THE DEVELOPMENT OF SUSTAINABLE LIME-BASED BUILDING WALL COMPONENTS

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CERTIFICATE OF RESEARCH

This is to certify that, except where specific reference is made, the work described in this thesis is the result of the candidate. Neither this thesis, nor any part of it, has been presented, or is currently submitted, in candidature for any degree at any other university.

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DEDICATION

To my husband
Associate Professor Dr. Mohamad Nidzam Rahmat

My children
Ikmal Hadi Nidzam
Imran Hadi Nidzam
Eira Ailbe Nidzam
Nia Hannah Nidzam

who are a constant source of love and encouragement

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ABSTRACT

Extensive laboratory work was carried out to investigate the performance of stabilised clay-based target material. Lower Oxford Clay (LOC) was used as the base clay, with and without combining it in equal proportions (50:50) with Pulverised Fly Ash (PFA) an industrial waste from the burning of coal in power stations. The traditional binders of Lime and Portland Cement (PC) were used as controls. In order to enhance sustainability, these two binders were partially replaced with Ground Granulated Blast-furnace Slag (GGBS) an industrial by-product from the manufacture of steel. During the preliminary phase of the research, two different approaches to establishing the moisture demand during compaction of test specimens were investigated, using both LOC and LOC-PFA mixtures at two stabiliser dosages of 10wt% and 20wt%. Results indicated that the approach resulting with a lower compaction moisture content achieved better strength with the lower stabiliser dosage of 10%, while the approach with a higher moisture content was better suited to the higher stabiliser dosage of 20%. With these preliminary results, pilot industrial and commercial trials were then carried out using typical full-size unfired bricks of size 295mm x 140mm x 55mm. These trials demonstrated that all the key parameters of compressive strength, durability and thermal properties were within the acceptable engineering standards for masonry units. Overall, the results suggested that with proper protection against excessive moisture ingress, the use of GGBS and PFA in the manufacture of unfired bricks is a viable alternative to fired bricks, especially in certain applications such as low-bearing load situations. From the environmental and sustainability analysis results, the unfired LOC-PFA bricks showed energy-efficiency and suggested viable economical alternatives to the traditionally fired building components. Using a five-tool environment assessment comparison method, the materials-related inputs were assessed, as criteria for achieving the sustainability rating of a building. The outcome suggested that with the new unfired Clay-PFA technology, innovation and enhanced waste management, the achievement and use of green building materials is real, and thus a great contribution towards the concept of "green building" has been made in this study.

LIST OF ABBREVIATIONS AND SYMBOLS

Al_2O_3	Aluminium oxide (alumina)
$Al_2Si_2O_7$	Metakaolin
C_2S	Dicalcium silicate
$C_3A.3C\overline{S}.H_{32}$	Ettringite
Ca	Calcium
$Ca(OH_2)$	Calcium hydroxide
$Ca_2Al_2SiO_7$	Gehlenite
$Ca_2SO_4.2H_2O$	Gypsum
$CaCO_3$	Calcium carbonate (calcite)
C-A-H	Calcium aluminate hydrate
CaO	Calcium oxide (quicklime)
C-A-S-H	Calcium alumino-silicate hydrate
CO_2	Carbon dioxide
C-S-H	Calcium silicate hydrate
D_fT	Department of Transport
Fe_2O_3	Iron oxide (haematite)
g	gram
GGBS	Ground Granulated Blastfurnace Slag
K_2O	Potassium monoxide
kg	kilogram
LL	Liquid Limit
LOC	Lower Oxford Clay
LOI	Loss on Ignition
MDD	Maximum Dry Density
MgO	Magnesium oxide
MnO	Manganese oxide
kN	KiloNewton
Na_2O	Sodium monoxide
Na_2O_3	Disodium trioxide
O	Oxygen
°C	degree Celsius
OMC	Optimum Moisture Content
P_2O_5	Phosphorus pentoxide
PC	Portland Cement
PFA	Pulverised Fuel Ash
PI	Plasticity Index
PL	Plastic Limit
SiO_2	Silicon oxide (Silica)
S	Sulfur
SO_3	Sulfur trioxide
SO_4	Sulfate
TGA	Thermogravimetric Analysis
UCS	Unconfined Compressive Strength

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CHAPTER 1

INTRODUCTION

This chapter gives a general introduction and an overview of problem identifications and definitions. The problems are in general on the current global environmental issues and sustainability faced by the construction industry. The chapter also gives the objectives and outlines of the current research and most importantly the contribution to the body of knowledge in the public domain, resulting from the current research work.

1.1 GENERAL

Sustainability is about balancing the Earth's physical resources with the social, economic, technical and environmental needs of our societies. Achieving sustainability will require stabilising or reducing the environmental burden. Too much emphasis on the environment will limit the ability to deliver infrastructure improvements and hence improvements in living standards, particularly in the developing world. The sustainability concept has been applied to characterise a type of development knowing as "sustainable development" (Mora, 2007). Today sustainable development is quickly becoming a global phenomenon, focused by many people who represent a wide range of professions and interests.

The construction industry is involved in creating the physical assets which are the basis of virtually every aspect of development, and thus in the creation of much of world's man-made capital. However, the industry, together with the building materials industries which supply it, are also some of the largest exploiters of natural resources, and are a major users of the world's non-renewable energy sources both mineral and biological (Spence and Mulligan, 1995). Their activities cause irreversible transformations of the natural environment, and add to accumulation of pollutants in the atmosphere. According to Doughty *et al.,* (2004) sustainability applied to construction industry can be interpreted in many different ways. Mora (2007) reported that sustainability in construction would only be possible when construction used renewable energy resources, renewable materials from construction waste or other industrial waste and/or by-product. This is supported by Mehta (2001) whose described the most efficient way for construction to approach sustainability is first to reuse waste products from other industrial activities as well as to improve the durability of the works.

1.2 PROBLEM IDENTIFICATION

One of the key targets and concerns in relation to the achievement of sustainable infrastructure development is energy consumption. For this reason, there has been a growing interest in reducing energy consumption in the manufacture of building components and construction materials in general. The production of conventional clay bricks for example involves very intensive firing. The average direct energy consumption of this production process is to be found ranging between 1,840 and 2,800 kJ/kg of fired brick (Moedinger, 2009).

Today there is an increasing need to develop building materials that are fit for purpose based on sustainability values in terms of the economy and environmental concern. The development of unfired clay building components for example enables the reduction in manufacturing energy costs as well as a reduction in carbon dioxide (CO_2) production. At the same time, using industrial waste and/or by-product materials such as Pulverised Fuel Ash (PFA) and Ground Granulated Blast-furnace Slag (GGBS) as raw materials to replace the amount of clay used to make unfired bricks or to enhance performance, is an effective way of recycling waste materials. It reduces the use of natural resources, reduces energy consumption and hence produces a new cost-effective product. The average direct energy consumption of the production process is to be found ranging between 1,840 and 2,800 kJ/kg of fired brick. All of this energy used is traditionally generated with fossil fuels (Moedinger, 2009).

1.2.1 Sustainability

The need for sustainability by reducing material processing costs and recycling waste materials is well established within the construction industry. The current research endeavours to use both recycling waste or by-product materials and remove firing costs in the production of bricks. The use of waste materials is one of the ways of integrating sustainable approaches in the construction industry. For this reason, the construction industry has always shown a receptive attitude towards research into new materials (Aggrawal and Gulati, 2007). Research by Malhotra and Tehri, (1996) has observed that good quality bricks can be produced by pressing slag-lime mixtures at sufficiently low pressures. Sustainable development can also be achieved by using unfired clay technology in the building industry for manufacturing bricks. The unfired clay technology can replace fired brick and concrete block in many applications, with significant reductions in the consumption of natural resources, and in waste sent to landfill as the raw materials. These benefits are inherent in the manufacture process, but continue through the whole life cycle (Lawrence *et. al.,* 2009). This is the objective of the current research project. It extends an existing unfired clay cementation technology that is currently viable for highway construction (Kinuthia and Wild, 2001), to commercial applications in the building industry. The introduction of lime slag mixture to the manufacturing process of bricks does not require any firing, autoclaving, or specialised plant or machinery (Malhotra and Dave, 1992).

1.2.2 Utilisation of Industrial Waste/By-products

The disposal of industrial waste is an environmentally sensitive problem facing waste managers throughout the world. As environmental quality standards have become more stringent and the volume of waste generated continues to increase, the traditional disposal methods are no longer acceptable and there is therefore great pressure to change. One possible long-term solution appears to be either recycling or utilising the waste for alternative beneficial purposes. This is already taking place in the construction industry.

The recycling of fly ash in concrete is much more than as an alternative for reducing costs (Cornelissen, 1997 & Bijen, 1996). Fly ash, a by-product of coal combustion, is frequently used in concrete production as an inexpensive substitute for Portland Cement (PC). However although fly ash is commonly used in cements, it has rarely been applied to bricks (Cultrone and Sebastian, 2008). Joshi and Lohtia (1997) reported that the major properties of fly ash exploited in the clay brick industry include the similarity in composition with clay, fuel (calorific) value due to the presence of unburnt carbon, reduced weight of the resultant product, and reduced shrinkage due to its inert nature and chemical compatibility with natural clays.

It has been shown that fly ash may improve the compressive strength of bricks and make them more resistant to frost, and there are other advantages in using fly ash as a raw material for bricks, such as saving in the firing energy. This is because of the amounts of carbon contained in fly ash (Lingling *et al.,* 2005). The unburnt carbon in the fly ash provides part of the heating process during the manufacture of fired bricks. Fly ash has also been used as a partial or total replacement of quartz sand in the production of sand-lime building bricks by using an autoclave process (Joshi and Lohtia, 1997).

In view of the huge demand for building bricks, along with reduced availability of suitable soil, it is necessary to explore alternative raw materials and energy efficient technologies for making bricks (Malhotra and Tehri, 1996). According to Joshi and Lohtia (1997), fly ash can be used to replace up to 40% of clay, the main raw material in building blocks and tiles. This will certainly contribute to the recycling of fly ash and hence minimise the impact of the fly ash landfills on the environment. This helps in the reduction of clay usage for the production of bricks.

The utilisation of Ground Granulated Blast-furnace Slag (GGBS), is also commonly used, mainly to reduce the reliance on the traditional cementitious materials such as lime and PC. GGBS is a latently hydraulic material that can be activated with lime, alkalis or PC, to give hydraulic properties (Gupta and Sheera, 1989). The production of GGBS leads to emissions of about 60kg of CO_2/tonne, primarily from the grinding process. Therefore, the use of materials such as GGBS can lead to significant reductions in CO_2 emissions (O'Rourke *et al.,* 2009). On its own GGBS has only slow cementitious properties and PC normally provides the necessary alkalinity to activate and accelerate these properties. Similarly lime can also be used to provide the necessary alkality for the activation of GGBS.

1.3 RESEARCH OBJECTIVES AND CONTRIBUTION TO KNOWLEDGE

The objective of this research project was to extend an existing unfired clay cementation technology, that is currently viable for highway construction, to commercial applications in the building industry. This will cut down the cost of firing that is currently a significant contibutor to the final cost of fired building components, due to energy used during the production process. Recent increases in gas prices and other energy resources used for firing exacerbate this cost element, a further justification for the need to carry out investigations on unfired clay systems at the present time. The schematic diagram of problem definition and objective tree are shown in figures 1.1 and 1.2 respectively.

The aims and objectives of the current work may be summarised as follows:

- To carry out applied research necessary for the development of an unfired lime-clay cementitious technology for building components, using slag-based binder,
- To carry out laboratory trials using the unfired technology to formulate sustainable lime-clay bricks as commercial building component(s).
- To carry out environmental impact analyses relating the formulated products.

The eventual aim of the current work is to evaluate the performance of brick formulations made with clay and pulverised fuel ash (PFA) and stabilised with Lime-GGBS and PC-GGBS blends. This will then enable the assessment of the potential application of these blended binders in unfired clay building components. This could produce cost savings in raw materials for brick manufacturers and serve as an efficient means of recycling waste or by-product materials. At the same time, this process will eliminate the high-energy consumption, associated with the present practice of manufacturing clay building components by way of intense firing.

In this research a new unfired clay-based material incorporating PFA was formulated by stabilising clay-PFA mixtures with various innovative blends of lime or PC with

GGBS. GGBS is a by-product of steel manufacture, and there are many steel plants worldwide that produce GGBS as a by-product. The use of activated slag in building components, besides in concrete as is the current practice, is innovative and novel. The outcome from this research will produce cost savings in raw materials for bricks manufacturers and illustrate an efficient and alternative means of stabilising soils and other materials during the recycling of waste materials.

Cementitious systems that do not need firing by utilising already embodied energy in their formulations have a high potential in the manufacture of building and construction components and materials. If the raw materials used in such processes contain a significant proportion of energy-embodied waste and/or by-product materials, there are enhanced economic and environmental benefits. In some cases, the engineering performance of these sustainable processes may exceed the ones using conventional (or traditional) materials such as PC. Basic research at the University of Glamorgan (UoG) has resulted in successful testing of GGBS-based formulations for their first application in road pavement construction in the UK, on the A421 Tingewick Bypass in Buckinghamshire, and on the A130 road near London (Wild *et al.,* 1998). In the past, GGBS has predominantly been used in concrete. The use of lime-slag formulations for building components (bricks and blocks) is therefore novel.

The production of conventional clay bricks involves very intensive firing for effective cementation to take place. The cost of providing this energy - gas, coal, electricity or other energy sources - is incorporated in the final product price. On the other hand, for concrete blocks, the use of PC introduces energy-related costs to the end products using this material. Portland cement manufacture also requires intensive heating to temperatures well above 1000 degrees Celcius. There is therefore an opportunity to lower the cost of bricks and blocks, if it would be possible to save on energy consumption in the manufacturing process. This is the key market opportunity that the proposed research project seeks to exploit. As the environmental awareness increases, consumers will start to address the overall product rating in terms of its efforts to address sustainability issues.

The key industrial problem that this research wishes to address is the high energy costs in the manufacture of building components. This high cost is currently being transfered to consumers, thus indirectly affecting the building industries of most countries and economies. With clay bricks that do not require firing and that do not totally rely on the use of the traditional binder – lime and Portland Cement (PC), not only is the final pricing of the building components going to be lower, but there are also added environmental advantages of utilising industrial waste and/or by-products in the region. It is also possible that the product will have certain technological of performance and advantage, such as lack of effloresence and other physical defects.

1.4 STRUCTURE OF THESIS

This introduction is followed by the literature review on the general description of the bricks and industrial wastes and by-products in Chapter 2, with a particular emphasis on sustainable development, environmental assessment methods with the discussion of environmental impact analysis on new construction products on sustainability of the building and construction sectors. The chapter has a discussion on sustainable clay brick production from traditional clay bricks to properties of waste and by-products. In Chapter 3, the materials used in this research are discussed while Chapter 4 contains a discussion of the experimental procedures, equipment design and techniques used in the research. Chapter 5 reports the results obtained, while Chapter 6 discusses them, gives the conclusions drawn from the entire research work. The Chapter ends with recommendations for future research, and this is followed by a listing of the references quoted throughout the thesis. The thesis ends with the associated appendices, including papers have been either, authored or been co-authored.

PROBLEM TREE

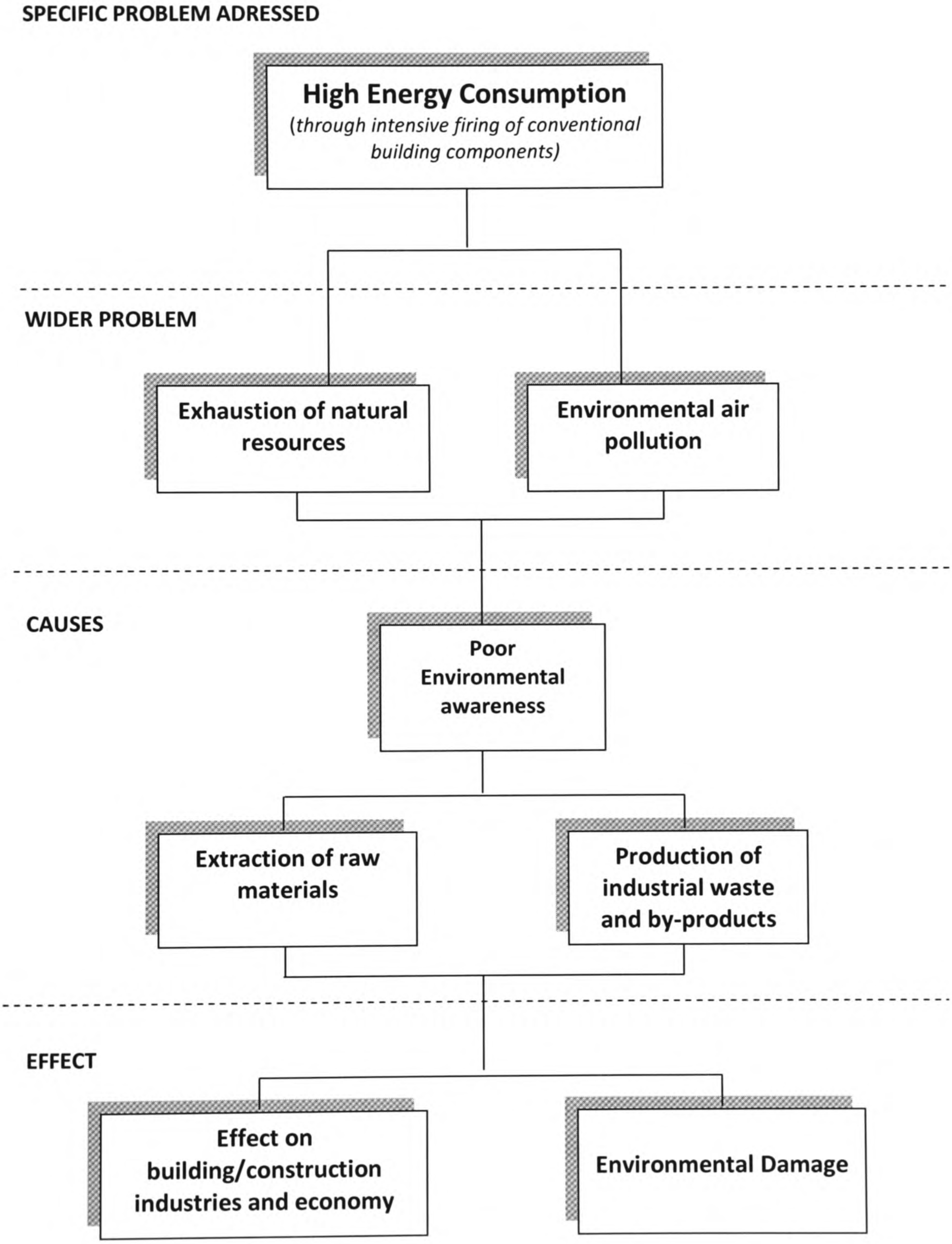


Figure 1.1: Schematic diagram of the Problem definition

OBJECTIVE TREE

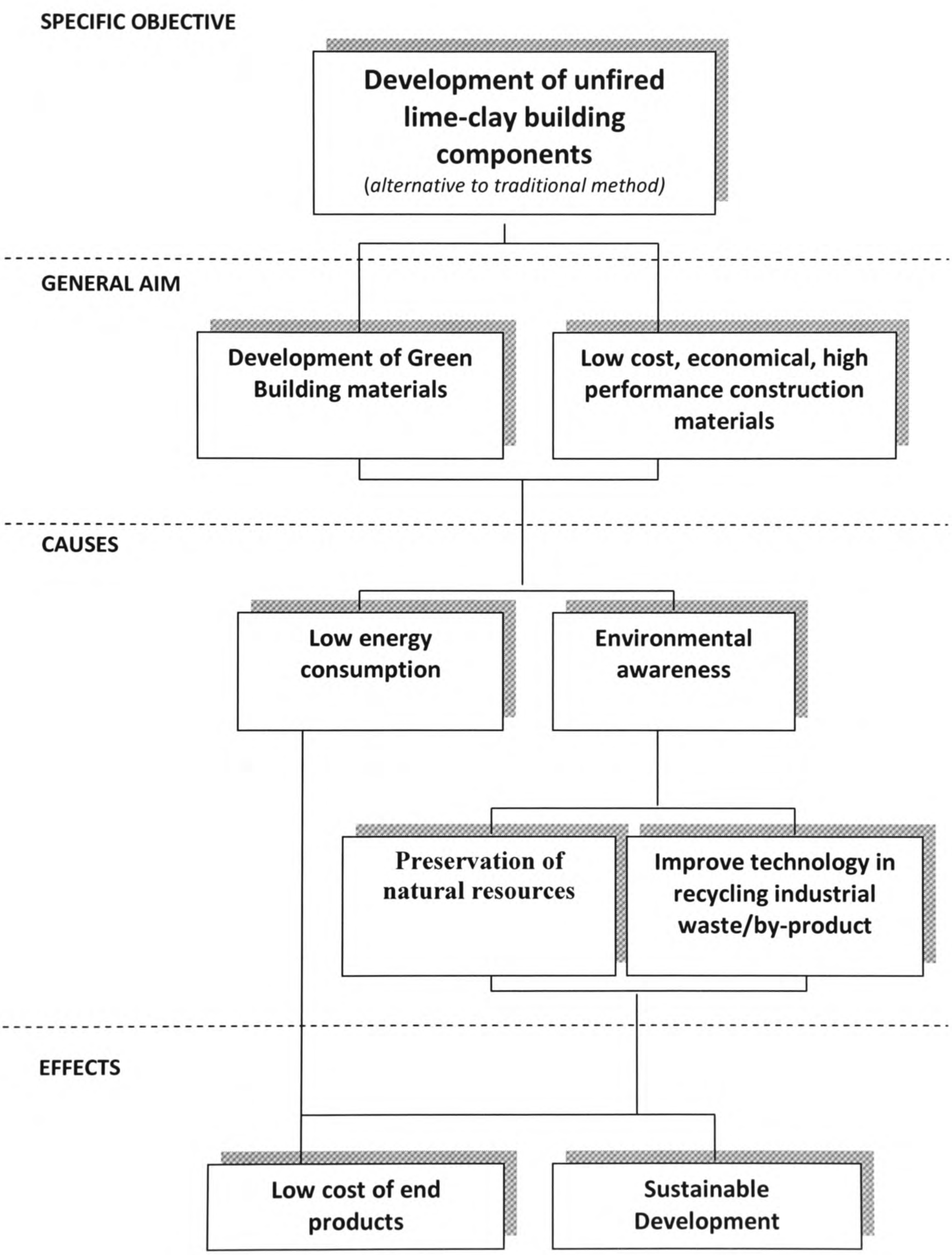


Figure 1.2: Schematic diagram of the Objective tree.

CHAPTER 2

LITERATURE REVIEW

This chapter is divided into three parts;
Part I – Sustainable Development
Part II- Environmental Assessment Methods
Part III – Sustainable Brick Production

It gives an overview of the concept of sustainable development, its application in the building industry, the overall view of the environmental assessment method that have widely been used for the assessment of sustainable buildings, and sustainable bricks production as part of green building materials. This chapter also discusses on the sustainable brick/block production with some background on soil-clay mineralogy.

PART I – SUSTAINABLE DEVELOPMENT

2.1 INTRODUCTION

Sustainable development was firmly established by 1987 as a matter of self-interest for individuals and society at the international policy level (Halliday, 2008). The World Commission on Environment and Development (WCED) also known as the Brundtland Commission (1987), define sustainable development as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. The International Council for Local Environmental Initiatives (ICLEI, 1996) define sustainable development as *"development that delivers basic environmental, social and economic services to all residences of a community without threatening the viability of natural, built and social systems upon which delivery of those systems depends"*. The definition of WCED also suggests that sustainability is often cast as the 'triple bottom line' of environment, society and economics (Hall and Purchase, 2006). According to Parkin *et al.*, (2003) there are over 200 definitions of sustainable development which was difficult to define and even harder to put it into practice. Although there is no general agreement regarding the precise meaning of sustainability, it is understood that most of times, the term 'sustainable' refers to the viability of natural resources and ecosystems over time, and also to the maintenance of human living standards and the economic development.

By the early 1990s there was a huge outpouring opinion that rigorous international action on environment and development was needed. In 1992, the UN Conference on Environment and Development (UNCED) or Rio Earth Summit was aimed to determine the requirements of achieving sustainable development and to agree worldwide response with the introduction of 'only one earth' approach. With political concern, all agreements signed at UNCED indicated a strong move to manage pollution in all forms. This including evidence from research on chemical dispersal, such as the climate change (methane, CO_2, N_2O, CFCs, tropospheric ozone) has continued to be the source of controversy (Halliday, 2008). Following UNCED, a number of international meetings were convened on a variety of international environment issues, including the World Summit for Sustainable Development (WSSD) in Johannesburg in 2002, which was considered a failure due to only few commitments made on environmental issues (Halliday, 2008). In 'A Better Quality of Life' (DETR, 1999) endeavour the UK Government states that sustainable development means meeting four objectives at the same time, in the UK and the world as a whole. The objectives are as follow;

a) Social progress that recognises the needs of everyone,
b) Effective protection of the environment,
c) Prudent use of natural resources, and
d) Maintenance of high and stable levels of economic growth and employment

These objectives are the most common way of conceptualizing sustainable development as three dimensions of environmental, economic and social (Fig. 2.1-1). On the other hand Vollenbroek (2002) described sustainable development as a balance between the available technologies, strategies of innovation and the policies of governments.

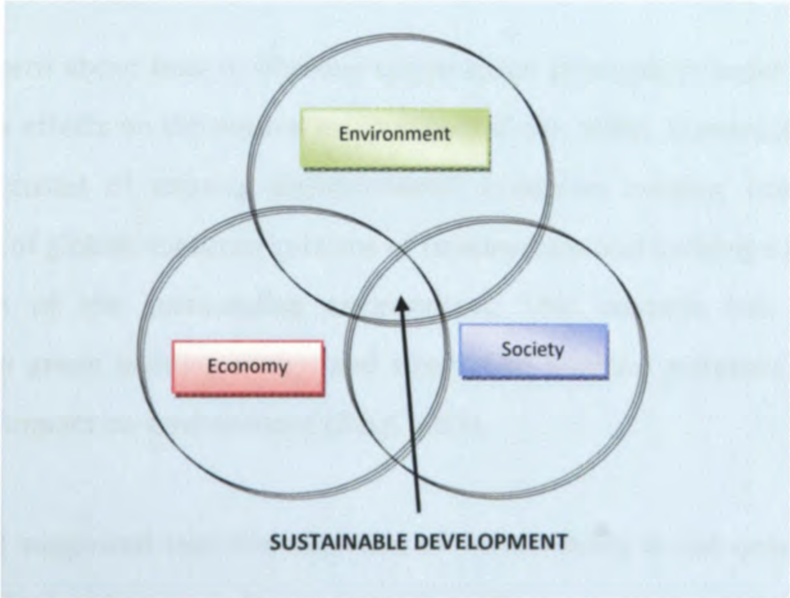


Figure 2.1-1: Venn diagram: Sustainable Development

2.1.1 Sustainable Construction and Building

The construction industry is very important, as it uses larger quantities of materials than any other industry. Lawson *et al.,* (2001) reported In England and Wales, the construction industry produces 53.5 Mt of construction and demolition waste, annually. With the implementation of sustainable construction, one of the biggest boosts for the construction and building materials sector is the clearly continuous raising by various national planning departments on "green" building. Market analysis done by qfinance (2011) reported that the green building materials market was worth some US$60 billion in 2009 in the United States alone. A truly sustainable construction project should incorporate economic, social and environmental issues in the planning, construction and demolition stages, with the aim of providing a building that is affordable, accessible and environmentally conscious. The first International Conference on Sustainable Construction held in Tampa in 1994 which introduced the following definition of sustainable construction *"the creation and responsible maintenance of a healthy built environment based on resource efficient and ecological principles"* (Kilbert, 1994). According to Sev (2009), sustainable construction principles, again can be differentiated according to the three dimensions of sustainable development, the environment, social and economy as illustrated in Figure 2.1-1

There is concern about how to improve construction practices in order to minimise their negative effects on the natural environment (Cole, 1999). Construction industry has been accused of causing environmental problems ranging from excessive consumption of global resources in terms of construction and building operations, to the pollution of the surrounding environment. This scenario has led to few researches on green building design and alternative building materials, in order to minimise the impact on environment (Ding, 2008).

Kohler (1999) suggested that the objective of sustainability is not only to improve qualitatively the building stock, but to improve without growth by reducing materials throughput and improve the functional quality and its durability. An interpretation by

Kohler (1999) stated that sustainability in built environment can be divided into three main areas, ecological sustainability, economic sustainability and social and cultural sustainability as shown in Figure. 2.1-2. Ecological sustainability is understood in terms of resource and ecosystem protection with respect to the energy and mass flows in time and space within the life cycle assessment. While, economic sustainability can be divided into investment and the use costs, it is preferable for given investment to find solutions that have the highest durability and reusability rather than to minimising investment through low-cost of building process and products (Kua and Lee, 2002). Cole (1999) described the social and cultural aspects of sustainability which include comfort and health protection, and preservation of values, considered as one of the main motivations behind any conservation and sustainability projects.

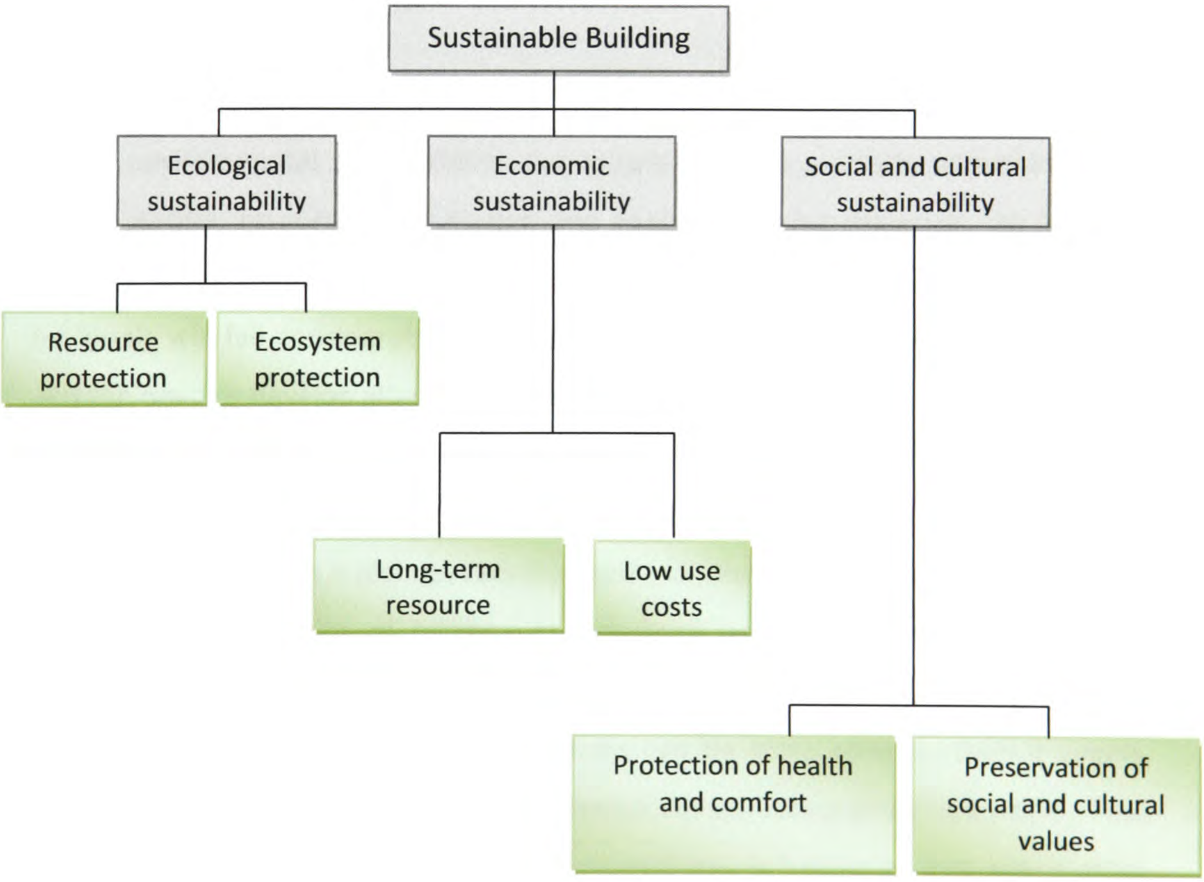


Figure 2.1-2: The Three Dimensions of Sustainable Building, adopted by Kohler, 1999.

Today 'Sustainability' is becoming a central concern and is recognised all over the world as a key issue facing twenty first century society (Komiyama and Takeuchi, 2006). Report by Bourdeau (1999) stated that different countries may have different approaches and priorities in the application of sustainable construction, some identify economic, social and cultural issues as part of their sustainable construction framework, but the main emphasis in national definitions is on ecological impacts to the environment (bio-diversity, tolerance and nature and resources). Bourdeau (1999) also concluded that the key elements in various sustainable construction definitions are:

- Reducing the use of energy sources and depletion of mineral resources;
- Conserving natural areas and bio-diversity;
- Maintaining the quality of the built environment and management of healthy indoor environments.

In the building industry, a sustainable construction can make a vast difference to global environmental sustainability, particularly through a drastic reduction in the use of natural resource consumption and energy intensive materials like Portland cement, steel, aggregates and aluminium. Availability of conventional construction materials will fall considerably short for demand in spite of improved productivity and the need to develop alternatives for them. According to Plessis (2001), ignorance and a lack of information of sustainable construction issues and solutions is a major obstacle that building industry needs to overcome. Today, the environmental impact of construction, green buildings, recycling and eco-labeling of building materials have captured the attention of building professionals across the world (Rees, 1999; Crawley and Aho, 1999; Cole, 1998 and Johnson, 1993). Designing, constructing and operating environmentally friendly buildings can be more complex than it seems, especially when it comes to materials selection. An increasing globalised world of the construction industry, like most human undertakings, is having to deal with a range of serious environmental issues such as global warming, biodiversity and resource (re)use, all within the context of striving for social and economic growth (Wilde and Goodhew, 2006).

A great effort is placed all over the world in achieving sustainable development in the construction industry with the aim in reducing energy consumption (Oti *et al.,* 2008: Bourdeau, 1999: Hakkinen, 1993: Malhotra and Dave, 1992). This phenomenon has occurred mainly in countries that waste large amounts of energy and resources. New laws aiming to increase environmental protection are in force, the ecological awareness of the general public has expanded, and the cost for consumption of resources has continued to grow. Almost every country indicates a need for improved energy efficiency of buildings and the built environment. The main focus is on the use of renewable energy, local energy resources and a wide range of opportunities for producers to market innovative energy saving materials and systems throughout the construction industry (Bourdeau, 1999). Mei *et al.,* (2007) reported apart from the Building Regulations, government planning policies have a crucial role in driving sustainability to the main stream of building design. In 2003, the UK government is committed to implementing the Energy Performance of Building Directives, implement on declaration of carbon and energy performance of dwellings, which was agreed within European countries (Mei *et al.,* 2007).

Most research, whether academic, industry, government technical or R & D revolves around energy issues; impact of the choice of building materials on the environment, and recommendations are addressed in order to produce environmental quality for building components and buildings. As buildings become increasingly energy efficient, many building materials and products are being offered as environmentally friendly or have been developed to meet the demand for 'green' sustainable materials. The challenge facing researchers is to achieve an equitable development for all human beings, including future generations, while preserving the integrity of the global environment.

In buildings the main challenges are to improve productivity in end use, reduction in operational energy, better durability and lower maintenance, greater reuse and right time for construction teams to lead the next revolution in construction technology on a global scale, one that aims to create a new sustainable building material. Therefore, lately, alternative materials have been studied and analysed for the production of new environmentally friendly building materials.

Buildings have a significant impact on the environment, consuming about 32% of the world's resources, including 12% of its water and up to 40% of its energy. Buildings also produce 40% of waste going to landfill and 40% of air emissions (Green Star, 2009).

2.1.2 Role of the Built Environment

The construction industry is a highly active sector all over the world, and is responsible for a high rate of energy consumption, environmental impact and resource depletion (NBT, 2009). It is responsible for a high percentage of the environment impacts produced by the developed countries (UNEP, 2003). In the UK, construction industries are responsible for the consumption of 40% of primary energy in the country (Defra, 2008). In the European Union, the construction and building sector is responsible for about 40% of the overall environmental burden (UNEP, 2003). California Integrated Waste Management Board (2000) reported that the building construction industry consumes 40% of the materials entering the global economy and generates 40% to 50% of the global output of green house gases (GHG) emissions and the agents of acid rain.

The cement sector in the construction industry is fully aware of the sustainable development stakes. Over the past decades, it has been actively involved in seeking ways to consume less energy and natural resources, and emit less CO_2 per unit of cement produced. It is estimated that cement industry produces approximately 5% of global manmade CO_2 emissions, but it emits almost no other GHGs (Damfort, 2008).

PART II – ENVIRONMENTAL ASSESSMENT METHOD

2.2 BACKGROUND

Since the beginning of the 1990's, environmental assessment methods have been developed and implemented in many countries to enhance the development of energy conservation buildings, green buildings and/or high performance buildings. Many countries have developed their own building environmental assessment methods or customised the existing methods. These methods present some similarities in scope, intent and structure, but yet had some differences in many core aspects including the environmental criteria, the quantification of performance, and the management of the whole assessment process. In this context, only five (5) main environmental assessment methods will be discussed;

i) **BREEAM** (Building Research Establishment Environmental Assessment Method), which was developed in the UK in 1990,
ii) **LEED** (Leadership in Energy and Environmental Design), was developed in the USA in 1998,
iii) **GBTool** (Green Building Assessment Tool), was developed by National Resource Canada and combined 14 countries in 1998
iv) **Green Star**, which was developed in 2003, an Australia, national, voluntary environmental rating system and
v) **CASBEE** (Comprehensive Assessment System for Building Environmental Efficiency), which was developed in Japan in 2003. Their logos are illustrated in Figure 2.2-1.

All these systems focus on the quality of sustainability trends on their perspectives and their capacity to move to the ultimate target of acceptable urban sustainability. The focus is to structure target requirement set, for sustainable building towards implications from the whole construction process until final evaluation of the building as an 'ecological' product. Most of these rating systems are commercial tools and more or less supported by their respective government agencies or private industry, sometimes within an academic frame. The different methods mostly address similar issues and even the methods of measurement are converging as development groups learn from each other (Howard, 2005). Cole (2005) reported that current rating systems are facing challenges to evolve in terms of simplicity, refining performance measures and indicators, improving verification methods, streamlining the certification process, and the necessary support documentation together with their capability to manage more complexity in a simple and practical form.

Figure 2.2-1: Some of the Logos of Building Environment Assessment Methods

For this study, the overall process involved only five used and most known environmental assessment methods BREEAM, LEED, GBTools, Green Star and CASBEE will be discussed (Fig.2.2-1). However, the detailed assessment on how each method works on building materials will only be discussed under BREEAM, since it is the most widely used assessment methods all over the world. The Environmental Assessment tools were primarily developed to assess, or measure specific aspects of a building, pertaining to sustainable goals. Once measured, buildings could be more easily compared with current and past practices and other green buildings. The focus areas were chosen to address key waste streams and inefficiencies in buildings and the effects on the end users (McKay, 2007). Most assessment methods focused on three main areas;

i) energy,
ii) water
iii) materials

This focus on the resources use in buildings and each area of it is typically evaluated on its net use, such as the building produces or reuses resources, its efficiencies, and its percentage of reused, recycled or virgin materials.

Method 1: LEED (Leadership in Energy and Environmental Design) - USA

LEED is an internationally recognised green building certification system, providing third-party verification that a building or community was designed and built using strategies aimed at improving performance in term of energy savings, water efficiency, the reduction of CO_2 emissions, improved indoor environmental quality, materials selection and administers of resources to their building or community impacts. LEED was developed by the U.S. Green Building Council (USGBC). It provides building owners and design teams with a concise framework for identifying and implementing practical and measurable green building design, construction operations and maintenance solutions. Besides that, it also provides the tools for an immediate and measurable impact on their buildings' performance. The first LEED pilot project program, known as LEED Version 1.0 was launched in 1998. Then, with extensive modifications, it was followed by LEED Green Building Rating System Version 2.0 in March 2000, LEED Version 2.1 in 2002 and LEED Version 2.2 in 2005.

The overall scope for the LEED rating system includes; new construction, existing building for operation and maintenance, commercial interiors, core and shell (covers base building elements such as structure, envelope and the heating, ventilating and air conditioning (HVAC) system, schools, retail, healthcare and homes. LEED certification provides independent, third-party verification that a proposed building project meets the highest green building and performance measures. In 2008 LEED interacted with the Green Building Certification Institute (GBCI) incorporated entity with the U.S Green Building Council for the project registration and certification. GBCI is an independent third party organisation committed to ensure accuracy in design, development and implementation of processed used and increase the way of measured green building performance (certification) and green building practice (credentialing).

The LEED rating systems is organised into 5 environment categories:

i) sustainable sites,
ii) water efficiency,
iii) energy and atmosphere,
iv) materials and resources, and
v) indoor environmental quality.

There is also an additional category for innovation in design to address sustainable building expertise as well as design measures. For their credit weighting, the allocation of points is based on the potential environmental impacts and human benefits. The impacts are defined as the environmental or human effect of the design, construction, operation and maintenance of the building, such as greenhouse gas emissions, fossil fuel use, toxins, air and water pollutants, and indoor environmental conditions.

Pyke *et al.* (2010) reported in Green Building & Human Experience Research Program by USGBC that current green building processes and practices have been successful in promoting the use of specific strategies of development process, with success in over 130,000 trained, accredited professionals and nearly 5,000 certified projects with another 20,000 in the process of pursuing certification, all these associated with LEED. According to McKay (2007) although criticisms have been made about the use of this assessment tool, application cost and why it was created, it is clear that LEED has achieved its goals of raising awareness and transforming the market of the green building.

It is suggested that sustainable building strategies should be considered at an early stage of the development cycle, involving an integrated project team that includes the major stakeholders of the project such as the developer/owner, architect, engineer, landscape architect, contractor, and asset and property management staff. Initial LEED assessment brings the project team together to evaluate and articulate the project's goals and the certification level sought. There are both environmental and financial benefits to earning LEED certification, which is designed to certify buildings with:

- lower operating costs and increase asset value,
- reduced waste sent to landfill,
- conserved energy and water,
- health and safety for occupants,
- reduced harmful greenhouse gas emissions.

Method 2: GBTool (Green Building Tool)

The GBTool system was completed in 1998, in a software format. It was implemented in the form of two distinct software modules:

i) A green Building Input (GBI) module, and
ii) A Green Building Assessment (GBA) module

It was developed by Green Building Challenge '98 (GBC '98) a 2 year development process involving international teams from 14 countries. The tool's overall goal was to develop, test and demonstrate an improved method for measuring building performance across a range of environmental and energy issues and then to inform the international community of scientist, designers, builders and clients about the results (Cole and Larsson, 1998). The committee was lead by Canada, but the other thirteen participating countries made substantial staff and financial contributions, and have had a decisive influence on the development of the system. The participating countries in GBC '98 were Australia, Canada, Denmark, Finland, France, Germany, Japan, Neatherlands, Norway, Poland, Sweden, Switzerland, UK and USA (Larsson and Cole, 1998).

GBTool used the following development principles of "designing a system that can be modified to suit variations in national, regional and building type characteristics". The assessment used by GBTool are based on benchmarks of applicable regulations or industry norms in each of the participating regions, and to ensure consistency and rigour in terminology, establish scoring system, including a weighting system and the implementation of software that facilitate the work and also simplify the task of inputting building data and assessing candidate buildings. The GBTool system was prepared for each of three major building categories; office buildings, multiunit residential buildings and schools, in which the building environmental performance in GBTool can be described at several levels of detail;

- performance areas which are considered for resource use,
- performance categories for materials,
- performance criteria for source and type of materials, and
- performance sub-criteria for the use of materials with high post consumer recycle content.

Performance categories in the GBC '98 assessment framework are the performance areas which collectively define the overall performance of case-study building, which are divided into six distinct 'green building' performance:

a) **Resource consumption** – related to the depletion of natural resources such as energy, land, water and materials.
b) **Environmental loadings** – the output from building construction, operation and demolition works: airborne emissions, solid, liquid and other waste.
c) **Indoor environment** – building characteristics which affect the health and comfort of building occupants and controllability of environmental systems: air quality, thermal quality, visual quality and controllability of systems.
d) **Longevity** – design features that potentially extend the useful life of building: adaptability and performance maintenance.
e) **Process** – construction process to ensure that the building will operate in the most effective way once fully operational: design and construction process, and building operations planning.
f) **Contextual factors** – building's location: location and transport, and loading on immediate surroundings.

In general a consistent scoring system has been established for GBTool, which ranges from -2 to +5, where 5 on the assessment scale is a 'demanding performance' condition, which represents a performance target that considerably in advance of current practice. A negative score indicates that performance is clearly inferior to be accepted by industry norms. Since GBTool is used across a wide range of regions and building types, with differing building practices, energy costs, materials choices and performance expectations, it was impossible to offer a precise and universally applicable metric (Cole and Larsson, 1998).

Method 3: Green Star – Australia

Green Star was developed by The Green Building Council of Australia (GBCA) to be a comprehensive, national, voluntary environmental rating scheme that evaluates the environmental design and achievements of buildings. Green Star has built on existing systems and tools in overseas markets including the British BREEAM (Building Research Establishment Environmental Assessment Method) system and the North American LEED (Leadership in Energy and Environmental Design) system. Green Star has established individual environmental measurement criteria with particular relevance to the Australian marketplace and environmental context. It is a comprehensive, national, voluntary environmental rating system in Australia that evaluates the environmental design and construction of buildings and, with 11 per cent of Australia's commercial office buildings (CBD) been certified by Green Star, building green is now considered as a business imperative. Green Star was developed for the property industry in order to:

- Set a standard of measurement for green buildings;
- Promote integrated, whole-building design;
- Recognise environmental leadership;
- Identify building life-cycle impacts; and
- Raise awareness of green building benefits.

In Australia, commercial buildings produce 8.8% of the national greenhouse emissions and have a major part to play in meeting Australia's international greenhouse obligations. A commercial building sector baseline study found that office buildings and hospitals were the two largest emitters by building type, causing around 40% of the total sectoral emissions.

Like other environmental assessment methods Green Star has its own rating tools categories:

a) **Management** - Credits address the adoption of sustainable development principles from project conception through design, construction, commissioning, and operation.
b) **Indoor Environment Quality** - Credits target environmental impact along with occupant wellbeing and performance by addressing the heating, ventilating and air conditioning (HVAC) system, lighting, occupant comfort and pollutants.
c) **Energy** - Credits target reduction of greenhouse emissions from building operation by addressing energy demand reduction, use efficiency, and generation from alternative sources.
d) **Transport** - Credits reward the reduction of demand for individual cars by both discouraging car commuting and encouraging use of alternative transportation.
e) **Water** - Credits address reduction of potable water through efficient design of building services, water reuse and substitution with other water sources (specifically rainwater).
f) **Materials** - Credits target resource consumption through material selection, reuse initiatives and efficient management practices.
g) **Land Use & Ecology** - Credits address a project's impact on its immediate ecosystem, by discouraging degradation and encouraging restoration of flora and fauna.
h) **Emissions** - Credits address point source pollution from buildings & building services to the atmosphere, watercourse, and local ecosystems.
i) **Innovations** - Green Star seeks to reward marketplace innovation that fosters the industry's transition to sustainable building.

Green Star rating tools award points for the achievement of specific credits in each rating category, as defined in the applicable Green Star Technical Manual.

The single (overall) score of a project is determined by (Fig. 2.2-2)

1. Calculating each category score;
2. Applying an environmental weighting to each category;

3. Adding all weighted category scores together; and
4. Adding any innovation points that may have been achieved.

A project's score is determined for each category based on the percentage of points achieved as follows:

$$\text{Category Score} = \frac{\text{No. of points achieved}}{\text{No. Of points available}} \times 100\%$$

Not all credits are applicable to every project, and many credits have an 'N/A' option. In these instances, the points for these credits are excluded from the 'Points Available' used to calculate the category score. This prevents distortion of the category scores (up or down) for issues that are not applicable in that project or building. On the other hand, an environmental weighting is applied to each category score (except innovation). This balances the inherent weighting that occurs through the number of points available in any rating category. The weighted category score is calculated as follows:

$$\text{Weighted Category Score} = \frac{\text{Category score (\%) X Weighting factor (\%)}}{100}$$

Finally, the single (overall) score is determined by adding together the entire weighted category scores plus any innovation points (which are not weighted) that may have been awarded. The maximum possible score for the weighted categories is 100 with an additional 5 points available for the innovation category.

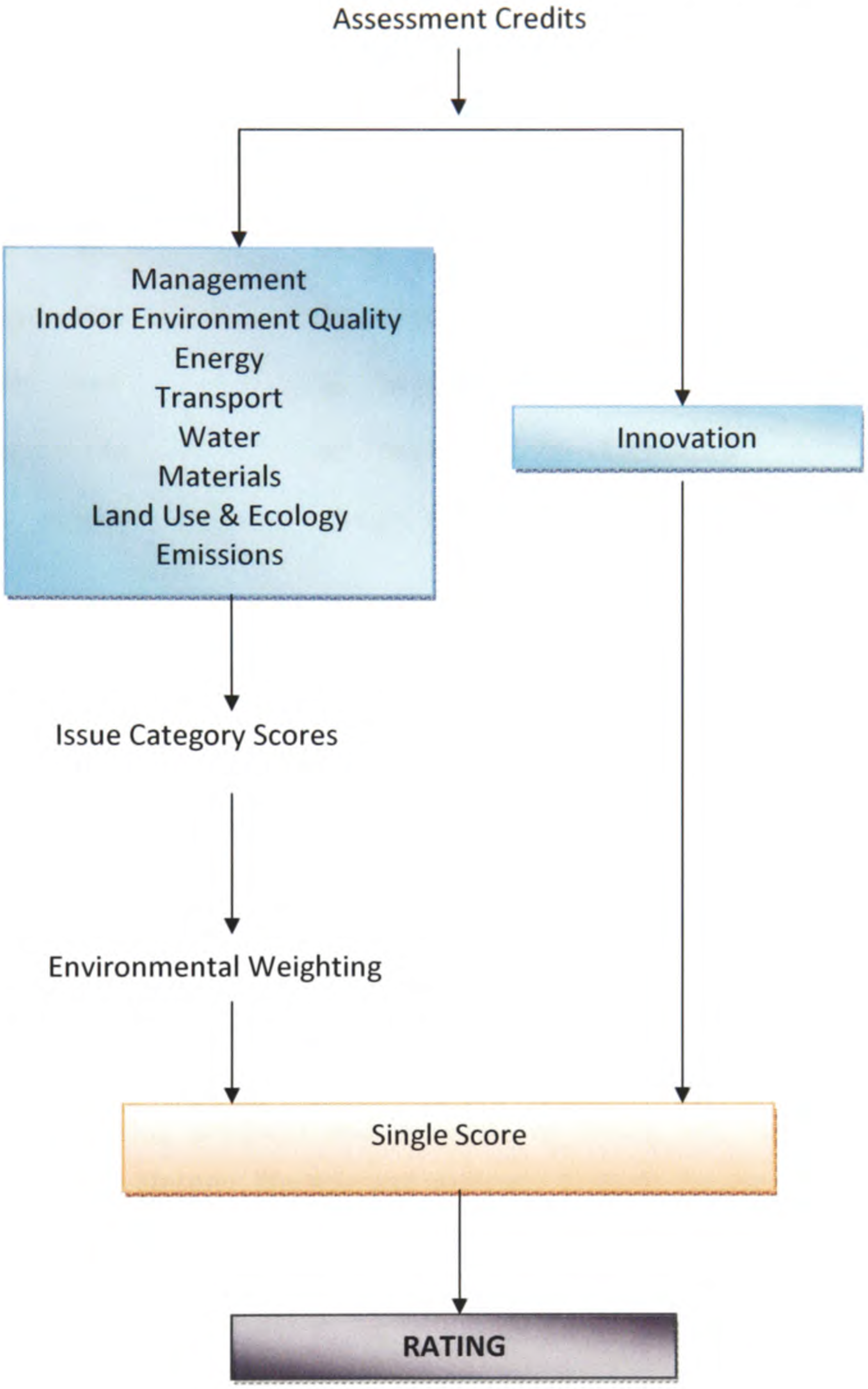


Figure 2.2-2: Green Star Assessment Credit

(Note: source from Green Star, 2010)

The Green Star rating is determined by comparing the overall score with the rating scale shown below.

One Star	*	10 - 19 pts
Two Star	**	20 - 29 pts
Three Star	***	30 - 44 pts
Four Star	****	45 - 59 pts Best Practice
Five Star	*****	60 - 74 pts Australian Excellence
Six Star	******	75+ pts World Leader

The Green Building Council of Australia only certifies buildings that achieve a rating of Four, Five or Six Stars. The Materials Category of the Green Star rating tools consist of credits which target the consumption of resources through selection, use, reuse and efficient management practices of building and fit out materials. The credits reward reduction, reuse and the use of recycled and recyclable materials wherever possible. The various environmental and human health impacts arising from building materials are reduced when use of virgin materials is limited and special attention is given to the selection of ecologically and health-preferable materials. Green Star Material credits aim to address and improve the environmental impacts of building products and materials by taking into consideration issues pertaining to the lifespan, lifecycle and approach towards the use of these resources within the building fabrics of Green Star certified projects.

Method 4: CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) - Japan

CASBEE was launched by the Japan Sustainable Building Consortium. The methodology used to calculate the score is called BEE (Building Environment Efficiency) that distinguishes between environmental load reduction and building quality performance. CASBEE is sold primarily as a 'self assessment check system' to permit users to raise the environmental performance of buildings, and also can be used as labelling system if the assessment is verified by a third party. Most of the information of CASSBEE was written in Japanese, although there are some guidance as it has been translated into English. This makes CASBEE much more accessible internationally. In general CASBEE assessment methods fall under 4 different versions;

1. CASBEE for Pre-Design,
2. CASBEE for New Construction,
3. CASBEE for Existing Buildings and
4. CASBEE for Renovation.

Like BREEAM, CASBEE for new construction uses weightings to balance the value addressing issues with the number of measures available, to improve environmental performance the more credits can be developed. With weighting system does not necessarily reflect the environmental impact of addressing the issues, but it to indicate the awareness towards green building.

Weightings applied to CASBEE fall under category of; indoor environment, outdoor environment onsite, energy and resources materials. Compared to BREEAM, LEED or Green Star, the weightings applied to CASBEE are much more complex (Saunders, 2007). Under each category there are headline issues such as service ability, lighting and illumination and building thermal load. This followed by individual issues including noise, ventilation and use of recycle materials. Then it is followed with final layer of weightings that applied to the sub-issues grouped under each of the individual issues that include ventilation rate, CO_2 monitoring, adaptability of floor plate, etc.

All the issues have then been split into two basic types, Quality measures and Load Reduction measures. The score is calculated once the assessment is completed, with a score between 1 to 5 points. With the final score presented as the BEE, then the rating will be applied. There are five different ratings available (Fig. 2.2-5):

C: BEE of 0 – 0.49

B-: BEE of 0.5 – 0.99

B+: BEE of 1 – 1.49

A: BEE of 1.5 – 2.99

S: BEE of 3.0

Method 5: BREEAM (Building Research Establishment Environmental Assessment Method) - UK

BREEAM is the earliest building rating system for environmental performance assessment. It was developed by the Building Research Establishment (BRE) in 1990, in partnership with 24 construction industry sector representatives. BRE has developed an environmental profiles methodology that assesses the environmental impact of building products throughout their lifetime – from cradle to grave. Over the years, BREEAM has evolved from a design checklist to a comprehensive assessment method/tool to be used in various stages of building life cycle. It not only takes into account building materials, but also energy, transportation links, ecology and land use, health and well being. Today BREEAM is the leading and most widely used environmental assessment method for buildings (BRE, 2009). It sets the standard for best practice in sustainable design and has become the actual measure used to describe a building's environmental performance. BREEAM addresses wide-ranging environmental and sustainability issues and enables developers and designers to prove the environmental credentials of their buildings to planners and clients. According to Rivera (2009), BREEAM provides a mechanism for the design team to pursue certification and buildings to receive a level of certification without placing burden upon the construction team. BREEAM uses a straightforward scoring system that is transparent, easy to understand and supported by evidence-based research, this scoring system also has positive influence on the design, construction and management of buildings. It sets and maintains a robust technical standard with rigorous quality assurance and certification.

BREEAM rewards performance of proposed project above regulation, which delivers environmental, higher comfort or health benefits. It awards points or 'credits' and groups the environmental impacts related to the project into the following sections:

(a) **Energy** – Operational energy and carbon dioxide (CO_2), considered for renewable energy and possible alternative energy to use
(b) **Management** – Management policy, commissioning, site management and procurement
(c) **Health and Wellbeing** – indoor and external issues (noise, light, air quality, heating, etc)
(d) **Transport** – transport related CO_2 and location related factors (access with public transport)
(e) **Water** – consumption and efficiency inside and out, e.g. flushing system
(f) **Materials** – embodied impacts of building materials, including lifecycle impacts like embodied carbon dioxide e.g. use recycle materials within 30 km from site
(g) **Waste** – construction resources efficiency and operational waste management and minimisation
(h) **Land Use** – type of site and building footprint
(i) **Pollution** – external air and water pollution
(j) **Ecology** – ecological value, conservation and enhancement of the site

The total number of points or credits gained in each section is multiplied by an environmental weighting factor which takes into account the relative importance of each section. Section scores are then added together to produce a single overall score. Once the overall score for the building is known this is translated into a rating on a scale of: **Pass, Good, Very Good, and Excellent or Outstanding** (Fig.2.2-5) together with a star rating from 1 to 5 stars. Cole (2003) stated this simple characterisation of building environmental issues currently has both positive and negative impacts on design; such methods can be an instrument of changing design practice by identifying a new standard of performance that encourages architects and engineers to break old habits and design norms.

Overall, the scope of BREEAM covers a number of building types: offices, retail, education, prisons, courts, healthcare, industrial and certain types of housing under Ecohomes. The BREEAM assessments are carried out by Independent Assessors who are trained and licensed by BRE Global. It is advisable to have an early involvement of the assessor in the design process to gain a high rating in the most cost-effective way. During the process, the appointed Assessor produces a report outlining the development's performance in each sections and its overall score. Upon completion of the assessment, the client is presented with a certificate confirming the BREEAM rating.

a) BREEAM Assessment Process

Inception of the cradle-to-the-grave assessment procedure for products and processes, started in the USA in the late 1960's (Jaques, 1998). It then traces the assessment procedures' development and progress through the decades, to its current application for buildings and building materials. Life Cycle Assessment (LCA) is the method of formally analysing a system, whether it is a material, component or multitude of components based on cradle-to-the-grave principles. A material or product is examined from when and how its raw materials were acquired, through to its production, use, and finally destruction (Fig. 2.2-4). In construction, the system could be a material manufacturing process, the fabrication of a building component, a building element such as an external wall, or even an entire building over its life (Anderson *et al.*, 2009). According to Hobbs *et al.*, (1996), the objective of LCA is:

i) to compare alternative processes,
ii) to improve the resource efficiency of individual processes,
iii) to provide information to interested parties on resource use,
iv) to assess the impact of the environment, and
v) to identify ways to reduce the impact to environment.

LCA is generally recognised as being composed of four step procedures called *life cycle analysis*. These four steps are generally referred to:

- Goal definition, which establishes goals and boundaries
- Inventory, which quantifies inputs and outputs over life cycle of a material or product,
- Impact analysis, which assesses the effects of the environmental burdens identified in the previous stage, and
- Evaluation process, which investigates on environmental burdens.

The overall idea of LCA focuses on environmental performance which measured in the units appropriate to each emission type of effect category. For example global warming gases are categorised in term of their heat trapping effect compared to the effects of CO_2. In LCA, the effects related with making, transporting, using, and disposing of products are referred to as 'embodied effects' which is not meant to imply on the physical embodiment, but it is rather spread of attribution or allocation throughout the life cycle of products (all the extraction, use, transportation, energy, etc). In the case of buildings, the energy required to operate a building over its life greatly over shadows the energy attributed to the materials used in its construction and maintenance (Trusty, 2010). For example repainting works throughout building life.

In the early 1990s saw generic LCA become more developed, in the building materials arena, a variety of labeling, certification and other environmental assessment programs have been implemented, and also the advent of voluntary practical, whole building environmental analysis, based on simplified LCA was applied (Jaques, 1998). Two of the most popular are the UK's BREEAM and the Austin, Texas Green Builder program, which focus on environmental assessment applied at the design stage of domestic buildings. It highlight the range of issues being addresses for sustainable built environment and the introduction of environmental weighting systems based on perceived environmental importance.

Anderson *et al.,* (2009) stated that LCA provides a holistic and comprehensive method for assessing environment performance because it applies a life-cycle-based approach to investigation, and it can be used to identify where environmental impacts are arising within a system's life cycle, by offering a process for examining opportunities for improving performance. LCA determines the environmental impact by examining the 'environmental interventions' that occur during the system's life cycle. These include emissions to water, air and land, as well as resource depletion.

For BREEAM, the materials assessment process was carried out by BREEAM Materials, a long established team in BRE Global, which focuses on quantifying the environmental impacts of construction products over their entire lifecycle through a variety of tools, in established the world renowned and respected Environmental Profiles Methodology using Life Cycle Analysis (LCA) (Fig. 2.2-3) to measure and evaluate the environmental impacts of building materials. With this methodology, they are able to certify the impacts of specific building products to produce Certified Environmental Profiles in order to demonstrate their environmental performance. It is important to note that the whole life environmental performance, in the life cycle assessment terminology impact, building material like brick cannot be quantified as individual, but only be determined when it expressed in term of primary building element such as brickwall.

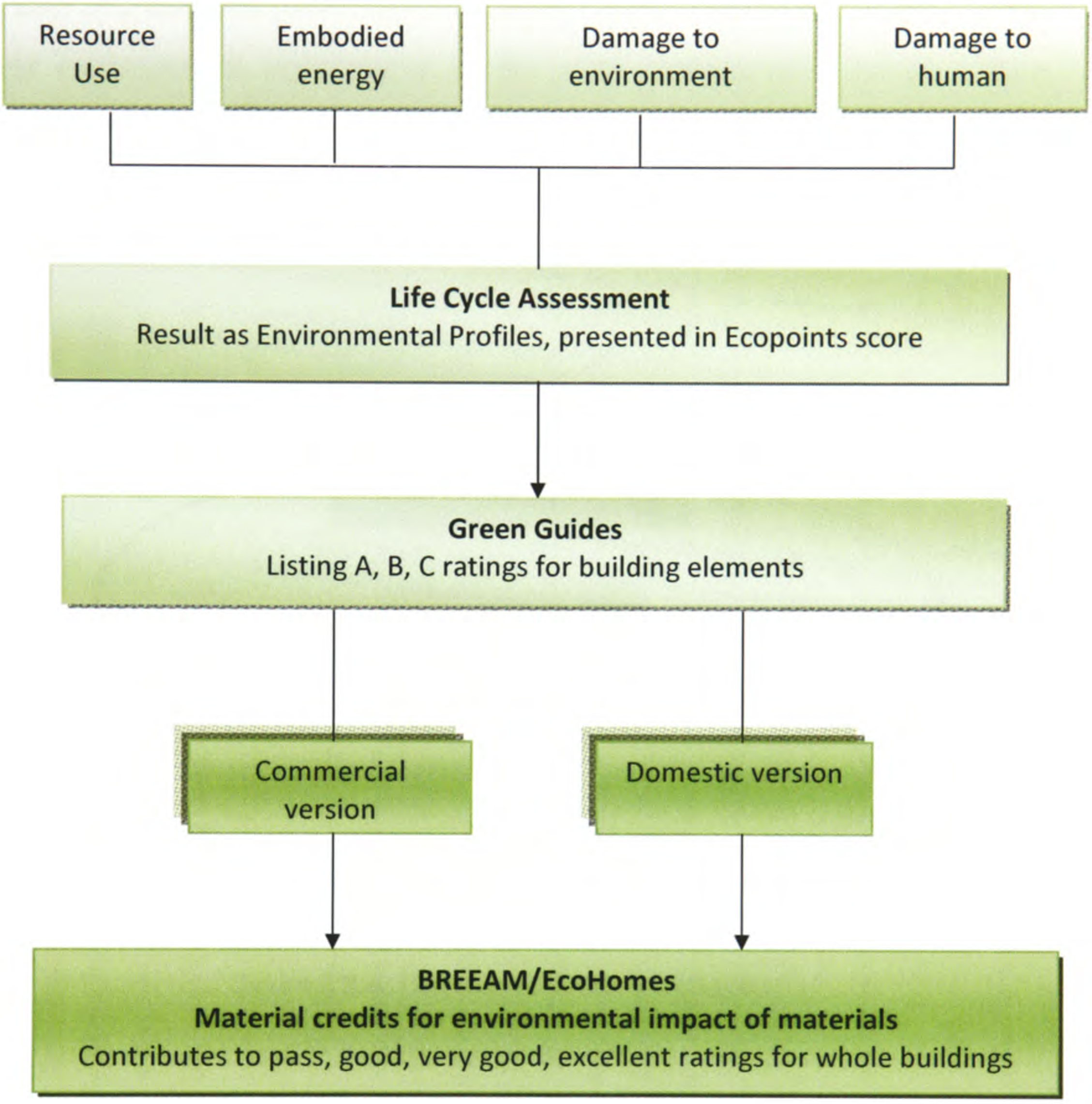


Figure 2.2-3: An illustration of the relationship of LCA and BREEAM

Note: Source from BRE (2004)

The team has developed the Green Guide to Specification, a tool to evaluate the impacts of building specifications by ranking them on scale of A+ to E. A+ represents the best environmental performance and least environmental impact, where E is the worst environmental performance or the most environmental impacts. These products along with other tools such as Envest2 that link into BREEAM and Code for Sustainable Homes schemes been used for assessing the environmental performance of whole buildings.

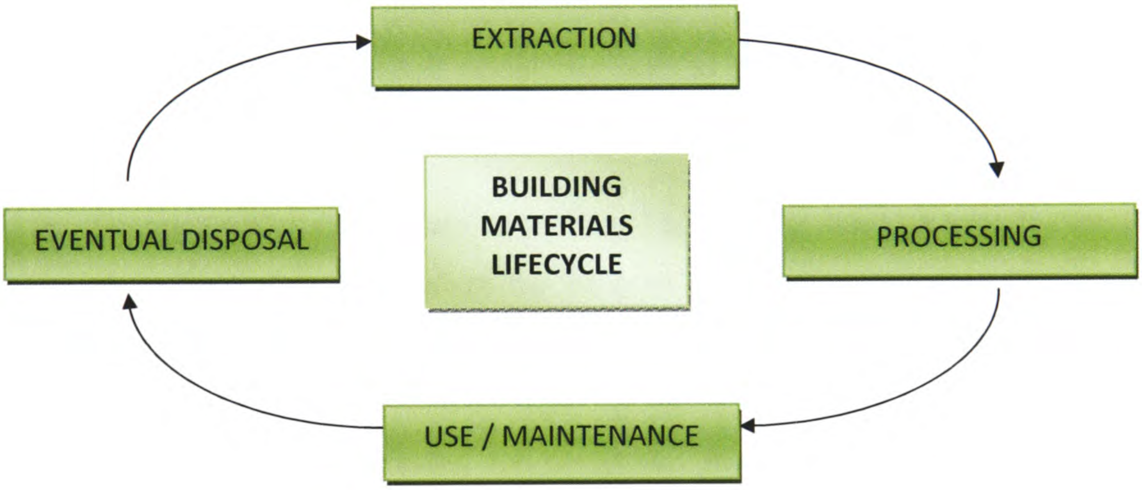


Figure 2.2-4: Lifecycle of Building Materials

i) *BRE Global Environmental Profiles and International Standards*

The Environmental Profiles Methodology is a standardised method of identifying and assessing the environmental effects associated with building materials over their life cycle, based on Life Cycle Assessment (LCA) analysis. In this regard, the methodology represents a set of 'product category rules' (PCR) for applying LCA to built environment life cycle scenarios. The BREEAM Certified Environmental Profile scheme has been in operation from 2002, which provides standardised, reliable and independent information about building materials and components that measure the environmental performance of materials and products over their entire lifecycle (Fig.

2.2-4) (BRE, 2009). When the building is demolished, parts of building materials can be reclaimed, and the reclaimable rates of various types of materials are different. Investigation by Zhang *et al.* (2006) stated that the reclaimable rates of several building materials are defined respectively as metal (90%), bricks (50%), wood (20%), and cement (10%). All un-reclaimed materials become the solid waste after demolition.

The BREEAM assessment has been externally peer reviewed and compiles with the international standards for Life Cycle Assessment (LCA), ISO 1404:2006 and ISO 14044:2006 and the standard for Environmental Product Declarations for Construction Products, ISO 21930:2007. These international standards have been developed Environmental Product Declaration such as Environmental Profiles (BRE, 2009). For the assessment there are two Environmental profiles set by BREEAM:

- Generic Profiles - using data on individual products to build up generic data about 'typical' product, which can be used by everyone. These profiles for most construction products have been developed with the UK Trade Associations.
- Certified Profiles – created for designated manufacturer's product using specific data collected and verified by BRE Global.

The profiles are based on the analysis of the product on per tonne of production basis. This information is then used alongside other LCA data generated by the Environmental Profiles project, to provide Environmental Profiles for the product with an elemental construction, for examples:

1m^2 of external wall or 1m^2 of floor finishes

This is to ensure the accuracy and comparability because the rules cannot consider a quantity of material on its own, since a construction material or product can only be defined in life cycle terms when considered in the context in which it is used (Anderson *et al.*, 2009). By using this approach, different materials can be compared on a like basis as a group of components that fulfill the same similar functions. With this, the important variables such as mass of material required to fulfill particular function are correctly accounted for, and this is critical for LCA because the material mass has direct link to environmental impact (Anderson *et al.*, 2009). Material mass is important as it is used within an Environmental Profile to determine life cycle inventory flows and enhance environmental impact. Inventory flows are the environmental interventions that take place between the study system and include extraction of raw materials and fuels, heat and water consumption, and emissions to air, discharges to water and emissions to land.

For the Environmental Profiles Methodology, and for The Green Guide to Specification, the 'generic' functional unit for building products has been chosen to be:

- $1m^2$ of the typical as built element
- Where appropriate a fixed U-value set using the 2006 Building Regulations (England and Wales) was used
- Physical characteristics was defined
- To include any repair, refurbishment or replacement over a period of 60 years (life-cycle of building).

During the assessment, The Environmental Profiles Methodology assesses environmental indicators that reflect impacts occurring globally, regionally and locally that cause damage to humans and the environment as well as resource depletion. Data associated with product is characterised into 13 impact categories;

- climate change – global warming or greenhouse gases,
- water extraction – mains, surface and ground water consumption,
- mineral resources extraction – metal ores, mineral and aggregates,
- stratospheric ozone depletion - gases destroying the ozone layer,
- human toxicity – pollutants toxic to humans,
- ecotoxicity - pollutants toxic to the ecosystem,
- nuclear waste,
- Freight transport – distance the mass of freight moved,

- waste disposal – material sent to landfill or incineration
- fossil fuel depletion – coal, oil and gas consumption,
- eutrophication – water pollutants promoting algae blooms etc,
- photochemical ozone creation – air pollutants causing respiratory problems,
- acidification – gases causing acid rain etc.

By creating product specific Certified Environmental Profiles, many products can be assessed, compared and their environmental performance improved. For the assessment process, any materials or products have to be provided with some information about their manufacturing process such as the production outputs, input materials, gas emissions during production, energy use and waste produced. All these data are then reviewed by BRE Global, and on the completion of the profile, a client or manufacturer obtains their certificate, which includes the Certified Environmental Profiles, Green Guide ratings (if relevant) and the report of the findings.

ii) *Green Guide to Specification*

The Green Guide is part of BREEAM. It contains more than 1500 specifications used in various types of building and information on the relative environmental performance of some materials and components which had been altered in the way how it is reflecting the changes in the manufacturing practices, and the way materials are used in buildings (www.bre.co.uk). The environmental rankings are based on Life Cycle Assessments (LCA), using BRE's Environmental Profiles Methodology 2008. Where, all materials and components are arranged on elemental basis under;

- external walls,
- internal walls and partitions,
- roofs,
- ground floors,

- upper floors,
- windows,
- insulation,
- floor finishes and
- landscaping

Based on this green guide, designers and specifiers can compare and select from comparable systems or materials as they compile their specification. There are guide catalogues of building specifications covering most common building materials across all the building elements categories. Materials and components are presented in their typical, as-built elemental form, then be compared on a like-for-like basis using Environmental Profiles Methodology, for 1m^2 of building element, as components that fulfill the same or very similar functions as example 'bricks and block walls' against 'cladding and timber frame walls'. Important variables such as the mass of a material required to fill a particular function are therefore taken into account. The Green Guide presents environmental impact information using simple scale system based on a metric of environmental performance called the Ecopoint. The data is converted as an A+ to E ranking system; A+ represents the best environmental performance and least environmental impact, where E is the worst environmental performance or the most environmental impacts. Menegazzo, (2006) reported that more than 300 building material specifications are rated as A, B and C in 13 environmental impact categories in this Green Guide to Specification.

2.2.1 Comparison of the Different Environmental Assessment Methods

The assessment tools attempt to achieve continuous improvements to optimise building performance and minimise environmental impact, which provides a measure of building's effect on the environment and set credible standards by which buildings can be judged objectively. Many of these tools measure sustainability of the built environment and have been developed to determine if any capacity exists for further development, or whether a development is sustainable, or whether progress is being made towards sustainable development. However, differences in location, governments, topography, building code or building regulation standards has resulted in the lack of consistency in baseline assumptions for each tool. Reed *et al.,*(2009), reported on comparison studies by BRE in 2008 on four key environmental assessment tools BREEAM, LEED, Green Star and CASBEE. It was established that there were differences when the processes of certification were evaluated. Table 2.2-0 illustrates the comparisons on how the rating systems were given between the four environmental assessment tools. The reliance on local building standards as a minimum starting point for the systems means that ratings they subsequently award are affected. The CASBEE system includes many credits that are not relevant to the UK, and others that do not have an equivalent credit assessed under BREEAM (Saunders, 2007). Therefore if a building achieves more CASBEE credits, it would not rest in more, or top of BREEAM credits.

BREEAM	***LEED***	***Green Star***	***CASBEE***
Excellent or outstanding			
Very Good	*Platinum*	*Six Stars*	
Good	*Gold*	*Five Stars* *Four Stars*	*S* *A*
Pass	*Silver*	*Three Stars*	*B+*
	Certified	*Two Stars* *One Star*	*B-* *C*

Table: 2.2-0: A Broad Comparison of the overall rating styles for four different rating tools *(source from BRE, 2008)*

Today, many studies on comparisons of environmental assessment tools have been carried out by researchers. Most have discussed on how these tools represent the green building concepts, while some intended to help designers to understand the structure of rating systems and tools in general, and discuss the design criteria and documentation requirements for obtaining these environment ratings. For the purpose of this study the key aim is to look into where and how the measurements and environmental ratings have been given, or emphasis placed, for materials, and on the overall sustainable and green approach. Table 2.2-1 shows the comparisons on five environmental assessments methods on their assessment criteria.

Based on the five comparison tools in Table. 2.2-1 it is obvious that materials are considered as one of the main criteria, with a great influence on the sustainability rating of a building. Table. 2.2-2 shows that for each assessment tool, there are different elements and weighting scores which have been given for most entries that fall under material categories. It illustrates that the reuse of existing building

structure and volume of recyclable materials are important aspects, based on BREEAM, LEED, Green Star and CASBEE. Based on CASBEE the criteria of rainwater and gray water reuse system are important as the criteria of water consumption. Overall comparisons show that BREEAM weighting score for materials considered the lowest, when compared to LEED, Green Star and CASBEE. Therefore, with new technologies, invention and waste management assistance, the use of green building materials will be a great contribution to the concept of green building.

