# ENGINEERING PROPERTIES OF COMPRESSED BRICKS BASED ON STABILISED PEAT SOILS

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**ABSTRACT**

Earth as a building material is available everywhere and exists in many different compositions. It is most efficiently used in developing countries to cater for the greatest number of people. With the increased awareness of climate change issues, it is now generally accepted that there is an urgent need to limit carbon dioxide emissions into the atmosphere. These emissions are becoming a major environmental concern in tropical countries. The research looked into the use of peat soil, a waste material in many construction works. There is no requirement for burning, hence saving energy and minimise emissions.

The thesis examines the interplay between three main factors: constituent materials (cement, soil, sand and suitable pozzolan materials), compaction pressure and the processing methods for bricks fabrication. Laboratory investigation was carried out to investigate the relation between mix design and the engineering performance taking into consideration the economic factors. The research examined the effects of chemical binders and sand at improving peat soil as solid and hollow bricks in terms of engineering properties including wet and dry compressive strength, total water absorption, bulk and dry density and total volume porosity. The characteristics of airborne sound insulation, fire resistance and axial load capacity of compressed stabilised peat masonry wall were also investigated.

Laboratory finding showed that peat based compressed bricks have the required physical properties to be used as construction bricks. Compressive strength of compressed stabilised peat bricks prospectively for PFA cement, PFA cement with lime, and OPC with lime, were 7.2 MPa, 7.66 MPa and 6.77 MPa which the minimum recommended strength for brick and block is 2 MPa. The highest compressive strength results were derived from the mixture of compressed stabilised peat brick was when used PFA cement and high compaction pressure.

For water absorption test of compressed stabilised peat bricks gained the best results of only 2.6%, which water absorption recommended by BS 3921 is 4.5% for category A and 7% for category B. The volume porosity test of compressed stabilised peat bricks obtained good results of only 4.75%, which maximum values recommended by BS 3921 is 10%.

Sound transmission and fire resistance in housing is a problem that exists in many countries. Compressed stabilised peat bricks sound insulation and fire resistance results indicated that an effective condition for construction insulation and fire resistance. Validation of the experimental results of the compressed stabilised peat brick masonry prism tests affirmed that the stress-strain of masonry prism evaluated experimentally could be reasonably back analyzed by the finite element method. The finite element program was then used to establish the various configuration of compressed stabilised peat masonry wall.

The thesis concludes that it is possible to significantly raise the strength and improve the engineering properties of compressed stabilised peat brick. This improvement is achieved via better bonding, reduction in voids and lowered water absorption. Hence, peat soils can be engineered to produce bricks and blocks for the construction industry.

# ABSTRAK

Bumi sebagai bahan bangunan yang terdapat di mana-mana dan ada dalam komposisi yang berbeza. Hal ini paling efisien digunakan di negara-negara membangun untuk melayani jumlah terbesar orang. Dengan meningkatnya kesedaran isu perubahan iklim, sekarang umum diterima bahawa ada keperluan mendesak untuk menyekat pembebasan karbon dioksida ke atmosfera. Pembebasan ini menjadi perhatian persekitaran utama di negara tropika. Penyelidikan ini melihat ke penggunaan tanah gambut, bahan sampah di kebanyakan tempat kerja pembinaan. Tidak ada keperluan untuk pembakaran, maka penjimatan tenaga dan pembebasan meminimumkan.

Tesis ini mengkaji interaksi antara tiga faktor utama: bahan penyusunnya (semen, tanah, pasir dan bahan pozzolan berpadanan), tekanan kompaksi dan kaedah pemprosesan untuk fabrikasi batu-bata. Makmal penyiasatan dilakukan untuk mengetahui hubungan antara rekabentuk campuran dan prestasi teknik dengan mempertimbangkan faktor ekonomi. Penelitian ini meneliti kesan daripada binder kimia dan pasir untuk memperbaiki tanah gambut sebagai batu-bata padat dan berongga dalam hal sifat teknikal termasuk kekuatan tekan basah dan kering, penyerapan air total, curah dan kepadatan kering dan isipadu porositi keseluruhan. Ciri-ciri ‘airborne sound insulation’, ketahanan api dan keupayaan beban paksi dinding pada bata gambut dikompres stabil juga diselidiki.

Penemuan makmal menunjukkan bahawa batu-bata termampat berasaskan gambut mempunyai sifat fizikal yang diperlukan untuk digunakan sebagai pembinaan batu-bata. Kekuatan tekanan dari tekanan batu-bata gambut stabil prospektif untuk semen PFA, semen PFA dengan kapur, dan OPC dengan kapur, adalah 7,2 MPa, 7,66 MPa dan 6,77

MPa minimum yang disyorkan kekuatan untuk batu-bata dan blok 2 MPa. Keputusan kekuatan tekanan tertinggi berasal dari campuran bata gambut dikompres stabil ketika digunakan PFA semen dan tekanan kompaksi tinggi.

Untuk uji penyerapan air dikompres bata gambut stabil memperoleh hasil yang terbaik dari hanya 2.6%, yang penyerapan air disarankan oleh BS 3921 adalah 4.5% untuk kategori A dan 7% untuk kategori B. Volume porositi ujian mampatan bata gambut stabil diperoleh hasil yang baik hanya 4.75%, yang nilai maksimum yang disyorkan oleh BS 3921 adalah 10%.

Penghantaran bunyi dan ketahanan api di perumahan merupakan masalah yang terdapat di kebanyakan negara. Kompres gambut stabil bata 'airborne sound insulation' dan hasil ketahanan api menunjukkan bahawa keadaan yang efektif untuk insulasi pembinaan dan ketahanan api. Validasi keputusan eksperimen dari kestabilan ujian dikompres prisma pasangan bata gambut menegaskan bahawa voltan-regangan prisma batu dinilai eksperimen boleh secara wajar kembali dianalisis dengan kaedah unsur hingga. Program elemen hingga kemudian digunakan untuk membina pelbagai konfigurasi dinding pasangan bata termampat stabil gambut.

Tesis ini menyimpulkan bahawa adalah mungkin untuk secara signifikan meningkatkan kekuatan dan memperbaiki sifat teknikal dari batu bata gambut termampat stabil. Peningkatan ini dicapai melalui ikatan yang lebih baik, pengurangan void dan menurunkan penyerapan air. Oleh kerana itu, tanah gambut boleh direkabentuk untuk menghasilkan batu bata dan blok untuk industri pembinaan.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| $C_2S$ | = | Dicalcium silicate |
| CSB | = | Compressed and stabilised block |
| $C_4ASH_{12}$ | = | Monosulphoaluminate |
| cm | = | Centimetre |
| CRM | = | Cement replacement materials |
| CSPB | = | Compressed Stabilised Peat bricks |
| $CO_2$ | = | Carbon dioxide |
| C-S-H | = | `Calcium sulfate hydrate |
| C-A-H | = | Calcium aluminate hydrate |
| $C_3S$ | = | Tricalcium aluminate |
| C | = | Spectrum 1: A-weighted pink |
| $C_{tr}$ | = | Spectrum 2: A- Traffic noise |
| $C_I$ | = | Factories emitting mainly low and medium frequency noise |
| GGBS | = | Ground granulated blast furnace slag |
| Hz | = | Hertz |
| ISO | = | International Standards Organisation |
| ILO | = | International Labour Organisation |
| kg | = | kilogram |
| $L_r$ | = | Sound pressure level in the receiving room |
| $L_s$ | = | Sound pressure level in the source room |
| mm | = | Millimetre |
| Mg | = | Mega gram |
| m | = | Meter |
| MPa | = | `Mega Pascal |
| OPC | = | Ordinary Portland cement |
| PFA | = | Pulverised fuel ash |

| | | |
|---|---|---|
| PG | = | Phosphogypsum |
| R | = | Fire resistance period |
| STC | = | Sound transmission class |
| TL | = | Transmission loss |
| T | = | Temperature |
| w/c | = | Free water to cement ratio |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background To The Study

This section presents the general context in which the study is based, the history of using earth for building materials, stabilised soil for bricks and blocks, and its advantages. The study also focuses on the need for development in terms of requirements as well as the need to understand the properties of building materials to increase the strength and durability of compressed stabilise earth bricks against destructive effects.

The history of brick industry is very old and can be traced back to about 5000 years old. Understanding of the brick microstructure as influenced by the range of temperature during firing cycle has been enhanced by the experimental work in this area (McConvile & lee. 2005). Earth as a building material is available everywhere and exists in many different compositions. It is most efficiently used in developing countries to house the greatest number of people with the least demand. Masonry is one of the most popular materials in many countries for construction of houses due to its useful properties such as durability, relatively low cost, wider availability, good sound and heat insulation, acceptable fire resistance, adequate resistance to weathering and attractive appearance (Jayasinghe & Mallawarachchi, 2009).

Historically, earth has been the most widely known and used building material in construction and probably has been the most important of all building materials (Legget, 1960). According to Middendorf (2001) recorded cases of the use of earth bricks dates back to Mesopotamia around 8000 BC. Recent reports indicated that, about half of the world's populations are still living in earth buildings (McHenry and Paul, 1984). Of all urban housing units worldwide there are about 25% that does not conform to building regulations while 18% are considered non-permanent structures (Habitat, 2001).

There are many benefits of earth buildings. For example, earth structures are completely recyclable, so sun-dried bricks return to the earth without polluting the soil (Rigassi, 1995). Many benefits that are offered by earth construction are often underutilised in the developed world where the use of earth as a low-embodied material is often the case (Middendorf, 2001).

The principal reason for using earth is due to its excellent characteristics. These include, the efficient use of finite resources, minimising pollution and waste and low carbon emissions especially in industrial countries (Little & Morton, 2001). Stabilised compressed earth materials are made using graded soils with the addition on hydraulic binder (eg. Portland cement) either statically or dynamically compacted into moulds to form compressed earth bricks, or monolithically inside formwork to create rammed earth walls (Hall & Allinson, 2009).

The conventional types can be identified as burnt clay bricks, but compressed stabilised peat soils consisting of solid and hollow bricks are alternative types of comparable performance and appearance which are also more environmental friendly and cost effective.

Actually, most developing countries are facing real housing deficiency (Harison & Sinha, 1995). Therefore, there is an urgent need to construct and build houses that are more durable at a low cost. In this regard, earth masonry has a long and illustrious record of providing durable and attractive buildings. Recently, the technology of traditional earth construction has undergone considerable developments that have enhanced earth's durability and quality as a construction material for low-cost buildings (Adam & Agib, 2001).

Buildings made from earth materials can be a way towards sustainable management of the earth's resources. They can be put in place using simple machinery and human energy. Earth buildings avoid high-energy costs in the initial manufacturing and construction period, in their use as homes, and eventually in their recycling process (Al-Temeemi & Harris, 2004). Several researches in Malaysia and in the world (Huat, 2006, Wong 2010, Habib & Ferral, 2003) were carried out on the subject of improvement engineering properties of peat soils using Ordinary Portland Cement as main binder and other binders. Stabilised peats researches did not show significant improvement to construction materials like bricks or blocks.

Previous research for peat ground was by stabilising peat columns (deep stabilisation) and shallow peat for embankment purposes. With regards to the current study, was carried out concentrating on laboratory investigations of engineering properties, sound insulation and fire resistance of compressed stabilised peat bricks to formulate a suitable and economical laboratory mix design which can be used for compressed stabilised peat bricks. In particular, this study examined the effects of cement type, acceleration and compaction pressure, siliceous sand on the characteristics of compressed stabilised peat brick at various curing time periods. Among effective materials used to stabilise peat as bricks are Ordinary Portland Cement, Portland Pluverised Fuel Ash Cement, and lime.

Stabilisation techniques can be divided into three categories:

- Mechanical stabilisation: compacting the soil and changing its density, compressibility, permeability and porosity.
- Physical stabilisation: changing the texture properties of the soil. It can be done by controlling the mixture of different grain fractions, drying or freezing, heat treatment and electrical treatment
- Chemical stabilisation: changing the properties of the soil by adding other chemicals or additives.

## 1.2 The Needs for study

Following increased awareness of climate change issues, it is now generally accepted that there is an urgent need to limit carbon dioxide emissions into the atmosphere. Large areas of peat soils in Malaysia and world are not used. Most researches investigate stabilised earth for brick and block, but no previous research has been conducted for stabilised peat as construction materials. All aspects should be considered to produce sustainable, durable and environmental friendly homes and industry constructions.

This study focuses on the positive aspect of chemical binders, sand and pressure to peat soils as bricks. The fabrication of compressed stabilised peat brick was by investigation of engineering properties, characteristics of sound insulation and fire resistance. Moreover, the study was also concerned about stress strain characteristics of compressed stabilised peat masonry prism.

### 1.3 The objective of Study

The objectives of this study revolve around six main aspects as drawn below:

- Gain a better understanding of characteristics of raw materials for the production of the bricks.
- Identify significant variables that influence the production of compressed bricks.
- Determine the relative composition of stabilisers for specific requirement of building construction taking into consideration cost effectiveness.
- Define laboratory mixtures and testing protocol to meet required parameters and develop new criteria for peat stabilisation.
- Establish the application of peat in combination with suitable binders as a building material.
- Determine the effects of sound and fire on bricks based on stabilised peat soils.

### 1.4 Scopes of Study

This study will focus on compressed stabilised peat bricks that can be better quality, faster construction, lightweight and economical. These aspects need to be clarified through literature regarding traditional brick like clay brick and concrete block properties. Thus it will show the problematic of previous bricks and blocks used and investigate the properties of compressed stabilised peat brick. The different mix design developed for compressed peat brick in this present study can be applied at any place in construction, like building walling, foundations, road construction, edge of bridge etc.

This study will also examine the characteristics of sound insulation, fire resistance Moreover, stress strain characteristics of compressed stabilised masonry prism. It will also determine the relationship between peat soil, stabiliser type and content and compaction pressure to develop new bricks for the construction industry.

## 1.5 Methodology

There is no information available on compressed stabilised peat bricks. Previous research for stabilised peat has focused more on peat found on ground. This study focuses on compressed stabilised peat for bricks as construction material. This new technique is to replace clay brick, reduce the cost and minimise pollution from the atmosphere. The three main purposes of research activity are the mix design using various binders and compaction pressures, suitable bricks for environment conditions like sound insulation and fire resistance, and characteristics of compression compressed stabilised peat masonry prism.

The use of a combination of various approaches was considered to be inevitable. These approaches included:

Literature review for traditional brick and block (eg, compressed earth block, clay brick and concrete block) to establish the level of thinking and knowledge and to provide the intellectual context for the research.

Laboratory experimentation and testing to provide the engineering properties of compressed stabilised peat brick, which was mix dry peat soils sieved through 2 mm sieve to remove wooden chips and vegetable fibre with different types of binder, siliceous sand and water, and then it was compressed inside steel moulds under 6 Mpa and 10 MPa pressure. The various binders used in the study were Ordinary Portland Cement, Portland Pluverised Fuel Ash Cement and lime.

After 1 day curing, the samples were demoulded and transferred to a water tank and moist cured room for various curing. Two sizes of mould were used in this study, small mould size (70 x 70 x 70 $mm^3$) was used to determine the engineering properties of bricks (wet and dry strength, water absorption, porosity and density), and the big mould size (220 x 100 x 70 $mm^3$) was used for preparation walls for sound insulation measurement, fire resistance and compression of masonry prism tests. Three walls were prepared with different mix design and plastered for sound insulation and fire resistance tests. A small scale system was prepared for sound insulation and fire resistance.

A compressed stabilised peat brick wall between two rooms size 1.2 x 0.9 x 1 $m^3$ was installed and the loss of sound transmission was read through the wall. The dimension of walls for fire resistance and sound insulation testing was 80 x 80 x 12 $cm^3$.

The dimension of compressed stabilised masonry prism was 400 x 220 x 10 $mm^3$ using axial loading to determine the stress- strain characteristic and deformation of masonry prism.

The study was carried out to investigate compressed stabilised peat bricks using various binders and pressures. All research testing were performed through laboratory testing. Computer simulation was performed to verify some experiment test results using SAP2000 finite element analysis software.

### 1.6 Structure of the Thesis

The body of this thesis consists of six chapters. Chapter 1 provides an introduction to the whole thesis. It discusses the background to the research and introduces problems of traditional bricks. It briefly explains the concept of compressed stabilised peat bricks by chemical binders and siliceous sand. This chapter also summarises the main aims, scopes and objectives of the research, it briefly emphasises the importance of research for compressed stabilised peat bricks.

Chapter 2 introduces the fundamental theoretical concepts of properties and deterioration in compressed earth blocks and clay bricks, sufficient information about previous research on engineering or durability properties of compressed earth block, clay brick and concrete blocks, literature review of environment conditions which include sound insulation and fire resistance. This chapter will also provide the stress-strain characteristic of masonry prism. The literature review is vital to provide enough evidence to support the research.

