lime Soil Blocks CLSB): 6MPa; 5% cc														
			7 days			14 days			21 days			28 days			56 days		
SN	**Item**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	Container Reference	-	Cl5571	Cl5572	Cl5573	Cl55141	Cl55142	Cl55143	Cl55211	Cl55212	Cl55213	Cl55281	Cl55282	Cl55283	Cl55561	Cl55562	Cl55563
2	Container mass	g	297.6	296.9	257.3	155.5	156.7	157.8	274.5	313.8	257.4	171.4	157.6	156.8	136.0	136.2	157.5
3	Container + pre-test dry mass (1)	g	814.4	817.9	767.9	619.2	629.9	639.9	780.6	827.8	777.9	647.7	621.1	639.9	561.8	566.5	603.7
4	Container + pre-test dry mass (2)	g	813.4	817.1	767.8	618.9	629.7	639.6	780.5	827.5	777.5	646.9	620.9	639.7	561.7	566.2	603.3
5	Container + pre-test dry mass (3)	g	813.3	817.0	767.7	618.8	629.5	639.4	780.4	827.5	777.3	646.9	620.7	639.6	561.6	566.3	603.3
6	Container + pre-test dry mass (4)	g	813.3	817.0	767.7	678.8	629.6	639.4	780.4	827.4	777.2	646.9	620.7	639.6	561.6	566.2	603.4
7	Pre-test dry mass less container mass	g	515.7	520.1	510.4	463.3	472.9	481.6	505.9	513.6	519.8	475.5	463.1	482.8	425.6	430.0	445.9
8	Container + post-test dry mass (1)	g	508.6	495.7	463.7	400.5	401.4	438.2	596.5	645.3	590.3	527.7	510.4	520.6	472.3	477.4	506.7

continued on next page

SN	Item	Units	7 days			14 days			21 days			28 days			56 days		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
9	Container + post-test dry mass (2)	g	507.5	495.2	463.6	400.3	401.2	437.9	596.4	646.9	589.9	527.7	501.9	520.1	471.9	477.2	506.3
10	Container + post-test dry mass (3)	g	507.0	495.2	463.6	400.1	401.2	437.8	596.3	646.8	589.6	527.6	501.7	519.9	471.9	477.2	506.2
11	Container + post-test dry mass (4)	g	507.0	495.1	463.5	400.1	401.2	437.8	596.3	646.6	589.6	527.5	501.7	519.9	471.8	477.2	506.2
12	Post-test dry mass less container mass	g	209.4	198.2	206.2	244.6	244.5	280.0	321.8	332.8	332.2	356.1	344.1	363.1	335.8	341.0	348.7
13	Slake durability Index	%	40.6	38.1	40.4	52.8	51.7	51.5	63.6	64.8	63.9	74.9	74.3	75.2	78.9	79.3	78.2
14	Mean SDI	%		39.7			52.0			64.1			74.8			78.8	
15	Mean total mass loss	%		60.3			48.0			39.5			25.2			21.2	