Table 2.2-1: A Broad Comparison of the different elements of different Rating Tools for assessing environmental concerns

REEAM	LEED	Green Star	CASBEE	GBTool
Management		Management		
Energy	Energy & Atmosphere	Energy	Energy Efficiency	Resource Consumption
Health & Wellbeing	Indoor Environment Quality	Indoor Environment Quality	Indoor Environment	Indoor Environment
Pollutions	_	Emission	_	Environmental Loadings
Transport	_	Transport	_	Contextual Factors
Water	Water Efficiency	Water	_	Resource Consumption
Materials	**Materials & Resources**	**Materials**	**Resources Efficiency**	**Resource Consumption**
Land Use & Ecology	Sustainable Site	Land Use & Ecology	Local Environment	Contextual Factors
Waste	_	_	_	Environmental Loadings
Innovation	Innovation	Innovation	_	_

Table 2.2-2: A Comparison on Four Assessment Criteria for Materials with a given Percentage of Weighted

BREEAM	% Score	LEED	% Score	Green Star	% Score	CASBEE	% Score
Materials	**10.9**	**Materials & Resources**	**18.8**	**Materials**	**17.6**	**Resources & Materials**	**15.0**
A' rating per Green Guide to Specs.	1.8	Storage and Collection of Recyclables	*C	Recycling Waste Storage	0.7	Water Saving	0.9
Occupants carpet Selection	0.5	Building Reuse	4.3	Reuse of Facade	1.4	Rainwater Use systems	0.9
50% of façade is reuse facade	0.5	Construction Waste Mgmt.	2.9	Reuse of Structure	2.1	Gray Water Reuse System	0.5
80% reuse of existing structures	0.5	Resource Reuse	2.9	Recycle Content of Concrete	2.1	Reuse Efficiency of Materials Used in Structure	3.0
Recycle Building Materials	0.5	Recycle Content	2.9	Recycle Content of Steel	1.4	Reuse Efficiency of Non-structural Materials	1.5
Materials Responsibly Sources	1.4	Local/Regional Materials	2.9	PVC Minimisation	1.4	Timber from Sustainable Forestry	0.5
Recyclable Materials Storage	2.3	Rapidly Renewable Materials	1.4	Sustainable Timber	1.4	Materials with low health Risks	1.1
Hazardous material Information	1.8	Certified Wood	1.4	Flooring	2.1	Reuse of Existing Building Structure etc.	2.3
Recycling Office Consumables	1.8			Joinery	1.4	Predicted Volume of Recyclable Materials	2.3
				Loose Furniture	2.1	Fire Retardant	0.8
				Recycle-Content & Reuse Products and Materials	0.7	Insulation materials	0.8
				Disassembly / Deconstruction	0.7	Refrigerants	0.8

Note: '*C' Represents compulsory condition that was not used in the weighting

Sources:www.breeam.org,www.usgbc.org, www.gbca.au, www.ibec.or.jp/CASBEE/english/overviewE.htm

PART III – SUSTAINABLE CLAY BRICK PRODUCTION

2.3 INTRODUCTION

2.3.1 History of Clay Bricks

Bricks have been used as building materials for thousands of years. The manufacture of bricks has evolved overtime from handmade, sun-dried adobe bricks to manufactured units made entirely by machine. Bricks have a history of use in buildings extending over 10,000 years. The earliest use of brick so far recorded is Jericho *c.*8000 Before Christ (BC), as firing bricks commenced from the third millennium BC (Lynch, 1994). Clay bricks were first made in Britain by the Romans and then later reintroduced from the Low Countries (Belgium, the Netherlands) and Germany in the thirteenth century (Everett, 1994). The earliest bricks, made in warm climates countries, were simply placed in the sunlight for hardening. In ancient times, sun-dried bricks, which were used extensively especially in Egypt, were made of clay mixed with straw. In the Americas, adobe bricks have been made for centuries in Central America, particularly in Mexico. Today, the Pyramid of the Sun, built by the Aztecs at Teotihuacan, Mexico, in the 15th century which is made of adobe blocks and basalt is still exist. In Britain during early thirteenth-century bricks were made either from estuarine clay of Jurassic deposits on the river banks or shallow clay beds, often termed as *'brickearth'*. By the late fourteenth century, the growing demand for bricks comes from the business in some areas and local towns of commercial yards with permanent kilns (Lynch, 1994).

Throughout medieval (1200-1485) and Tudor periods (1485-1603) the bricks colour are varied with local clay, firing temperature, fuel and position of the brick in the kiln or clamp, from pale pinks and yellows to the more popular deep red. In 1571 brick size became regulated by the British government law, with the name 'statute bricks' also used to prevent abuse on the sale of bricks by number as opposed to weight. In 1625 Charles I's Royal Proclamation introduced further rules to control the continuing non-uniformity of bricks size, in which bricks were to be 9" (229mm) long, 4" (102mm) breadth and 2 ¼" (57mm) in thickness. Then, the early seventeenth and eighteenth centuries saw a considerable development in the quality of bricks, largely influenced by Dutch practices.

Today, most clay bricks are fired in permanent kilns, either intermittent or continuous-burning. Intermittent kilns are used only where special colour effects are required. By the 1870s the majority of bricks were manufactured by machine, either by wirecut process or being 'pressed' into metal moulds, resulting in regularity of colour, texture and size, giving a uniformity to the brickwork. In Britain, in 1965 the size of brick became a British Standard BS3921, and a first national and unifying standard size, which became metricated in 1969 by BS3921 at 215mm x 102.5mm x 65mm (Lynch, 1994).

2.3.1.1 Modern Bricks

In a good quality clay brick, the majority clay minerals are kaolinite and illite (British Geological Survey, 2005). The qualities and characteristics of clay, and an assessment of its suitability for manufacturing quality bricks, are determined by practical trials and scientific chemical analysis. The main constituents of clay used for making brick are silica (60%) and alumina (20%) and also with minor phases of iron oxide, calcium, magnesium, sodium and potassium. The actual processes of brick manufacture starts from the selection of clay types, in common with other industries that utilise natural raw materials. The process is initiated with the extraction of raw material from the ground. In the manufacture of bricks and other clay products, the term 'clay' is used relatively loosely, since the clay mineral content of raw materials may vary from 20% to 80%. The British Geological Survey (2005) reported approximately 3 tons of clay/shale are used in the manufacture of 1000 bricks and the decline in demand for 'brick clay' from 16 million tons in 1974 to some 7.6 million tons in 2004 is mainly due to the demise of common bricks which have been replaced by concrete blocks and plasterboard for the inner leaves of cavity walls and as internal walls.

After extraction, the raw material is prepared for firing normally by homogenisation, increasing the water content, moulding and the addition of any surface effects. In clay brick there must be sufficient presence of clay minerals to make it plastic to mould and to retain the shape prior to firing. Sufficient fluxing materials must also be present for the clay to vitrify at temperatures between 900-1100°C. An adequate proportion of non-plastic constituents, usually quartz, are also required to prevent excessive shrinkage and deformation during drying and firing.

During the firing process, the fresh bricks are loaded onto kiln cars for drying, from here using conveyor system the cars enter the kiln for firing. The maximum firing temperature reached by most clay brick manufactures is 1100°C and depending on demand the bricks usually spend between 36 to 48 hours in the kiln (O'Farrell, 1999). Once fired, the bricks are cooled in a controlled environment, packaged and finally distributed for sale. Although a very high proportion of clay bricks are machine made, hand making is still common, particularly in producing premium-quality facing bricks and special request shaped (O'Farrell, 1999). Bricks properties include strength, water absorption (porosity) and frost resistance, which are important to ensure durability and performance in service. Non-clay minerals, such as quartz, iron oxide and calcium carbonate, can profoundly affect the colour and properties of fired bricks, whereas materials such as carbon, sulphur and gypsum are important impurities during the firing, either by adding to the calorific value during firing (carbon and sulphur), or add to the reactivity and hence better strength development (gypsum).

Fox and Murrell (1989) described the environmental situation concerning bricks include their non-renewable aspect; quarrying for the raw material destroys habitats and water tables, and brick-making is one of the energy-guzzling industries. In China, to save cultivated land, fired clay bricks have been prohibited to use in construction by their government (Lingling *et al.,* 2005). Moreover, as with all ceramics products, impurities burned off during the firing process give rise to undesirable substances in the flue gases, as experiments in recycling heat from such gases have indirectly indicated, and this has caused great difficulties in creating viable energy-saving systems in brick manufacture. The environmental impact of the clay brick production is primarily due to the energy consumption for firing of the bricks and quarrying of raw materials. The average direct energy consumption of the production process is to be found ranging between 1,840 and 2,800 kJ/kg of fired brick. All of this energy used is traditionally generated with fossil fuels (Moedinger, 2009).

Since extensive quarrying is required in order to acquire the raw materials for clay bricks production. There is therefore a need to research towards a more sustainable system by the utilisation of waste materials in the development of sustainable construction rather than continuously consuming non renewable resources. One method of achieving this is the partial replacement of clay by secondary cementing materials such as pozzolans which lead to low cost construction materials and generally results in increased durability of the new building wall materials. Many pozzolans are waste materials from other industrial processes and with more extensive use could significantly reduce cement consumption in bricks making and the associated environmental damage caused during brick manufacture.

In order to minimise the impact of the manufacture of bricks on the environment today through innovative development, many researches have shown that it is possible to adopt alternative ways in replacing traditional sources of raw materials by renewable alternatives in sustainable brick making (Oti, 2010; Lawrence *et al., 2009*). In a further innovative step it has been possible to introduce a selective blend of industrial waste/by-products into the manufacture of bricks in order to partially replace normally quarried clay. The successful introduction of a selective blend of industrial by-products into the feedstock replacing quarried raw materials will lead to lesser environmental footprint of a production process. Unfired clay bricks for internal non-load-bearing applications are produced from clay which would be less suitable for standard clay bricks. Earth bricks require only low energy input for drying and have high potential recyclability.

2.3.2 Soil – Clay Mineralogy

The main ingredient for brick production is clay soil. The large majority of soils consist of a mixture of inorganic material particles, together with some water and air. Soil is the result of the process of the gradual breakdown of rock - the solid geology that makes up the earth. As rock becomes broken down through a variety of processes, such as weathering and erosion, the particles become ground into smaller and smaller particles. There are considered to be three main mineral parts to soil; 'sand', 'silt' and 'clay'. These parts give the soil its 'mineral texture'.

There is an enormous diversity of soils across the world. This is hardly surprising given the fact that soil formation and soil type are influenced by several key factors: the parent material, usually rock or sediment, but occasionally organic materials such as peat; climate, particularly temperature, and rainfall; vegetation and other biota; topography; time; and, increasingly, the influence of humans. All these factors will have an influence on soil development and hence soil type. For engineering purposes, soil is best considered as a naturally occurring particulate material of variable composition having properties of compressibility, permeability and strength (Whitlow, 2001).

2.3.2.1 Clay Minerals

The term 'clay' can have several meanings:

1. *Clay soil* – the soil behaves as a 'clay' because of its cohesiveness and plasticity even though the clay mineral content may be small.
2. *Clay size* – most classification systems describe particles less than 2 μm as 'clay' which is a reasonably convenient size. However some clay mineral particles may be greater than 2 μm and some soil particles less than 2 μm such as rock flour which may not contain many clay mineral particles at all.

3. *Clay minerals* – these are small crystalline substances with a distinctive sheet-like structure producing plate-shaped particles (Barnes, 2000)

In general clay implies a natural, earthy, fine-grained material which develops plasticity when mixed with a limited amount of water. Grim (1968) described several factors that effect the properties of a clay soil or clay material as clay mineral composition, non-clay-mineral composition, organic material, exchangeable ions and soluble salts. Certain clay minerals can have remarkable influence on clay soil, even if present in small amounts. The crystallinity and variability in clay minerals affects such properties of soil, like for example its plasticity. Non-clay minerals, such as calcite, dolomite, mica, quartz, pyrite, feldspar, gibbsite and other minerals are abundant in clay soil, and the effect of these minerals on the properties of clay soil can influence the potential uses of the clay soil. Organic materials usually act as a pigment in clay soil giving the material a dark-grey or black colour. Kinuthia (1997) reported that the presence of a small amount of organic material in a soil can bring a major effect on its behaviour. In recent times, there has been increasing realisation that not only the amount, but also the chemical composition of organic material can influence the sorption properties of soil (Baldock and Skjemstad, 2000; Grathwohl, 1990). A number of researchers have suggested that it is the physical conformation, rather than the chemical composition of the organic matter that mostly affected the water sorption (Wang *et al.*, 2007; Liang *et al.*, 2006).

2.3.2.2 Clay Mineral Structures

The clay minerals are generally derived from weathering of pre-existing materials. The majority of clay minerals are insoluble in acids. They appear to have appreciable affinity for water, are plastic when wet, water retentive and coherent when dry. Most clay minerals are crystalline, with sheet-like or layered structures of two varieties: silica sheets and alumina sheets. The silica sheet is composed of tetrahedral units, each being bounded by four triangular plane surfaces, with four equally spaced oxygen atoms at the vertices and a silicon atom within the interior, equally spaced from the oxygen atoms. The tetrahedral units are combined into hexagonal units, in a repetitious manner, to form the lattice of the mineral.

The alumina sheet has two-row units, consisting of one aluminium or magnesium or iron atom at the centre of an octahedron, with oxygen atoms or hydroxyl (OH) units at the vertices of alternate rows, respectively. The oxygen and hydroxyl ions dominate the mineral structure because of their numbers and their size (they are about 2-3 times larger than an aluminium ion and about 3-4 times larger than a silicate ion). Even if their negative charges are satisfied, the O^{2-} and OH^{-} ions existing on the surface of the sheets will impart a slightly negative character.

Clay mineral particles are quite small, less than 2 μm (1 micron, μm = 1×10^{-6}m), and electrochemically very active. For example, minute clay particles carry similar electrical charges, which induce mutual repulsion. Neutralization of these charges, say through electrolytes, can bring about coagulation and subsequent precipitation of the floccules of clay. This charge must be balanced by cations between the layers, which provide chemical bonding between layers (Bentabol *et al.*, 2009; Peng *et al.*, 2009; Varma, 2002). Furthermore as the size of the particles decreases below 2μm, the electrical charges on the particles increase with the decrease in size. Hence, it would be useful to the civil engineer to be able to manipulate the cation-exchange feature towards a desired goal when confronted with a flocculation situation. Without fundamental data on how and why clay minerals are held together, it is impossible always to predict safely from any empirical data how a clay material will act when load is applied, when the water table is altered, or when other conditions are changed (Grim, 1968).

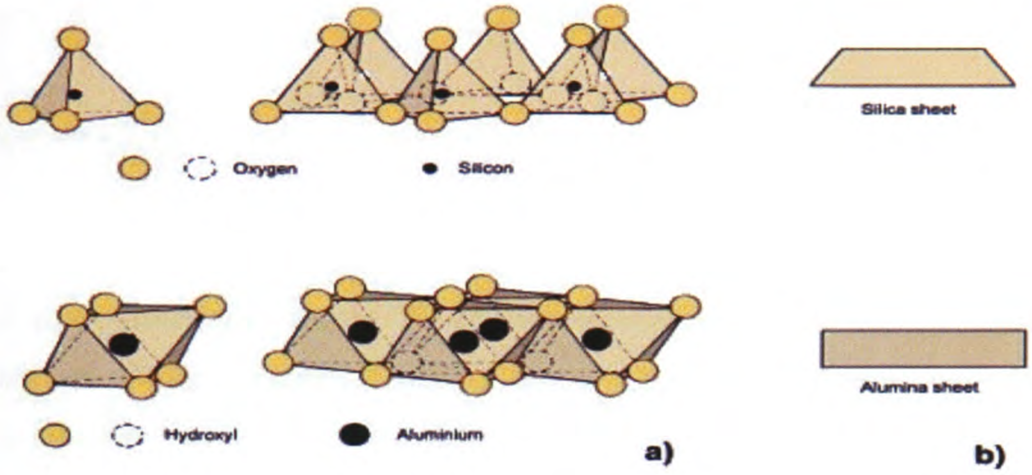


Figure 2.3-1: Basic units of clay minerals and the silica and alumina sheets (source, Mitchell, 1993)

2.3.2.3 Clay Mineral Types

The clay minerals are usually divided into three main groups, they are the kaolinites, the montmorillonites and the illites. Most clays formed by sedimentation are a mixture of kaolinite and illite with a variable amount of montmorillonite, whereas clays formed by chemical weathering of rocks may also contain chlorites and halloysites.

a) Kaolinite

The kaolinite minerals are formed of units consisting of a single tetrahedral silica and a single octahedral alumina sheet. These units may repeat themselves indefinitely to form the lattice of the mineral. Variation between members of the kaolinite subgroup consists of the way layers are stacked above each other and possibly in the position of aluminium ions within the available sizes in the octahedral sheet.

Figure 2.3-2 gives a symbolic arrangement of the kaolinite minerals. Their general chemical composition is expressed by the formula;

$$(OH)_8\,Al_4Si_4O_{10}.$$

Kaolinite is the most abundant constituent of residual clay deposits, derived mostly as a by-product of the weathering of rock or certain clay minerals, and is commonly intermixed with illites in sedimentary clay. Kaolinites are very stable, possess a tight cohesive structure that resists the penetration of water into the lattice and generally are not subject to expansion when saturated. Penetration of water molecules and ions between the layers is difficult because of the strong hydrogen bonding. Also the coefficient of internal friction is somewhat higher than that of most other clay minerals.

Halloysites are minerals that belong to the kaolinite family. They possess a round or flattened tube-like shape. Some other members of the kaolinite group are nacrite and dickite. The halloysites are distinguished by one additional water molecule to the basic kaolinite unit. This is given by the formula;

$$(OH)_8\,Al_4Si_4O_{10}.4H_2O.$$

When wet, halloysite masses have a tendency to creep or flow horizontally. Thus, they may be viewed as potentially unstable, and less than desirable as materials for embankments. Both kaolinites and halloysites are common materials in the pottery industry (Cernica, 1995). According to Cuevas *et al.*, (2009), kaolinite is the preferable type of clay for industrial application.

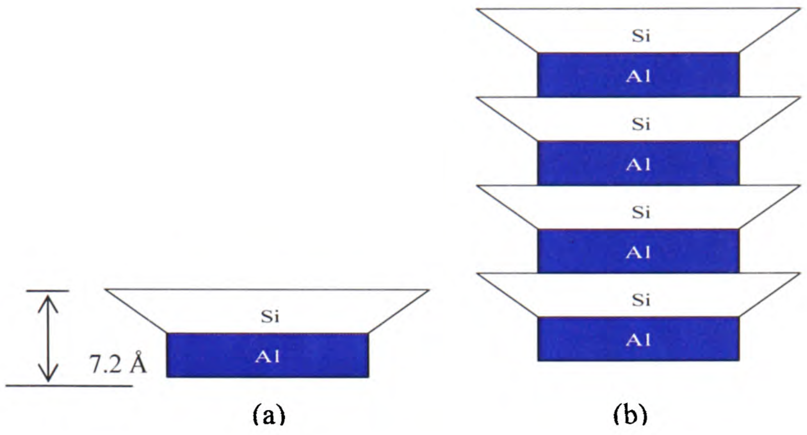


Figure 2.3-2: Schematic drawing of the kaolinite mineral (a) Basic kaolinite unit (b) Lattice of kaolinite mineral.

b) Montmorillonite

Montmorillonites are formed from the weathering of volcanic ash under poor drainage conditions. They have a high shrinkage and swelling potential which can be several times their dry volume. The general chemical composition of this group is expressed by the formula;

$$(OH)_4Al_4Si_8O_{20}.\ nH_2O$$

The montmorillonites are made up of sheet-like units comprising an alumina octahedral sheet between two silica tetrahedral sheets, as shown in Figure 2.3-3. The bonding of these sheets is rather weak, resulting in a rather unstable mineral, especially when wet. In fact, montmorillonites display a significant affinity for water, with subsequent swelling and expansion. Conversely, upon drying a saturated montmorillonite, the result is appreciable shrinkage and cracking. In practical terms, such characteristics may be of significance to the engineer. For example, the expansion of clay may mean lifting of slabs, excessive lateral thrusts on retaining structures, and the endangering of the stability of slopes (Cernica, 1995). Soils containing a large proportion of montmorillonite are poor foundation materials, because they have the tendency to absorb large amounts of water and show a large volume change between the wet and dry seasons (Mitchell, 1976).

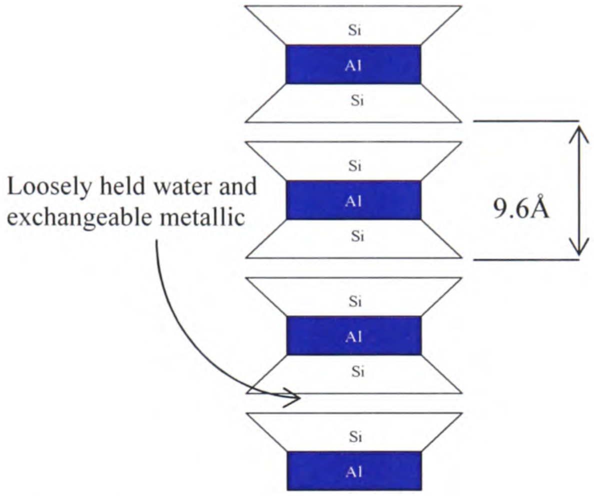


Figure 2.3-3: Schematic drawing of the montmorillonite minerals

c) Illites

The illites are somewhat similar to the montmorillonites in their structural units, but are different in their chemical composition. The chemical composition of illites is expressed by the formula;

$$(OH)_4K_y(Al_4Fe_4Mg_4)\ (Si_{8-y}Al_y)O_{20}$$

'y' varies from 1 to 1.5. The symbolic structure of illites is shown in Figure 2.3-4. The basic structure of the illite unit consists of a gibbsite octahedral sheet between two silica tetrahedral sheets. Unlike montmorillonite particles, which are extremely small and have a great affinity for water, the illite particles will normally aggregate and due to the strongly bonding interlayer potassium atoms, they develop less affinity for water than montmorillonites. Correspondingly, their expansion properties are less. The angle of internal friction is higher than that of montmorillonite. Illites usually occur as very small, flaky particles mixed with other clay and non-clay materials. Nature of clay mineral particles are described in Table 2.3-1.

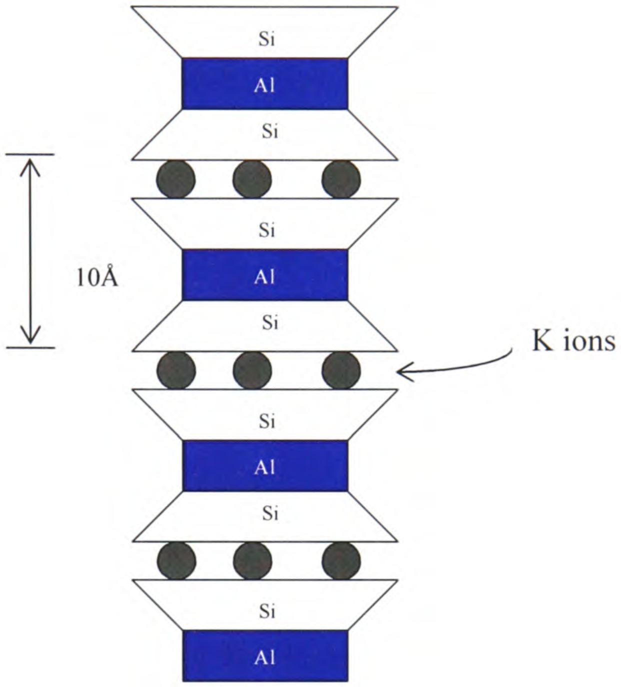


Figure 2.3-4: Schematic drawing of the Illites minerals

2.3.2.4 *Characteristics of Clay Minerals*

a) Ion Exchange

Ion exchange is the replacement of one ion adsorbed on the clay lattice surface by another. The physical properties of clays are dependent on the exchangeable ions. Ion exchange is of great importance in the applied sciences where clay minerals are used. Clay minerals have the property of sorbing certain anions and cations and retaining them in an exchangeable state; i.e. these ions are exchangeable for other anions or cations by treatment with such ions in a water solution (the exchange reactions may also take place in a non-aqueous environment). The exchangeable ions are held around the outside of the silica-alumina clay-mineral structural unit, and the exchange reaction generally does not affect the structure of the silica-alumina packet.

Grim (1962, 1968) stated that clay surfaces are usually negatively charged and this is the cause for cation attraction to the clay particle surfaces. There are three main causes of the negative charge:

1) ***Broken bonds*** around the edges of the silica-aluminate units leaving unbalanced charges which are balanced by adsorbed cations. The number of broken bonds per unit mass and hence the ion exchange capacity increases as the particle size decreases.
2) ***Substitution within the lattice structure*** of trivalent aluminium Al^{3+} for quadrivalent silicon Si^{4+} in the tetrahedral sheet and of lower valence ions particularly Mg^{2+}, for trivalent aluminium Al^{3+} in the octahedral sheet both result in unbalanced charges in the structural units of some clay minerals. This charge imbalance may be balanced either by substitution in other lattices (i.e. OH^- for O^{2-}) or adsorption of positive cations.
3) ***The hydrogen of exposed hydroxyls*** may be replaced by a cation which is exchangeable. Some hydroxyl groups are exposed around the broken edges of all clay minerals, and cation exchange due to broken bonds can, in part at least, occur by replacement of the hydrogens of exposed hydroxyls.

Exchangeable cations are positively charged ions which are attracted to the surface of clay particles to balance the excess negative charge. Cation exchange occurs because one cation can be replaced by another of similar valence, or by two of one-half the valence of the original one and so on (Yong and Warkentin, 1975).

Cations can be arranged in a series on the basis of their replacing power. Early studies stated that under a given set of conditions, various cations were not equally replaceable and did not have the same replacing power. The general order of replacement of the adsorbed cations is : $Li^+ < Na^+ < H^+ < K^+ < NH^+ << Mg^{2+} < Ca^{2+} <<$

Al^{3+} . At equal cencentration, any cation will tend to replace those to its left in the series (Grim, 1968).

The number of cations that are exchangeable is defined as the cation exchange capacity and is usually expressed in milliequivalents of cations per 100 grams of oven dry soil (meq/100g). The milliequivalent may be defined as one milligram of hydrogen ions (H^+) or the amount of any other cation that will replace it on the clay mineral surface. The cation exchange capacity should be measured at pH 7. At higher pH more cations are adsorbed, because of increasing dissociation of weekly bonded $Si\text{-}OH^-$ groups on exposed clay crystal edges. Below pH 5 the cation exchange capacity is constant (Grim, 1962).

Mukherjee *et al.*, (1943) (from Grim, 1968) found that the exchange capacity might vary with the nature of the cation. It was considerably larger with divalent cations, such as Ca^{2+}, than with monovalent cations (e.g. Na^+). Other factors such as particle size, lattice distortion, clogging of exchange positions etc. may also affect the cation-exchange capacity (Grim, 1968).

Table 2.3-1 gives the cation exchange capacity of common clay minerals. The large net negative charge carried by the montmorillonite particles and its large specific surface area means that the cation exchange capacity of montmorillonite is very high compared to kaolinite, illite or chlorite.

Table 2.3-1: Cation exchange capacity of clay minerals in milliequivalents per 100g at pH 7 (Grim, 1968)

Clay Minerals	Exchange Capacity (meq/100g)
Kaolinite	3-15
Illite	10-40
Chlorite	10-40
Montmorillonite	80-150

b) Water Adsorption and Swelling Properties of Clay Minerals

Clay soils may suffer from volume changes due to moisture content changes which result in swelling and shrinkage (Bell, 1983). The ability of clay to imbibe water leads to swelling and when it becomes dry, it shrinks. Clay particles in soils are almost always hydrated, i.e. surrounded by layers of water molecules adsorbed onto the clay particles. This water layer affects all soil properties including plasticity, compaction, strength and water movement in soil (Abdi, 1992; Gillot, 1987; Yong and Warkentin, 1975). Surface forces on clay minerals may make it adsorb water and swell due to the movement of water into the interlayer region. Mokni *et al.,* (2009) reported that the swelling can be from a few percent to more than 30%. In the case of montmorillite, water moves into the interlayer region in response to the of interlayer cations, producing a net expansion in the crystal structure, and either swelling of the clay mineral or build up of swelling pressure. However, kaolinite and illite do not show this swelling behaviour (Mitchell and Soga, 2005).

Barshad (1955) stated that water adsorption in clays starts with the hydration of the external clay particle surface by a unimolecular layer of water. This layer builds up with time to multimolecular water layers at a rate dependent on the type of clay. These multilayers then find a way into the interior surfaces of the clay particles themselves through diffusion of water vapour through the clay particle and/or seepage at the clay particles edges. The interlayer cations are still in position at this stage attached as they are to the oxygen sheets. As more molecular water layers find their way into the interlayer spaces, and with subsequent expansion of the interlayer distances, the cations get detached creating an external surface. If the water is in vapour form (as during curing of stabilised soil), the expansion is minimal. If in liquid form, further expansion occurs.

2.3.3 Soil Stabilisation and Modification

According to Huat *et al.,* (2004), in construction, soils can be stabilised through chemical and mechanical processes (vibration and compaction). Several methods are available for stabilising clay soils in order to increase the strength properties and to reduce the swelling or expansion behaviour. These can be achieved by the use of chemical additives, soil replacement, compaction control, moisture control, surcharge loading and by thermal methods (Moavenian and Yasrobi, 2008; Yong and Ouhadi, 2007; Nelson and Miller, 1992).

Chemical stabilisation involves the formation of strong bonds between the clay minerals and other soil particles and it is therefore ineffective in granular soils. Lime stabilisation is one of the common and earlier chemical stabilisation. This type of stabilisation also can be achieved by using fairly expensive organic agents which are either water-repellent, oily, or bituminous compounds or cementing resins.

In mechanical stabilisation, fibrous and other non-biodegradable reinforcement of geo-materials can be used to improve strength. The compaction method of soil stabilisation concentrates on soil densification which involves the rolling or tamping of the soil, where the soil is usually placed in layers of specific thickness, and each layer is then subjected to a specified amount of compactive effort. Normally this can be found in the construction of road bases, earth dams, runaways and embankments. For mechanical vibration, a vibratory poker is placed into granular material causing compaction.

In recent years much research has been directed at the identification and investigation of a wide range of new pozzolanic materials such as, metakaolin, fly ash, red mud, rice husk ash, burnt clay and wheat straw ash or by latently hydraulic materials. The partial replacement of cement by pozzolanic materials results in the effective reduction of the cost of concrete production (Veerapan, 2003). This is achieved by decreasing energy consumption in reducing cement production and by utilising materials with lower cost compared to cement. As in concrete, Portland Cement (PC) is one of the binders used in brick making industry, being largely used as a cementitious material. Therefore, there are significant numbers of research projects on the application cement-blended binders in soil stabilisation, which offer sustainability advantages over cement (Jegandan *et al.*, 2010). Research by Wild *et al.*, (1998) reported that it is feasible that new clay-based materials may be formulated by stabilising clay soil with various blended stabilisers.

The suitability of these various wastes and industrial by-products, non-conventional and conventional stabilisers as stabilisation materials are reviewed later for a better understanding of the underlying principles. The use of waste and industrial by-products as a target material for soil stabilisation has both cost and environmental benefits. These include the avoidance of dumping waste to landfill and evading of landfill tax and other waste disposal costs, recovering the energy value in the waste generated, and results in a suitable way of dealing with material utilisation.

2.3.3.1 Traditional Binders

2.3.3.1.1 Clay-Lime Stabilisation

Lime had been used as one of the traditional stabilisers for clay soil. The use of cementitious materials such as Portland Cement (PC), hydraulic lime and lime-pozzolana mixes as stabilisers is quite common (Al-Rawas *et al.*, 2005; Bell, 1998; Sherwood, 1993). Researchers now believe that with the addition of small amount of lime, the calcium present causes an ionic exchange, which results in flocculation that has a dramatic effect on the soil, in terms of improved workability and shear strength. Stabilisation of clay soil by the incorporation of lime is a technique widely used throughout the world to improve soil for use in construction (Bell, 1996). The main application of lime in relation to soil stabilisation is the modification of engineering properties of the potentially target material, and for use with clay soils that are difficult to stabilise with cement alone (Nidzam, 2004). Roger *et al.,* (1997) reported lime stabilisation can be defined as the reaction between silica and alumina within the clay structure and lime and water to form calcium silicate hydrates, calcium-aluminate-hydrates and calcium-alumino-silicate-hydrates (C-S-H, C-A-H & C-A-S-H) gels, which subsequently crystallise to bind the structure together and the reaction will be stronger in the case of high silicate content in the soil. Until the discovery of PC in the 19th Century, lime was widely used for building construction.

The strength development of lime-stabilised soil is primarily dependent on the pozzolans present and has been extensively studied by several researchers (Nidzam, 2004; Thomas, 2001). It has been found that the strength gain is influenced by several factors such as clay type, amount and type of lime added, moisture content, curing period and time elapsed between mixing and compaction (Bell and Coulthard, 1990; Ingles and Metcalf, 1972). Clay minerals present in a soil have been found to have an important influence on the strength properties as each type of clay has a different mineralogy which will affects the reaction products. Clay minerals are natural pozzolans and have the ability to react with the lime added to the soil in order to produce cementitious products. The reactions between lime, silica and alumina in clay to form cementitious products are referred to as the soil-lime pozzolanic reactions.

When lime is added to a clay soil, it has an immediate effect on the properties of the soil as cation exchange begins to take place between the metallic ions associated with the surfaces of the clay particles and the calcium ions of the lime (Bell, 1996). Regardless of the stabilisation method, the ultimate goal is to ensure adequate final density and strength of the soil. The point of achieving optimum moisture content (OMC) and maximum dry density (MDD) of a soil plays an important role in compaction as well as in permeability and strength of compacted soils, where the properties of a soil and its performance are influenced by the molding moisture content due to its effect on the structure and orientation of clay particles. The addition of lime to all clays in general increases the OMC and reduces the MDD (Nidzam, 2004; Thomas, 2001; Kinuthia, 1997; Abdi and Wild, 1993). Pozzolanic reactions happen during the longer-term soil stabilisation process and occur slowly. They produce long-term strength gain by the progressive crystallisation of gels between lime and certain clay minerals to form a variety of cement-like compounds that can bind soil particles together and at the same time reduce water absorption by clay particles.

Galloway and Buchanan (1951) suggested that the effect of lime on soils was due to an exchange of calcium ions for absorbed cations on the clay particle surfaces, where the reactivity of soil towards hydrated lime increased as the plasticity index and cation exchange (flocculation and agglomeration happen during the soil modification process and occur rapidly after addition of lime to clay) capacity of the soil increased.

Lime used in soil stabilisation may be in many forms such as quicklime (CaO), hydrated lime ($Ca(OH)_2$) and dolomitic lime. Generally quicklime is more effective stabiliser than hydrated lime (Bell, 1988). Strength does not increase linearly with lime content, and generally below a certain limit, lime addition increases the strength of soil and excessive addition of lime reduces strength (Abdi, 1992; Bell 1988). Research by Bell (1996) described the optimum addition of lime needed for maximum modification of the soil to be normally between 1% and 3%, added by weight. Beyond this point any lime available is used to increase the strength of the soil. According to Ingles (1987), a good rule of thumb in practice is to allow 1% by weight of lime for each 10% of clay in the soil. For economic reasons it is necessary to use the minimum amount of lime which achieves the required strength.

2.3.3.1.2 Soil Stabilisation with Portland Cement (PC)

Portland cement has been used effectively in strengthening of granular materials such as soils. It is a primary stabilising agent, which can be used alone to bring about a stabilising action (Sherwood, 1993). PC consists mostly of calcium silicate, obtained by heating to partial fusion a predetermined and homogenous mixture of materials containing principally lime (CaO) and silica (SiO_2) with small proportions of alumina (Al_2O_3) and iron oxide (Fe_2O_3). The hydration of PC is a chemical reaction between the phases present in the cement powder and water, resulting in the formation of a number of hydration products. These hydration products contribute to the properties of the hardened cementitious material. The C-S-H gel and C-A-H phases that form during the hydration process produce a strong, hard matrix in which granular material, like clay soil is embedded. The strength of the soil can be increased reasonably by cementing clusters of particles in a similar way of binding aggregates in concrete (Hossain, 2010).

2.3.3.2 Alternative Materials for Soil Stabilisation

The potential for using industrial by-products for stabilisation of soils such as fly ash, rice husk ash, cement kiln dust, blast-furnace slag is promising and has been investigated by several researchers (Oti, 2010; Sezer *et al.*, 2006; Nidzam, 2004; Veerapan, 2003; Miller and Azad, 2000; Kaniraj and Havanagi, 1999). Efforts are now being made, to quantify and rank the environmental performance of different materials used in buildings. In the UK, continuing pressure from environmental groups, the media and combined with increasing amounts of government legislation promoting *'sustainable communities through sustainable development'* means that today the construction industry is increasingly required to take account of its effects on the environment. In effect, sound evidence of the sustainability of a construction material or product is becoming an increasingly important tool for marketing purposes and sales generally.

Today efforts are being made on reducing waste, maximising the use of renewable and recycled materials, the used of industrial by-products, reduce pollution and thereby reduce impact on the upper atmosphere (Head, 2001). The chemistry and physical properties of many industrial by-products may vary as the sources of raw materials change and/or the production process is improved (Jegandan *et al.*, 2010). The increasing pressures to reuse industrial by-products and wastes means that a much wider range of materials is available and potentially suitable for building materials and other construction applications.

In buildings the main challenges are to improve productivity in end use, reduction in operational energy, better durability and lower maintenance, greater reuse and recycling of components and adaptability for change of use. It would seem to be the right time for construction teams to lead the next revolution in construction technology on a global scale, one that aims to create new sustainable building materials. Therefore, recently alternative materials have been studied and analysed for the production of new environmentally friendly building materials.

There is an increasing need to develop building materials that are fit for purpose based on sustainability principles in terms of the economy and environment factors and the concern on the major impact of energy usage and new innovative products. As an example, the use of waste and by-products materials in concrete, either as components of blended cements or admixtures, has increased tremendously over the last 30 years (Veerapan, 2003). The benefits derived from the use of these alternative materials in building industry can be divided into three categories: functional or engineering benefits where they can enhance the ultimate strength, impermeability and durability of products. Second is the economic benefits, since a significant amount of alternative materials (pozzolanic and cementitious materials) in use today are industrial by-products, which require relatively little or no expenditure of energy. The third benefit is ecological; the total volume of pozzolanic and cementitious by-products generated every year by thermal power plants and metallurgical furnaces exceeds 500 million tons (Maholtra and Mehta (1996). In the interest of environment, it is desirable to use these materials as supplementary cementing materials rather than further increasing the cement production.

2.3.3.2.1 Pozzolanic and Cementitious Materials

Pozzolanic and cementitious admixtures are generally classified under the term mineral admixtures (Malhotra and Mehta, 1996). To develop cementing action, a pozzolan has to be mixed either with lime or with PC. According to Malhotra and Mehta, (1996) a pozzolan is a siliceous or siliceous and aluminous material which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementing properties. Pozzolans are commonly used as an addition to Portland cement in concrete mixtures to increase the long-term strength and other concrete properties. The extent of the strength development depends upon the chemical composition of the pozzolan, where the greater the composition of alumina and silica along with vitreous phases in the material, the better the pozzolanic reaction and strength. During hydration of Portland cement, $Ca(OH)_2$ is produced as one of the hydration by-products, but when certain pozzolanic materials containing amorphous silica are added during hydration of cement, they react with lime giving additional amount of calcium silicate hydrate (C-S-H) gel, the main cementing component. Thus the pozzolanic material reduces the amount of $Ca(OH)_2$ and increases the amount of C-H-S gel.

Pozzolanic materials can be divided into two groups, natural and artificial. Natural pozzolanic materials include volcanic ash (the original pozzolan), pumicite, opaline shales and certs (Mehta, 1987). Calcined clay and some industrial waste such as fly ash (PFA) and silica fume are grouped as artificial pozzolans (Detwiler *et al.*, 1996). The main oxides in pozolanic materials are SiO_2, Al_2O_3, Fe_2O_3, CaO and MgO, and pozzolanic activity is generally determined by the amount and form of SiO_2 present (Veerapan, 2003).

In order to achieve a good pozzolanic material, the physical properties of the artificial pozzolans may need to be improved. This normally involves a calcination process, generally in the temperature range of 550° to 110°C (Detwiler *et al.*, 1996). Wild *et al.*, (1997) reported that calcination temperatures below 900°C for particular brick clays produced a marked loss in sulphate resistance when the pozzolanic product was used to partially replace cement in mortar, whilst calcining at temperatures of 1000-1100°C resulted in a product which imparted good sulphate resistance and also reduced the calcium hydroxide content.

Among the commonly used pozzolanic materials is pulverised coal ash from thermal power plant (PFA). Cementitious materials are mainly from non-crystalline or poorly crystalline materials similar to pozzolans but containing sufficient calcium to form compounds which possess cementing properties after interaction with water. As an example, ground granulated blastfurnace slag (GGBS) is a non-metallic product, consisting essentially of silicates and aluminosilicates of calcium and magnesium. A brief discussion of a few examples of the by-product materials that have been commonly used as alternatives supplementary cementitious pozzolans for building materials is given below;

a) Pulverised Fuel Ash (PFA)

Coal fly ash or Pulverised Fly Ash (PFA) or fly ash is a by-product of burning coal for heating or generation of electricity. For many years, many research projects and research papers have been published on the subject. Fly ash has in the past been regarded by the public as a solid waste material, though it is increasingly now being used for various beneficial purposes.

As a by-product material it has been reviled, researched, praised and criticised. Although coal is readily available source of energy, it is predominantly carbon and when burnt, produces carbon dioxide (CO_2). Today, fly ash has been used in a number of applications in the construction industry, as an ingredient in making concrete, used for strengthening road beds. It has also been used as part of the raw materials for manufacturing cement and it has also been used in many other ways including in soil stabilisation (Liu, 2007).

In Greece for example the production of fly ashes in year 2000 was more than 10 million tons, but only 10% of the fly ash produced is used for the production of cement, the remaining amount being deposited in mines, causing environment and financial concerns (Koukouzas *et al.*, 2007). In Europe, the utilization rate for fly ash used in the construction industry is approximately 46% which is about 20 million tons, mostly used in concrete production (33%), cement-mill-raw-feed material (23%), road construction (22%), blended cement (11%), and concrete blocks (6%). Over 100 million tons of fly ash is available as waste from thermal power plants in India, but only about 20% is being utilised at present in spite of incentives provided by the government of India (Manjit and Grag, 2007). In China the output of fly ash is about 130 million tons per annum and the utilization ratio recorded about 45% (Shen *et al.*, 2006). In China many brick making factories have utilised fly as a raw material to make bricks, but only with low volume ratio of about 10% to 30% by volume (Lingling *et al.*, 2005). Improved engineering properties of fly ash-stabilised soil were reported by Tunner (1997), who conducted research on a fly ash stabilised sub-base along with nine other stabilisation alternatives. This study indicated that increasing the fly ash content to soil mixes has a considerable effect on the strength properties of soil, which strongly depends on the water/binder ratio.

Due to the increased use of pulverised coal as fuel for electric power generation; fly ash is now available in many areas of the world. Most thermal power plants use coal-fired boilers which consume coal ground to finess of 70% to 80% particles passing at 74μm. The particle size distribution of fly ash can vary considerably depending on how a power station is being operated. It has no intrinsic impact in respect of global warming gases. However, its unique properties can be used to reduce the impacts of other industries. The utilisation of fly ash for replacing naturally occurring aggregates and minerals, e.g. in-fill, road construction and brickmaking applications can significantly reduce the demand for virgin aggregate. By way of the pozzolanic reaction, fly ash can complement and replace Portland cement in cementitious applications. Several studies have been carried out on the effectiveness of clay stabilisation by fly ash admixtures (Göktepe *et al.*, 2008). Report by the British Geological Survey (2005) has indicated that the use of PFA is increasing in the manufacture of both pressed and soft-mud bricks where it typically replaces in between 10% to 20% of the clay.

Although fly ash is commonly used in cements, it has however rarely been applied to make bricks (Cultrone and Sebastian, 2008). Joshi and Lohtia, (1997) reported that the major properties of fly ash exploited in the clay brick industry are the similar composition as that of clay, fuel value due to the presence of unburnt carbon, reduced weight of the resultant product, reduced shrinkage due to its inert nature, and chemical compatibility with natural clays. According to Randal *et al.*, (1996), the study of brick manufacturing with fly ash from Illinois coals also showed that fly ash can be advantageous without any significant adverse effect on the quality of bricks produced.

It has been shown that fly ash may improve the compressive strength of bricks and make them more resistant to frost. There are other advantages in using fly ash as a raw material for bricks, such as saving in the firing energy. This is because of the amounts of carbon contained in fly ash where the unburnt carbon in the fly ash provides part of the process heat during the manufacture of fired bricks (Lingling *et. al.*, 2005). Fly ash has also been used as a partial or total replacement of quartz sand in the production of sand-lime building bricks by using an autoclave process (Joshi and Lohtia, 1997).

In view of the huge demand for building bricks, along with reduced availability of suitable soil, there is a need to explore alternative raw materials and energy efficient technologies for making bricks (Malhotra and Dave, 1992). Fly ash can be used to replace up to 40% of clay, the main raw material in building blocks and tiles (Joshi and Lohtia, 1997). This will certainly contribute to the recycling of fly ash and hence minimise the impact of the fly ash landfills on the environment. This helps in the reduction of clay usage for the production of bricks. The cement research aims to contribute knowledge to this area of clay-fly ash pozzolanicity, for the production of sustainable building bricks.

b) Metakaolin

Metakaolin (MK) is one of the pazzolanic materials with very high pozzolanic properties and undergoes hydration in the presence of lime. From mid 1980' there has been an increasing interest in utilisation of Metakaolin (MK) as a supplementary cementitious material in concrete (Palomo *et al.*, 1999; Wild *et al.*, 1996; Ambroise, *et al.*, 1994). MK is a nearly anhydrous semi amorphous solid obtained by heating kaolin in the temperature between 700-900^{0}C for 2 to 4 hours and consists predominantly of silica and alumina (Khatib and Hibbert 2005; Veerapan, 2003). The main constituents of MK are the following oxides: SiO_2 (49-56%), Al_2O_3 (40-44%), CaO (0.02-2.71%), Fe_2O_3 (0.3-4.0%) and MgO (0.05-1.0%) (Poon *et al.*, 2001). The pozzolanic reactivity of MK is determined by the composition of the feed clay and its processing conditions, where during the heating process, the clay is broken down forming the transition phase with a high reactivity by de-hydroxylation (removal of the –OH component in the clay). As a result, metakaolinite ($AL_2O_3{\cdot}2SiO_2$) or AS_2 is formed (Sabir *et al.*, 2001). The feed clay (kaoline) should be either naturally pure or refined by standard mineral processing techniques, otherwise the impurities would act as diluents (Sabir *et al.*, 2001; Kostuch *et al.*, 2000)

c) Rice Husk Ash

Rice husks (RH) are the outer shells of rice grains discarded in the preparation of rice for food consumption. RH have been found to contain pozzolanic materials and make good fillers and pozzolans for addition to cement (Yin *et al.*, 2006; Basha *et al.*, 2005; Muntohar, 2002; Ajiwe *et al.*, 2000). About 10^8 tons of rice husks are generated annually in the world (Okafor and Okonkwo, 2009). Over the years, rice husk ash (RHA) also has been utilised as stabilising agents with cement and lime for upgrading soils (Yin *et al.*, 2006; Haji Ali *et al.*, 1992). Rice husk ash which contains around 85% to 90% amorphous silica and fine amorphous silica has a growing demand in the production of special cement and concrete mixes, high performance concrete, high strength, low permeability concrete, for use in bridges, marine environment, nuclear power plants, etc (www.ricehushkash.com, 2010).

d) Ground Granulated Blast-furnace Slag (GGBS)

The utilisation of GGBS in soil stabilisation is common, mainly to reduce the reliance on the traditional cementitious materials such as lime and PC. GGBS was first developed in Germany in 1853 (Malhotra and Mehta, 1996). It is a latently hydraulic material that can be activated with lime, alkalis or PC, to give hydraulic properties (Gupta and Sheera, 1989). The production of GGBS leads to emissions of about 60kg of CO_2/tonne, primarily from the grinding process. As such, the use of materials such as GGBS can lead to significant reductions in CO_2 emissions (O'Rourke *et. al.*, 2009). On its own GGBS has only slow cementitious properties and PC normally provides the necessary alkalinity to activate and accelerate these properties. Similarly lime can also be used to provide the necessary alkality for the activation of GGBS.

Earlier research at the University of Glamorgan (Nidzam, 2004; Kinuthia and Wild, 2001; Wild *et. al.,* 1999) has reported that GGBS has minor effects on lime consumption, Atterberg limits and optimum moisture content, and at the same time it was found that inclusion of GGBS can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime-only. The use of GGBS is beneficial since GGBS has environmental benefits relative to lime or PC, as GGBS is a by-product material. Its manufacture involves only a fraction of the energy used and CO_2 emissions associated with either PC or lime (Hakkinen, 1993). In terms of the applicability of GGBS-based stabilisers for highway construction, the performance of the stabilised material has recently been fairly well established. However, in terms of building components, the current research is among the pioneering endeavours to utilise GGBS in building applications besides its use in concrete.

2.3.4 Energy Efficient Technology

The need for sustainability by reducing material processing costs and recycling waste materials is well established within the construction industry. The current research endeavours to use both recycling waste or by-product materials and reducing firing costs in the production of bricks. The use of waste materials is one of the ways of integrating sustainable approaches in the construction industry. For this reason, the construction industry has always shown a receptive attitude towards research into new materials (Aggarwal and Gulati, 2007). Research by Malhotra and Tehri (1996), has observed that good quality bricks can be produced by pressing slag-lime mixtures at sufficiently low pressures. The manufacturing process is simple and does not require any firing, autoclaving, or specialised plant or machinery (Malhotra and Dave, 1992).

Sustainable development can also be achieved by using unfired clay technology in the building industry for manufacturing bricks where, unfired clay materials provide a sustainable and healthy alternative as a replacement to conventional masonry materials, such as fired clay and concrete block. Their environmental benefits include significantly reduced embodied energy, thermal mass and regulation of humidity. The demand to reduce climate change impact of modern building has offered new opportunities for building materials including bricks. The low embodied carbon, hygrothermal performance and high aesthetic value, has encouraged consideration and modern use of unfired clay techniques. For wider, mainstream, uptake unfired clay building materials must fit in with modern methods of construction, deliver high level and consistent performance, and on the other hand be available at a competitive economic cost.

Another key target and concerns in relation to the achievement of sustainable infrastructure development is energy consumption. For this reason, there has been a growing interest in reducing energy consumption in the manufacturing of building components and construction materials in general including brick makings. This is one of the objectives of the current research project. It extends an existing unfired clay cementation technology that is currently viable for highway construction (Kinuthia and Wild, 2001) to commercial applications in the building industry.

As mentioned earlier, PC has been widely used in clay bricks production. Increasing environmental concerns have led to a reassessment of the role of PC as one of the world's dominant construction materials. The embodied energy and carbon dioxide (CO_2) associated with cement manufacture is coming under particular scrutiny. It is estimated that for every tonne of PC clinker produced worldwide, approximately 940 kg of CO_2 is released (Price, 2009). According to Damtoft *et al.,* (2008) much scientific evidence links climate change to green house emissions of which CO_2 ranks amongst the most important, accounting for 82% of the total $C0_2$ omissions. A step in PC production is the calcinations of limestone, which is not only highly energy intensive but also releases CO_2. Today, it must be stressed and understood that true sustainability encompasses much more than embodied CO_2 in building materials, but it also considered the complete construction process, including transport of materials, construction techniques and minimisation of waste, has a role to play. Humpreys and Mahasenan (2002) reported that an analysis was carried out by Battelle shows that CO_2 emissions from cement sector are set to rise dramatically in the coming decades. Customers are demanding a more sustainable approach to construction and focusing particularly on the embodied energy and carbon dioxide in construction materials.

The significant environment impact associated with the production of cement in terms of high energy consumption and CO_2 emissions have encouraged the investigation and application of most sustainable options (Jegandan *et al.*, 2010). One extensively applied option has been the use of blended cements incorporating industrial by-products such as ground granulated blast-furnace slag (GGBS) and fly ash which offer enhanced in durability performance that lead to increased life span and reduced costs (Sear, 2007; Higgins, 2005).

The eventual aim of the current research is to evaluate the performance of bricks made with clay and pulverised fuel ash (PFA) stabilised with Lime-GGBS and PC-GGBS blends. This will then enable the assessment of the potential application of these blended binders in unfired clay building components. This could produce cost savings in raw materials for brick manufacturers and serve as an efficient means of recycling industrial waste or by-products. At the same time, this process will eliminate the high-energy consumption associated with the present practice of manufacturing clay building components by intense firing.

CHAPTER 3

MATERIALS

This chapter describes the materials used in the current research and includes mineralogical, oxide and/or chemical composition of the target stabilisation material (Lower Oxford Clay and Pulverised Fuel Ash) and contains detailed analytical data on all stabilisers used (PC, Quicklime and GGBS)

3.1 LOWER OXFORD CLAY (LOC)

Lower Oxford Clay is the principal soil under investigation with regard to producing unfired bricks, combined with pulverised fuel ash a waste by-product from the coal industry. This clay material is currently being used by Hanson Brick Company Ltd., Stewartby, Bedford to make fired "London" brick. It is therefore an excellent choice of clay material and the most practical attempt for the unfired clay building material development. Investigation by Wild *et al.,* (1996) and other researchers (Thomas, 2001; Nidzam, 2004) established that Lower Oxford Clay consists predominantly of chlorite, kaolinite, mica, feldspar (sanidine and anorthite), quartzite, and calcite, with minor quantities of gibbsite, geothite (a hydrated iron oxide) and anatase (titanium oxide). The clay is grey in colour and mineralogy and chemical analyses have found that Lower Oxford Clay has many minor ingredients, such as pyrites (Fe_2S) and gypsum ($CaSO_4.2H_2O$), which can be contributors to the formation of deleterious minerals such as ettringite and thaumasite during its stabilization with lime (Nidzam, 2004). Figure 3.0 shows the formation of Lower Oxford Clay.

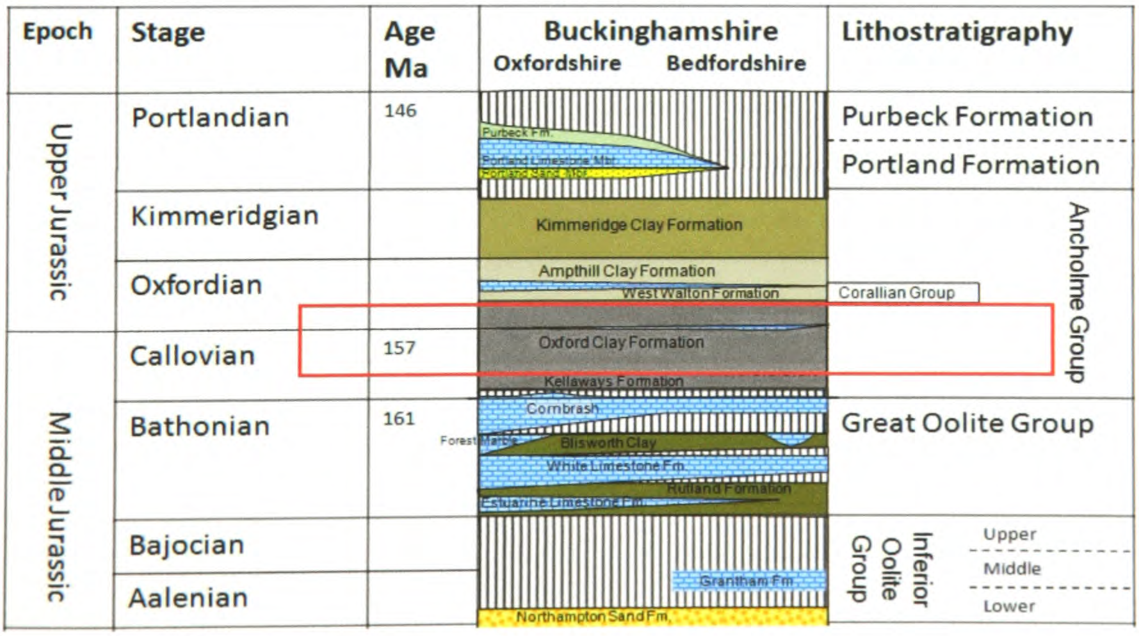


Figure 3.0: Stratigraphy of the Middle and Upper Jurassic in Buckinghamshire (Oxford Clay Formation highlighted) (Source, Bucks Earth Heritage Group, 2011).

Table 3.1: Oxide and mineral analyses of the Lower Oxford Clay

Oxide	Hanson Brick Ltd. (Smith, 1999) (wt.%)
SiO_2	46.73
TiO_2	1.13
Al_2O_3	18.51
Fe_2O_3	6.21
FeO	≤0.80
Mn_2O	0.07
CaO	6.15
MgO	1.13
K_2O	4.06
P_2O_5	≤ 0.17
Na_2O_3	≤0.52
LI	15.79
Mineralogy	
Chlorite	7.00
Illite	23.00
Gypsum	2.00
Kaolinite	10.00
Quartz	29.00
K-feldspar	8.00
Plagioclase	-
Calcite	10.00
Siderite	-
Anatase	-
Pyrite	4.00
Apatite	-
Organic matter	7.00

Table 3.2: Chemical composition of LOC (Bodycote Material Testing, July 2003)

Chemical Composition	(%)
CO_3	5.02
CaO	5.60
Cl	≤0.01
IR	91.6
S	≤0.018
SO_4	≤1.29
SiO_2	≤0.43
Total sulfur	≤1.50

3.2 PULVERISED FUEL ASH (PFA)

Pulverised Fuel Ash (PFA) or "fly" ash is the fine ash produced in the furnaces of coal-fired power stations. It is therefore a by-product from the combustion of pulverised coal at very high temperatures and pressures. Due to the increased use of pulverised coal as fuel for electric power generation, fly ash is now available in many areas of the world including Malaysia. There are two types of fly ash, Class F and Class C.

(i) Class F PFA is generally low in lime, usually under 15% and contains a greater combination of silica, alumina and iron.

(ii) Class C PFA has higher lime content, higher than 15% and sometimes as high as 30%. The elevated CaO may give Class C PFA unique self-hardening characteristic.

Fly ash has three main elements, silicon, aluminium and iron. Silicon and aluminium are mainly present in the glassy phase, with small amounts of quartz (SiO_2) and mullite ($3Al_2O_3$, $2SiO_2$) included. The iron appears partly as the oxides magnetite (Fe_3O_4) and haematite (Fe_2O_3), with the rest in glassy phase. The oxides of which account for 75% - 85% of the material. The greater proportion of fly ash is glass content and varies from 66% to 88%. The SiO_2 + Al_2O_3 content varies between 70% and about 88%. Other constituents include calcium, magnesium, sodium, potassium and titanium.

PFA is a material with pozzolanic properties (Sherwood, 1993). The pozzolanic activity of fly ash depends upon many parameters, most important of which are fineness, amorphous matter, chemical and mineralogical composition, and the unburned carbon content or loss on ignition of the fly ash (Joshi, 1979). Several investigators have reported that when fly ash is pulverised to increase fineness, its pozzolanic activity increases significantly (Joshi and Lohtia, 1997). The chemical pozzolanic reaction of fly ash and lime occurs readily under thermal treatment, creating strong structures with an increase of mechanical strength. This reaction involves the formation of calcium silicate hydrate (C-S-H) and calcium alumino-silicate hydrate (C-A-S-H) gels, and enhances the strength of the resultant materials.

The PFA used in this research is BS EN 450 Fly Ash from SCOTASH. It was supplied from Scottish Power's Longannet Power Station (A Lafarge Scottish Power Joint Venture), which manufactures the PFA under a Quality Management System (QMS) that complies with the requirements of BS EN ISO:9001. The fly ash particles resemble cement in appearance and are very similar chemically, containing the same basic oxides, and only differing in proportions and mineralogy as represented in Tables 3.3. and Table 3.4.

Table 3.3: Physical properties of PFA (Scottish Power Longannet Power Station)

Property	Typical ScotAsh Results	BS EN 450 Requirement	
		Lower Limit	Upper Limit
Loss of Ignition (%)	2.1 – 4.0		5.0
Finenessss on 45 micron (%)	12.5 – 18.0	5.0	25.0
Sulfuric anhydride as SO_3 (%)	0.22 – 0.69		3.0
Particle Dencity $(kg/m^3)^2$	2090 – 2120		
Soundness (mm)	0.5		10.0
Chlorides (%)	<0.010		0.10
Reactive Calcium Oxide (%)	1.26 – 3.9		10.0
Activity Index (%)	78 – 82	28 Day	75
Activity Index (%)	92 - 95	90 Day	85

Table 3.4: Oxide composition of PFA (Ash Resources)

Oxide	(%)
CaO	2.4
SiO_2	47.6
Al_2O_3	26.2
MgO	1.42
Fe_2O_3	9.4
K_2O	3.02
Na_2O	1.1
SO_3	0.86

3.3 STABILISERS

3.3.1 Portland Cement (PC)

The Portland Cement (PC) used was manufactured in accordance with the British Standard BS EN 197-1:200, and was supplied by Lafarge Cement Ltd, UK. The PC was used as an alternative to lime, as the activator to GGBS in order to stabilise the clay to make building components. The oxide compositions and other properties of the PC are shown in Table 3.5.

Table 3.5: Oxide and compositions and other Lafarge Cement Ltd.

Oxide	(%)
CaO	63
SiO_2	20
Al_2O_3	6
Fe_2O_3	3
MgO	4.21
MnO	0.03-1.11
SO_3	2.3
Loss on Ignition	-
Insoluble residue	0.5
Relative density	3.15
Bulk density (kg/m^3)	1400
Colour	Grey

3.3.2 Lime

The lime used in this study was quick lime (CaO) supplied by Calch Tŷ Mawr Lime, near Breacon, Wales, UK. The reason for using quicklime rather than hydrated lime as a binder is that quick lime is denser, less dusty, and is more effective as a stabiliser than hydrated lime. Quick lime has a higher available lime content per unit mass than hydrated lime, where 3% CaO is normally equivalent to 4% hydrated lime (Nidzam, 2004). The oxide and physical composition of the quicklime used are shown in Table 3.6.

Table 3.6: Oxide composition and physical properties of quicklime (Calch Tŷ Mawr lime, UK)

Oxide	(%)
CaO	95.9
SiO_2	≤0.9
Al_2O_3	≤0.15
MgO	≤0.46
Fe_2O_3	≤0.07
$CaCO_3$	2.2
Specific Gravity	2.3
Bulk Density, kg m^{-3}	480
Colour	White

3.3.3 Ground Granulated Blastfurnace Slag (GGBS)

Ground Granulated Blastfurnace Slag (GGBS) was supplied by Civil and Marine Slag Cement Ltd, Llanwern, Newport, South Wales, UK. It is a latently hydraulic material that occurs as a by-product of the steel industry when molten slag is rapidly cooled and granulated. GGBS is readily available throughout the UK. Its main use is in concrete and most ready mixed concrete plants have a silo of GGBS, which they use to replace between 40% to 70% of PC (Hakkinen, 1993). Researchers at the University of Glamorgan, UK, have established that inclusion of GGBS in the traditional stabilisers of lime and PC can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime or PC only (Higgins, 2005; Kinuthia and Wild, 2001). The use of GGBS as a cementitious material blended with PC is based on its activation with alkalis (mainly $Ca(OH)_2$) released from hydration of PC (Hakkinen, 1993). The use of GGBS has so far been primarily in concrete. More recently, GGBS has been used in stabilised soils for roads (Kinuthia and Wild, 2001). The current work wishes to extend the application of GGBS to uses in compacted building components, such as bricks and blocks. Table 3.7 shows its oxide composition and some physical properties.

Table 3.7: Oxide composition and some physical properties of GGBS (Civil and Marine Slag Cement Ltd.)

Oxide	(%)
CaO	41.99
SiO_2	35.34
Al_2O_3	11.59
MgO	8.04
Fe_2O_3	0.35
MnO	0.45
S_2	1.18
SO_3	0.23
Insoluble residue	0.30
Relative density	2.90
Bulk Density (kg/ m^3)	1200
Colour	Off-white
Glass content	$\approx$ 90

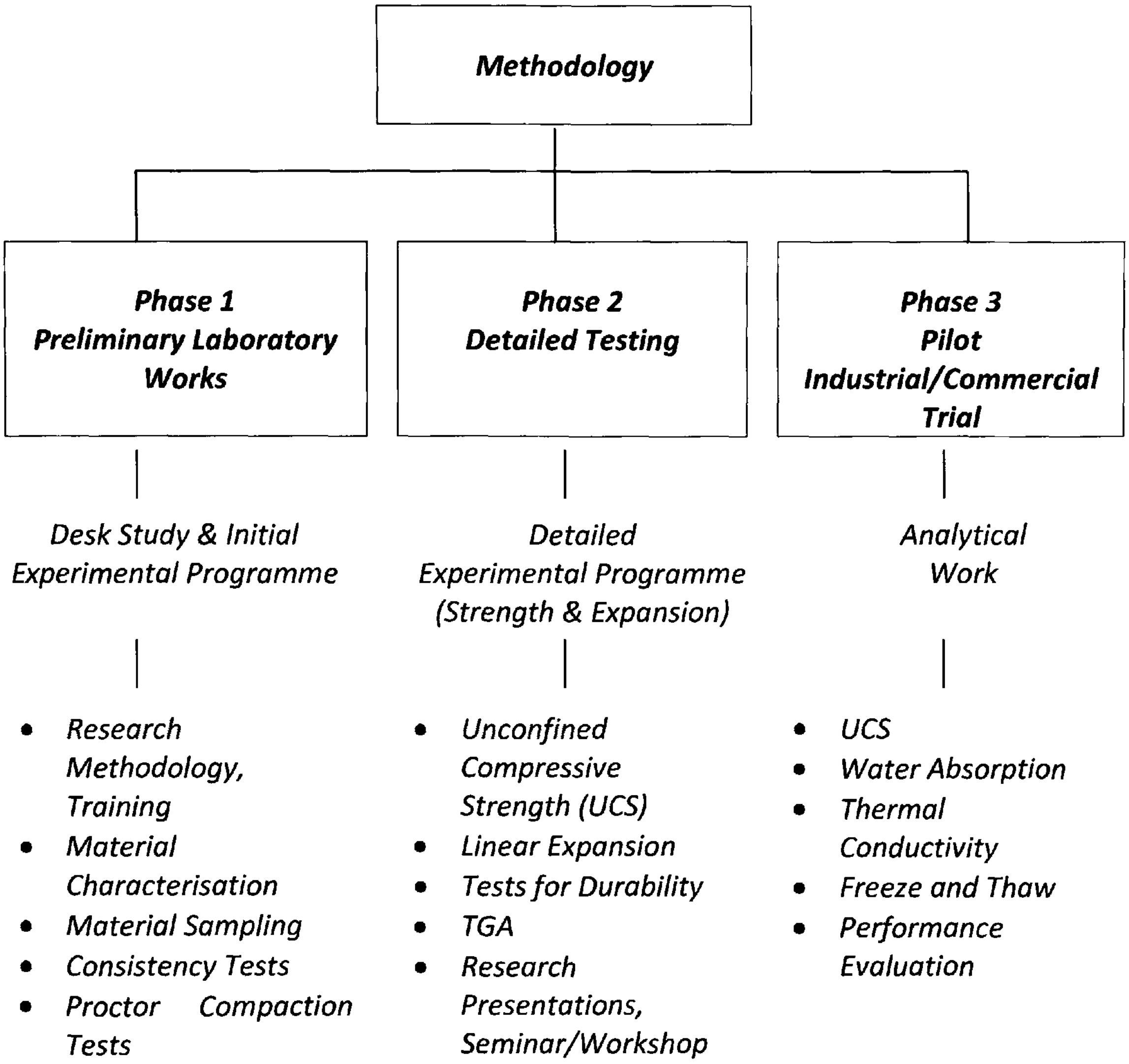
CHAPTER 4

EXPERIMENTAL PROCEDURES

This chapter describes the mix compositions, sample preparation, testing and other experimental procedures and analytical techniques used in the current work, namely:

1. *Basic Preliminary Material Tests and Procedures Tests*
2. *Initial Consumption of Stabiliser*
3. *Consistency (Atterberg) Limits*
4. *Proctor Compaction Test*
5. *Unconfined Compressive Strength (UCS) test*
6. *Durability tests*
7. *Analytical Tests*
8. *Pilot Industrial/Commercial Trial*

The methodology in this study was divided into 3 phases as illustrated below;



4.1 BASIC PRELIMINARY TESTS

4.1.1 Specific Gravity

Specific gravity test were carried out on all granular materials used in the research study, namely: LOC, PFA and stabilisers (PC, lime and GGBS). These were carried out using small pcynometer method in accordance to BS 1377:2:1990:8.3. Specific gravity is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature. The purpose of the tests was to determine the density of particles finer than 2 mm but heavier than water. About 20g material was sieved through the 2mm sieve. For each test two pcynometer bottles were cleaned, dried in the oven and weighed. Each bottle was then filled with 10g of test specimen using a spatula and weighed. De-ionised water was then carefully added up to half way the bottle and stirred. The bottles were placed in a vacuum desiccator for few minutes to remove the entrapped air. More water was added to fill the bottle and again placed in a vacuum desiccator for another few minutes. The bottles were then removed from the vacuum desiccator, and the stoppers inserted. The surplus liquid that extruded through the capillary bore in the stopper were wiped dry and the bottle and contents weighed. Each bottle was then emptied completely, cleaned, filled with de-ionised water and air extracted by vacuum before weighing.

4.1.2 Linear Shrinkage

Linear shrinkage test were carried out in accordance with BS 1377:2:1990:6.5. The test specimen was prepared by weighing 200g of target materials LOC of PFA that passed through the 425μm sieve. The test specimen was placed on a glass plate and mixed with water (the material to pre-determined Optimum Moisture Content (OMC)) so as to achieve a homogeneous paste. Two linear shrinkage moulds were oiled, filled with the test specimen and levelled off with a palette knife (Figure 4.2). The test specimens were left to dry overnight at room temperature, and then oven dried at 105°C for 24 hours. After air cooling, the length of the bar of test specimen was measured with digital vernier callipers. The linear shrinkage was calculated as the dried length of test specimen as a percentage of the original length of the wet specimen (equal to internal length of mould).

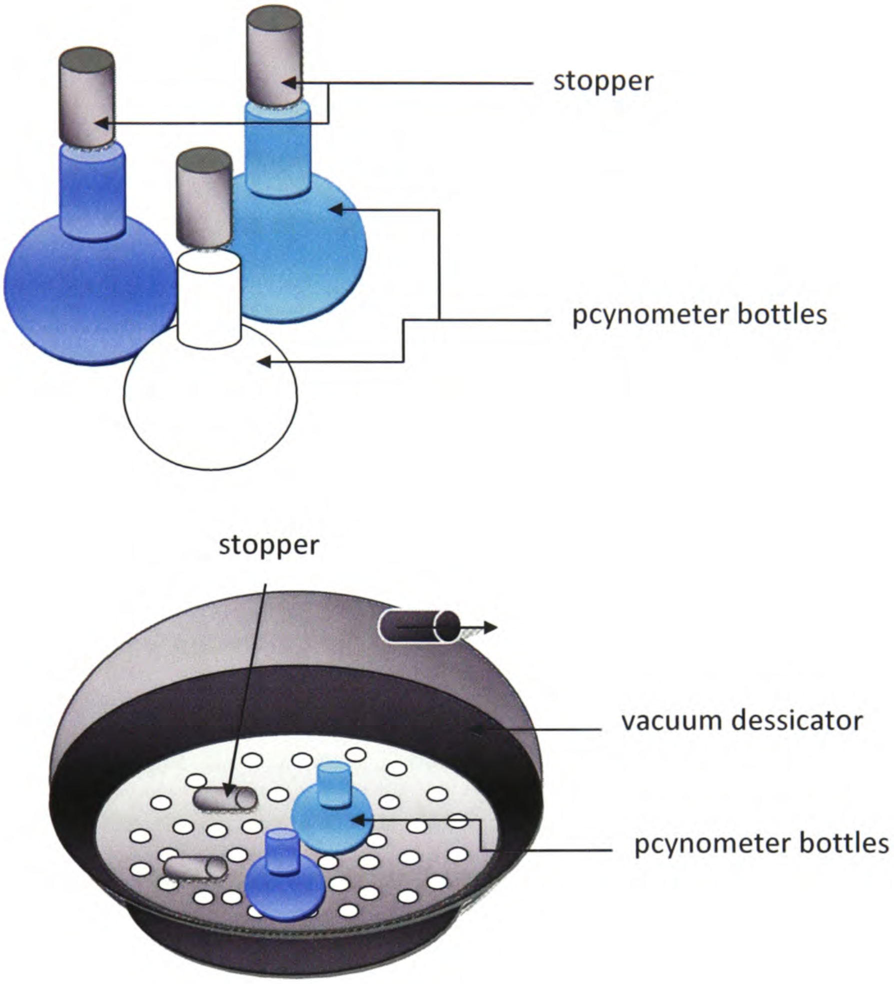


Figure 4.1: Specific gravity test – Pcynometer bottles in vacuum desiccators

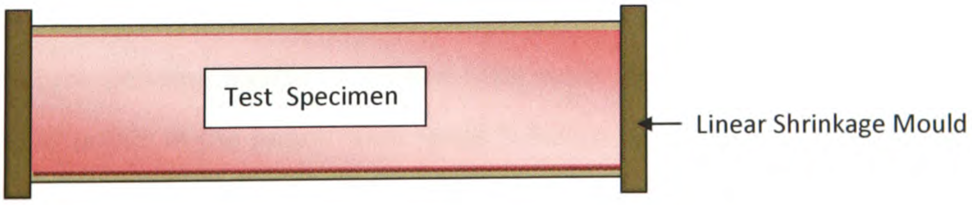


Figure 4.2: Linear shrinkage Test

4.2 CONSISTENCY (ATTERBERG) LIMITS

The Consistency Atterberg Limit tests were carried out in accordance with BS 1377 (1990) Part 2 – Classification Test (British Standard Methods of Test for Soils for Civil Engineering Purposes). They were carried out on Lower Oxford Clay (LOC) that was dried, crushed and sieved passing 425µm (in accordance with the BS). The measurement of Atterberg limits is significant in order to understand the nature of fine-grained soil, this test can distinguish between different types of silts and clays.

4.2.1 Liquid Limit

A small amount of de-ionised water was first added to about 200g of LOC that had been homogeneously mixed with stabilisers. The wet materials were then thoroughly mixed with palette knives into a plastic paste. A small amount of this material was set aside for the later determination of the Plastic Limit. The remaining material was then used to fill a brass cup (56mm diameter and 41mm deep) for cone penetration. A metal cone of angle $30 \pm 1^{\circ}$ and 35mm height (see Figure 4.3) was allowed to penetrate into the material's surface for 5 seconds (automatically timed by an attached electrical timing device). After 5 seconds, the penetration of the cone was automatically stopped by a locking mechanism incorporated in the penetration apparatus and the penetration of the cone determined by a scale and dial pointer attached to the cone. The penetration was recorded and a small amount of material taken within the zone of penetration, for moisture content determination. The moisture content was determined in accordance with BS 1377 (1990) using the oven drying method. The residual material in the cup was removed and re-mixed with the rest of the sample and more water was added. Further penetration tests, together with their corresponding moisture content tests were performed so as to obtain at least 4 sets of points in the penetration range 5-30mm. The liquid limit was taken as the moisture content corresponding to a penetration of 20mm from a graph of penetration (in mm) against moisture content (%).

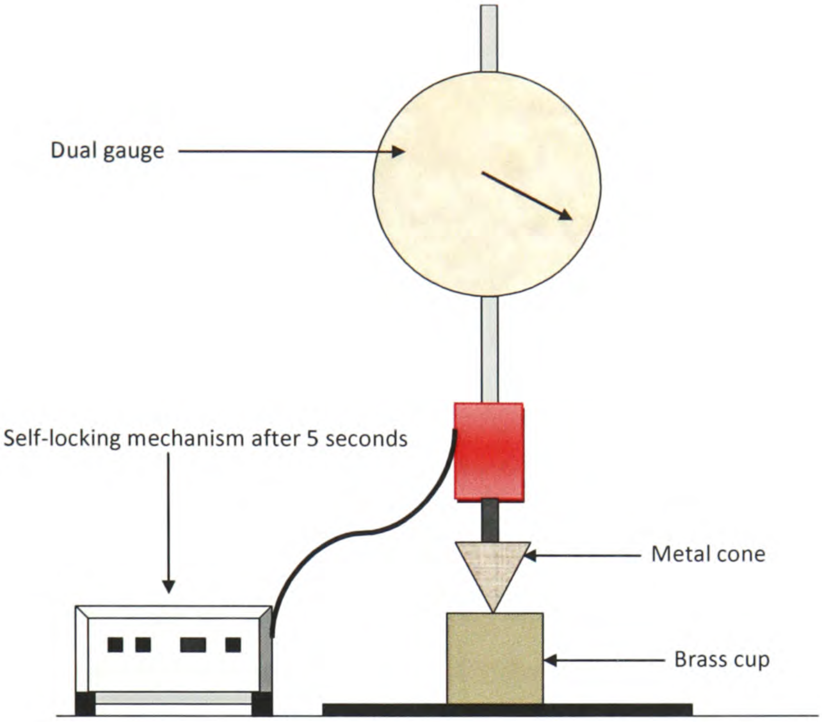


Figure 4.3: Cone Penetrometer apparatus.