The research methodology is included in chapter 3. This chapter provides details of the methods and standards used to implement the testing program of the research. Details of each testing method (basic properties wet and dry compressive strength, water absorption, density, porosity, sound insulation, fire resistance and stress-strain of compressed stabilised peat masonry prism). The number and types of tests involved in the research are described in this chapter.

Chapter 4 presents the results and discussions of the research. Findings on the engineering properties, compression masonry prism of compressed stabilised peat bricks and focus is on the analysis and comparison of experimental and numerical solutions of masonry prism of compressed stabilised peat bricks and clay masonry prism in compression tests to compare the characteristics of stress- strain for masonry prism were solved numerically and validated with the ones solved experimental problem. SAP2000 software was used to find the numerical solution to the problems with the finite element method. Comparison of the experimental results for compressed stabilised peat bricks is made and discussed with traditional and previous types of bricks and blocks in this chapter.

In chapter 5, the effects of sound transmission through single compressed stabilised peat brick wall by using a small scale of sound transmission loss system is presented. This chapter also investigates the rating fire resistance for compressed stabilised peat brick walls with different mix design and plaster materials.

Chapter 6 concludes the thesis and recommendation for further application of the research. It summarises the overall findings of the research and provides the best mix design for compressed stabilised peat bricks. It also highlights the significance of the research contribution for compressed stabilised peat bricks, which is required to seek alternative materials for bricks for purposes of the construction industry to solve the problems of traditional bricks.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 General

Masonry is one of the most popular materials in many countries for construction of houses due to its useful properties such as durability, relatively low cost, wider availability, good sound and heat insulation, acceptable fire resistance, adequate resistance to weathering and attractive appearance. Masonry can be either of conventional types or alternative types. The conventional types can be identified as burnt clay bricks or cement sand blocks. The alternative types of comparable performance and appearance can be identified as compressed stabilised peat bricks.

The prevision of good quality housing is recognised as an important responsibility for the welfare of people in any country. For this, building materials based on natural resources are often used. Some examples are the use of clay for making bricks and river sand for making cement sand blocks. The commercial exploitation of these resources often leads to various environmental problems.

Soil stabilisation is a technique practical long ago in construction. It permits to modify the properties of the soil-water-air system and makes them permanent and compatible with desired applications in construction. There are several types of stabilisation: mechanical stabilisation, which consists of compacting the soil to increase its density, its mechanical strength and decrease its permeability and porosity. Stabilised compressed earth materials are made using graded soils with the addition on hydraulic binder (eg. Portland cement) and either statically or dynamically compacted into moulds to form compressed earth bricks.

## 2.2 History of Earth Materials and Traditional Clay Buildings

The history of civilisation is synonymous to the history of masonry. Man's first civilisation, which started about 6000 years ago, was evident from the remains of the Mesopotamians masonry heritage. During those days, masonry buildings were constructed from any available material at hand. The Mesopotamians used bricks, made from alluvial deposits of the nearby River Euphrates and Tigris to build their cities beside two rivers. Where civilisation existed in the vicinity of mountains or rocky outcrops, stone was used. The Egyptian pyramids that existed along the rocky borders of the Nile valley were examples of such stone masonry. In the Eastern civilisation remains of historical masonry is the reputed Great Wall of China, which is considered as one of the seven construction wonders in the world.

The clay mines are not properly filled up; they can collect water and allow mosquitoes to breed. Extensive sand mining can lower the river- beds and allow salt-water intrusion inland. Therefore, the development of as many alternative walling materials as possible will be of immense benefit to minimise the impact on the environment. Earth can be used for construction of walls in many ways. However, there are few undesirable properties such as loss of strength when saturated with water, erosion due to wind or driving rain and poor dimensional stability. These draw backs can be eliminated significantly by stabilising the soil with a chemical agent such as cement.

The early forms of masonry application in Malaysia dates back to approximatly 350 years ago with the construction of the Stadthuys in Malacca, built by the Dutch in 1650. The British who colonised the Malaysia Peninsula initiated a more modern form of masonry construction. Brickwork buildings were at that time built specially for government offices, quarters and residential homes. The administrative block, Sultan Abdul Samad building built in 1894 and given a face-lift during the Fourth Malaysia Plan (1981- 1985) is an example of a masonry heritage, which stands as a remarkable landmark of Kuala Lumpur (see Figure 2.1)

**Figure 2.1**: Sultan Abdul Samad building Kuala Lumpur (1894)

Earth has been used in the construction of shelters for thousands of years, and approximately 30% of the world's present population still lives in earth dwellings (Coffman et al., 1990). A large quantity of energy is consumed to manufacture fired bricks and cement for the building industry. This generates a large quantity of greenhouse gases which can destructive to the environment. Earth is a cheap, environmentally friendly and abundantly available building material. It has been used extensively for wall construction around the world, typically in developing countries. Mud structures are able to perform satisfactorily under certain environmental conditions. However, mud walls have a tendency to erode under impact of rain and can collapse when exposed to continuous rain for several hours. Water is a serious factor for mud brick deterioration. Absorption of water causes the swelling of clay minerals while evaporation of water from the clay gives rise to shrinkage and cracking. Therefore, mud buildings which are not protected suffer greatly from durability problems due to water penetration and evaporation.

Earth structures may be protected by the design of the roof and veranda of the building to offer protection from weathering. In order to improve the durability of exposed mud buildings, cement has been used to stabilise the mud brick by mixing up to 15% cement with soil (Bryan, 1988; Middleton, 1992).

Earth building in Spain has been used from ancient times. Generally speaking, it can be stated that it was stopped being used in the middle of the developed century. Nowadays, it is ignored and even underestimated, in part due to the fascination for modern materials such as concrete, bricks or steel. We can find examples in almost all parts of the country, but in the central area it is especially easy to find examples of earth buildings in any small town. It is noticeable in the Tierra de Campos district, shared by the provinces of Leon, Zamora, Valladolid and Palencia. Traditional earth buildings, such as dovecotes or huts, found in the rural areas of Castilla-Leon can be found through Ponga (Carmen and Ignacio, 2005).

The ancient earth building technique known as rammed earth produces dense, load-bearing walls by dynamically compacting moist sub-soil between removable shuttering to create an in-situ monolithic compressed earth wall that is both strong and durable.

There has been much rammed interest in modern rammed earth construction throughout the world as a highly sustainable alternative construction material. In areas of certain developed countries, such as the south-west region of the United States and Western Australia, rammed earth is currently experiencing a renaissance that is unparalleled anywhere else in the world (Hall and Djerbib, 2004; Easton, 1996).

### 2.2.1 Clay Brick

Firing of clay bricks produces a series of mineralogical, textural, and physical changes that depend on many factors and influence porosity. As an example, grain size is a significant parameter, since ceramics manufactured with a high sand fraction tend to be very porous and permeable (Warren, 1999). Significant variations in the composition or concentration of mineral phases also cause changes in the pore system (Valdeo et al., 1993). It has been shown, for instance, that a high proportion of calcite produces more porous ceramics due to its high temperature (T) decomposition and the release of $CO_2$ . Esbert et al (1997) reported that the physical–chemical changes that occur during firing are partly responsible for volume changes in ceramics.

These changes comprise rapid, uneven expansion and contraction associated with chemical–structural changes that can show up as exothermic or endothermic reactions. (Singer & Singer 1963) Generally, products fired at high temperature are more vitreous and undergo the greatest changes in size and porosity (Whiteley et al., 1977; Delbrouck et al., 1993; Whittemore and Halesy, 1983). Contraction and, consequentially an excessive reduction in porosity during the firing of raw clay, can be reduced by mixing it with brick dust obtained by firing the same clay. The added brick dust does not cause changes in the mineralogical composition, and its volume is not reduced during the second firing (Fabbri et al., 1997). On the other hand, porosity can be increased without altering the composition by adding to the clay a material that will calcinate completely, for example, coal powder (Esbert et al., 1997).

Bricks have been used over 5000 years as construction material throughout the world. Today, the bricks are still being used for the same purpose. As urbanisation expands, demand for bricks gradually increases (Prasertsan and Theppaya, 1995). Although brick is a building material of excellent durability, the quality of bricks is still a major concern in most places in the world. Data regarding the properties of masonry components like bricks are abundant, but there is still much to learn about bricks (Beamish and Donovan, 1993).

Chemical and structural modification of clay material during firing generally improves mechanical strength and durability of bricks (Murad and Wagner, 1998). Physical and chemical properties of the bricks are determined by the properties of the minerals present in the clay material, and the intensity of the heat they are subjected to (Jordan et al., 1999). The temperature required for firing varies with the clay material and density, degree of hardness and colour desired. The same clay can yield different results when fired at varying temperatures. When clay bricks are heated to a high temperature, a series of chemical reactions occur in the clay, which make the brick permanently hard, durable and resistant to weathering. Temperatures of 900 ℃ and above cause vitrification to occur. This means that a small quantity of glass-like material forms which helps glue all the elements in the clay together. Therefore, the final quality of the brick depends mainly on the degree of verification (Beamish and Donovan, 1993).

## 2.3 New Techniques of Stabilisation

Following increased awareness of climate change issues, it is now generally accepted that there is an urgent need to limit carbon dioxide emissions into the atmosphere. During the fired earth brick manufacturing process for example, several gases ($CO_2$ etc.) are typically released from the brick kilns (US EPA, 2003). These emissions are becoming a major environmental concern for many countries including Malaysia. Thus, this new technology focusing on stabilised earth masonry brick development incorporating an industrial by-product material is vital for the future of construction in many countries. The stabilised earth masonry brick technology relies on the use of an activated industrial by-product (Ground Granulated Blast-furnace Slag – GGBS) and natural earth. Due to the use of a by-product material in the formulation, it is anticipated that the final pricing of the stabilised earth masonry building brick will be reduced. The added environmental advantages of utilising industrial by-products available in the development countries, will further improve the sustainability profile of masonry brick production.

The use of a cement replacement material (GGBS) with a lower environmental burden offers opportunities for significant reductions in energy use and carbon dioxide emissions. One of the most effective alternatives to Portland cement is GGBS, which has the potential to typically replace up to 80 percent of the Portland cement (Oti et al., 2008a). GGBS has extremely low energy usage and $CO_2$ emission when compared with OPC. The energy usage of 1 tons of GGBS is 1300 MJ, with a corresponding $CO_2$ emission of just 0.07 tons while the equivalent energy usage of 1 ton of PC is about 5000 MJ (Higgins, 2007), with at least 1 ton of $CO_2$ emitted to the 213 atmosphere (Wild, 2003).

Literature review on stabilised earth masonry bricks and blocks revealed that there is a growing interest in stabilised earth building materials development with respect to an energy conscious and ecological design, which fulfils all strength and serviceability requirements for thermal transmittance. Researcher have (Heathcote, 1991; Walker, 2004; Jayasinghe and Kamaladasa, 2007) conducted studies on compressive strength and erosion characteristics of earth blocks and rammed earth wall. The work by Jayasinghe and Mallawaarachchi (2009) was on flexural strength of compressed stabilised earth masonry materials. Reddy et al. (2007) reported on enhancing bond strength and characteristics of soil-cement block masonry. This resurgence of renewed research interest in recent years in stabilised earth building bricks may be partially due to its potential as a commercial construction material. The fact that a single element can fulfill several functions including structural integrity, thermal transmittance and durability in service makes the material an excellent walling material when compared to the fired earth bricks used in mainstream construction of today.

High $CO_2$ emission of manufacturing fired earth masonry bricks which is currently a significant contributor to the final cost of building components. This high cost is currently being transferred to the consumer, thus indirectly affecting the building industry and the economy in general.

As part of a global agreement, to significantly reduce emissions in the built environment, new sustainable engineering materials research and development which is aimed at improving the efficiency of the building sector, could make a contribution towards achieving emissions targets. Another sustainability issue is the current lack of significant engagement regarding the building industry utilisation of by-product materials from various industrial processes. It should be noted that the use of activated slag (GGBS) with natural earth in building components (outside the normal use in concrete applications) is recommended.

### 2.3.1 Soil Stabilisation

#### 2.3.1.1 Background of Peat Stabilisation

Peat contains a significant amount of organic materials. Peat is well known to deform and fail under a light surcharge load, and it is characterised with low shear strength, low compressibility and high water content (Huat, 2004).

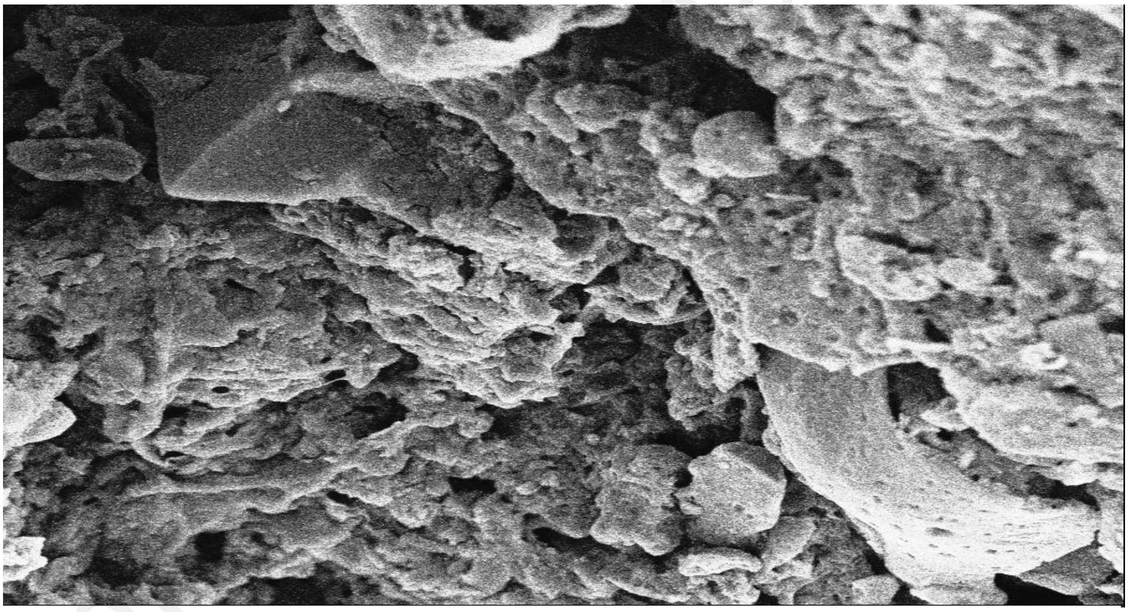


**Figure 2.2:** Scanning Electron Microscopy of peat soil (Huat, 2004)

Peat is described as a naturally occurring highly organic substance derived primarily from plant materials. Figure 2.2 presents the Scanning Electron Microscopy of Malaysia peat soils. The brownish, fibrous and partially decomposed peat is termed fibric and hemic, and is highly humified. The black and powdery peat is termed sapric. The total tropical peat land in the word amounts to about 30 million hectares. In Malaysia, some 3 million hectares of the country’s land area is covered with peat. Peat soils are extremely soft and unconsolidated superficial deposits constituting the subsurface of wetland systems (Huat, 2004). These soils are geotechnically problematic due to their very high compressibility and very low shear strength (Duraisamy et al., 2007). They are usually very difficult to access as the water table is often at, near, or above ground surface.

Peat soils have large surface area (approximately 200 $m^2$, high negative charge and high CEC (100-300 cm/kg), and high water holding capacity (4 - 5 times its mass). The bulk densities of peat soils are in the range of 0.8-1.2 $Mg/m^3$. Their quantity is indirectly correlated to the grain-size. The fibre contents can be low on top of the peat soils because of declining of water table level in evaporative periods and severe oxidation conditions (Huat, 2004).

The decomposition processes of organic soils include enzymes as well as chemical and biological processes. Water logging poor anaerobic and acidic conditions affects the decomposition process (Yule and Gomez, 2008). There is a distinct relationship between CEC, organic matter and decomposition degree as well. While the decomposition degree decreases, the organic matter and consequently, the CEC increases (Dengiz et al., 2009).

Stevenson and Williams (2000) reported that four types of organic matter exist: (i) humins, (ii) humic acids, (iii) fulvic acids, and yellow organic acids. Humic acids are larger and more aromatic than fulvic acids. Fulvic acids are more water soluble and more oxygenated than humic acids. It is noteworthy that fulvic acids have more total acidity and more carboxylic acid functional groups than humic acids.

In Malaysia, the depth of the peat ranges from less than a metre up to 25 m, depending on location (Hooijer, 2006). The high temperatures (up to 32ºC) of the tropics have previously been cited as a reason for rapid decomposition processes (Mathuriau and Chauvet, 2002). Tropical peat typically develops at a rate of between 2 and 5 mm per year. The mean annual rainfall in the region ranges from 1,500 mm to over 2,500 mm with approximately 1,750 mm near the coast to 2,750 mm in the inland areas (Yule and Gomez, 2008).