4.2.2 Plastic Limit and Plasticity Index

Plastic Limit (PL) was determined by using the material that had been set aside after the initial mixing during the liquid limit testing. The material was gently rolled on a flat glass plate into rods, and rolling continued until the rods crumbled when they were approximately 3 mm in diameter. When the desired crumbling occurred, a few samples were taken for moisture content determination. This moisture content at which the clay rods crumble at a diameter of 3 mm is defined as the plastic limit of the material. From the liquid limit and the plastic limit, the plasticity index (PI) of the material is normally obtained as the difference between these two limits. The specification for the design and construction of lime stabilised capping (D_fT, 2000) states that clay soil must have a PI of 10% or more in order to be considered for lime stabilization.

4.3 BS PROCTOR COMPACTION TESTS

British Standard Proctor compaction tests were carried out in accordance with BS 1377 (1990) Part 2. They were carried out in order to establish values of the maximum dry density (MDD) and optimum moisture content (OMC) of LOC and PFA, for later use in the preparation of cylinder specimens for the determination of unconfined compressive strength (UCS) and durability tests.

4.3.1 Material preparation

Approximately 4.5kg of air-dried materials was used for the test. Mixing of this material was achieved using a Model SE-401 Hobart 40 Qt mixer. Approximately 5% water (calculated based on amount of material used for the test) was added to the air-dried material in order to increase the moisture content. This process of water addition was repeated after every compaction process until the wettest material condition was quite wet and plastic.

4.3.2 Compaction

After every, time water was added and the material thoroughly mixed, compaction was achieved by dynamic compaction using an automatic Proctor/CBR compaction machine (see Figure 4.4). The material was compacted in 3 equal layers in a mould of dimensions 105 ± 0.5 mm in diameter and 115.5 ± 1 mm in height, each layer being subjected to 27 blows using a 2.5 kg rammer. After weighing the mould together with the compacted cylinder, a small amount of material was taken from the interior of the compacted material, for moisture content determination. The dry density-moisture content curves were plotted, each with at least four data points. These graphs were used to determine the MDD and OMC values. These values were used for the compaction of cylindrical test specimens.

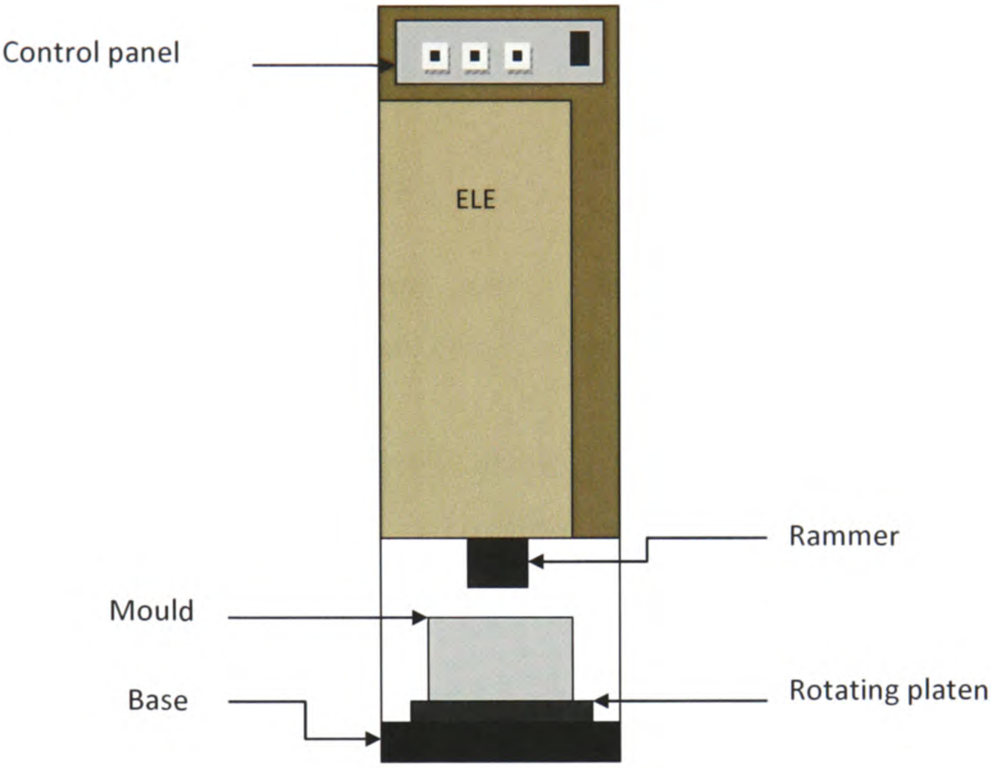


Figure 4.4: Automatic Soil Compactor

4.4 TEST SPECIMEN COMPOSITION AND PREPARATION

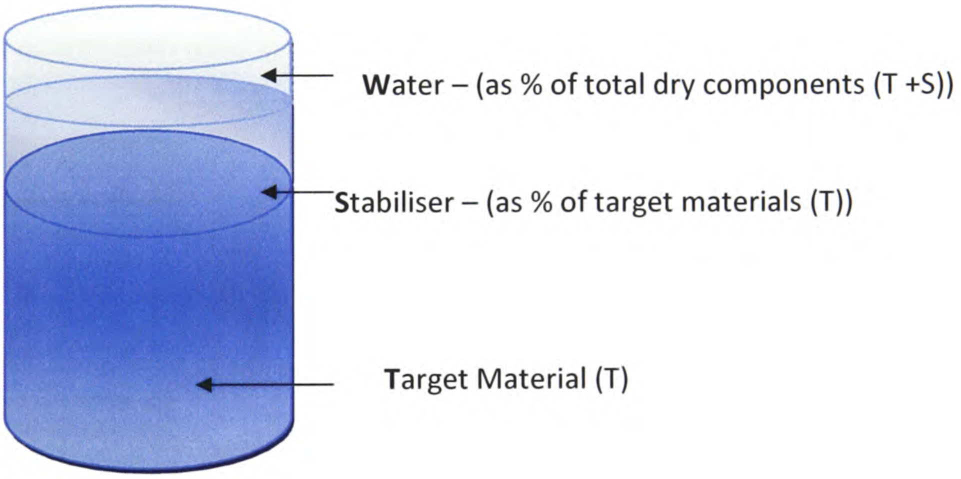
4.4.1 Bulk Density

Bulk density of a soil is the mass per unit volume of the soil deposit including the water contains. It varies with structural condition of the soil, particularly that related to packing. The mass weight of the cylindrical test specimen produced for target materials, the Lower Oxford Clay (LOC) alone and a combination of LOC and pulverised fuel ash (FPA) was carried out in accordance with BS 1377-2:1990. For sample preparation, it was necessary to establish a common dry density and moisture content. Therefore, results of the Maximum Dry Density (MMD) and Optimum Moisture Content (OMC) from BS Proctor compaction tests described earlier were adopted. From the tests, an average MDD value of 1.42 Mg/m^3 for both LOC and PFA were established. This MDD value for PFA appears to be in agreement with the MDD values observed by Coombs *et al.,* (2001) of between 1.42-1.48 Mg/m^3. On the other hand, mean OMC values of 24% for LOC and 19% for PFA were established.

4.4.2 Compaction Moisture Content

The two alternative approaches were used to calculate the amount of moisture content, symbolised by two formulae F1 and F2 as follows:-

Formula 1 (F1) : T + ST + W (T+ST) = 380g.......(I) at W = OMC and 1.2 OMC
Formula 2 (F1) : T + ST + WT = 380g.......(II) at W = OMC and 1.2 OMC



Where;

T = Target Soil or Soil + Siliceous Additive (PFA),
S = Stabiliser dosage (%) and W = Water (%) at OMC and 1.2 OMC

Formula 1 (F1) - the calculation of water was made based on the total amount of soil and stabiliser.

Formula 2 (F2) - the calculation of water was only based on the amount of soil only.

4.4.3 Specimen Composition

There were two target materials stabilised in the current research, LOC was used alone and a blend of LOC with PFA at a 50:50 blending ratio. Lime and PC were used as control stabilisers, whereas for blended stabilisers, lime-GGBS (at 50:50 and 30:70 ratios) and PC-GGBS (at 40:60 and 60:40 ratios) were used. The stabiliser dosage levels used were 10wt% and 20wt%. These stabiliser dosages are much higher than the typical ones used in highway construction (3%-8%) (Oti *et al.*, 2008). This is because the current work is aimed at the building industry where higher strength values are needed for bricks and blocks. The stabilisers were weighed individually and blended thoroughly in a SE-401 Hobart 40 Qt mixer until a homogeneous mixture was obtained. Figure 4.3, shows a schematic summary of all the mixes for the entire programme of research while Tables 4.1 and 4.2 show the weights of material constituents used in the research.

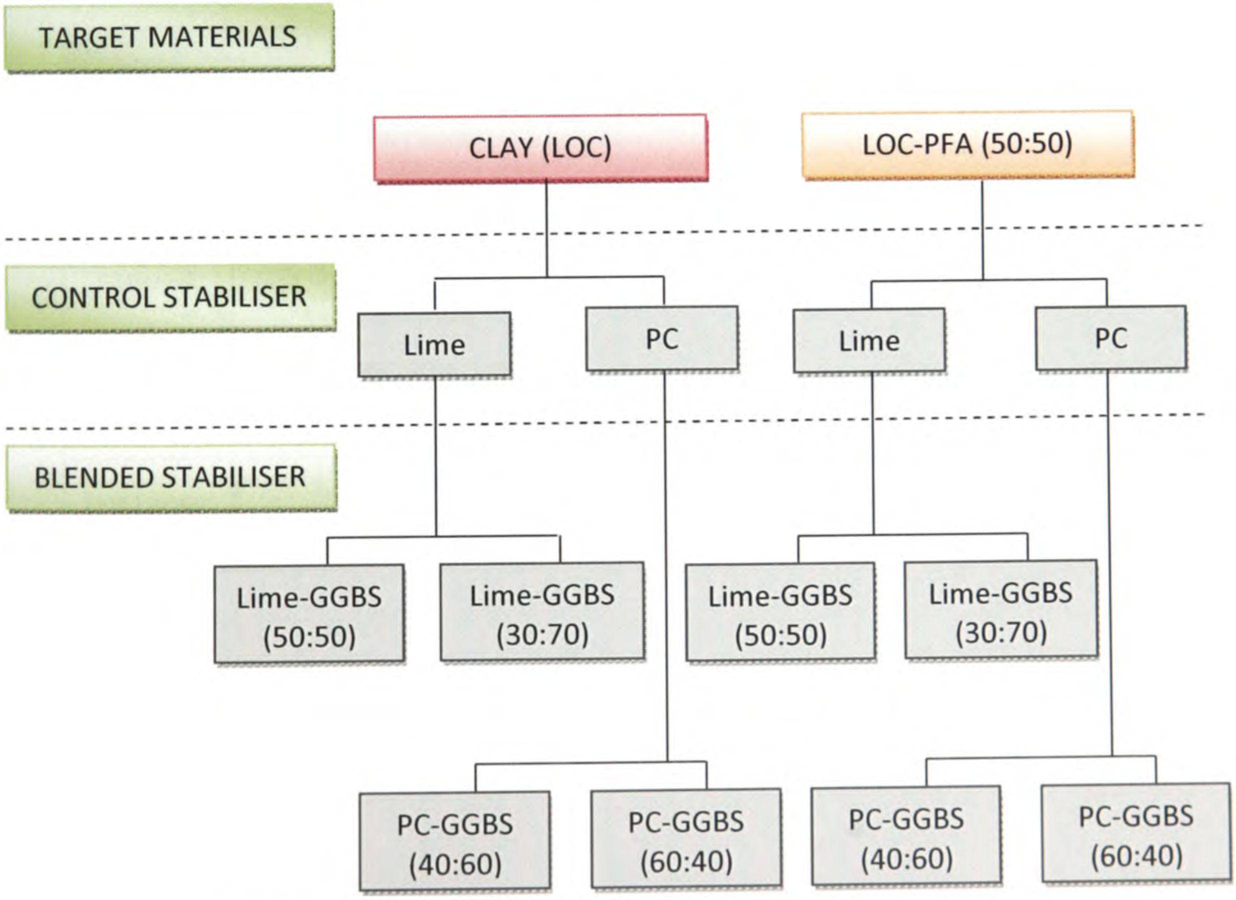


Figure 4.5: Schematic flow diagram of the mix compositions

Tables 4.1: Weights of material constituents using 10% stabiliser dosage

FORMULA		TARGET MATERIAL (LOC or LOC+PFA) (g)	STABILISER (g)	WATER (g)
F1@OMC	OMC (24%) S + kS + w(S + kS)=380g S +0.10S +0.24(S + 0.10S)=380g	278.6	27.86	73.55
F2@OMC	OMC (24%) S + kS + wS = 380g S + 0.10S + 0.24S = 380g	283.58	28.36	68.06
F1@1.2OMC	1.2 OMC (OMC = 29%) S + kS + w(S + kS)=380g S +0.10S +0.29(S + 0.10S)=380g	267.80	27.78	85.43
F2@1.2OMC	1.2 OMC (OMC = 29%) S + kS + wS = 380g S + 0.10S + 0.29S = 380g	273.38	27.34	79.28

Tables 4.2: Weights of material constituents using 20% stabiliser dosage

FORMULA		TARGET MATERIAL (LOC or LOC+PFA) (g)	STABILISER (g)	WATER (g)
F1@OMC	OMC (24%) S + kS + w(S + kS)=380g S +0.20S +0.24(S + 0.20S)=380g	255.37	51.07	73.55
F2@OMC	OMC (24%) S + kS + wS = 380g S + 0.20S + 0.24S = 380g	263.89	52.78	63.33
F1@1.2OMC	1.2 OMC (OMC = 29%) S + kS + w(S + kS)=380g S +0.20S +0.29(S + 0.20S)=380g	245.48	49.10	85.43
F2@1.2OMC	1.2 OMC (OMC = 29%) S + kS + wS = 380g S + 0.20S + 0.29S = 380g	255.03	51.01	73.96

Table 4.3: Details of mix compositions for LOC and LOC-PFA + Stabilisers systems

Target Materials	Stabilisers	Ratio	Wt.%
LOC	Lime (control)	100	10, 20
	PC (control)	100	10, 20
	Lime-GGBS	30:70	10, 20
		50:50	10, 20
	PC-GGBS	40:60	10, 20
		60:40	10, 20
LOC-PFA (50:50)	Lime (control)	100	10, 20
	PC (control)	100	10, 20
	Lime-GGBS	30:70	10, 20
		50:50	10, 20
	PC-GGBS	40:60	10, 20
		60:40	10, 20

4.4.4 Specimen preparation

For this study, test specimens were prepared using target materials at OMC and at 1.2 OMC. The target materials, stabilisers and stabiliser blending ratios were as shown in Figure 4.5. The bulk density was established from the MDD value of 1.42 Mg/m^3. Cylinders weighing 380g were prepared for all mix proportions. Two formulae F1 and F2 were used to calculate the amount of water used to prepare a series of cylinders of 50mm diameter and 100mm in height, at the targeted bulk densities. Using this bulk density and moisture content values, the quantities of the dry materials enough to produce a compacted cylindrical specimen were established using the equation I and II. The materials were mixed thoroughly and the pre-calculated amount of water was added, using each of the formulae F1 and F2 in turns. Hand mixing with palette knives was used to achieve a homogenous mix. A steel mould fitted with a collar, was used to compact the material into a cylinder of the prescribed dry density and moisture content. Compaction was achieved using a hydraulic jack. After compaction, the cylinders were extruded using a steel plunger, trimmed, and wrapped in several runs of cling film, labelled and placed in sealed plastic containers. All samples were cured in a temperature controlled room at 20± 1°C and 100% relative humidity.

4.5 UNCONFINED COMPRESSIVE STRENGTH (UCS)

The initials tests for the unconfined compressive strength were carried out after moist curing for only 7 and 28 days. Further 56 days samples were only prepared based on the best mix results from 7 and 28 days. Three cylinders per mix proportion were subjected to UCS tests and the mean strength determined.

For this study, test specimens were prepared using target materials at OMC and at 1.2 OMC. The target materials, stabilisers and stabiliser blending ratios were as shown in Figure 4.5. The bulk density was established from the MDD value of 1.42 Mg/m^3. Two formulae F1 and F2 were used to calculate the amount of water used to prepare a series of cylinders of 50mm diameter and 100mm in height, at the targeted bulk densities. Using this bulk density and moisture content values, the quantities of the dry materials enough to produce a compacted cylindrical specimen were established using the equation I and II. The materials were mixed thoroughly and adding the pre-calculated amount of water, using each of the formulae F1 and F2 in turns. Hand mixing with palette knives was used to achieve a homogenous mix. Cylinders weighing 380g were prepared for all mix proportions. A steel mould fitted with a collar, was used to compact the material into a cylinder of the prescribed dry density and moisture content. Compaction was achieved using a hydraulic jack. After compaction, the cylinders were extruded using a steel plunger, trimmed, and wrapped in several runs of cling film, labelled and placed in sealed plastic containers. All samples were cured in a temperature controlled room at 20± 1°C and 100% relative humidity.

Table 4.4: Details of mix compositions for LOC and LOC-PFA + Stabilisers systems for UCS

Target Materials	Stabilisers	Ratio	Curing Period	Wt.%
LOC	Lime (control	100	7, 28	10, 20
	PC (control)	100	7, 28	10, 20
	Lime-GGBS	30:70	7, 28	10, 20
		50:50	7, 28	10, 20
	PC-GGBS	40:60	7, 28	10, 20
		60:40	7, 28	10, 20
LOC-PFA (50:50)	Lime (control)	100	7, 28, 56	10, 20
	PC (control)	100	7, 28, 56	10, 20
	Lime-GGBS	30:70	7, 28, 56	10, 20
		50:50	7, 28	10, 20
	PC-GGBS	40:60	7, 28, 56	10, 20
		60:40	7, 28	10, 20

4.5.1 Testing

Unconfined Compressive Strength (UCS) of stabilised clay test specimens was determined using a Hounsfield testing machine capable of loading up to 10kN at a compression rate of 1mm/min (see Figure 4.6). A self-levelling device was used to ensure uniaxial load application. Before testing, the end surfaces of samples were examined to ensure a flat surface and good contact with the testing rig platens. Three cylinders per mix proportion were tested and the mean value taken.

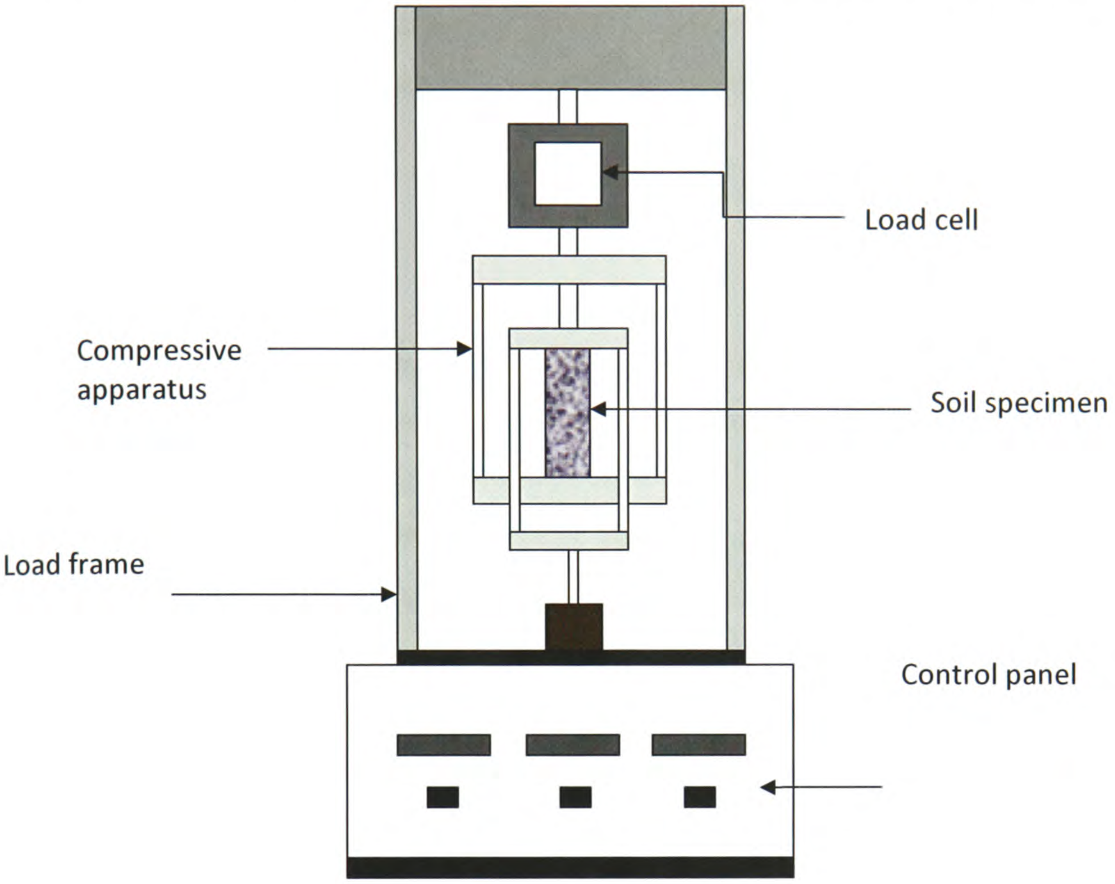


Figure 4.6: The Hounsfield Test Equipment H10KM used for UCS test.

4.6 DURABILITY TEST

4.6.1 Linear Expansion

4.6.1.1 Specimen preparation

Cylindrical test specimens were prepared at both OMC and at 1.2 OMC, and only for selected mixes based on best strength outcome from the UCS test results. For this test, only specimens from LOC-PFA (50:50) stabilised with lime-GGBS (30:70) and PC-GGBS (40:60) were prepared together with specimens of LOC-PFA (50:50) stabilised with lime and PC only as the control sets. All these specimens were prepared at only 10% stabiliser dosage, since these were the more vulnerable mix compositions compared with those stabilised at 20wt% stabiliser dosage. Which were stronger and hence more durable. All samples were tested for duration of 56 days.

4.6.1.2 Testing

Immediately after sample fabrication, approximately 10mm of the bottom of a test specimen meant for linear expansion test (one for each of the various mix compositions investigated) were exposed by cutting and removing the cling film to expose the specimens. The specimen was then placed on a porous disc to allow water seepage, and disc and specimen arrangement placed on a platform situated in a perspex container. Separate perspex containers were used for individual test specimens. The perspex containers were covered with lids fitted with dial gauges to monitor any linear changes in the test specimens. The entire arrangement is shown in Figure 4.7.

A layer of water was always maintained below the platforms to provide high humidity and ensure that there was no excessive evaporation from the sample. This process which is termed moist curing was commenced immediately after sample fabrication. After moist curing for 7 days, the specimens were partially immersed in water to cover the exposed part of the bottom of the specimen 10mm by carefully increasing the water level in the perspex containers. This was carried out while; ensuring that disturbance of the specimens was kept to a minimum. This process is termed soaking. During these processes, the containers were kept in a room at a temperature of about 20°C±2°C. Linear expansion during moist curing and the subsequent soaking was monitored on a daily basis for at least 56 days.

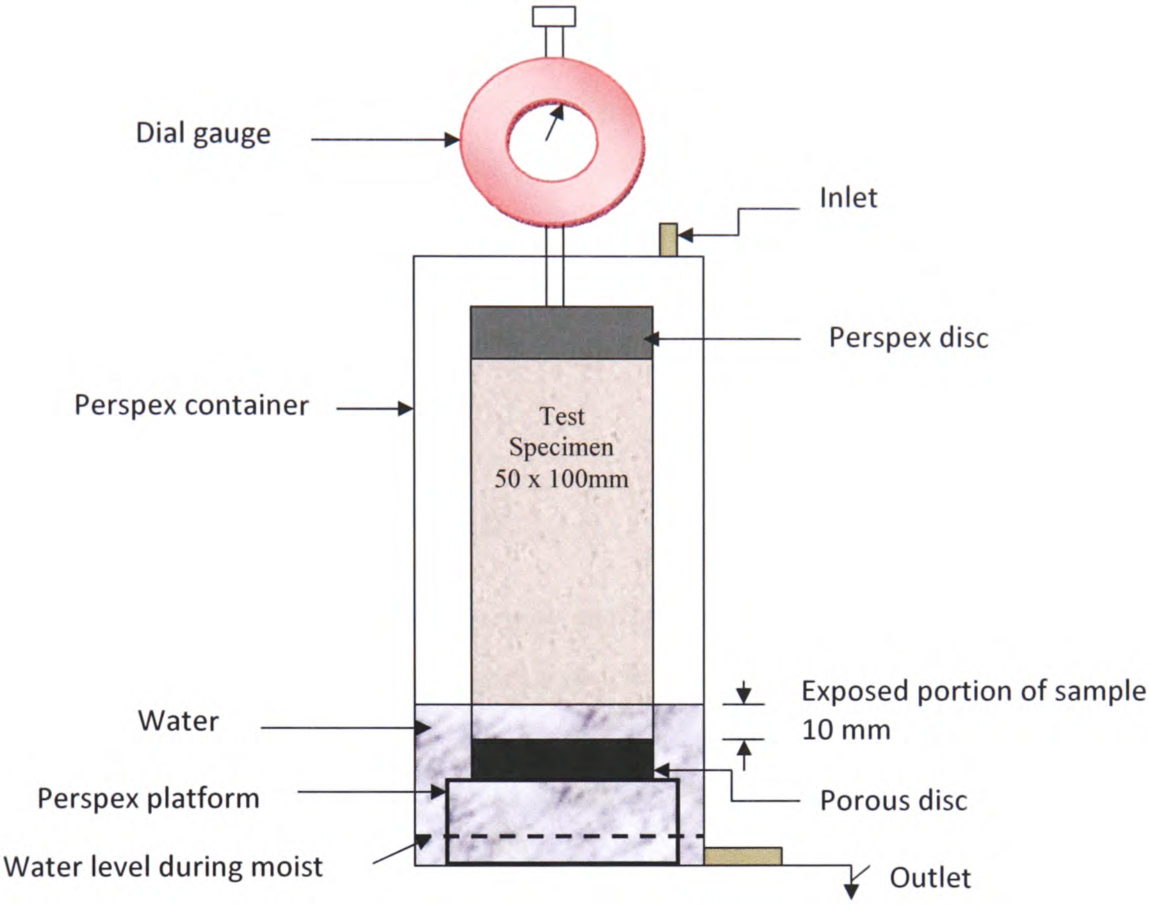


Figure 4.7: Schematic diagram of the test set-up for measuring linear expansion during moist curing and subsequent soaking.

4.6.2 Durability Index

4.6.2.1 Specimen Composition

In order to determine the effectiveness of lime, PC and GGBS addition on the durability of stabilised LOC-PFA (50:50), a modified linear expansion test was used as a test for durability. Specimens were only prepared for LOC-PFA since results from UCS test had shown that stabilised LOC-PFA had a better strength when compared to LOC stabilised alone. Also, blended lime-GGBS stabiliser at a 30:70 blending ratio was used. This binder was chosen based on its better strength development when compared to blended lime-GGBS at a 50:50 ratio. Further more, the 30:70 mix was regarded more economical and sustainable as it uses more of by-product material - GGBS - relative to the less sustainable lime. The blended PC-GGBS, (40:60) was also chosen, based on the economical composition and equal in strength development patterns when compared with the less sustainable PC-GGBS at a 60:40 ratio. PC-GGBS at a 40:60 uses more GGBS relative to 60:40, while the performance is not compromised. For this durability index test the specimens were prepared in the same process as described for specimens for the UCS test.

4.6.2.2 Specimen Curing and Testing

The test involved moist curing test specimens (50mmϕ x 100mm in length) at room temperature for 7, 28 and 56 days in a similar way as for the UCS test, followed by full soaking the cured specimens in water for 4 days. The unwrapped specimens were individually soaked in separate glass containers, where each container was covered with a lid fitted with a dial gauge for measuring the linear expansion. This arrangement is illustrated schematically in Figure 4.8. Linear expansion was monitored on a daily basis during the 4 days of soaking. The weights of the soaked specimens were also determined and recorded on a daily basis during the 4 days of soaking, in order to determine any changes in weight during the soaking process. Two cylinders per mix proportion were subjected to the soaking process, and the mean UCS strength determined for each mix composition. The control specimens were also cured for 7, 28 and 56 days at room temperature and the compressive strength determined without the cured specimens being subjected to soaking in water. Table 4.4 shows the mix compositions used for the durability index tests.

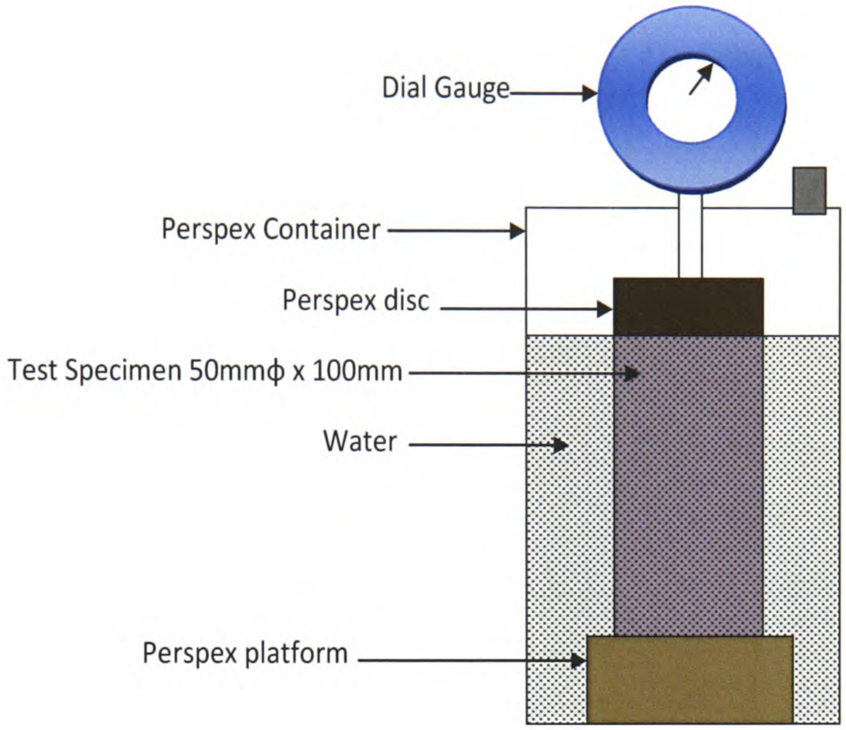


Figure 4.8: Schematic diagram of the test set-up for Durability Index (DI) test

The durability index was obtained by determining the compressive strength of the soaked specimens as a percentage of compressive strength of the control specimens.

$$\text{Durability Index (DI)} = \frac{\text{Soaked Specimen}}{\text{Control Specimen}} \times 100\%$$

Table 4.4: Mixed Compositions of Lower Oxford Clay – Pulverised Fuel Ash (50:50) subjected to UCS and durability test.

Mixed Composition	Stabiliser Dosage (%)	Formula	Specimens (cylinders)
LOC-PFA + L-GGBS (30:70)	10	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
	20	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
LOC-PFA + L (Control)	10	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
	20	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
LOC-PFA + PC-GGBS (40:60)	10	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
	20	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
LOC-PFA + PC (Control)	10	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2
	20	FI @OMC	2
		F2@ OMC	2
		FI @1.2OMC	2
		F2@1.2OMC	2

4.7 THERMOGRAVIMETRIC ANALYSIS (TGA)

Thermogravimetric analysis (TGA) is a thermal analysis technique for measuring the amount and rate of change in sample mass as a function of temperature and/or time. TGA can be used to characterise any material that exhibits weight change as a result of, for example, dehydration (loss of water of crystallization), dehydroxylation (loss of OH ions), oxidation (e.g. combustion of organic matter) or decarbonation (loss of CO_2).

Heating of clay results in a pattern of weight loss that is characterised by the attractive force with which water is retained within or on the clay structure at different temperatures. Similar weight losses occur on heating hydrated cement. During the hydration of cement a number of chemical changes result in the formation of various phases. These include formation of ettringite, C-S-H gel, $Ca(OH)_2$ and carbonation of $Ca(OH)_2$ to give $CaCO_3$.

On heating, each of the above phases show a weight loss over a specific temperature range due to either partial or total decomposition. The weight loss results from the loss of water (dehydration or dehydroxylation) or carbon dioxide (from decarbonation). From the thermogravimetric measurements it is therefore possible to estimate, and in some cases accurately determine, the amount of each phase which is present at different stages of the hydration process.

In thermal analysis tests the specimens are heated at a controlled rate and the weight changes can be recorded in two ways:-

(i). Percentage weight loss against temperature (TG) and/or

(ii). Rate of loss in weight against temperature (DTG), this being the derivative of the curve in (i).

A weight loss at a specific temperature produces a step in (i) and a peak (maximum) in (ii). A weight gain will also produce changes but in the opposite direction. The curves are useful in illustrating the manner in which the amount of any particular phase present changes with curing time, and also providing reliable quantitative data giving the actual amounts of particular phases present. However, this technique requires prior knowledge of the chemical composition of the individual phases and their characteristic TG and DTG curves or decomposition temperature. There are a number of factors that influence the values of the peak temperatures observed on TG plots, for example the amount of sample used in the test, the heating rate, the furnace atmosphere, the particle size of the sample and the degree of crystallinity of the compound being tested.

The major thermogravimetric effects that characterise clay soils can be observed at temperatures ranging between 60°C and 300°C (loss of adsorbed water and water of hydration) and between 450°C and 1000°C (dehydroxylation & decarboxylation). At temperatures beyond 900°C most clay minerals undergo an exothermic recrystallisation process and new crystals form from amorphous materials derived from old crystals destroyed at lower temperatures (Mitchell, 1993). However, it should be noted that the thermal behaviour of clay soils could differ considerably from that of pure clay minerals, due to the presence of various elements such as organic matter or carbonates that decompose on heating.

4.7.1 Testing

For this study, the TGA work was carried out using a TA Instrument 2950Hi-Res ™ TGA thermogravimetric analyser using a TA5000 Thermal Analyse Controller and software (see Figure 4.9). The heating rate was chosen as 10°C per minute within the temperature range from room temperature to 1000°C. The sample was taken from the interior of a compacted cylinder (used in the UCS tests), only best mixes that obtained from UCS results were carried out for TGA test, this including specimens that stabilised with lime and PC only as a control (Table 4.5). The sample was dried in an oven at 40°C under silica gel and carbosorb (a carbon-dioxide-absorbing agent). After drying the sample was crushed to a powder in a Mixermill 2000. Between 8mg to 10mg of the crushed sample was ignited in a closed alumina pan. Heating was carried out in an inert environment of argon gas. Weight losses and temperature increases were plotted during the test and resulting graphs supplied the TGA weight loss curve (%). The former plots the total weight loss in percent over the temperature range to which the sample was subjected, whereas the latter shows the derivative of the weight loss with increase in temperature, resulting in a curve with pronounced peaks, thus allowing conclusions and calculations to be made as to the identity and quality of particular compounds or phases present.

Table 4.5: Details of mix compositions for LOC-PFA + Stabilisers systems for TGA

Target Materials	Stabilisers	Ratio	Curing Period (days)	Formula	Wt.%
LOC-PFA (50:50)	Lime (control)	100	7, 28, 56	F1@1.2OMC	10, 20
	PC (control)	100	7, 28, 56	F1@1.2OMC	10, 20
	Lime-GGBS	30:70	7, 28, 56	F1@1.2OMC	10, 20
	PC-GGBS	40:60	7, 28, 56	F1@1.2OMC	10, 20

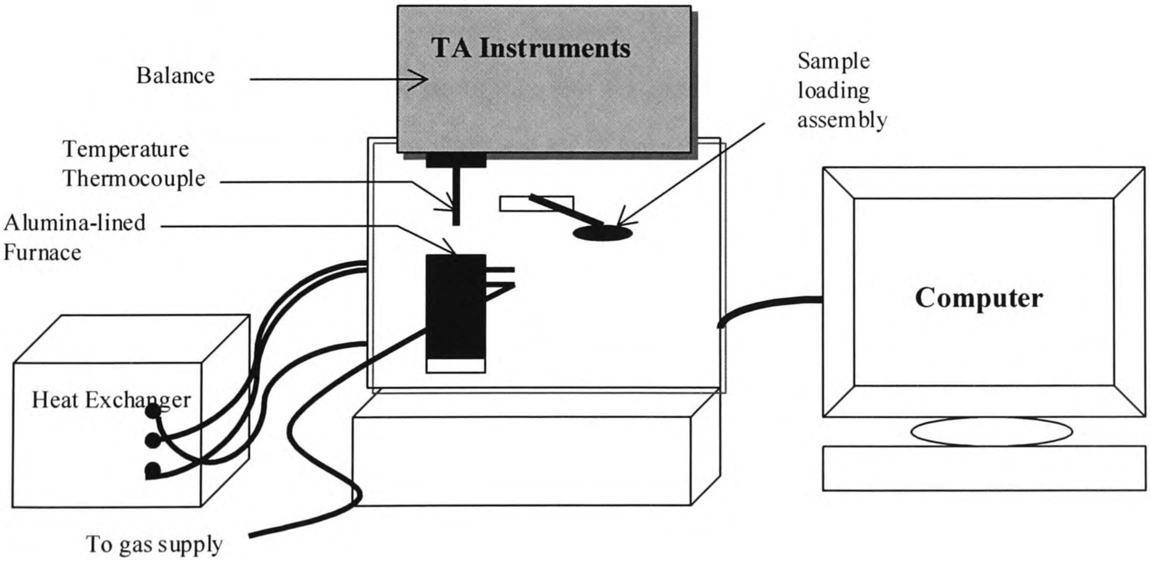


Figure 4.9: Diagram of a TGA 2950 thermogravimetric analyser

4.8 PILOT INDUSTRIAL COMMERCIAL TRIAL

After the initial laboratory stage where, mixes in previous tests were investigated for strength, durability and thermogravimetric analysis. A blend optimisation stage followed. At this stage LOC-PFA (50:50) stabilised with Lime-GGBS (30:70) and PC-GGBS (40:60) at 10% stabiliser dosage using the formula F1@1.2OMC followed by lime and PC only as the control mixed. These optimal blends (lime-GGBS (30:70) and PC-GGBS (40:60)) were adopted due to their superior performance in relation to strength, durability, and environmental and potential economic benefits. A brick size of 140mm width x 295mm length x 55mm thick with a density of 1540kg/m^3 was made.

A 10wt% stabiliser dosage was found more economical and comparable to 20wt% dosage in term of strength and durability results. Formula F1@1.2OMC was chosen based on results obtained from varying the optimum moisture content using two formulae F1 and F2 and at OMC and 1.2OMC. Results showed that there is no consistent trend of change on variation in the strength, and by raising the level of stabiliser from 10wt% to 20wt%, results indicate that those formulae with higher moisture contents achieve better strength. For this reason, the formula that takes into account the changes in water demand as a result changes in stabiliser dosage (F1) henceforth be adopted.

Table 4.6: Details of mix compositions for LOC-PFA + stabilisers systems for unfired bricks

Target Materials	Stabilisers	Blending ratio	Formula for	Wt.%
LOC-PFA (50:50)	Lime (control)	100%	F1@1.2OMC	10
	PC (control)	100%	F1@1.2OMC	10
	Lime-GGBS	30:70	F1@1.2OMC	10
	PC-GGBS	40:60	F1@1.2OMC	10

Table 4.7: Mix compositions for LOC-PFA + Stabilisers systems for one unfired brick sample

Target Materials	Stabilisers	Target Material (g)	Stabiliser (g)	Water (g)	Total (g)
LOC-PFA (50:50)	Lime (control)	2545	254	701	3500
	PC (control)				
	Lime-GGBS (30:70)				
	PC-GGBS (40:60)				

4.8.1 Preparation of Test Bricks for Unconfined Compressive Strength (UCS)

The tests for the unconfined compressive strength were carried out after moist curing for 7 and 28 days. This is because, for bricks, the development of early strength is very important. Two bricks per mix proportion were subjected to UCS tests and the mean strength determined.

The specimens were prepared using the target materials (LOC-PFA) at 1.2OMC. The target materials, stabilisers and blending ratios were as shown in Tables 4.6 and 4.7. The materials were mixed thoroughly after adding the pre-calculated amount of water. Mixing of the material was achieved by using Model SE-401 Hobart 40 Qt mixer. Bricks weighing 3500g were prepared for all mix proportions. A manual steel mould fitted with a lid and handle was used to compact the material into brick forms of size of 140mm x 295mm x 55mm thick (see Figures 4.10 and 4.11). Compaction of the bricks was aimed to be similar to that achieved for the laboratory cylinder specimens. After compaction, the bricks were extruded from the mould, trimmed, and wrapped with cling film to prevent further moisture loss (see Figure 4.12). All the brick samples were cured at a room temperature of ±20°C and at 100% relative humidity.

Figure 4.10: Manual brick mould

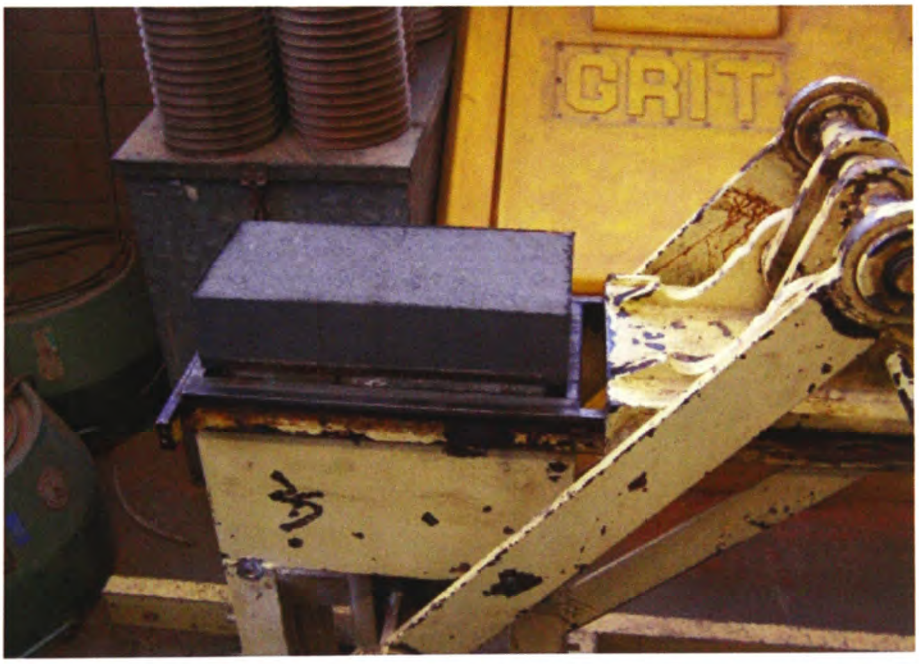


Figure 4.11: Unfired LOC-PFA brick freshly extruded from the steel mould

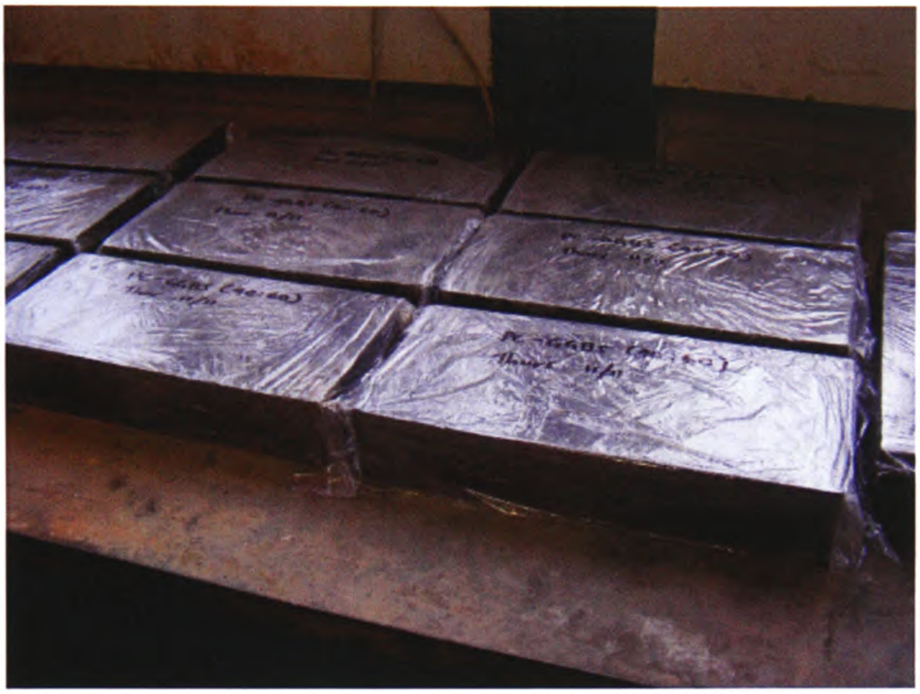


Figure 4.12: Unfired LOC-PFA bricks

4.8.1.1 Testing

Unconfined Compressive Strength (UCS) of the stabilised LOC-PFA unfired bricks was determined using a Hounsfield testing machine capable of loading up to 100kN at a compression rate of 0.15kN/min (see Figure 4.13). A self levelling device was used to ensure uniaxial load application.

Figure 4.13: Using a Hounsfield testing machine used for the determination of the UCS was carried out on formulated unfired brick

4.8.2 Water Absorption

The water absorption test for laboratory unfired bricks specimens was determined in accordance with BS EN 771-1:2003 (Specification for masonry units – Part 1: Clay masonry units). Two bricks per mix composition were subjected to tests and the mean water absorption % determined. First the specimens were moist cured for 28 days. The weight of the dry specimens was then determined, and then the specimens placed in a water tank that had the capacity to submerge the whole specimen, at a room temperature of 20°C. After 24 hour of soaking, the specimens were removed from the tank, the surface water on the specimens was wiped off with damp cloth, and their weights established. This was repeated every day for the first 7days of soaking period. Thereafter, next the readings were taken after a total soaking period of the 14 and 28 and 56 days.

Water absorption, % by mass, after 24 hours immersion in cold water in given by the formula:

$$W = \frac{M_2 - M_1}{M_1} X\ 100$$

M1 = Weight of specimen before soak

M2 = Weight of wet specimen after being removed from the water tank

4.8.3 Thermal Conductivity Test

The thermal conductivity was determined in compliance with BS EN 1745:2002 (Masonry and masonry products – Methods for determining design thermal values). Test specimens of dimensions 140mm x 147mm x 40mm thick were prepared (see Figure 4.14). As mentioned earlier, for the production of LOC-PFA (50:50) unfired bricks, only 4 sets of stabilisers were adopted at 10%wt dosage as shown in Table 4.8. These are blended lime-GGBS at (30:70), PC-GGBS at (40:60), and with lime and PC only as a controls, all made using formula F1@1.2OMC.

Prior to the testing, the specimens were cured for 28 days at room temperature. The specimens were wrapped with cling film to prevent excess drying. The thermal properties of the stabilised unfired bricks were then determined using the measured lower and upper lambda (λ) limits. A thermal conductivity instrument FOX200 equipped with WinTherm32 software as shown in Figure 4.15 was employed for the laboratory data collection and analysis. The equipment is in compliance with BS EN 1745:2002 and was designed according to ASTM C518-98 (Standard test method for steady state thermal transmission properties by mean of the heat flow meter apparatus). During the test, the specimen was placed flat between two plates in the test chamber. The upper plate is defined as the 'hot plate' and the lower one as the 'cold plate'. The upper plate is stationary, while the lower one can move up and down to suit the thickness of the test specimen. The actual measuring area for this equipment is 76mm x 76mm in the centre of the plate. For each test specimen, the thermal conductivity measurements were carried out for eight sets of temperature settings as shown in Table 4.9. The settings were selected at different temperature to stimulate the exposure conditions of the bricks for different temperature exposure.

Table 4.8: Thermal conductivity test specimens

Target Materials	Stabilisers	Blending ratio
LOC-PFA (50:50) (140mm x 147mm x 40mm)	Lime (control)	100%
	PC (control)	100%
	Lime-GGBS	30:70
	PC-GGBS	40:60

Table 4.9: Temperature settings for thermal conductivity test.

Test No.	Temperature of lower plate (T_L)°C	Temperature of upper plate (T_U)°C	Temperature difference °C	Mean temperature °C
1	-20	5	25	-7.5
2	-10	15	25	2.5
3	0	25	25	12.5
4	10	35	25	22.5
5	20	45	25	32.5
6	30	55	25	42.5
7	40	65	25	52.5
8	50	75	25	62.5

Figure 4.14: Unfired LOC-PFA test specimens

Figure 4.15: A thermal conductivity instrument FOX200 equipped with WinTherm32 software

4.8.4 Freeze and Thaw Test

The freeze-thaw testing was performed according to BS 5628-3:2005 (Code of practice for the use of masonry: Materials and components, design and workmanship) and to DD CEN/TS 12390-9:2006 (Testing hardened concrete. Freeze-thaw resistance scaling). The test was performed in a Prior Clave LCH/600/25 model $0.7m^3$ volume capacity environmental chamber. The apparatus consisted of refrigerating and heating unit, with continuous freeze thaw cycles at chamber temperatures in the range of ±20°C (see Figure 4.17). Both dry and wet freezing-thawing test were adopted for this study, modified from the above concrete-based standards in order to determine freeze and thaw properties of the target materials (unfired LOC-PFA bricks).

4.8.4.1 Dry freeze-thaw test

Prior to the test, brick specimens were cured for 28 days at room temperature. The unfired brick specimens of 140mm x 295mm x 55mm thick were individually placed in steel containers supported with Perspex bars. Each container was closed with a lid and labelled for further identification. The specimen temperature was observed during the entire test. Each specimen was subjected to freeze-thaw cycles at temperatures of 20°C to -15°C in the first 16 hours as shown in Table 4.10. The temperature was then raised again to +20°C (within 2 hours) for thawing and remained constant at +20°C for 6 hours to complete the 24 hours cycle (Figure 4.15). The 24 hour freeze-thaw cycle was designed to be repeated for 30 times, and the weight losses at 7, 14, 28 and 30 cycles were recorded. At the end of the 30th freeze-thaw cycle, visible damage, change in length and weight loss from the unfired brick surface was recorded. This was intended to determine the effects of different brick formulations on the resistance to the action of freezing and thawing.

4.8.4.2 Wet freeze-thaw test

After 28 days of curing at the room temperature, the brick specimens were fully soaked in water at room temperature to the maximum absorption. This was to ensure that no further absorption would occur during the freeze-thaw test. Similar to the dry test, the unfired LOC-PFA brick specimens of 140mm x 295mm x 55mm thick were individually placed in steel container supported with Perspex spacer bars. However, for the wet freeze-thaw test, the specimens were submerged in water for about 3mm from the bottom face (Figure 4.16). Each container was closed with a lid and labelled for further identification, and placed into the freeze-thaw chamber. The same method of freeze and thaw cycles was applied as described in the dry test.

Table 4.10: 24 hour-cycle temperature profile adopted in the freeze-thaw test

t in hour	*T* in °C		
	Upper limit	Nominal value	Lower limit
0	+22	+20	+18
2	+2	0	-2
4	+2	0	-2
14	-13	-15	-17
16	-13	-15	-17
18	+22	+20	+18
24	+22	+20	+18

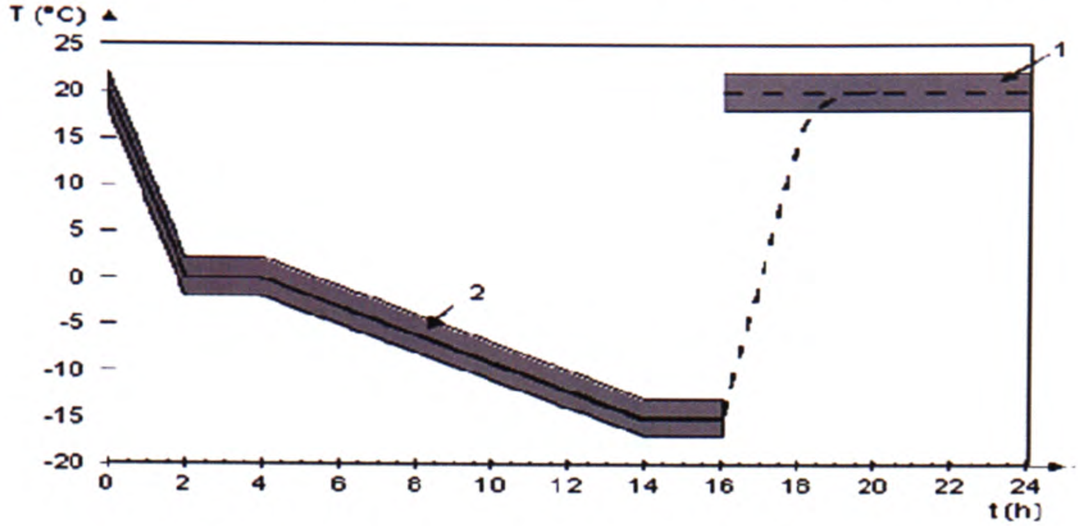


Figure 4.15: Temperature profile for the freeze–thaw test

Note:
1 – Temperature of thawing
2 – Temperature in the centre of unfired bricks
(*source: DD CEN/TS 12390-9:2006*)

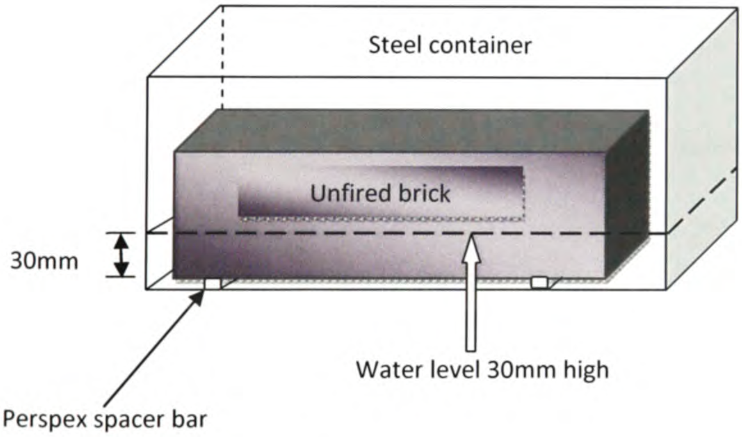


Figure 4.16: Cross section: unfired bricks placed in steel container for the wet freeze-thaw test

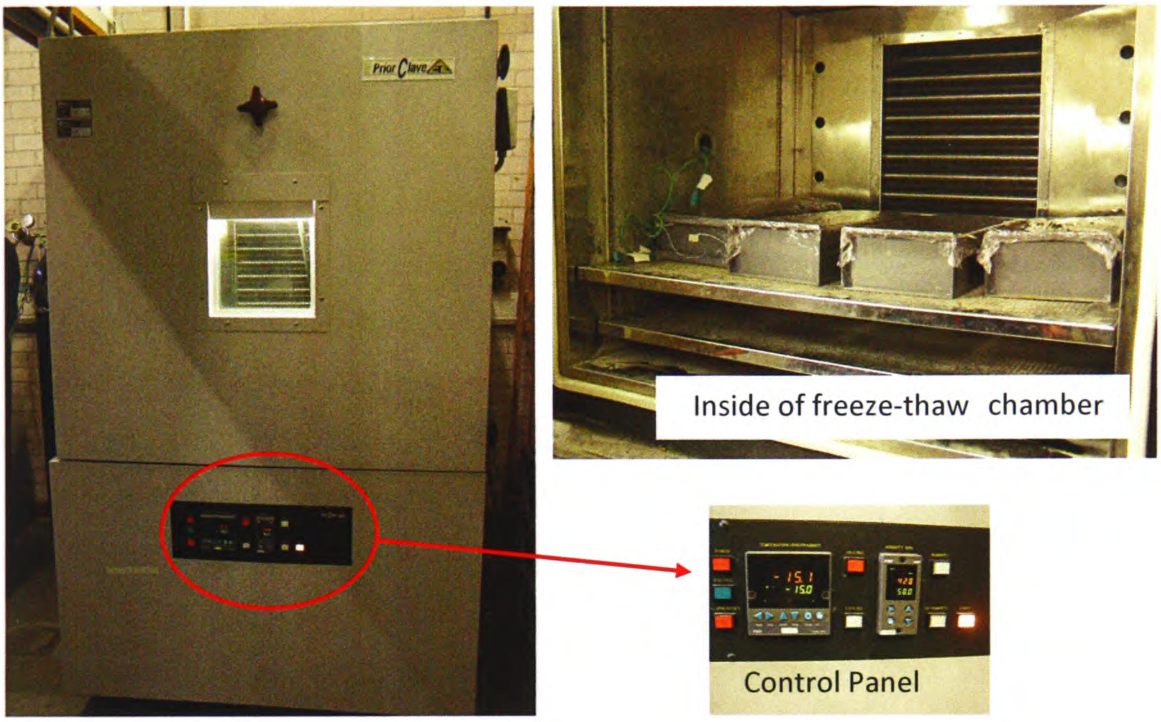


Figure 4.17: Freeze-thaw Chamber used for freeze-thaw tests

4.8.5 Evaluation of Environmental Performance

The evaluations of the environmental performance of the lime, PC, GGBS and activated LOC-PFA stabilised system was studied based on chosen formulae F1@1.2OMC at 10wt% comparison to fired bricks, PC-stabilised bricks and unfired brick samples with 100% stabilised LOC only without the combination with PFA.

The analysis of some major environmental concerns relating to new product development was carried out using the criteria commonly set by most environmental analysis methods such as BREEAM, LEEDS, Green Star, CASBEE and others. These including consideration for transportation, carbon dioxide emissions, embodied energy, depletion of resources, use of waste material, landfill, occupant's health due to end products, product reuse and overall perception in term of care for the environment.

In the current studies, the environmental characteristics on input energy and emissions output of the production process are considered as target for the production of sustainable materials. At this stage it is not yet possible to quantify the environmental profile for the whole life-cycle of the product which involves time consuming collection of data and extensive calculations. Focus was only maintained on obtaining an indication of the carbon dioxide and energy inventory of inputs and emissions outputs for the production process for a tonne of unfired bricks. Oti (2010) reported that there are widely quoted values of embodied energy and carbon dioxide emissions for pressed unfired clay with no binder of about 525.6 MJ/t and 25 $kgCO_2/t$ respectively. In order to determine the embodied energy and carbon dioxide of the unfired bricks, values of embodied energy of binder combinations were added to the pressed unfired without binder.

CHAPTER 5

EXPERIMENTAL RESULTS

In this chapter the results from experiments carried out on the Lower Oxford Clay and blended LOC-PFA, are presented. It deals with the interaction of these target materials with lime, PC and blended stabilisers incorporating GGBS. The experimental results include basic preliminary tests, consistency (Atterberg) limits tests, Proctor compaction tests, unconfined compressive strength (UCS), durability and linear expansion. The results of the analytical tests on thermogravimetric analysis (TGA) and tests on pilot industrial/commercial trial are also presented in this chapter.

5.1 BASIC PRELIMINARY TESTS

5.1.1 Specific Gravity

The specific gravity is the ratio of the unit weight of soil particles to the unit weight of distilled water. For finer-grained soil, the specific gravity is determined by using a vacuum dessicator. For this study, the specific gravity (Gs) was determined for the target materials LOC and PFA, and also for all the stabilisers-lime, PC and GGBS, using the following equation:

$$G_S = \frac{G_L (m_2 - m_1)}{(m_4 - m_1) - (m_3 - m_2)}$$

Where:

G_L = Specific gravity of the liquid used (for distilled water = 1)
m_1 = Mass of density bottle (g)
m_2 = Mass of bottle + dry soil (g)
m_3 = Mass of bottle + soil + liquid (g)
m_4 = Mass of bottle + liquid only (g)

Table 5.1: Specific gravity test results

Material	Specific Gravity (G_S)
LOC	2.35
PFA	2.15
Lime	2.71
PC	3.29
GGBS	2.72

Table 5.1 shows specific gravity test results for current research. From the table it is clear that PC has a significant higher specific gravity than others except for LOC. PC and GGBS have a comparable value of specific gravity. These results attained were comparable to others results done by others researchers.

5.1.2 Linear Shrinkage

The linear shrinkage test was performed to determine the percentage linear shrinkage of the target materials. The test is usually carried out on silts and clay soils with low plasticity. The test was only carried out on the Lower Oxford Clay, as the test requires material to be mixed to their approximate liquid limit, which was not carried out for the PFA due to it being non-plastic. The linear shrinkage (LS) of the material is calculated as a percentage of the original length (in a brass mould) using the procedure and equation shown in Table 5.2.

Table 5.2: Calculation of linear shrinkage for LOC

Sample	A	B	Average
Original length of sample (L_o) (mm)	140	140	-
Length of sample after drying (L_D)(mm)	118.4	118.9	-
Linear shrinkage $100(1-L_D/L_o)$	18.20%	17.78%	18%

5.2 CONSISTANCY (ATTERBERG) LIMIT

The plasticity characteristics of soils are normally expressed in terms of their liquid limit (LL), plastic limit (PL) and plasticity index (PI) as proposed by Atterberg (1911) and as described in the British Standard (BS 1377:2:1990). Atterberg limits are expressed as the percentage of moisture by dry weight of soil commonly referred to as the moisture content of the soil. Atterberg Limits are used as index properties for the classification of soils. Certain ranges of Atterberg limits are associated with certain characteristic types of soil behaviour. However, only a general indication should be drawn from these limits, since consistency limits of clays are generally affected by their chemical environment and composition (Abdelkader, 1985).

Figure 5.2-1 illustrates how the liquid limit was determined for LOC using the cone penetrometer test method. The liquid limit is determined at the point at which the moisture content allowed the cone to penetrate 20mm into the soil. The liquid limit (LL) for LOC was 67.8% (reported as 68%), which is comparable to other results from previous researchers between 59% and 68% (Nidzam, 2004; Thomas, 2001).

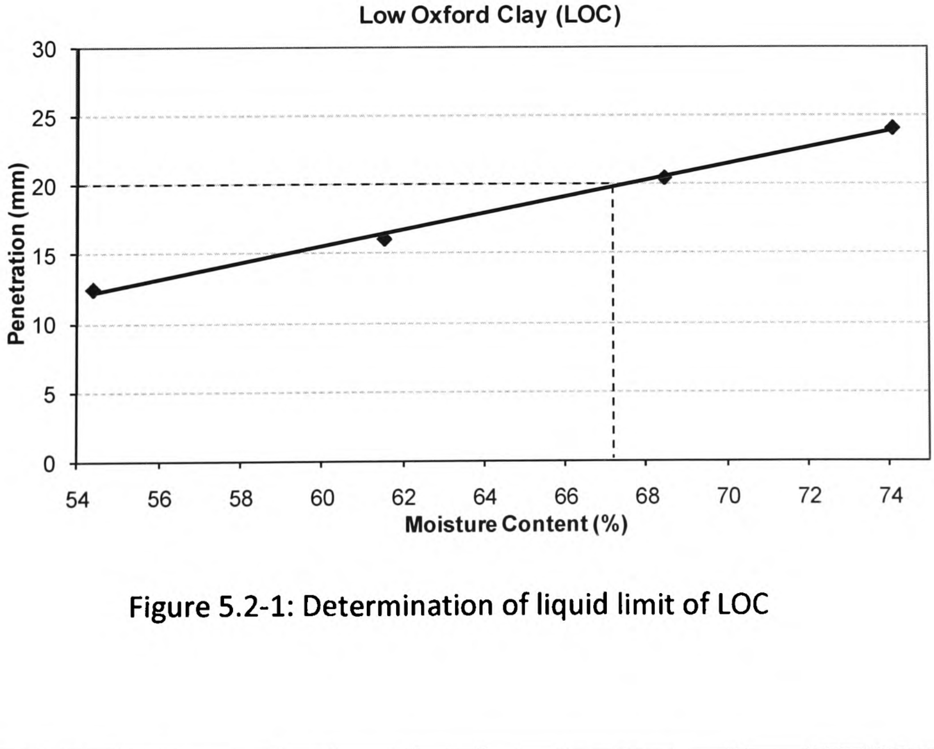


Figure 5.2-1: Determination of liquid limit of LOC

The plastic limit (PL) of LOC was determined by gently rolling the soils on a flat glass plate, until the rods crumbled when they were approximately 3mm in diameter. Few samples were taken for moisture content determination. The results for PL was 35.9% (reported as 36%), which was close compared to tests carried out by previous researchers found to be 32% to 35% (Nidzam, 2004; Thomas, 2001)

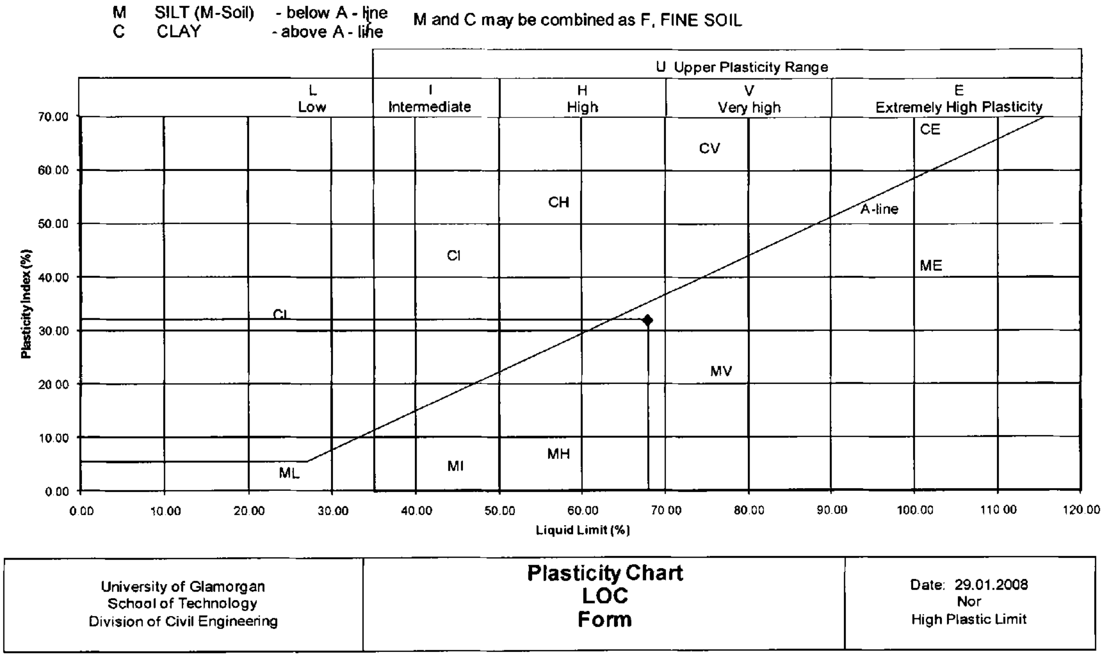


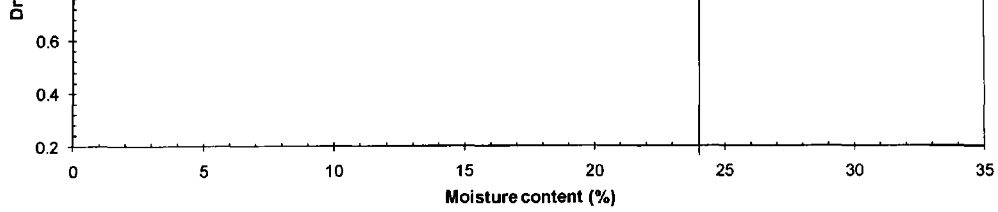
Figure 5.2-2: Plasticity chart displaying used to classify soils, showing location of LOC

From the LL and the PL, the plastic index (PI) of the soil was obtained as the difference between these two limits. The PI is the range of water contents within which the soil exhibits plastic properties. Classification of soils is usually accomplished by means of the plasticity chart also referred to A-line chart (see Fig. 5.2-2). This line was derived from experimental evidence and does not represent a well defined boundary between soil types, but does form a useful reference datum (Head, 2006). Using the chart, the location of LOC was found to be MV, below the A-line, within the upper plasticity range. It showed very high plasticity silt category.

5.3 BS PROCTOR COMPACTION TESTS

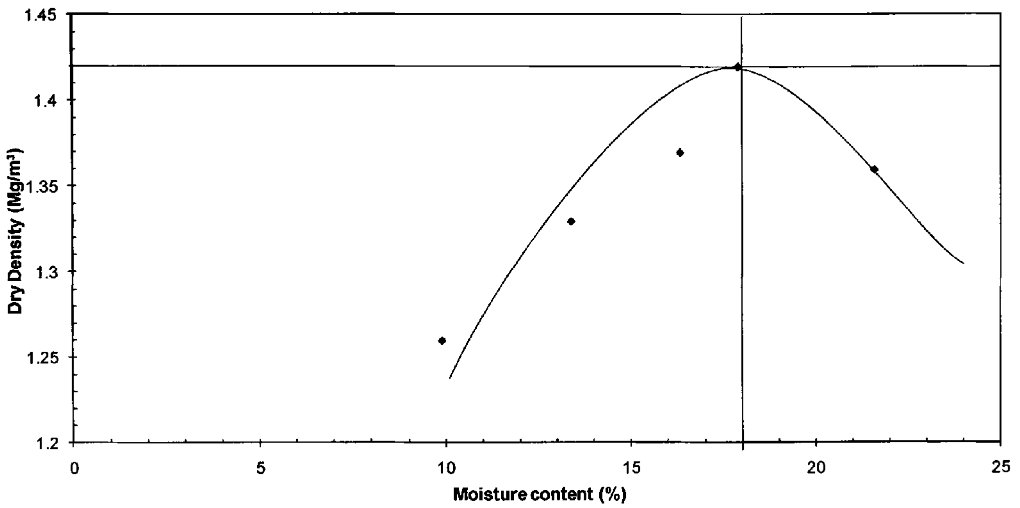
For the purpose of sample preparation, it was found necessary to establish the target dry density and moisture content values. Standard Proctor compaction tests were carried out in accordance with BS 1377 (1990) Part 2, in order to establish values of the maximum dry density (MDD) and optimum moisture content (OMC). For this study, standard Proctor compaction tests were carried out on target materials-LOC and PFA-to establish the approximate maximum dry density and optimum moisture content to be adopted during the preparation of specimens for the unconfined compressive strength, durability and linear expansion tests.

Figures 5.3-1 and 5.3-2 show clearly defined peaks in the compaction curves for the LOC and PFA compaction test. To overcome the problem of defining the optimum condition, a conjuncture defined curve for each test was created to provide a line of best fit in effect. From the tests, an average MDD value of 1.42 Mg/m^3 for both LOC and PFA were established (MDD of PFA ranges between 1.42-1.48 Mg/m^3 (Coombs *et al.*, 2001)). OMC values of 24% for LOC and 19% for PFA were established.



University of Glamorgan School of Technology Division of Civil Engineering	**Determination of optimum moisture content** **Form**	Date: 05/02/08 LOC Nor

Figure 5.3-1: Density against moisture content of LOC



University of Glamorgan School of Technology Division of Civil Engineering	**Determination of optimum moisture content** **Form**	Date: 25/06/08 PFA Nor

Figure 5.3-1: Dry density against moisture content of PFA

5.4 UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

The effects of various blended stabilisers on the strength characteristics of LOC and LOC-PFA (50:50) as target materials were studied. The UCS test was carried out as described in the British Standard (BS 1377-7:1990), to assess the strength development of these target materials incorporating varying ratios and contents of blended stabiliser. The effects of two different methods of calculating compaction water content and for various curing periods were also investigated.

At the first stage, two stabiliser blending ratios were applied, at 10wt% and 20wt% of stabiliser dosage and two curing periods were employed at 7 and 28 days. Further, 56 days curing periods were only applied to LOC-PFA (50:50) stabilised with Lime and PC as the control sets and blended stabiliser Lime-GGBS (30:70) and PC-GGBS (40:60), which were chosen based on better strength values as determined from the UCS results at 7 and 28 days of curing as well as based on the economy of using a stabiliser blend with more GGBS (a by-product) relative to the traditional stabiliser of lime or PC. Cylinders of dimensions 50mm in diameter and 100mm in height were made from both target materials-stabiliser mixtures. They were compacted at OMC and at 1.2 OMC, as explained in section 4.4. Three specimens were tested for each of the blended soil mixtures and the mean strength value taken.

5.4.1 Unconfined Compressive Strength of the Lime system

5.4.1.1 Stabilised LOC at 7 and 28 days

Figures 5.4-1 (a) and (b) show the effects of different methods of calculating the moisture content [(F1: OMC, 1.2OMC) and (F2: OMC, 1.2OMC)] on the UCS of LOC, when stabilised with lime alone and with Lime-GGBS blended stabilisers at 30:70 and 50:50 ratios, at 10wt% and 20wt% stabiliser dosages. The overall results show that there are increases in strength with increasing stabiliser content from 10wt% to

20wt% and with increased curing period from 7 to 28 days for both methods of calculating the initial compaction water input.

At 10wt% (Fig. 5.4-1(a)), LOC stabilised with at 50:50 ratio shows most of the highest UCS values (at all ages) with both formulae for calculating compaction water content. At 7 days of curing, F2@OMC recorded the highest strength, with UCS value of 876 kN/m^2 when the LOC was stabilised with the lime-GGBS at a 50:50 ratio. At this curing stage the lowest strength value was 402 kN/m^2 for formula F1@1.2OMC stabilised with lime only. This formula also indicates lowest strength values for all 7-day UCS using the lime-GGBS stabilisers. At 28 days of curing, the same pattern in strength development is observed as at 7 days but with significant increased strength values.

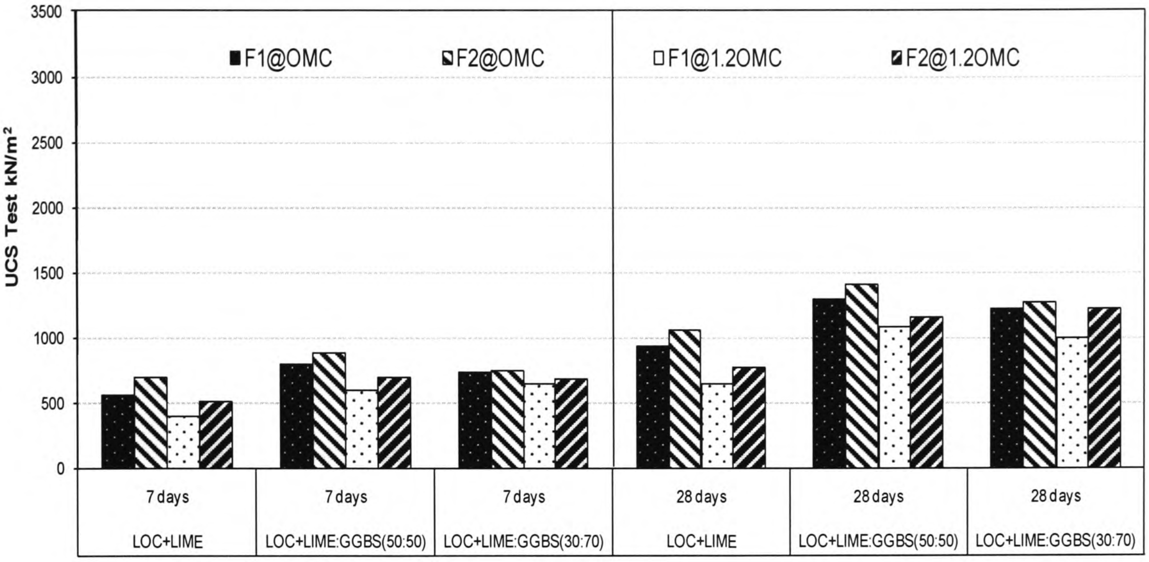
Fig. 5.4-1(b) illustrates the strength development of the same lime system as in Fig. 5.4-1(a), but with increased stabiliser dosage at 20wt%. In general, the strength development increased from 7 days to 28 days of curing with all stabilisers and formulae, in a similar manner as when a 10wt% stabiliser was used. However, the strength magnitudes were higher. At 7 days of curing, LOC stabilised with lime-GGBS (50:50) continued to indicate most of the highest strength values. The highest strength value was recorded at 1180 kN/m^2, when F1@OMC was used, while F2@OMC showed the lowest strength value when lime only was used as the stabiliser.

At 28 days of curing, LOC stabilised with lime only continued to show the lowest strength values with both formulae, compared to other stabilisers, with a strength value of 539 kN/m^2 when formula F2@OMC was used. The highest strength values with all formulae was obtained when LOC was stabilised with lime-GGBS at 30:70 ratio, with F1@1.2OMC showing the highest strength value of 2169 kN/m^2. At this stage, with increased the amount of GGBS from (50:50) to (30:70) ratio, the overall results have shown that, there was an increment in strength value with both formulae of compacting moisture content (see. Fig. 5.4-1(b)).

Summary observations:

- At 10wt% stabiliser content, there is little difference between the two stabiliser blending ratios 50:50 and 30:70.
- At 20wt% stabiliser content, the 30:70 blend is better than 50:50 pattern at 28 days of curing
- There is little difference between F1 and F2 in general, or between compaction moisture contents OMC and 1.2OMC.

(a) 10% stabiliser



(b) 20% stabiliser

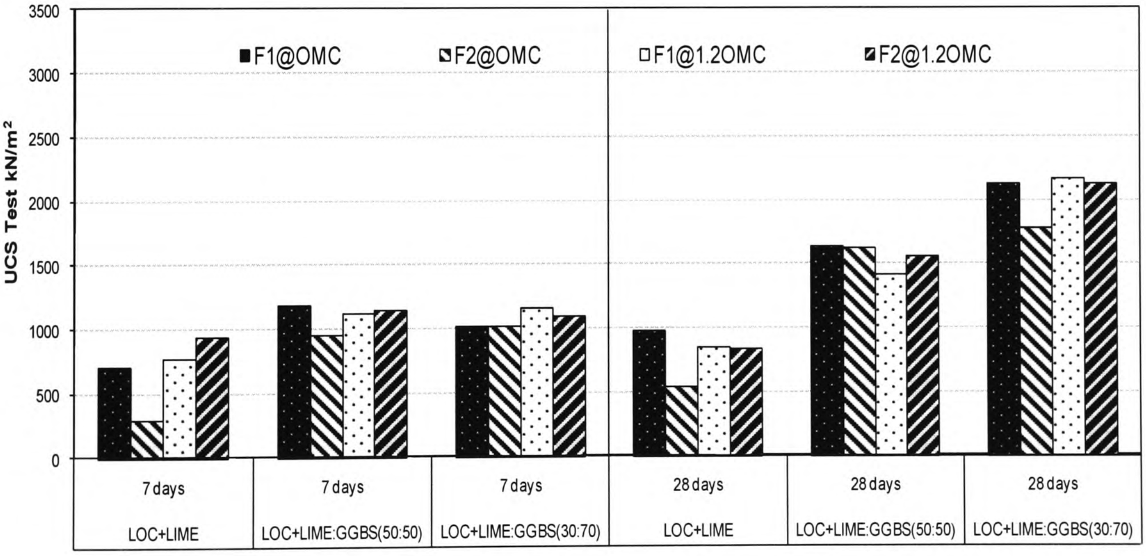


Figure 5.4-1: UCS of stabilised LOC with lime-GGBS with various method of calculating compaction moisture content at (a) 10wt% and (b) 20wt% stabiliser content

5.4.1.2 Stabilised LOC-PFA (50:50) at 7 and 28 days

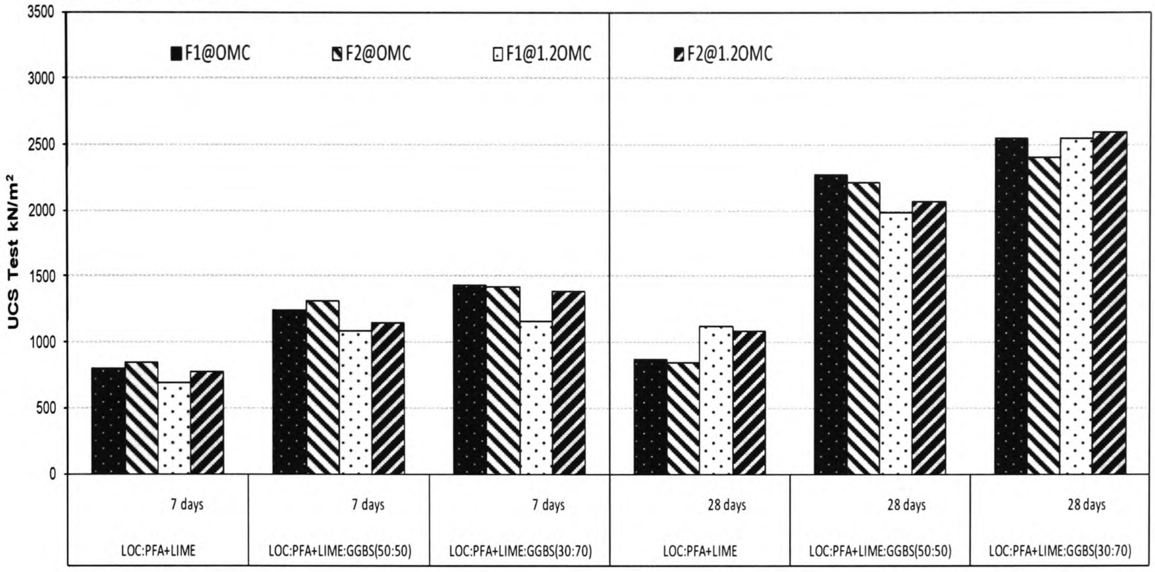
Figure 5.4-2(a) shows the effects of different methods of calculating the compaction water content, when combined LOC-PFA (at 50:50) was used as the target material for stabilization at 10wt% stabiliser level. Within this system, most of the highest UCS values (at all ages) with all formulae were observed with LOC-PFA stabilised with lime-GGBS (30:70). At 7 days of curing (Fig. 5.4-2(a)), F1@OMC recorded the highest strength, with a UCS value of 1430 kN/m^2, with the lime-GGBS 30:70 ratio. At this curing stage the lowest strength value was shown by Formula F1@1.2OMC using lime only. This formula also indicates lowest strength values with all the lime-GGBS stabilisers. At 28 days of curing, F2@1.2OMC gives in highest strength value of 2591 kN/m^2 when stabilised with lime-GGBS at (30:70) ratio. The lowest strength values again were observed when lime was only used to stabilise LOC-PFA, at all the different formulae. The lowest strength was 839 kN/m^2 when F2 was used at OMC.

Fig. 5.4-2(b) illustrates the strength development of lime system when 20wt% stabiliser dosage was used to stabilise LOC-PFA. At 7 days of curing, LOC-PFA stabilised with lime-GGBS (30:70) indicated the highest strength values with a highest strength of 2015 kN/m^2 recorded when F2@OMC was used. Meanwhile for the same F2 at OMC, the test specimens totally collapsed with no strength gain, when lime only was used as the stabiliser. The strength at 7 days with 20 wt% lime was detrimental compared to when 10 wt% lime was used. At 28 days of curing, LOC-PFA stabilised with lime only continued to show the lowest strength values with all formulae compared to other stabilisers, with the lowest strength value of 90 kN/m^2 being observed when formula F2@OMC was used. Incorporating GGBS at both 50:50 ratio and 30:70 ratios tremendously increased the strength in the system for all formulae. However, the highest strength values were obtained with lime-GGBS at 30:70, where F2@1.2OMC recorded the highest strength value of 3208 kN/m^2.

Summary Observations:

- Collapse with lime at 20wt% and not at10wt%
- Blended 30:70 ratio superiority
- Little variation between F1 and F2, OMC and 1.2OMC
- Marginally better strength with F1 at 10wt%, and F2 at 20wt% plus curing.

(a) 10% stabiliser



(b) 20% stabiliser

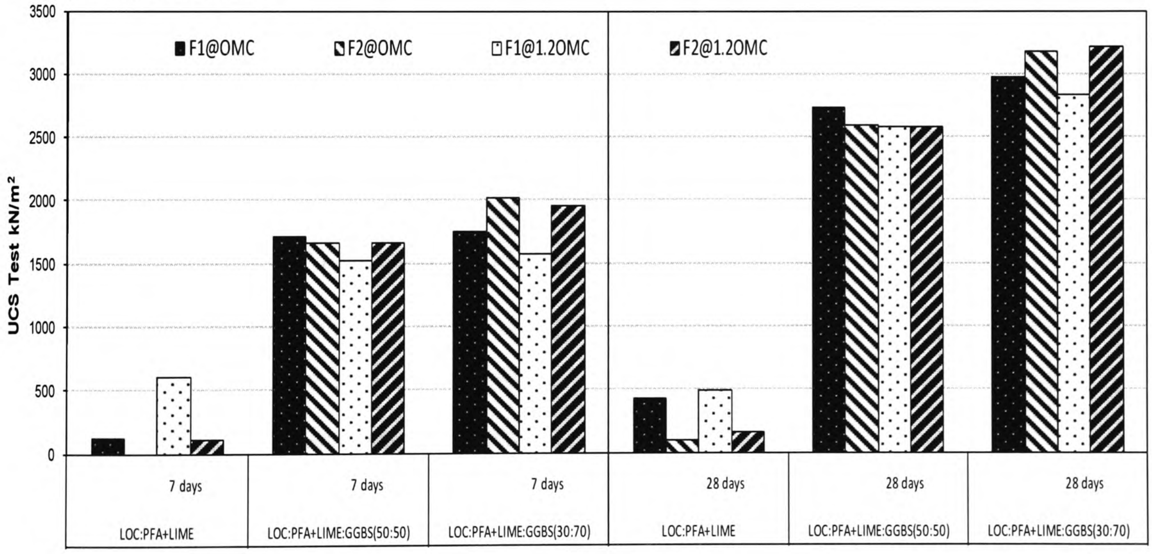


Figure 5.4-2: UCS of stabilised LOC-PFA with lime-GGBS with various method of calculating compaction moisture content at (a) 10wt% and (b) 20wt% stabiliser content

5.4.1.3 Stabilised LOC-PFA (50:50) at 56 days

At this curing period only blended Lime-GGBS at 30:70 ratio, at both stabiliser dosages with all methods of calculating compaction moisture content was implemented. This was followed with LOC-PFA stabilised with the lime only as a control set. This action was taken based on previous results determined from UCS at both 7 and 28 days. Results shown higher UCS development was achieved with this mixed composition compared to LOC-PFA stabilised with blended lime-GGBS at 50:50 ratios. At the same time, the 30:70 mixes is more economical and sustainable as it uses the more economical GGBS relative to lime.

Figures 5.4-3(a) and (b) show the overall effects of different methods of calculating the compaction water content for LOC-PFA stabilised with lime only as a control, and with blended lime-GGBS at a ratio of 30:70 for prolonged curing at 56 days at 10wt% and 20wt%. Within this system, with all formulae, it shows most of the highest UCS values occurred when LOC-PFA was stabilised with lime-GGBS (30:70) compared to lime only with all formulae. When LOC-PFA stabilised with lime-GGBS at a ratio of 30:70, the overall results show that there is little or no increase in strength with increasing stabiliser dosage from 10wt% to 20wt%. Mysteriously, the strength generally decreased from 28 days to 56 days of curing, at both stabiliser dosages for all methods of calculating the initial compaction water input. For lime only, the results illustrate that the strength development deteriorated more significantly with increasing stabiliser dosage from 10wt% to 20wt%.

Fig. 5.4-3(a) illustrates the strength development at 10wt% stabiliser dosage. It reveals that the highest strength development was achieved at 2689 kN/m^2 when LOC-PFA was stabilised with lime-GGBS (30:70) using formula F2@OMC at 56 days. At this curing stage the lowest strength value was 1316 kN/m^2 with formula F2@1.2OMC when LOC-PFA stabilised with lime only.

Fig. 5.4-3(b) shows the strength development when LOC-PFA stabilised at 20wt% stabiliser dosage. In general, with lime only there are insignificant changes in strength with increased curing period from, 7 to 28 and 56 days for all methods of calculating compaction water input, with formula F1@1.2OMC showing highest strength value at all curing period averaging at about 500 kN/m^2. On the other hand when lime-GGBS (30:70) was used as stabiliser, there are significant increases in strength development from 7 days to 28 days of curing, but the strength decreased from 28 days to 56 days of curing with all methods of calculating compaction water input. At 56 days curing period, the highest strength value was achieved at 2765kN/m^2 when LOC-PFA was stabilised with lime-GGBS (30:70) using formula F1@OMC. LOC-PFA stabilised with lime only continued to show the lowest strength values with all formulae, with the lowest strength value at 49 kN/m^2 when formula F2@OMC was used.

Summary Observations:

- At 10wt% it shows similar strength development when compared with 28 days curing
- At 20wt%, UCS results show decreased in strength compared to strength at 28 days with all formulae
- Little variation between F1 and F2, OMC and 1.2OMC
- For LOC-PFA stabilised with the lime only, similar pattern was shown when compared with 28 days curing.

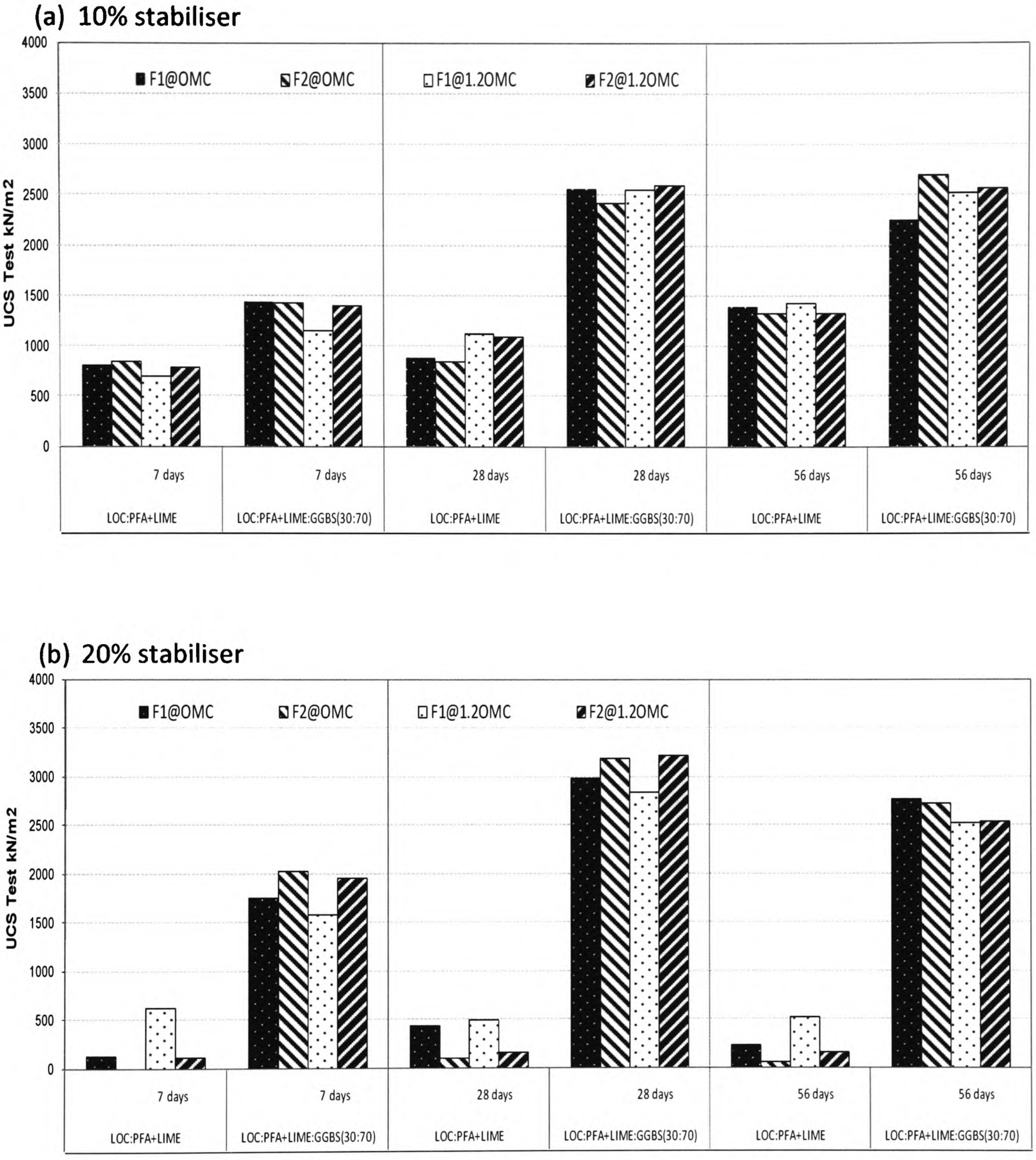


Figure 5.4-3: UCS for stabilised LOC-PFA prolong to 56 days curing with lime-GGBS with various method of calculating compaction moisture content at (a) 10wt% and (b) 20wt% stabiliser content

5.4.2 Unconfined Compressive Strength of PC System

5.4.2.1 Stabilised LOC at 7 and 28 days

Figures 5.4-4(a) and (b) illustrate the UCS development of LOC when stabilised with PC alone and with PC-GGBS (at 40:60 and 60:40 ratios) for the different methods of calculating the compaction moisture content. The stabiliser dosages used are 10wt% and 20wt% for the two figures respectively. Like in the lime system, the overall results show that there is increase in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating the compaction moisture content. However, compared with the lime-GGBS system, the strength magnitudes are lower with the PC-GGBS system at both curing periods.

With the 10wt% stabiliser dosage, at 7 days of curing (Fig. 5.4-4(a)), an average UCS value of 580 kN/m^2 was observed. Formula F2 at OMC recorded the highest UCS values when PC was used on its own or when blended with GGBS, at both 7 and 28 days of curing, with a maximum 7 day value of 723 kN/m^2 with PC-GGBS (60:40), and 991 kN/m^2 at 28 days when stabilised with PC-GGBS (40:60). Formula F1@1.2OMC gives the lowest strength value of 422 kN/m^2 at 7 days of curing when PC only was used, and 455 kN/m^2 at 28 days of curing when stabilised with PC-GGBS (60:40).

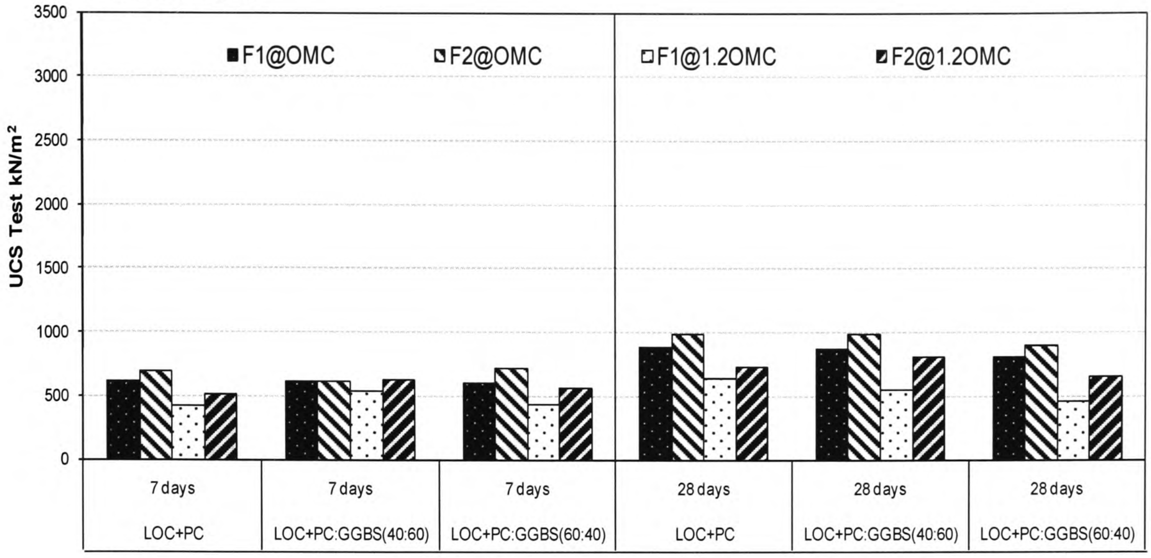
Fig. 5.4-4(b) illustrates the strength development when 20wt% stabiliser dosage was used. In general, the strength development increased progressively from 7 days to 28 days of curing with all types of stabiliser blends and formulae. At 7 days of curing, F2@OMC shows the highest strength values with a UCS value of 1117 kN/m^2 when LOC was stabilised with PC only. Meanwhile, Formula F1@1.2OMC indicates the lowest strength values when LOC was stabilised with PC used on its own (587 kN/m^2). At 28 days of curing, F1@1.2OMC shows the highest strength value of 1600 kN/m^2 with blended PC-GGBS (40:60) and F2@OMC stabilised with same blended stabiliser indicates the lowest strength improvement at 1153 kN/m^2. Overall, with the 20wt% stabiliser dosage, LOC stabilised with PC-GGBS (60:40) blends demonstrates almost equal strength magnitudes with both formulae.

In general, by blending PC with GGBS, equal or better strength development patterns and magnitudes were observed at both 10wt% and 20wt% stabiliser level, compared to LOC stabilised with PC on its own. This indicates that GGBS has a good potential as a partial replacement material for PC. This is beneficial since GGBS has environmental benefits relative to lime or cement, and GGBS is a by-product material. The system with more GGBS (40:60) indicates higher strength values than (60:40), further improving on the environmental and economic advantages of the PC-GGBS system.

Summary observations:

- At 10wt% stabiliser content, there is little difference between the two stabiliser blending ratios 40:60 and 60:40.
- At 20wt% stabiliser content, the 40:60 blend is better than 60:40 pattern at 28 days of curing
- There is little difference between F1 and F2 in general, or between compaction moisture contents OMC and 1.2OMC.
- By blending PC with GGBS almost equal strength patterns and magnitudes when compared to LOC stabilised with PC on its own

(a) 10% stabiliser



(b) 20% stabiliser

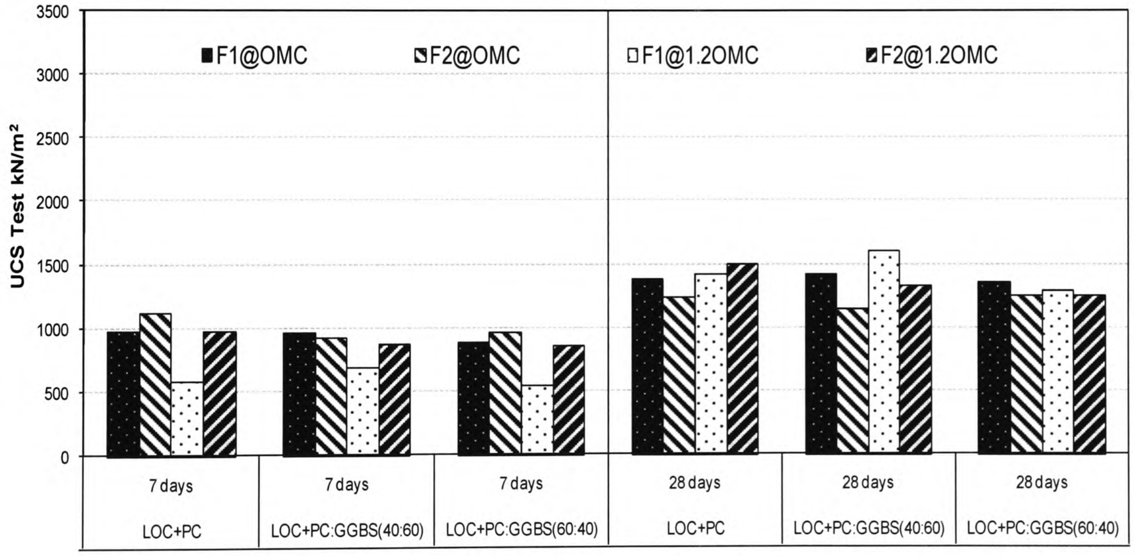


Figure 5.4-4: UCS of stabilised LOC with PC-GGBS with various method of calculating compaction moisture content at (a) 10wt% and (b) 20wt% stabiliser content

5.4.2.2 Stabilised LOC-PFA (50:50) at 7 and 28 days

Figures 5.4-5(a) and (b) illustrate the UCS development of the LOC-PFA stabilised system. Similar to the lime system (Fig. 5.4-2a & b), the overall results shows increase in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days, and for variations in moisture content values. With 10wt% stabiliser dosage, at 7 and 28 days of curing (Fig. 5.4-5(a)), LOC-PFA stabilised with PC alone shows higher strength increases compared to the blended stabiliser PC-GGBS. At 7 days of curing, the highest strength was observed with PC using Formula F1@OMC at 954 kN/m^2. Formula F2@OMC gives the lowest strength value of 451 kN/m^2 when PC-GGBS (40:60) was used. At 28 days of curing F1@1.2OMC indicates the lowest strength value of 900 kN/m^2 when stabilised with PC-GGBS (60:40) ratio. While the highest strength of 2399 kN/m^2 was recorded with PC only with formula F1@OMC.

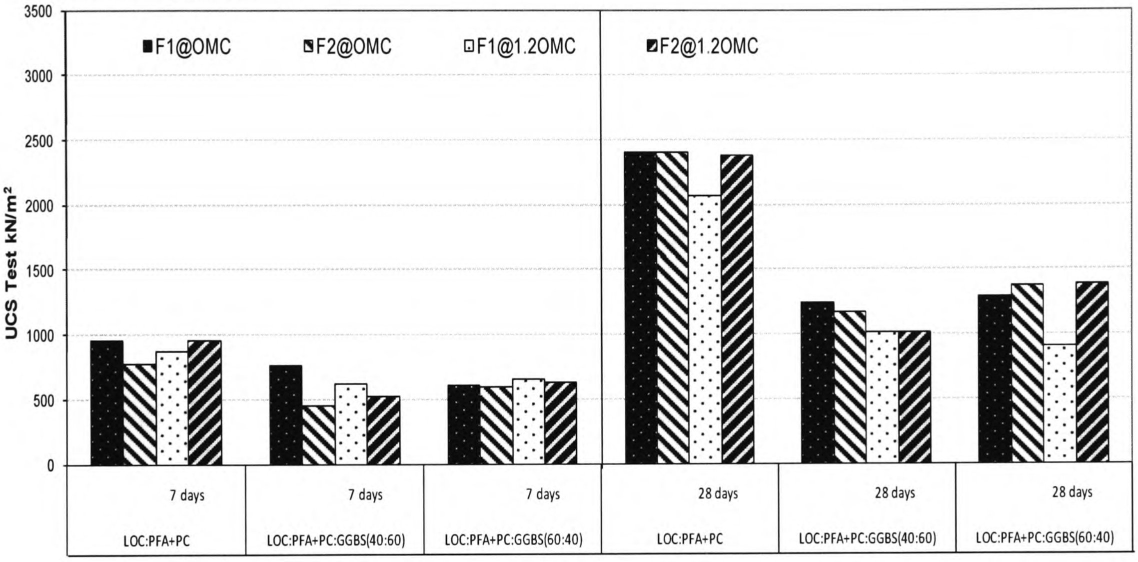
Fig. 5.4-5(b) illustrates the strength development when 20wt% stabiliser dosage was used in the PC system. There are increases in strength development upon increasing the stabiliser dosage to 20wt% at both 7 and 28 days with all formulae. At 7 days of curing, F2@OMC shows the highest strength value of 1591 kN/m^2 with PC only. Meanwhile, Formula F1 (1.2 OMC) indicates the lowest strength values when LOC-PFA was stabilised with PC-GGBS (60:40) (1036 kN/m^2). At 28 days of curing, F2@1.2OMC shows the highest strength value of 2754 kN/m^2 with PC only and F1@OMC stabilised with PC:GGBS (40:60) indicates the lowest strength at 1712 kN/m^2. Overall, at 20wt% stabiliser level, LOC-PFA stabilised with PC only demonstrates highest strength improvement with all formulae compared to the blended stabilisers.

Summary observations:

- At 10wt% stabiliser content, there is little difference between the two stabiliser blending ratios 40:60 and 60:40, at 28 days of curing PC only, shows better increment in strength compared to both blending ratios .

- At 20wt% stabiliser content, by blending PC with GGBS - both 7 and 28 days curing show almost equal strength pattern when compared to LOC stabilised with PC alone.
- There is little difference between F1 and F2 in general, or between compaction moisture contents OMC and 1.2OMC.

(a) 10% stabiliser



(b) 20% stabiliser

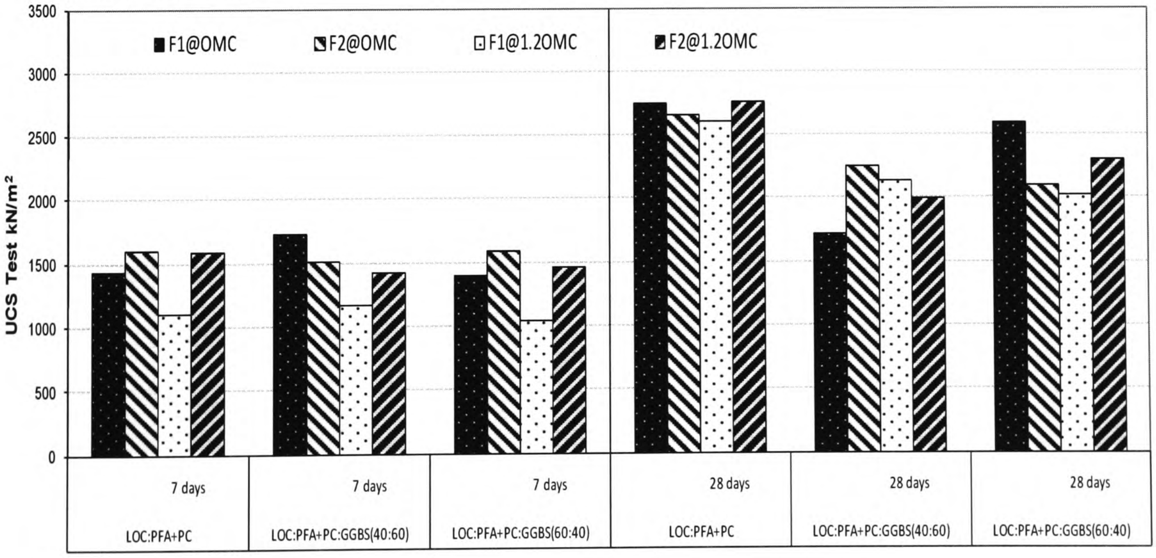


Figure 5.4-5: UCS of stabilised LOC-PFA with PC-GGBS with various method of calculating compaction moisture content at (a) 10wt% and (b) 20wt% stabiliser content

5.4.2.3 Stabilised LOC-PFA (50:50) at 56 days

Figures 5.4-6(a) and (b) show the overall effects of different methods of calculating the compaction water content for LOC-PFA stabilised with PC only and blended PC-GGBS (40:60) upon prolonged curing up to 56 days at 10wt% and 20wt%. In contrast with the lime system, this system shows most of the highest UCS values occurring when LOC-PFA was stabilised with PC only compared to the use of blended PC-GGBS with all formulae. The overall results show that there are progressive increases in strength development with increasing stabiliser dosage from 10wt% to 20wt%, together with increase in curing period from 7 day to 28 and then to 56 days at both stabiliser dosages for all methods of calculating the initial compaction water input.

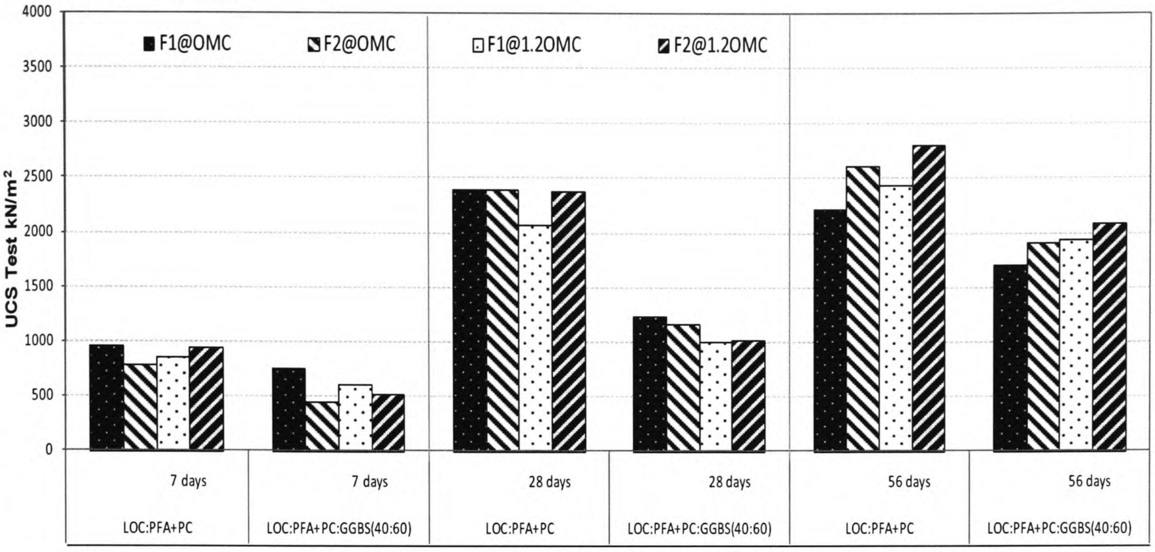
At 10wt% stabiliser dosage (Fig. 5.4-6(a)) F2@1.2OMC recorded the highest 56-day strength, with a UCS value of 2813 kN/m^2, when LOC-PFA was stabilised with PC only. At this curing stage the lowest strength value was shown by Formula F1@OMC using blended PC-GGBS (40:60) was used, with a strength value of 1707 kN/m^2.

With 20wt% stabiliser dosage at 56 days of curing (Fig. 5.4-6(b)), again LOC-PFA stabilised with PC alone shows higher strength increment compared to blended PC-GGBS stabiliser. The highest strength was observed with Formula F1@1.2OMC at 3862 kN/m^2. Formula F2@1.2OMC gives the lowest strength value of 2948 kN/m^2 when PC-GGBS (40:60) was used. Overall the results show that there are increases in strength development with increasing in curing period with all methods of calculating the initial compaction water input, with the PC only stabiliser showing best performance.

Summary Observations:

- At 10wt% it shows there are increase in strength for both blended PC-GGBS at 40:60 ratios and PC alone when compared to 7 and 28 days curing
- At 20wt%, UCS results for 56-day shows increased in strength when compared to UCS strength at 28 days with all formulae
- Little variable between F1 and F2, OMC and 1.2OMC

(a) 10% stabiliser



(b) 20% stabiliser

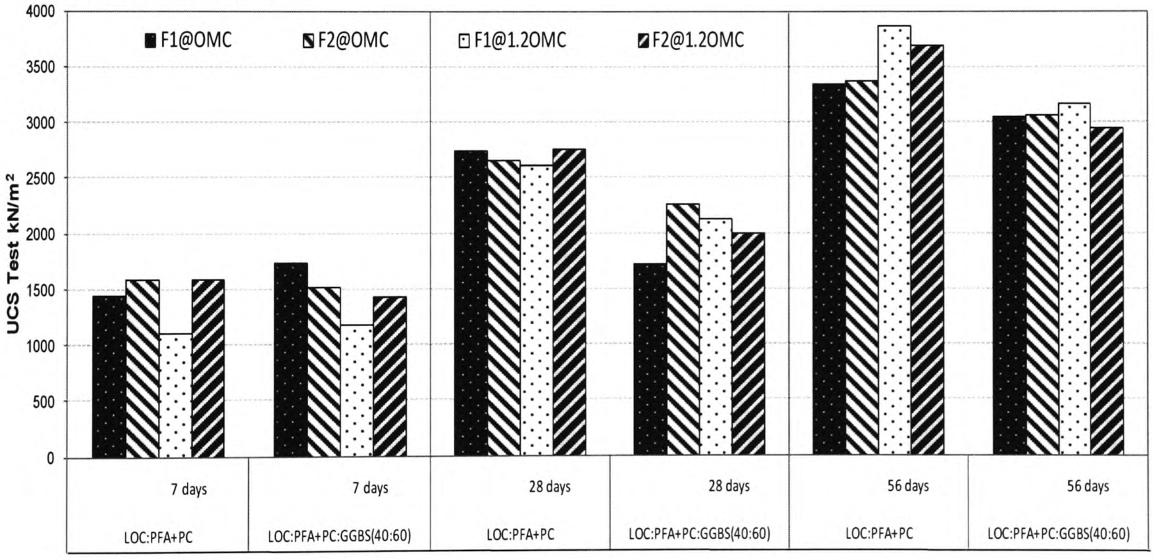


Figure 5.4-6: UCS for stabilised LOC-PFA prolong to 56 days curing with PC-GGBS with various method of calculating compaction moisture content at (a) 10wt% and (b) 20wt% stabiliser content

5.4.3 Summary

Figures 5.4-7 and 5.4-8 summarise all the different strength results obtained with the two target materials (LOC and LOC-PFA), stabilised with various stabilisers. It is evident that:

1. In general, increased amount of stabiliser dosage resulted in increased UCS with increasing curing period for both stabilised LOC and LOC-PFA target materials, except for when lime alone was used as stabiliser. Low strength values were observed with both formulae for material compacted at the OMC, probably due to good compaction but incomplete hydration. Research by Nidzam (2001) has attributed the variability in strength of stabilised soil mixtures especially at high lime dosages, to incomplete hydration of lime due to lack of adequate water. Overall results therefore show that lime alone is not suitable for use as stabiliser for both LOC and LOC-PFA.

2. The lime-GGBS blended stabiliser will be used at a 30:70 blending ratio for further investigations. This is based on better strength development when compared to blended lime-GGBS at a 50:50 ratio. At the same time, the 30:70 mix is more economical and sustainable as it uses the more economical and sustainable GGBS relative to lime. The blended PC-GGBS, (40:60) will also be chosen, based on the cost and good strength development patterns when compared with PC-GGBS blended at a 60:40 ratio. The PC-GGBS (40:60) uses more GGBS relative to PC-GGBS at 60:40, while the performance is not compromised. Besides saving in energy, the use of GGBS to replace a traditional stabiliser such as PC or lime will reduce the production of CO_2 and its accumulation in the atmosphere.

3. For prolonged curing up to 56 days, the highest UCS values in LOC-PFA were recorded in the system stabilised using PC at 20wt% stabiliser dosage, using formula F1 (1.2OMC). The strength developments patterns were much similar for both PC-GGBS (40:60) and lime-GGBS (30:70).

4. There are little differences in strength development in general between the two formulae for both stabilised LOC and LOC-PFA as target materials for stabilization. The Formula F1 at 1.2 OMC will continue to be used for further exploration, since by raising the level of stabiliser from 10wt% to 20wt%, results indicate that those formulae with higher moisture contents achieve better strength. For both Lime and PC stabiliser systems, it was more suitable to use the formula that took care of variations in stabiliser types and dosage. Formula F1 takes into account any variations in stabiliser dosage. By using 1.2 OMC as opposed to OMC, prolonged strength gain is ensured, coupled with low linear expansion magnitudes.

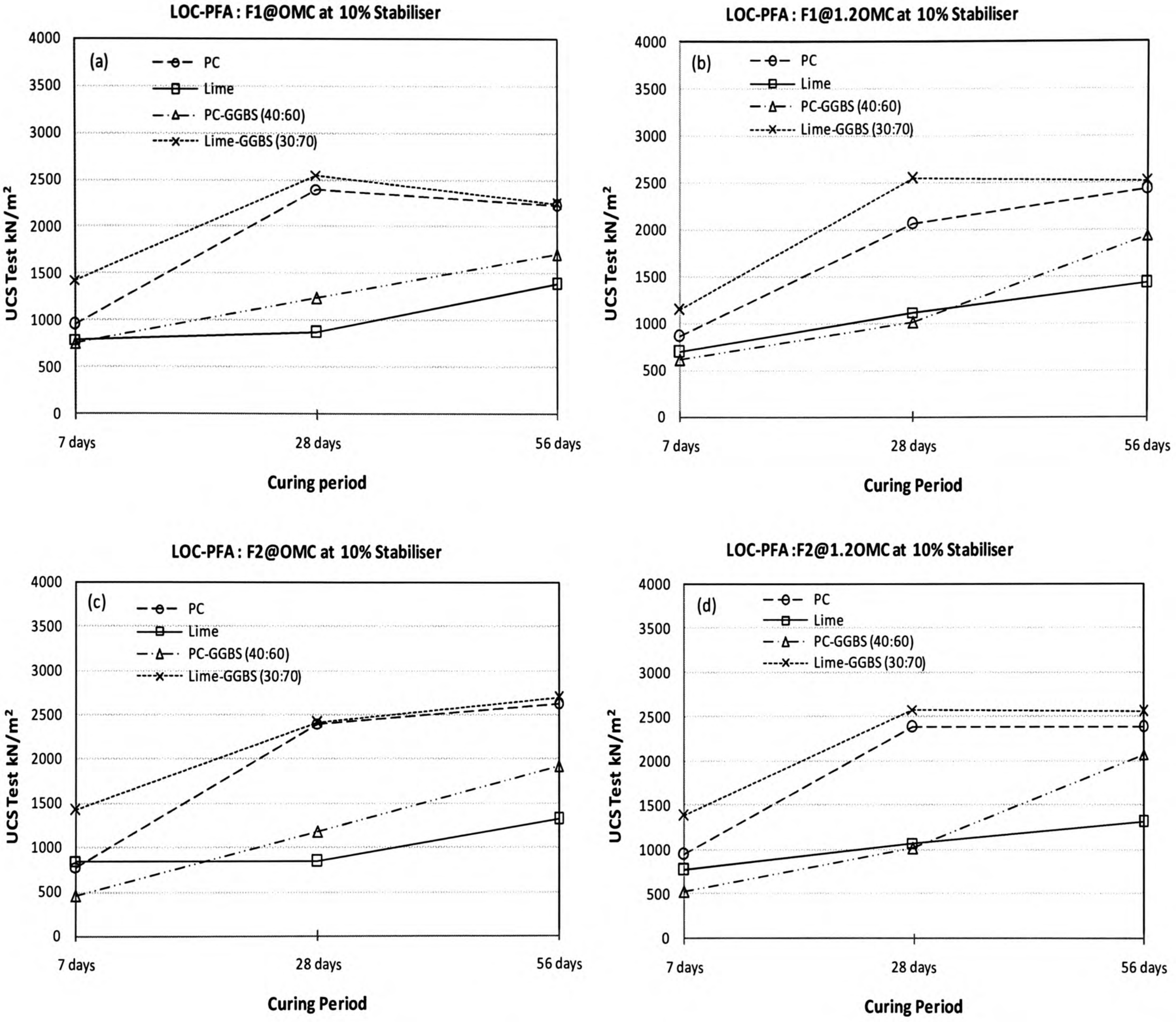


Figure 5.4-7(a-d): Stabilised LOC-PFA with 10wt% stabiliser dosage using different method of calculating compaction moisture content

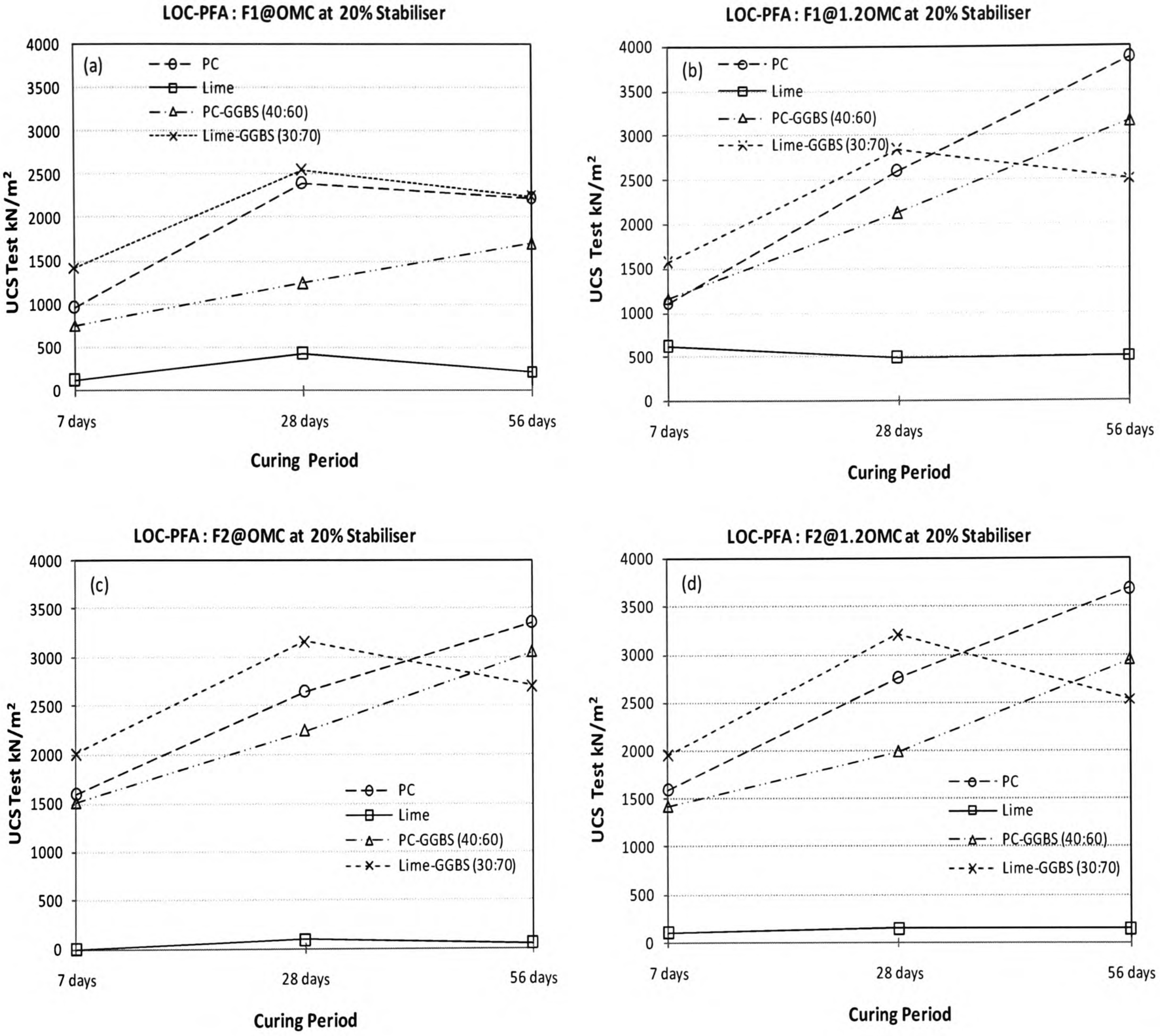


Figure 5.4-8(a-d): Stabilised LOC-PFA with 20wt% stabiliser dosage using different method of calculating compaction moisture content

5.5 DURABILITY TEST

For durability test, only specimens from blended LOC-PFA (50:50) were tested. This was based on the results from UCS tests, which shown blended LOC-PFA has better strength values, when compared to LOC alone. This section presents data concerning the effects of lime, PC and the blended stabilisers incorporating GGBS – lime-GGBS at (30:70) and PC-GGBS at (40:60) - on the durability of the target materials, LOC-PFA (50:50). Both blended stabilisers were chosen based on higher strength performance during UCS tests, and in consideration of their sustainability and economic potential. The test specimens were made by compacting stabilised mixtures into cylinder form in the same way as the UCS test specimens. As stated earlier, compaction was carried out at OMC and at 1.2OMC values at both 10wt% and 20wt% of stabiliser dosages. All the stabilised specimens were cured for 7, 28 and 56 days at room temperature and prior to fully soaking in water for 4 days. Linear expansion was monitored on a daily basis during the 4 days of soaking.

5.5.1 Durability Index

a) LOC-PFA in Lime System

Figures 5.5-1(a) and (b) illustrate the durability index (DI) of the LOC-PFA mixture stabilised with the lime-based binders at 10wt% and 20wt% stabiliser dosages. Figure 5.5-1(a) shows the durability index of the LOC-PFA mixture when stabilised with lime only and the lime-GGBS (30:70) blended at 10wt% of stabiliser, specimens were cured for 7, 28 and 56 days and then were fully soaked in the water for 4 days. The durability index was established as explained in section 4.6.2.2. The overall results show that at 10wt% stabiliser dosage, there is a slight increase in the DI patterns from 7 days to 56 days of curing, with all of the formulae used for both stabilisers. In general, the DI of the stabilised LOC-PFA mixture using lime only demonstrates higher values of DI when compared to the values for LOC-PFA mixture stabilised with the blended lime-GGBS (30:70) stabiliser at all ages.

For 7 days of curing at 10wt% stabiliser dosage (Fig 5.5-1(a)), the highest DI value achieved was 159% when the LOC-PFA mixture was stabilised with lime only, using formula F1@1.2OMC. The lowest reading was 85% when the LOC-PFA mixture was stabilised with lime-GGBS at (30:70) using formula FI@OMC. For 28 days of curing, formula FI@OMC recorded the highest DI value at 173% when LOC-PFA stabilised with lime only. As happened for the 7 days curing, the lowest DI value was recorded (75%). when LOC-PFA was stabilised with blended lime-GGBS (30:70) using formula FI@OMC.

For 56 days of curing, the highest DI value was again recorded when the LOC-PFA was stabilised with lime only using formula F2@1.2OMC at 198%, and the lowest DI value was 94%, observed with blended lime-GGBS at (30:70) ratio using formula F1@1.2OMC.

At 20wt% stabiliser dosage (Fig. 5.5-(b)), for 7 days of curing, specimens with both formula F2@OMC and F2@1.2OMC collapsed when lime only was used to stabilise the LOC-PFA mixture. This was probably due to the high lime dosage, which lead to incomplete lime hydration due to lack of adequate water (Nidzam, 2004). The highest DI value was 142% achieved with the blended lime-GGBS (30:70) for stabilise action of the LOC-PFA, using formula FI@OMC. For 28 days curing, there are small differences in DI reading for both stabilisers with all formulae of calculating compaction moisture content, from 75% to 111% which, is the highest percentage was recorded with lime-GGBS (30:70) with formula F1@1.2OMC and the lowest with same stabiliser but this time with formula F2@OMC.

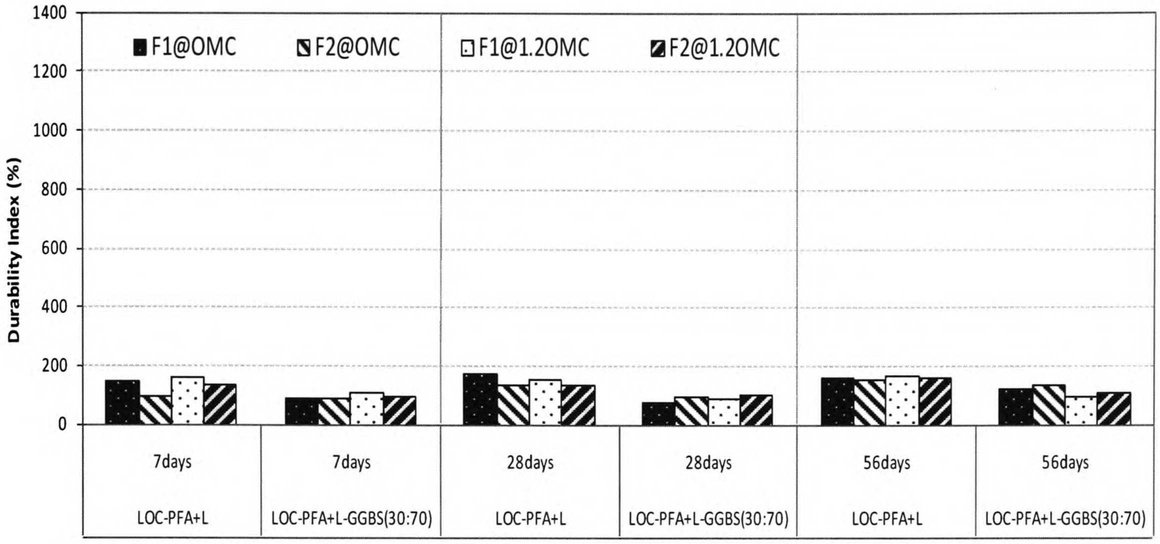
For 56 days of curing, there are obvious differences in DI when lime only was used to stabilised LOC-PFA mixture, compared to DI at 7 and 28 days. At this stage with lime only, formulae F2@OMC and F2@1.2OMC showed higher DI value compared to formulae FI@OMC and F1@1.2OMC. Highest DI was recorded at 1329% with formulae F2@OMC (see Figure 5.5-1 (b)). However, when blended lime-GGBS (30:70) was used to stabilise LOC-PFA mixture, results showed there was slightly increased in

DI when compared to DI at 7 and 28 days, with all formulae of calculating compaction moisture content.

Summary Observations:

- At 10wt% stabiliser content, there is little difference in DI between the two stabilisers at all aging.
- At 20wt% stabiliser content, lime only shows higher DI compared to blended lime-GGBS (30:70) at 56 days curing, with dramatic increased when compared to DI at 28 days.
- Little variable between F1 and F2, OMC and 1.2OMC, except for lime only at 56 days.

(a) 10% Stabiliser



(b) 20% Stabiliser

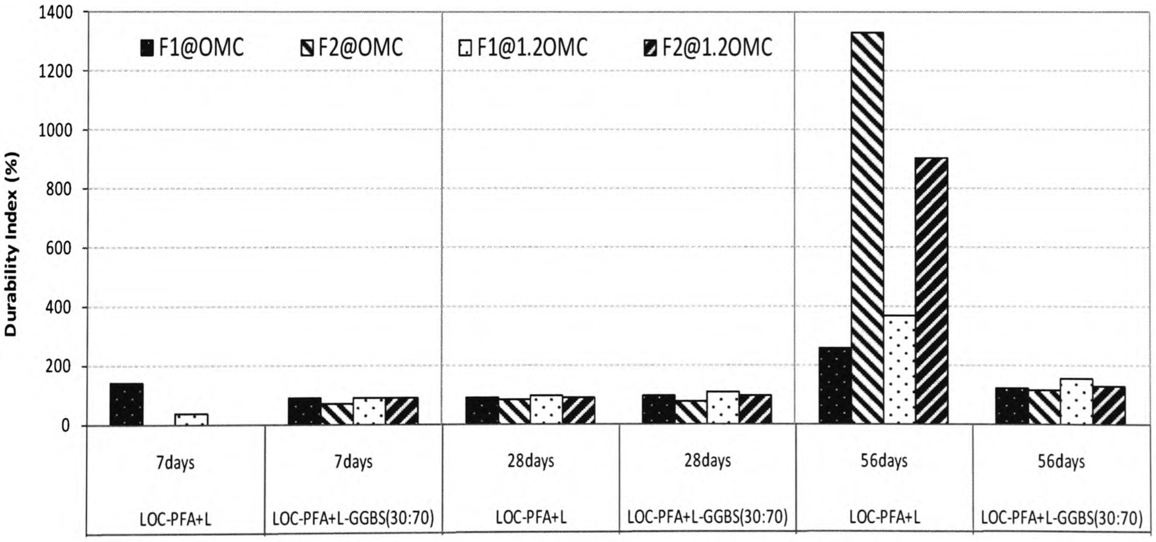


Figure 5.5-1: Durability Index of LOC-PFA stabilised with lime and lime-GGBS (30:70) at (a) 10wt% (b) 20wt% stabiliser dosages

b) LOC-PFA in PC System

Figures 5.5-2(a) and (b) illustrate the durability index (DI) of the LOC-PFA blend, stabilised with the PC-based stabilisers at 10wt% and 20wt% of stabiliser dosages. Figure 5.5-2(a) shows the durability index of the LOC-PFA when stabilised with PC only and with PC-GGBS (40:60) at 10wt% stabiliser dosage, stabilised specimens were cured for 7, 28 and 56 days, before fully soaking in water for 4 days.

At 10wt% of stabiliser dosage (Figure 5.5-2(a)), for 7 days curing, the overall result showed that LOC-PFA stabilised with PC only recorded higher DI values compared to LOC-PFA stabilised with the blended PC-GGBS stabiliser at (40:60) ratio, except when formula F2 was applied at 1.2OMC. This formula recorded the highest DI value at 253% with the blended PC-GGBS (40:60) stabiliser. The lowest DI value at this stage was 40% recorded when LOC-PFA was stabilised with blended PC-GGBS (40:60) using formula F2@OMC. There are changes in the DI pattern for 28 days curing compared to 7 days. In general, results show that a higher DI value was recorded when LOC-PFA was stabilised with the blended PC-GGBS (40:60) stabiliser using all formulae compared to PC only. With the highest DI value was 182% using formula F2@1.2OMC and the lowest was 61% when LOC-PFA was stabilised with PC only using formula F2@OMC.

In general, similar DI pattern was observed for 56 days of curing as for 28 days. However, curing for 56 days demonstrated overall lower DI value compared to 28 days curing with both stabilisers and with all formulae of calculating compaction moisture content. At this stage, the highest DI value at 100% was recorded when PC-GGBS (40:60) was used to stabilise the LOC-PFA mixture, using formula F1@1.2OMC. This formula also recorded the lowest DI value at 53% when LOC-PFA was stabilised with PC only using formula F2@1.2OMC to calculate the amount of water.

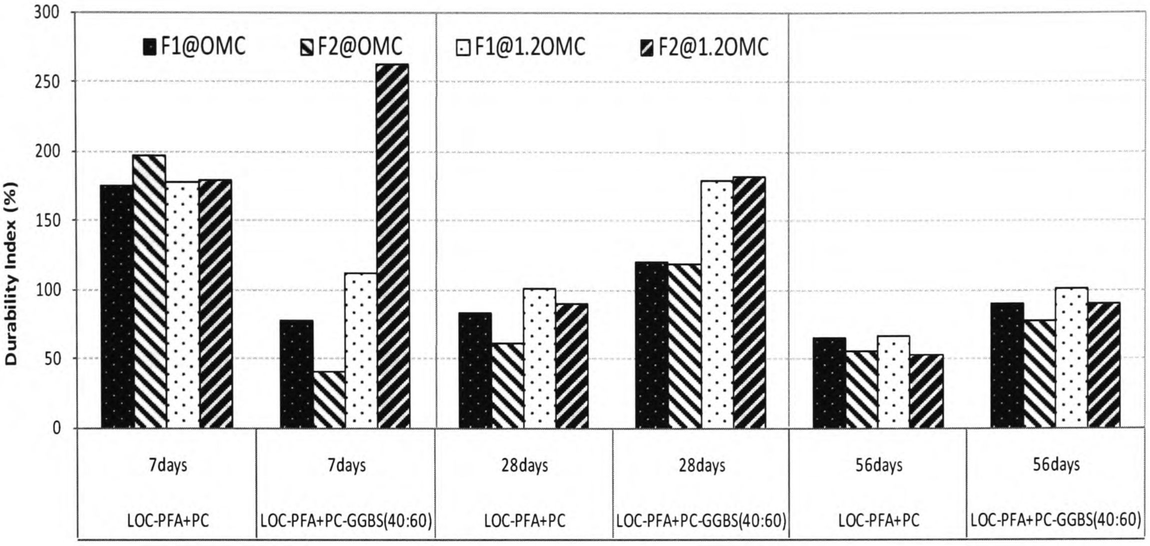
At 20wt% stabiliser dosage (Fig. 5.5-2(b)), for 7 days of curing, the overall results showed, that when PC only was used to stabilise the LOC-PFA blend, higher DI values was observed when compared to the use of the blended stabiliser PC-GGBS (40:60), with all formulae of calculating compaction moisture content. At this stage, the highest DI value (201%) was recorded when PC only was used with formula F1@1.2OMC and the lowest was recorded at 67% when LOC-PFA was stabilised with PC-GGBS (40:60) with formula FI@OMC. For 28 days of curing, in general, PC-GGBS (40:60) recorded higher DI value when compared to PC only with all formulae for calculating compaction water content. The highest DI value (140%) was recorded with PC-GGBS (40:60) using formula FI@OMC and the lowest value was 80% when stabilised with PC only with formula F2@OMC.

As with the 10wt% stabiliser dosage, at 20wt% and 56 days curing, the overall DI value was lowered when compared to DI values for both 7 and 28 days of curing with all formulae. For 56 days of curing, significantly lower in DI values were observed relative to those observed for 28 days, with both stabilisers with all formulae. Formula F2@1.2OMC demonstrated the highest DI value at 96% with PC-GGBS (40:60), whereas the lowest DI was 53% observed when LOC-PFA was stabilised with PC only, using the formulae with least water (F2@OMC).

Summary Observations:

- At 10wt% stabiliser content, there was decreased in DI at 56 days compared to DI at 7 and 28 days with both stabilisers.
- At 20wt% stabiliser content, both stabilisers show decreased in DI at 56 days curing when compared to DI at 7 and 28 days.
- Marginally higher DI at 1.2OMC compared to OMC with both formulae, F1 and F2.

(a) 10% Stabiliser



(b) 20% Stabiliser

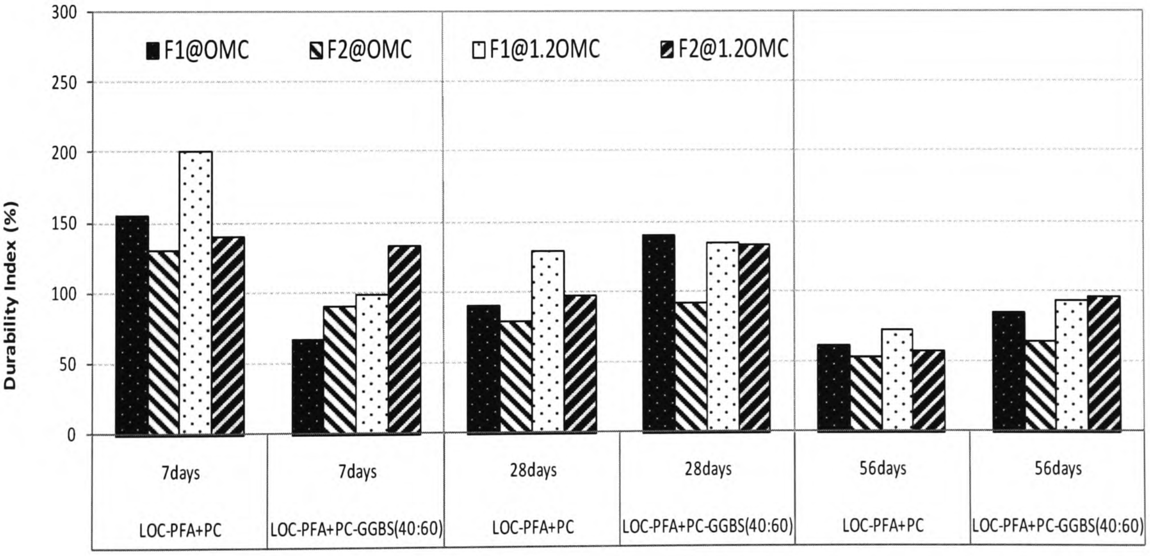


Figure 5.5-2: Durability Index of LOC-PFA stabilised with PC and PC-GGBS blends at (a) 10wt%, (b) 20wt% stabiliser dosages

5.5.2 Change in weight upon soaking

a) LOC-PFA mixture stabilised with Lime-based Stabilisers

Figures 5.5-3(a) to (d) illustrate the percentage of weight increase for stabilised specimens for the lime-based system of stabilised LOC-PFA at 10wt% and 20wt% of stabiliser dosages. Stabilised specimens were cured for 7, 28 and 56 days, before each being fully soaked in the water for 4 days. Each specimen was then weighed at day 4, before the UCS test was carried out.

At 10wt% of stabiliser dosage, using lime only (Figure 5.5-3(a)) for 28 days curing there were slightly an increased in the weight gain due to fully soaked in water for both formulae (Fl@OMC and F2@1.2OMC) compared to 7 days of curing. All formulae showed decreased in weight gain for 56 days when compared 28 days of curing. On the other hand, for the blended lime-GGBS (30:70) (Figure 5.5-3(b)) all the specimens showed decreased in weight gain at 28 days of curing compared to weight increase at 7 days of curing. With lime-GGBS (30:70) all formulae showed no weight increase from 28 days to 56 days of curing.

At 7 days, the highest weight increase was lime stabilised LOC-PFA with formula F2@OMC (12%) (Figure 5.5-3(a)) and the lowest was 5% when LOC-PFA was stabilised with lime only with formulae F1@1.2OMC (Figure 5.5-3(a)). For 7 and 28 days, lime stabilised LOC-PFA shows higher increase in weight compared to blended lime-GGBS (30:70). For 56 days (Fig. 5.5-3(a) and (b)), almost a similar weight increase was showed when both lime only and the blended lime-GGBS at (30:70) ratio were used as stabiliser. The highest reading was 7%, recorded when LOC-PFA was stabilised with both stabilisers with formula F2@OMC. The lowest reading was 3% with formula F1@1.2OMC with both stabilisers.

Figure 5.5-3(c) and (d) show the weight increase in specimens at 20wt% of stabiliser dosage. The overall results showed there were higher weight increase compared to the one at 10wt% dosage with both stabilisers (Lime only and lime-GGBS (30:70)) used at all method of calculating compaction moisture content. For 7 days curing, it illustrates that specimens with lime only stabilised LOC-PFA with 2 formulae of calculating compaction water content totally collapsed (F2@OMC and F2@1.2OMC). On the other hand formulae F2@OMC and F2@1.2OMC have shown higher weight increase compared to all formulae of calculating compaction moisture content when LOC-PFA was stabilised with blended stabiliser lime-GGBS (30:70) for 7 days of curing(Fig. 5.5-3(d)).

For 7 days of curing, the highest weight increase was 23% with lime only with formulae FI@OMC and the lowest was 6% with blended lime-GGBS (30:70) stabilised LOC-PFA with formula F1@1.2OMC. For 28 days curing (Fig. 5.5-3(c)), lime only recorded higher weight increase compared to blended lime-GGBS (30:70) with all formulae (Fig. 5.5-3(d)), and also when compared to 10wt% dosage with all calculated formulae (Fig. 5.5-3(a) and (b)) with both stabilisers. For 56 days, it illustrates that, there are decreased in weight gain for both stabilisers with all formulae compared to results recorded for the 28 days. The highest reading was 11% when lime only stabilised LOC-PFA with formula F2@OMC and the lowest was 4% recorded by both stabilisers with formula FI@OMC.

Summary Observations:

- At 10wt% stabiliser content, there was decreased in weight with both stabilisers with all formulae for 56 days curing compared to weight increase for 7 and 28 days.
- At 20wt% stabiliser content, for 28 day curing, lime stabilised LOC-PFA showed higher weight increase compared to curing periods for both stabilisers.
- Marginally higher weight increase at OMC compared to 1.2 OMC with both formulae, F1 and F2.

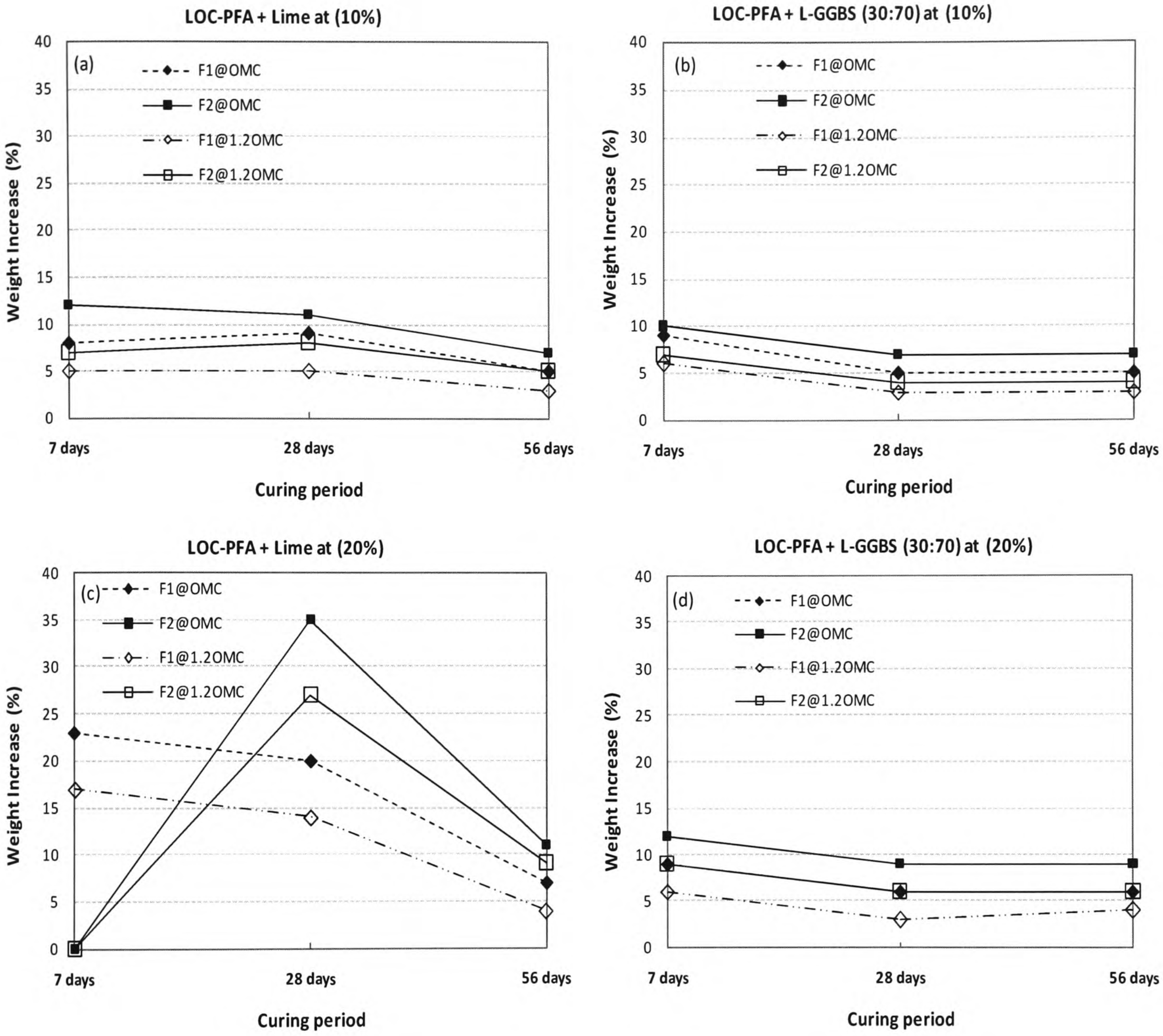


Figure 5.5-3: Increased in weight of stabilised LOC-PFA with lime system (a) 10wt% lime only (b) 10wt% lime-GGBS (30:70) (c) 20wt% lime only (d) 20wt% lime-GGBS (30:70)

b) LOC-PFA mixture Stabilised with PC-based Stabilisers

Figures 5.5-4(a) to (d) illustrate the percentage of weight increase for stabilised specimens from the PC based system, for LOC-PFA stabilised at 10wt% and 20wt% of stabiliser dosages. Stabilised specimens were cured for 7, 28 and 56 days and each was fully soaked in water for 4 days. Each specimen was weighed at day 4, before the UCS test was carried out.

Figures 5.5.4(a) and (b) demonstrate the pattern of weight increased for LOC-PFA stabilised with PC only and blended PC-GGBS (40:60) at 10wt% stabiliser dosage with all formulae of calculating compaction water content. At 10wt% stabiliser dosage formula with less water content F2@OMC illustrated higher weight increase compared to others formulae at all curing periods, except for 7 days curing, which demonstrated the lowest weight increase at 2%. The highest reading for 7 days was when LOC-PFA stabilised with blended PC-GGBS (40:60) with formula F2@OMC (Fig. 5.5-4(b)). For 28 days curing, the highest weight increased was 8% with PC-GGBS (40:60) with formula F2@OMC. The lowest was 2% with formula F1@1.2OMC with PC-GGBS at (40:60) ratio. For 56 days curing, the overall results showed, blended PC-GGBS (40:60) stabilised LOC-PFA demonstrated lower weight increase compared to PC stabilised LOC-PFA with all formulae of calculating compaction moisture content. The highest reading recorded was 8% when LOC-PFA stabilised with PC only with formula F2@OMC, and the lowest was 2% with blended PC-GGBS at (40:60) ratio with formula F1@1.2OMC.

Figure 5.5-4(c) and (d) show the weight increase in specimens at 20wt% of stabiliser dosage. Like in the lime system and PC based system at 10wt% stabiliser dosage, at 20wt% dosage, the formula with less water content F2@OMC illustrated higher weight increase compared to others formulae at all curing period. For 7 days curing, highest increased in weight was 8% with both stabilisers with formula F2@OMC. The lowest was 2% when LOC-PFA was stabilised with PC only with formula F1@1.2OMC. For 28 days, formula F2@OMC indicated highest weight increase at 9% when PC was used as the stabiliser. F1@1.2OMC recorded the lowest reading at 2% when LOC-PFA was stabilised with blended PC-GGBS at 40:60 ratio (Fig. 5.5-4(d)). For 56 days, the highest weight increased was 10% with formula F2@OMC when LOC-PFA was stabilised with PC only and the lowest was 3% with formula F1@1.2OMC when blended PC-GGBS (40:60) was used to stabilise LOC-PFA.

In general, in contrast with the lime system, in this PC based system the weight increase are lower with both stabilisers at 20wt% stabiliser dosage compared to at 10wt% dosage with all formulae of calculating compaction moisture content, except for formula F1@1.2OMC with PC only.

Summary Observations:

- At 10wt% stabiliser content, with PC only it shows higher weight increase for 7 days curing compared to both 28 and 56 days of curing, whereas with blended PC-GGBS
- Weight increase reduced with the increase in the curing period.
- At 20wt% stabiliser content, formula with least water content F2@OMC showed higher weight increase with both stabilisers at all curing period compared to all others formulae.