In the peat soils with lower organic content, mineral portion can be a key role of the soil behaviour. Weathering is the principal process that acts upon the earth's primary minerals to form the smaller and finer particles. There are two types of weathering: physical and chemical weathering. In the tropics, chemical weathering is very important. Since the climate is typically warm and moist year-round, it provides a suitable environment for continuous chemical weathering to occur. Overtime, with sufficient amounts of rainfall and warm temperatures, mineral particles weather into smaller soil particles. As a result, tropical soils tend to be highly weathered soils (Huat, 2004; Deepthy and Balakrishnan, 2005).

### 2.3.1.2 Fundamental Concept of Soil-Cement Stabilisation

Cement is mainly composed of Lime (CaO) and Silica ($SiO_2$), which react with each other and the other components in the mix when water is added. This reaction forms combinations of Tri-calcium silicate and Di-calcium silicate referred to as $C_3S$ and $C_2S$ in the cement literature, (Akroyd, 1962; Lea, 1970; Neville, 1995). The chemical reaction eventually generates a matrix of interlocking crystals that cover any inert filler and provide a high compressive strength and stability.

When the pore water of inorganic soil interacts with Ordinary Portland Cement, hydration of the cement occurs rapidly, and the major hydration (primary cementation) products are hydrated calcium silicates($C_3S_2H_4$) ettringite ($C_6A\,S_3H_{32}$), monsoulfate ($C_4ASH_{12}$), and hydrated lime C-H (Janz and Jahonsson, 2002). The addition of water to Ordinary Portland Cement initiates a chemical process known as hydration. In hydration, and hard cement past is produced as a result of chemical reactions that create a system of interlocking crystals that weave the material together (Elbadri, 1998). According to Elbadri (1998), it is not the cement itself but the mixture of cement and water that form the binding agent. When a cement particles undergoes hydration extremely fine-pored cement gel forms around the particle (Janz and Johansson, 2002).

The presence of chemically combined water (water crystalisation) in cement gel and its porous nature indicates that the volume of cement gel is greater than that of cement particle prior to hydration, Hence, during the reaction between cement and water in the soil, the cement gel would gradually fill the void spaces between cement and soil particles. The cement gel would bind the adjacent cement grains together during hardening and form a hardened skeleton matrix, which encloses unaltered soil particles

(Bargado et al., 1996). Eventually, the soil-cement past would grow denser and stronger with lime. If such cement particles are widely separated from each other, this results in a high porosity and low strength of soil-cement past. Since the strength of the soil-cement past is dependent primarily on its porosity, a measure of water to cement ration (wcr) can give an indication of its strength. The water to cement ratio is give in Equation 2.1 (Wong, 2010).

$$\text{wcr} = \frac{W}{C} \tag{2.1}$$

Where W is the weight of mixing water (kg) and C is the weight of cement (kg).

The water used to mix the concrete plays an important role both in placing the material and in achieving strength. The quantity of water used is typically calculated using an appropriate "water-cement ratio". The minimum water/cement volume ratio is between 0.22 and 0.25 (Akroyd, 1962), for adequate cement hydration, but this is generally increased to the order of between 0.5 and 0.8 for normal mixes (Lea, 1970).

The transformation of Ordinary Portland Cement with addition of water into cement past can be chemically illustrated in Equations 2.2, 2.3, 2.4, 2.5 and 2.6 (Bargado et al., 1996). With calcium silicates forming 75% of Ordinary Portland Cement, Equations 2.2 and 2.3 indicate that the two types of calcium silicate (tricalcium silicate and bicalcium silicate) produce two new compounds, namely lime and tobermorite gel (Bargado et al., 1996). Tobermorite gel is also referred to as C-S-H gel or hydrated gel or primary cementation product (Bargado et al., 1996; Janz and Johansson, 2002). It is the bermorite gel that governs the bond strength and volume variations within the soil-cement mixture.

$$2(3\ CaO.SiO_2) + 6\ H_2O = 3CaO.2\ SiO_2.3H_2O + 3Ca(OH)_2 \quad (2.2)$$

[tricalcium Silicate] [water] [tobermorite gel = primary cementation product] [calcium hydroxide]

$$2(2CaO.\ SiO_2) + 4\ H_2O = 3CaO.\ 2\ SiO_2\ .\ 3\ H_2O + Ca\ (OH)_2 \quad (2.3)$$

[bicalcium Silicate] [water] [tobermorite gel = primary cementation products] [ calcium hydroxide]

$$4CaO.\ AL_2O_3\ .\ F_{e2}O_3 + 10\ H_2O + 2Ca\ (OH)_2 = 6CaO.\ AL_2O_3.\ F_{e2}O_3.12H_2 \quad (2.4)$$

[tetracalcium Aluminoofeerite] [water] [calcium aluminoferrite hydrate]

$$3CaO.\ AL_2O_3 + 12\ H_2O + Ca\ (OH)_2 = 3CaO.\ AL_2O_3\ .\ Ca(OH)_2\ .12\ H_2O \quad (2.5)$$

[tricalcium Aluminate] [calcium aluminoferrite hydrate]

$$3CaO.\ AL_2O_3 + 10\ H_2O + CaSO_4\ 2\ H_2O = 3CaO.\ AL_2O_3\ .CaSO_4.12\ H_2O \quad (2.6)$$

[tricalcium Aluminate] [water] [gypsum] [calcium monosulfoaluminate]

Chemical reactions for the hydrolysis process in the soil-cement paste of tricalcium silicate ($3CaO.\ SiO_2$ ) for the most important component of ordinary Portland Cement are given in Equations 2.7, 2.8, 2.9 and 2.10 (Bargado et al., 1996). These equations have been developed from the dissociation of hydrated lime ($(CaOH)_2$) from Equation 2.2. With the silicate and aluminate phases internally mixed and a part of the hydrated lime available to be mixed with other hydrated phases, none of them is completely crystalline. Furthermore, the hydration of cement leads to increase in the pH values of the pore water, which is caused by the dissociation on the hydrated lime ($(CaOH)_2$).

Like a reaction between a weak acid and strong base, the strong bases eventually dissolve the soil silica and alumina, which are acidic in nature from both the soil mineral and amorphous materials on the soil particle surface to form hydrous silica and alumina (Bergado et al., 1996). Generally, the hydrous silica and alumina will react to the calcium ions produced from the cement hydrolysis to generate insoluble compounds, also known as secondary cementation products. The secondary cementation products will harden upon curing to stabilise the soil. Such secondary reaction is referred to as pozzolanic reaction (Wong, 2010).

With the cement hydration and the pozzolanic reaction lasting for months, or even years after the mixing, it is expected that the strength of the soil- cement mixture increases with time. As such, it can be stated that with the formation of the primary and secondary cementing substances after mixing, the primary cementation products increase the strength and durability of the soil in such a way that they provide extra cementation to further increase the bounding strength between soil particles. This secondary reaction is known as the pozzolanic reaction.

$$Ca\,(OH)_2 \longrightarrow Ca^+ + 2(OH)^- \quad (2.7)$$

$$Ca^+ + 2(OH)^- + SiO_2 \text{ (soil silica)} \longrightarrow CaO.\,SiO_2.H_2O \quad (2.8)$$

[Secondary cementation product]

$$Ca^+ + 2(OH)^- + Al_2O_3 \text{ (soil alumina)} \longrightarrow CaO.\,Al_2O_3.\,H_2O \quad (2.9)$$

[Secondary cementation product]

When pH< 12.6, then the following reaction occurs:

$$3CaO.\,SiO_2 \longrightarrow 3CaO.\,SiO_2 \text{ ( hydrated gel)} + Ca(OH)_2 \quad (2.10)$$

It is well recognised that organic soils can retard or prevent the proper hydration of binders such as cement in binder-soil mixtures (Habib and Farrell, 2003). With high organic content and less solid particles in peat, cement alone as chemical admixtures is insufficient to provide the desirable function for peat stabilisation. Compared with clay and silt, peat has a considerably lower content of clay particles that can enter into the secondary pozzolanic reactions (Janz and Johansson, 2002). As such, the interaction between hydrated lime and the soil yields less effect in secondary pozzolanic reactions. Therefore, no significant strength gain can be achieved from peat stabilisation by cement unless it is added to the soil in a large dosage. Chen and Wang (2006) reported that the impediment to cementation and hardening of peat –cement admixture is attributed to the presence of black humic acid in peat soil. Humic acid, fulvic acid, and humin are humic substances, which form the major components of peat organic matter. Humin is the main composition of tightly combined humus, while himic and fulvic acids exist not only in loosely combined humus but also in stable, combined humus.

A general composition of cement is indicated by the following oxide composition ranges for Portland cements: lime (CaO) 60%- 67%, silica ($SiO_2$) 17% - 25%, alumina ($AL_2O_3$) 3% - 8%, iron oxide ($Fe_2O_3$) 0.5% - 6%, magnesia (MgO) 0.1% - 4%, sulphur trioxide ($SO_3$) 1% - 3%, soda ($Na_2O$) and potash ($K_2O$) 0.5% - 1.3% (Alwi, 2008).

The quantity of cement that is required for adequate stabilisation depends on several criteria, namely; the required compressive strength, soil type, environmental conditions and levels of quality control. Cement can very easily be wasted if it is not utilised in the correct manner and significant cement reduction can be attained through good production management and quality control. Controlling the moisture content, level of compaction and the curing regime play a major role in getting the most from the added cement.

For relatively quick analysis of soil characteristics for cement stabilisation the CSSB literature suggests the use of a linear shrinkage mould, (Houben & Guillaud, 1994; Norton, 1997; International Labour Office, 1987; Rigassi, 1995). Soil is mixed with water to its liquid limit and then left to dry out in a mould with dimensions 40 × 40 × 600 mm. The linear shrinkage is measured and the quantity of cement required to adequately stabilise the soil is calculated.

#### 2.3.1.3 Effect of Acceleration Hardening Cement in Peat Stabilisation

Although Ordinary Portland Cement in the most widely used cement for soil stabilisation, it is inadequate for highly organic soil such as peat due to insufficient calcium in the cement to stabilise the soil. In such case, rapid hardening cements may be useful in organic soils as they provide extra calcium to counteract the presence of organic matter (Ingles and Metcalf, 1972). PFA cement has ash in its composition to accelerate the hardening of cements which is particularly beneficial to producing effective stabilised peat brick.

#### 2.3.1.4 Effect of Siliceous Sand as Filler in Peat Stabilisation

In order to build strong stabilised peat, it important to provide maximum densification to the stabilised soil by introducing a suitable amount as well graded siliceous sand into it. Well gradation is necessary considering the fact that void spaces within the stabilised soil is reduced to a minimum when it is well packed with coarse grained sand with interstices in between which are filled with fine grained sand (Wong, 2010). The inclusion of the siliceous sand as filler produces no chemical reaction but enhances the strength of stabilised peat by the binder by increasing the number of soil particles available for the binder.

Janz and Johansson (2002) stated that since no filler is absolutely inert, it is possible that fillers may enter into secondary pozzolanic reactions, for example, the inclusion of siliceous sand results in secondary pozzolanic reaction with calcium hydroxide ($Ca(OH)_2$) and contribute to the strength gain. However, with large size of sand particles with low specific surface; only a relatively small surface area is exposed to the calcium hydroxide for the secondary pozzolanic reaction. The effect of filler on the secondary pozzolanic reaction is therefore neglected. Theoretically, it may be economical to reduce the cost of stabilised peat bricks by replacing a certain portion of the binder with filler.

Cementation effect in siliceous sand as a granular soil takes place in the form of cementation products that bind the solid particles together as its contact points (spot welding). In this way, the organic particles in peat not only fill up the void spaces in between the solid particles but also, they are interlocked by the cementation of the siliceous sand. Thus, according to Kazdi (1979), no continuous matrix is formed, and the fracture type depends on whether the interparticle bond or natural strength of the particles themselves is stronger.

Ismail et al. (2002) reported on the effects of sand inclusion in the cementation of porous materials using calcite. They also mentioned that the excellent strength performance of the rounded sand particles is attributable partly to their rounded shape. The particle shape of the sand is almost spherical and uniformed, and the structure of each grain is strong with almost no internal voids. They further stated that the spherical particle of sand allows the sand to be exposed to more contact points within the surrounding grains and this contributed to cemented matrix of many welded point contacts among the sand particles.

## 2.4 Current Role of Stabilisation

It is usually the poor or underprivileged who need and build low-cost housing and this has an effect on the processes used to make the building material. Minimising material cost and machine requirements are typically more important than reducing labour costs. Consequently it is not uncommon to find block manufacturers using cheap machinery and minimising the stabiliser content. This illustrates the need for better understanding of the processes at work in soil stabilisation and improved quality control throughout the process of production. Significant savings in cement or much higher quality blocks could be attained if these were put in place. Furthermore, there is little way of knowing the performance of a finished CSSB without conducting crushing tests so the purchaser has to trust the seller as to the quality of the blocks being sold.

Apart from improving the understanding of cement use and implementing better quality control in production there are advancements that can be made in the production technology as well. A study conducted by Gooding & Thomas (1995), as part of an overseas development agency report, calculated that using more expensive high-pressure compression machinery to make blocks was not as economically attractive as adding more cement and using a low-pressure machine for the estimated life of each machine.

Table 2.1 shown the terms used for different moulding pressures as described in Houben & Guillaud (1994).

**Table 2.1**: Different moulding pressure (Houben & Guillaud, 1994)

| Pressure type | Values (Mpa) |
|---|---|
| Very low pressure | 1 – 2 |
| Low pressure | 2 – 4 |
| Average pressure | 4 – 6 |
| High pressure | 6 – 10 |
| Hyper pressure | 10 – 20 |
| Mega pressure | 20 – 40 |

Rigassi (1995) suggested stabilisation of soil to improve the properties for building purposes which in fact is an ancient practice. These procedures have been passed on from generation to generation without actually understanding the main mechanisms involved. It was only from the 1920, that systematic scientific approaches emerged. Attempts were then made to replace the longstanding adhoc techniques previously adopted for soil stabilisation. Unfortunately, despite all the recent scientific advances made, soil stabilisation still remains an inexact science (Dunlap, 1975). By soil stabilisation in essence it means the modification of soil properties by varying the soil water - air interface (Fitzmaurice, 1958; UN, 1964; Ingles & Metcalfe, 1972). This is done to achieve more lasting characteristics than hitherto possible when the soil still in its natural state. Some of the methods used to modify soil can result in irreversible changes, while others may result in reversible changes. The latter are likely to occur due to the lack of resistance offered by soil to environmental agents (PCA, 1971; Aksa, 1984). Agarwal, (1981); Fullerton, (1979); BRE, (1980) investigated the evidence of poor resistance which is in most evident in the third world where houses built out of soil require to be regularly maintained during and after rainy seasons. Perennial problems of this type can be effectively overcome by stabilising the soil. Addition of a suitable stabiliser, especially a binder, can enable the soil to retain its shape and dimensions. The soil will also gain in compressive strength and durability (Fitzmaurice, 1958).

As several input variables are involved, soil stabilisation is likely to remain a complex process. For effective stabilisation to be achieved the soil should be modified to give it the properties it lacks. There are several options for stabilising soil, but the courses of action are likely to be more effective which consideration on targeting its interstitial voids and improvement of bonding between its particles. Thus, it is generally accepted that: by reducing the volume of interstitial voids in a soil through mechanical compaction, direct action is taken to significantly reduce porosity (Rigassi, 1995). Reduction in porosity is an effective way of increasing density and shear strength in soil. By filling the voids in the soil which cannot be eliminated completely through compaction, direct action is also taken to reduce its permeability (Houben & Guillaud, 1994). Reduction in permeability has the positive effect of restricting circulation and retention of water within the soil fabric by improving the cohesion and bonding in a soil, action is taken to cement and link the soil particles together. This way dimensional stability, increase in compressive strength and improved durability can all be expected to be reached. The method also ensures that changes in volume that would normally occur due to shrinkage and swelling are significantly reduced. Improved bonding also minimises the vulnerability of the soil to surface abrasion and erosions caused by rainwater and wind (Dohud, 1979; Evans, 1980).

Chemical stabilisation involves the addition of a binder or bonding agent to a soil. The binder modifies the soil properties through cementation or linkage of its particles

(Houben & Guillaud, 1994). Both cementation and linkage are a result of chemical reactions involving the binder and water. Cementation creates a strong and inert matrix that can appreciably limit movement in a soil. The voids in the soil are also filled with insoluble by-products of the hydration reaction while some soil particles are coated and firmly held together by the binder (Ingles, 1962). The key binder that acts in this manner is Ordinary Portland cement. The full mechanism of the reaction as presently understood is discussed in the next section. It is generally reported in CSB literature that the effect of chemical stabilisation is more permanent and may take several years or even decades to partially reverse. For this reason, chemical stabilisation of soil is so far considered to be the superior method of choice. It is also well established that the effect of chemical stabilisation is significantly increased by improving the soil grading and compacting the mix (Dunlap, 1975; Gooding, 1994).