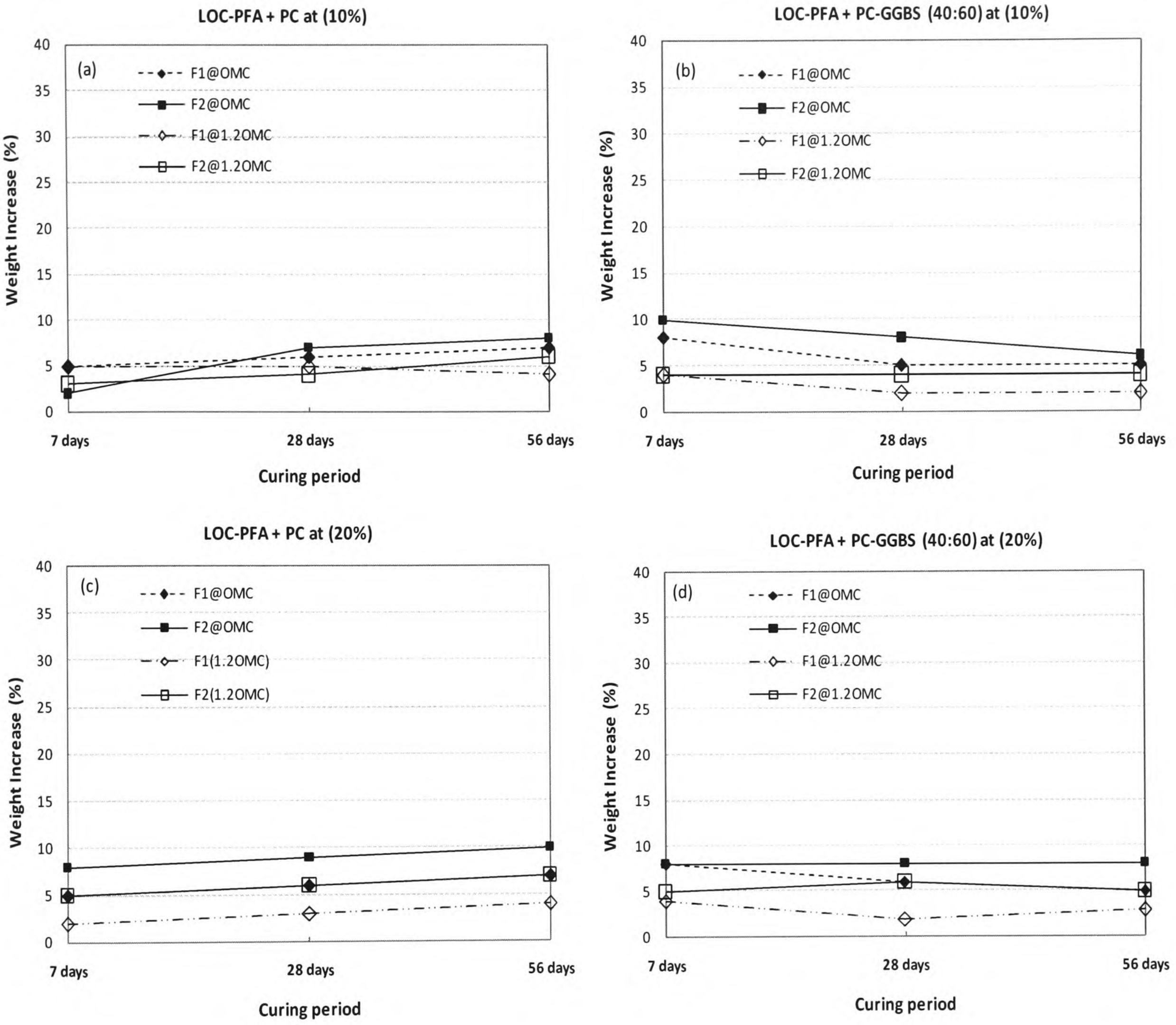


Figure 5.5-4: Increased in weight of stabilised LOC-PFA with PC system (a) at 10wt% PC only (b) at 10wt% PC-GGBS (40:60) (c) at 20wt% PC only (d) at 20wt% PC-GGBS (40:60)

5.5.3 Linear Expansion of LOC-PFA stabilised using Lime based binders

a) After Curing for 7 days

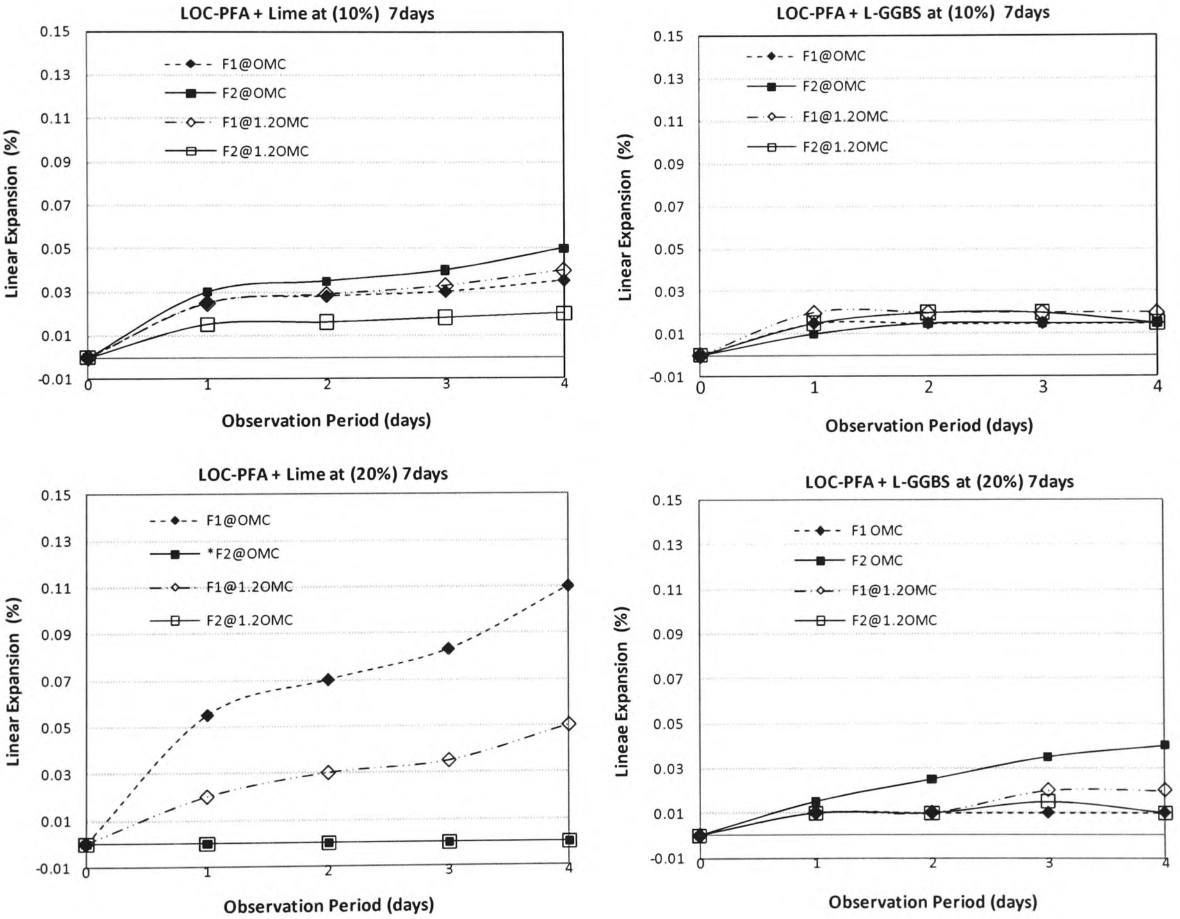
Figures 5.5-5(a) to (d) illustrate the linear expansion of the LOC-PFA stabilised with the lime-based system at 10wt% and 20wt% of stabiliser dosage. Specimens were cured for 7 days at room temperature prior to fully soaking in water for 4 days, two specimens were tested for each type of stabiliser and each formula of calculating compaction moisture content at OMC and 1.2OMC, the linear expansion was monitored on a daily basis during the 4 days of soaking.

Figures 5.5-5(a) and (b) show the linear expansion of the LOC-PFA stabilised with lime only and with blended lime-GGBS (30:70) at 10wt% of stabiliser dosage after 7 days curing. The overall monitoring showed that there were only small magnitudes of linear expansion occurred for 7 days curing. Lime stabilised LOC-PFA demonstrated higher expansion rate compared to that stabilised using lime-GGBS at 30:70 ratio with all formulae of calculating compaction moisture content. The highest expansion was shown by formula F2@OMC with the highest linear expansion value of 0.05%, recorded after the 4 days of soaking. In general, the lowest expansion was shown by formula F2@OMC when blended lime-GGBS (30:70) was used as the stabiliser (see. Fig.5.5-5(b)).

At 20wt% of stabiliser dosage (Figures 5.5-5(c) and (d)), the overall results showed that, there were higher expansion magnitude compared to those at 10wt% stabiliser dosage. However, when LOC-PFA was stabilised using lime and adopting formulae F2@OMC and F2@1.2OMC, both specimens collapsed. The highest expansion was 0.11% at day 4 of soaking, when LOC-PFA was stabilised with lime only with formula Fl@OMC. The overall pattern showed that, there was an increased in the linear expansion from the day 1 until day 4 of soaking with both stabilisers with all methods of calculating compaction moisture content. In general, the overall expansion magnitudes were lower with blended lime-GGBS (see Fig. 5.5-5(d)) when compared to LOC-PFA stabilised with lime only.

Summary Observations:

- At 10wt% stabiliser content, with Lime only it shows higher linear expansion magnitudes compared to those with blended lime-GGBS (30:70) with all formulae at OMC and I.2OMC.
- At 20wt% stabiliser content, both stabilisers showed higher linear expansion magnitudes compared to those at 10wt% stabiliser dosage.
- At 20wt%, LOC-PFA stabilised with lime only using formula F1 at both OMC and 1.2OMC were totally collapsed



F2@OMC - Specimens collapsed

F2@1.2OMC-Specimens collapsed

Figure 5.5-5: Linear Expansion stabilised of LOC-PFA blended material stabilised using (a) Lime only@10wt% (b) lime-GGBS (30:70)@10wt% (c) Lime only@20wt% (d) lime-GGBS (30:70)@20wt%, during soaking in water after being moist-cured for 7 days

b) After Curing for 28 days

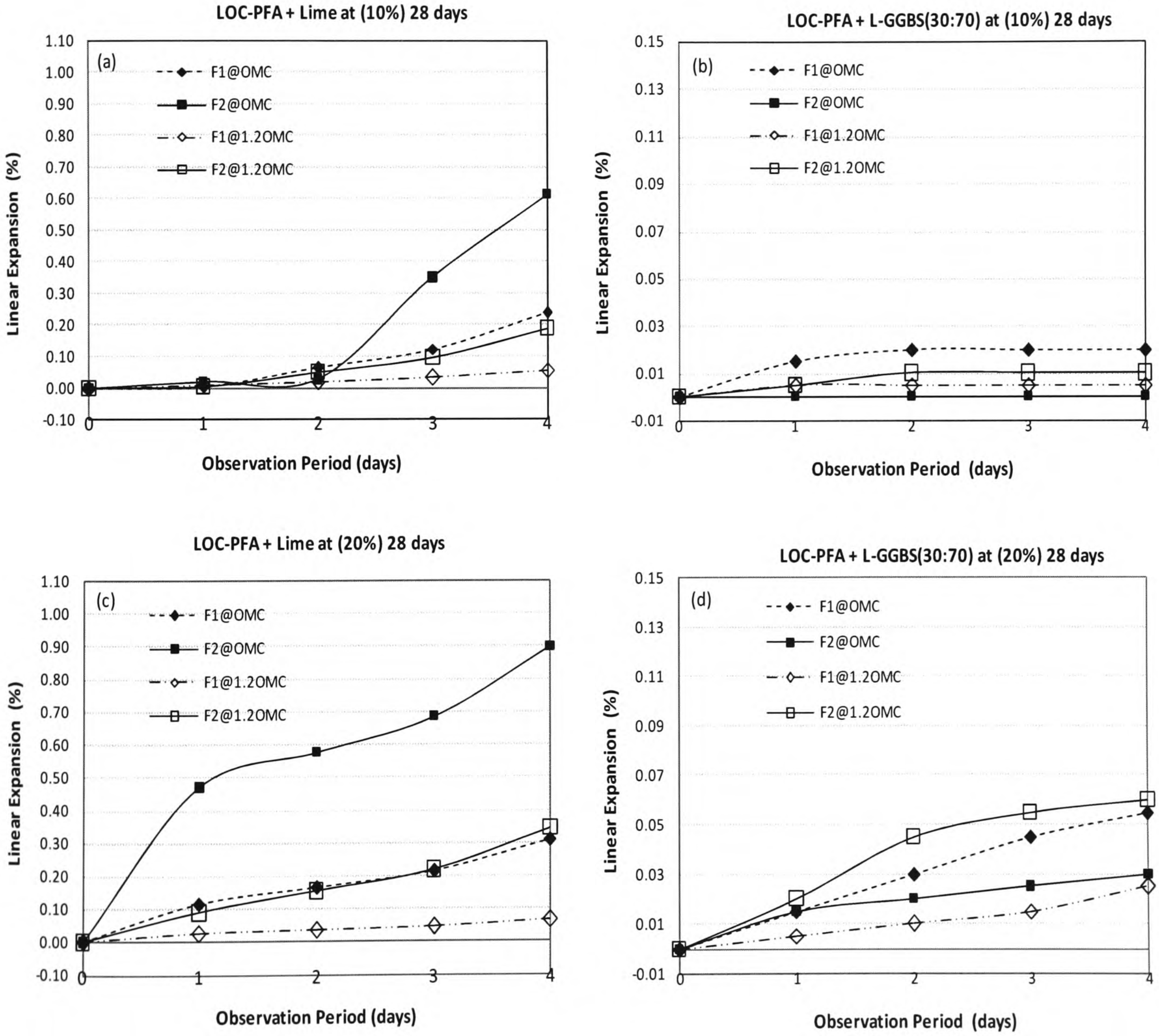
Figures 5.5-6(a) to (d) illustrate the linear expansion of the LOC-PFA stabilised with lime-based stabilisers at 10wt% and 20wt% of stabiliser dosage. Specimens were cured for 28 days at room temperature, to fully soaking in water for 4 days, where the linear expansion was monitored on a daily basis during the 4 days of soaking.

At 10wt% stabiliser dosage (see Fig. 5.5.6-(a) and (b)), the overall pattern demonstrates that the lime stabilised LOC-PFA recorded higher expansion compared to that recorded on the blended lime-GGBS (30:70). Highest expansion was observed when lime only was used to stabilise the LOC-PFA blend, with formula F2@OMC, where the expansion started after day 2 of soaking until it reach the highest magnitude of 0.60% at day 4. On the other hand, with blended lime-GGBS (30:70) stabiliser, the LOC-PFA stabilised based on formula F2@OMC recorded no expansion at all ages (Fig. 5.5.6-b)).

At 20wt% stabiliser dosage (see Fig. 5.5-6(c) and (d)), the overall results demonstrate that lime only stabilised LOC-PFA showed higher expansion magnitudes compared to using blended lime-GGBS (30:70), with all formulae of calculating compaction moisture content. The overall expansion at 20wt% was higher compared with the one shown at 10wt% of stabiliser dosage, for both lime-based stabilisers. Again, at this stage formula F2@OMC demonstrated the highest expansion when lime only was used to stabilise LOC-PFA. The highest reading of 0.09% expansion was recorded at day 4(see Fig. 5.5-6(c)). The overall results have shown, that for blended lime-GGBS stabilised LOC-PFA, the expansion magnitudes recorded were generally below 0.07%, with lowest expansion being demonstrated by blended lime-GGBS stabilised LOC-PFA with formula FI (1.2OMC).

Summary Observations:

- At 10wt% stabiliser content, with Lime only it shows higher linear expansion magnitudes compared to those with blended lime-GGBS (30:70) with all formulae at OMC and I.2OMC.
- At 20wt% stabiliser content, both stabilisers showed higher linear expansion magnitudes compared to those at 10wt% stabiliser dosage.


LOC-PFA + Lime at (10%) 28 days

LOC-PFA + L-GGBS(30:70) at (10%) 28 days

LOC-PFA + Lime at (20%) 28 days

LOC-PFA + L-GGBS(30:70) at (20%) 28 days

Figure 5.5-6: Linear Expansion stabilised of LOC-PFA blended material stabilised using (a) Lime only@10wt% (b) lime-GGBS (30:70)@10wt% (c) Lime only@20wt% (d) lime-GGBS (30:70)@20wt%, during soaking in water after being moist-cured for 28 days

b) After Curing for 56 days

Figures 5.5-7(a) to (d) shows the linear expansion of the LOC-PFA stabilised with the lime system at 10wt% and 20wt% stabiliser dosages, with two stabilisers involved - lime only and blended lime-GGBS at (30:70) ratio. The specimens were first cured for 56 days at room temperature, prior to fully soaking in water for 4 days. Linear expansion was monitored on a daily basis during the 4 days of soaking.

Figure 5.5-7(a) and (b) shows the linear expansion of the LOC-PFA when stabilised with lime only and lime-GGBS (30:70) at 10wt% stabiliser dosage. In general, there are significant decreases in expansion magnitudes for lime only stabilised LOC-PFA compared to the values recorded for the 28 days cured specimens (see figure 5.5-6(a)) with all formulae of calculating compaction moisture content. The lime stabilised LOC-PFA demonstrated higher expansion values compared to those stabilised using lime-GGBS at 30:70 ratio, with all formulae. The highest expansion was shown by formula F2@OMC with blended lime-GGBS (30:70), with the highest reading just below 0.07% (Fig. 5.5-7(b)). When lime only was used to stabilise LOC-PFA, there was no increase in expansion from day 2 to day 4 (see Fig. 5.5-7(a)). The lowest expansion was demonstrated by blended lime-GGBS (30:70) with formula F2@1.2OMC, with overall reading below 0.01% (see Fig. 5.5-7(b)).

At 20wt% stabiliser dosage (see Fig. 5.5-7(c) and (d)), like at 10wt%, there are apparent increases in expansion for lime only stabilised LOC-PFA compared to the magnitudes recorded for the 28 days curing (see Fig. 5.5-6(c)) with all formulae of calculating compaction moisture content. At this stage, the results show that the, lime only stabilised LOC-PFA demonstrated higher expansion at day 4 of soaking, compared to lime-GGBS (30:70) with all formulae, except for formula F1@1.2OMC which recorded the lowest expansion of just below 0.01% (Fig. 5.5-7(c)). Blended lime-GGBS stabilised LOC-PFA demonstrates an almost similar pattern of expansion with all formulae, (see Fig. 5.5-7(d)), although the expansion magnitudes are lower than those for lime only stabiliser, except when formula F1@1.2OMC was used.

Summary Observations:

- At 10wt% stabiliser content, with Lime only shows higher linear expansion magnitudes compared to those with blended lime-GGBS (30:70) with all formulae except for formula F2@OMC with blended lime-GGBS (30:70).
- At 20wt% stabiliser content, both stabilisers showed higher linear expansion magnitudes compared to those at 10wt% stabiliser dosage.

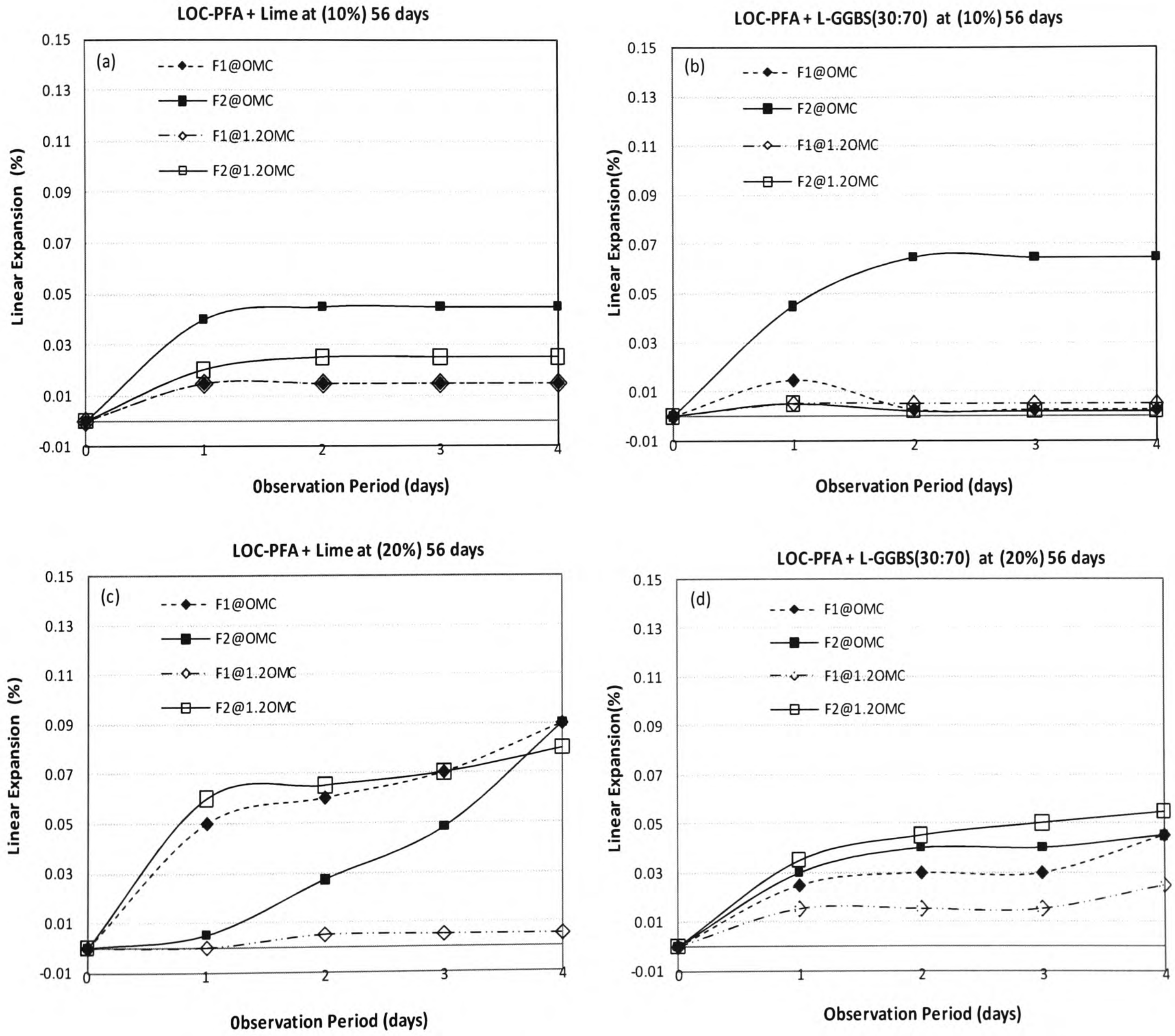


Figure 5.5-7: Linear Expansion stabilised of LOC-PFA blended material stabilised using (a) Lime@10wt% (b) lime-GGBS (30:70)@10wt% (c) Lime@20wt% (d) lime-GGBS (30:70)@20wt%, during soaking in water after being moist-cured for 56 days

5.5.4 Linear Expansion of LOC-PFA stabilised using PC based binders

a) After Curing for 7 days

Figures 5.5-8(a) to (d) illustrate the linear expansion of the LOC-PFA blended material, stabilised with the PC system at 10wt% and 20wt% stabiliser dosages. The specimens were cured for 7 days at room temperature prior to fully soaking in water for 4 days, and the linear expansion was monitored on a daily basis during the 4 days of soaking.

Figures 5.5-8(a) and (b) show the linear expansion of the LOC-PFA stabilised with - PC only and PC-GGBS (30:70) at 10wt% of stabiliser dosage. In general, there are almost similar patterns in expansion rate with both stabilisers. The overall results show that only a small expansion occurred at this stage with both stabilisers, where mostly the expansion lasted for only up to day 1 of soaking and then it started to settle from day 2 up to day 4 of soaking. However, for formula FI@OMC with PC only and formula F2@1.2OMC with blended PC-GGBS (40:60), there were no signs of expansion at all. Overall the highest expansion recorded at this stage was 0.015%, using PC only with formulae FI (1.2 OMC) and with F2@1.2OMC.

At 20wt% of stabiliser dosage (see Fig. 5.5.8-(c) and (d)), most formulae with both stabilisers showed increases in expansion compared with the 10wt% stabiliser dosage. The overall results show that PC only stabilised LOC-PFA demonstrated higher expansion values compared to blended PC-GGBS (40:60) except for formula F1@1.2OMC which indicated no sign of expansion at all (0%), (see Fig. 5.5-8(c)) . At this stage, specimen PC-stabilised LOC-PFA recorded the highest expansion at day 4, with the highest reading at 0.09% with formula FI@OMC.

Summary Observations:

- At 10wt% stabiliser content, small linear expansion magnitudes with both PC-based stabilisers with all formulae of calculating compaction moisture content.
- At 20wt% stabiliser content, overall results showed there are higher linear expansion magnitudes when PC only been used as stabiliser compared to blended PC-GGBS (40:60).

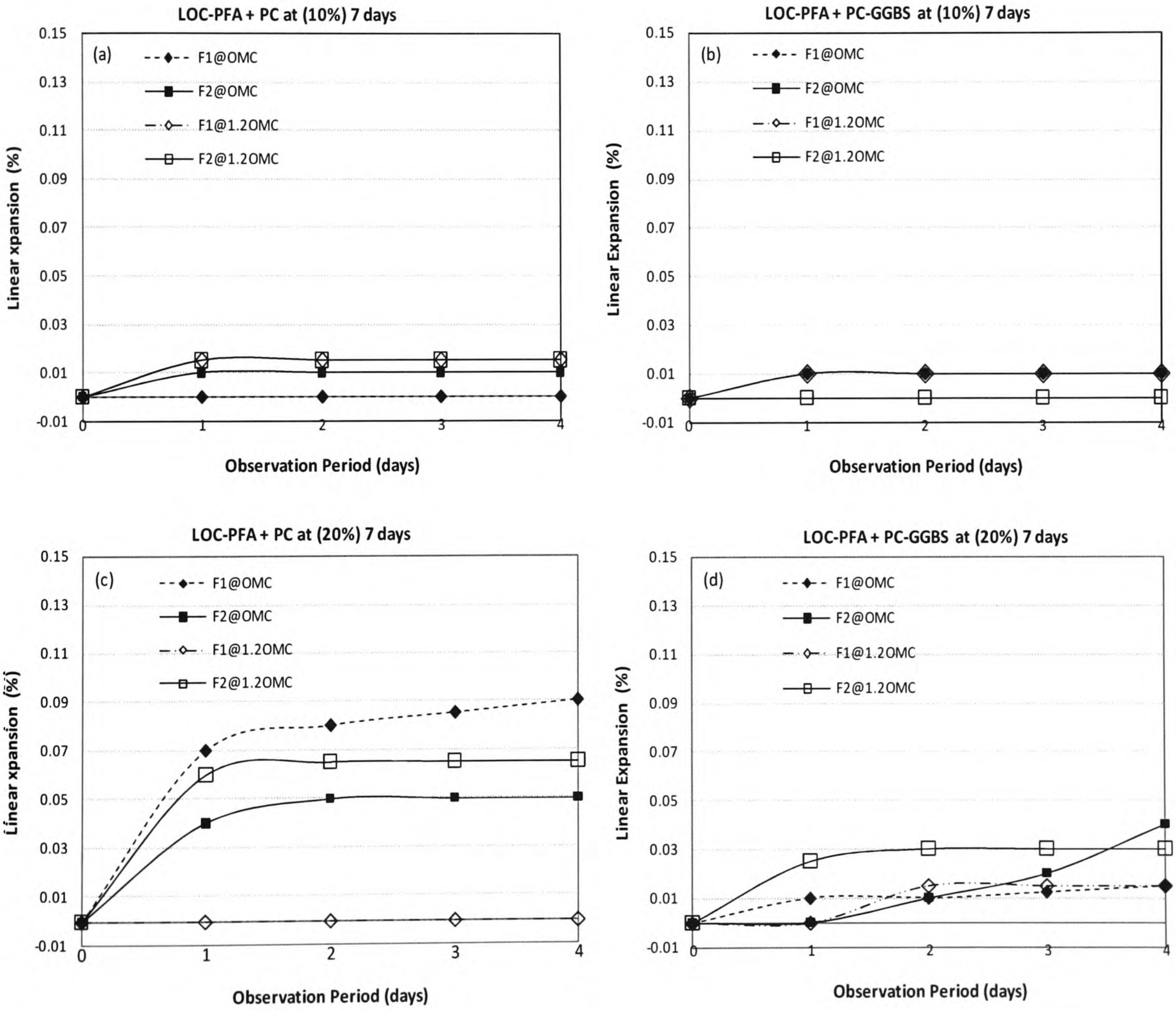


Figure 5.5-8: Linear Expansion stabilised of LOC-PFA blended material stabilised using (a) PC@10wt% (b) PC-GGBS (40:60)@10wt% (c) PC@20wt% (d) PC-GGBS (40:60)@20wt%, during soaking in water after being moist-cured for 7 days

b) After Curing for 28 days

Figures 5.5-9(a) to (d) shows the linear expansion of the LOC-PFA blended stabilised with the PC system, at 10wt% and 20wt% of stabiliser dosages. Specimens were cured for 28 days at room temperature prior to fully soaking in water for 4 days. The linear expansion was monitored on a daily basis during the 4 days of soaking.

Figures 5.5-9(a) and (b) show the linear expansion of the PC system at 10wt% of stabiliser dosage. At this stage, the overall results show that, there was higher expansion when blended PC-GGBS (40:60) was used to stabilise LOC-PFA compared to using PC only with most of formulae of calculating compaction moisture content. The highest expansion was shown by formula F2@OMC, when PC-GGBS (40:60) was used to stabilise LOC-PFA. However, the overall expansion readings were all below 0.03%.

At 20wt% of stabiliser dosage (see Fig. 5.5-9(c) and (d)), there was a contrasting expansion pattern compared to the one at 10wt% of stabiliser dosage. The PC only stabilised LOC-PFA showed much higher expansion magnitudes compared to the blended PC-GGBS stabiliser. When PC only stabiliser was used with formula F2@OMC, there was significant expansion during the first 2 days of soaking, and continued to increase up to day 4. The highest reading was recorded at 0.15% (see Fig. 5.5-9(c)).

Summary Observations:

- At 10wt% stabiliser content, the LOC-PFA stabilised with PC-GGBS (40:60) showed higher linear expansion magnitudes compared with PC only.
- At 20wt% stabiliser content, higher linear expansion was observed when PC was used as stabiliser using formula F2@OMC.

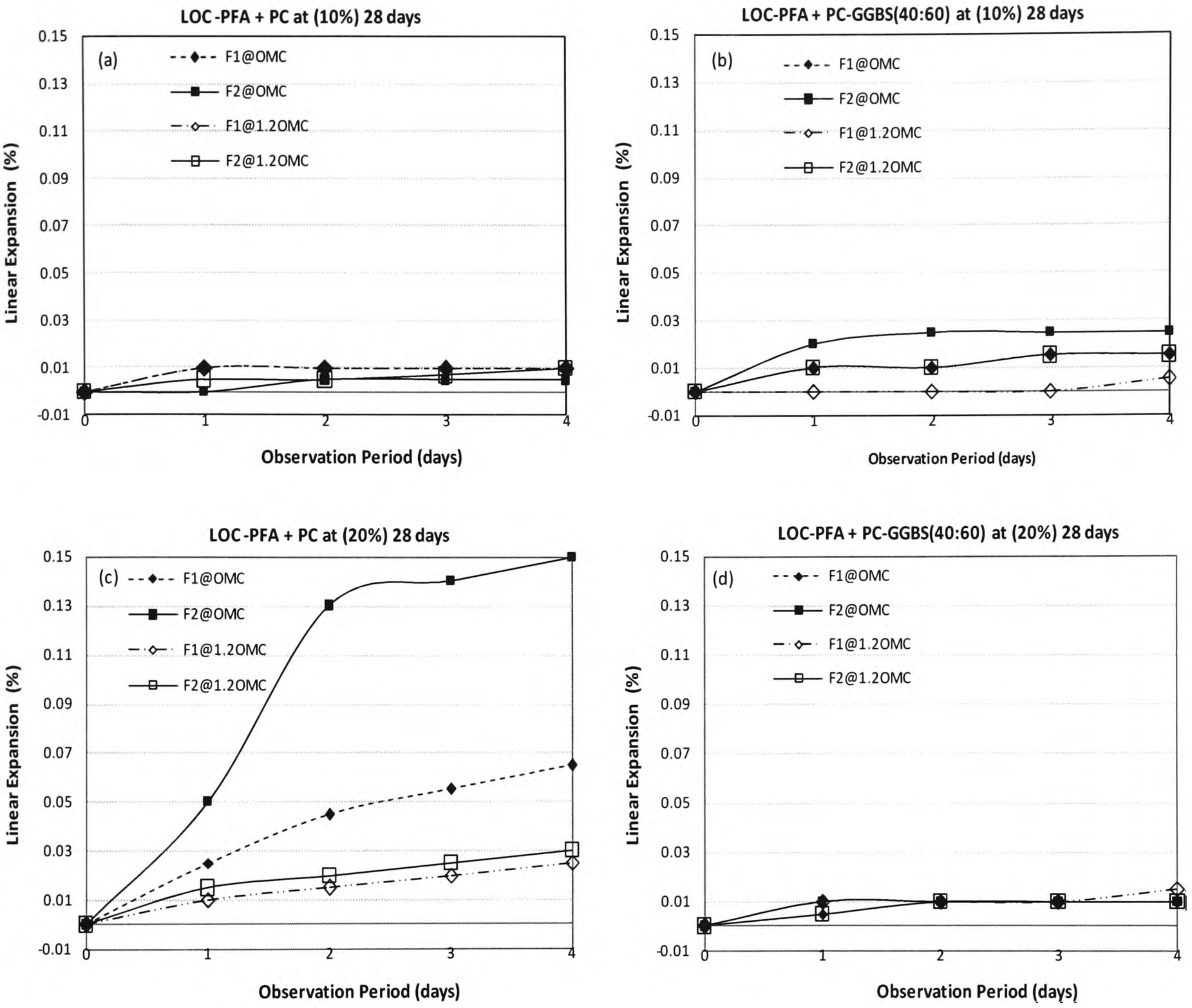


Figure 5.5-9: Linear Expansion stabilised of LOC-PFA blended material stabilised using (a) PC@10wt% (b) PC-GGBS (40:60)@10wt% (c) PC@20wt% (d) PC-GGBS (40:60)@20wt%, during soaking in water after being moist-cured for 28 days

c) After Curing for 56 days

Figures 5.5-10(a) to (d) show the linear expansion of the LOC-PFA blended material after stabilizing with the PC-based system at 10wt% and 20wt% of stabiliser dosage. Two stabilisers involved were PC only and a PC-GGBS blend at (40:60) ratio. Specimens were cured for 56 days at room temperature prior to fully soaking for 4 days, where the linear expansion was monitored on a daily basis during the 4 days of soaking.

Figure 5.5-10(a) and (b) show the linear expansion of the LOC-PFA when stabilised at 10wt% stabiliser dosage. In general, there was almost a similar pattern in expansion as the one shown at the 7 days curing (see Fig. 5.5-8(a) and (b)). The highest expansion rate was recorded when PC was used to stabilise LOC-PFA, using formula F1@OMC. It demonstrated that, the expansion stabilised from day 2, at 0.02%. On the other hand, there are no signs of expansion with formula F1@1.2OMC when PC only stabiliser was used when formula F2@OMC and the blended PC-GGBS stabiliser were used (Fig. 5.5-10(d)).

At 20wt% stabiliser dosage (see Fig. 5.5-10(c) and (d)), the highest expansion was 0.03%, recorded when PC - stabilised LOC-PFA was monitored with formula F2@OMC and when blended PC-GGBS (40:60) stabilised LOC-PFA adopted formula F1@OMC. However this formula recorded a decrease in expansion towards day 4 of soaking. In general the lowest expansion rate was shown by the blended PC-GGBS stabiliser using formulae F1@1.2OMC and F2@1.2OMC (see Fig. 5.5-10(d)).

Summary Observations:

- At 10wt% stabiliser content, small linear expansion magnitudes with both PC-based stabilisers with all formulae of calculating compaction moisture content.
- At 20wt% stabiliser content, overall results showed linear expansion magnitudes were below 0.03%.

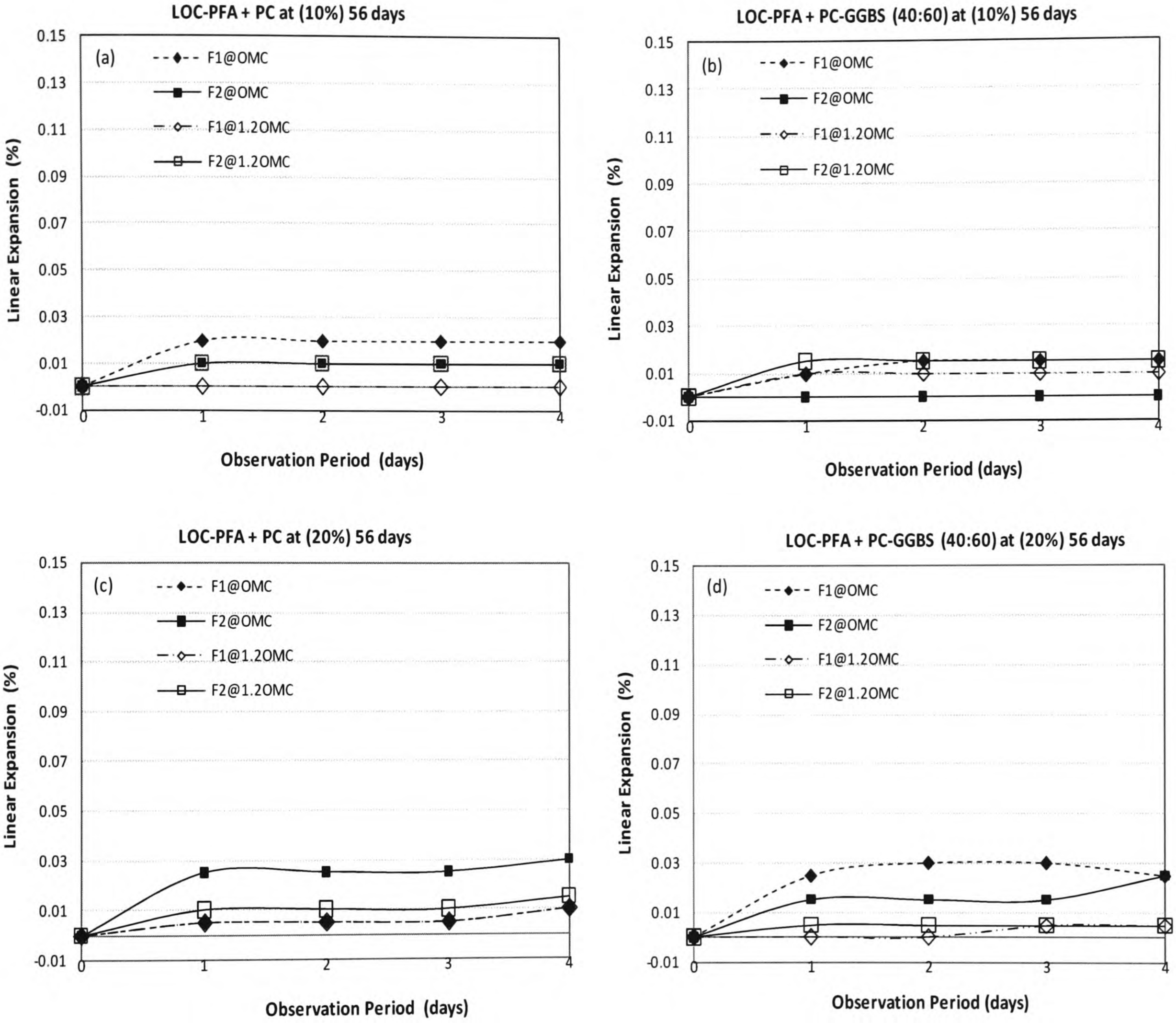


Figure 5.5-10: Linear Expansion stabilised of LOC-PFA blended material stabilised using (a) PC@10wt% (b) PC-GGBS (40:60)@10wt% (c) PC@20wt% (d) PC-GGBS (40:60)@20wt%, during soaking in water after being moist-cured for 56 days

5.5.5 Summary

(Figures 5.5-11 and 5.5-12) An attempt was made to summarise the linear expansion data just discussed, and contained in several Figures from Figure 5.5-5 to 5.5-10 (6 Figures). In the summary Figures, the expansion magnitudes at the end of the 4-day soaking period, has been used.

In addition to figures 5.5-11 at 5.5-12 that show the summary of linear expansion, the Figures 5.5-13 and 5.5-14 show the overall weight changes (mainly increases) that were observed after the 4-day soaking period.

Overall, the following bullet points attempt to further summarise the observations on linear expansion data contained in all the Figures mentioned.

1. In general, LOC-PFA stabilised with lime on its own has a higher Durability Index (DI) compared to LOC-PFA stabilised with blended lime-GGBS (30:70) at all ages and at both stabiliser dosages (10% and 20%). In contrast, with PC system results shown that, by incorporating GGSBS it has demonstrated higher DI value, especially at the later age of curing period with all formulae of calculating compaction moisture content.

2. In most cases, both systems (lime and PC systems) have illustrated that the formula with more moisture content recorded a higher DI value at all ages and at both stabiliser dosages.

3. In the lime system it has been shown that, there are higher percentage increases in weight at 7 days compared to at 28 and 56 days of curing period with all formulae of calculating compaction moisture content. In fact, 2 specimens (F2@OMC and F2@1.2OMC) totally collapsed at 7 days curing. The overall results showed that the PC suggested a lower percentage weight increase compared to the lime, with overall weight increase recorded below 10% at all ages, dosages and all formulae. However, the GGBS blended (both lime-GGBS and PC-GGBS) systems showed comparable magnitudes of weight increase.

4. LOC-PFA stabilised with lime on its own has the highest expansion compared to PC and other blended stabilisers, especially for 28 days of curing. In general, all stabilised LOC-PFA specimens in both systems, with all method of calculating compaction moisture content either attained terminal linear expansion or continued to expand at a negligible rate of increase.

5. In both lime and PC systems, formulae with less moisture content (e.g F2) indicated the most expansion rate. Overall formula F1@1.2OMC has less expansion rate compared to others.

6. Addition of stabiliser dosage from 10wt% to 20wt% is not necessary beneficial, for both lime and PC systems, and for both blended and unblended systems.

7. The system using lime is more sensitive to stabiliser dosage. This perhaps due to the sensitivity of lime-stabilisation of sulphate bearing clay soil. Even with the very robust lime-GGBS stabiliser, increase in stabiliser dosage is detrimental.

8. Moist-curing up to 56 days does not completely eliminate the risk to expansion. This is an interesting observation. Perhaps some property of cured material-porosity, brittleness, carbonation etc is at play.

9. There is no consistent trend to differentiate the two formulae. However formula F2@OMC appears to predominate the high expansions for the lime system at all curing stages. This is followed by F2@1.2OMC. On the other hand, formula F2@OMC and F1@OMC are the most expansive for the PC system. Formula F1@1.2OMC appears most stable for both systems. Those results appear to confirm the commonly held view that compaction on the wet side of the OMC is preferable, in order to eliminate swelling of compacted clay soil in both stabilised and unstabilised states.

10. For both lime and PC systems, blending with GGBS is beneficial.

11. The results of weight gain corroborate those of linear expansion.

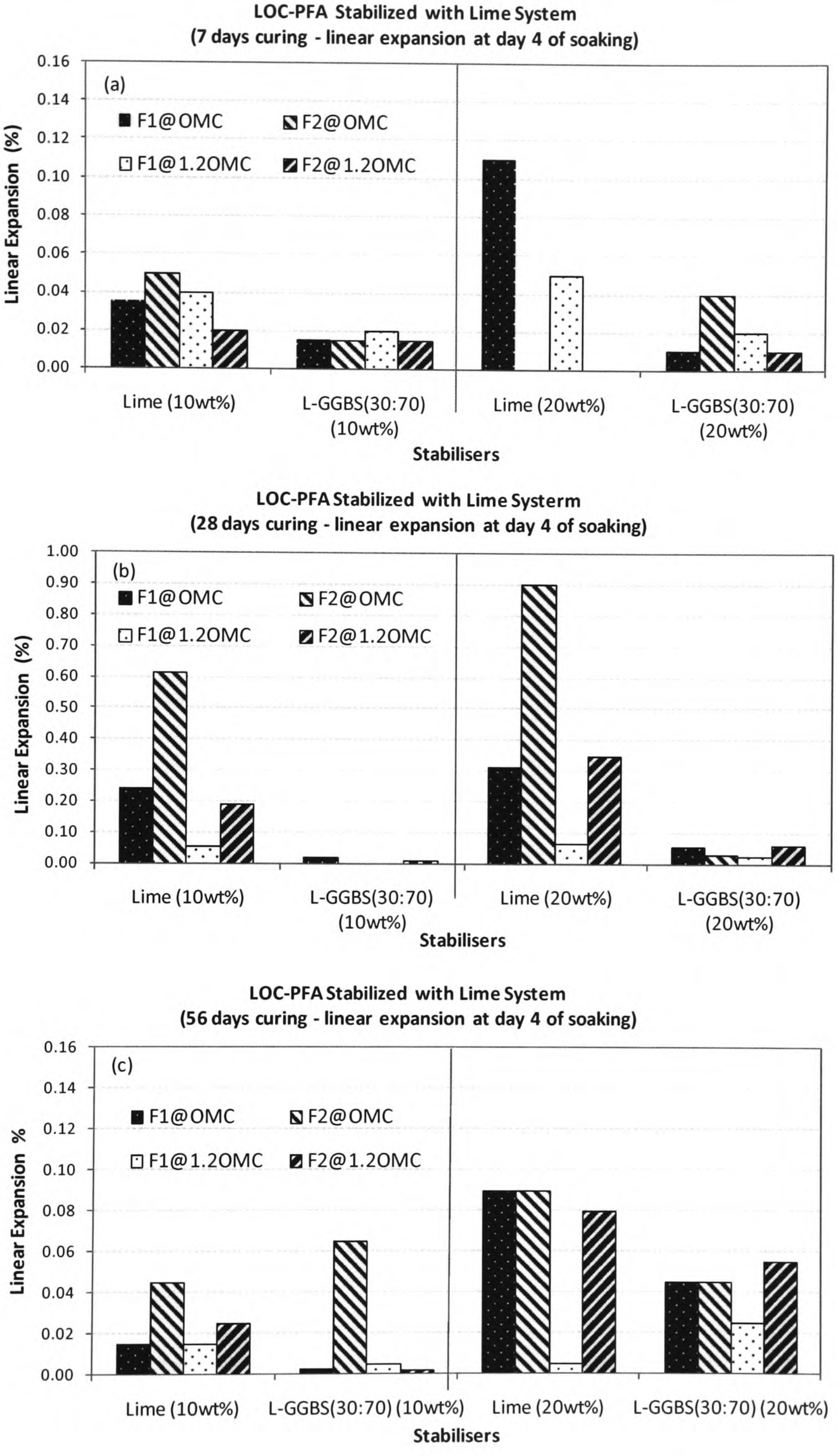


Figure 5.5-11: Summary of Linear Expansion of Stabilised LOC-PFA with Lime System at 10wt% and 20wt% on day 4 of Soaking (a) for 7 days curing (b) for 28 days curing (c) for 56 days curing

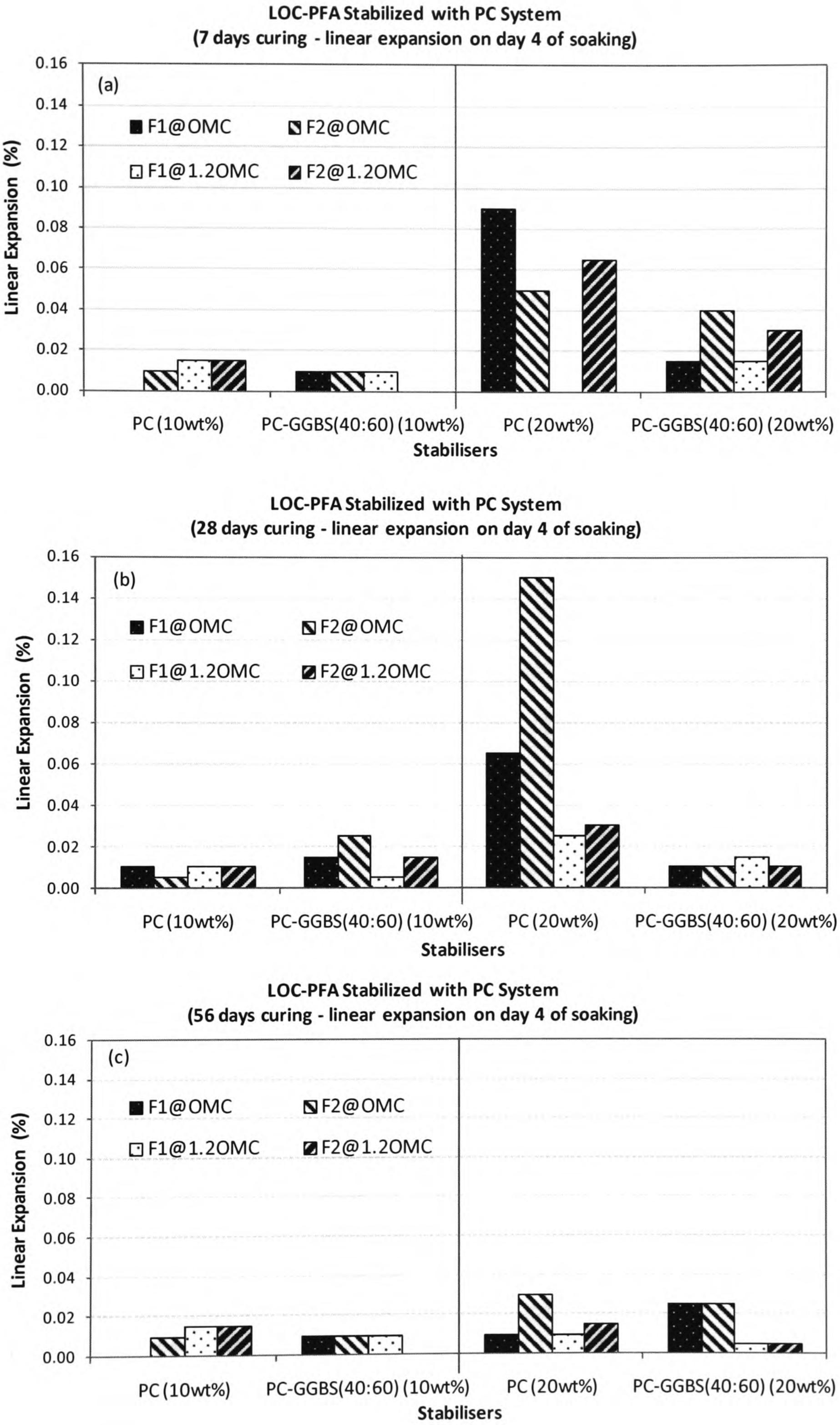


Figure 5.5-12: Summary of Linear Expansion of Stabilised LOC-PFA with PC System at 10wt% and 20wt% on day 4 of Soaking (a) for 7 days curing (b) for 28 days curing (c) for 56 days curing

5.6 LINEAR EXPANSION

This section presents data concerning the effects of lime, PC and the blended stabilisers incorporating GGBS (Lime-GGBS and PC-GGBS at 30:70 and 40:60 blending ratios) - on the linear expansion characteristics of the target materials LOC-PFA (50:50) compacted at OMC and 1.2 OMC. The test specimens were made using the methods of calculating compaction water content described earlier in section 4.4.2. The target material was compacted into cylinder forms in the same way as the UCS test specimens. All the stabilised specimens were moist cured for 7 days prior to soaking. Monitoring of linear expansion was carried out during the 7 days moist-curing period and also during the subsequent soaking period, for a total period of 56 days about when no further significant expansion was observed.

Swelling and linear expansion of lime-stabilised, sulfate-bearing soil is common and is known to be associated with the formation of a colloidal product (a precursor to ettringite formation), which forms on the surface of the clay particles during curing (Wild *et al.*, 1993). When in a saturated condition, ettringite grows and develops from this colloidal product, it has a capability of imbibing large amounts of water and dramatically increases the swelling potential of the lime-stabilised soil. However, the introduction of a cementing agent such as PFA with or without the combined action with GGBS modifies the chemical interaction of the clay-lime system, thereby altering the types of reaction products and thus potentially altering any disruptions that the reaction products may cause. Using PFA and GGBS as raw materials to replace clay is an effective measure of recycling wastes materials, reduces the use of natural resources, reduces energy consumption, and enhances the development of a new cost effective construction materials and products.

5.6.1 Linear Expansion of the LOC-PFA (50:50) with Lime System

Figures 5.6-1(a) and (b) illustrate the linear expansion and the effects of the Lime-GGBS blended stabiliser on stabilised LOC-PFA-Lime system, using both methods of calculating compaction moisture content described earlier, at 10wt% stabiliser dosage. A bar chart of the linear expansion of the stabilised specimens at the end of the 56-day period is also presented.

Over the 56-day observation period, both the lime and Lime-GGBS systems appear to have either attained terminal linear expansion or to continue to expand at a very negligible rate of increase. In most cases, with both methods of calculating compaction moisture content, almost all the ultimate expansion occurred within the first 7 days of soaking.

When the LOC-PFA target material was stabilised with lime only (see Figure 5.6-1(a)), formula F2@OMC specimens were observed to expand more than the other formulae. This was also observed with specimens cured for longer periods, as seen in the previous section (section 5.5.3). In this lime only system, the highest expansion magnitudes were observed, compared with LOC-PFA stabilised with the blended lime-GGBS stabiliser as shown in Figure 5.6-1(b). The linear expansion was immediate when the specimens were soaked in water after the 7-day moist-curing period in particular when the target material was stabilised using lime only. As already mentioned, this expansion was more stable after about 7 days of soaking. The LOC-PFA material stabilised with lime-GGBS (30:70) recorded significantly lower expansion values at or below 1.0%, compared with the LOC-PFA stabilised with lime only which recorded well above 1.0% linear expansion, for all methods of calculating compaction moisture content. Similar to LOC-PFA stabilised with lime only, formula F1@1.2OMC indicates the lowest expansion rate when compared to other formulae at 10wt% stabiliser dosage. Again this is similar observation to that made in the previous section, where specimens were cured for longer periods prior to soaking in water. In this system stabilised LOC-PFA showed a consistent reduction in expansion when GGBS was used in a blended lime-GGBS stabiliser with all methods of calculating compaction moisture content.

Overall, the results have shown that by blending GGBS with lime at the blending ratio of (30:70) resulted in a reduction in linear expansion of LOC-PFA when compared to LOC-PFA stabilised with lime only. The highest linear expansion was recorded when formula F2@OMC was used in both stabilisers. At 56 days of soaking, the LOC-PFA stabilised with lime only recorded above 2% linear expansion with formula F2@OMC, compared to below 1.5% for LOC-PFA stabilised with lime-GGBS at (30:70) using the same formula (see Figure 5.6-1(c)).

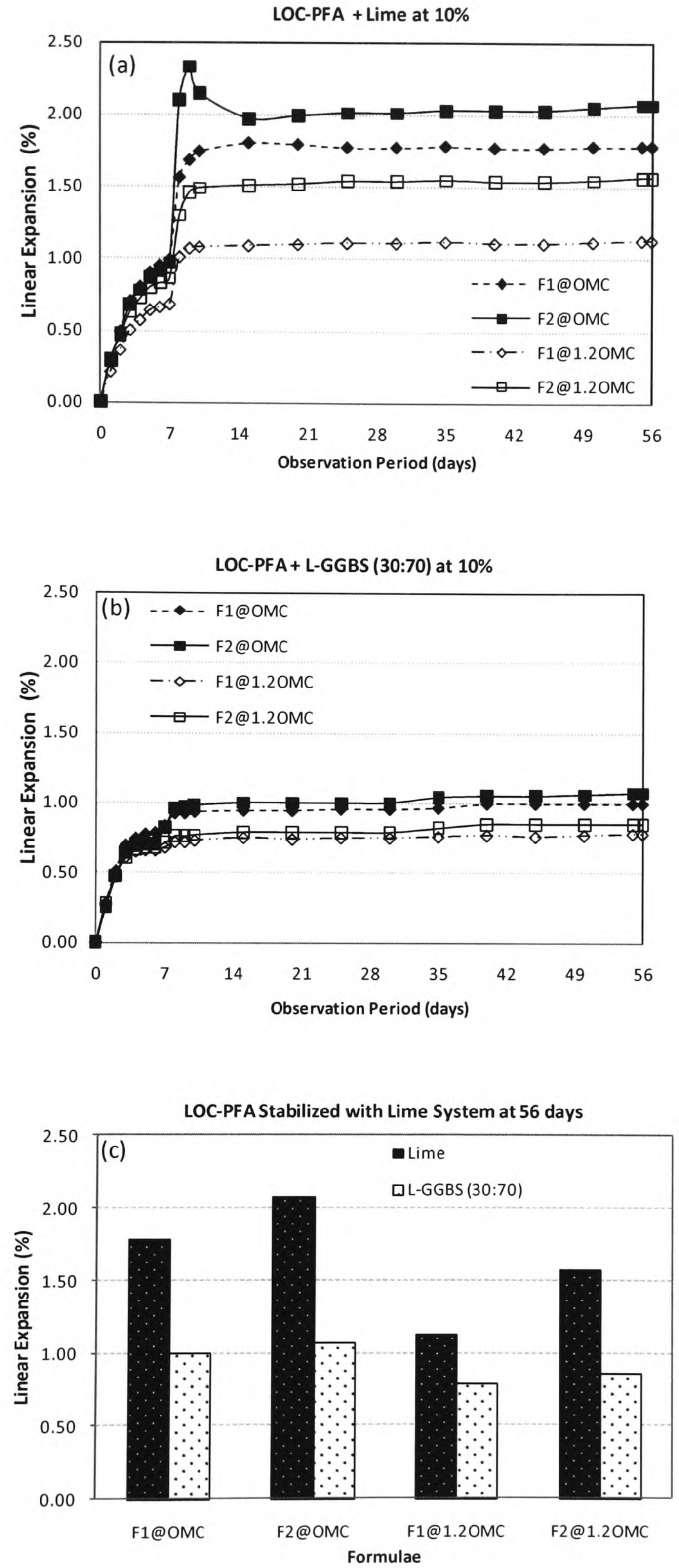


Figure 5.6-1: Linear Expansion of stabilised LOC-PFA (50:50) at 10wt% stabiliser dosage (a) lime only (b) lime-GGBS at (30:70) ratio (c) Linear Expansion at 56 days

5.6.2 Linear Expansion of the LOC-PFA with PC System

Figures 5.6-2(a-c) illustrate the linear expansion and the effects of the blended stabiliser on LOC-PFA material with the PC stabilised system, using all methods of calculating compaction moisture content, at 10wt% stabiliser dosage. A bar chart of the linear expansion of the stabilised specimens at 56 days is also presented.

Figure 5.6-2(a) shows the linear expansion of LOC-PFA specimens stabilised with PC only. As for the lime system, there was an immediate linear expansion after the specimens were soaked in water after the 7 day moist-curing period, with all methods of calculating compaction water content. However, the increase in expansion upon soaking was much less using PC as the stabiliser compared to the immediate expansion upon soaking when lime alone was used as stabiliser. In this PC system, formula F2@OMC again demonstrated the highest linear expansion rate when compared to other formulae, and showed identical expansion magnitudes with LOC-PFA specimens stabilised with either PC only or PC-GGBS blend at 40:60 ratio. Similar to the lime system, formulae with more water content showed less expansion, an observation made using both stabilisers (PC only and PC-GGBS (40:60)). Again as in lime system formula F1@1.2OMC indicated the lowest linear expansion magnitudes (Fig. 5.6-2(a) and (b)).

Figure 5.6-2(b) shows the linear expansion of LOC-PFA material stabilised with PC-GGBS. By blending PC with GGBS, the same pattern of linear expansion was observed at both LOC-PFA stabilised with PC only and blended PC-GGBS at (40:60). Again, formula F2@OMC recorded the highest linear expansion rate compared to other formulae. On the other hand, formula F1@1.2OMC and F2@1.2OMC demonstrates almost equal linear expansion magnitudes. This indicates that GGBS has a high potential as a partial replacement material for PC and has environment benefits since it is a by-product material.

In contrast with the lime system, at 56 days of soaking, all stabilised specimens recorded at the highest linear expansion readings well below 1%, even with the most expansive formula F2@OMC. The lowest readings were recorded well below 0.5% (see Figure 5.6-2(c)).

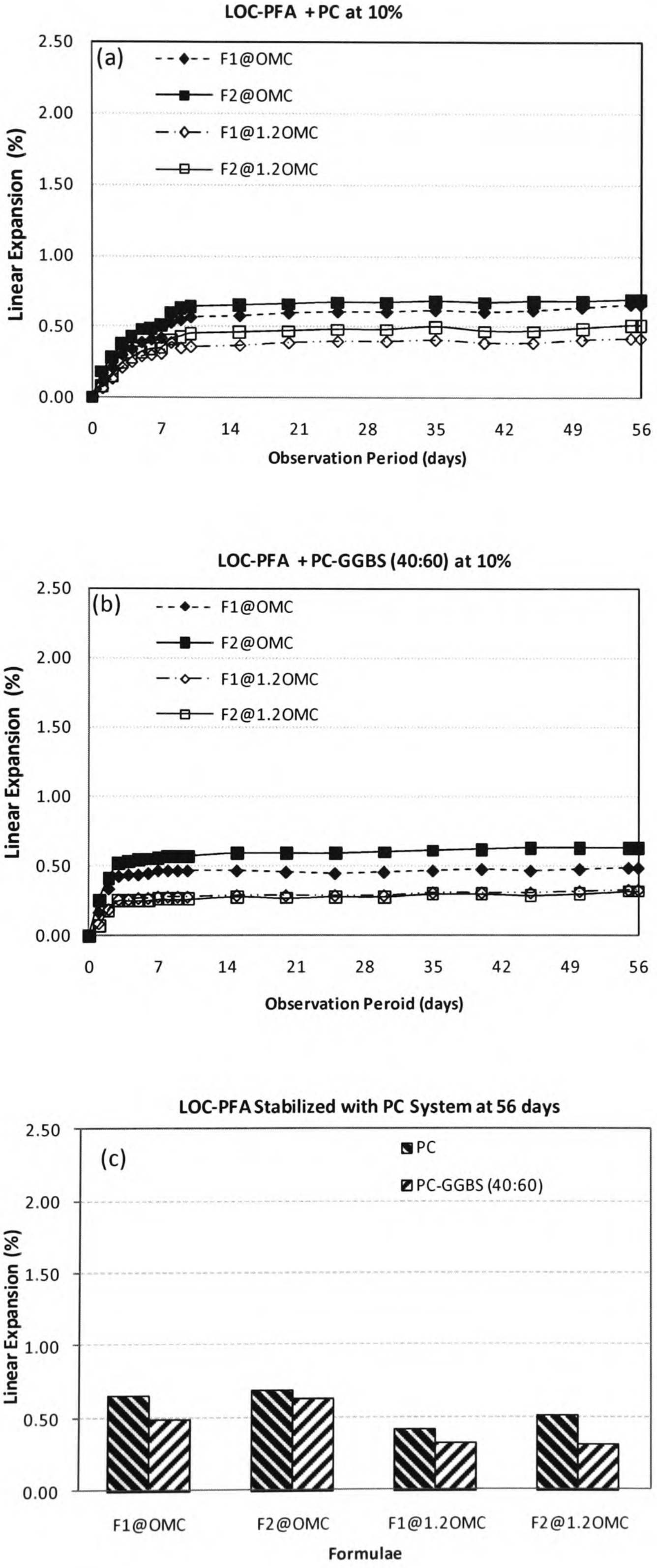


Figure 5.6-2: Linear Expansion of stabilised LOC-PFA (50:50) at 10wt% stabiliser dosage (a) PC only (b) PC-GGBS at (40:60) ratio (c) Linear Expansion at 56 days

5.6.3 SUMMARY

1. In both lime and PC based systems, linear expansion was immediate upon soaking after 7 days of moist curing. The expansion after soaking was however more significant when lime was used as the stabiliser, compared to PC. Both systems however showed decreased linear expansion magnitudes with the blended stabilisers incorporating GGBS compared to lime or PC used alone.

2. LOC-PFA target material stabilised with lime has showed the highest expansion rate compared to PC and other blended stabilisers. The lowest expansion was observed when LOC-PFA material was stabilised with PC-GGBS (40:60) using formula F1@1.2OMC.

3. Over the 56-days observation period, all the stabilised LOC-PFA specimens in both lime and PC systems, with all method of calculating compaction moisture content, demonstrated either terminal linear expansion or continued to expand at a very negligible rate of increase.

4. In both lime and PC systems, the formulae resulting with less moisture content in the stabilised mixture (F2) indicated the most expansion. Overall formula F1@1.2OMC showed least expansion magnitude compared to all the others.

5.7 THERMOGRAVIMETRIC ANALYSIS (TGA)

5.7.1 Introduction

Thermogravimetric analysis was carried out on LOC-PFA blends, stabilised using lime, PC and the blended stabilisers incorporating GGBS – lime-GGBS at (30:70) and PC-GGBS at (40:60). Both blended stabilisers were chosen based on their higher strength performance during UCS tests, and in consideration of their sustainability and economic potential. Two stabiliser blending ratios were applied, at 10wt% and 20wt% of stabiliser dosage, and three curing periods were employed at 7, 28 and 56 days. Since results from UCS indicated that those formulae with higher moisture contents achieved better strength, all the tests specimens were compacted using formula F1 which resulted in higher compaction moisture content and was used at 1.2OMC. Formula F1 takes into account any variations in stabiliser dosage. By using 1.2OMC as opposed to OMC, prolonged strength gain was ensured.

For TGA results there were 5 distinct temperature zones where significant weight losses were observed.

1. **Zone 1** (< 100°C)

This zone represents moisture loss, and therefore weight loss resulting from the expulsion of the chemically uncombined (i.e. adsorbed) water in the stabilised/unstabilised clay soil. This is the moisture in the material that was not lost during the initial drying process using silica gel. The principal ettringite dehydration according to most reports (Negro and Bachiorrini, 1982; Giergiezny and Weryuska, 1989; De Silva and Glasser, 1990), occurs in the temperature region between 70°C and 140°C. Thus the peaks between 70°C – 100°C may also be attributable to any ettringite present, especially because the samples were thoroughly dried before TG analysis, removing most of the free water.

2. **Zone 2** (100°C-200°C)

This zone represents weight loss due to water loss partly from ettringite as explained above and also from gypsum ($CaSO_4.2H_2O$). The most common, and perhaps the most important, weight loss in this zone is the principal dehydration of the C-S-H phases (typically between 120°C-140°C) formed as hydration products of the pozzolanic reactions. In addition to ettringite and C-S-H gel, gypsum also loses combined water between 130°C and 170°C (one major peak at about 140°C and a smaller one at about 160°C). Weight-loss peaks (due to gypsum) over this temperature range was observed by Parson *et al.*, (1997) when analysing LOC using evolved gas analysis (EGA) techniques.

3. **Zone 3** (200°C-400°C)

The report by Parson *et al.*, (1997) also suggested that organic matter is oxidised within this temperature region. It is thought that peaks due to the evolution of SO_2 are located between 300°C to 400°C, due to the oxidation of organic bound sulphur and also the oxidation of pyrites (Fe_2S).

4. **Zone 4** (400°C-650°C)

This zone represents the loss of water due to the dehydroxylation of clay minerals, resulting in the weight losses occurring around 500°C. More specifically kaolinite loses its combined water at about 570°C (Liptay, 1974). Thus, as LOC contains about 10% kaolinite and 23% illite, significant weight losses are expected within this temperature region. El-Jazairi and Illston (1977), in their work on chemical shrinkage of hydrating cement paste, detected the dehydroxylation of lime between 400°C and 600°C. Thus, for stabilised materials where lime ($Ca(OH)_2$) is likely to be present, weight losses due to lime are also anticipated. Because of the possible overlap between clay and lime peaks within this temperature region, it is quite hard to quantify the amount of lime present in most hydrated lime-clay systems. However, lime peaks tend to be located towards the lower end of this zone – near the 400°C mark, while the clay peaks are more towards 500-600°C range.

5. **Zone 5** (650°C-850°C)

Represents the loss of carbon dioxide (CO_2) evolved from calcium carbonate and other carbonates. The decomposition of sulphides, which is thought to occur as early as from 400°C to 950°C (Dunham *et al.*, 1992)), is also expected to contribute towards weight losses in this zone.

5.7.2 TGA of LOC-PFA Stabilised with the Lime System

5.7.2.1 TGA of LOC-PFA with Lime only

Figures 5.7-1(a) and (b) illustrate the TGA traces of powder test specimens obtained from fragments sampled from the specimens that had been tested for UCS, for the Lime-stabilised LOC-PFA. The samples for UCS had been prepared by compacting material into cylinders using formula F1@1.2OMC of calculating compaction moisture content, at 10wt% and 20wt% stabiliser dosages, and moist curing for 7, 28 and 56 days prior to testing. The three zones that represent the main weight losses due to hydration, lime content and carbonation are clearly identified, as shown by the dashed lines.

In zone 1 (between 50°C to 150°C), at both stabiliser dosages (see Fig. 5.7-1(a) and (b)), the weight losses may be attributed to the dehydration of calcium alumino-silicate hydrate (C-A-S-H) gels as well as ettringite and gypsum. With the presence of sulphate in LOC, the formation of calcium-sulfo aluminate hydrates (e.g ettringite is expected). The sharp peaks at about 100°C are most likely due to ettringite (the peaks are too sharp to be gel, and at too low a temperature to be due to C-S-H gel or gypsum). Both stabiliser dosages displayed similar trends, where ettringite peaks are clearly shown to increase with curing time. The formation of ettringite is clear at both stabiliser dosages, but the consumption of gypsum is masked by the production of secondary gypsum from the on-going oxidation of LOC-PFA mixture. On the other hand, at this stage (zone 1), at both stabiliser dosages, the principal dehydration of the C-S-H phases formed as hydration products of the pozzolanic reactions, shows that the C-S-H gel peaks decreased marginally as curing time increases. This is perhaps due to the changing morphology of the gel.

Figures 5.7-2 shows, the data obtained from the plots shown in Figure 5.7-1. Figure 5.7-1 (a) and (b) illustrate the weight losses due to hydration in LOC-PFA stabilised with lime only at 10wt% stabiliser dosages. In general, both dosages show weight losses of between 4% to 5% at all curing periods. Overall results indicate that at 10wt% dosage, percentage weight loss was lower compared to that observedat 20wt% except for 56 days of curing. At 20wt% dosage, by increasing the curing period to 56 days caused a decrease in the weight loss while with the lower lime dosage, weight loss showed a slight increase with increase in curing time. The results would appear to suggest the existence of an optimum lime content (e.g 10%), beyond which hydration is reduced due to saturation of lime in the system.

In zone 2 (between 400°C to 550°C) (Fig. 5.7-2 (b)), the dehydroxylation of clay minerals is known to occur around 500°C. This temperature band at 400°C to 550°C is also the result of dehydration of lime in the stabilised mixture (Nidzam, 2004). The weight losses thought to be due to calcium hydroxide were observed at 400°C to 450°C. The weight loss appears to be greater for the higher lime dosage level of 20wt% (see Figure 5.7-2(b)) compared to 10wt% dosage.

Both lime dosages indicated higher weight losses at 28 days curing compared to at 7 and 56 days of curing period. This is perhaps caused by the carbonation of lime at the long curing period of 56 days.

Zone 3 (between 650°C to 850°C) (Fig. 5.7-2 (c)), represents the loss of carbon dioxide (CO_2) evolved from calcium carbonate and other carbonates. At 28 days of curing both stabiliser dosages indicated decrease in weight loss when compared to 7 and 56 days of curing. Thus, for both dosages the carbonation trends shown between 650°C and 850°C are a mirror image of the lime trends shown in Fig. 5.7-2 (b). This is because low amounts of lime in a lime system most likely suggest high amounts of carbonate due to carbonation effects. Like in the hydration and residual lime zones, at 20wt% dosage, the weight losses were higher when compared to those at 10wt% stabiliser dosage at all ages.

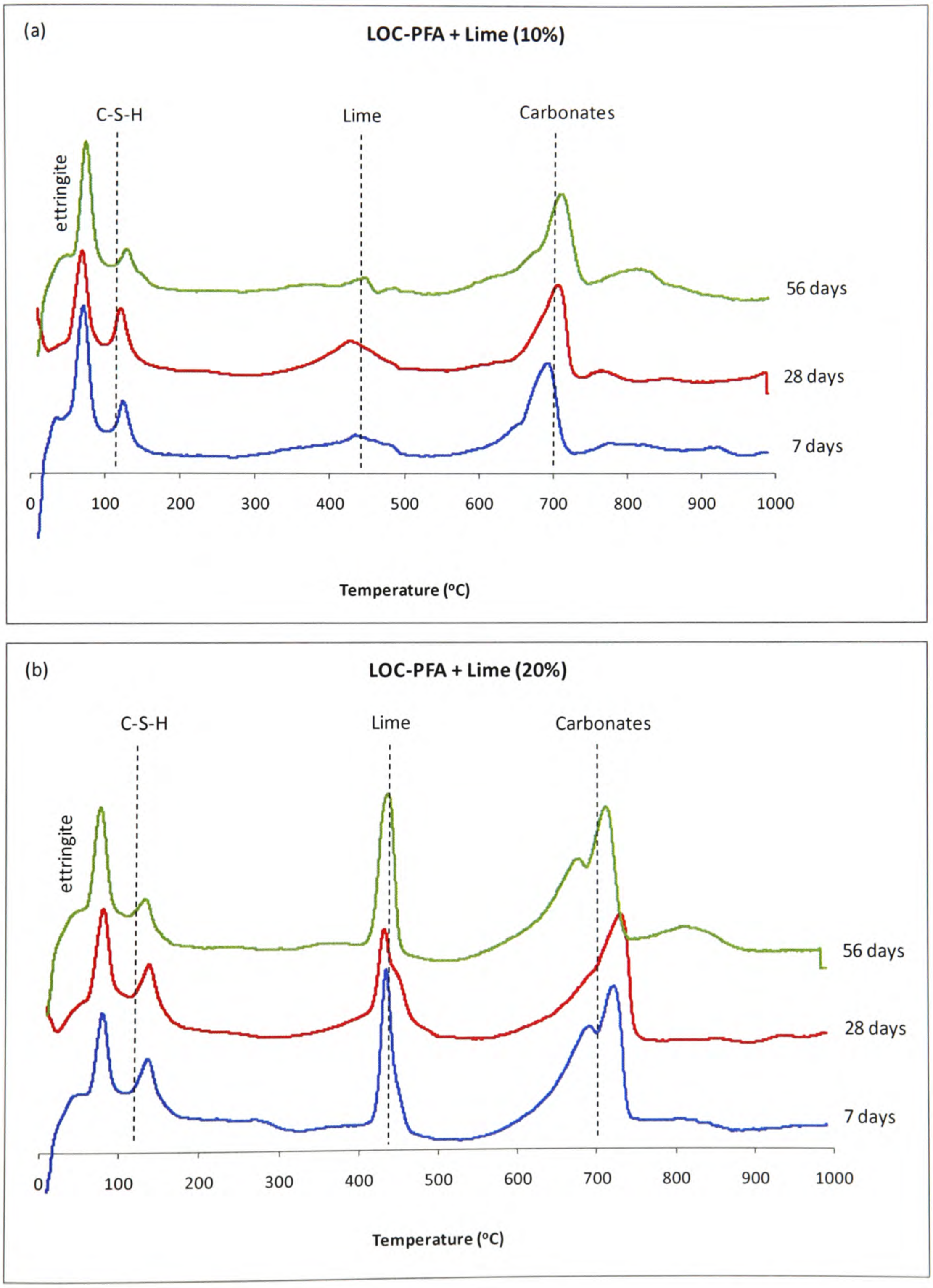


Figure 5.7-1: TGA traces of lime stabilised LOC-PFA blend stabilised with lime at (a) 10wt% lime (b) 20wt% lime dosage.

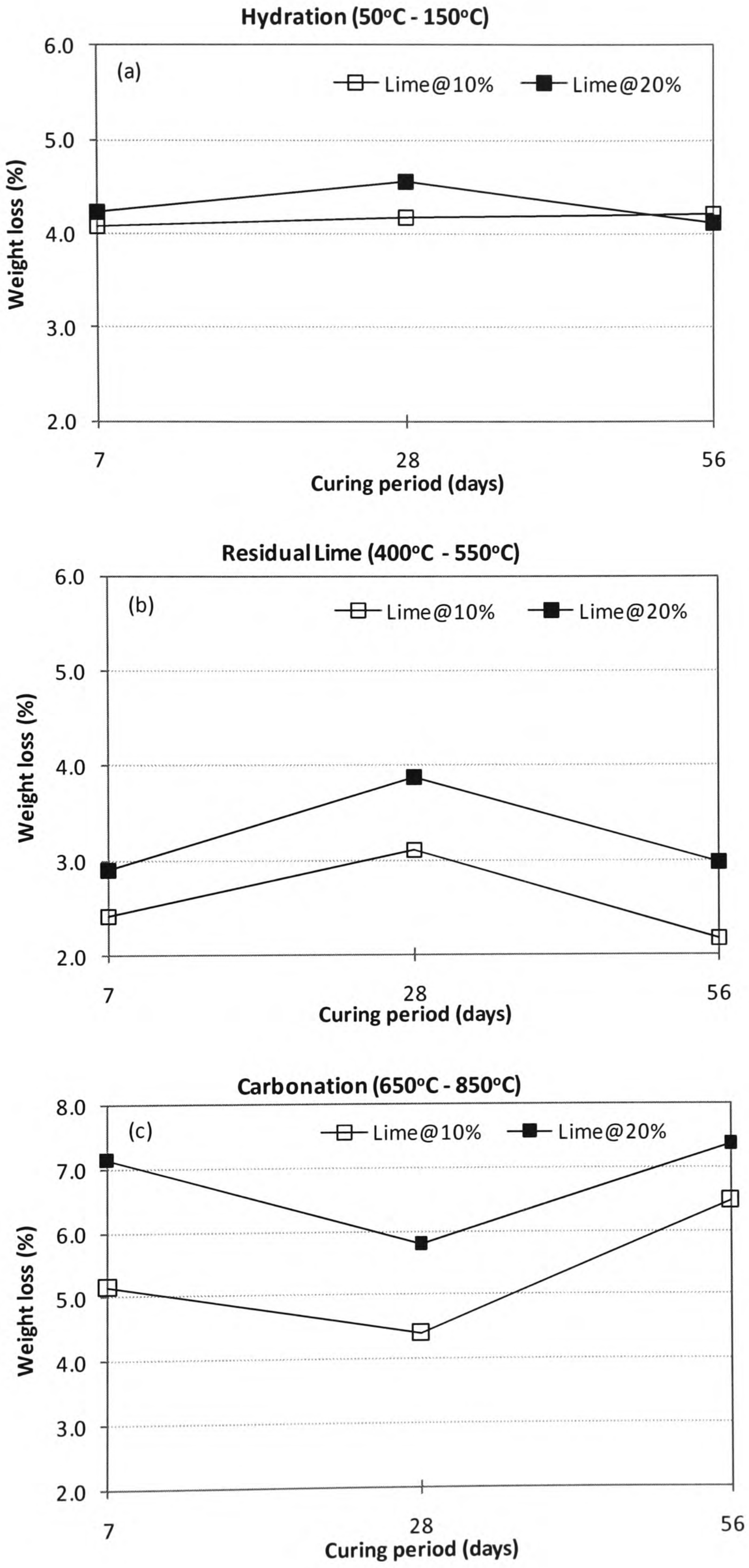


Figure 5.7-2: LOC-PFA stabilised with lime (a) hydration (50°C -150°C) (b) residual lime (400°C – 550°C) and (c) carbonation (650°C – 850°C)

5.7.2.2 TGA of LOC-PFA with Lime-GGBS (30:70)

The thermogravimetric analysis trends of LOC-PFA blends stabilised using Lime-GGBS blends (at 30:70 blending ratio) are shown in Figure 5.7-3. The data extracted from these traces is further plotted in Figure 5.7-4. Analysing this information zone by zone,:

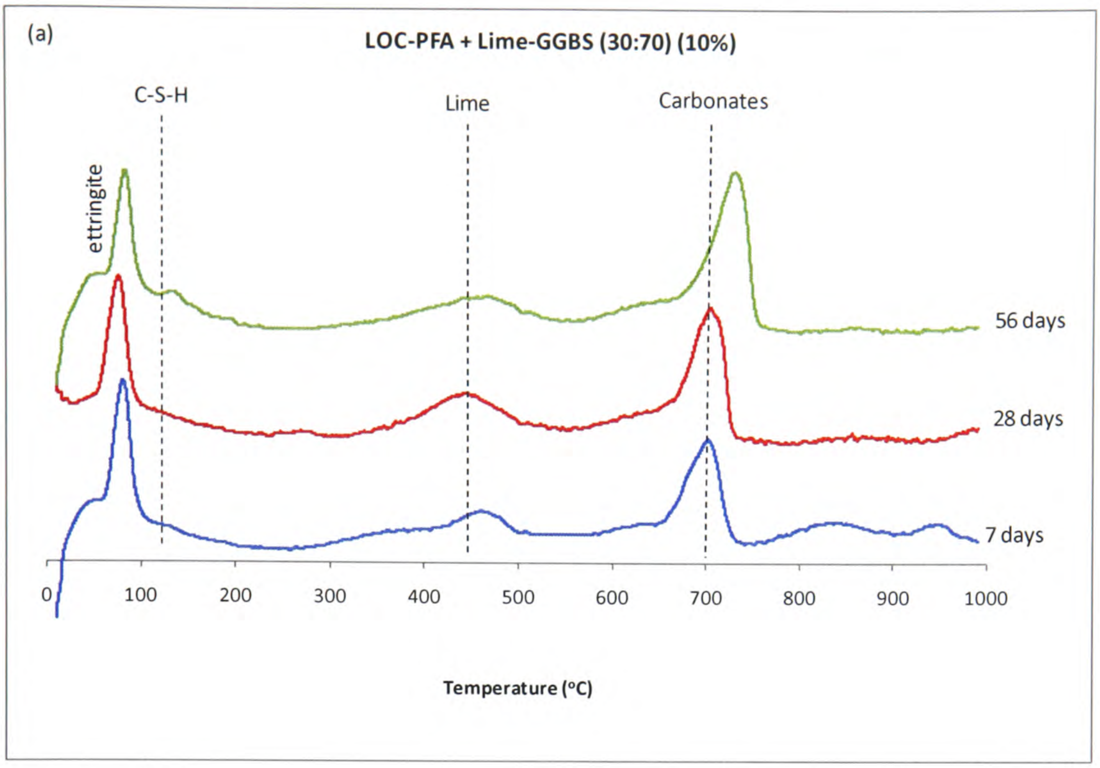
In zone 1 (between 50°C to 150°C), at both stabiliser dosages (see Fig. 5.7-3(a)), both sets of curves show weight losses. The sharp peaks at about 100°C are most likely to be due to ettringite. Also occuring within this zone is the principal dehydration of C-H-S phases formed as hydration products of pozzolanic reactions. In general, both lime systems (lime only and blended lime-GGBS (30:70)) display similar trends, where ettringite is clearly shown to be present at all dosages and ages.

Figure 5.7-4(a) shows, the weight loss due to hydration in LOC-PFA stabilised with lime-GGBS at (30:70) ratio at 10wt% and 20wt% stabiliser dosages. In general, both dosages show weight losses within 3% to 4%, at all curing period. Overall results show that the weight loss was greater in the higher stabiliser level of 20wt% compared to at 10wt% dosage. At 10wt% dosage, increase in curing period lead to increases in the percentage of the weight loss, while at 20wt% results indicate that there was only a very slight increase in weight loss from 7 days to 56 days of curing.

In zone 2 (between 400°C to 550°C), with blended lime-GGBS (30:70), there are smaller lime peaks at both stabiliser dosages when compared to the lime only peaks. This suggests that part of lime was used up by the GGBS in the system, and /or due to pozzolanic reactions. The lime peaks were also reduced as curing period increased.

Figure 5.7-4(b) shows, the weight loss due to residual lime in the LOC-PFA mixture stabilised with lime-GGBS (30:70) at 10wt% and 20wt% stabiliser dosages. With this stabiliser, both stabilisers dosages show low weight losses of between 2%-3% at all curing period. At 10wt%, higher amounts of lime are present at 28 days of curing time, while at 20wt% dosage the amount of lime at this time is at its lowest. The highest quantities of lime are shown at 56 days of the curing time with the 20% stabiliser.

Zone 3 (between 650°C to 850°C) represents the loss of carbon dioxide (CO_2) evolved from calcium carbonate and other carbonates. For both dosages, like in the case for lime only stabiliser, there were carbonation peaks between 650°C and 850°C. The data is summarised in Figure 5.7-4(c). Both dosages show weight losses of between 4-5% at all curing periods. The highest weight loss of about 5% occurred at 56 days of curing.



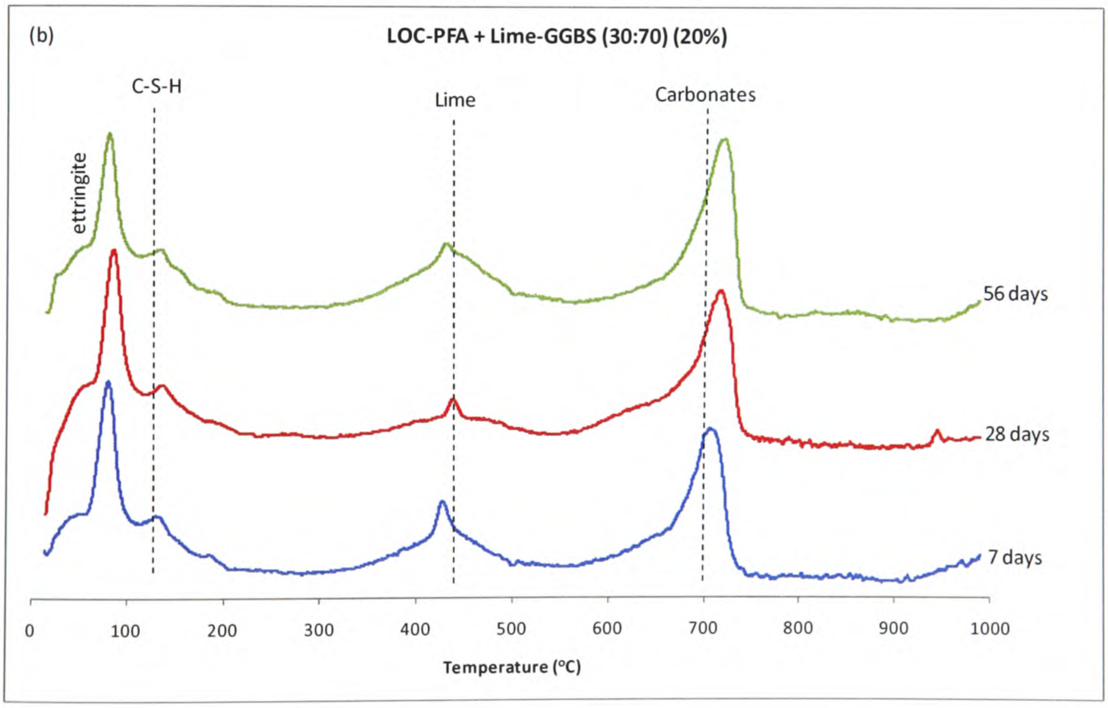


Figure 5.7-3: TGA traces of blended lime-GGBS (30:70) stabilised LOC-PFA at (a) 10wt% lime-GGBS(30:70) (b) 20wt% lime-GGBS(30:70)

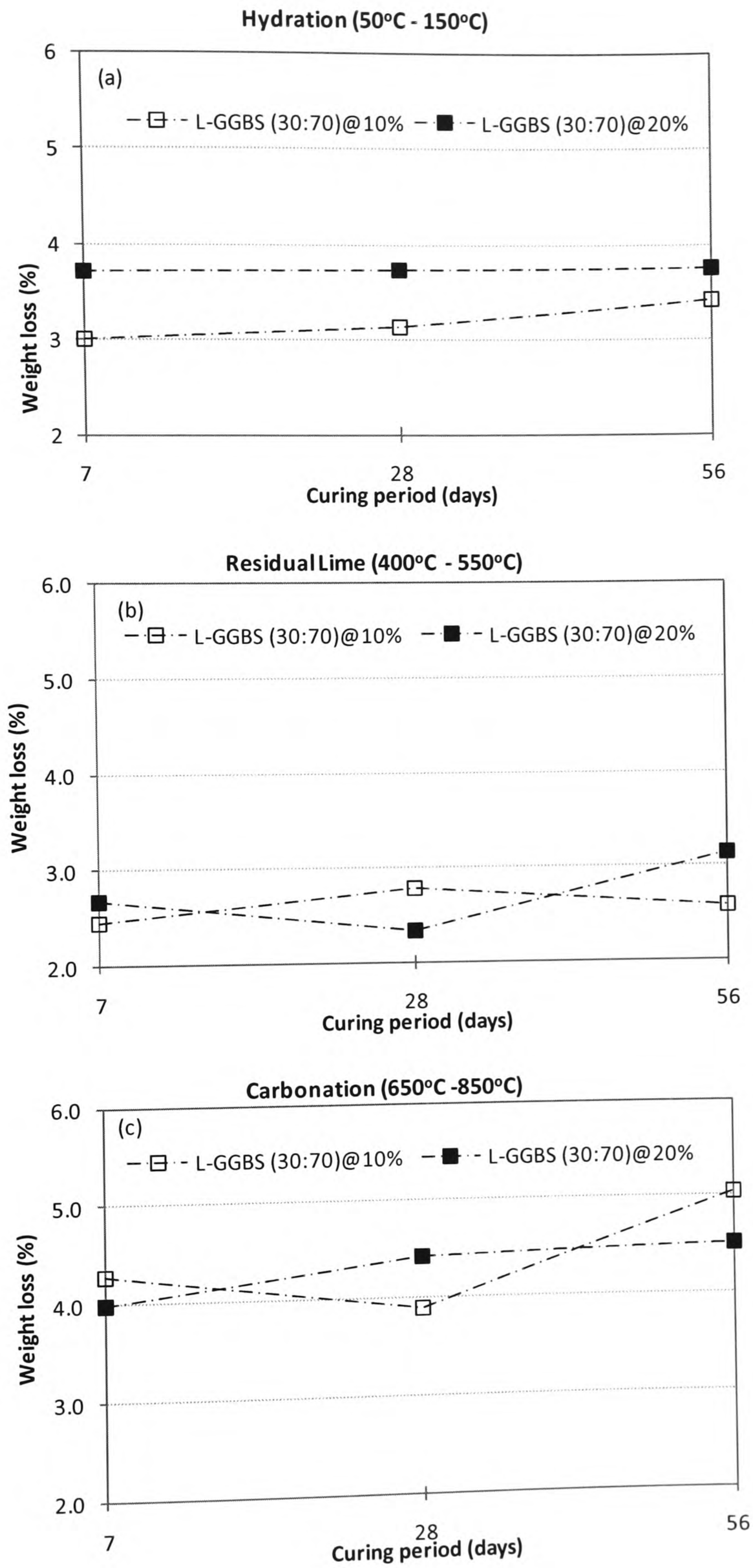


Figure 5.7-4: LOC-PFA stabilised with lime-GGBS (30:70) (a) hydration (50°C -150°C) (b) residual lime (400°C – 550°C) and (c) carbonation (650°C – 850°C)

5.7.3 TGA of LOC-PFA Stabilised with the PC System

5.7.3.1 TGA of LOC-PFA with PC only

Figures 5.7-5(a) and (b) illustrate the TGA traces of test specimens sampled from the specimens that had been tested for UCS on the PC only stabilised LOC-PFA, using formulae F1@1.2OMC of calculating compaction moisture content, at 10wt% and 20wt% stabiliser dosages. The specimens had been moist cured for 7, 28 and 56 days. Test reports are made based on the 3 zones that represent the main weight losses, due to hydration, residual lime content and due to residual carbonate.

In zone 1 (between 50°C to 150°C), at both stabiliser dosages (see Figs. 5.7-5(a) and (b)), like in the lime system, all sets of curves show broad temperature weight loss, which may be attributed to the dehydration of calcium alumino-silicate hydrate (C-A-S-H) gels as well as possible presence of ettringite and gypsum. In general, both stabiliser dosages display similar trends, where ettringite peaks are clearly shown at about 100°C. At 10wt% dosage, there are no definite C-S-H phases and gypsum peaks in the stabilised system, until the samples had been moist cured for 56 days of curing. On the other hand, with 20wt% dosage, C-S-H gel peaks are identifiable at all curing ages. The C-S-H gel peaks in the PC-system are smaller when compared to those observed with both stabiliser dosages in the lime system (see Figure 5.7-1 and 5.7-3).

Figure 5.7-6(a) shows, the weight loss due to the hydration in LOC-PFA blend stabilised with PC only at 10wt% and 20wt% stabiliser dosages. Greater weight losses occurred with the higher stabiliser dosage, at all ages. The highest weight loss was about 4.2% at 20wt%, at 56 day of curing. There was increasing weight loss with the increase in curing period, whereas at 10wt% dosage, with increases in the curing period from 28 to 56 days, results shows a reduction in weight loss (see Figure 5.7-6(a)).

In zone 2 (between 400°C to 550°C), (see Figures 5.7-5 (b) and 5.7-6(b)) the weight losses thought to be due to calcium hydroxide were observed at 400°C to 450°C. Unlike in the lime system, with PC only, the lime peaks appear to be greater at the lower PC level (10wt%) compared to at 20wt% dosage and decreased with increasing curing time.

Zone 3 (between 650°C to 850°C) represents the loss of carbon dioxide (CO_2) evolved from calcium carbonate and other carbonates. For both dosages the carbonation peaks are shown between 650°C and 850°C. The peaks appeared to increase with increase in curing period at 10wt% stabiliser dosage, up to 28 days of curing, beyond which there is no further increase in carbonate content. At 20wt% stabiliser dosage, this peak seems to decrease as curing period increased beyond 28 days (Fig. 5.7-6(c)).

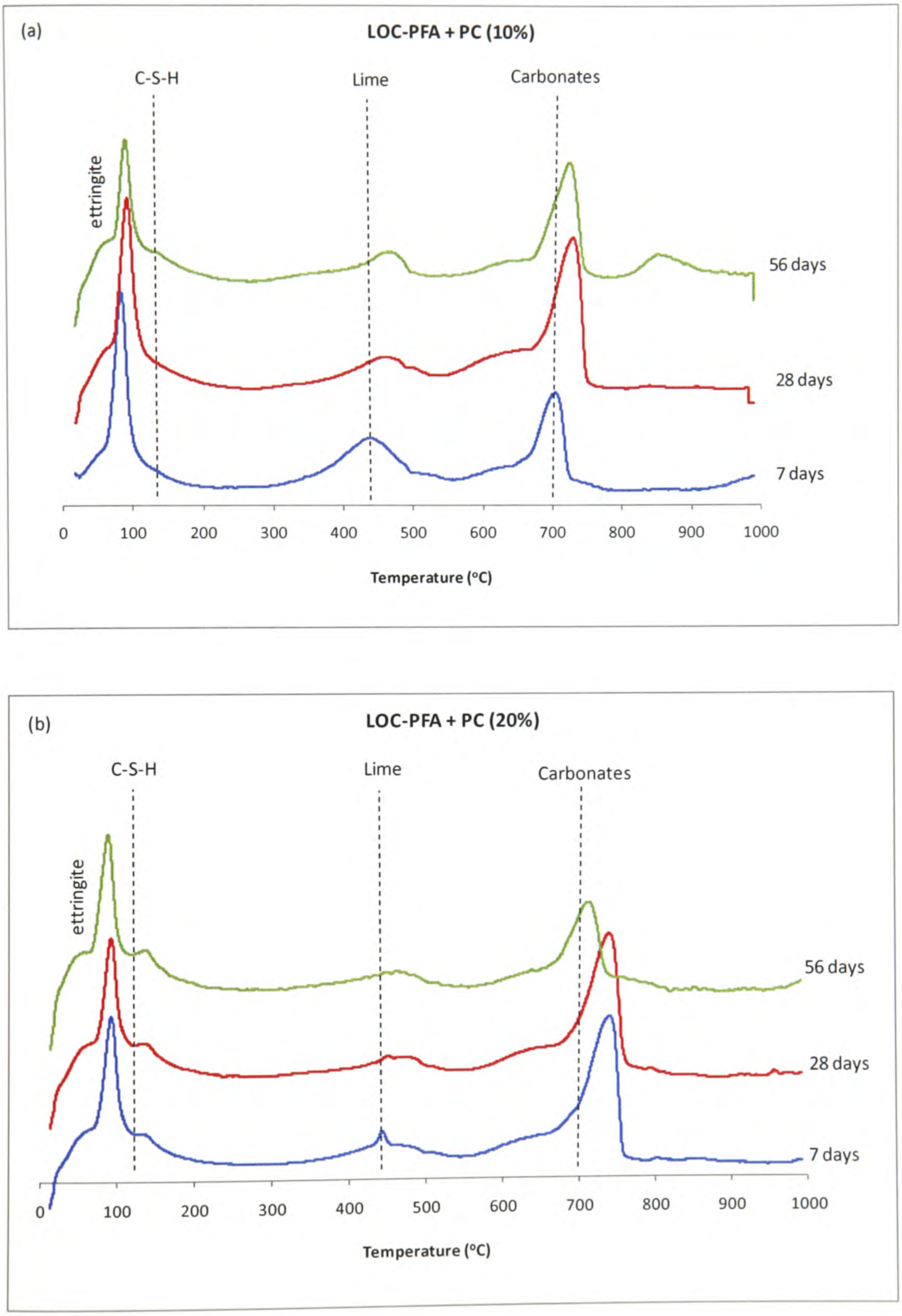


Figure 5.7-5: TGA traces of LOC-PFA blend stabilised with PC at (a) 10wt% PC (b) 20wt% PC dosage.

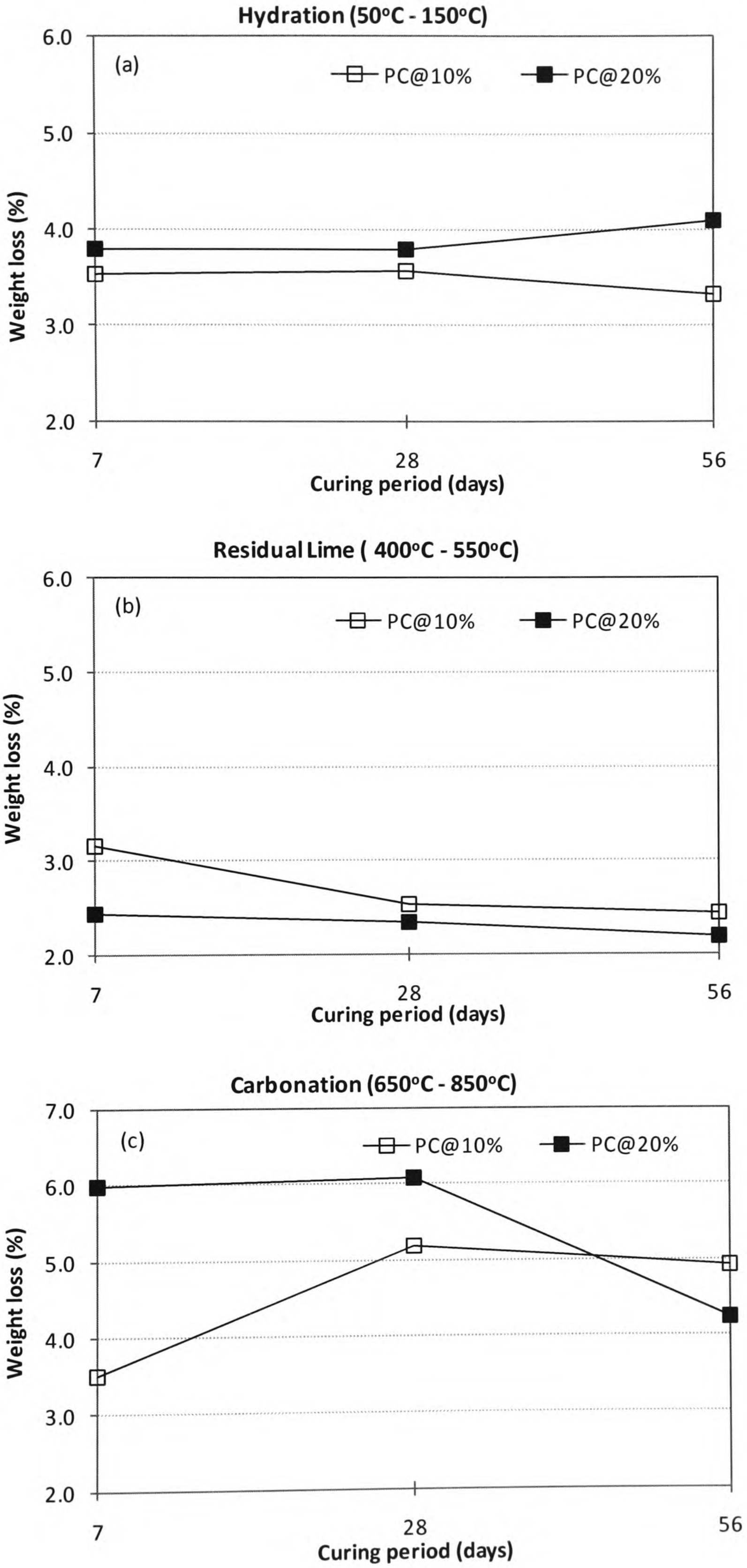


Figure 5.7-6: LOC-PFA stabilised with PC (a) hydration (50°C -150°C) (b) residual lime (400°C – 550°C) (c) and carbonation (650°C – 850°C)

5.7.3.2 TGA of LOC-PFA with PC-GGBS (40:60)

In zone 1 (between 50°C to 150°C), at both stabiliser dosages (see Fig. 5.7-7(a) and (b)), both sets of curves show broad temperature weight losses, the sharp peaks at about 100°C are most likely to be due to ettringite. Also accruing at this zone is the principal dehydration of C-S-H gel phases formed as hydration products of pozzolanic reaction. With the incorporation of GGBS in the system, the GGBS may have reacted with the excess calcium aluminate sulphate hydrate minerals (Wild *et al.,* 1998), reducing the capacity to retain large quantities of water within the structure, and thus reducing the continuous formation of ettringite. In general, both stabilisers PC only and blended PC-GGBS (40:60) display similar trends as in the lime system, where ettringite peaks are clearly identifiable at all dosages and curing ages. C-S-H gel peaks are slightly more clearly identifiable at 20wt% dosage, especially at 56 days of curing.

Figure 5.7-8(a) shows, the weight loss due to hydration in LOC-PFA stabilised with PC-GGBS (40:60) at 10wt% and 20wt% stabiliser dosages. At 20wt% dosage, there was increase in weight loss with the increase in curing period, but at 10wt% dosage, there was a decrease in weight loss at 28 days and then a slightly increase again at 56 days of curing.

In zone 2 (between 400°C to 550°C), the weight losses thought to be due to calcium hydroxide were observed at 400°C to 450°C. Unlike with the lime system, and like PC only, the lime peaks appear to be greater at the lower stabiliser level compared to at 20wt% stabiliser dosage. This was expected, as more residual lime would be expected with the higher stabiliser dosage of 20%. However, due to complications of carbonation, it may well be that there is more carbonation at the higher stabiliser dosage. Thus at 20wt% stabiliser dosage the lime peaks are still present and become marginally smaller as curing time increases.

Figure 5.7-8(b) shows, the weight loss due to residual lime in LOC-PFA stabilised with PC only at 10wt% and 20wt% stabiliser dosages. There are definite lime traces in both plots. Overall results show there was more weight loss at 10wt% dosage compared to at 20wt% dosage, at all curing times. Both dosages indicated higher weight losses at 7 days of the curing compared to 28 and 56 days of curing. Increasing the curing period to 56 days caused a decrease in the weight loss band at both stabiliser dosages.

In zone 3 (between 650°C to 850°C), the loss of carbon dioxide (CO_2) evolved from calcium carbonate and other carbonates is indicated. For both dosages the carbonation peaks are shown between 650°C and 850°C. The carbonation peaks are comparable at both stabiliser dosages at all ages. This is best illustrated in Figure 5.7-8(c) which further shows the weight loss due carbonation process in LOC-PFA stabilised with PC only at 10wt% and 20wt% stabiliser dosages. At 20wt% dosage, there is slight increased in weight loss as increases in the curing time.

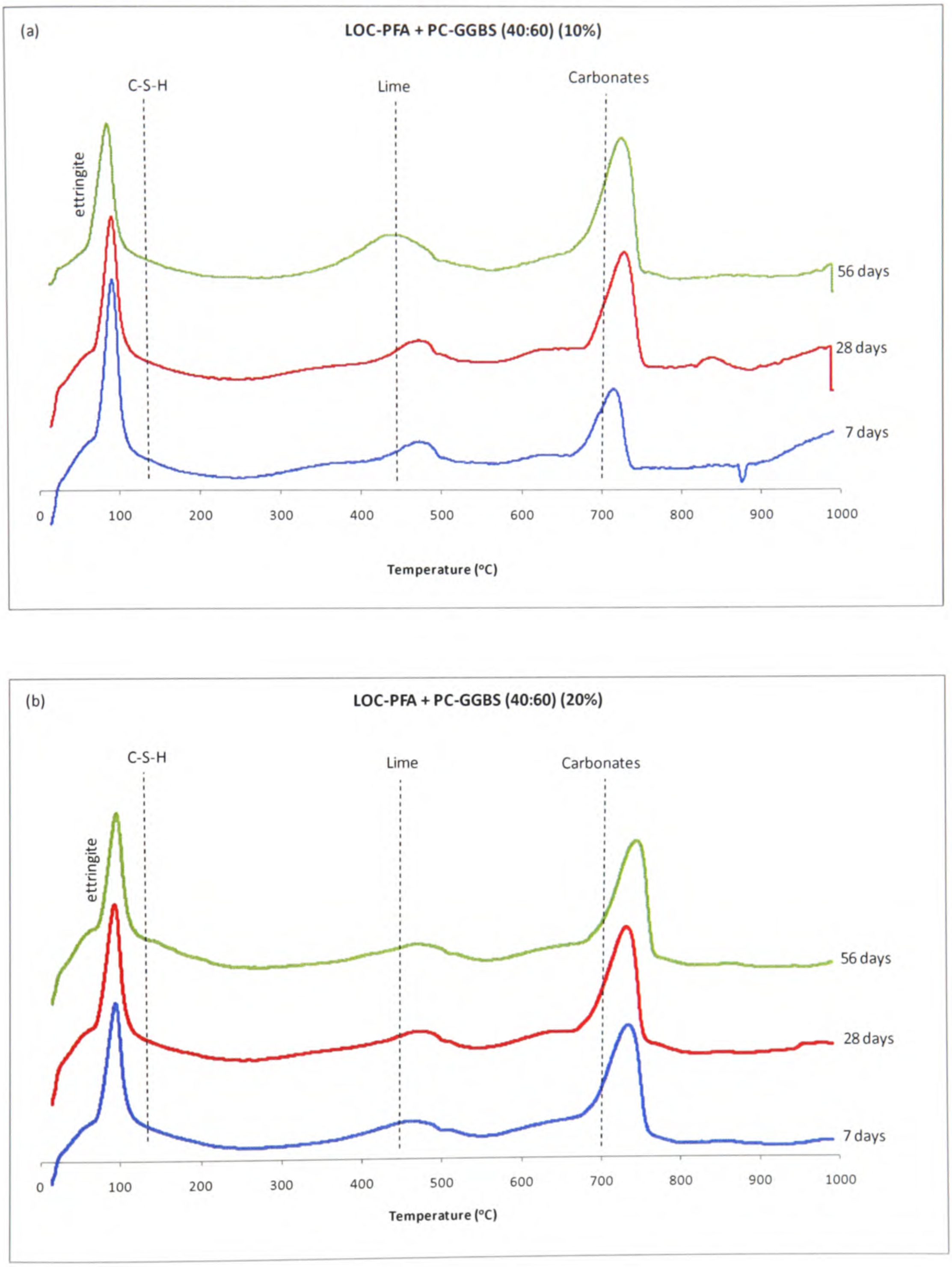


Figure 5.7-7: TGA traces of blended PC-GGBS (40:60) stabilised LOC-PFA at 10wt% (b) 20wt%

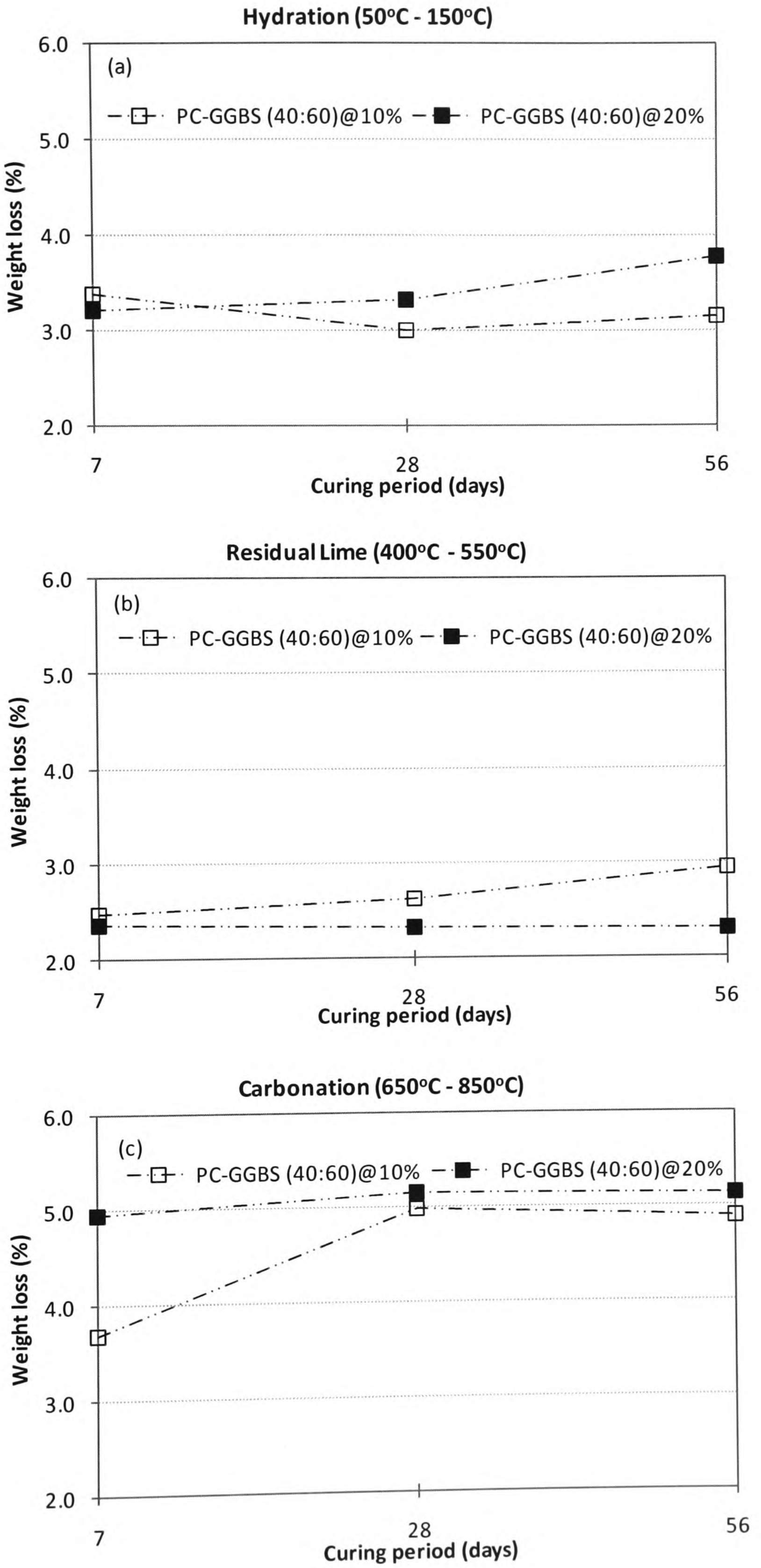


Figure 5.7-6: LOC-PFA stabilised with PC-GGBS (40:60) (a) hydration (50°C -150°C) (b) residual lime (400°C – 550°C) (c) carbonation (650°C – 850°C)

5.8 PILOT INDUSTRIAL COMMERCIAL TRIAL

5.8.1 Testing for Unconfined Compressive Strength (UCS) Pilot Trial Bricks

The initials tests for the unconfined compressive strength were carried out after moist curing for 7 and 28 days. The UCS test was carried out as described in the British Standard BS 1377-7:1990 (Soils for engineering purposes), to assess the strength development of formulated unfired bricks. Unfired bricks of dimensions of 285mm x 140mm x 55mm thick were prepared. For brick production only 4 sets of stabilisers were applied, blended lime-GGBS at (30:70), PC-GGBS at (40:60), lime and PC at 10wt% dosage. Two bricks per mix proportion were subjected to UCS tests and the mean strength determined. The Unconfined Compressive Strength of stabilised LOC-PFA unfired bricks was determined using a Hounsfield testing machine, on the 55mm x 285mm side surface of the bricks, at a compression rate of 0.15kN/min (see Figure 4.13).

5.8.1.1 Unconfined Compressive Strength of the Lime System

Figures 5.8-1 shows the UCS test results of unfired bricks stabilised with lime system at 10wt% stabiliser dosage. The overall results show that there are increases in strength with increased curing period from 7 to 28 days for both stabilisers - lime only and blended lime-GGBS at 30:70 blending ratio.

At 7 days of curing, the highest strength value of 1005 kN/m^2 was achieved, when LOC-PFA was stabilised with blended lime-GGBS (30:70). At this stage, the lowest strength value was 364 kN/m^2 when lime only was used as stabiliser. A similar strength pattern was recorded at 28 days curing. The highest strength of 1972 kN/m^2 was recorded when LOC-PFA was stabilised with blended Lime-GGBS (30:70) ratio and the lowest strength value of 888 kN/m^2 was recorded when LOC-PFA was stabilised with lime only.

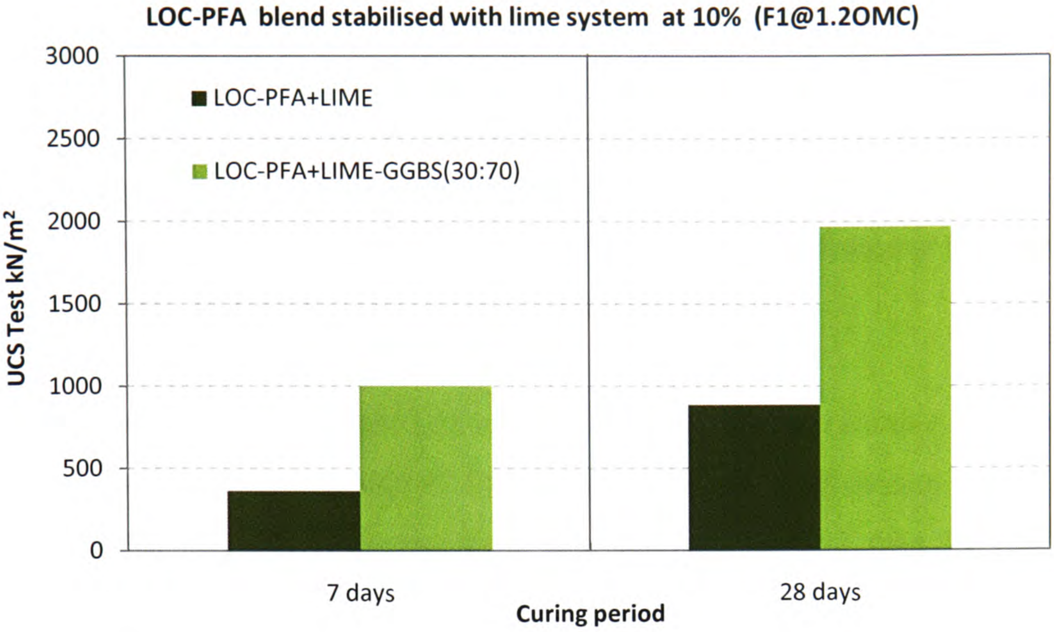


Figure 5.8-1: LOC-PFA Stabilised with the lime stabiliser system

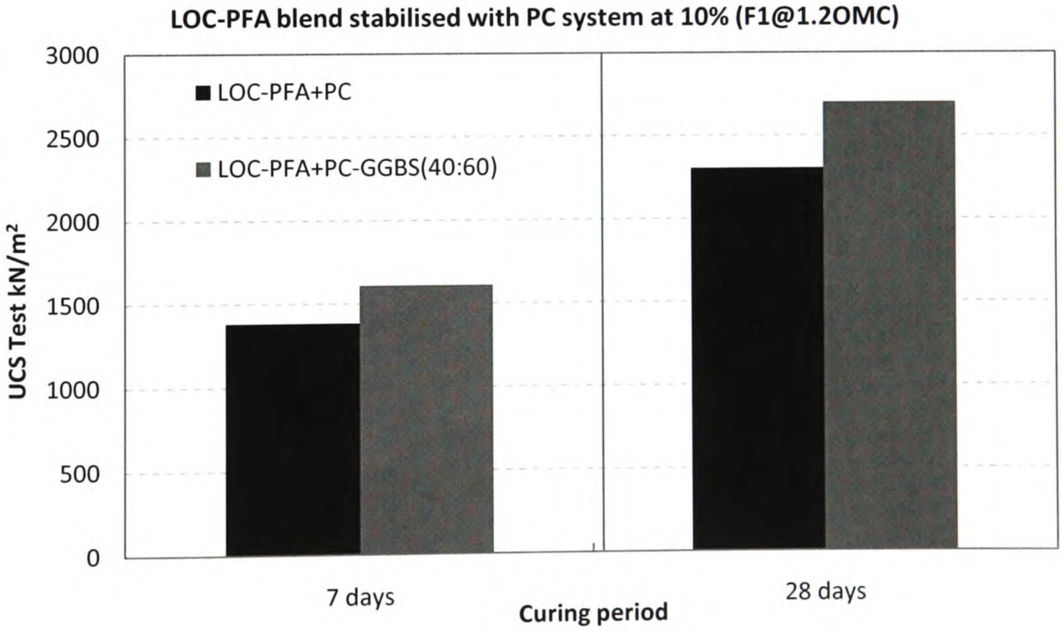


Figure 5.8-2: LOC-PFA Stabilised with the PC stabiliser system

5.8.1.2 Unconfined Compressive Strength of the PC System

Figures 5.8-2 shows the UCS test results of LOC-PFA unfired bricks stabilised with the PC stabiliser system at a 10wt% stabiliser dosage. Like in the lime system, the strength development increased progressively from 7 days to 28 days of curing with both stabilisers (PC only and blended PC-GGBS at (40:60) ratio.

At 7 days of curing, the highest UCS value of 1609 kN/m^2 was recorded when LOC-PFA was stabilised with blended PC-GGBS at (40:60) ratio. At 28 days of curing, the same pattern in strength development was observed as at 7 days but with a significant increase in strength values. At this stage, as at 7 days of curing, LOC-PFA stabilised with a blended PC-GGBS (40:60) showed the highest strength value of 2700 kN/m^2 compared to PC only at strength value of 2302 kN/m^2. It is therefore evident that for the trial pilot bricks, the PC stabiliser system showed better performance relative to the lime stabiliser system.

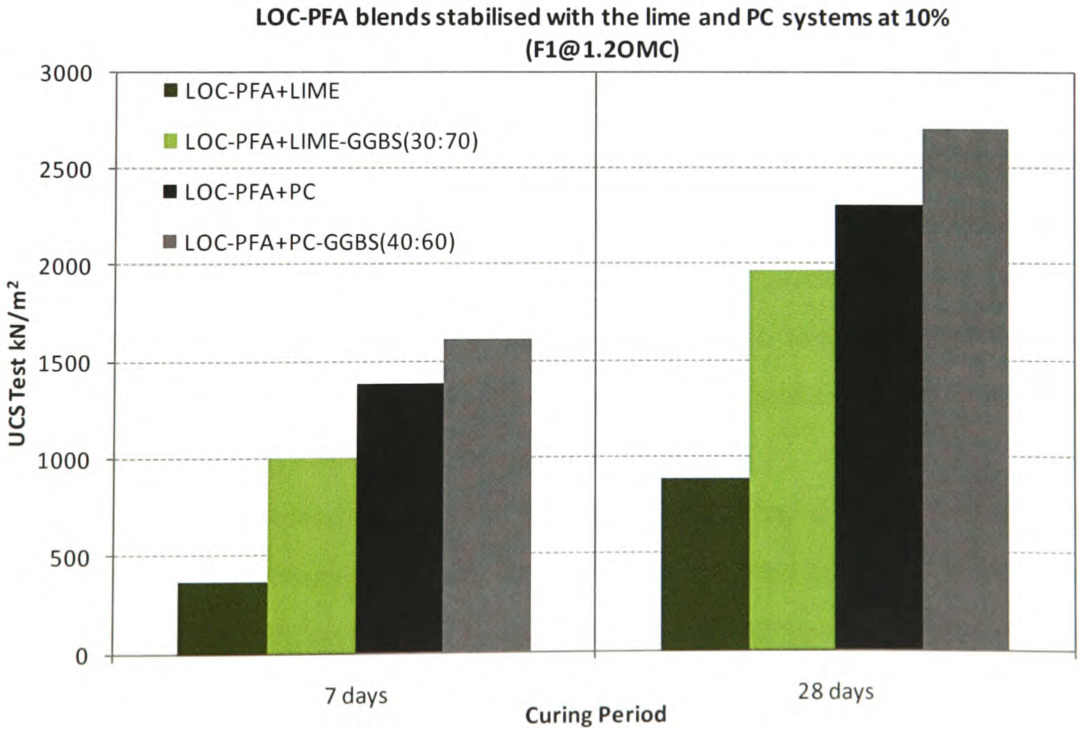


Figure 5.8-3: LOC-PFA Stabilised with lime and PC systems

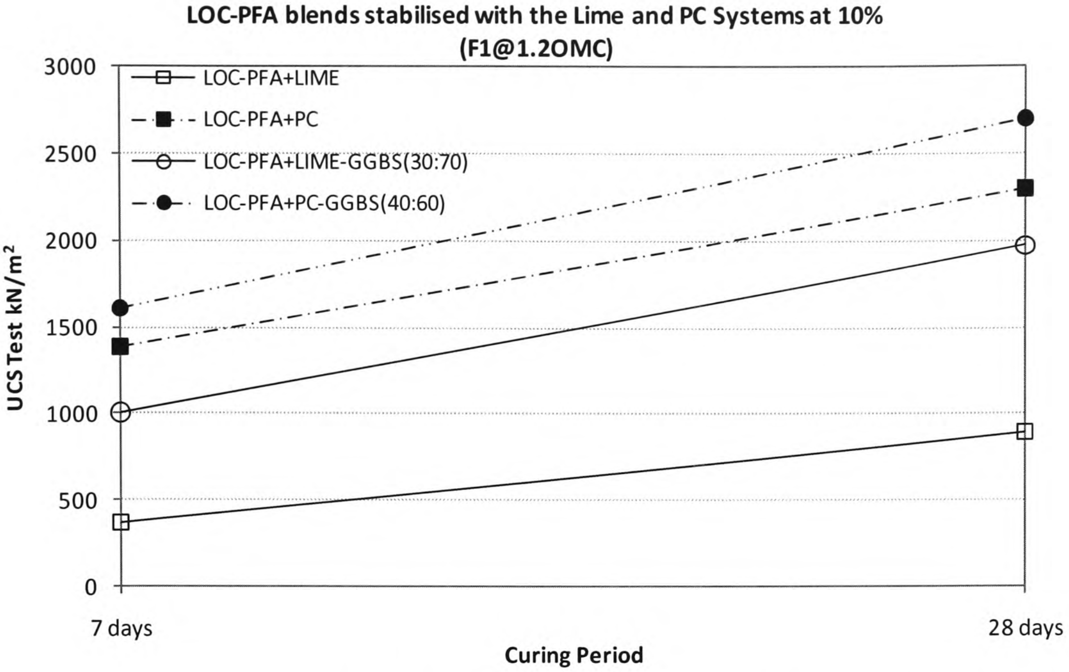


Figure 5.8-4: LOC-PFA Stabilised with lime and PC systems

Together with separate performances illustrated in Figures 5.8-1 and 5.8.2, the following summary observations may be made:-

Summary observations:

- Figures 5.8-3 and 5.8-4 show a summary of the strength development of the pilot trial unfired bricks made with the LOC-PFA blended target material.
- The overall results showed that the blended PC-GGBS (40:60) stabiliser indicated the highest strength values compared to the other stabilisers, at both curing periods of the 7 and 28 days. The PC stabiliser system recorded higher strength values when compared to the lime.
- In general, by blending lime and PC with GGBS, better strength development patterns and magnitudes were observed, compared to LOC-PFA stabilised with lime and PC on its own. This indicates that GGBS has a high potential as a partial replacement material for the traditional stabilisers such as lime and PC. This is beneficial since GGBS has environmental benefits relative to lime or cement, as GGBS is a by-product material.

5.8.2 Water Absorption Test

The water absorption tests for laboratory unfired bricks specimens were carried out in accordance with BS EN 771-1:2003 (Specification for masonry units – Part 1: Clay masonry units). Two bricks per mix composition were subjected to water absorption tests, and the mean % water absorption determined. Overall, results shows higher percentage of water absorption occurred when lime only was used as the stabiliser when compared to other. In general, the increase percentage of water absorption was reduced with the increase in the soaking period.

5.8.2.1 Water Absorption of the Lime Stabiliser System

Figure 5.8-5 shows the percentage water absorption for LOC-PFA unfired bricks stabilised with the lime system, at 10wt% stabiliser dosage. In general, it shows that the combined lime and GGBS stabiliser reduced the percentage water absorption of the stabilised unfired bricks. The overall results of LOC-PFA unfired bricks stabilised with lime only shows a water absorption capacity of 20-22% from day 1 up to 56 days of soaking, while the blended lime-GGBS (30:70) showed a slightly lower water absorption of 16-18%. The water absorption is highest during the first 3 days of soaking, and reduced at later ages when the water absorption is fairly gentle.

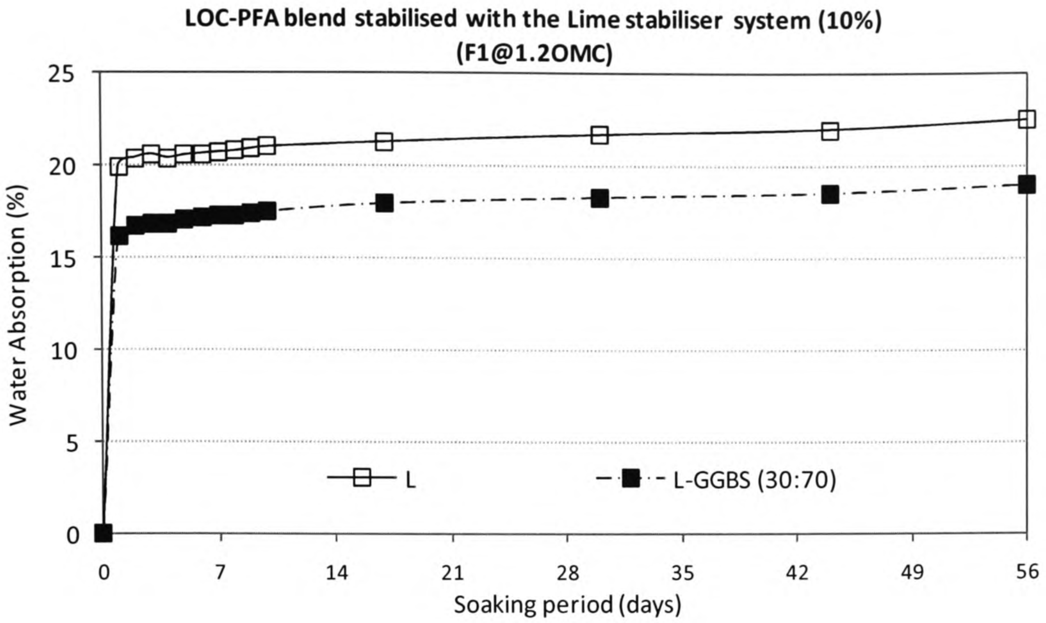


Figure 5.8-5: Water absorption against soaking period of unfired bricks stabilised with the lime stabiliser system

5.8.2.2 Water Absorption of the PC Stabiliser System

Figure 5.8-6 shows the percentage water absorption for LOC-PFA unfired bricks stabilised with PC system at 10wt% stabiliser dosage. In general, both stabilisers show a similar pattern of water absorption capacity. The blended PC-GGBS absorbed marginally more water at the beginning of soaking period when compared to PC, but ultimate absorption rate was minimal for both stabilisers, after 10 days of soaking period. The overall absorption for both PC stabilisers was between 7-10%.

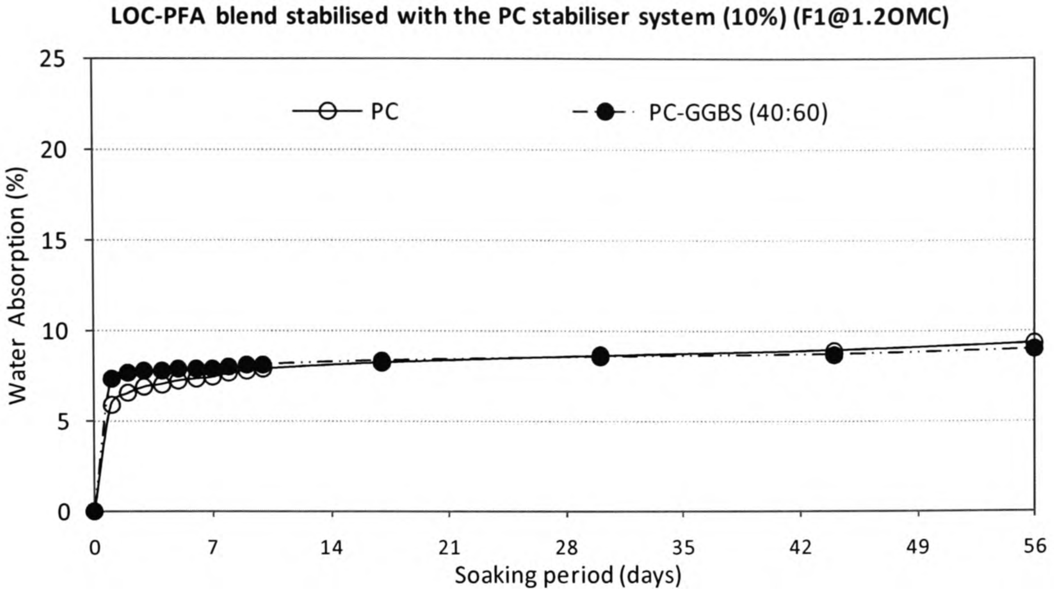


Figure 5.8-6: Water absorption against soaking period of unfired bricks stabilised with the PC stabiliser system

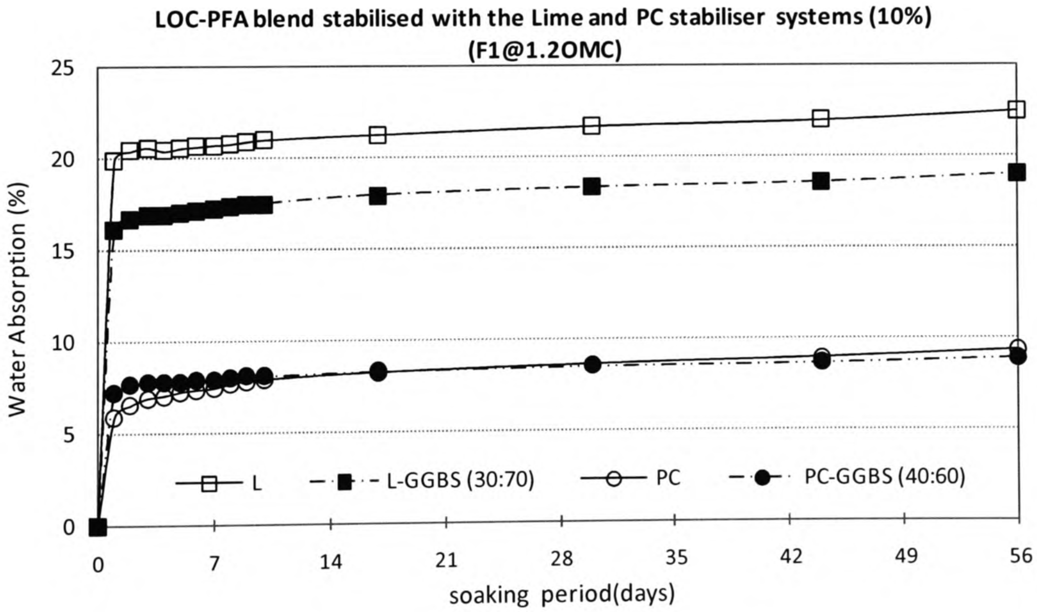


Figure 5.8-7: Water absorption against soaking period of unfired bricks stabilised with the lime and PC stabilisers systems

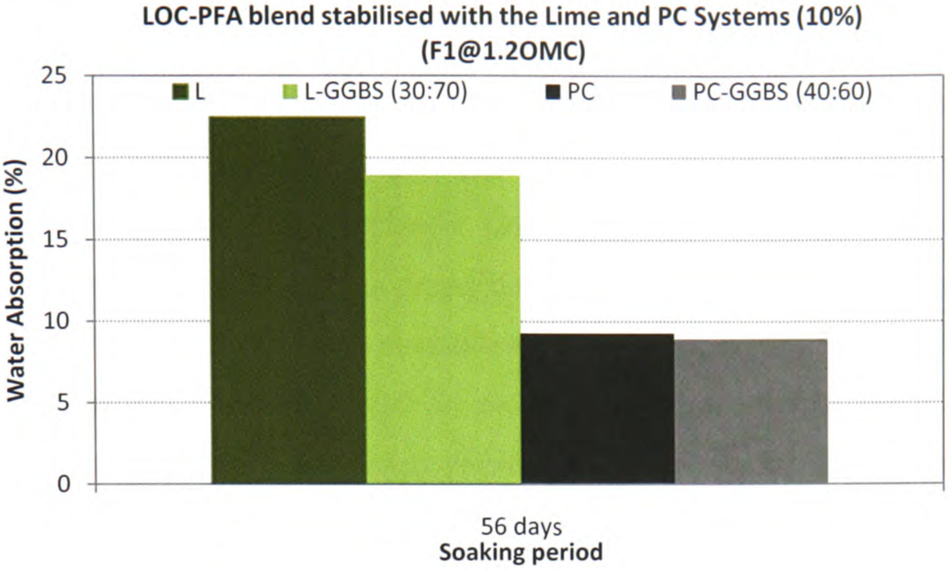


Figure 5.8-8: Bar chart shows, water absorption against soaking period of unfired bricks stabilised with lime and PC systems at 56 days of soaking

Figures 5.8-7 and 5.8-8 show a summary of the water absorption test results for both lime and PC - based stabiliser systems. The following summaries may be made:-

Summary observations:

- The overall results showed that the PC stabiliser system demonstrated better performance with regard to their water absorption behaviour compared to the lime system.
- In general, blending lime with GGBS, resulted in better performance with regard to water absorption behaviour.
- In all cases with lime and PC systems, water absorption decreased with increasing soaking period.

5.8.3 Thermal Conductivity

The thermal conductivity was determined in compliance with BS EN 1745.2002 (Masonry and masonry products – Methods for determining design thermal values). Test specimens of dimension 140mm x 147mm x 40mm thick with a density of 1540kg/m^3 were prepared. For the production of LOC-PFA (50:50) unfired bricks for thermal conductivity tests, 4 sets of stabilisers were adopted, all at 10%wt dosage. They were blended lime-GGBS at (30:70) and PC-GGBS at (40:60) together with lime and PC only as control sets using formula F1@1.2OMC for establishing the compaction moisture content. For each test specimen, thermal conductivity measurements were carried out for eight temperature settings as shown in Table 4.8 (Chapter 4 – Experimental Procedures). Two samples were carried out for each stabiliser, and mean value was taken.

Thermal conductivity (*k*) used to assess the ability of material to transfer heat by conduction. It also refers to the heat flow rate (Φ), and represents thermal energy transfer in unit time and is measured in Watts (joules/second). The building regulations in the UK (Building Regulation L1 & L2, 2000) specifies a thermal conductivity value of 0.77W/mK for outer leaf brickwork having a density of 1700kg/m^3.

5.8.3.1 Thermal Conductivity of the Lime Stabiliser System

Figure 5.8-9 shows, the results for the thermal conductivity of unfired LOC-PFA bricks stabilised with the lime system, with two specimens tested for each stabiliser. Figure 5.8-10 shows, the mean values for each of the two specimens per mix composition. The overall results indicated that LOC-PFA stabilised with lime only showed higher thermal conductivity value compared to LOC-PFA stabilised with blended lime-GGBS at 30:70 ratio. Kim *et al.,* (2003) have reported that replacing cement with fly ash and slag decreased the thermal conductivity. Increase in temperature also indicated an increase in the thermal conductivity. This was supported by Wang (2003) in his report for U.S Department of Energy on 'Thermal Conductivity Measurement of Kaolite' who has reported as temperature increase, thermal conductivity of most insulating materials also increases. For this system the highest mean thermal conductivity value was 0.368W/mK at 62.5°C when LOC-PFA was stabilised with lime only. The lowest value was 0.264W/mK at -7.5°C with lime- GGBS (30:70).

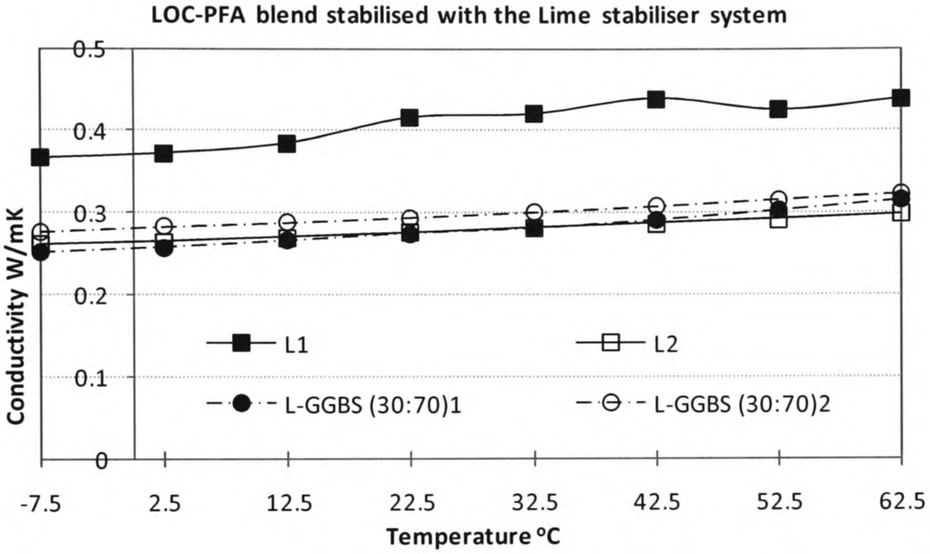


Figure 5.8-9: Thermal conductivity against temperature for LOC-PFA stabilised with the stabiliser lime system

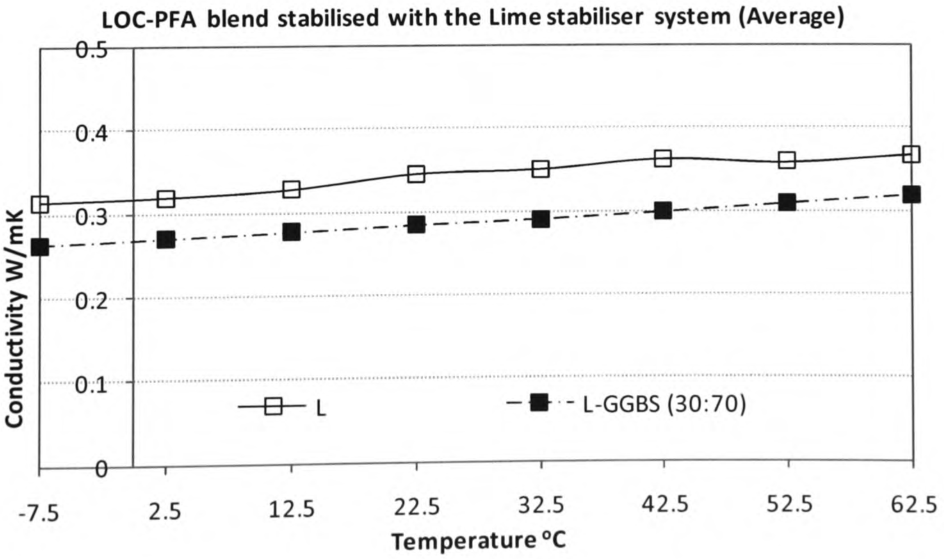


Figure 5.8-10: Thermal conductivity against temperature for LOC-PFA stabilised with the lime stabiliser system (mean value)

5.8.3.2 Thermal Conductivity of the PC System

Figure 5.8-11 shows, the overall results for thermal conductivity of unfired LOC-PFA bricks stabilised with the PC system, with two specimens were tested for each stabiliser. Figure 5.8-12 shows, the mean values from the two specimens. Like in the lime system, blending PC with GGBS showed a decrease in the thermal conductivity and with the increase in the temperatures there was increased thermal conductivity. In general, LOC-PFA stabilised with PC only indicated higher thermal conductivity values compared to LOC-PFA stabilised with blended PC-GGBS (40:60) at all temperature levels.

For this PC system, the highest mean thermal conductivity value was 0.353W/mK at 62.5°C when LOC-PFA was stabilised with blended PC only. The lowest value was 0.271W/mK at -7.5°C with blended PC-GGBS (40:60).

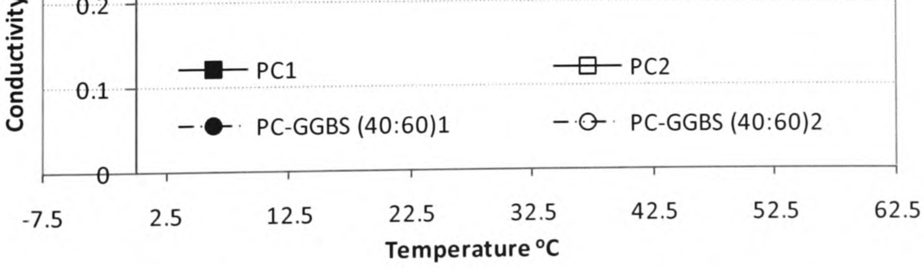


Figure 5.8-11: Thermal conductivity against temperature for LOC-PFA stabilised with the PC stabiliser system

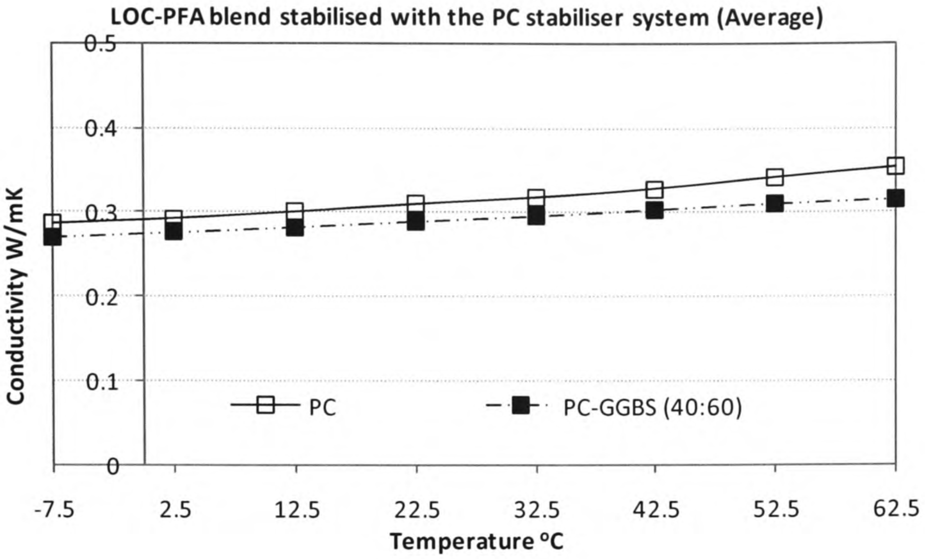


Figure 5.8-12: Thermal conductivity against temperature for LOC-PFA stabilised with the PC stabiliser system (mean value)

Summary observations:-

The summary trends of the thermal conductivity results for both lime and PC systems are shown in Figure 5.8-13. The maximum and minimum thermal conductivity values are then summarised in the Table 5.8-1 and Figure 5.8-14. From these summarised data, it is evident that:-

- By blending GGBS with lime and PC, there is reduced thermal conductivity of stabilised LOC-PFA unfired bricks when compared LOC-PFA stabilised with lime and PC on their own.
- Lime-GGBS (30:70) indicated lowest thermal conductivity at all temperatures when compared to all other stabilisers.
- In all cases increase in temperatures increased the thermal conductivity values.

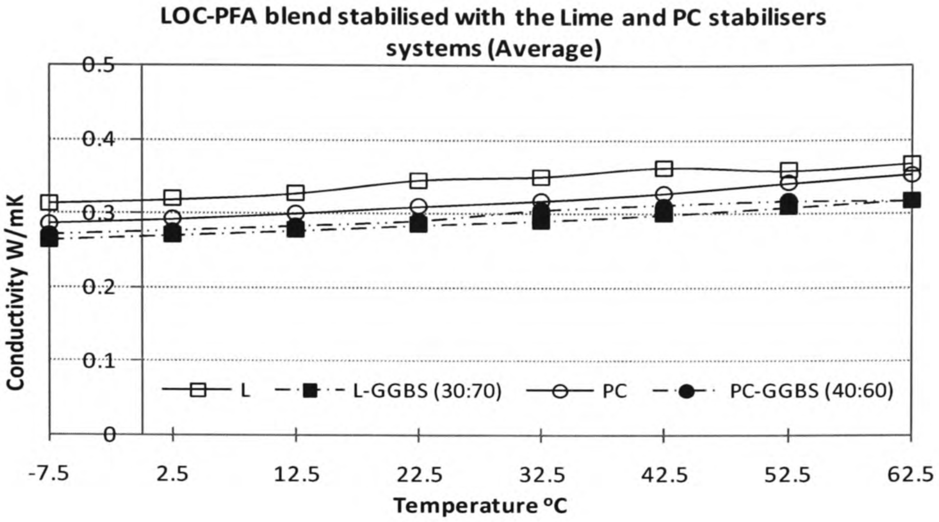


Figure 5.8-13: Thermal conductivity against temperature for stabilised unfired LOC-PFA bricks stabilised with the lime and PC stabilisers systems

Table 5.8-1: Thermal Conductivity of unfired LOC-PFA bricks stabilised with the lime and PC stabilisers systems at 7.5°C and 62.5°C

Stabiliser	Thermal Conductivity (W/mK) at -7.5°C	Thermal Conductivity (W/mK) at 62.5°C
Lime	0.31	0.37
Lime-GGBS (30:70)	0.26	0.32
PC	0.29	0.35
PC-GGBS (40:60)	0.27	0.32

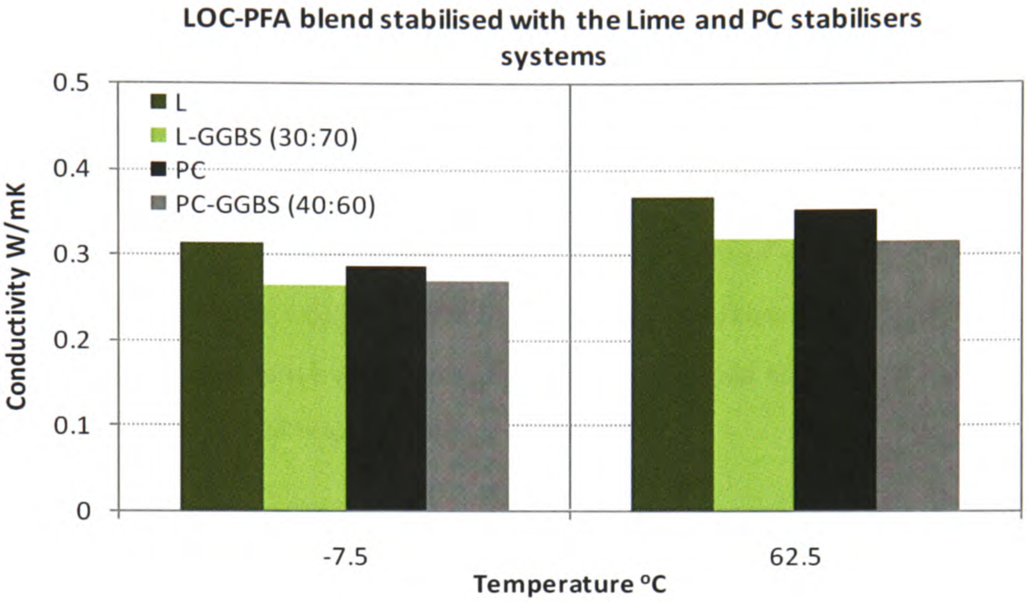


Figure 5.8-14: Bar chart of thermal conductivity against temperature for stabilised unfired LOC-PFA bricks with the lime and PC stabilisers systems

5.8.4 Freeze and Thaw

The effect of freezing and thawing on LOC-PFA blends stabilised with lime and PC binder systems was studied using the unfired bricks produced at laboratory scale pilot trials. The test adopted for this study was modified from DD CEN/TS 12390-9:2006 (Testing harden concrete: Freeze-thaw resistance) and BS 5628-3:2005 (Code of practice for the use of masonry: Materials and components, design and workmanship). These were based on dry and wet tests (see Chapter 4.8.4). The specimens were subjected to freeze-thaw cycles at temperature of +20°C to -15°C in the first 16 hours (see Table 4.6). The temperature was then raised again to +20°C (within 2 hours) for the purpose of thawing and was maintained constant at +20°C for 6 hours to complete the 24 hours cycle (see Figure 4.10).

5.8.4.1 Weight loss due to dry freezing and thawing: Lime-based System

Figure 5.8-15 shows the overall freezing-thawing the results for unfired LOC-PFA bricks stabilised with the lime-based system. As the freezing and thawing cycle increased, the weight losses of the bricks also increased. The weight losses are within the range of 0.80% –2.58% at the end of 30th cycle. Test specimen stabilised with lime only showed higher percentage weight losses when compared to blended lime-GGBS (30:70) stabiliser. Both stabilisers show reduction in the percentage weight loss starting from the 21st cycle. There is only about 0.20% increases in weight loss with both stabilisers from the 14th to the 28th cycle. The highest weight loss being 2.58% with lime only at 30th cycles.

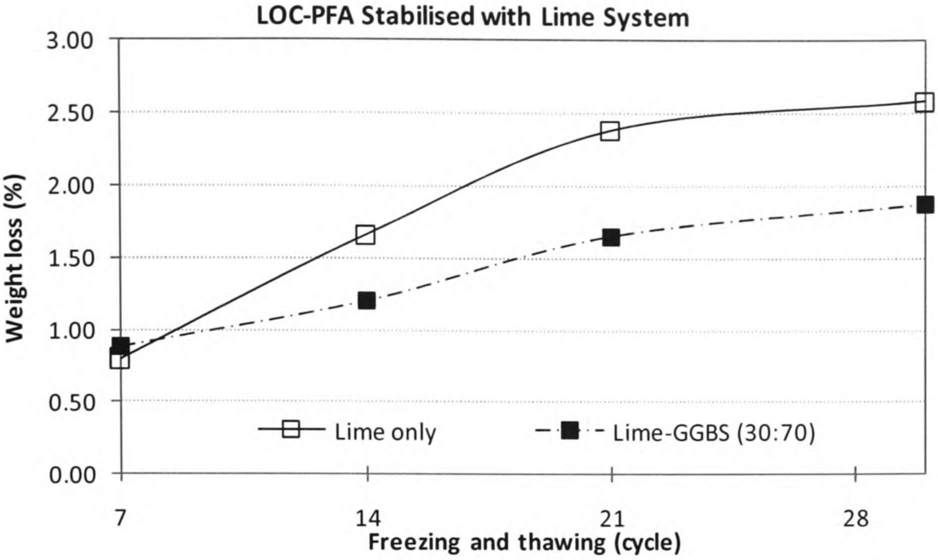


Figure 5.8-15: Percentage weight loss in unfired LOC-PFA bricks stabilised with the lime-based system.

5.8.4.2 Weight loss due to dry freezing and thawing: PC-based System

Figure 5.8-16 shows, the overall results for the unfired LOC-PFA bricks stabilised with the PC-based system. The weight losses are similar to those in the lime system which being within the range of 0.26% – 2.70% at the end of 30th cycle. PC only, showed higher percentage of weight loss when compared to blended PC-GGBS (40:60), lime or lime-GGBS (30:70). PC only test specimens showed higher percentage weight losses during the first 7 cycles of freezing and thawing when compared to the blended PC-GGBS (40:60). However with PC only, the weight loss was stable after the 21st freezing and thawing cycle. The overall results indicated that the blended PC-GGBS at 40:60 ratio had the lowest percentage weight loss (at 0.74%) within the 30th cycle of the freezing and thawing when compared to PC only, and compared with both stabilisers in the lime system.

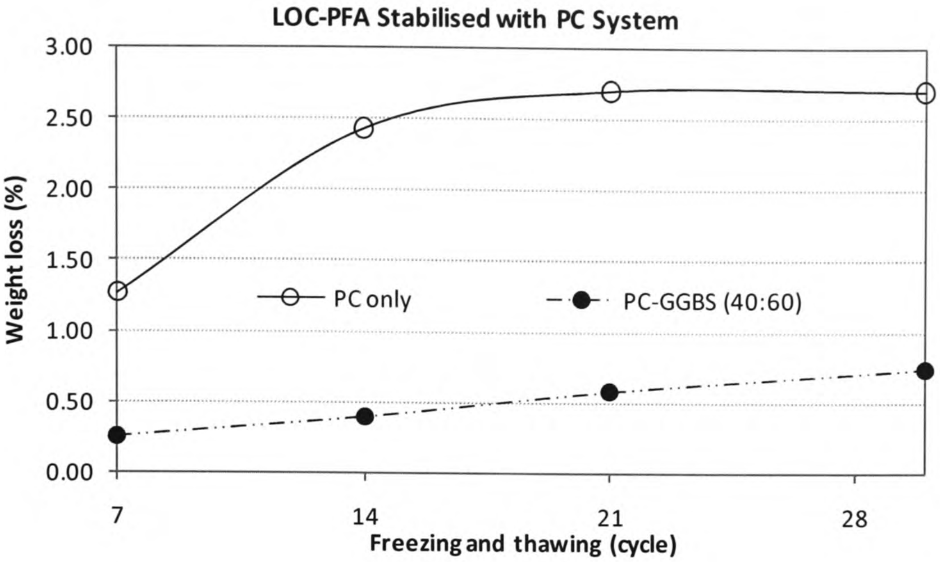


Figure 5.8-16: The percentage of weight loss of LOC-PFA unfired bricks stabilised with PC systems.

5.8.4.3 Physical Assessment at the end of the 30th freezing-thawing cycle (Dry Test)

The analysis of results of the examination of the specimens after the 30th freezing and thawing showed no damage of any type with both stabiliser systems. The condition of bricks at the end of the test can be seen in the Figure 5.8-17. Table 5.8-2 shows the detailed assessment of the results of unfired LOC-PFA bricks after the 30th freezing and thawing.

Table 5.8-2: Assessment of physical damage on the unfired LOC-PFA bricks at the end of the 30th freezing and thawing cycle.

Description of Damage	Remarks
Hair Crack > 0.2mm	No hair cracks were observed
Minor Crack	No minor cracks were observed
Surface Crack > 0.2mm	No surface cracks were found
Chipping	No chipping were noted
Peeling	No pilling were noted
Scaling	No scaling were noted
Fracture	No fracture were observed
Breaking, delaminating	No sorts of breaking or delaminating were noted during the entire freezing and thawing cycles.