## 2.5 Mechanism of Cement-Soil Stabilisation

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

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

The mechanism of the reaction is as follows:

- Primary reaction involving OPC constituents:

$$\left\{\begin{matrix} C_3S \\ C_2S \\ C_4AF \end{matrix}\right. + H_2O \longrightarrow \text{C-S-H} + C_4ASH_{12} + Ca(OH)_2 \tag{2.11}$$

$$\text{(Cement)} + \text{(water)} \quad \begin{bmatrix} \text{Calcium} \\ \text{silicate} \\ \text{hydrate} \end{bmatrix} + \text{(monosulphoaluminate)} + \begin{bmatrix} \text{Calcium} \\ \text{Hydroxide} \end{bmatrix}$$

The main products of the above reaction are: calcium silicate hydrates, monosulphoal uminates and calcium hydroxide. It is the first two, namely the C-S-H and $C_4ASH_{12}$ that are responsible for strength development in a block (Ingles & Metcalf, 1972). It is the gravel and sandy fractions in the soil that are affected by this reaction. Both the C-S-H and $C_4ASH_{12}$ are known to have high binding capacity.

The binding forces they generate are responsible for intertwining and embedding the gravel and sand fractions creating a strong network within the soil fabric. This inert and anisotropic network introduces rigidity not previously present in the soil. Due to the network, movement of the coarse soil fraction is resisted and subsequently becomes highly limited. Nett effect results in the development a particulate composite structure.

As expected, the properties of the composite are influenced by the amount of cement used relative to the soil fraction, and by the nature of the bye-products resulting from the reaction. The reaction is known to liberate free lime which then sets off the secondary reaction with the clay component in the soil.

- Secondary reaction involving freed lime and clay:

$$\underset{\text{(Clay)}}{A.S} + \underset{\begin{bmatrix}\text{Calcium}\\ \text{Hydroxide}\end{bmatrix}}{Ca(OH)_2} \longrightarrow \underset{\begin{bmatrix}\text{Calcium}\\ \text{silicate}\\ \text{hydrate}\end{bmatrix}}{C\text{-}S\text{-}H} + \underset{\begin{bmatrix}\text{Calcium}\\ \text{alumate}\\ \text{hydrate}\end{bmatrix}}{C\text{-}A\text{-}H} \qquad (2.12)$$

The two main products of this reaction (the C-S-H and the C-A-H) both have binding capacity not very different from the ones of the primary reaction. This reaction is mainly pozzolanic with the gelatinous amorphous hydrates equally contributing to hardening of the block. Following the reaction, a stable chemical bond develops between the clay crystals, through a mechanism known as linkage. The reaction proceeds slowly but is dependent on the quantity and quality of clay, and on the amount of free lime available (Spence and Cook, 1983; Houben and Guillaud, 1994).

The amount of calcium hydroxide released is limited by the lime saturation factor (LSF) of the OPC. The LSF is fixed at the time of manufacture of the OPC, often ranging between 0.66 and 1.02 (Spence and Cook, 1983). Restriction of the upper limit is mainly done to control the amount of free lime in the cement paste which is otherwise associated with unsoundness and undesirable expansion.

## 2.6 Effect of Lime on Soil Stabilisation

Lime in the form of quicklime (calcium oxide (CaO)), hydrated lime (calcium hydroxide ($Ca(OH)_2$) or lime slurry can be used to treat soils. Quicklime is manufactured by chemically transforming calcium carbonate (limestone ($CaCO_3$)) into calcium oxide. Hydrated lime is created when quicklime chemically reacts with water. It is hydrated lime that reacts with clay particles and permanently transforms them into a strong cementitious matrix. Most lime used for soil treatment is “high calcium” lime, which contains no more than 5 percent magnesium oxide or hydroxide. On some occasions, however, "Dolomitic" lime is used. Dolomitic lime contains 35 to 46 percent magnesium oxide or hydroxide. Dolomitic lime can perform well in soil stabilisation, although the magnesium fraction reacts more slowly than the calcium fraction. Sudhakar & Shivinanda. (2003) studied the effects of curing temperature at semiarid regions of Karnataka, India for the progress of lime-soil reactions. The in situ progress of lime treatment was monitored by the use of electrical conductivity measurements, based on the suggestion of Boardman et al. (2001) additionally; variations in pH of lime-soil mixes were employed to monitor the progress of lime-soil reactions. The lime-soil mixes were cured at 25℃, representative of mean temperatures prevalent in semi-arid regions of Karnataka, India. Lime contents greater than the lime modification optimum were added to the expansive clay. They found that, lime addition immediately (curing period 1 hour) increasesed the electrical conductivity of the expansive soil from 0.6 microsiemen/cm (representative soil value) to 3.9–4.2 microsiemen/cm. The pH of the lime-soil mixes also increased from 8.3 (pH of representative soil) to 12.46 on 4% and 7% lime additions. In conclusion, they indicated that ambient temperature affects the progress of lime-soil reactions. A higher curing temperature accelerated the progress of lime-soil reactions at lime additions above the lime modification optimum value of the soil. Consequently pozzolanic activity commenced after 1 day of curing at 250 ℃ in comparison to 7 days needed at 1150 ℃. These conclusions also imply that strength development from pozzolanic activity will occur more quickly in hot semi-arid climatic zones than in cool temperature climate zones at lime additions above the ICL value of the soil.

Lime is also sometimes used to describe by products of the lime manufacturing process (such as lime kiln dust), which, although they contain some reactive lime, generally have only a fraction of the oxide or hydroxide content of the manufactured product. In this study, lime means quicklime, hydrated lime, or hydrated lime slurry.

Soil stabilisation significantly changes the characteristics of a soil to produce long-term permanent strength and stability, particularly with respect to the action of water and frost. Lime, either alone or in combination with other materials, can be used to treat a range of soil types. Soils containing significant amounts of organic material (greater than about 1 percent) or sulphates (greater than 0.3 percent) may require additional lime and special construction procedures.

Most Mexican low-income housing units are made with red bricks or blocks as shown in Figure 2.3. Red brick is made of clay that is baked in hand-made kilns. The block is made with fine gravel and cement, which is vibrantly-compacted and ambient-cured. To construct walls with these bricks or blocks, lime-based mortars are widely used. Hydrated lime is a low-cost component of mortar in Mexico. The use of hydrated lime also improves many characteristics of the mortar.

The beneficial properties of hydrated lime may be appreciated in both phases of mortar. The first phase begins after the mortar is mixed with water and becomes highly plastic. The second phase is when the mortar hardens after it cures. In the first phase, hydrated lime improves workability and water-retention of the mortar. Mortars containing only cement are difficult to trowel. The enhanced workability of lime-based mortars provides better coverage of the masonry units. A mortar that fills joints completely produces more intimate contact with masonry units and enhances bond strength (Palmer 1935). Lime sticks to and works into the rough masonry surface. The use of lime optimises mortar curing by providing water for cement hydration (if cement is present) or enhancing carbonation in lime mortars. Water-retentive mortars also provide good board life, which minimises the need to re-temper the mortar. Mortars made with lime also increase sand yields and cover more area for less cost.

**Figure 2.3:** Mixican Lime red block (Vazquez et al, 2005).

Lime-based mortars gain strength over time by the reaction of hydrated lime with carbon dioxide. This reaction returns hydrated lime to its original limestone form. This reaction also provides the ability for the mortar to seal hairline cracks. This property, called autogenous healing, is created by carbonation of the exposed hydrated lime in the crack.

## 2.7 Concrete Block Production

The common block used for building is made of fine gravel which has a size distribution between 2 and 10 millimeters, and cement. This mix produces a heavy and expensive block. Hydrated lime can be a beneficial additive to the block. Dependent on the quality of the aggregate used, hydrated lime has been added to these masonry units up to a level of 30% by weight of the cementitious materials.

As seen in Table 2.2, substitution of hydrated lime for cement can be beneficial for the development of initial strength in these masonry units. The presence of lime assists in retention of water in the block to optimise development of cement strength. An additional benefit gained by the inclusion of lime is that blocks containing lime can become stronger as they age, due to the carbonation reaction which is presented in Figure 2.4.

**Table 2.2**: Effect of hydrated lime addition on block compressive strength (Vazquez et al., 2005).

| Days | Compressive Strength ($kg/cm^2$) | | | |
|---|---|---|---|---|
| | 0% lime | 15% lime | 20% lime | 25% lime |
| 3 | 119 | 124 | 167 | 155 |
| 7 | 148 | 137 | 175 | 171 |
| 14 | 164 | 164 | 184 | 185 |
| 21 | 178 | 202 | 201 | 192 |
| 28 | 195 | 214 | 214 | 215 |

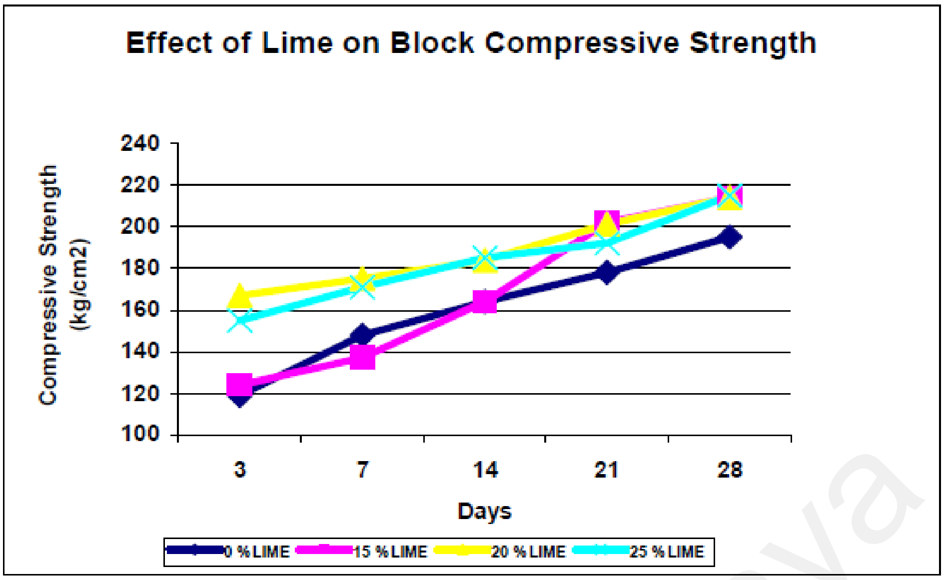



**Figure 2.4:** Effect of lime on block compressive strength (Vazquez et al., 2005)

The addition of hydrated lime can potentially lower the weight of the block. Common concrete block measures 20 x 20 x 40 cm and weighs 4.5 kg. The reduction in weight may be up to 10%, depending on the percent lime substitution.

## 2.8 Compressive Strength of Bricks and Blocks

### 2.8.1 Clay Brick Strength

Compressive strength of brick is important as an indicator of masonry strength and as a result brick strength has become an important requirement in brickwork design. A considerable amount of past research and studies on masonry indicate that stronger bricks contribute to greater brickwork strength. (Hendry, 1990; Lenczer, 1972). In tandem with Singapore Standard 103 (1974), compressive strengths are classified as First, Second and Third Grade with minimum compressive strength of 35 N/mm$^2$, 20 N/ mm$^2$ and 5.2 N/ mm$^2$ respectively. Figure 2.5 shows the relationship between strength of brick and strength of wall.

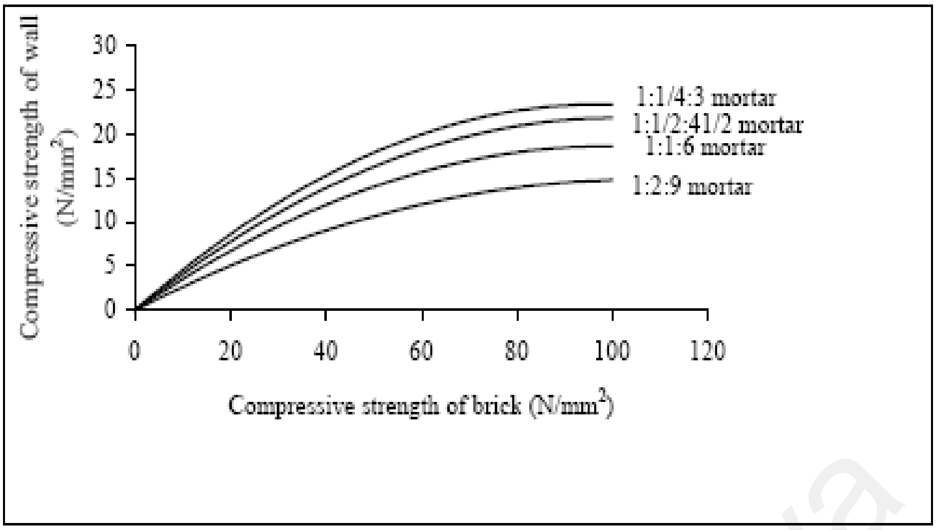



**Figure 2.5:** Mean compressive strength of walls against strength for 102 mm thick brickwork in various mortars (Hendry, 1990).

The British standard (BS 3921: 1985) categorised compressive strength into classes of engineering A and B as presented in Table 2.3. These classifications of bricks commonly used for construction with aesthetics and strength requirements. All other brick and damp proof- course bricks should have strengths not less than 5 $N/mm^2$. However, the damp-proof course is divided into two in accordance to water absorption.

**Table 2.3**: Classification of bricks by compressive strength and water absorption (BS 3921, 1985)

| Class | Average compressive strength ($N/mm^2$) | Water absorption (5-hr. boiling) % by weight |
|---|---|---|
| Engineering A | ≥ 70 | ≤ 4.5 |
| Engineering B | ≥ 50 | ≤ 7.0 |
| Damp-proof course 1 | ≥ 5 | ≤ 4.5 |
| Damp-proof course 2 | ≥ 5 | ≤ 7.0 |
| All others | ≥ 5 | No limits |

As for the American Standard (ASTM), compressive strengths are classified in accordance to the different grades of weathering and exposure condition as indicated in Table 2.4. The grades of weathering can be negligible (NW), moderate (MW) or server (SW) depending on the damp zoning as given in ASTM.

**Table 2.4**: Physical requirement for building bricks (ASTM C62-89a, 1990)

| Designation | Minimum compressive strengths brick flat wise lb/in$^2$ (N/mm$^2$) | | Maximum water absorption (5-hr. boiling), % | | Maximum saturation coefficient | |
|---|---|---|---|---|---|---|
| | Average of 5 bricks | Individual | Average of 5 bricks | Individual | Average of 5 bricks | Individual |
| Grade SW | 3000(20.7) | 2500(17.2) | 17.0 | 20.0 | 0.78 | 0.80 |
| Grade MW | 2500(17.2) | 2200(15.2) | 22.0 | 25.0 | 0.88 | 0.90 |
| Grade NW | 1500(10.3) | 1250(8.6) | No limit | No limit | No Limit | No limit |

According to the Australian Standard (AS 1225: 1984), the compressive strength characteristics are specified against values for the ration of manufacturing height to manufacturing width as reflected in Table 2.5.

**Table 2.5**: Compressive strength characteristics in accordance to Australia Standard (AS 1225, 1984)

| Ratio of manufacturing height to manufacturing width | Characteristics compressive strength, MPa |
|---|---|
| ≤0.7<br>≥2 | 7.0<br>5.0 |

Kumar (2002) reported that the FaL-G combination, fly ash acts as a source of reactive silica and alumina, to give silicate and aluminate hydrates, which are responsible for the development of strength. Silica, present in fly ash, reacts with lime and forms calcium silicate hydrate. Alumina, together with lime, reacts with gypsum to form calcium trisulfoaluminate hydrate. Normally the compressive strength investigation comprises of 5 to 10 specimens from different standards. For example with the Indian standard (IS: 456, 2000), the compressive strength is based an average of 6 specimens. Figure 2.6 shows the average compressive strength of each mix proportion with age, based on the average of 6 specimens which have an individual variation not more than 15% of the average value as per the recommendation of Indian code (IS: 456, 2000).