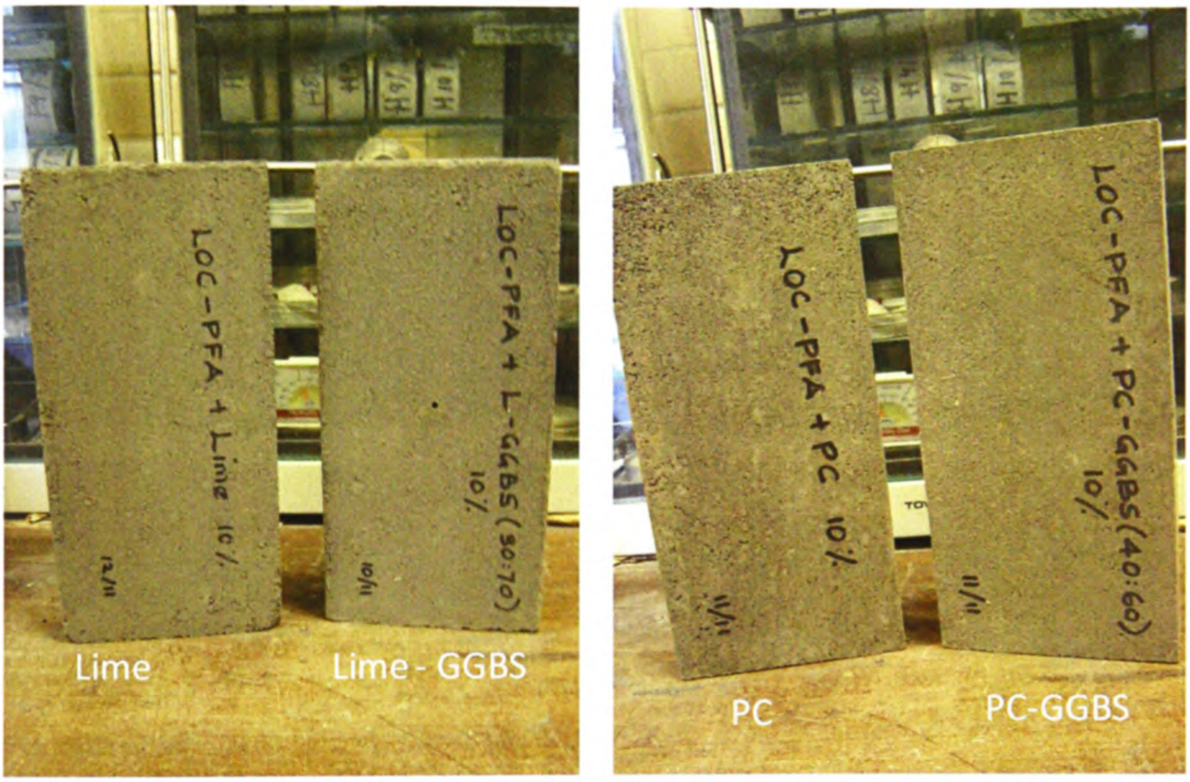
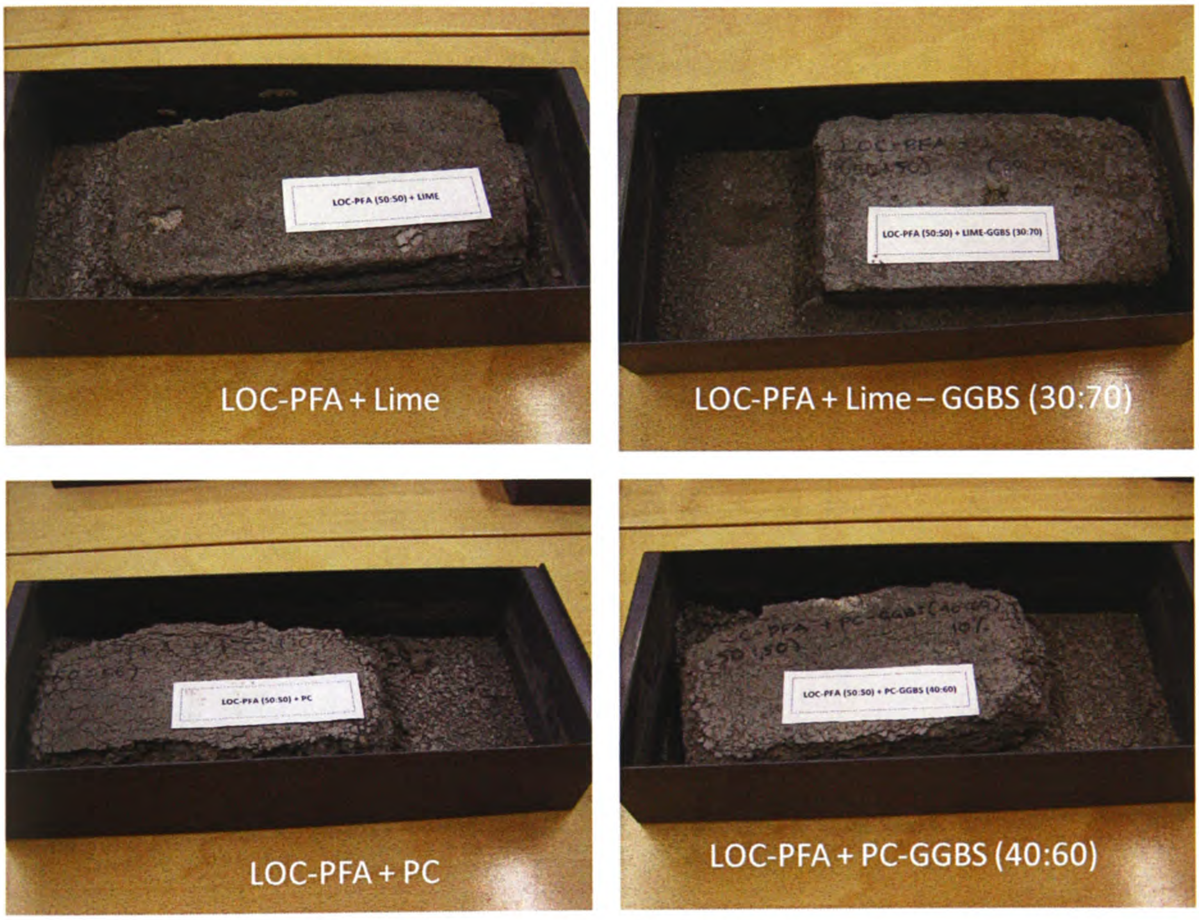


Figure 5.8-17: Condition of unfired LOC-PFA bricks after 30th cycle of dry freeze and thaw test.

5.8.4.4 Physical assessment at the end of the wet freezing and thawing test

The analysis of results of the examination of the specimens after the wet freezing and thawing cycle, showed all the specimens were collapsed, and test was terminated after 7th cycle. The condition of the bricks at the end of the test can be seen in the Figures 5.8-18.


LOC-PFA + Lime

LOC-PFA + Lime – GGBS (30:70)

LOC-PFA + PC

LOC-PFA + PC-GGBS (40:60)

Figure 5.8-18: Condition of unfired LOC-PFA bricks after 7th cycle of wet freeze and thaw test.

Summary observations:

- The overall results (see Fig. 5.8-(19) and (20)) showed that by blending GGBS with lime and PC, the percentage weight loss of stabilised unfired LOC-PFA bricks was reduced when compared with stabilisation it with lime and PC on their own.
- PC-GGBS (40:60) indicated lowest weight losses at all cycles when compared to other stabilisers.

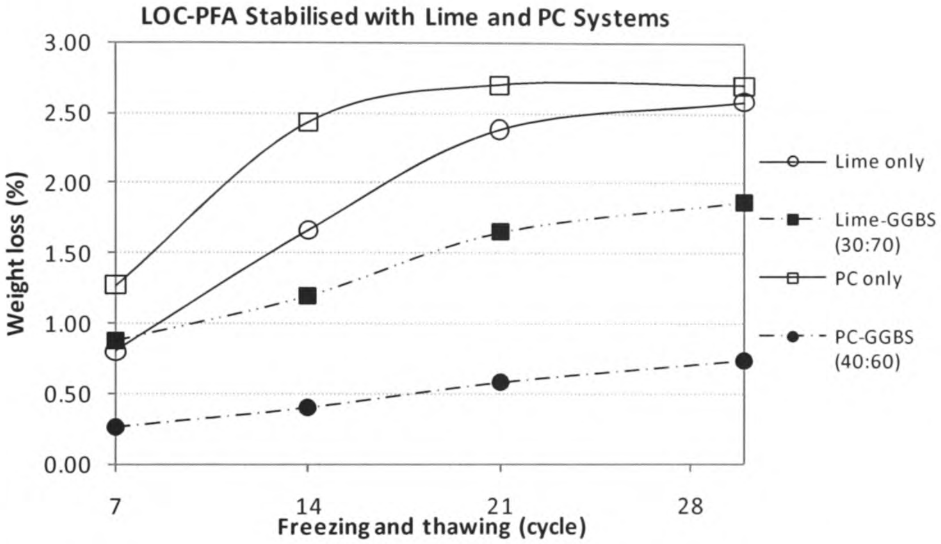


Figure 5.8-19: Percentage of weight loss of unfired LOC-PFA bricks stabilised with the lime and PC binder systems.

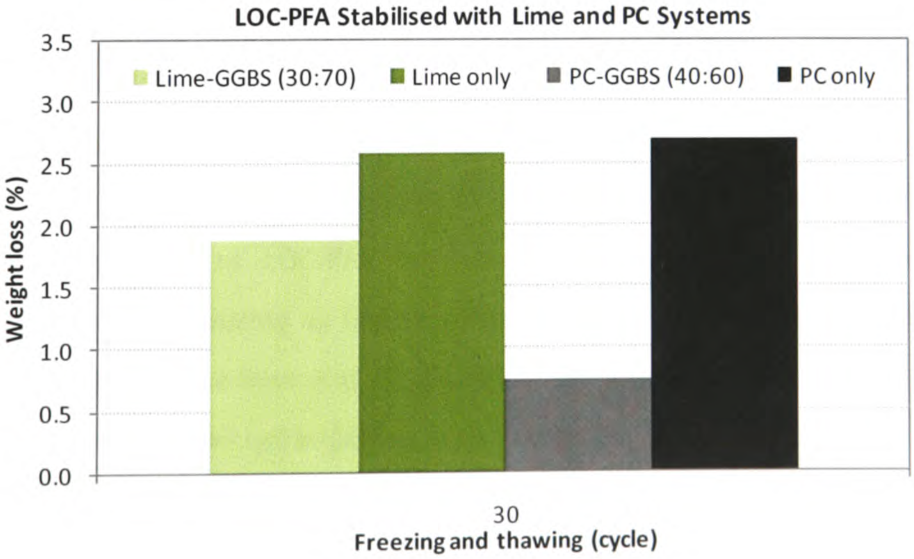


Figure 5.8-20: Weight losses at the 30th cycle of freezing and thawing of unfired LOC-PFA bricks stabilised with lime and PC binder systems

5.8.5 Environmental Evaluation

The environmental evaluation of the LOC-PFA target blend stabilised with the lime and PC stabilisers systems were studied using the experimental unfired LOC-PFA bricks made during the pilot industrial commercial trials reported in Chapter 4. A comparison was made between the unfired bricks in the current study and common fired clay bricks, and also with other brick types such as sun baked clay and PC-stabilised bricks that widely used in the construction industry today.

The comparison used in this study includes firing energy, stabiliser content, durability, design applications, overall cost of end product and the use of PC. It is expected that the final outcome of the experimental unfired LOC-PFA bricks in the current study demonstrate relatively low end product costs and low impact to the environment. Based on test results from this research, this is achievable when compared to common fired clay, sun baked and PC-stabilised bricks which have comparative application in the building industry. With the acceptable UCS values (see Section 5.8.1) and other durability properties, this product is expected to be part of effective internal brickwall that well competes with conventional fired bricks, sun baked clay bricks and PC-stabilised bricks, especially for low cost and non-load bearing wall. The most important key, due to its sustainable this unfired LOC-PFA brick is acceptable to be used in environmentally friendly building application.

By stabilising LOC-PFA with the lime and PC stabiliser systems, this product has overcome the problem with traditional sun baked clay bricks of vulnerability to water damage (see Section 5.8.2–water absorption). The additional of the lime-and-PC-based stabiliser systems to LOC-PFA has enhanced many of the engineering properties of the soil, producing an improved building material. At the same time, the addition of GGBS to the lime and PC-stabilised soil system has improved many engineering properties of the soil including its durability.

The unfired clay technology using GGBS as the main stabilising agent for production of building bricks helps remove the energy costs of the firing process, reduce environment damage associated with the manufacturing of traditional stabilisers, and thus, reduce greenhouse gas emissions that contribute to global warming (Oti, *et al,*. 2008). GGBS has extremely low energy usage and CO_2 emission when compared with PC (Higgins, 2005). On the other hand, in view of the huge demand for building bricks, along with reduced availability of suitable soil, there is need to explore alternative raw materials and energy efficient technologies for making bricks (Malhotra and Dave, (1992)). According to Joshi and Lohtia (1997), fly ash can be used to replace up to 40% clay, the main raw material in building blocks and tiles. These certainly contribute to the recycling of fly ash and hence minimise the impact of fly ash landfills on the environment. At the same time, this helps in the reduction of clay usage for the production of bricks. There are also advantages in using fly ash as a raw material for bricks, such as saving in the firing energy due to the amounts of carbon contained in fly ash (Lingling *et al,*. (2005)). Products that contain coal ash such as PFA are considered "green" products because their use conserves land, energy, and natural resources. It also reduces carbon dioxide emissions generated in the production of competing materials, improves the balance of trade, and reduces solid waste (Univ. Of North Dakota, Energy & Environment Research (2003)). According to ScotAsh (2008) each tonne of PFA re used in cementitious products saves an average 900kg of CO_2 emission.

Today, there are few numbers of the environmental assessment methods have been developed and being used in the new product development. As for BREEAM which was developed by the Building research Establishment (BRE) (see Chapter 2, Part II), criteria such as transportation, CO_2 emissions, embodied energy, depletion of resources; use of waste materials, landfill, occupants' health (regarding end-products), product reuse and overall perception in terms of care for the environment were considered.

To allow a comparison of building products, BRE has produced a scoring system that allocates 'Ecopoints' (higher Ecopoints represent higher impact to environment). Under this method, GGBS scores 0.47 Ecopoints, PFA scores 0.066 Ecopoints which are much lesser compared to PC at 4.6 Ecopoints (Higgins, 2007; BRE, 2007). Therefore by taking all the considerations of using waste by-products, it will:

- reduced the amounts of raw material (clay) used and,
- reduced embodied CO_2 through invention of unfired building materials.

The outcome product of this study is certainly acceptable. It is parallel with sustainability concept that had been set by most of the environmental analysis methods. Tables 5.8-(3) and (4) show the environmental benefit of replacing PC with GGBS or PFA, in building materials.

Table 5.8-3: Impact on environment by replacing PC with GGBS or PFA (Higgins, 2007).

Environmental issue	Effect of using 50% GGBS: % reduction	Effect of using 30% PFA: % reduction
Emission of CO_2	40	27
Acidification	35	15
Winter smog	35	15
Eutrophication	30	13
Primary energy requirement	30	17

Table 5.8-4: Embodied CO_2 of UK cement, additions and cementitious materials (Clear et al., 2008)

Material	Embodied CO_2 ($kgCO_2/t$)
PC	930
GGBS	52
PFA	4

Table 5.8-5 shows the energy and carbon dioxide emission data found in the literature for the materials used in the current investigation (PFA, PC, lime and

GGBS). Using these values, the energy and CO_2 emission inputs for PFA and the binders combinations in the current study were assessed using the dosage levels adopted. For common fired bricks, the total energy usage is estimated at 4186.8 MJ/t with an equivalent output omissions of 202 CO_2kg/t (Brick Development Association, 2009). Common PC-stabilised bricks with 12% stabiliser dosage have an energy usage of 1025.6 MJ/t, with CO_2 emission of 125.1 CO_2kg/t. Morton (2008) estimated the energy input and CO_2 involved for pressed sun-baked clay bricks were 525.6 MJ/t and 25.1 CO_2kg/t. Using the estimate used by sun-baked clay bricks, the extra energy inputs and CO_2 emissions associated with PFA and blended stabilisers were applied to the unfired bricks in this research. The energy and CO_2 emissions values from the proposed unfired LOC-PFA brick were combined with those from sun-baked clay brick estimated by Morton (2008) for the estimating of energy and CO_2 emission from this current research.

Table 5.8-5: Energy and CO_2 emission values for PFA, PC, lime and GGBS ((Oti, 2010; Swamy, 2010; Clear et al., 2008; Higgins, 2007; Wild, 2003)

Material	At 100% output	
	Energy (MJ/t)	Embodied CO_2 (CO_2kg/t)
PFA	150-400	4
PC	5000	930
Lime	4000	800
GGBS	1300	52

Table 5.8-6: Energy usage and CO_2 emission from bricks production (Brick Development Association, 2009; Morton, 2008).

Types of bricks	Energy usage (MJ/t)	CO_2 emission (CO_2kg/t)
Sun-baked clay brick	525.6	25.1
PC-stabilised brick	1025.6	125.1
Common fired brick	4186.8	202

a) Unfired LOC-PFA target blend stabilised with Lime-GGBS (30:70) at 10% stabiliser dosage

1. **Target material** = LOC-PFA at 50:50 ratio

2. **Stabiliser contents (10%)**

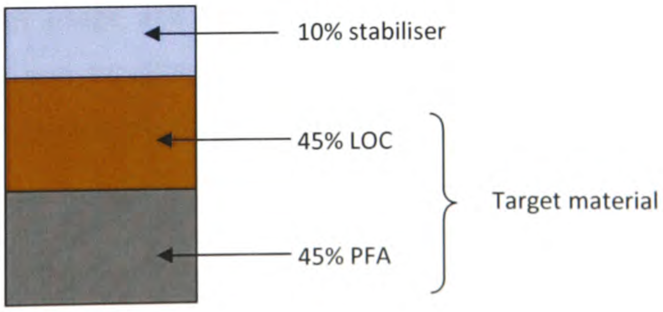
   Lime-GGBS (30:70)

   i. Lime = 3%

   ii. GGBS = 7%

3. Energy inputs (MJ/t)		Energy (MJ/t)
i. PFA	(45% of 275)	= 123.75
ii. Lime	(3% of 4000)	= 120
iii. GGBS	(7% of 1300)	= 91
		≈ <u>335</u>

4. Emission of CO_2		CO_2kg/t
i. PFA	(45% of 4)	= 1.8
ii. Lime	(3% of 800)	= 24
iii. GGBS	(7% of 52)	= 3.64
		≈ <u>29</u>



b) Unfired LOC-PFA stabilised with PC-GGBS (40:60) at 10% stabiliser dosage

1. **Target material** = LOC-PFA at 50:50 ratio

2. **Stabiliser contents (10%)**

   PC-GGBS (40:60)

   iii. PC = 4%

   iv. GGBS = 6%

3. **Energy inputs (MJ/t)**

			Energy (MJ/t)
iv.	PFA	(45% of 275)	= 123.75
v.	PC	(4% of 5000)	= 200
vi.	GGBS	(6% of 1300)	= 78
			≈ <u>402</u>

4. **Emission of CO_2**

			CO_2kg/t
iv.	PFA	(45% of 4)	= 1.8
v.	PC	(4% of 930)	= 37.2
vi.	GGBS	(6% of 52)	= 3.14
			≈ <u>42</u>

Therefore quantification for energy usage and CO_2 emission for unfired LOC-PFA stabilised with lime-GGBS (30:70) and PC-GGBS (40:60) at 10% stabiliser dosage compared to estimated sun-baked clay brick (Morton, 2008) is shows in Tables 5.8-7 and 5.8-8.

Table 5.8-7: Quantification for energy usage of unfired LOC-PFA bricks stabilised with blended lime and PC systems at 10% stabiliser dosage

Analysis for energy usage	**MJ/tonne**
i. Sun-baked clay brick (100% clay)	**525.6MJ/tonne**
ii. LOC-PFA (50:50) + Lime-GGBS (30:70)	
LOC-PFA (50:50) – (50% of 525.6)	262.8
add	
PFA	123.75
Lime	120
GGBS	91
TOTAL	**597.55MJ/tonne**
iii. LOC-PFA (50:50) – PC-GGBS (40:60)	
LOC-PFA (50:50) – (50% of 525.6)	262.8
add	
PFA	123.75
PC	200
GGBS	78
TOTAL	**664.55 MJ/tonne**

Table 5.8-8: Quantification for CO_2 emission of unfired LOC-PFA bricks stabilised with blended lime and PC systems at 10% stabiliser dosage

Analysis for energy usage	**CO_2kg/tonne**
i. Sun-baked clay brick (100% clay)	**25.1 CO_2kg/tonne**
ii. LOC-PFA (50:50) + Lime-GGBS (30:70)	
LOC-PFA (50:50) – (50% of 25.1)	12.55
add	
PFA	1.80
Lime	24.00
GGBS	3.64
TOTAL	**41.99 CO_2kg/tonne**
iii. LOC-PFA (50:50) – PC-GGBS (40:60)	
LOC-PFA (50:50) – (50% of 25.1)	12.55
add	
PFA	1.80
PC	37.20
GGBS	3.64
TOTAL	**55.19 CO_2kg/tonne**

From the above quantification of energy usage and CO_2 emission, it is shown that unfired LOC-PFA bricks contribute much lesser energy usage and emission of CO_2 to the environment when compared to common fired bricks that currently used in the building industry (see Table 5.8-6). Figure 5.8-21 illustrates energy inputs and emissions outputs for the production process of a tonne of the unfired LOC-PFA and others common bricks in building industry as a comparison.

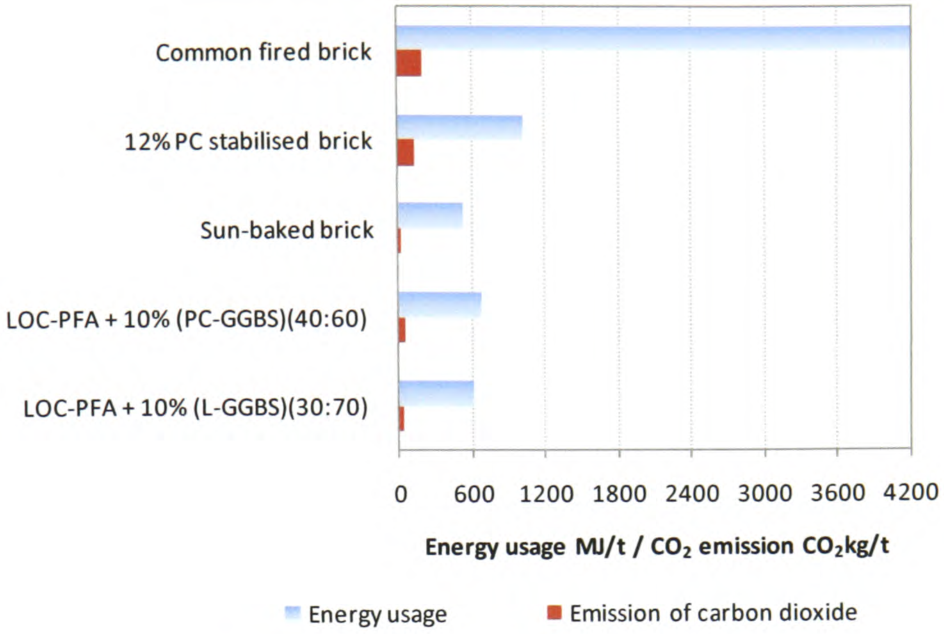


Figure 5.8-21: Estimated energy usage and emission of CO_2 for the production of 1 tonne of bricks

The calculation below shows the total of energy saving in the production of unfired LOC-PFA bricks when compared to the common clay bricks.

Energy used in the production of common brick	≈	4200 MJ/t
Energy used in the production of unfired LOC-PFA	≈	600 MJ/t
Total reduced in energy	≈	3600 MJ/t

Therefore saving in energy used in production:-

3600/4200 x 100% = **85%**

CHAPTER 6

DISCUSSION, CONCLUSSIONS AND RECOMMENDATIONS

In this chapter the experimental results that have been reported in Chapter 5 will be discussed in detail. Observations from experimental results are interpreted and suggestions for possible mechanisms, with respect to the research findings are made, before drawing concluding and making recommendations for further work.

6.1 GENERAL

In the current research, an effort was undertaken to investigate the overall performance of blended Lower Oxford Clay (LOC) and Pulverised Fuel Ash (PFA) an industrial by-product from the coal industry, LOC-PFA blended material. This target material was stabilised with the traditional stabilisers of lime and PC, and also with blended binders comprising of lime or PC with Ground Granulated Blast-furnace Slag (GGBS) a by-product from the steel industry. The use of industrial by-product such as PFA and GGBS, as part of recycle and reused waste toward the production of sustainable building material, is currently a topical issue.

The research work into increasing the strength and durability of unfired clay cementitious technology is original, and has a contribution to knowledge. The main benefit of unfired clay building components is the reduction in manufacturing energy costs and also a reduction in global carbon dioxide (CO_2) production. This research work will be the key to the assessment of the potential of the application of these blended binders in the manufacture of unfired clay building components.

6.2 COMPACTION MOISTURE CONTENT

According to Kaliyan and Vance (2009), moisture content has a significant effect on strength development and durability of the stabilised material. When LOC was stabilised with lime, at a 10wt% dosage, the low strength at both 7 days and 28 days of curing period is thought to be associated with the increase in the amount of water available to the samples. This is evidenced by the fact that by raising stabiliser level from 10wt% to 20wt%, those test specimens with higher moisture contents achieved better strength. It is due to the fact that there was sufficient water to cater for evaporation, hydration and for preventing cracking/expansion. Therefore the tendency to compact soils on the wet side of OMC is good and should continue.

The higher strength development was probably due to the formation of relatively higher amounts of C-S-H gel (Wild *et. al.,* (1999). Low strength values were observed with the test specimens with less compaction water probably due to poor compaction, and a poor hydration. Mitchell *et. al.,* (1959) established that when a cohesive soils were compacted at water contents below the OMC (dry of optimum), it much higher permeability was observed than with the same soil compacted at moulding water contents above the OMC (wet optimum). It is therefore recommended that fine-grained soils be compacted at moisture contents slightly higher than their OMC's (2% - 3% wet of optimum) (Yacoub *et. al.,* (1996)).

Results obtained from varying the optimum moisture content using the two formulae, at OMC and at 1.2OMC showed that there was no consistent trend of change on variation in the strength. This is excellent outcome, as in practice, it is difficult to maintain a consistent material water content in different practical conditions. By raising the level of stabiliser from 10wt% to 20wt%, results indicated that those formulae with higher moisture content achieved better strength. For this reason, the formula that takes into account the changes in water demand and stabiliser dosage (F1) was adopted. The disadvantage of reduced early strength was compensated by the continued strength development at later curing periods, thus avoiding excessive drying and compromised hydration.

6.3 UNCONFINED COMPRESSIVE STRENGTH

Unconfined Compressive Strength (UCS) of stabilised LOC-PFA was investigated using compacted cylindrical specimens of 100mm in length and 50mm in diameter and using the pilot industrial/commercial trial unfired bricks of 295mm x 140mm x 55mm thick. Compaction was followed by subsequent curing periods of 7, 28 and 56 days for the cylindrical specimens and 7 and 28 days for the unfired bricks. It was hard to make strength comparison of the overall results for these two types of specimens due to:

- difference in compacting methods,
- difference in the test methods and
- difference in shape

For both tested specimens the UCS of stabilised LOC-PFA significantly increased after prolonged curing period. Generally, increasing the amount of stabiliser and curing time resulted in increased compressive strength. The preliminary research work demonstrates that changing the target material to include industrial waste/by-products (such as PFA) to clay soil enhance the compressive strength. Using PFA and GGBS as raw materials to replace clay to produce unfired bricks was an effective measure of recycling waste materials, reduces the use of natural resources, reduces energy consumption, and hence produces a new cost-effective product. This fulfils the requirements from most environmental assessment methods, such as BREEAM which required embodied impacts of building materials, including lifecycle impacts like embodied carbon dioxide.

The UK building regulations require minimum brick strengths of 5-8 N/mm^2, for most of clay masonry walling application, but this is not applied to unfired stabilised clay-based material (Oti, 2010). For fired clay brick it requires higher strength but this comes with energy-intensive during the firing processes. This resulted in large production of CO_2 and other omissions. The high strength comes at cost and effects to the environment which caused by firing in the kiln. The unfired stabilised LOC-PFA bricks totally eliminated the firing cost, with little or no environmental burden and adaptation of reused industrial-by products. The current laboratory research product of unfired stabilised LOC-PFA brick is able to resist swelling, shrinkage, cracking, freezing/thawing, and thermal changes due to direct or indirect effect of water and weather conditions.

6.3.1 UCS of LOC-PFA stabilised with the Lime system

In general, with the lime system, increased amount of stabiliser dosage resulted in increased UCS with increasing curing period for both stabilised LOC and LOC-PFA except when lime alone was used as stabiliser (see Chapter 5.4). Low strength values were observed with both formulae for material compacted at the OMC. Research by Nidzam (2004) on soil stabilisation of Oxford Clay with lime-based stabilisers has reported that there was a variability in strength of stabilised soil mixtures especially at high lime dosages, due to lack of adequate water to complete lime hydration.

When lime is added to clay soil, it has an immediate effect on the properties of the soil as cation exchange begins to take place between the metallic ions associated with the surfaces of the clay particles and the calcium ions of the lime. The highly alkaline environment produced by the addition of lime gives rise to the slow dissolution of alumino-silicates, which then participate in the formation of hydrated cementitious reaction products (Diamond and Kinter, 1966). Research by Bell (1996) described the optimum addition of lime needed for maximum modification of the soil as normally between 1% and 3% lime by weight. Beyond this point any lime available is used to increase the strength of the soil. According to Ingles (1987) a good rule of thumb in practice is to allow 1% by weight of lime for each 10% of clay in the soil.

Increasing addition of lime resulted in increased strength after extended curing periods. This is due to increased pozzolanic reaction between lime and the clay fractions. It is recognised that the principal cementitious product of pozzolanic reactions is calcium-alumino-silicate-hydrate (C-A-S-H) gel (Bell and Coulthard, 1990; Brandle, 1981). The strength development of lime-clay material may be attributed to either the gradual crystallisation of C-A-S-H gel (Bell, 1988) or to its continued formation, without necessarily developing a crystalline structure, but blocking pores and providing strength as it develops (Wild *et al.*, 1989).

The overall research findings therefore showed that lime alone at a higher dosage level (20%) when used as a stabiliser was not suitable for both LOC and LOC-PFA.

When GGBS was introduced to the lime system, the lime-GGBS blended stabiliser showed superior strength development relative to the use of lime alone. Based on UCS results, the lime-GGBS blended stabiliser at a 30:70 blending ratio was chosen for further investigations. This was based on better strength development when compared to blended lime-GGBS at 50:50 ratio (see Chapter 5.4). In addition to better strength, the 30:70 mixes is more economical and sustainable as it uses substantial amounts of GGBS relative to lime. Earlier research at the University of Glamorgan (Higgins, 2005; Nidzam, 2004; Kinuthia *et al.,* 2001; Wild *et al.,* 1999) reported that GGBS has minor effects on lime consumption, Atterberg limits and optimum moisture content, and at the same time it was found that inclusion of GGBS can markedly increase the compressive strength of stabilised clays, relative to that achieved by the lime-only.

The use of GGBS is beneficial since GGBS has environmental benefits relative to the lime or PC. Its manufacture involves only a fraction of the energy used and CO_2 emissions associated with either PC or lime (Hakkinen, 1993). In terms of the applicability of GGBS-based stabilisers for highway construction, the performance of the stabilised material has recently been fairly well established. However, in terms of building components, the current research is among the pioneering endeavours to utilise GGBS in building applications besides in concrete.

By blending quicklime or calcium oxide (CaO) with GGBS, the combined pozzolanic reactions result in more gel formation and hence pore refinement and preventing the formation of more voids GGBS may also dilute the stabilised system, thus reducing the amount of expansive potential in the pore space and at the same time increasing the effective water to stabiliser ratio, and this enables a greater level of CaO hydration (Oti, 2010). In the most cases reported by previous researchers dealing with GGBS in supplementary cementing materials, CaO-activated GGBS improves the properties of clay soils during the stabilisation process (Antiohos *et al.*, 2008; Antiohos and Timas, 2004; Bai *et al.*, 2008; Wild *et al.*, 1999; Zhang, 1995).

6.3.2 UCS of LOC-PFA stabilised with PC system

By blending PC with GGBS, almost equal strength development patterns and magnitudes were observed at both 10wt% and 20wt% stabiliser level, compared to LOC and LOC-PFA stabilised with PC on its own. On the other hand, UCS results for pilot industrial/commercial trial, unfired bricks of 295mm x 140mm x 55mm thick indicated higher strength value at both 7 and 28 days when LOC-PFA was stabilised with blended PC-GGBS compared to LOC-PFA was stabilised with PC alone. As mentioned earlier, the differences were due to differences in specimen preparation (compaction, the shape) and test methods. Variations in the strength of the cylinder and brick test specimens is very complex due to the various pozzolanic and other reactions involved in the hydration process within the systems. The overall results indicated higher strength development of stabilised LOC-PFA with lime-GGBS compared to the LOC-PFA stabilised with PC-GGBS in the cylinder specimens. This may be attributed to either the gradual and continued formation of relatively more C-H-S gel within the pore structure, without necessarily developing a crystalline structure, but blocking pores and providing strength as it develops (Wild, *et al.*, 1998).

Results indicated that there was not a good agreement between specimens in the form of block/brick and cylinder. However, both results indicate that GGBS has a good potential as a partial replacement material for PC. This is beneficial since GGBS has environmental benefits relative to lime or cement, as GGBS is a by-product material. Based on these laboratory results, there are possible economic as well as environmental advantages accruing from the use of lime-GGBS blended binders, with or without additional PC to stabilise target materials for the production of unfired clay brick as a building materials.

6.4 DURABILITY

6.4.1 Linear Expansion

To some degree, all building materials containing clay do swell upon contact with water and shrink upon drying. The extent of swelling and shrinking is very much dependent on the present of clay minerals, soil grading and changes in moisture content. When the non-sulfate bearing clays are subjected to moisture, they show intercrystalline swelling (Arabi and Wild, 1989). Water, is strongly adsorbed at the negatively charged clay particle surfaces. An extensive adsorbed layer is formed due to the concentration gradient between the bulk solution and the electrical double layer (consisting of water molecules and exchangeable cations).

The addition of lime or stabiliser modifies the electrical double layer, reducing the thickness of the adsorbed water layer and thus reducing the expansion capacity. There is also a slow chemical reaction which produces cementitious C-A-S-H gels and in some cases crystalline calcium aluminate hydrate and calcium aluminate silicate hydrate phases. The cementing effect of these reaction products binds the clay particles together, thus further resisting expansion. Expansion can lead to cracking of stabilised clay resulting in loss of strength, a decreased service life, or other serviceability and durability problems.

The linear expansion in a sulfate-bearing clay is caused by the sulfate modifying the cementitious products that are produced by the reaction between the soil and stabilising agent. The 'attack' forms expansive compounds such as ettringite. In Lower Oxford Clay soils, where gypsum is usually present, the formation of a colloidal product consisting of a complex calcium-sulpho-aluminate-silicate hydrate (C-A-S-$\bar{S}$-H) is reported to form on the surface of the clay plates (Wild *et al.*, 1993). Ettringite peaks in stabilised LOC-PFA are clearly evident in TGA traces of all LOC-PFA-stabiliser systems (see Figures 5.7-(1), (3), (5) and (7)). The formation of expansive products that lead to linear expansion in the presence of moisture in the stabilised soil is further enhanced by the oxidation of pyrites (FeS_2) in the LOC. This oxidation is known to produce gypsum ($CaSO_4.2H_2O$), evidenced by significant linear expansion when LOC-PFA was stabilised with lime only.

In the lime-stabilised LOC-PFA system, samples exhibited immediate linear expansion upon soaking after 7 days of moist curing (see Figure 5.6-1(a)). The expansion was more stable after 7 days of soaking (day 14) with formulae for calculating compaction moisture content. This lime-only-system showed the highest expansion relative to the PC stabilised systems, as a result of readily available lime and gypsum. When GGBS was used to stabilise LOC-PFA in both (lime and PC) stabiliser systems, a reduction in linear expansion was observed with both methods of calculating compaction moisture content (see Figures 5.6-1(b) and 5.6-2(b)). This is probably due to the formation of cementitious products from GGBS hydration reactions. This resulted in enhanced strength in the LOC-PFA stabilised with GGBS blended binder, with subsequent reduction in linear expansion, compared with the LOC-PFA stabilised with lime only. The results thus show a high potential for GGBS when blended with lime.

When LOC-PFA was stabilised with the PC system, similar linear expansion trends were observed with or without GGBS. This system recorded the least expansion compared to the lime stabilised system, possibly because this system produces a wide range of reaction products resulting from hydration reactions of (i) GGBS and PC themselves separately, (ii) GGBS and PC with each other, and (iii) the separate and combined reactions of GGBS and PC with the LOC-PFA blended target material.

Higgins *et al.,* (2002) reported that stabilisation with lime or cement can produce both physical disturbance and chemical environment that comprise conditions very conducive for pyrite to oxidise to sulfate. The results of the present investigation have shown that for the sulfate-bearing Lower Oxford Clay combined with PFA, stabilisation with blended GGBS was definitely enhanced in terms of compressive strength and linear expansion. Due to non-expansive characteristic and the particle size and shape of fly ash, by increased amount of fly ash in soils it leads to further reduction in swelling (Prabakar *et al.,*(2004). Thus, it can be concluded that for LOC-PFA stabilised with blended GGBS is a significant advantage, not only in terms of engineering properties but also in the environmental aspects, such as reduced in embodied energy and the emission of CO_2.

6.4.2 Water Absorption

Like in the UCS, the variation of water absorption by the test specimens follows a similar pattern; higher initial water absorption reduces with increases in soaking period. For all mixes, the water absorption rate was higher during the first 3 to 7 days of soaking and at later ages lower and fairly stable. The addition of PFA in soils changes the porosity and void ratio within the range of void ratio of fly ash and soils, at bulk density under compaction, the void ratios and porosity are minimum. By adding fly ash up to 46%, the void ratio of soils can be increased by 25% (Prabakar *et al.*,(2004). In both stabiliser systems, blended GGBS reduces the amount of water absorption when compared to the lime or PC on their own. Lime stabilised LOC-PFA blend resulted in the highest water absorption at all ages. Like in the UCS and linear expansion, there were almost similar pattern of water absorption between PC and blended PC-GGBS.

6.4.3 Thermal Conductivity

Blending GGBS with lime and PC reduced thermal conductivity of unfired LOC-PFA bricks. This results were supported by Kim *et al.*(2003) who reported that by replacing cement with fly ash and slag the thermal conductivity decreased .The overall research findings showed that increase in temperatures increased thermal conductivity values of LOC-PFA with all the stabiliser systems. The outcome from this research demonstrates by combining soils with fly ash and stabilised with GGBS the thermal conductivity of bricks is improved. This shows that it is viable to use the bricks developed as part of building elements.

6.4.4 Freeze and Thaw

There were variations in the weight loss due to repeated freezing and thawing tests for both stabiliser systems. The weight loss decreased with increases in the number of cycles. The percentage weight loss of the blended stabilisers (lime and PC) reduced with the incorporation of GGBS due to freezing and thawing cycles. During the test, it was evident that the unfired LOC-PFA bricks stabilised with all the stabiliser systems were able to resist the ice crystallization pressure, resulting with only minor loss in weight and without any breaking. Blended PC-GGBS demonstrated the lowest percentage weight loss compared to others stabilised systems. At the end of 30th cycle, the assessment conducted showed no damage of any type for all stabilised systems (see Figure 5.8-17). This was totally in contrast with the results showed by wet freezing and thawing test, where all the bricks were totally damaged at the end of 7th cycle (see Figure 5.8-18). Most stabilised clay masonry building materials are durable as long as they are not saturated with water (Oti, 2010). According to Cultrone *et al.*,(2007), in most cases, freezing of pore water inside masonry building material occurs when it is subjected to repeated freezing and thawing.

6.5 ENVIRONMENTAL PERFORMANCE

The current research analysed the environmental performance of unfired LOC-PFA bricks in term of carbon emissions and energy balance compared to other common bricks in the construction industry. The results show (see Section 5.8.5) that unfired LOC-PFA bricks can be used to replace or be used concurrently with other available bricks in the building industry. The practical implications of this experimental programmed is that unfired bricks can be used for community-based housing development and can be applied to internal wall construction, with the overall target of improving the quality, cost effectiveness and most importantly, it can be considered as part of sustainable building materials. With less energy output and less CO_2 emissions during the production stage this type of unfired brick can be classified as a 'green building material'. The use of GGBS as blended stabiliser with lime and PC has reduced the amount of traditional stabiliser used in brick making, especially with PC which is known as one of the main contributors of CO_2 in the construction industry.

This study has shown that unfired bricks can be produced using a combination of LOC and PFA, stabilised with activated GGBS. This outcome would offset the current decline in the production of fired bricks arising as a result of growing sustainability awareness and new emissions target (Oti, 2010). With low energy used and no kiln firing required during production, this reduces the cost of the end products. Using similar techniques, there is also possibility of using alternative types of binder combinations or other types of pozzolans as has been demonstrated such as adopted in the current research.

From the environmental assessment point of view, the use of lime-GGBS is more sustainable and practical, since blends containing PC have more impact to the environment with the production of PC being associated with high energy consumption and high emission of CO_2. On the other hand, the embodied energy from the unfired bricks technology using PFA and GGBS is considered a practical and realistic aim for engineers and developers with interests in low-embodied energy design.

6.6 CONCLUSIONS

The main objective of this research work was to study the potential development of unfired bricks from blended clay (LOC) and industrial waste and/or by-products (PFA). The use of PFA and GGBS certainly improves the properties of building material, and can become a wealth generator by making use it for producing 'green building' materials. By avoiding firing and reducing the amount of PC in bricks, industry will reduce the amount of CO_2 emitted into the atmosphere. There are possible high benefits from this study in terms of technology, economy and of the environment. This section deals with the conclusions of the research work.

The following conclusions may be drawn from the work described in this thesis:

- The results obtained from this investigation suggest that there is potential in the use of PFA with low CaO content as substitute or additive to clay for unfired bricks. This will certainly contribute to the recycling of fly ash and hence to minimise the impact of the fly ash landfills on the environment. At the same time this helps in the reduction in clay usage for the production of bricks. Furthermore, the hazardous emissions of the firing process from bricks making will be minimised.

- Using PFA and GGBS as raw materials to make unfired bricks is an effective step towards enhancing recycling of waste and by-product materials, reducing the use of natural resources, reduces energy consumption, and hence produces a new cost-effective product. This is also fulfilling the criteria set by most environmental assessment methods for the selection of the materials for use for "green" building.

- Results obtained from varying the optimum moisture content using two formulae at OMC and at 1.2OMC showed that there is no consistent trend of in the variation of the compressive strength. This is good outcome, as in practice, it is difficult to maintain a consistent material water content in different practical conditions. By raising the level of stabiliser from 10wt% to 20wt%, results indicated that those formulae resulting in higher moisture contents achieved better strength. For this reason, the formula that takes into account the changes in water demand as a result of changes in stabiliser dosage (F1) are recommended. By compacting at relatively higher moisture content, the disadvantages of reduced early strength are by far compensated development when compared to the blended lime-GGBS at a 50:50 ratio. At the same time, the 30:70 stabiliser blend is more economical and sustainable as it uses the more economical and sustainable GGBS relative to lime. The blended PC-GGBS (40:60) may also be chosen, based on the economic considerations, and also for showing equal strength development patterns when compared with PC-GGBS at a 60:40 blending ratio. The PC-GGBS 40:60 uses more GGBS relative to 60:40, while the performance is not compromised. Besides saving in energy, the use of GGBS to replace traditional stabilisers such as PC will reduce the production of CO_2.

- The success of pilot industrial commercial trials for unfired LOC-PFA bricks was a good outcome as it showed that it is possible to utilise lime-GGBS blends without dosing with PC as viable binders for the manufacture of sustainable building materials.

- The research findings showed that lime alone at higher dosage when used as a stabiliser was not suitable for both LOC and LOC-PFA. With the incorporation of GGBS in the lime system, production of more C-S-H gel within the pore structure was promoted; this resulted in better strength and durability properties in the stabilised LOC or LOC-PFA-Lime-GGBS system.

- The research finding showed contrasting results in terms of UCS between cylinder test specimens and blocks/bricks used in the pilot industrial commercial trials. This variation can be attributed to differences in the method of sample preparation, with cylinder specimens compaction using a hydraulic jack resulted in more compact material, and bricks are based on manual compaction by hand resulted in lower density as suggested by reduced strength.

- Most of environmental assessment methods used LCA for the assessment of building materials. This method to ensure the accuracy and comparability of each materials to other, the LCA rules cannot consider a quantity of material on its own, since a construction material or product can only be defined in life

- Most of environmental assessment methods used LCA for the assessment of building materials. This method to ensure the accuracy and comparability of each materials to other, the LCA rules cannot consider a quantity of material on its own, since a construction material or product can only be defined in life cycle terms when considered in the context in which it is used. By using this approach, different materials can only be compared on a like basis as a group of components that fulfil the same similar functions and not as individual products.

- The research outcome showed compliance with the thermal properties of masonry bricks. It can therefore be used for low-medium cost construction and economical alternative to the fired building wall elements.

6.7 RECOMMENDATIONS FOR FURTHER WORK

Although this research work successfully covered a wide area on the effects of using PFA with low CaO contents as part of the target materials for unfired bricks, and effects of utilising GGBS as a stabiliser, there are still several questions that can be raised by the work presented in this thesis which could not be included over the relatively short period of 3 years. The following are outlines of practical implications of the current research work worthy of further study.

- The current work has indicated that there is an increasing number of potential non-traditional sustainable soil stabilising agents, with same techniques applied in this research, other stabilising agents can be used as part of the main target materials (e.g magnesium oxide, brick dust, filter cake (aggregate dust)), and as stabilisers (e.g aluminium waste, cereal ash, rice husk ash) with appropriate ratios for the better strength and durability achievement.

- A wider range of analytical studies on the cured stabilised samples is advocated, especially on the microstructure of the harden mixture, such as X-Ray Diffraction (XRD) and Nuclear Magnetic Resonance (NMR), with a view to further characterizing and understanding the nature of the cementitious materials.

- Investigation and test for sound and acoustic should be carried out on the research product, as these criteria also considered as part of the requirement for building wall materials.

- Trial application could be done on the research product, for example built a shed or wall to further investigate on the durability of the unfired bricks.

- A market study is also important to learn or investigate the pricing, against the readily available similar products in the market.

- Different design and sizes of unfired LOC-PFA brick need to be further develop, e.g hollow and interlocking bricks.

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APPENDICES

Appendix A – Sample of calculation

Appendix B – Experimental results

Appendix C– Presented paper

CLAY:PFA (50:50) (OMC) S + kS + w(S + kS) B

10% Stabiliser

Water in clay	73.55 / 2	36.78g	
Water in PFA	60.67 / 2	30.34g	
		67.12g	(wS)

S + 0.10S + 67.12g = 380g
1.10S = 380 - 67.12
S = 312.88/1.10
S = 284.45g (S)

Stabiliser = 0.10 x 282.04g = **28.45g** (kS)
380g

15% Stabiliser

Water in clay	73.56 / 2	36.78g	
Water in PFA	60.67 / 2	30.34g	
		67.12g	(wS)

S + 0.15S + 67.12g = 380g
1.15S = 380 - 67.12
S = 312.88/1.15
S = 272.07g (S)

Stabiliser = 0.15 x 272.07g = **40.81g** (kS)
380g

20% Stabiliser

Water in clay	73.56 / 2	36.78g	
Water in PFA	60.67 / 2	30.34g	
		67.12g	(wS)

S + 0.20S + 67.12g = 380g
1.20S = 380 - 67.12
S = 312.88/1.2
S = 260.73g (S)

Stabiliser = 0.20 x 260.73g = **52.15g** (kS)
380g

CLAY:PFA (50:50) (1.2 OMC) S + kS + w(S + kS) C

10% Stabiliser

Water in clay	85.43 / 2	42.72g	
Water in PFA	71.06 / 2	35.53g	
		78.25g	(wS)

S + 0.10S + 78.25g = 380g
1.10S = 380 - 78.25
S = 301.75/1.10
S = 274.32g (S)

Stabiliser = 0.10 x 274.32g = **27.43g** (kS)
380g

15% Stabiliser

Water in clay	85.43 / 2	42.72g	
Water in PFA	71.06 / 2	35.53g	
		78.25g	(wS)

S + 0.15S + 78.25g = 380g
1.15S = 380 - 78.25
S = 301.75/1.15
S = 262.39g (S)

Stabiliser = 0.15 x 262.39g = **39.36g** (kS)
380g

20% Stabiliser

Water in clay	85.43 / 2	42.72g	
Water in PFA	71.06 / 2	35.53g	
		78.25g	(wS)

S + 0.20S + 78.25g = 380g
1.20S = 380 - 78.25
S = 301.75/1.2
S = 251.46g (S)

Stabiliser = 0.20 x 251.46g = **50.29g** (kS)
380g

CLAY:PFA (50:50) (OMC) S + kS + wS (D)

10% Stabiliser

Water in clay	68.06 / 2	34.03g	
Water in PFA	55.97 / 2	27.99g	
		62.02g	(wS)

S + 0.10S + 62.02g = 380g
1.10S = 380 - 62.02
S = 317.98/1.10
S = 289.07g (S)

Stabiliser = 0.10 x 289.07g = **28.91g** (kS)
380g

15% Stabiliser

Water in clay	65.61 / 2	32.81g	
Water in PFA	53.88 / 2	26.94g	
		59.75g	(wS)

S + 0.15S + 59.75g = 380g
1.15S = 380 - 59.75
S = 320.25/1.15
S = 278.48g (S)

Stabiliser = 0.15 x 278.48g = **41.77g** (kS)
380g

20% Stabiliser

Water in clay	63.33 / 2	31.67g	
Water in PFA	51.94 / 2	25.97g	
		57.64g	(wS)

S + 0.20S + 57.64g = 380g
1.20S = 380 - 57.64
S = 322.36/1.2
S = 268.63g (S)

Stabiliser = 0.20 x 268.63g = **53.73g** (kS)
380g

CLAY:PFA (50:50) (1.2 OMC) S + kS + wS (E)

10% Stabiliser

Water in clay	79.28 / 2	39.64g	
Water in PFA	65.71 / 2	32.96g	
		72.60g	(wS)

S + 0.10S + 72.60g = 380g
1.10S = 380 - 72.60
S = 307.40/1.10
S = 279.45g (S)

Stabiliser = 0.10 x 279.45g = **27.95g** (kS)
380g

15% Stabiliser

Water in clay	76.53 / 2	38.27g	
Water in PFA	63.33 / 2	31.67g	
		69.94g	(wS)

S + 0.15S + 69.94g = 380g
1.15S = 380 - 69.94
S = 310.06/1.15
S = 269.62g (S)

Stabiliser = 0.15 x 269.62g = **40.44g** (kS)
380g

20% Stabiliser

Water in clay	73.96 / 2	36.98g	
Water in PFA	61.12 / 2	30.56g	
		67.54g	(wS)

S + 0.20S + 67.54g = 380g
1.20S = 380 - 67.54
S = 312.46/1.2
S = 260.38g (S)

Stabiliser = 0.20 x 260.38g = **52.08g** (kS)
380g

LOC + LIME (10%) 380g (16.7.08) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.124	0.0019625	572.74	557
		2	278.6	27.86	73.55	1.078	0.0019625	549.30	
		3	278.6	27.86	73.55	1.078	0.0019625	549.30	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	0.782	0.0019625	398.47	402
		2	267.8	26.78	85.43	0.784	0.0019625	399.49	
		3	267.8	26.78	85.43	0.8	0.0019625	407.64	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.414	0.0019625	720.51	699
		2	283.58	28.36	68.06	1.302	0.0019625	663.44	
		3	283.58	28.36	68.06	1.402	0.0019625	714.39	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	0.988	0.0019625	503.44	503
		2	273.38	27.34	79.28	1.004	0.0019625	511.59	
		3	273.38	27.34	79.28	0.972	0.0019625	495.29	

LOC + LIME:GGBS(50:50) (10%) 380g (16.7.08) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.466	0.0019625	747.01	790
		2	278.6	27.86	73.55	1.54	0.0019625	784.71	
		3	278.6	27.86	73.55	1.644	0.0019625	837.71	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	1.102	0.0019625	561.53	598
		2	267.8	26.78	85.43	1.2	0.0019625	611.46	
		3	267.8	26.78	85.43	1.216	0.0019625	619.62	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.758	0.0019625	895.80	876
		2	283.58	28.36	68.06	1.692	0.0019625	862.17	
		3	283.58	28.36	68.06	1.71	0.0019625	871.34	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.394	0.0019625	710.32	699
		2	273.38	27.34	79.28	1.292	0.0019625	658.34	
		3	273.38	27.34	79.28	1.428	0.0019625	727.64	

LOC + PC (10%) 380g (21.8.08)-23 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.284	0.0019625	654.27	619
		2	278.6	27.86	73.55	1.144	0.0019625	582.93	
		3							
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	0.81	0.0019625	412.74	422
		2	267.8	26.78	85.43	0.846	0.0019625	431.08	
		3							
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.342	0.0019625	683.82	696
		2	283.58	28.36	68.06	1.388	0.0019625	707.26	
		3							
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.066	0.0019625	543.18	512
		2	273.38	27.34	79.28	0.944	0.0019625	481.02	
		3							

LOC + PC:GGBS(60:40) (10%) 380g (16.7.08) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.072	0.0019625	546.24	605
		2	278.6	27.86	73.55	1.302	0.0019625	663.44	
		3	278.6	27.86	73.55		0.0019625		
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	0.766	0.0019625	390.32	433
		2	267.8	26.78	85.43	0.938	0.0019625	477.96	
		3	267.8	26.78	85.43	0.848	0.0019625	432.10	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.436	0.0019625	731.72	723
		2	283.58	28.36	68.06	1.454	0.0019625	740.89	
		3	283.58	28.36	68.06	1.364	0.0019625	695.03	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.118	0.0019625	569.68	568
		2	273.38	27.34	79.28	1.174	0.0019625	598.22	
		3	273.38	27.34	79.28	1.054	0.0019625	537.07	

LOC + LIME (20%) 380g (8.8.08)-19 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	1.232	0.0019625	627.77	700
		2	255.37	51.07	73.55	1.306	0.0019625	665.48	
		3	255.37	51.07	73.55	1.582	0.0019625	806.11	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	1.618	0.0019625	824.46	763
		2	245.48	49.1	85.43	1.362	0.0019625	694.01	
		3	245.48	49.1	85.43	1.514	0.0019625	771.46	
D	F2 OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	0.548	0.0019625	279.24	293
		2	263.89	52.78	63.33		0.0019625		
		3	263.89	52.78	63.33	0.602	0.0019625	306.75	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	1.508	0.0019625	768.41	935
		2	255.03	51.01	73.96	1.992	0.0019625	1015.03	
		3	255.03	51.01	73.96	2.006	0.0019625	1022.17	

LOC + LIME:GGBS (50:50) (20%) 380g (13.8.08)-20 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	2.19	0.0019625	1115.92	1180
		2	255.37	51.07	73.55	2.368	0.0019625	1206.62	
		3	255.37	51.07	73.55	2.39	0.0019625	1217.83	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	2.168	0.0019625	1104.71	1111
		2	245.48	49.1	85.43	2.172	0.0019625	1106.75	
		3	245.48	49.1	85.43	2.202	0.0019625	1122.04	
D	F2 OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	1.804	0.0019625	919.24	943
		2	263.89	52.78	63.33	1.864	0.0019625	949.81	
		3	263.89	52.78	63.33	1.884	0.0019625	960.00	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	2.274	0.0019625	1158.73	1143
		2	255.03	51.01	73.96	1.954	0.0019625	995.67	
		3	255.03	51.01	73.96	2.504	0.0019625	1275.92	

LOC + LIME:GGBS (30:70) (20%) 380g (15.8.08)-21 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	2.204	0.0019625	1123.06	1014
		2	255.37	51.07	73.55	1.644	0.0019625	837.71	
		3	255.37	51.07	73.55	2.124	0.0019625	1082.29	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	2.224	0.0019625	1133.25	1160
		2	245.48	49.1	85.43	2.382	0.0019625	1213.76	
		3	245.48	49.1	85.43	2.226	0.0019625	1134.27	
D	F2 OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	1.654	0.0019625	842.80	1017
		2	263.89	52.78	63.33	2.118	0.0019625	1079.24	
		3	263.89	52.78	63.33	2.214	0.0019625	1128.15	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	2.296	0.0019625	1169.94	1095
		2	255.03	51.01	73.96	2.26	0.0019625	1151.59	
		3	255.03	51.01	73.96	1.892	0.0019625	964.08	

LOC + PC (20%) 380g (21.8.08)-23 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	1.942	0.0019625	989.55	977
		2	255.37	51.07	73.55	1.94	0.0019625	988.54	
		3	255.37	51.07	73.55	1.868	0.0019625	951.85	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	1.156	0.0019625	589.04	587
		2	245.48	49.1	85.43	1.122	0.0019625	571.72	
		3	245.48	49.1	85.43	1.178	0.0019625	600.25	
D	F2 OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	2.166	0.0019625	1103.69	1117
		2	263.89	52.78	63.33	2.228	0.0019625	1135.29	
		3	263.89	52.78	63.33	2.184	0.0019625	1112.87	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	1.906	0.0019625	971.21	973
		2	255.03	51.01	73.96	1.952	0.0019625	994.65	
		3	255.03	51.01	73.96	1.87	0.0019625	952.87	

LOC + PC:GGBS (60:40) (20%) 380g (22.8.08)-24 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	1.684	0.0019625	858.09	884
		2	255.37	51.07	73.55	1.712	0.0019625	872.36	
		3	255.37	51.07	73.55	1.806	0.0019625	920.25	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	1.082	0.0019625	551.34	538
		2	245.48	49.1	85.43	1.052	0.0019625	536.05	
		3	245.48	49.1	85.43	1.036	0.0019625	527.90	
D	F2 OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	1.81	0.0019625	922.29	967
		2	263.89	52.78	63.33	1.962	0.0019625	999.75	
		3	263.89	52.78	63.33	1.922	0.0019625	979.36	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	1.694	0.0019625	863.18	863
		2	255.03	51.01	73.96	1.648	0.0019625	839.75	
		3	255.03	51.01	73.96	1.738	0.0019625	885.61	

LOC + PC:GGBS (40:60) (20%) 380g (20.8.08)-22 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	1.96	0.0019625	998.73	962
		2	255.37	51.07	73.55	1.884	0.0019625	960.00	
		3	255.37	51.07	73.55	1.822	0.0019625	928.41	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	1.336	0.0019625	680.76	691
		2	245.48	49.1	85.43	1.588	0.0019625	809.17	
		3	245.48	49.1	85.43	1.142	0.0019625	581.91	
D	F2 OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	1.74	0.0019625	886.62	923
		2	263.89	52.78	63.33	1.826	0.0019625	930.45	
		3	263.89	52.78	63.33	1.868	0.0019625	951.85	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	1.686	0.0019625	859.11	877
		2	255.03	51.01	73.96	1.638	0.0019625	834.65	
		3	255.03	51.01	73.96	1.84	0.0019625	937.58	

LOC + LIME (10%) 380g (31.7.08) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.768	0.0019625	900.89	934
		2	278.6	27.86	73.55	1.908	0.0019625	972.23	
		3	278.6	27.86	73.55	1.824	0.0019625	929.43	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	1.252	0.0019625	637.96	647
		2	267.8	26.78	85.43	1.318	0.0019625	671.59	
		3	267.8	26.78	85.43	1.238	0.0019625	630.83	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	2.206	0.0019625	1124.08	1061
		2	283.58	28.36	68.06	2.062	0.0019625	1050.70	
		3	283.58	28.36	68.06	1.978	0.0019625	1007.90	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.466	0.0019625	747.01	763
		2	273.38	27.34	79.28	1.722	0.0019625	877.45	
		3	273.38	27.34	79.28	1.302	0.0019625	663.44	

LOC + LIME :GGBS (50:50)(10%) 380g (1.8.08) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	2.46	0.0019625	1253.50	1295
		2	278.6	27.86	73.55	2.59	0.0019625	1319.75	
		3	278.6	27.86	73.55	2.572	0.0019625	1310.57	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	2.232	0.0019625	1137.32	1083
		2	267.8	26.78	85.43	2.138	0.0019625	1089.43	
		3	267.8	26.78	85.43	2.004	0.0019625	1021.15	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	2.95	0.0019625	1503.18	1410
		2	283.58	28.36	68.06	2.626	0.0019625	1338.09	
		3	283.58	28.36	68.06	2.726	0.0019625	1389.04	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	2.446	0.0019625	1246.37	1155
		2	273.38	27.34	79.28	2.154	0.0019625	1097.58	
		3	273.38	27.34	79.28	2.2	0.0019625	1121.02	

LOC + LIME :GGBS (30:70)(10%) 380g (30.7.08) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	2.388	0.0019625	1216.82	1220
		2	278.6	27.86	73.55	2.546	0.0019625	1297.32	
		3	278.6	27.86	73.55	2.246	0.0019625	1144.46	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	1.888	0.0019625	962.04	996
		2	267.8	26.78	85.43	2.102	0.0019625	1071.08	
		3	267.8	26.78	85.43	1.874	0.0019625	954.90	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	2.666	0.0019625	1358.47	1271
		2	283.58	28.36	68.06	2.414	0.0019625	1230.06	
		3	283.58	28.36	68.06	2.402	0.0019625	1223.95	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	2.462	0.0019625	1254.52	1220
		2	273.38	27.34	79.28	2.368	0.0019625	1206.62	
		3	273.38	27.34	79.28	2.35	0.0019625	1197.45	

LOC + PC (10%) 380g (4.8.08) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.704	0.0019625	868.28	887
		2	278.6	27.86	73.55	1.71	0.0019625	871.34	
		3	278.6	27.86	73.55	1.81	0.0019625	922.29	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	1.212	0.0019625	617.58	642
		2	267.8	26.78	85.43	1.332	0.0019625	678.73	
		3	267.8	26.78	85.43	1.238	0.0019625	630.83	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.966	0.0019625	1001.78	987
		2	283.58	28.36	68.06	1.846	0.0019625	940.64	
		3	283.58	28.36	68.06	2	0.0019625	1019.11	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.45	0.0019625	738.85	726
		2	273.38	27.34	79.28	1.502	0.0019625	765.35	
		3	273.38	27.34	79.28	1.32	0.0019625	672.61	

LOC + PC:GGBS (60:40)(10%) 380g (31.7.08) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55		0.0019625		807
		2	278.6	27.86	73.55	1.586	0.0019625	808.15	
		3	278.6	27.86	73.55	1.582	0.0019625	806.11	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	0.992	0.0019625	505.48	455
		2	267.8	26.78	85.43	0.786	0.0019625	400.51	
		3	267.8	26.78	85.43	0.9	0.0019625	458.60	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.798	0.0019625	916.18	895
		2	283.58	28.36	68.06	1.728	0.0019625	880.51	
		3	283.58	28.36	68.06	1.742	0.0019625	887.64	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.184	0.0019625	603.31	646
		2	273.38	27.34	79.28	1.276	0.0019625	650.19	
		3	273.38	27.34	79.28	1.342	0.0019625	683.82	

LOC + PC:GGBS (40:60)(10%) 380g (30.7.08) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	278.6	27.86	73.55	1.796	0.0019625	915.16	872
		2	278.6	27.86	73.55	1.378	0.0019625	702.17	
		3	278.6	27.86	73.55	1.96	0.0019625	998.73	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	267.8	26.78	85.43	1.246	0.0019625	634.90	548
		2	267.8	26.78	85.43	0.828	0.0019625	421.91	
		3	267.8	26.78	85.43	1.154	0.0019625	588.03	
D	**F2** OMC (24%) S+0.10S+0.24S=380g	1	283.58	28.36	68.06	1.898	0.0019625	967.13	991
		2	283.58	28.36	68.06	1.9	0.0019625	968.15	
		3	283.58	28.36	68.06	2.036	0.0019625	1037.45	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	273.38	27.34	79.28	1.496	0.0019625	762.29	802
		2	273.38	27.34	79.28	1.634	0.0019625	832.61	
		3	273.38	27.34	79.28	1.594	0.0019625	812.23	

LOC + LIME (20%) 380g (7.8.08)-13 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	1.902	0.0019625	969.17	975
		2	255.37	51.07	73.55	1.992	0.0019625	1015.03	
		3	255.37	51.07	73.55	1.848	0.0019625	941.66	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	1.65	0.0019625	840.76	850
		2	245.48	49.1	85.43	1.658	0.0019625	844.84	
		3	245.48	49.1	85.43	1.694	0.0019625	863.18	
D	**F2** OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	1.274	0.0019625	649.17	539
		2	263.89	52.78	63.33	1.094	0.0019625	557.45	
		3	263.89	52.78	63.33	0.804	0.0019625	409.68	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	1.49	0.0019625	759.24	839
		2	255.03	51.01	73.96	1.65	0.0019625	840.76	
		3	255.03	51.01	73.96	1.802	0.0019625	918.22	

LOC + LIME:GGBS(50:50) (20%) 380g (8.8.08)-14 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	3.212	0.0019625	1636.69	1631
		2	255.37	51.07	73.55	3.312	0.0019625	1687.64	
		3	255.37	51.07	73.55	3.08	0.0019625	1569.43	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	2.664	0.0019625	1357.45	1412
		2	245.48	49.1	85.43	2.556	0.0019625	1302.42	
		3	245.48	49.1	85.43	3.094	0.0019625	1576.56	
D	**F2** OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	3.266	0.0019625	1664.20	1627
		2	263.89	52.78	63.33	3.09	0.0019625	1574.52	
		3	263.89	52.78	63.33	3.224	0.0019625	1642.80	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	3.096	0.0019625	1577.58	1552
		2	255.03	51.01	73.96	2.98	0.0019625	1518.47	
		3	255.03	51.01	73.96	3.06	0.0019625	1559.24	

LOC + LIME:GGBS(30:70) (20%) 380g (12.8.08)-15 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	4.262	0.0019625	2171.72	2127
		2	255.37	51.07	73.55	4.398	0.0019625	2241.02	
		3	255.37	51.07	73.55	3.86	0.0019625	1966.88	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	4.28	0.0019625	2180.89	2169
		2	245.48	49.1	85.43	4.348	0.0019625	2215.54	
		3	245.48	49.1	85.43	4.14	0.0019625	2109.55	
D	**F2** OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33		0.0019625		1779
		2	263.89	52.78	63.33	3.614	0.0019625	1841.53	
		3	263.89	52.78	63.33	3.37	0.0019625	1717.20	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	4.346	0.0019625	2214.52	2127
		2	255.03	51.01	73.96	4.072	0.0019625	2074.90	
		3	255.03	51.01	73.96	4.104	0.0019625	2091.21	

LOC + PC (20%) 380g (28.8.08)-18 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	**F1** OMC (24%) S+0.20S+0.24(S+0.20S)=380g	1	255.37	51.07	73.55	2.518	0.0019625	1283.06	1387
		2	255.37	51.07	73.55	2.896	0.0019625	1475.67	
		3	255.37	51.07	73.55	2.752	0.0019625	1402.29	
C	**F1 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29(S+0.20S)=380g	1	245.48	49.1	85.43	2.858	0.0019625	1456.31	1424
		2	245.48	49.1	85.43	2.912	0.0019625	1483.82	
		3	245.48	49.1	85.43	2.614	0.0019625	1331.97	
D	**F2** OMC (24%) S+0.20S+0.24S=380g	1	263.89	52.78	63.33	2.36	0.0019625	1202.55	1244
		2	263.89	52.78	63.33	2.448	0.0019625	1247.39	
		3	263.89	52.78	63.33	2.514	0.0019625	1281.02	
E	**F2 1.2 OMC** 1.2 OMC (OMC = 24%) S+0.20S+0.29S=380g	1	255.03	51.01	73.96	2.994	0.0019625	1525.61	1500
		2	255.03	51.01	73.96	2.89	0.0019625	1472.61	
		3	255.03	51.01	73.96	2.948	0.0019625	1502.17	

LOC:PFA (50:50) + LIME (10%) 380g (25.9.08)-31 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	1.562	0.0019625	795.92	797
		2	284.45	28.45	67.12	1.566	0.0019625	797.96	
		3	284.45	28.45	67.12	0	0.0019625	0.00	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	1.356	0.0019625	690.96	691
		2	274.32	27.43	78.25	1.356	0.0019625	690.96	
		3	274.32	27.43	78.25	0	0.0019625	0.00	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	1.692	0.0019625	862.17	844
		2	289.07	28.91	62.02	1.474	0.0019625	751.08	
		3	289.07	28.91	62.02	1.802	0.0019625	918.22	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	1.402	0.0019625	714.39	775
		2	279.45	27.95	72.6	1.362	0.0019625	694.01	
		3	279.45	27.95	72.6	1.796	0.0019625	915.16	

LOC:PFA (50:50) + L:GGBS(50:50) (10%) 380g (26.9.08)-32 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	2.498	0.0019625	1272.87	1245
		2	284.45	28.45	67.12	2.696	0.0019625	1373.76	
		3	284.45	28.45	67.12	2.138	0.0019625	1089.43	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	2.016	0.0019625	1027.26	1085
		2	274.32	27.43	78.25	2.088	0.0019625	1063.95	
		3	274.32	27.43	78.25	2.282	0.0019625	1162.80	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	2.572	0.0019625	1310.57	1312
		2	289.07	28.91	62.02	2.604	0.0019625	1326.88	
		3	289.07	28.91	62.02	2.55	0.0019625	1299.36	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	2.148	0.0019625	1094.52	1142
		2	279.45	27.95	72.6	2.398	0.0019625	1221.91	
		3	279.45	27.95	72.6	2.176	0.0019625	1108.79	

LOC:PFA (50:50) + L:GGBS(30:70) (10%) 380g (29.9.08)-32 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	2.942	0.0019625	1499.11	1430
		2	284.45	28.45	67.12	2.672	0.0019625	1361.53	
		3	284.45	28.45	67.12	0	0.0019625	0.00	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	2.332	0.0019625	1188.28	1152
		2	274.32	27.43	78.25	2.172	0.0019625	1106.75	
		3	274.32	27.43	78.25	2.28	0.0019625	1161.78	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	2.742	0.0019625	1397.20	1418
		2	289.07	28.91	62.02	2.816	0.0019625	1434.90	
		3	289.07	28.91	62.02	2.79	0.0019625	1421.66	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	0	0.0019625	0.00	1389
		2	279.45	27.95	72.6	2.808	0.0019625	1430.83	
		3	279.45	27.95	72.6	2.642	0.0019625	1346.24	

LOC:PFA (50:50) + PC (10%) 380g (01.10.08)-34a RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	1.842	0.0019625	938.60	954
		2	284.45	28.45	67.12	2.086	0.0019625	1062.93	
		3	284.45	28.45	67.12	1.686	0.0019625	859.11	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	1.774	0.0019625	903.95	863
		2	274.32	27.43	78.25	1.412	0.0019625	719.49	
		3	274.32	27.43	78.25	1.894	0.0019625	965.10	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	1.486	0.0019625	757.20	778
		2	289.07	28.91	62.02	1.326	0.0019625	675.67	
		3	289.07	28.91	62.02	1.77	0.0019625	901.91	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	1.95	0.0019625	993.63	949
		2	279.45	27.95	72.6	1.602	0.0019625	816.31	
		3	279.45	27.95	72.6	2.038	0.0019625	1038.47	

LOC:PFA (50:50) + PC:GGBS(60:40) (10%) 380g (02.10.08)-35 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	1.34	0.0019625	682.80	605
		2	284.45	28.45	67.12	1.174	0.0019625	598.22	
		3	284.45	28.45	67.12	1.048	0.0019625	534.01	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	1.09	0.0019625	555.41	650
		2	274.32	27.43	78.25	1.458	0.0019625	742.93	
		3	274.32	27.43	78.25	1.276	0.0019625	650.19	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	0.964	0.0019625	491.21	598
		2	289.07	28.91	62.02	1.26	0.0019625	642.04	
		3	289.07	28.91	62.02	1.296	0.0019625	660.38	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	1.308	0.0019625	666.50	634
		2	279.45	27.95	72.6	1.264	0.0019625	644.08	
		3	279.45	27.95	72.6	1.162	0.0019625	592.10	

LOC:PFA (50:50) + PC:GGBS(40:60) (10%) 380g (01.10.08)-34b RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	1.434	0.0019625	730.70	759
		2	284.45	28.45	67.12	1.54	0.0019625	784.71	
		3	284.45	28.45	67.12	1.496	0.0019625	762.29	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	1.308	0.0019625	666.50	615
		2	274.32	27.43	78.25	1.158	0.0019625	590.06	
		3	274.32	27.43	78.25	1.156	0.0019625	589.04	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	0.866	0.0019625	441.27	451
		2	289.07	28.91	62.02	0.748	0.0019625	381.15	
		3	289.07	28.91	62.02	1.04	0.0019625	529.94	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	1.14	0.0019625	580.89	521
		2	279.45	27.95	72.6	0.962	0.0019625	490.19	
		3	279.45	27.95	72.6	0.964	0.0019625	491.21	

LOC:PFA (50:50) + LIME (20%) 380g (18.11.08)-39 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	0	0.0019625	0.00	0
		2	260.73	52.15	67.12	0	0.0019625	0.00	
		3	260.73	52.15	67.12	0	0.0019625	0.00	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	0.86	0.0019625	438.22	833
		2	251.46	50.29	78.25	1.534	0.0019625	781.66	
		3	251.46	50.29	78.25	2.512	0.0019625	1280.00	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	0	0.0019625	0.00	0
		2	268.63	53.73	57.64	0	0.0019625	0.00	
		3	268.63	53.73	57.64	0	0.0019625	0.00	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	0.262	0.0019625	133.50	112
		2	260.38	52.08	67.54	0.178	0.0019625	90.70	
		3	260.38	52.08	67.54	0	0.0019625	0.00	

LOC:PFA (50:50) + L:GGBS(50:50) (20%) 380g (18.11.08)-39a RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	3.538	0.0019625	1802.80	1706
		2	260.73	52.15	67.12	3.532	0.0019625	1799.75	
		3	260.73	52.15	67.12	2.976	0.0019625	1516.43	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	3.242	0.0019625	1651.97	1521
		2	251.46	50.29	78.25	2.962	0.0019625	1509.30	
		3	251.46	50.29	78.25	2.75	0.0019625	1401.27	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	3.602	0.0019625	1835.41	1661
		2	268.63	53.73	57.64	3.028	0.0019625	1542.93	
		3	268.63	53.73	57.64	3.152	0.0019625	1606.11	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	3.162	0.0019625	1611.21	1655
		2	260.38	52.08	67.54	3.28	0.0019625	1671.34	
		3	260.38	52.08	67.54	3.3	0.0019625	1681.53	

LOC:PFA (50:50) + L:GGBS(30:70) (20%) 380g (26.11.08)-40 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	3.192	0.0019625	1626.50	1749
		2	260.73	52.15	67.12	3.636	0.0019625	1852.74	
		3	260.73	52.15	67.12	3.47	0.0019625	1768.15	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	2.822	0.0019625	1437.96	1572
		2	251.46	50.29	78.25	3.126	0.0019625	1592.87	
		3	251.46	50.29	78.25	3.306	0.0019625	1684.59	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	3.906	0.0019625	1990.32	2015
		2	268.63	53.73	57.64	3.73	0.0019625	1900.64	
		3	268.63	53.73	57.64	4.228	0.0019625	2154.39	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	3.662	0.0019625	1865.99	1955
		2	260.38	52.08	67.54	3.784	0.0019625	1928.15	
		3	260.38	52.08	67.54	4.066	0.0019625	2071.85	

LOC:PFA (50:50) + PC (20%) 380g (27.11.08)-41 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	2.96	0.0019625	1508.28	1438
		2	260.73	52.15	67.12	3.01	0.0019625	1533.76	
		3	260.73	52.15	67.12	2.496	0.0019625	1271.85	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	2.246	0.0019625	1144.46	1097
		2	251.46	50.29	78.25	2.36	0.0019625	1202.55	
		3	251.46	50.29	78.25	1.854	0.0019625	944.71	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	3.202	0.0019625	1631.59	1591
		2	268.63	53.73	57.64	2.892	0.0019625	1473.63	
		3	268.63	53.73	57.64	3.272	0.0019625	1667.26	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	2.804	0.0019625	1428.79	1588
		2	260.38	52.08	67.54	3.216	0.0019625	1638.73	
		3	260.38	52.08	67.54	3.33	0.0019625	1696.82	

LOC:PFA (50:50) + PC:GGBS(40:60) (20%) 380g (28.11.08)-42 RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	3.048	0.0019625	1553.12	1727
		2	260.73	52.15	67.12	3.272	0.0019625	1667.26	
		3	260.73	52.15	67.12	3.85	0.0019625	1961.78	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	2.172	0.0019625	1106.75	1169
		2	251.46	50.29	78.25	2.524	0.0019625	1286.11	
		3	251.46	50.29	78.25	2.186	0.0019625	1113.89	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	2.838	0.0019625	1446.11	1511
		2	268.63	53.73	57.64	2.898	0.0019625	1476.69	
		3	268.63	53.73	57.64	3.162	0.0019625	1611.21	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	3.126	0.0019625	1592.87	1421
		2	260.38	52.08	67.54	2.382	0.0019625	1213.76	
		3	260.38	52.08	67.54	2.86	0.0019625	1457.32	

LOC:PFA (50:50) + PC:GGBS(60:40) (20%) 380g (28.11.08)-42a RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	2.758	0.0019625	1405.35	1395
		2	260.73	52.15	67.12	2.62	0.0019625	1335.03	
		3	260.73	52.15	67.12	2.834	0.0019625	1444.08	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	2.116	0.0019625	1078.22	1036
		2	251.46	50.29	78.25	1.936	0.0019625	986.50	
		3	251.46	50.29	78.25	2.048	0.0019625	1043.57	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	3.122	0.0019625	1590.83	1588
		2	268.63	53.73	57.64	3.33	0.0019625	1696.82	
		3	268.63	53.73	57.64	2.9	0.0019625	1477.71	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	2.522	0.0019625	1285.10	1461
		2	260.38	52.08	67.54	3.25	0.0019625	1656.05	
		3	260.38	52.08	67.54	2.832	0.0019625	1443.06	

LOC:PFA(50:50) + LIME (10%) 380g (07.10.08)-25 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	1.608	0.0019625	819.36	874
		2	284.45	28.45	67.12	1.684	0.0019625	858.09	
		3	284.45	28.45	67.12	1.856	0.0019625	945.73	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	2.08	0.0019625	1059.87	1120
		2	274.32	27.43	78.25	2.334	0.0019625	1189.30	
		3	274.32	27.43	78.25	2.178	0.0019625	1109.81	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	1.816	0.0019625	925.35	839
		2	289.07	28.91	62.02	1.484	0.0019625	756.18	
		3	289.07	28.91	62.02	1.64	0.0019625	835.67	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	1.998	0.0019625	1018.09	1082
		2	279.45	27.95	72.6	2.118	0.0019625	1079.24	
		3	279.45	27.95	72.6	2.254	0.0019625	1148.54	

LOC:PFA(50:50) + L:GGBS(50:50) (10%) 380g (08.10.08)-26 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	4.302	0.0019625	2192.10	2272
		2	284.45	28.45	67.12	4.338	0.0019625	2210.45	
		3	284.45	28.45	67.12	4.738	0.0019625	2414.27	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	3.836	0.0019625	1954.65	1989
		2	274.32	27.43	78.25	4.058	0.0019625	2067.77	
		3	274.32	27.43	78.25	3.814	0.0019625	1943.44	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	4.11	0.0019625	2094.27	2212
		2	289.07	28.91	62.02	4.604	0.0019625	2345.99	
		3	289.07	28.91	62.02	4.312	0.0019625	2197.20	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	3.844	0.0019625	1958.73	2063
		2	279.45	27.95	72.6	4.404	0.0019625	2244.08	
		3	279.45	27.95	72.6	3.898	0.0019625	1986.24	

LOC:PFA(50:50) + L:GGBS(30:70) (10%) 380g (09.10.08)-27 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	5.292	0.0019625	2696.56	2551
		2	284.45	28.45	67.12	4.834	0.0019625	2463.18	
		3	284.45	28.45	67.12	4.892	0.0019625	2492.74	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	4.67	0.0019625	2379.62	2546
		2	274.32	27.43	78.25	5.088	0.0019625	2592.61	
		3	274.32	27.43	78.25	5.23	0.0019625	2664.97	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	5.056	0.0019625	2576.31	2409
		2	289.07	28.91	62.02	4.712	0.0019625	2401.02	
		3	289.07	28.91	62.02	4.416	0.0019625	2250.19	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	5.24	0.0019625	2670.06	2591
		2	279.45	27.95	72.6	4.858	0.0019625	2475.41	
		3	279.45	27.95	72.6	5.158	0.0019625	2628.28	

LOC:PFA(50:50) + PC (10%) 380g (13.10.08)-28 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	4.758	0.0019625	2424.46	2399
		2	284.45	28.45	67.12	4.894	0.0019625	2493.76	
		3	284.45	28.45	67.12	4.472	0.0019625	2278.73	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	0	0.0019625	0.00	2068
		2	274.32	27.43	78.25	0	0.0019625	0.00	
		3	274.32	27.43	78.25	4.058	0.0019625	2067.77	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	4.85	0.0019625	2471.34	2398
		2	289.07	28.91	62.02	4.562	0.0019625	2324.59	
		3	289.07	28.91	62.02	0	0.0019625	0.00	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	0	0.0019625	0.00	2383
		2	279.45	27.95	72.6	0	0.0019625	0.00	
		3	279.45	27.95	72.6	4.676	0.0019625	2382.68	

LOC:PFA(50:50) + PC:GGBS(40:60) (10%) 380g (14.10.08)-29 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	2.506	0.0019625	1276.94	1242
		2	284.45	28.45	67.12	2.502	0.0019625	1274.90	
		3	284.45	28.45	67.12	2.306	0.0019625	1175.03	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	2.194	0.0019625	1117.96	1010
		2	274.32	27.43	78.25	1.974	0.0019625	1005.86	
		3	274.32	27.43	78.25	1.78	0.0019625	907.01	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	2.46	0.0019625	1253.50	1169
		2	289.07	28.91	62.02	2.118	0.0019625	1079.24	
		3	289.07	28.91	62.02	2.302	0.0019625	1172.99	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	1.81	0.0019625	922.29	1018
		2	279.45	27.95	72.6	2.342	0.0019625	1193.38	
		3	279.45	27.95	72.6	1.844	0.0019625	939.62	

LOC:PFA(50:50) + PC:GGBS(60:40) (10%) 380g (15.10.08)-30 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	284.45	28.45	67.12	2.158	0.0019625	1099.62	1289
		2	284.45	28.45	67.12	2.754	0.0019625	1403.31	
		3	284.45	28.45	67.12	2.678	0.0019625	1364.59	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	274.32	27.43	78.25	1.466	0.0019625	747.01	900
		2	274.32	27.43	78.25	2.124	0.0019625	1082.29	
		3	274.32	27.43	78.25	1.708	0.0019625	870.32	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	289.07	28.91	62.02	3.052	0.0019625	1555.16	1377
		2	289.07	28.91	62.02	2.532	0.0019625	1290.19	
		3	289.07	28.91	62.02	2.522	0.0019625	1285.10	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	279.45	27.95	72.6	2.436	0.0019625	1241.27	1385
		2	279.45	27.95	72.6	2.842	0.0019625	1448.15	
		3	279.45	27.95	72.6	2.876	0.0019625	1465.48	

LOC:PFA(50:50) + LIME (20%) 380g (24.11.08)-36 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	0.978	0.0019625	498.34	429
		2	260.73	52.15	67.12	0.822	0.0019625	418.85	
		3	260.73	52.15	67.12	0.728	0.0019625	370.96	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	0.87	0.0019625	443.31	485
		2	251.46	50.29	78.25	0.984	0.0019625	501.40	
		3	251.46	50.29	78.25	1.004	0.0019625	511.59	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	0.146	0.0019625	74.39	90
		2	268.63	53.73	57.64	0.274	0.0019625	139.62	
		3	268.63	53.73	57.64	0.112	0.0019625	57.07	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	0.356	0.0019625	181.40	154
		2	260.38	52.08	67.54	0.319	0.0019625	162.55	
		3	260.38	52.08	67.54	0.23	0.0019625	117.20	

LOC:PFA(50:50) + L:GGBS(50:50) (20%) 380g (24.11.08)-36a RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	0	0.0019625	0.00	2732
		2	260.73	52.15	67.12	5.348	0.0019625	2725.10	
		3	260.73	52.15	67.12	5.376	0.0019625	2739.36	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	4.96	0.0019625	2527.39	2571
		2	251.46	50.29	78.25	5.44	0.0019625	2771.97	
		3	251.46	50.29	78.25	4.736	0.0019625	2413.25	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	4.948	0.0019625	2521.27	2584
		2	268.63	53.73	57.64	5.174	0.0019625	2636.43	
		3	268.63	53.73	57.64	5.092	0.0019625	2594.65	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	5.02	0.0019625	2557.96	2577
		2	260.38	52.08	67.54	4.906	0.0019625	2499.87	
		3	260.38	52.08	67.54	5.244	0.0019625	2672.10	

LOC:PFA(50:50) + L:GGBS(30:70) (20%) 380g (25.11.08)-37 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	5.746	0.0019625	2927.90	2977
		2	260.73	52.15	67.12	5.49	0.0019625	2797.45	
		3	260.73	52.15	67.12	6.29	0.0019625	3205.10	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	5.6	0.0019625	2853.50	2835
		2	251.46	50.29	78.25	5.1	0.0019625	2598.73	
		3	251.46	50.29	78.25	5.992	0.0019625	3053.25	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	5.918	0.0019625	3015.54	3174
		2	268.63	53.73	57.64	6.152	0.0019625	3134.78	
		3	268.63	53.73	57.64	6.614	0.0019625	3370.19	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	6.034	0.0019625	3074.65	3208
		2	260.38	52.08	67.54	6.828	0.0019625	3479.24	
		3	260.38	52.08	67.54	6.028	0.0019625	3071.59	

LOC:PFA(50:50) + PC (20%) 380g (25.11.08)-37a RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	4.772	0.0019625	2431.59	2738
		2	260.73	52.15	67.12	5.704	0.0019625	2906.50	
		3	260.73	52.15	67.12	5.642	0.0019625	2874.90	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	5.078	0.0019625	2587.52	2599
		2	251.46	50.29	78.25	4.346	0.0019625	2214.52	
		3	251.46	50.29	78.25	5.876	0.0019625	2994.14	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	5.13	0.0019625	2614.01	2653
		2	268.63	53.73	57.64	5.688	0.0019625	2898.34	
		3	268.63	53.73	57.64	4.802	0.0019625	2446.88	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	5.31	0.0019625	2705.73	2754
		2	260.38	52.08	67.54	6.156	0.0019625	3136.82	
		3	260.38	52.08	67.54	4.746	0.0019625	2418.34	

LOC:PFA(50:50) + PC:GGBS(40:60) (20%) 380g (26.11.08)-38 RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	3.074	0.0019625	1566.37	1712
		2	260.73	52.15	67.12	3.602	0.0019625	1835.41	
		3	260.73	52.15	67.12	3.406	0.0019625	1735.54	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	4.166	0.0019625	2122.80	2130
		2	251.46	50.29	78.25	4.87	0.0019625	2481.53	
		3	251.46	50.29	78.25	3.502	0.0019625	1784.46	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	4.044	0.0019625	2060.64	2250
		2	268.63	53.73	57.64	4.656	0.0019625	2372.48	
		3	268.63	53.73	57.64	4.546	0.0019625	2316.43	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	3.834	0.0019625	1953.63	1989
		2	260.38	52.08	67.54	4.226	0.0019625	2153.38	
		3	260.38	52.08	67.54	3.648	0.0019625	1858.85	

LOC:PFA(50:50) + PC:GGBS(60:40) (20%) 380g (26.11.08)-38a RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
B	F1 OMC (24%) S+0.10S+0.24(S+0.10S)=380g	1	260.73	52.15	67.12	4.87	0.0019625	2481.53	2592
		2	260.73	52.15	67.12	4.738	0.0019625	2414.27	
		3	260.73	52.15	67.12	5.65	0.0019625	2878.98	
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=380g	1	251.46	50.29	78.25	4.202	0.0019625	2141.15	2011
		2	251.46	50.29	78.25	3.902	0.0019625	1988.28	
		3	251.46	50.29	78.25	3.738	0.0019625	1904.71	
D	F2 OMC (24%) S+0.10S+0.24S=380g	1	268.63	53.73	57.64	3.806	0.0019625	1939.36	2094
		2	268.63	53.73	57.64	4.368	0.0019625	2225.73	
		3	268.63	53.73	57.64	4.156	0.0019625	2117.71	
E	F2 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29S=380g	1	260.38	52.08	67.54	4.756	0.0019625	2423.44	2300
		2	260.38	52.08	67.54	5.002	0.0019625	2548.79	
		3	260.38	52.08	67.54	3.782	0.0019625	1927.13	

SUMMARY OF UCS and DI at 7 days of curing

Mixed Composition	Stabiliser Dosage (%)	Formula	Control Specimen (kN/m^2)	Soaked Specimen (kN/m^2)	Durability Index (DI) (%)
LOC-PFA + L-GGBS (30:70)	10	F1 OMC	1430	1214	85
		F2 OMC	1418	1282	90
		F1 (1.2 OMC)	1152	1194	104
		F2 (1.2 OMC)	1389	1273	92
	20	F1 OMC	1749	1605	92
		F2 OMC	2015	1444	72
		F1 (1.2 OMC)	1572	1383	88
		F2 (1.2 OMC)	1955	1678	86
LOC-PFA + PC-GGBS (30:70)	10	F1 OMC	759	593	78
		F2 OMC	451	632	140
		F1 (1.2 OMC)	615	691	112
		F2 (1.2 OMC)	521	1375	263
	20	F1 OMC	1727	1162	67
		F2 OMC	1511	1376	91
		F1 (1.2 OMC)	1169	1154	99
		F2 (1.2 OMC)	1421	1900	134
LOC-PFA + L	10	F1 OMC	797	1157	145
		F2 OMC	844	783	93
		F1 (1.2 OMC)	691	1099	159
		F2 (1.2 OMC)	775	1046	135
	20	F1 OMC	119	169	142
		F2 OMC	610	243	40
		F1 (1.2 OMC)	0	0	0
		F2 (1.2 OMC)	112	0	0
LOC-PFA + PC	10	F1 OMC	954	1657	174
		F2 OMC	778	1529	196
		F1 (1.2 OMC)	963	1521	177
		F2 (1.2 OMC)	949	1697	179
	20	F1 OMC	1438	2232	155
		F2 OMC	1591	2076	130
		F1 (1.2 OMC)	1097	2207	201
		F2 (1.2 OMC)	1588	2445	140

$$\text{Durability Index (DI)} = \frac{\text{Soaked Specimen}}{\text{Control Specimen}} \times 100\%$$

SUMMARY OF UCS and DI at 28 days of curing

Mixed Composition	Stabiliser Dosage (%)	Formula	Control Specimen (kN/m²)	Soaked Specimen (kN/m²)	Durability Index (DI) (%)
LOC-PFA + L-GGBS (30:70)	10	F1 OMC	2551	1916	75
		F2 OMC	2409	2299	95
		F1 (1.2 OMC)	2546	2254	89
		F2 (1.2 OMC)	2591	2558	99
	20	F1 OMC	2977	2921	98
		F2 OMC	3174	2308	73
		F1 (1.2 OMC)	2835	3152	111
		F2 (1.2 OMC)	3208	3059	95
LOC-PFA + PC-GGBS (30:70)	10	F1 OMC	1242	1495	120
		F2 OMC	1169	1379	118
		F1 (1.2 OMC)	1010	1807	179
		F2 (1.2 OMC)	1018	1850	182
	20	F1 OMC	1712	2394	140
		F2 OMC	2250	2077	92
		F1 (1.2 OMC)	2130	2878	135
		F2 (1.2 OMC)	1989	2639	133
LOC-PFA + L	10	F1 OMC	874	1515	173
		F2 OMC	839	1099	131
		F1 (1.2 OMC)	1120	1729	154
		F2 (1.2 OMC)	1082	1461	135
	20	F1 OMC	429	371	86
		F2 OMC	90	76	84
		F1 (1.2 OMC)	485	454	94
		F2 (1.2 OMC)	154	138	90
LOC-PFA + PC	10	F1 OMC	2399	1998	83
		F2 OMC	2398	1456	61
		F1 (1.2 OMC)	2068	2075	100
		F2 (1.2 OMC)	2383	2151	90
	20	F1 OMC	2738	2484	91
		F2 OMC	2653	2110	80
		F1 (1.2 OMC)	2599	3353	129
		F2 (1.2 OMC)	2754	2664	97

$$\text{Durability Index (DI)} = \frac{\text{Soaked Specimen}}{\text{Control Specimen}} \times 100\%$$

SUMMARY OF UCS and DI at 56 days of curing

Mixed Composition	Stabiliser Dosage (%)	Formula	Control Specimen (kN/m^2)	Soaked Specimen (kN/m^2)	Durability Index (DI) (%)
LOC-PFA + L-GGBS (30:70)	10	F1 OMC	2245	2691	120
		F2 OMC	2689	2524	94
		F1 (1.2 OMC)	2521	3373	134
		F2 (1.2 OMC)	2567	2775	108
	20	F1 OMC	2765	3432	124
		F2 OMC	2715	3086	114
		F1 (1.2 OMC)	2512	3895	155
		F2 (1.2 OMC)	2532	3289	130
LOC-PFA + PC-GGBS (30:70)	10	F1 OMC	1707	1537	90
		F2 OMC	1910	1465	77
		F1 (1.2 OMC)	1941	1947	100
		F2 (1.2 OMC)	2082	1845	89
	20	F1 OMC	3039	2578	85
		F2 OMC	3063	1967	64
		F1 (1.2 OMC)	3157	2948	93
		F2 (1.2 OMC)	2948	2836	96
LOC-PFA + L	10	F1 OMC	1391	2393	172
		F2 OMC	1318	2221	109
		F1 (1.2 OMC)	1427	2464	173
		F2 (1.2 OMC)	1316	2602	98
	20	F1 OMC	226	2948	1304
		F2 OMC	49	2484	5080
		F1 (1.2 OMC)	511	3291	644
		F2 (1.2 OMC)	149	2334	1556
LOC-PFA + PC	10	F1 OMC	2226	1455	65
		F2 OMC	2618	1473	56
		F1 (1.2 OMC)	2435	1622	67
		F2 (1.2 OMC)	2813	1478	53
	20	F1 OMC	3342	2033	61
		F2 OMC	3368	1775	53
		F1 (1.2 OMC)	3862	2837	73
		F2 (1.2 OMC)	3686	2144	57

$$\text{Durability Index (DI)} = \frac{\text{Soaked Specimen}}{\text{Control Specimen}} \times 100\%$$

SUMMARY OF UCS and DI at 56 days of curing (REPEAT) Sept 10

LOC-PFA + L	10	F1 OMC	1391	2245	161
		F2 OMC	1318	2029	154
		F1 (1.2 OMC)	1427	2379	166
		F2 (1.2 OMC)	1316	2127	161
	20	F1 OMC	226	589	260
		F2 OMC	49	651	1329
		F1 (1.2 OMC)	511	1868	365
		F2 (1.2 OMC)	149	1345	903

$$\text{Durability Index (DI)} = \frac{\text{Soaked Specimen}}{\text{Control Specimen}} \times 100\%$$

7 DAYS BRICKS

LOC:PFA (50:50) + L-GGBS(30:70) (10%) 3500g (17-11-10) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	2535.43	253.53	723.23	16.9	0.016225	1041.60	1152 (cylinder) 1005
		2	2535.43	253.53	723.23	15.7	0.016225	967.64	

LOC:PFA (50:50) + L (10%) 3500g (19-11-10) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	2535.43	253.53	723.23	6.6	0.016225	406.78	691 (cylinder) 364
		2	2535.43	253.53	723.23	5.2	0.016225	320.49	

LOC:PFA (50:50) + PC-GGBS(40:60) (10%) 3500g (17-11-10) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	2535.43	253.53	723.23	23.8	0.016225	1466.87	615 (cylinder) 1609
		2	2535.43	253.53	723.23	28.4	0.016225	1750.39	

LOC:PFA (50:50) + PC (10%) 3500g (18-11-10) RESULTS: 7 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	274.32	27.43	78.25	25.3	0.016225	1559.32	863 (cylinder) 1384
		2	274.32	27.43	78.25	19.6	0.016225	1208.01	

28 DAYS BRICKS

LOC:PFA (50:50) + L-GGBS(30:70) (10%) 3500g (08-12-10) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	2535.43	253.53	723.23	31.6	0.016225	1947.61	2546 (cylinder) 1972
		2	2535.43	253.53	723.23	32.4	0.016225	1996.92	

LOC:PFA (50:50) + L (10%) 3500g (10-12-10) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	2535.43	253.53	723.23	16	0.016225	986.13	1120 (cylinder) 888
		2	2535.43	253.53	723.23	12.8	0.016225	788.91	

LOC:PFA (50:50) + PC-GGBS(40:60) (10%) 3500g (08-12-10) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	2535.43	253.53	723.23	42.2	0.016225	2600.92	1010 (cylinder) 2700
		2	2535.43	253.53	723.23	45.4	0.016225	2798.15	

LOC:PFA (50:50) + PC (10%) 3500g (09-12-10) RESULTS: 28 DAYS UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

SET	FORMULA	SAMPLE	SOIL(g)	STABILISER (g)	WATER (g)	LOAD (kN)	AREA (m2)	STRENGTH (kN/m2)	AVERAGE (kN/m2)
C	F1 1.2 OMC 1.2 OMC (OMC = 24%) S+0.10S+0.29(S+0.10S)=3.5kg	1	274.32	27.43	78.25	36	0.016225	2218.80	2068 (cylinder) 2302
		2	274.32	27.43	78.25	38.7	0.016225	2385.21	

The Development of Sustainable Lime-Clay Building Components

Norsalisma Ismail, J.M. Kinuthia, and R.B. Robinson, Faculty of Advanced Technology

Abstract—**The most efficient way for construction to approach sustainability is to reuse waste materials and by-products from other industrial activities. This paper reports on the investigations on the development of unfired bricks for building components.**

In this research Lower Oxford Clay (LOC) alone and combined with Pulverised Fly Ash (PFA) as target materials were stabilised with Lime, Portland Cement (PC) and blended binders comprising of Lime and PC blended with Ground Granulated Blast-furnace Slag (GGBS). Stabilised cylinders were made under controlled laboratory conditions at varying moisture contents and stabilised with varying stabiliser dosages. After fabrication, samples were wrapped with several runs of cling film and cured for 7 and 28 days prior to testing for the unconfined compressive strength (UCS).

The results obtained showed that the UCS values of stabilised cylinders incorporating PC only or GGBS blended binders were higher than those stabilised with the traditional lime. Lime-GGBS blends (30:70 ratio) recorded the highest strength values compared with the Lime-GGBS (50:50), or the other unblended stabilisers used. Overall results showed that stabilised LOC-PFA (50:50) gives higher UCS values compared to LOC stabilised on its own.

There are technological, economic as well as environmental advantages and potential of utilising PFA, an industrial by-product from coal industry, and GGBS a by-product from the steel industry, in the development of sustainable lime-clay building components.

Index Terms— **Compressive strength, bricks, sustainability, lime, Portland cement, industrial by-product.**

I. INTRODUCTION

THE need for sustainability, reduction of material processing costs such as reduction of firing costs is well established within the construction industry. The construction industry has always shown a receptive attitude to research into new materials [1].

The recycling of GGBS, or fly ash as concrete admixture nowadays is much more than an alternative for reducing costs [2,3]. Fly ash, a by-product of coal combustion, is frequently used in concrete production as an inexpensive substitute for PC. However although fly ash is commonly used in cements, it has rarely been applied to bricks [4]. Joshi et al. [5] reported that, the major properties of fly ash exploited in the clay brick industry are based on their similar composition as that of clay, the fuel value due to the presence of unburnt carbon, reduced weight of the resultant product, reduced shrinkage due to its inert nature and chemical compatibility with natural clays.

Recently it has been shown that fly ash may improve the compressive strength of bricks, more resistant to frost, and saving in the firing energy [6]. Fly ash has also been used as a partial or total replacement of quartz sand in the production of sand-lime building bricks by using an autoclave process [5]. It also has been used to replace up to 40% of raw material, clay, in building blocks and tiles [5].

In view of the huge demand for building bricks, along with non-availability of suitable soil, there is need to explore alternative raw materials and energy efficient technologies for making bricks [7]. Recently efforts have been made to produce bricks using different types of industrial/mining by-products. Research by Malhotra et al [8] has observed that good quality bricks can be produced by pressing slag-lime mixtures at sufficiently low pressure. The manufacturing process is simple and does not require any firing, or autoclaving, specialised plant or machinery [7].

The objective of this research project is to extend an existing unfired clay cementation technology that is currently viable for highway construction [9]. The work evaluates the engineering properties of bricks made with clay and pulverised fly ash (PFA), stabilised with Lime-GGBS and PC-GGBS blends, and then assesses their potential application as unfired clay building components.

II. METHODOLOGY

A. Materials

1) Lower Oxford Clay (LOC)

The LOC used in this study was supplied by Hanson Bricks Ltd., from their brick works at Stewartby, Bedfordshire, UK. The clay is grey in colour and is known to have high sulfate and sulfide contents. Mineralogical studies by Hanson Brick Ltd. have established that LOC contains illite (23%), kaolinite (10%), chlorite (7%), calcite (10%), quartz (29%), gypsum (2%), pyrite (4%), feldspar (8%) and organics (7%) [10].

2) Pulverised Fly Ash (PFA)

PFA is a material with pozzolanic properties. Several investigators have reported that when fly ash is pulverised to increase fineness, its pozzolanic activity increases significantly [5]. Chemical constituents in fly ash reported in

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terms of oxides include silica (SiO_2), alumina (Al_2O_3), and oxides of calcium (CaO), iron (Fe_2O_3), magnesium (MgO), titanium or vertiel (TiO_2), sulphur (SO_3), sodium (Na_2O) and potassium (K_2O). Among these SiO_2 and Al_2O_3 together make up about 40% to 80% of the total ash [5].

3) Lime

The lime used in this study was quick lime (CaO) supplied by Calch Tŷ Mawr Lime, UK. The reason for using quicklime rather a hydrated lime as a binder is that it is denser and less dusty than hydrated lime. It is also more effective as a stabiliser than hydrated lime.

4) Ground Granulated Blastfurnace Slag (GGBS)

The GGBS used in this study was supplied by Civil and Marine Slag Cement Ltd, Newport, UK. It is a latently hydraulic material that occurs as a by-product the steel industry. Researchers at the University of Glamorgan, UK, have established that inclusion of GGBS in the traditional stabilisers of lime and PC can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime or PC only [11].

5) Portland Cement (PC)

The Portland Cement (PC) used was manufactured in accordance with the British Standard BS EN 197 – 1 [12]. Table 1 shows the chemical/oxide composition of GGBS, PC and lime.

TABLE 1
Chemical composition and physical properties of GGBS (Civil and Marine Slag Cement Ltd.) and typical ordinary PC and lime.

Oxide	**Composition (%)**		
	GGBS	**PC**	**LIME**
CaO	41.99	63	-
$Ca(OH)_2$	-	-	78
$CaCO_3$	-	-	3
SiO_2	35.34	20	5.08
Al_2O_3	11.59	6	1.42
MgO	8.04	4.21	0.65
Fe_2O_3	0.35	3	-
MnO	0.45	0.03-1.11	-
S_2	1.18	-	-
SO_3	0.23	2.3	-
Insoluble residue	0.30	0.5	-
Relative density	2.90	3.15	-
Bulk density (kg/m^3)	1200	1400	-
Colour	Off-white	Grey	-
Glass content	~90	-	-

B. Experimental Procedure (Specimen preparation)

Proctor compaction tests were carried out in accordance with BS 1377 (1990) Part 2, in order to establish values of the maximum dry density (MDD) and optimum moisture content (OMC) for LOC and PFA. From the tests, the MDD value of 1.42 Mg/m^3 for both LOC and PFA, an OMC value of 24% for LOC and 18% for PFA were established. For this study, test specimens were then prepared at OMC and also at 1.2 OMC.

Using two formulae F1 and F2 for calculating the compaction moisture content, compacted cylinders of 50mm diameter and 100mm in height were fabricated, at approximately comparable bulk densities. Using the density and moisture content values, the quantities of the dry materials, enough to produce a compacted cylindrical specimen were established. The materials were mixed thoroughly and adding the pre-calculated amount of water. Hand mixing with palette knives was used to achieve a homogenous mix. Cylinders weighing 380g were prepared for all proportions. A steel mould fitted with a collar, was used to compact the material. Compaction was achieved using a hydraulic jack. After compaction, the cylinders were extruded using a steel plunger, trimmed, and wrapped in several runs of cling film, labelled and placed in sealed plastic containers. All samples were cured for 7 and 28 days. The two formulae used to calculate the amount of moisture content used for compaction are:-

Formula 1 (F1) : $S + kS + w(S + kS) = 380g$...(I) at OMC and 1.2 OMC

Formula 2 (F2) : $S + kS + wS = 380g$..... (II) at OMC and 1.2 OMC

Where S = Soil, k = Stabiliser dosage (%) and w = Water (%) at OMC and 1.2 OMC

From equations I and II, two sets of formulae each with w = OMC and w = 1.2 OMC were used. Therefore, using formula 1 (F1), the calculation of water was made based on the total amount of soil and stabiliser, whereas, with formula 2 (F2), the calculation of water was only based on the amount of soil. Three cylinders per mix proportion were subjected to UCS test and the mean strength determined.

III. RESULTS

A. UCS – Early strength development

1) Lime System: Stabilised LOC

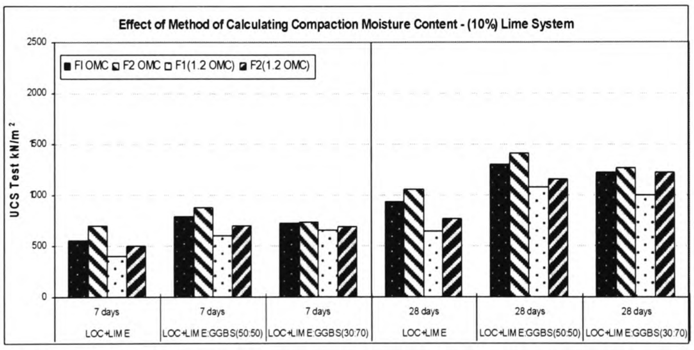

Figure 1(a) – UCS of LOC, stabilised with 10wt% Lime-slag stabiliser.

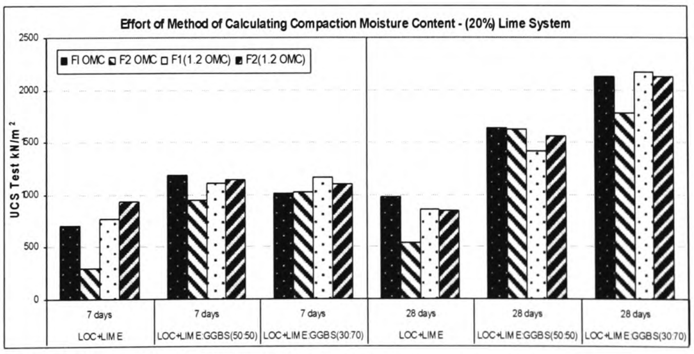

Figure 1(b) – UCS of LOC, stabilised with 20wt% Lime-slag stabiliser.

Figures 1 (a) and (b) show the effects of different methods of calculating the moisture content [(F1: OMC, 1.2OMC) and (F2: OMC, 1.2OMC)] on the UCS of LOC, when stabilised with lime alone and Lime-GGBS at 30:70 and 50:50 ratios, at 10wt% and 20wt% stabiliser dosage. These stabilization levels are much higher than the typical ones used in highway construction (3-8%), because the current work is aimed at the building industry where higher strength values are needed for bricks, blocks and mortar. The overall results show that there are increases in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating the initial compaction water input.

When lime was used on its own and with GGBS (Lime-GGBS, 50:50 and 30:70 ratio) at 10wt% (Fig. 1(a)), there is significant strength development with increasing curing period from 7 to 28 days. Within this system, lime-GGBS stabilised LOC at (50:50) ratio shows most of the highest UCS values (at all ages) with all formulae for calculating compaction water content. At 7 days of curing, F2 OMC recorded the highest strength, with a UCS value of 876 kN/m^2 when the LOC was stabilised with the lime-GGBS (50:50) ratio. At this curing stage the lowest strength value was 402 kN/m^2 for formula F1 (1.2 OMC) stabilised with lime only. This formula also indicates lowest strength values for all the lime-based stabilisers.

At 28 days of curing, the same pattern in strength development is observed as at 7 days. F2 OMC still gives in highest strength value when compared with others formulae. As seen for 7-day strength, the highest strength in value is when LOC was stabilised with lime-GGBS at (50:50) ratio, at 1410 kN/m^2. The lowest strength values again were observed when lime only was used to stabilise LOC, using all the different formulae.

Fig. 1(b) illustrates the strength development of the same lime system as in Fig. 1(a), but this time a 20wt% stabiliser dosage was used to stabilise the LOC. In general, the strength development increased from 7 days to 28 days of curing with all stabilisers and formulae in a similar manner as when a 10wt% stabiliser was used. However, the strength magnitudes were higher. At 7 days of curing, LOC stabilised with lime-GGBS (50:50) ratio indicated the highest strength values. The highest strength value was 1180 kN/m^2, when FI OMC was used. Meanwhile F2 OMC showed the lowest strength value of 293 kN/m^2, when lime only was used as the stabiliser.

At 28 days of curing, LOC stabilised with lime only continued to show the lowest strength values with all formulae, compared to other stabilisers, with a strength value of 539 kN/m^2 when formula F2 OMC was used. In this system, the highest strength values with all formulae was obtained when LOC was stabilised with lime-GGBS (30:70) ratio. When F1 (1.2 OMC) was used to calculate the amount of moisture content of the samples, the highest strength value of 2169 kN/m^2 was recorded.

2) Lime System: Stabilised LOC-PFA (50:50)

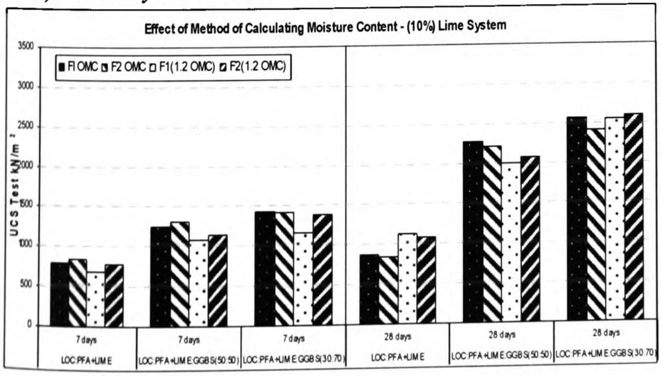

Figure 2(a) – UCS of LOC-PFA (50:50), stabilised with 10wt% Lime-slag stabiliser.

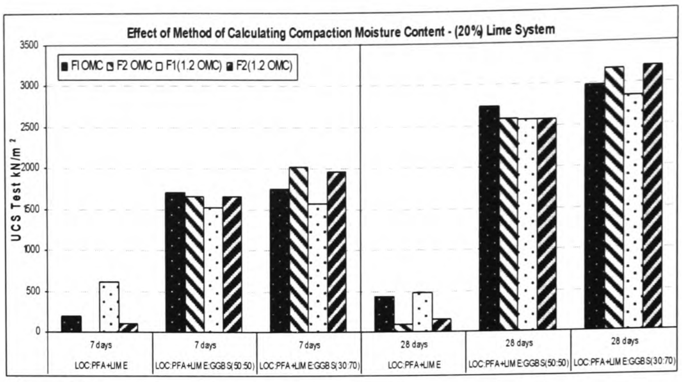

Figure 2(b) – UCS of LOC-PFA (50:50), stabilised with 20wt% Lime-slag stabiliser.

Within this system, LOC-PFA most of the highest UCS values (at all ages) with all formulae were observed with LOC-PFA stabilised with lime-GGBS (30:70) compared to LOC-PFA stabilised with lime alone and with lime-GGBS (50:50). At 7 days of curing, F1 OMC recorded the highest strength, with a UCS value of 1430 kN/m^2 when stabilised with the lime-GGBS (30:70). At this curing stage the lowest strength value was 691kN/m^2 was shown by formula F1 (1.2 OMC) stabilised with lime only. This formula also indicates lowest strength values with all the others lime-based stabilisers.

At 28 days of curing, F2 (1.2 OMC) gives in highest strength value. As seen with 7-day strength, the highest strength value is when LOC-PFA was stabilised with lime-GGBS (30:70) 2591 kN/m^2. The lowest strength values again were observed when lime only was used to stabilise LOC-PFA, using all the different formulae. The lowest strength was 839 kN/m^2 when F2 was used at OMC, (Fig. 2(a)).

Fig. 2(b) illustrates the strength development of the same lime system as in Fig. 2(a), but this time a 20wt% stabiliser dosage was used to stabilise LOC-PFA. In general, the strength development increased from 7 days to 28 days of curing. At 7 days of curing, LOC-PFA stabilised with lime-GGBS (30:70) indicated the highest strength values. The highest strength value was 2015 kN/m^2, when F2 OMC was used. Meanwhile for F2 at OMC, the test specimens totally collapsed with no strength gain, when lime only was used as the stabiliser. In other words, the strength at 28 days with 20 wt% lime was worse than for 10 wt% lime.

At 28 days of curing, LOC-PFA stabilised with lime only continued to show the lowest strength values with all formulae, compared to other stabilisers, with the lowest strength value of 90 kN/m^2 when formula F2 OMC was used. In this system, the highest strength values with all formulae were obtained when LOC-PFA was stabilised with lime-GGBS (30:70), when F2 (1.2 OMC) was used to calculate the amount of moisture content of the samples. The highest strength value of 3208 kN/m^2 was recorded.

3) PC System: Stabilised LOC

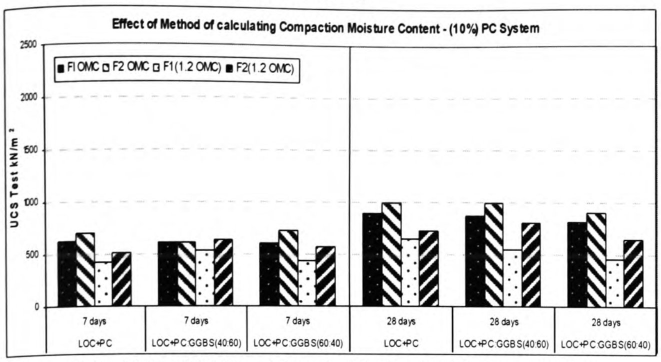

Figure 3(a) – UCS of LOC, stabilised with 10wt% PC-slag stabiliser.

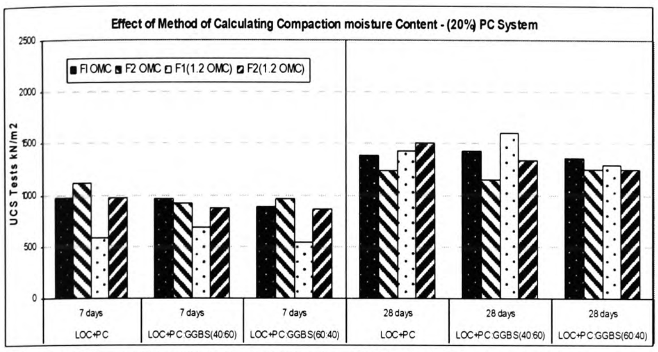

Figure 3(b) – UCS of LOC, stabilised with 20wt% PC-slag stabiliser.

Figures 3(a) and (b) illustrate the UCS development of LOC with the different methods of calculating the compaction moisture content, when stabilised with PC alone and with PC incorporating varying ratios of blended stabiliser (PC-GGBS at 40:60 and 60:40 ratios). The stabiliser dosages used are 10wt% and 20wt% for the two figures respectively. Like in the lime system, the overall results shows that there is increase in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating of moisture content. However, compared with the lime-GGBS System, the strength magnitudes are lower with the PC-GGBS System at both curing periods.

With the 10wt% stabiliser dosage, at 7 days of curing (Fig. 3(a)), stabilised LOC either with PC alone or with blended stabiliser shows an average UCS value of 580 kN/m^2. F2 OMC recorded the highest UCS values when PC was used on its own or when blended with GGBS, at both 7 and 28 days of curing, with a maximum value of 723 kN/m^2 at 7 days when stabilised with PC-GGBS (60:40) and 991 kN/m^2 at 28 days when stabilised with PC-GGBS (40:60). Formula F1 (1.2 OMC) gives the lowest strength value of 422 kN/m^2 at 7 days of curing when PC only was used, and 455 kN/m^2 at 28 days of curing when stabilised with PC-GGBS (60:40).

Fig.3 (b) illustrates the strength development when 20wt% stabiliser dosage was used. In general, the strength development increased progressively from 7 days to 28 days of curing with all types of stabiliser blends and formulae. At 7 days of curing, F2 OMC shows the highest strength values with UCS value of 1117 kN/m^2 when LOC was stabilised with PC only. Meanwhile, formula F1 (1.2 OMC) indicates the lowest strength values when LOC was stabilised with PC used on its own (587 kN/m^2). At 28 days of curing, F1 (1.2 OMC) shows the highest strength value of 1600 kN/m^2 with blended PC-GGBS (40:60) and F2 OMC stabilised with same blended stabiliser indicates the lowest strength improvement at 1153 kN/m^2. Overall, with the 20wt% stabiliser dosage, LOC stabilised with PC-GGBS (60:40) blends demonstrates almost equal magnitudes of strength development with both formulae.

In general, by blending PC with GGBS, almost equal in strength development patterns and magnitudes were observed at both 10wt% and 20wt% stabiliser level, compared to LOC stabilised with PC on its own. This indicates that GGBS has a good potential as a partial replacement material for PC. This is beneficial since GGBS has environmental benefits relative to lime or cement, as a by-product material.

4) PC System: Stabilised LOC-PFA (50:50)

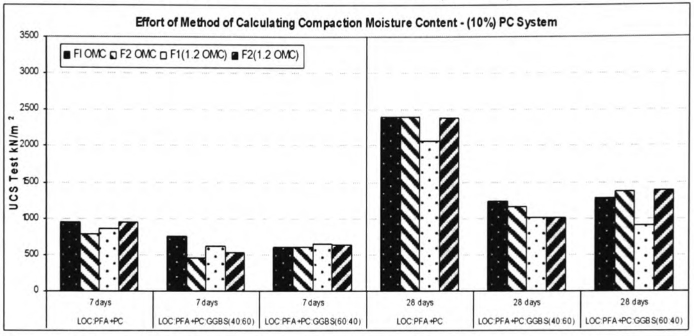

Figure 4(a) – UCS of LOC-PFA (50:50), stabilised with 10wt% PC-slag stabiliser.

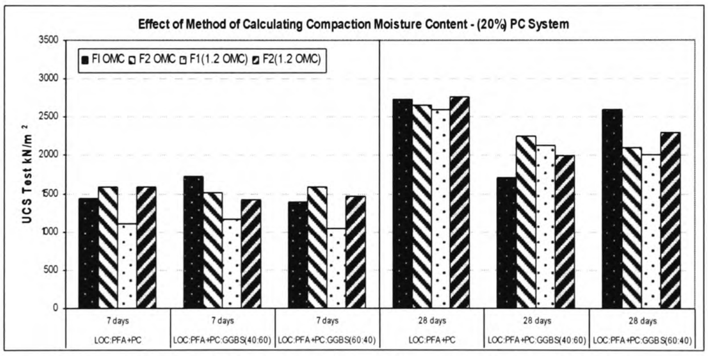

Figure 4(b) – UCS of LOC-PFA (50:50), stabilised with 20wt% PC-slag stabiliser.

Figures 4(a) and (b) illustrate the UCS development of LOC-PFA, like in the lime system (Fig. 2a & b), the overall results shows increase in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating of moisture content.

With 10wt% stabiliser dosage, at 7 days of curing (Fig. 4(a)), LOC-PFA stabilised with PC alone shows higher strength increment compared to blended stabiliser PC-GGBS. The highest strength was observed with formula F1 OMC at 954 kN/m^2. Formula F2 OMC gives the lowest strength value of 451 kN/m^2 at 7 days curing when PC-GGBS (40:60) was used, and F1 (1.2 OMC) indicates the lowest strength value of 900 kN/m^2 at 28 days of curing when stabilised with PC-GGBS (60:40) ratio.

There is increase in strength development upon increasing the stabiliser dosage to 20wt% at both 7 and 28 days with all formulae. Fig. 4(b) illustrates the strength development when 20wt% stabiliser dosage was used in the PC system. In general, the strength development increased progressively from 7 days to 28 days of curing with all types of stabiliser blends and formulae. At 7 days of curing, F2 OMC shows the highest strength values with PC only and PC-GGBS (60:40) with strength values of 1591 kN/m^2 and 1588 kN/m^2. Meanwhile, formula F1 (1.2 OMC) indicates the lowest strength values when LOC-PFA was stabilised with PC-GGBS (60:40) (1036 kN/m^2). At 28 days of curing, F2 (1.2 OMC) shows the highest strength value of 2754 kN/m^2 with PC only and F1 OMC stabilised with PC:GGBS (40:60) indicates the lowest strength at 1712 kN/m^2. Overall, at 20wt% stabiliser level, LOC-PFA stabilised with PC only demonstrates highest strength improvement with all formulae compared to others stabilisers.

IV. DISCUSSION

When lime is added to a clay soil, it has an immediate effect on the properties of the soil as cation exchange begins to take place between the metallic ions associated with the surfaces of the clay particles and the calcium ions of the lime. The highly alkaline environment produced by the addition of limes gives rise to the slow dissolution of alumino-silicates which then participate in the formation of hydrated cementitious reaction products [13]. Research by Bell [14] described the optimum addition of lime needed for maximum modification of the soil is normally between 1% and 3% lime added, by weight. Beyond this point any lime available is used to increase the strength of the soil. According to Ingles [15] a good rule of thumb in practice is to allow 1% by weight of lime for each 10% of clay in the soil.

When LOC was stabilised with lime, at 10wt% dosage, low strength at both 7 days and 28 days of curing period is associated with an increase in the amount of water available to the samples. However, by raising the level of stabiliser from 10wt% to 20wt%, results indicate, that those formulae with higher moisture contents achieve better strength. This explains the fact, that due to evaporation, hydration and cracking/expansion the existing tendency to compact on the wet side of OMC is good and should continue. The higher strength development is probably due to the formation of relatively higher amounts of C-S-H gel [16]. Lower in strength with the OMC formula is probably due to poor compaction, and a poor hydration. Research by Nidzam [10] has attributed the variability in strength with differences in dosage of lime to incomplete hydration of lime due to lack of adequate water.

A cohesive soil compacted at water contents below the OMC (dry of optimum), was found to have a much higher permeability than the same soil compacted at moulding water contents above the OMC (wet optimum) [17]. As a result, in clay liner applications, it is recommended that fine-grained soils be compacted at moisture contents slightly higher than their OMC's (2-3% wet of optimum) [18].

Earlier research at the University of Glamorgan reported that GGBS has minor effects on lime consumption, Atterberg limits and optimum moisture content and at the same time it was found that inclusion of GGBS can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime-only as seen in Fig. 1 & 2. When, compared with the lime-GGBS system, the strength magnitudes are lower with the PC-System especially at 28 days (Fig. 2a & b). However, LOC-PFA (50:50) with PC only stabilising indicated highest strength increment at both 7 and 28 days when compared to blended stabiliser PC-GGBS (40:60) and (60:40) ratios. This was not the case for lime system, where the lime-GGBS system showed superior strength development relative to the use of lime alone. The use of GGBS is beneficial since GGBS has environmental benefits relative to lime or cement, as a by-product material. Its manufacture involves only a fraction of the energy used and CO_2 emissions, associated with either cement or lime [19].

V. CONCLUSION

The results obtained from this preliminary investigation suggest that there is potential for the use of PFA as substitutes of clay for unfired bricks. Fly ash can be used to replace up to 40% of the raw material, clay, in building blocks and tiles [5]. Overall, UCS results show that with stabilised LOC-PFA the strength values are much higher compared to stabilised LOC alone accept when LOC-PFA stabilised with lime only. This will certainly contribute to the recycling of fly ash and hence minimise the impact of the fly ash landfills on the environment. At the same time this helps in the reduction in clay usage for the production of bricks. Furthermore, the hazardous emissions of the firing processes from bricks making will be reduced.

Based on the laboratory results it was observed that there is an economic as well as environmental advantage from using lime-GGBS and PC-GGBS systems. The results indicate that the strength values of system incorporating GGBS are comparable to those achieved using lime and PC only. The amount of mix water and the length of curing period influence the gain in strength. Strength continues to increase with increasing length of curing time but generally, the most notable increases occur within the first 7 days. It was observed that the compaction water content absorption and compressive strength are closely related. The moisture may be considered very close between the two formulae and based on the results it shows that there is no consistent trend for strength increment in both formulae. This is good outcome, as in practice, it is difficult to maintain a consistent material water content in different seasonal conditions.

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The Development of Sustainable Lime-Clay Building Components

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Abstract—**The most efficient way for construction to approach sustainability is to reuse waste materials and by-products from other industrial activities. This paper reports on the investigations on the development of unfired bricks for building components.**

In this research Lower Oxford Clay (LOC) alone and combined with Pulverised Fly Ash (PFA) as target materials were stabilised with Lime, Portland Cement (PC) and blended binders comprising of Lime and PC blended with Ground Granulated Blast-furnace Slag (GGBS). Stabilised cylinders were made under controlled laboratory conditions at varying moisture contents and stabilised with varying stabiliser dosages. After fabrication, samples were wrapped with several runs of cling film and cured for 7 and 28 days prior to testing for the unconfined compressive strength (UCS).

The results obtained showed that the UCS values of stabilised cylinders incorporating PC only or GGBS blended binders were higher than those stabilised with the traditional lime. Lime-GGBS blends (30:70 ratio) recorded the highest strength values compared with the Lime-GGBS (50:50), or the other unblended stabilisers used. Overall results showed that stabilised LOC-PFA (50:50) gives higher UCS values compared to LOC stabilised on its own.

There are technological, economic as well as environmental advantages and potential of utilising PFA, an industrial by-product from coal industry, and GGBS a by-product from the steel industry, in the development of sustainable lime-clay building components.

Index Terms— **Compressive strength, bricks, sustainability, lime, Portland cement, industrial by-product.**

I. INTRODUCTION

THE need for sustainability, reduction of material processing costs such as reduction of firing costs is well established within the construction industry. The construction industry has always shown a receptive attitude to research into new materials [1].

The recycling of GGBS, or fly ash as concrete admixture nowadays is much more than an alternative for reducing costs [2,3]. Fly ash, a by-product of coal combustion, is frequently used in concrete production as an inexpensive substitute for PC. However although fly ash is commonly used in cements, it has rarely been applied to bricks [4]. Joshi et al. [5] reported that, the major properties of fly ash exploited in the clay brick industry are based on their similar composition as that of clay, the fuel value due to the presence of unburnt carbon, reduced weight of the resultant product, reduced shrinkage due to its inert nature and chemical compatibility with natural clays.

Recently it has been shown that fly ash may improve the compressive strength of bricks, more resistant to frost, and saving in the firing energy [6]. Fly ash has also been used as a partial or total replacement of quartz sand in the production of sand-lime building bricks by using an autoclave process [5]. It also has been used to replace up to 40% of raw material, clay, in building blocks and tiles [5].

In view of the huge demand for building bricks, along with non-availability of suitable soil, there is need to explore alternative raw materials and energy efficient technologies for making bricks [7]. Recently efforts have been made to produce bricks using different types of industrial/mining by-products. Research by Malhotra et al [8] has observed that good quality bricks can be produced by pressing slag-lime mixtures at sufficiently low pressure. The manufacturing process is simple and does not require any firing, or autoclaving, specialised plant or machinery [7].

The objective of this research project is to extend an existing unfired clay cementation technology that is currently viable for highway construction [9]. The work evaluates the engineering properties of bricks made with clay and pulverised fly ash (PFA), stabilised with Lime-GGBS and PC-GGBS blends, and then assesses their potential application as unfired clay building components.

II. METHODOLOGY

A. Materials

1) Lower Oxford Clay (LOC)

The LOC used in this study was supplied by Hanson Bricks Ltd., from their brick works at Stewartby, Bedfordshire, UK. The clay is grey in colour and is known to have high sulfate and sulfide contents. Mineralogical studies by Hanson Brick Ltd. have established that LOC contains illite (23%), kaolinite (10%), chlorite (7%), calcite (10%), quartz (29%), gypsum (2%), pyrite (4%), feldspar (8%) and organics (7%) [10].

2) Pulverised Fly Ash (PFA)

PFA is a material with pozzolanic properties. Several investigators have reported that when fly ash is pulverised to increase fineness, its pozzolanic activity increases significantly [5]. Chemical constituents in fly ash reported in

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terms of oxides include silica (SiO_2), alumina (Al_2O_3), and oxides of calcium (CaO), iron (Fe_2O_3), magnesium (MgO), titanium or vertiel (TiO_2), sulphur (SO_3), sodium (Na_2O) and potassium (K_2O). Among these SiO_2 and Al_2O_3 together make up about 40% to 80% of the total ash [5].

3) Lime

The lime used in this study was quick lime (CaO) supplied by Calch Tŷ Mawr Lime, UK. The reason for using quicklime rather a hydrated lime as a binder is that it is denser and less dusty than hydrated lime. It is also more effective as a stabiliser than hydrated lime.

4) Ground Granulated Blastfurnace Slag (GGBS)

The GGBS used in this study was supplied by Civil and Marine Slag Cement Ltd, Newport, UK. It is a latently hydraulic material that occurs as a by-product the steel industry. Researchers at the University of Glamorgan, UK, have established that inclusion of GGBS in the traditional stabilisers of lime and PC can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime or PC only [11].

5) Portland Cement (PC)

The Portland Cement (PC) used was manufactured in accordance with the British Standard BS EN 197 – 1 [12]. Table 1 shows the chemical/oxide composition of GGBS, PC and lime.

TABLE 1

Chemical composition and physical properties of GGBS (Civil and Marine Slag Cement Ltd.) and typical ordinary PC and lime.

Oxide	Composition (%)		
	GGBS	PC	LIME
CaO	41.99	63	-
Ca $(OH)_2$	-	-	78
$CaCO_3$	-	-	3
SiO_2	35.34	20	5.08
Al_2O_3	11.59	6	1.42
MgO	8.04	4.21	0.65
Fe_2O_3	0.35	3	-
MnO	0.45	0.03-1.11	-
S_2	1.18	-	-
SO_3	0.23	2.3	-
Insoluble residue	0.30	0.5	-
Relative density	2.90	3.15	-
Bulk density (kg/m^3)	1200	1400	-
Colour	Off-white	Grey	-
Glass content	~90	-	-

B. Experimental Procedure (Specimen preparation)

Proctor compaction tests were carried out in accordance with BS 1377 (1990) Part 2, in order to establish values of the maximum dry density (MDD) and optimum moisture content (OMC) for LOC and PFA. From the tests, the MDD value of 1.42 Mg/m^3 for both LOC and PFA, an OMC value of 24% for LOC and 18% for PFA were established. For this study, test specimens were then prepared at OMC and also at 1.2 OMC.

Using two formulae F1 and F2 for calculating the compaction moisture content, compacted cylinders of 50mm diameter and 100mm in height were fabricated, at approximately comparable bulk densities. Using the density and moisture content values, the quantities of the dry materials, enough to produce a compacted cylindrical specimen were established. The materials were mixed thoroughly and adding the pre-calculated amount of water. Hand mixing with palette knives was used to achieve a homogenous mix. Cylinders weighing 380g were prepared for all proportions. A steel mould fitted with a collar, was used to compact the material. Compaction was achieved using a hydraulic jack. After compaction, the cylinders were extruded using a steel plunger, trimmed, and wrapped in several runs of cling film, labelled and placed in sealed plastic containers. All samples were cured for 7 and 28 days. The two formulae used to calculate the amount of moisture content used for compaction are:-

Formula 1 (F1) : $S + kS + w(S + kS) = 380g$…(I) at OMC and 1.2 OMC

Formula 2 (F2) : $S + kS + wS = 380g$….. (II) at OMC and 1.2 OMC

Where S = Soil, k = Stabiliser dosage (%) and w = Water (%) at OMC and 1.2 OMC

From equations I and II, two sets of formulae each with w = OMC and w = 1.2 OMC were used. Therefore, using formula 1 (F1), the calculation of water was made based on the total amount of soil and stabiliser, whereas, with formula 2 (F2), the calculation of water was only based on the amount of soil. Three cylinders per mix proportion were subjected to UCS test and the mean strength determined.

III. RESULTS

A. UCS – Early strength development

1) Lime System: Stabilised LOC

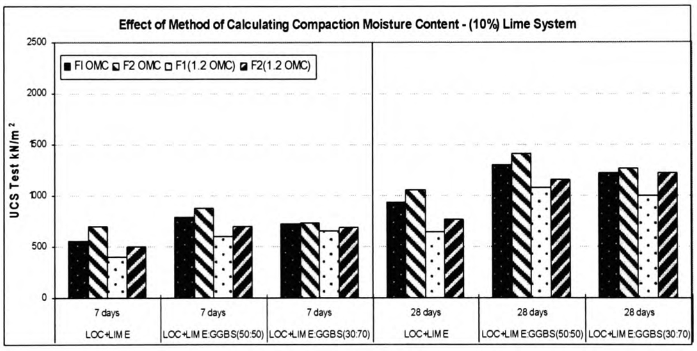

Figure 1(a) – UCS of LOC, stabilised with 10wt% Lime-slag stabiliser.

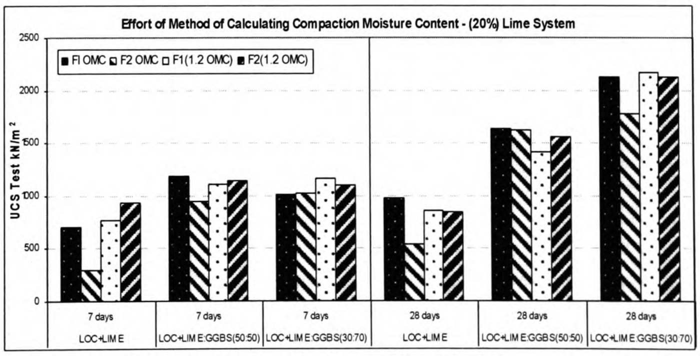

Figure 1(b) – UCS of LOC, stabilised with 20wt% Lime-slag stabiliser.

Figures 1 (a) and (b) show the effects of different methods of calculating the moisture content [(F1: OMC, 1.2OMC) and (F2: OMC, 1.2OMC)] on the UCS of LOC, when stabilised with lime alone and Lime-GGBS at 30:70 and 50:50 ratios, at 10wt% and 20wt% stabiliser dosage. These stabilization levels are much higher than the typical ones used in highway construction (3-8%), because the current work is aimed at the building industry where higher strength values are needed for bricks, blocks and mortar. The overall results show that there are increases in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating the initial compaction water input.

When lime was used on its own and with GGBS (Lime-GGBS, 50:50 and 30:70 ratio) at 10wt% (Fig. 1(a)), there is significant strength development with increasing curing period from 7 to 28 days. Within this system, lime-GGBS stabilised LOC at (50:50) ratio shows most of the highest UCS values (at all ages) with all formulae for calculating compaction water content. At 7 days of curing, F2 OMC recorded the highest strength, with a UCS value of 876 kN/m^2 when the LOC was stabilised with the lime-GGBS (50:50) ratio. At this curing stage the lowest strength value was 402 kN/m^2 for formula F1 (1.2 OMC) stabilised with lime only. This formula also indicates lowest strength values for all the lime-based stabilisers.

At 28 days of curing, the same pattern in strength development is observed as at 7 days. F2 OMC still gives in highest strength value when compared with others formulae. As seen for 7-day strength, the highest strength in value is when LOC was stabilised with lime-GGBS at (50:50) ratio, at 1410 kN/m^2. The lowest strength values again were observed when lime only was used to stabilise LOC, using all the different formulae.

Fig. 1(b) illustrates the strength development of the same lime system as in Fig. 1(a), but this time a 20wt% stabiliser dosage was used to stabilise the LOC. In general, the strength development increased from 7 days to 28 days of curing with all stabilisers and formulae in a similar manner as when a 10wt% stabiliser was used. However, the strength magnitudes were higher. At 7 days of curing, LOC stabilised with lime-GGBS (50:50) ratio indicated the highest strength values. The highest strength value was 1180 kN/m^2, when FI OMC was used. Meanwhile F2 OMC showed the lowest strength value of 293 kN/m^2, when lime only was used as the stabiliser.

At 28 days of curing, LOC stabilised with lime only continued to show the lowest strength values with all formulae, compared to other stabilisers, with a strength value of 539 kN/m^2 when formula F2 OMC was used. In this system, the highest strength values with all formulae was obtained when LOC was stabilised with lime-GGBS (30:70) ratio. When F1 (1.2 OMC) was used to calculate the amount of moisture content of the samples, the highest strength value of 2169 kN/m^2 was recorded.

2) *Lime System: Stabilised LOC-PFA (50:50)*

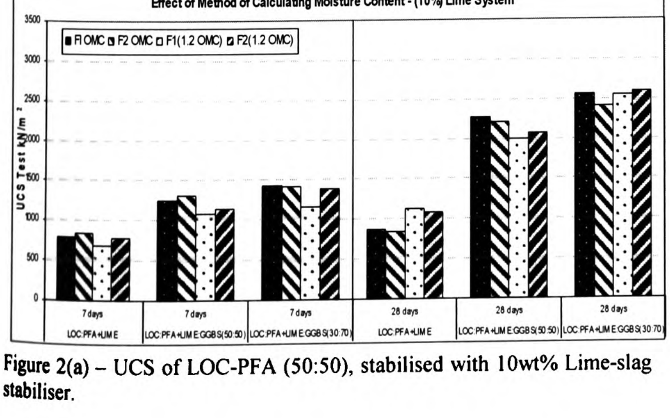

Figure 2(a) – UCS of LOC-PFA (50:50), stabilised with 10wt% Lime-slag stabiliser.

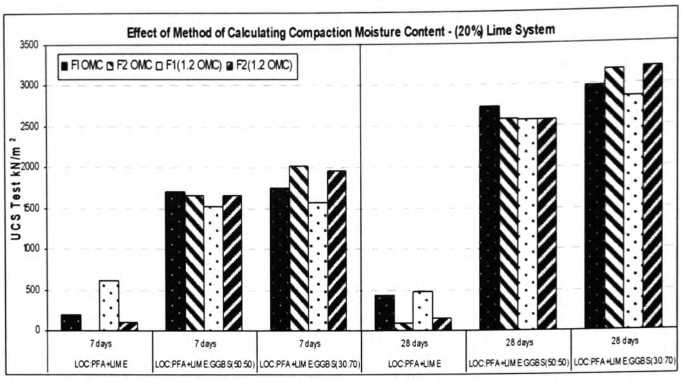

Figure 2(b) – UCS of LOC-PFA (50:50), stabilised with 20wt% Lime-slag stabiliser.

Within this system, LOC-PFA most of the highest UCS values (at all ages) with all formulae were observed with LOC-PFA stabilised with lime-GGBS (30:70) compared to LOC-PFA stabilised with lime alone and with lime-GGBS (50:50). At 7 days of curing, F1 OMC recorded the highest strength, with a UCS value of 1430 kN/m^2 when stabilised with the lime-GGBS (30:70). At this curing stage the lowest strength value was 691kN/m^2 was shown by formula F1 (1.2 OMC) stabilised with lime only. This formula also indicates lowest strength values with all the others lime-based stabilisers.

At 28 days of curing, F2 (1.2 OMC) gives in highest strength value. As seen with 7-day strength, the highest strength value is when LOC-PFA was stabilised with lime-GGBS (30:70) 2591 kN/m^2. The lowest strength values again were observed when lime only was used to stabilise LOC-PFA, using all the different formulae. The lowest strength was 839 kN/m^2 when F2 was used at OMC, (Fig. 2(a)).

Fig. 2(b) illustrates the strength development of the same lime system as in Fig. 2(a), but this time a 20wt% stabiliser dosage was used to stabilise LOC-PFA. In general, the strength development increased from 7 days to 28 days of curing. At 7 days of curing, LOC-PFA stabilised with lime-GGBS (30:70) indicated the highest strength values. The highest strength value was 2015 kN/m^2, when F2 OMC was used. Meanwhile for F2 at OMC, the test specimens totally collapsed with no strength gain, when lime only was used as the stabiliser. In other words, the strength at 28 days with 20 wt% lime was worse than for 10 wt% lime.

At 28 days of curing, LOC-PFA stabilised with lime only continued to show the lowest strength values with all formulae, compared to other stabilisers, with the lowest strength value of 90 kN/m^2 when formula F2 OMC was used. In this system, the highest strength values with all formulae were obtained when LOC-PFA was stabilised with lime-GGBS (30:70), when F2 (1.2 OMC) was used to calculate the amount of moisture content of the samples. The highest strength value of 3208 kN/m^2 was recorded.

3) *PC System: Stabilised LOC*

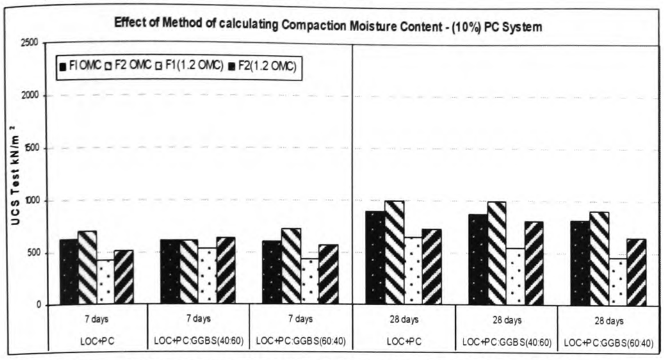

Figure 3(a) – UCS of LOC, stabilised with 10wt% PC-slag stabiliser.

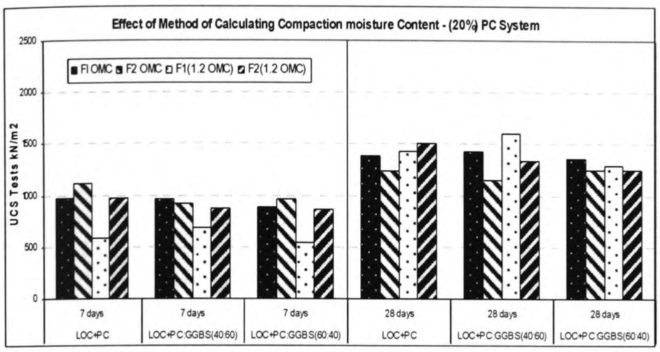

Figure 3(b) – UCS of LOC, stabilised with 20wt% PC-slag stabiliser.

Figures 3(a) and (b) illustrate the UCS development of LOC with the different methods of calculating the compaction moisture content, when stabilised with PC alone and with PC incorporating varying ratios of blended stabiliser (PC-GGBS at 40:60 and 60:40 ratios). The stabiliser dosages used are 10wt% and 20wt% for the two figures respectively. Like in the lime system, the overall results shows that there is increase in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating of moisture content. However, compared with the lime-GGBS System, the strength magnitudes are lower with the PC-GGBS System at both curing periods.

With the 10wt% stabiliser dosage, at 7 days of curing (Fig. 3(a)), stabilised LOC either with PC alone or with blended stabiliser shows an average UCS value of 580 kN/m^2. F2 OMC recorded the highest UCS values when PC was used on its own or when blended with GGBS, at both 7 and 28 days of curing, with a maximum value of 723 kN/m^2 at 7 days when stabilised with PC-GGBS (60:40) and 991 kN/m^2 at 28 days when stabilised with PC-GGBS (40:60). Formula F1 (1.2 OMC) gives the lowest strength value of 422 kN/m^2 at 7 days of curing when PC only was used, and 455 kN/m^2 at 28 days of curing when stabilised with PC-GGBS (60:40).

Fig.3 (b) illustrates the strength development when 20wt% stabiliser dosage was used. In general, the strength development increased progressively from 7 days to 28 days of curing with all types of stabiliser blends and formulae. At 7 days of curing, F2 OMC shows the highest strength values with UCS value of 1117 kN/m^2 when LOC was stabilised with PC only. Meanwhile, formula F1 (1.2 OMC) indicates the lowest strength values when LOC was stabilised with PC used on its own (587 kN/m^2). At 28 days of curing, F1 (1.2 OMC) shows the highest strength value of 1600 kN/m^2 with blended PC-GGBS (40:60) and F2 OMC stabilised with same blended stabiliser indicates the lowest strength improvement at 1153 kN/m^2. Overall, with the 20wt% stabiliser dosage, LOC stabilised with PC-GGBS (60:40) blends demonstrates almost equal magnitudes of strength development with both formulae.

In general, by blending PC with GGBS, almost equal in strength development patterns and magnitudes were observed at both 10wt% and 20wt% stabiliser level, compared to LOC stabilised with PC on its own. This indicates that GGBS has a good potential as a partial replacement material for PC. This is beneficial since GGBS has environmental benefits relative to lime or cement, as a by-product material.

4) *PC System: Stabilised LOC-PFA (50:50)*

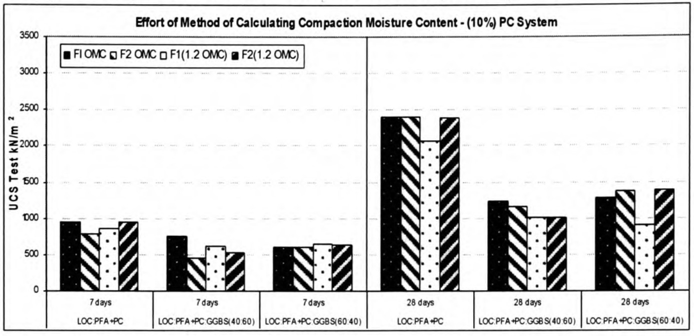

Figure 4(a) – UCS of LOC-PFA (50:50), stabilised with 10wt% PC-slag stabiliser.

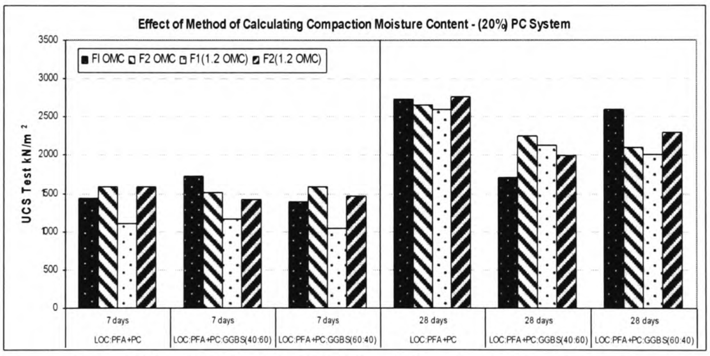

Figure 4(b) – UCS of LOC-PFA (50:50), stabilised with 20wt% PC-slag stabiliser.

Figures 4(a) and (b) illustrate the UCS development of LOC-PFA, like in the lime system (Fig. 2a & b), the overall results shows increase in strength with increasing stabiliser from 10wt% to 20wt% and with increased curing period from 7 to 28 days for all methods of calculating of moisture content.

With 10wt% stabiliser dosage, at 7 days of curing (Fig. 4(a)), LOC-PFA stabilised with PC alone shows higher strength increment compared to blended stabiliser PC-GGBS. The highest strength was observed with formula F1 OMC at 954 kN/m^2. Formula F2 OMC gives the lowest strength value of 451 kN/m^2 at 7 days curing when PC-GGBS (40:60) was used, and F1 (1.2 OMC) indicates the lowest strength value of 900 kN/m^2 at 28 days of curing when stabilised with PC-GGBS (60:40) ratio.

There is increase in strength development upon increasing the stabiliser dosage to 20wt% at both 7 and 28 days with all formulae. Fig. 4(b) illustrates the strength development when 20wt% stabiliser dosage was used in the PC system. In general, the strength development increased progressively from 7 days to 28 days of curing with all types of stabiliser blends and formulae. At 7 days of curing, F2 OMC shows the highest strength values with PC only and PC-GGBS (60:40) with strength values of 1591 kN/m^2 and 1588 kN/m^2. Meanwhile, formula F1 (1.2 OMC) indicates the lowest strength values when LOC-PFA was stabilised with PC-GGBS (60:40) (1036 kN/m^2). At 28 days of curing, F2 (1.2 OMC) shows the highest strength value of 2754 kN/m^2 with PC only and F1 OMC stabilised with PC:GGBS (40:60) indicates the lowest strength at 1712 kN/m^2. Overall, at 20wt% stabiliser level, LOC-PFA stabilised with PC only demonstrates highest strength improvement with all formulae compared to others stabilisers.

IV. DISCUSSION

When lime is added to a clay soil, it has an immediate effect on the properties of the soil as cation exchange begins to take place between the metallic ions associated with the surfaces of the clay particles and the calcium ions of the lime. The highly alkaline environment produced by the addition of limes gives rise to the slow dissolution of alumino-silicates which then participate in the formation of hydrated cementitious reaction products [13]. Research by Bell [14] described the optimum addition of lime needed for maximum modification of the soil is normally between 1% and 3% lime added, by weight. Beyond this point any lime available is used to increase the strength of the soil. According to Ingles [15] a good rule of thumb in practice is to allow 1% by weight of lime for each 10% of clay in the soil.

When LOC was stabilised with lime, at 10wt% dosage, low strength at both 7 days and 28 days of curing period is associated with an increase in the amount of water available to the samples. However, by raising the level of stabiliser from 10wt% to 20wt%, results indicate, that those formulae with higher moisture contents achieve better strength. This explains the fact, that due to evaporation, hydration and cracking/expansion the existing tendency to compact on the wet side of OMC is good and should continue. The higher strength development is probably due to the formation of relatively higher amounts of C-S-H gel [16]. Lower in strength with the OMC formula is probably due to poor compaction, and a poor hydration. Research by Nidzam [10] has attributed the variability in strength with differences in dosage of lime to incomplete hydration of lime due to lack of adequate water.

A cohesive soil compacted at water contents below the OMC (dry of optimum), was found to have a much higher permeability than the same soil compacted at moulding water contents above the OMC (wet optimum) [17]. As a result, in clay liner applications, it is recommended that fine-grained soils be compacted at moisture contents slightly higher than their OMC's (2-3% wet of optimum) [18].

Earlier research at the University of Glamorgan reported that GGBS has minor effects on lime consumption, Atterberg limits and optimum moisture content and at the same time it was found that inclusion of GGBS can markedly increase the compressive strength of stabilised clays, relative to that achieved by lime-only as seen in Fig. 1 & 2. When, compared with the lime-GGBS system, the strength magnitudes are lower with the PC-System especially at 28 days (Fig. 2a & b). However, LOC-PFA (50:50) with PC only stabilising indicated highest strength increment at both 7 and 28 days when compared to blended stabiliser PC-GGBS (40:60) and (60:40) ratios. This was not the case for lime system, where the lime-GGBS system showed superior strength development relative to the use of lime alone. The use of GGBS is beneficial since GGBS has environmental benefits relative to lime or cement, as a by-product material. Its manufacture involves only a fraction of the energy used and CO_2 emissions, associated with either cement or lime [19].

V. CONCLUSION

The results obtained from this preliminary investigation suggest that there is potential for the use of PFA as substitutes of clay for unfired bricks. Fly ash can be used to replace up to 40% of the raw material, clay, in building blocks and tiles [5]. Overall, UCS results show that with stabilised LOC-PFA the strength values are much higher compared to stabilised LOC alone accept when LOC-PFA stabilised with lime only. This will certainly contribute to the recycling of fly ash and hence minimise the impact of the fly ash landfills on the environment. At the same time this helps in the reduction in clay usage for the production of bricks. Furthermore, the hazardous emissions of the firing processes from bricks making will be reduced.

Based on the laboratory results it was observed that there is an economic as well as environmental advantage from using lime-GGBS and PC-GGBS systems. The results indicate that the strength values of system incorporating GGBS are comparable to those achieved using lime and PC only. The amount of mix water and the length of curing period influence the gain in strength. Strength continues to increase with increasing length of curing time but generally, the most notable increases occur within the first 7 days. It was observed that the compaction water content absorption and compressive strength are closely related. The moisture may be considered very close between the two formulae and based on the results it shows that there is no consistent trend for strength increment in both formulae. This is good outcome, as in practice, it is difficult to maintain a consistent material water content in different seasonal conditions.

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