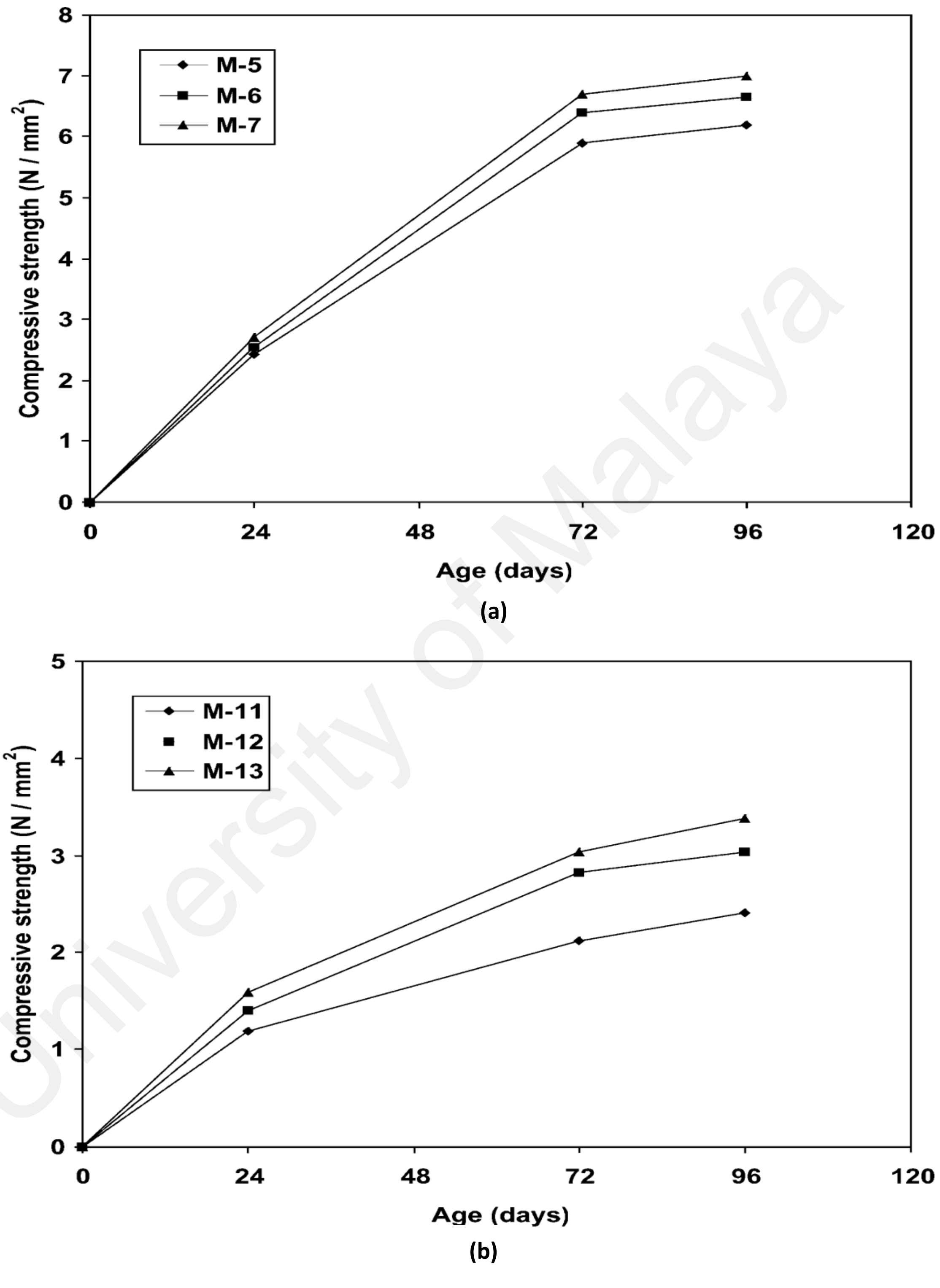



**Figure: 2.6:** (a) and (b): Effect of curing on compressive strength of brick (Kumar, 2002)

According to Anthony (2001), the values of the average 28-day wet compressive strength for both traditional and improved blocks were satisfactory. The values ranged between 1.43 MPa and 8.99 MPa in the case of the former and between 3.12 MPa and 18.3 MPa in the case of the latter. The lower values in either case correspond to the cement content of 3%, while the higher ones to 11%. As can be seen, the WCS values in improved blocks were found to be considerably higher than in traditional blocks made in exactly the same manner but without the addition of microsilica. On average, the addition of microsilica resulted in the doubling of strength in blocks. Although some improvement had been expected, the magnitude of the strength gain achieved was surprising. Such high values had not been previously obtained with the corresponding amounts of OPC according to current CSB literature (Rigassi, 1995). The inclusion of partial cement replacement materials such as microsilica therefore appears to be an effective way of increasing the WCS of blocks. These results also confirm the theoretical assumptions described in chapter 3. This approach represents a new way forward in terms of strengthening compressed stabilised block fabrics for wider engineering applications. It is also likely to be particularly useful for blocks exposed to severe environmental conditions.

The relationship between strength and various cements is presented in Figure 2.7**.**

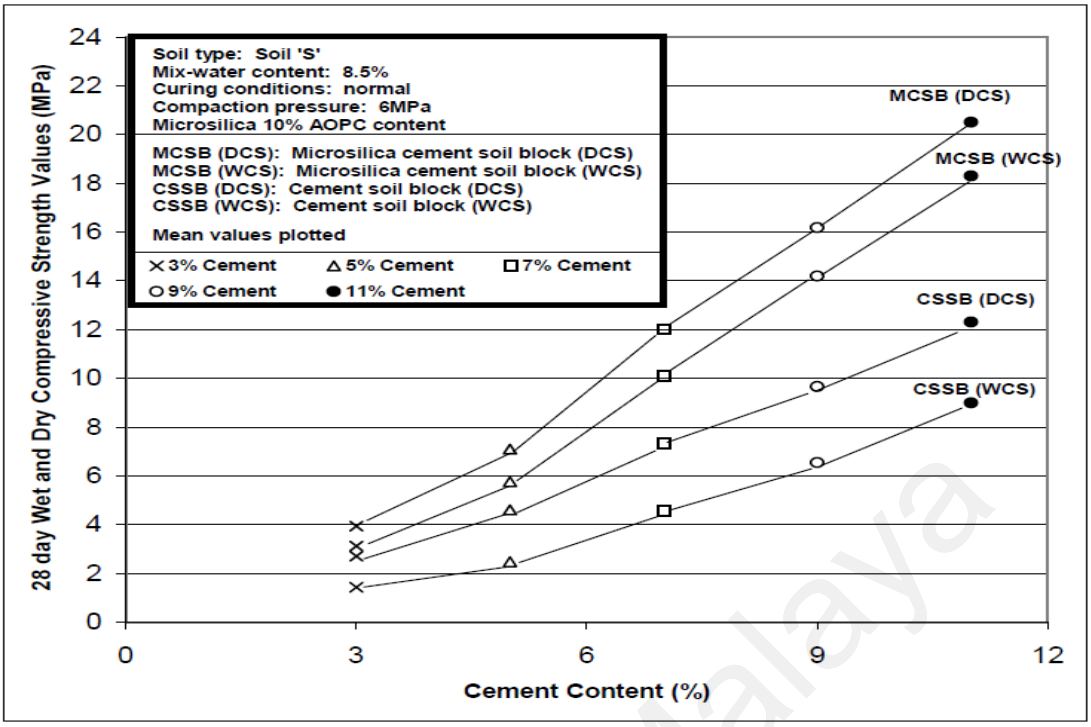



**Figure 2.7**: Comparison of the mean wet and dry compressive strengths in both Traditional and improved blocks (Anthony, 2001)

## 2.9 Brick and Block Density

Raw materials and manufacturing process affect bricks, density, which could vary between 1300 kg/m$^3$ to 2200 kg/m$^3$. The density of bricks influences the weight of walls and the variations in weight have implications on structural, acoustical and thermal design of the wall. Incorrect assumptions on wall weight can result in inaccurate dead loads and seismic loads, reduced factor of safety in shear walls and overestimate of acoustical transmission loss (Grimm, 1996).

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

- Block dry density (usually indicating the oven-dried value when desiccated to 105 ± 5° C for 26 hours)
- Block bulk density (based on the pre-existing state of moisture, e.g. soon after demoulding)
- Saturated block density when soaked in water for between 24 and 48 hours after oven drying as before). It is the dry density that is commonly used in building specifications (BS 6073: Part 2, 1981) and is the one discussed in this thesis. In addition to the solid phases that exist in a block, the material also contains pore spaces filled partly with air and partly with water (Jackson & Dhir, 1996). The amount of either phase depends on the moisture state of the block (varies from block to block). When both air and water are driven out (by oven drying to constant mass), the block dry density value is obtained.

Apart from the state of moisture in a block, its density also depends on the following:

- The degree of compaction used (moderate 4 MPa and high >7 MPa)
- The density of the constituent materials (especially the coarse sand fraction)
- Sand has a dry density value of about 2,200 kg/m3 while that for clay is about 2000 kg/m3 (Houben & Guillaud, 1994).
- The size and grading of the soil particles
- The form of the block (solid and hollow)

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

The density of a block can have implications on most of its other bulk properties (Markus, 1979). These include compressive strength, permeability, water absorption, porosity, thermal capacity, sound insulation, hardness and durability (Lunt, 1980; BRE, 1980; Spence & Cook, 1983). The higher the density of a block, the better its performance can be expected. For example, density has commonly been closely associated with the strength of a block (UN, 1964; Spence, 1975).Figures 2.8, 2.9 and 2.10 shows the correlation between Dry density and strength, water absorption and porosity.

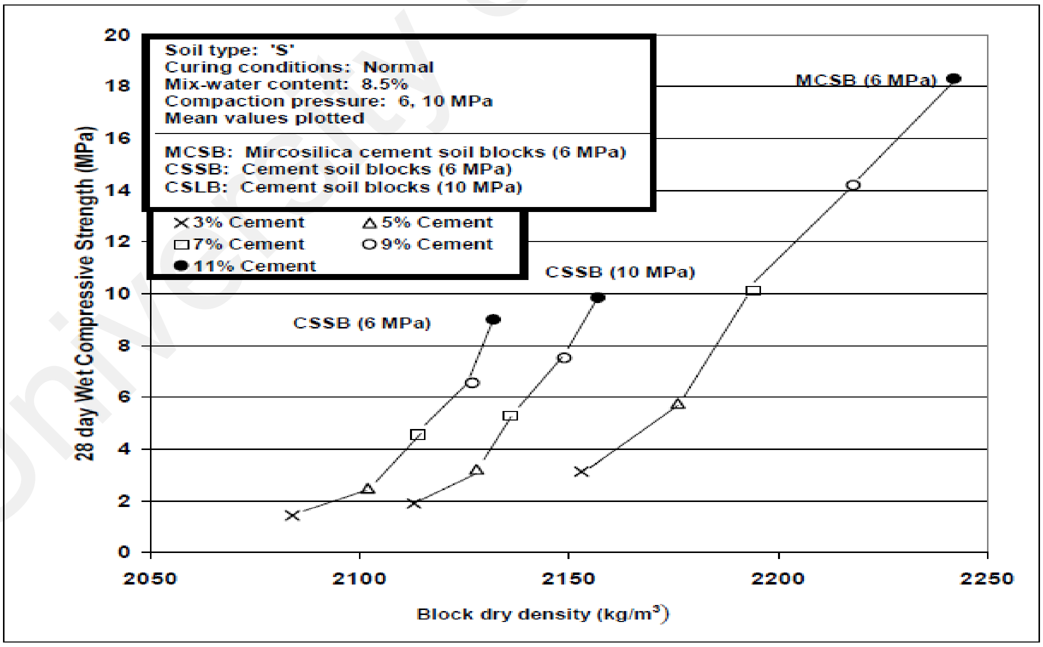



**Figure 2.8**: Correlation between dry density and Compressive strength (Anthony 2001)

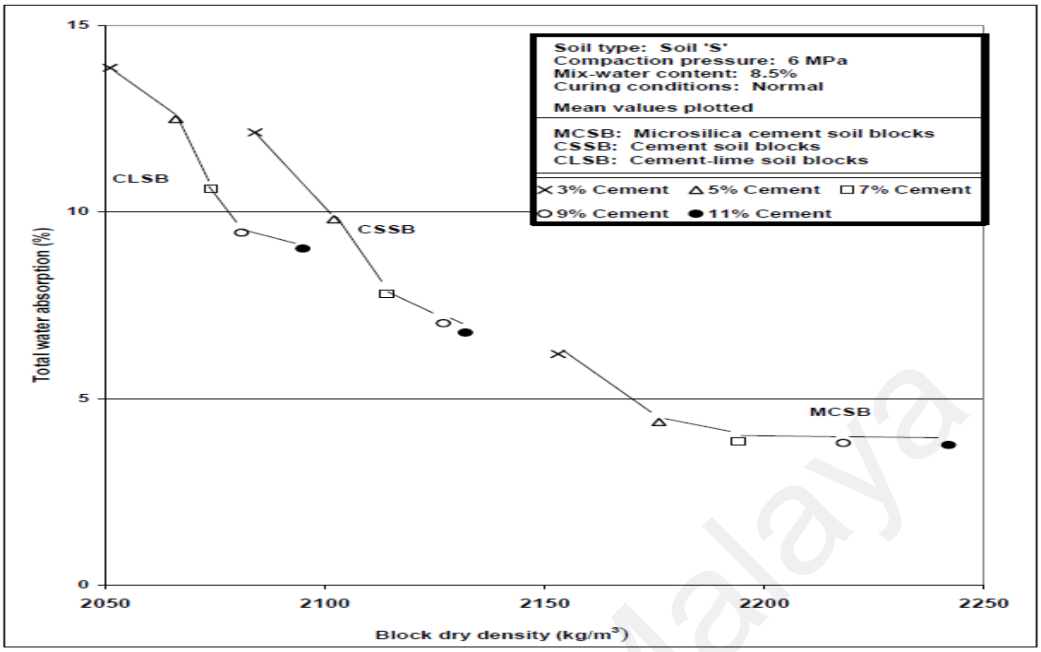



**Figure 2.9:** Correlation between dry density and total water absorption (Anthony 2001)

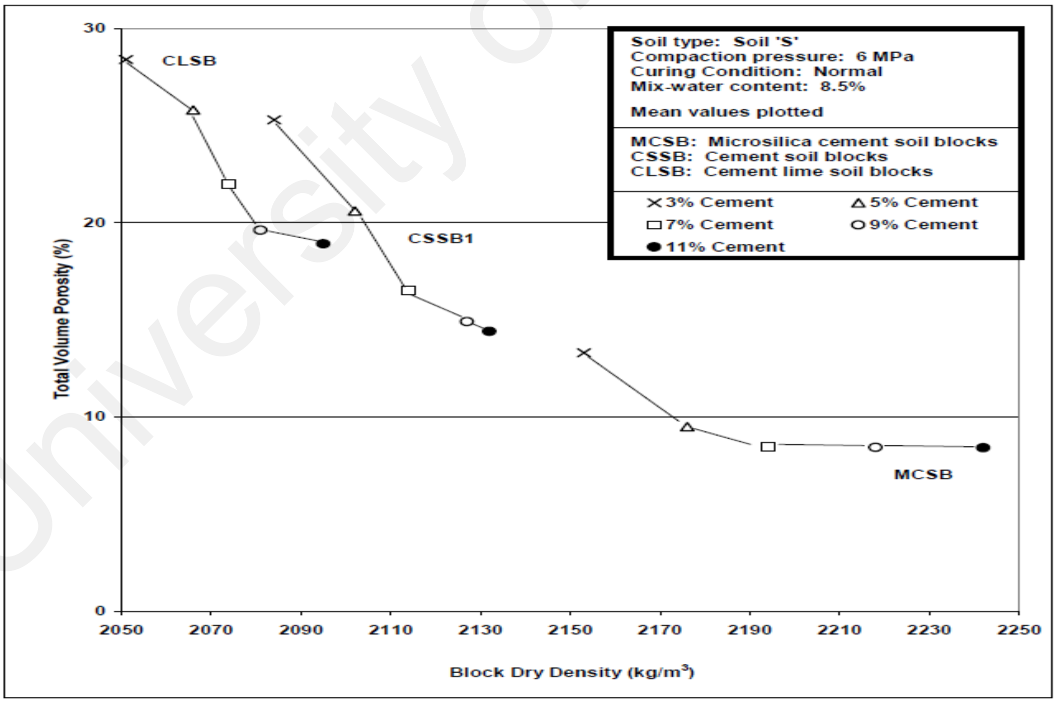



**Figure 2.10:** Correlation between dry density and porosity (Anthony 2001)

## 2.10 Total Water Absorption of Compressed Soil Blocks and Bricks

Anthony (2001) investigated the existence of pores of varying magnitudes in these materials which confer marked capillarity in them. The total amount of water absorbed is a useful measure of bulk quality almost all bricks and blocks can absorb water by capillarity (Keddi & Cleghorn, 1980). The reason for this is that the total volume of voids (or pore space) in a block can be estimated by the amount of water it can absorb. This property is clearly distinct from the ease with which water can penetrate a block and permeate through it (Neville, 1995).

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

- Comparison purposes with set standards and values for other similar materials
- The classification of blocks according to required durability and structural use
- Approximation of the voids content of a block

Various procedures can be used to determine the total water absorption capacity of a block (BS 3921):

1985) which include:

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

With the above methods, widely differing results can still be obtained (Bungey & Millard, 1996). It is reported that none of the three methods above show any precise convergence (BS 3921, 1985). The results obtained from each of these three methods can be different, and neither proportional nor equivalent to one another (Neville, 1995) Higher compression reduces the amount of voids and increases inter-particle contact within a brick. Higher density always has been associated with higher strength (Spence, 1975; Gooding, 1994).

**2.11 Porosity of Brick and Block**

Materials with total volume porosity above 30% are considered to be of high porosity (Jackson & Dhir, 1996). All the blocks examined during this study can therefore be considered to be of low porosity. The decrease in compressive strength with increase in porosity can be partly explained as follows. The compressive strength of a block is limited by brittle fracture. It is therefore sensitive to individual flaws in the block sample under test.

Discontinuities between solid phases in a block (due to the presence of voids and pore structure) constitute flaws in it. The higher the amount of voids, the weaker the block is likely to be. Large coarse soil fractions in a block can also create flaws in it. The combination of such large particles and voids in a block can make it more susceptible to brittle fracture failure (Anthony 2001). Figure 2.11 presents the correlation between wet compressive strength and porosity.

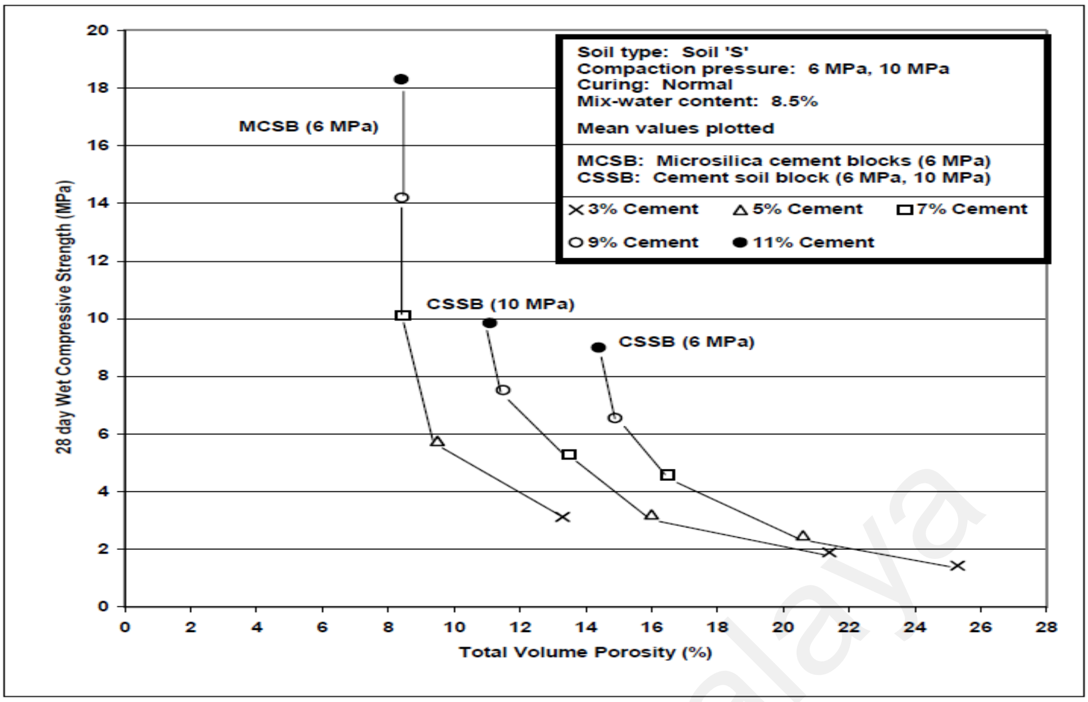



**Figure 2.11:** Correlation between wet compressive strength and porosity of block (Anthony, 2001)

## 2.12 Effect of Sound Insulation on Construction Buildings

A number of wall configurations have been invented and tested for their sound transmission loss characteristics by building materials manufacturers. Wall systems are generally broken down into two categories: load bearing walls and non-load bearing walls. Most load bearing are masonry or wood studs. Trusses and long-span joists allow non-load bearing systems to be used in residential buildings, hotels and single-family and multifamily constructions.

### 2.12.1 Sound Transmission Standards

ASTM E-90 test method is a laboratory measurement of airborne-sound transmission loss of building partitions. This method for evaluating transmission loss of materials and systems is used in building construction, such as interior partitions, doors, widows, and floor ceiling assemblies.

From this standard the transmission loss (TL) and sound transmission class (STC) can be calculated. A test specimen is installed in an opening between two adjacent reverberation rooms, care being taken that the only significant sound path between rooms is by way of the specimen. An approximately diffused field is produced in one room, and the resulting space-time average sound pressure levels in the two rooms are determined at a number of one-third-octave band frequencies. In addition, the sound absorption in the receiving room is determined. The sound transmission loss is calculated from basic relationship involving difference between sound levels, the receiving room absorption and the test specimen size.

When the first legal sound insulation requirements appeared more than 50 years ago, the frequency range 100–3150 Hz in 1/3 octave bands became the ‘‘traditional” frequency range for requirements in Europe. However, in countries with a tradition for lightweight building practices such as Sweden and Norway, the need to include lower frequencies (< 100 Hz) gradually became obvious. Since 1999, the frequency bands down to 50 Hz have been included in the regulatory minimum requirements in Sweden. During the past decade, low-frequency descriptors (down to 50 Hz) have been introduced in the criteria the higher, voluntary quality classes in the classification schemes in five Nordic countries (Denmark, Sweden, Norway, Finland, Iceland) and in Lithuania. A step in a different direction was taken a few years ago in England and Wales by introducing the spectrum adaptation term $C_{tr}$ (and thus keeping the frequency range 100–3150 Hz) as a part of the regulatory requirements for airborne sound insulation between dwellings in general, although the $C_{tr}$ -spectrum is intended to optimise sound insulation against traffic and other sources with significant low frequency contents, for instance disco music.

The early sound insulation requirements were sometimes ‘‘comparative”, for example requiring a sound insulation as good as a 1/1 stone brick wall or another construction providing at least the same sound insulation. Later, more specific requirements and descriptors appeared, for e.g. $R_m$ being an arithmetic average of 1/3 octave values for the frequency range 100–3150 Hz. The first international standard for rating sound insulation of dwellings was ISO/R 717:1968, which was based on extensive investigations in Germany. Rasmussen & Jens (2009) supported these field measurements according to ISO/R 140:1960. Which this standard, the concept of reference curves for the evaluation of sound insulation was introduced, the maximum allowable unfavourable deviation at a single 1/3 octave band from the reference curves defined in ISO/R 717 was 8 dB.

A revised ISO 717 consisting of three parts was published in 1982, and the series supporting the ISO 140 series published was later in 1978. The basic reference curves were the same as in ISO/ R 717:1968, but the 8 dB rules (max unfavourable deviation from the reference curve) was removed, although deviations exceeding 8 dB had to be reported.

A different approach was taken in France with the descriptors Rrose and Rroute, which can briefly be described as the A-weighted level difference when the source spectrum is either pink noise or a generalised road traffic noise spectrum. The next (and most recent) revision of ISO 717 was an attempt to combine the French and the German approaches, and concurrently include evaluation methods for sound insulation against traffic noise. The solution was the introduction of a range of spectrum adaptation terms, several of them with extended frequency range (50 Hz–5000 Hz). Thus in tandem, ISO 140 was updated. A historical overview of ISO 717 standards as well as the main characteristics is presented in Table 2.6.

**Table 2.6**: Historical overview of ISO 717 standards with indication of its main characteristics (Rasmussen, 2009)

| Sound insulation Standards ISO 717 |
|---|
| 1968 ISO/R 717:1968, Rating of sound insulation for dwellings<br>1982 ISO 717:1982, Acoustics – Rating of sound insulation in buildings and of building elements<br>Part 1: Airborne sound insulation in buildings and of interior building elements Part 1<br>Part 3: Airborne sound insulation of facade elements and facades Part 3<br>1996 ISO 717:1996, Acoustics – Rating of sound insulation in buildings and of building elements<br>Part 1: Airborne sound insulation |

The single-number quantities and the spectrum adaptation terms are derived from 1/3 octave values (laboratory and field) or 1/1 octave values (field only) measured according to (ISO 140: Part 1 to 17). For simplicity, only 1/3 octave quantities and C-terms are included in Table 2.7, although some countries allow 1/1 octave measurements for field check. The different C - corrections (see Table 2.7) make it possible to take into account different types of noise spectra, without leaving the well-known reference curve system introduced in 1968. Thus, C, $C_{tr}$ and $C_I$ have not been included directly in any single-number quantities, but have been introduced as separate terms to be added: C and $C_{tr}$ (corresponding to pink noise and road traffic noise, respectively) for airborne sound insulation, see ISO 717-1:1996, and $C_I$ for impact sound insulation, see ISO 717-2:1996. $L'_{n,w} + C_I + 15$ corresponds to the energy sum of the impact sound pressure levels of the 1/3 octave bands 100–2500 Hz.

The spectrum adaptation terms – colloquially named C- corrections – may be calculated for the usual frequency range or for an enlarged frequency range including the 1/3 octave frequency bands 50 + 63 + 80 Hz (C, $C_{tr}$, $C_I$) and/or 4000 + 5000 Hz (C and $C_{tr}$ only). Measurement results in 1/1 octave bands may be used to rate field measurements. The C-corrections are equipped with indices specifying the type of spectrum and the frequency range, if extended. The maximum unfavourable deviation no longer needs to be indicated, even if it exceeds 8 dB. However, the procedures for determination of C-corrections are more restrictive to dips and peaks in the airborne and impact sound insulation curves, respectively. To some extent this substitutes the former 8 dB rules.

A requirement may be expressed as the sum of a single-number quantity and a spectrum adaptation term or solely as the single number quantity. Examples of statements of airborne and impact sound insulation requirements could be:

$$D_{nT,w} \geq 55 \text{ dB}; \; L'_{nT,w} \leq 50 \text{ dB} \tag{2.13}$$

$$D_{nT,w} + C \geq 55 \text{ dB}; \; L'_{nT,w} + C_1 \leq 50 \text{ dB} \tag{2.14}$$

$$D_{nT,w} + C_{50-3150} \geq 55 \text{ dB}; \; L'_{nT,w} + C_{1,50-2500} \leq 50\text{dB} \tag{2.15}$$

The main reason for applying a new sound insulation weighting is to raise standards in the frequency range with too low performance and thus create a better home environment for occupants. At the same time, the change should not adversely affect performance at other important frequencies. The idea behind including $C_{tr}$ for evaluation of sound insulation between dwellings is to take into account low frequencies without actually testing at low frequencies. However there are indications that this is not a balanced way to meet the needs for increased sound insulation at low frequencies.

Some drawbacks have been recognised according to Smith et al. (2003) and Smith et al. (2007) $D_{nT,w}$ + $C_{tr}$ is used as the only criteria for airborne sound insulation which is considered not effective enough in dealing with normal living noise issues and generates too much emphasis at low frequencies. It also significantly concentrates on performance outcomes on the basis of the results at 100 Hz to 160 Hz. Raising the overall single weighted performance level could also increase the mid and high frequencies, but there is an effective ceiling limit to the possible gains at such low frequencies.

Another drawback according to Smith et al. (2007), is a high measurement uncertainty due to the strong $C_{tr}$ emphasis on a few frequencies in the lower part of the frequency range applied, implying that the result at 100 Hz could often is decisive for the final result. It is concluded that one solution could be to use $D_{nT,w}$ alone, by increasing the regulatory minimum level, implying that the low frequency performance will be raised at the same time. Another solution could be a composition of $D_{nT,w}$ and $D_{nT,w}$ +$C_{tr}$ used as a collective approach to airborne sound insulation criteria. However, the implication would be that, a more complex approach had to be adopted by designers and acoustic consultants to meet both criteria.

**Table 2.7**: Relevant spectrum adaptation term for different types of noise sources (Rasmussen, 2009)

| **Different types of noise** | **Spectrum term** |
|---|---|
| Living activities (talking, music, radio, tv) | C (Spectrum 1: A-weighted pink ) |
| Railway traffic at medium and high speed | |
| Highway road traffic > 80 km/h | |
| Jet aircraft short distance | |
| Factories emitting mainly medium and high frequency noise | $C_{tr}$ (Spectrum 2: A- Traffic noise) |
| Urban road traffic | |
| Railway traffic at low speeds | |
| Aircraft propeller driven | |
| Jet aircraft large distance | |
| Disco music | |
| Factories emitting mainly low and medium frequency noise | $C_I$ |
| ISO tapping machine | |

To conclude on the application of $C_{tr}$ as a part criterion for sound insulation between dwellings, it seems to be an unbalanced choice. Equations for sound insulation field properties compliance with requirements that can be checked out by conducting field tests in the completed building. The names of these field properties are in Table 2.7. When testing sound insulation in buildings, Equation. 2.16, 2.17 and 2.18 are applied for the relevant calculations.

For airborne sound insulation, the equations according to ISO 140-4:1998 are:

$$R' = L_1 - L_2 + 10\mathrm{Log}_{10}\left({S}/{A}\right) \text{ dB} \tag{2.16}$$

$$D_n = L_1 - L_2 + 10Log_{10}\left(A/A_0\right) dB \quad (2.17)$$

$$D_{nT} = L_1 - L_2 + 10Log_{10}\left(T/T_0\right) dB \quad (2.18)$$

In terms of explanation of $L_1$ symbols: is the average SPL in the source room, $L_2$ is the average SPL in the receiving room, S is the area of the separating element, A is the equivalent sound absorption area in the receiving room, $A_0$ is the reference absorption area;

$A_0$= 10 $m^2$, T is the reverberation time in the receiving room, $T_0$ is the reference reverberation time; for dwellings, $T_0$= 0.5 s,

A = 0.16 V/T, where V is the room volume.

**Table 2.8**: Single-number quantities for sound insulation between rooms in buildings

| Single number quantities for sound insulation between rooms in building | | | | |
|---|---|---|---|---|
| Single number quantities (100-3150Hz) | | 1/3-orctave band values | | |
| **Term** | **Symbol** | **Term** | **Symbol** | **Defined in** |
| Weighted apparent sound reduction index | $R_w$ | Apparent sound reduction | R | (1) ISO 140-4:1998; Eq. (1) |
| Weighted normalised level difference | $D_{n,w}$ | Normalized level difference | $D_n$ | (2) ISO 140-4:1998; Eq. (3) |
| Weighted standardised level difference | $D_{nT,w}$ | Standardized level difference | $D_{nT}$ | (3) ISO 140-4:1998; Eq. (4) |

## 2.13 Fire Resistance of Brick Masonry Wall

Building codes and other local ordinances require critical building components to have a certain level of fire resistance to protect occupants and to allow a means of escape. Several factors contribute to the level of fire resistance required of a wall, floor or roof assembly, including whether combustible (wood) or non combustible (steel, concrete and masonry) construction is used. Other factors include the use of the building floor area and height, the location of the assembly, and whether a fire suppression system such as stand pipes or sprinklers are installed.

Fire resistance is the property of a building element, component or assembly that prevents or retards the passage of excessive heat, hot gases or flames under conditions of use. The period of fire resistance is duration of time determined by a fire test or method based on a fire test that a building element, component or assembly maintains the ability to confine a fire, continues to perform a given structural function or both.

The fire resistance Rating is duration of time not exceeding 4 hours (as established by the building code) that a building element, component or assembly maintains the ability to confine a fire, continues to perform a given structural function or both. It is a necessary building code legal requirement for various types of construction and occupancies.

A fire resistance rating is based on a fire resistance period and usually given in half-hour or hourly increments. For example, a wall with a fire resistance period of 2 hours and 25 minutes may only attain a fire resistance rating of 2 hours. It is also referred to as a fire rating, fire resistance classification or hourly rating.

### 2.13.1 Determining a Fire Resistance Rating

Traditionally, a fire resistance rating is established through testing. The most common test method used is ASTM E-119, Standard Test Methods for Fire Tests of Building Construction and Materials (ASTM E 119-07, 2007). In this test, a sample of the wall must perform successfully during exposure to a controlled fire for the specified period of time, followed by the impact of a stream of water from a hose.

This standard test, along with other ASTM fire test standards, is used to measure and describe the response of materials, products or assemblies to heat and flame under controlled conditions, but does not by itself replicate actual fire conditions in a building. Rather, the intent of the test is to provide comparative performance to specific fire-test conditions during the period of exposure. Further, the test is valid only for the specific assembly tested.

Fire testing is expensive because each specific assembly must be tested by constructing a large specimen, placing multiple monitoring devices on that specimen and subjecting the specimen to both a fire and a hose stream. As a result, a calculated fire resistance method developed jointly by The Masonry Society and the American Concrete Institute and based on past ASTM E-119 tests have largely replaced further fire resistance testing for masonry and concrete materials (TMS, 2007).

#### 2.13.1.1 Fire Resistance Rating of Walls

There are several sources of fire resistance ratings for brick masonry assemblies that will typically satisfy the requirements of the local building official. Model building codes contain results based on testing. Private laboratories report fire test results. Individual associations and companies sponsor fire tests and subsequently make these results available.

#### 2.13.1.2 Fire Resistance Testing.

The test methods described in ASTM E-119 are applicable to assemblies of masonry units and to composite assemblies of structural materials for buildings, including bearing and other walls and partitions, columns, girders, beams, slabs and composite slab and beam assemblies for floors and roofs.

When fire testing a wall assembly according to ASTM E-119, a sample of the wall is built using the materials and details of the assembly to be used in construction, the specimen is then subjected to a controlled fire until a failure occurs (termination point is reached) or a designated extent of time passes. ASTM E-119 requires that the air temperature at a distance of 6 in. (152 mm) from the exposed fire side of the specimen conform to the standard time-temperature curve, as shown in Figure 2.12.

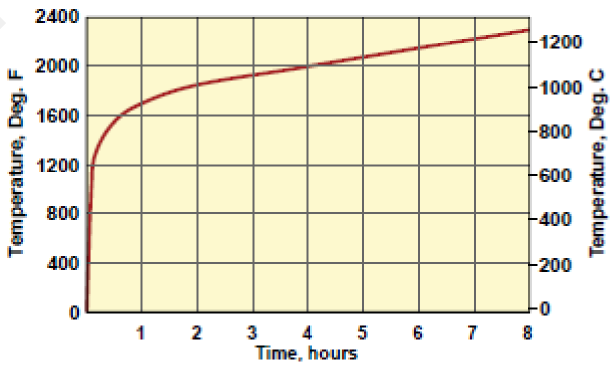



**Figure 2.12:** Time-Temperature Curve for ASTM Standard E-119

Hose stream test for most fire resistance ratings ASTM E-119 requires that walls be subjected to both a fire endurance test and a hose stream test. The hose stream test subjects a specimen to impact, erosion and cooling effects over the entire surface area that has been exposed to the fire. The procedure stipulates nozzle size, distance, duration of application and water pressure at the base of the nozzle. Some of these requirements vary with the fire resistance rating. The hose stream test may be performed on a duplicate wall specimen that has been subjected to a fire endurance test for one-half of the period determined by the fire test (but not more than 1 hour); or the hose stream test may be performed on the wall specimen immediately after the full duration of fire exposure. The latter option is typically used to test brick walls because the test termination point is almost always a temperature rise rather than a failure by passage of hot gases or it collapses where there is a degradation of the brick from the hose stream test. Some other materials rely on the duplicate specimen to meet certain fire ratings.

**2.13.1.3 Conditions of Acceptance of Fire Resistance**

The number of criteria considered as termination points for a fire test on an assembly depends on whether the assembly is load bearing.

* *Non-Bearing walls and partitions*: The test is successful and a fire resistance rating is assigned to the construction if all of the following criteria are met:

- The assembly withstands the fire endurance test without passage of flame or gases hot enough to ignite cotton waste for a period equal to that for which classification is desired.
- The assembly withstands the fire endurance test without passage of flame and the hose stream test without passage of water from the hose stream. If an

opening develops in the wall specimen that permits a projection of water beyond the surface of the unexposed side during the hose stream test, then the assembly is considered to have failed the test.

- The average rise in temperature of nine thermocouples on the unexposed surface is not more than 250 ºF (139 ºC) above their average initial temperature, and the temperature rise of a single thermocouple is not more than 325 ºF (181 ºC) above its initial temperature.

* *Bearing walls*: The conditions of acceptance for bearing walls are the same as for non-bearing walls and partitions with the following addition:

- The specimen must also sustain the applied load during the fire endurance and hose stream tests.
- The first three criteria relate to providing a barrier against the spread of fire by penetration of the assembly; the fourth relates to structural integrity. The termination point for fire tests of brick masonry walls is almost invariably due to temperature rise (heat transmission) of the unexposed surface. Brick masonry walls successfully withstand the load during the fire endurance test and the hose stream test conducted immediately after the wall has been subjected to the fire exposure. This structural integrity of brick masonry walls is attested to in many fires where the masonry walls have remained standing when other parts of the building have been destroyed or consumed during the fire.

Referring to International Building Code (2006), Table 2.9 presents fire resistance ratings for various masonry wall assemblies while Table 2.10 presents fire resistance ratings for brick veneer/steel stud wall assemblies.

**Table 2.9**: Fire Resistance Ratings (Periods) for Various Walls and Partitions (IBC, 2006).

| Material | Item Number | Construction | Minimum Finished Thickness, Face-to-Face, in. (mm) | | | |
|---|---|---|---|---|---|---|
| | | | 4 hr | 3 hr | 2 hr | 1 hr |
| 1. Brick of clay or shale[2] | 1-1.1 | Solid brick of clay or shale[1] | 6.0 (152) | 4.9 (124) | 3.8 (97) | 2.7 (69) |
| | 1-1.2 | Hollow brick, not filled | 5.0 (127) | 4.3 (109) | 3.4 (86) | 2.3 (58) |
| | 1-1.3 | Hollow brick unit wall, grouted solid or filled with perlite vermiculite or expanded shale aggregate | 6.6 (168) | 5.5 (140) | 4.4 (112) | 3.0 (76) |
| | 1-2.1 | 4 in. (102 mm) nominal thick units at least 75 percent solid backed with hat-shaped metal furring channel ¾ in. (76 mm) thick formed from 0.021 in. (0.53 mm) sheet metal attached to the brick wall at 24 in. (610 mm) o.c. with approved fasteners, and ½ in. (12.7 mm) Type X gypsum wallboard attached to the metal furring strips with 1 in. (25.4 mm) long Type S screws spaced at 8 in. (203 mm) o.c. | — | — | 5[3] (127) | — |
| 2. Combination of clay brick and loadbearing hollow clay tile[2] | 2-1.1 | 4 in. (102 mm) solid brick and 4 in. (102 mm) tile (at least 40 percent solid) | — | 8 (203) | — | — |
| | 2-1.2 | 4 in. (102 mm) solid brick and 8 in. (203 mm) tile (at least 40 percent solid) | 12 (305) | — | — | — |
| 15. Exterior or interior walls[4,5,6] | 15-1.5[7] | 2¼ × 3¾ in. (57 × 95 mm) clay face brick with cored holes over ½ in. (12.7 mm) gypsum sheathing on exterior surface of 2 × 4 in. (51 × 102 mm) wood studs at 16 in. (406 mm) o.c. and two layers ⅝ in. (15.9 mm) Type X gypsum wallboard on interior surface. Sheathing placed horizontally or vertically with vertical joints over studs nailed 6 in. (152 mm) on center with 1¾ in. (44 mm) by No. 11 gage by 7/16 in. (11.1 mm) head galvanized nails. Inner layer of wallboard placed horizontally or vertically and nailed 8 in. (203 mm) on center with 6d cooler or wallboard nails. Outer layer of wallboard placed horizontally or vertically and nailed 8 in. (203 mm) on center with 8d cooler or wallboard nails. All joints staggered with vertical joints over studs. Outer layer joints taped and finished with compound. Nail heads covered with joint compound. 0.035 in. (0.89 mm) (No. 20 galvanized sheet gage) corrugated galvanized steel wall ties ¾ × 6⅝ in. (19.1 × 168 mm) attached to each stud with two 8d cooler or wallboard nails every sixth course of bricks. | — | — | 10 (254) | — |

Explanation of indices 1, 2…..and 7 presented below:

(1) For units in which the nett cross-sectional area of cored brick in any plane parallel to the surface containing the cores is at least 75 percent of the gross cross-sectional area measured in the same plane.

(2) Thickness shown for brick and clay tile are nominal thicknesses unless plastered, in which case thicknesses are net. Thickness shown for clay masonry is equivalent thickness defined by Equation 3. Where all cells are solid grouted

or filled with silicone-treated perlite loose-fill insulation; vermiculite loose-fill insulation; or expanded clay, shale or slate lightweight aggregate, the equivalent thickness shall be the thickness of the brick using specified dimensions. Equivalent thickness may also include the thickness of applied plaster and lath or gypsum wallboard, where specified.

(3) Shall be used for non-bearing purposes only.

(4) Staples with equivalent holding power and penetration shall be permitted to be used as alternate fasteners to nails for attachment to wood framing.

(5) For all construction with gypsum wallboard described in this table, gypsum base for veneer plaster of the same size, thickness and core type shall be permitted to be substituted for gypsum wallboard, provided attachment is identical to that specified for the wallboard, and the joints on the face layer are reinforced and the entire surface is covered with a minimum of 1.6 mm gypsum veneer plaster.

(6) For properties of cooler or wallboard nails, see ASTM C-514, ASTM C-547 or ASTM F-1667.

(7) The design stress of studs shall be reduced to 78 percent of allowable $F'_C$ with the maximum not greater than 78 percent of the calculated stress with studs having a slenderness ratio *l/d* of 33.

**Table 2.10**: Fire Resistance Ratings for Brick Veneer/Steel Stud Assemblies (Underwriters Laboratories, 2007).

| Wall or Partition Assembly | Plaster Side Exposed (hours) | Brick Faced Side Exposed (hours) |
|---|---|---|
| **Outside facing of steel studs:** ½ in. (12.7 mm) wood fiberboard sheathing next to studs, ¾ in. (19.1 mm) air space formed with ¾ × 1⅝ in. (19.1 × 41 mm) wood strips placed over the fiberboard and secured to the studs; metal or wire lath nailed to such strips, 3¾ in. (95 mm) brick veneer held in place by filling ¾ in. (19.1 mm) air space between the brick and lath with mortar. **Inside facing of studs:** ¾ in. (19.1 mm) unsanded gypsum plaster on metal or wire lath attached to 5/16 in. (7.9 mm) wood strips secured to edges of the studs. | 1.5 | 4 |
| **Outside facing of steel studs:** 1 in. (25.4 mm) insulation board sheathing attached to studs, 1 in. (25.4 mm) air space, and 3¾ in. (95 mm) brick veneer attached to steel frame with metal ties every fifth course. **Inside facing of studs:** ⅞ in. (22.2 mm) sanded gypsum plaster (1:2 mix) applied on metal or wire lath attached directly to the studs. | 1.5 | 4 |
| Same as above except use ⅞ in. (22.2 mm) vermiculite — gypsum plaster — or 1 in. (25.4 mm) sanded gypsum plaster (1:2 mix) applied to metal or wire. | 2 | 4 |
| **Outside facing of steel studs:** ½ in. (12.7 mm) gypsum sheathing board, attached to studs, and 3¾ in. (95 mm) brick veneer attached to steel frame with metal ties every fifth course. **Inside facing of studs:** ½ in. (12.7 mm) sanded gypsum plaster (1:2 mix) applied to ½ in. (12.7 mm) perforated gypsum lath securely attached to studs and having strips of metal lath 3 in. (76 mm) wide applied to all horizontal joints of gypsum lath. | 2 | 4 |

Underwriters Laboratories (2007) recognised throughout the building industry has thousands of published fire resistance rated designs and product certifications that appear in the UL Fire Resistance Directory and their rating are typically accepted without modifications by building officials. The UL certification is based on an assembly complying with the ASTM E-119 test, as described previously. The directory lists several masonry wall assemblies with various potential alternates in materials as shown in Table 2.11.

**Table 2.11**: UL Fire Resistance Ratings for Brick Masonry Walls (Underwriters Laboratories, 2007)

| Design Number | Rating[1] | Assembly |
|---|---|---|
| Brick Veneer/Wood Stud, Loadbearing | | |
| U302 | 2 hr | • (2) layers ⅝ in. (15.9 mm) thick gypsum wallboard or nominal 3/32 in. (2.4 mm) thick gypsum veneer plaster on Classified veneer baseboard<br>• (1) layer ½ in. (12.7 mm) thick exterior gypsum sheathing<br>• 1 (25.4 mm) in. (51 × 102 mm) air space<br>• nominal 2 × 4 in. wood studs spaced at 16 in. (406 mm) o.c.<br>• nominal 4 in. (102 mm) clay facing brick laid in mortar with ¾ in. (19.1 mm) wide × 6⅝ in. 168 mm) long 20 MSG corrugated wall ties spaced at 16 in. (406 mm) o.c. each way |

**Note**: Fire resistance rating applies to both sides of assembly.

**Table 2.11** 'continued'

| Design Number | Rating[1] | Assembly |
|---|---|---|
| **Brick Veneer/Wood Stud, Loadbearing (continued)** | | |
| U356 | 1 hr | • (1) layer ⅝ in. (15.9 mm) thick gypsum board<br>• nominal 2 × 4 in. (51 × 102 mm) wood studs spaced at 16 in. (406 mm) o.c., with 3½ in. (89 mm) thick glass fiber batt or spray applied cellulose insulation<br>• 7/16 in. (11.1 mm) min. thick wood structural panels or min. ½ in. (12.7 mm) thick mineral and fiber boards<br>• 1 in. (25.4 mm) air space<br>• nominal 4 in. (102 mm) brick veneer with corrugated metal wall ties spaced not more than each sixth course of brick and max. 32 in. (813 mm) o.c. horizontally |
| U371 | 1 hr | • (2) layer ⅝ in. (15.9 mm) thick gypsum board<br>• nominal 2 × 4 in. (51 × 102 mm) wood studs spaced at 16 in. (406 mm) o.c. with min. 3 in. (76 mm) mineral wool batt insulation<br>• (1) layer ⅝ in. (15.9 mm) thick gypsum board<br>• 1 in. (25.4 mm) air space<br>• nominal 4 in. (102 mm) brick veneer with corrugated metal wall ties attached with screws and spaced not more than each fourth course and a max. 24 in. (610 mm) o.c. horizontally |
| **Brick Veneer/Steel Stud, Loadbearing** | | |
| U418 | 45 min<br>1 hr<br>2 hr | • (45 min): (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>(1 hr): (2) layers ½ in. (12.7 mm) thick gypsum wallboard<br>(2 hr): (3) layers ½ in. (12.7 mm) thick gypsum wallboard<br>• 3½ or 5½ in., (89 or 140 mm) 18 gage, steel studs, spaced at 24 in. (610 mm) o.c., with 3½ in. (89 mm) thick glass fiber batt insulation<br>• (1) layer ½ in. (12.7 mm) thick exterior gypsum sheathing<br>• 1 in. (25.4 mm) air space<br>• 4 in. (102 mm) nominal clay facing brick laid in mortar with metal ties at 24 in. (610 mm) o.c. horizontally and 16 in. (406 mm) o.c. vertically |
| U424 | 45 min<br>1 hr<br>1½ hr<br>2 hr | • (45 min): (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>(1 hr): (2) layers ½ in. (12.7 mm) thick gypsum wallboard<br>(1½ hr): (2) layers ⅝ in. (15.9 mm) thick gypsum wallboard<br>(2 hr): (3) layers ½ in. (12.7 mm) or (2) layers ¾ in. (19.1 mm) thick gypsum wallboard<br>• 3½ in. (89 mm), 20 gage steel studs, spaced up to 24 in. (610 mm) o.c., with 3½ in. (89 mm) thick glass fiber or mineral wool batt or blanket insulation<br>• (1) layer ½ or ⅝ in. (12.7 or 15.9 mm) thick exterior gypsum sheathing<br>• Air space thickness not specified<br>• 3¾ in. (95 mm) min. brick veneer with corrugated metal wall ties attached to each stud with steel screws, not more than each sixth course of brick |
| U425 | 45 min<br>1 hr<br>1½ hr<br>2 hr | • (45 min): (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>(1 hr): (2) layers ½ in. (12.7 mm) thick gypsum wallboard<br>(1½ hr): (2) layers ⅝ in. (15.9 mm) thick gypsum wallboard<br>(2 hr): (3) layers ½ in. (12.7 mm) or (2) layers ¾ in. (19.1 mm) thick gypsum wallboard<br>• 3½ in. (89 mm), 20 gage steel studs, spaced up to 24 in. (610 mm) o.c., with 3½ in. (89 mm) thick glass fiber or mineral wool batt or blanket insulation<br>• (1) layer ½ or ⅝ in. (12.7 or 15.9 mm) thick exterior gypsum sheathing<br>• Air space thickness not specified<br>• 3¾ in. (95 mm) brick veneer with corrugated metal wall ties attached to each stud with steel screws, not more than each sixth course of brick |

**Note**: Fire resistance rating applies to both sides of assembly.

**Table 2.11:** 'continued'

| Design Number | Rating[1] | Assembly |
|---|---|---|
| **Brick Veneer/Steel Stud, Loadbearing (continued)** | | |
| V434 | 1 hr | • (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>• 3½ in. (89 mm), 20 gage, steel studs with max. spacing at 24 in. (610 mm) o.c., with 3½ in. (89 mm) thick glass fiber batt insulation<br>• 2 in. (51 mm) max. thick foamed plastic<br>• 1 in. (25.4 mm) min. air space<br>• 4 in. (102 mm) nominal brick veneer with wall anchor ties attached to studs at max. 24 in. (610 mm) o.c. |
| V454 | 1 hr | • (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>• 3½ in. (89 mm), 20 gage, steel studs at max. spacing of 24 in. (610 mm) o.c.<br>• (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>• 4 in. (102 mm) max. thick rigid polystyrene insulation<br>• 1 in. (25.4 mm) min. air space<br>• 4 in. (102 mm) nominal brick veneer with wall anchor ties attached to studs at max. 24 in. (610 mm) o.c. |
| V458 | 45 min | • (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard bearing UL Classification Mark<br>• 3⅝ in. (92 mm) 18 gage steel studs at max. spacing of 24 in. (610 mm) o.c. with nominal 3.5 pcf mineral wool batt<br>• (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>• 1 in. (25.4 mm) min. air space<br>• 3¾ in. (95 mm) min. thick brick veneer with corrugated metal wall ties attached to each stud with steel screws, not more than each sixth course of brick |
| **Brick Veneer/Steel Stud, Non-Loadbearing** | | |
| V414 | 3 hr, interior<br><br>1 hr, exterior | • (1) layer ⅝ in. (15.9 mm) thick gypsum wallboard<br>• 3⅝ in. (92 mm) wide, 1⅝ in. (41 mm) legs, 20 gage steel studs, spaced 16 in. (406 mm) o.c., studs cut ¾ in. (19.1 mm) less than assembly height<br>• 2 in. (51 mm) thick foamed plastic (rigid insulation)<br>• 2 in. (51 mm) air space<br>• 4 in. (102 mm) nominal clay facing brick laid in mortar with metal ties at 16 in. (406 mm) o.c. max. each way |
| **Brick/Concrete Masonry, Loadbearing** | | |
| U902 | 4 hr | • 4 in. (102 mm) nominal loadbearing concrete masonry unit laid with full mortar beds and with 9 gage joint reinforcement at 16 in. (406 mm) o.c. vertically<br>• min. 1 in. (25.4 mm) air space with up to 4 in. (102 mm) foamed plastic (rigid insulation) as option<br>• ¾ in. (19.1 mm) wide, 7 in. (178 mm) long, 26 gage corrugated metal ties spaced at 8 in. (203 mm) o.c. horizontally and 16 in. (406 mm) o.c. vertically or truss or ladder type joint reinforcement of 9 gage wire for full width of wall assembly, cross wires at 16 in. (406 mm) o.c., spaced at 16 in. (406 mm) o.c. vertically<br>• 4 in. (102 mm) nominal clay facing brick laid in mortar |

**Note**: Fire resistance rating applies to both sides of assembly

Several other assemblies previously tested with results published in past building codes as presented in Table 2.12.

**Table 2.12** Fire Resistance Ratings for Other Brick Masonry Wall Assemblies (Borchelt, and Swink, 2008)

| Test | Rating[2] | Assembly |
|---|---|---|
| | | **Brick Veneer/Wood Stud** |
| 1 | 1 hr | • (1) layer ½ in. (12.7 mm) thick gypsum wallboard<br>• 2 × 4 in. (51 × 102 mm) wood studs spaced at 16 in. (406 mm) o.c. with 3½ in. (89 mm) glass fiber batt insulation between studs<br>• (1) layer ½ in. (12.7 mm) thick wood fiberboard sheathing<br>• (1) layer No. 15 asphalt felt paper<br>• 1 in. (25.4 mm) air space<br>• 3½ in. (89 mm) actual width hollow clay brick with void area of 34.5% (equivalent thickness of 2.3 in. (58 mm)), laid in mortar with ⅞ in. (22.2 mm) wide, 22 gage corrugated wall ties spaced at 24 in. (610 mm) o.c. horizontally and 16 in. (406 mm) o.c. vertically |
| 2 | 1 hr | • (1) layer ½ in. (12.7 mm) thick gypsum wallboard<br>• 2 × 4 in. (51 × 102 mm) wood studs spaced at 16 in. (406 mm) o.c. with 3½ in. (89 mm) glass fiber batt insulation between studs<br>• (1) layer ½ in. (12.7 mm) thick wood fiberboard sheathing<br>• (1) layer No. 15 asphalt felt paper<br>• 1 in. (25.4 mm) air space<br>• 2⅞ in. (73 mm) actual width hollow clay brick with void area of 36% (equivalent thickness of 1.8 in. (46 mm)), laid in mortar with ⅞ in. (22.2 mm) wide, 22 gage corrugated wall ties spaced at 24 in. (610 mm) o.c. horizontally and 16 in. (406 mm) o.c. vertically |
| 3 | 1 hr | • (1) layer ½ in. (12.7 mm) thick gypsum wallboard<br>• 2 × 4 in. (51 × 102 mm) wood studs spaced at 16 in. (406 mm) o.c. with 3½ in. (89 mm) glass fiber batt insulation between studs<br>• (1) layer ½ in. (12.7 mm) thick wood fiberboard sheathing<br>• (1) layer No. 15 asphalt felt paper<br>• 1 in. (25.4 mm) air space<br>• 1¾ in. (44 mm) actual width[3] hollow clay brick with void area of 26.9% (equivalent thickness of 1.3 in. (32 mm)), laid in mortar with ⅞ in. (22.2 mm) wide, 22 gage corrugated wall ties spaced at 24 in. (610 mm) o.c. horizontally and 16 in. (406 mm) o.c. vertically |

**Note**: Fire resistance rating applies to brick (exterior) side only. Test stopped at 1 hour.

### 2.13.2 Calculation Rating of Fire Resistance

#### 2.13.2.1 Theory and Derivation

The extent of fire resistance provided by a clay masonry wall is a function of the wall's mass or thickness. This well-established fact is based on the results of many fire resistance tests conducted on walls of solid and hollow clay units. During the ASTM E-119 fire test, the fire resistance period of clay masonry walls is usually established by the temperature rise on the unexposed side of the wall specimen. In fact very few masonry walls have failed due to loading or thermal shock of the hose stream.

The method for calculating a fire resistance period is described in NBS, BMS 92, Fire-Resistance Classifications of Building Construction (NBS, 1942). The construction must be similar to others for which the fire resistance periods are known or of composite construction for which the fire resistance period of each component is known. The calculated fire resistance formulas are based on the temperature rise on the unexposed side of the wall.

Heat transmission theory states that when a wall made of a given material is exposed to a heat source that maintains a constant temperature at the surface of the exposed side and the unexposed side is protected against heat loss, the unexposed side will attain a given temperature rise inversely proportional to the square of the wall's thickness. In the standard fire test, the time required to attain a given temperature rise on the unexposed side will be different than when the temperature on the exposed side remains constant. This is because the fire in the standard fire test increases the temperature at the exposed surface of the wall as the test proceeds. Based on fire test data collected from many fire tests, the following formula has been derived to express the fire resistance period of a wall based on its thickness:

$$R = (cV)^{n} \qquad (2.19)$$

where:

R = fire resistance period, hr

c = coefficient depending on the material, design of the wall, and the units of measurement of R and V

V = volume of solid material per unit area of wall surface, and

n = exponent depending on the rate of increase of temperature at the exposed face of the wall

For walls of a given material and design, an increase of 50 percent in volume of solid material per unit area of wall surface results in a 100 percent increase in the fire resistance period. This relationship results in a value of 1.7 for n. The lower value for n compared with 2 for the theoretical condition should be anticipated since a rising temperature at the exposed surface will shorten the fire resistance period of a wall.

For a wall composed of layers of multiple materials, the fire resistance period may be expressed as follows:

$$R = (c_1V_1 + c_2V_2 + c_3V_3)^{\ n} \qquad (2.20)$$

$$= (R_1^{1/n} + R_2^{1/n} + R_3^{1/n})^{\ n}$$

Where available, the fire resistance period (the full duration of the fire test before a termination point is reached) should be used. Where this period is not available (many brick wall tests are stopped after the desired rating time period elapses), the fire resistance rating (typically truncated to be the highest full hour of fire test duration) can be used. However, using the fire resistance rating for a component layer will generally result in a lower calculated fire resistance period for the overall assembly than using the fire resistance period for each component layer.

The calculated fire resistance calculated using either the fire resistance period or fire resistance rating of each layer can then be used to verify that the wall assembly equals or exceeds the fire resistance rating required by the building code (NBS, 1942).

#### 2.13.2.2 Standards Using for Fire Resistance Calculation

The 2006 International Building Code (IBC, 2006) permits the fire resistance of masonry assemblies to be calculated in accordance with TMS-0216. In addition, the IBC also includes methods for calculating the fire resistance of a masonry assembly that are based on and very similar to those in TMS-0216.

##### 2.13.2.2.1 Equivalent Thickness of a Single Wall

The average thickness of the solid material (minus cores or cells) in a masonry unit as placed in the wall is the equivalent thickness of the masonry unit. This is determined by measuring the total volume of the masonry unit, subtracting the volume of the core or cell spaces and dividing by the area of the exposed face of the masonry unit, which is expressed as follows:

$$T_e = V_n / LH \tag{2.21}$$

where

Te = Equivalent thickness of the masonry unit, in.

Vn = Net volume of the masonry unit, inch

L = Specified length of the masonry unit, inch

H = Specified height of the masonry unit, inch

Equation 2.21 can be simplified as follows

$$T_e = [WLH \times (1- P_v)] / LH$$

$$= (1- P_v) \times W$$

$$= P_s \times W \quad (2.22)$$

where

W = Specified width of the masonry unit, inch

Pv = Percent void of the masonry unit

Ps = Percent solid of the masonry unit

**2.13.2.2.2 Fire Resistance of a Single Wall**

The minimum equivalent thickness required to achieve a given fire resistance rating with a clay masonry Wythe as listed in Table 2.13. The Table is organised by material type and hourly fire resistance ratings, for fire resistance periods that are between the hourly increments as listed in the Table 2.13, the minimum equivalent thickness may be determined by linear interpolation. Where combustible members such as wood floor joists are framed into the wall, the thickness of solid material between the end of each member and the opposite face of the wall, or between members set in from opposite sides is allowed to be no less than 93 percent of the thickness is also shown in Table 2.13.

**Table 2.13**: Fire Resistance Ratings of Clay Masonry Walls (www.gobrick.com)

| Material Type | Minimum Equivalent Thickness for Fire Resistance, in. (mm)[1,2,3] | | | |
|---|---|---|---|---|
| | 1 hr | 2 hr | 3 hr | 4 hr |
| Solid brick of clay or shale[4] | 2.7 (69) | 3.8 (97) | 4.9 (124) | 6.0 (152) |
| Hollow brick or tile of clay or shale, unfilled | 2.3 (58) | 3.4 (86) | 4.3 (109) | 5.0 (127) |
| Hollow brick or tile of clay or shale, grouted or filled with materials specified | 3.0 (76) | 4.4 (112) | 5.5 (140) | 6.6 (168) |

Explanation indices 1, 2, 3 and 4 by following

(1) Equivalent thickness as determined from Equations 2.21 and 2.22.

(2) Calculated fire resistance between the hourly increments listed shall be determined by linear interpolation.

(3) Where combustible members are framed into the wall, the thickness of solid material between the end of each member and the opposite face of the wall, or between members set in from opposite sides, shall not be less than 93% percent of the thickness shown.

(4) Units in which the net cross-sectional area of cored or deep frogged brick in any plane parallel to the surface containing the cores or deep frogged is at least 75 percent of the gross cross-sectional area measured in the same plane.

**2.13.2.2.3 Finish Materials.**

When drywall, stucco or plaster finishes are applied to a masonry wall, the fire resistance of the wall is increased. Where finish materials are used to attain a required fire resistance rating, the fire resistance provided by the masonry alone must be a minimum of half the required fire resistance rating to ensure the structural integrity of the wall. For finishes applied to the non-fire exposed side of a wall, the finish is converted to an equivalent thickness of brickwork. This adjusted thickness is then calculated by multiplying the thickness of the finish by the applicable factor from Table 2.14 established by the durability of the finish and the wall material. The adjusted finish thickness is then added to the base equivalent thickness of the wall a shown in Table 2.14.

**Table 2.14**: Multiplying Factor for Finishes on Non-Fire Exposed Side of Masonry and Concrete Walls (www.gobrick.com)

| Type of Material Used in Slab or Wall | Type of Finish Applied to Slab or Wall | | | |
|---|---|---|---|---|
| | Portland Cement-Sand Plaster[1] or Terrazzo | Gypsum-Sand Plaster | Gypsum-Vermiculite or Perlite Plaster | Gypsum Wallboard |
| Clay masonry – solid brick of clay or shale | 1.00 | 1.25 | 1.75 | 3.00 |
| Clay masonry – hollow brick or tile of clay or shale | 0.75 | 1.00 | 1.50 | 2.25 |
| Concrete masonry – siliceous, calcareous, lime-stone, cinders, sir-cooled blast-furnace slag | 1.00 | 1.25 | 1.75 | 3.00 |
| Concrete masonry – made with 80% of more by volume of expanded shale, slate or clay, expanded slag, or pumice | 0.75 | 1.00 | 1.25 | 2.25 |
| Concrete – siliceous, carbonate, air-cooled blast-furnace slag | 1.00 | 1.25 | 1.75 | 3.00 |
| Concrete – semi-lightweight | 0.75 | 1.00 | 1.50 | 2.25 |
| Concrete – lightweight, insulating concrete | 0.75 | 1.00 | 1.25 | 2.25 |

**Note**: For Portland cement-sand plaster (15.9 mm) or less in thickness and applied directly to clay masonry on the non-fire exposed side of the wall, the multiplying factor shall be 1.0.

For finishes on the fire exposed side of the wall, a time is assigned to the finish according to Table 2.15, which is the length of time. The finish will contribute toward the fire resistance rating of the fire exposed side of the wall. This time is then added to the fire resistance rating determined for the base wall and non-fire exposed finish.

**Table 2.15**: Time Assigned to Finish Materials on Fire Exposed Side of Wall (www.gobrick.com).

| Finish | Thickness | Time (minutes) |
|---|---|---|
| Gypsum wallboard | ⅜ in. (9.5 mm) | 10 |
| | ½ in. (12.7 mm) | 15 |
| | ⅝ in. (15.9 mm) | 20 |
| | Two layers of ⅜ in. (9.5 mm) | 25 |
| | One layer of ⅜ in. (9.5 mm) and one layer of ½ in. (12.7 mm) | 35 |
| | Two layers of ½ in. (12.7 mm) | 40 |
| Type X gypsum wallboard | ½ in. (12.7 mm) | 25 |
| | ⅝ in. (15.9 mm) | 40 |
| Direct-applied portland cement-sand plaster | See Note 1 | |
| Portland cement-sand plaster on metal lath | ¾ in. (19.1 mm) | 20 |
| | ⅞ in. (22.2 mm) | 25 |
| | 1 in. (25.4 mm) | 30 |
| Gypsum-sand plaster on ⅜ in. (9.5 mm) gypsum lath | ½ in. (12.7 mm) | 35 |
| | ⅝ in. (15.9 mm) | 40 |
| | ¾ in. (19.1 mm) | 50 |
| Gypsum-sand plaster on metal lath | ¾ in. (19.1 mm) | 50 |
| | ⅞ in. (22.2 mm) | 60 |
| | 1 in. (25.4 mm) | 80 |

## 2.14 Stress Strain Characteristics of Masonry Prism

Masonry is a material built from units and mortar that induce an anisotropic behaviour for the composite. The lack of knowledge on the properties of the composite material imposes low assessments of the strength capacity of the masonry wall. Atkinson et al. (1985) stated that the prediction of compressive strength and deformation of full scale masonry based on compressive tests of stack-bond masonry prism and the interpretation of the results of prism tests have a significant influence on the allowable stress and stiffness used in masonry design

When structural masonry is subjected to vertical and horizontal loading, one of the most important parameters for design is the stress-strain relationship. In particular, elasticity modulus is a mechanical property influenced by different factors, such as the large scatter of experimental tests, compressive strength of unit, shape of unit (hollow or solid), compressive strength of mortar and state of stress developed during loading.

Knutson (1993) evaluated the stress-strain diagrams for various masonry materials and showed that they can be cast into a mathematical form. At present, a complete understanding of the mechanisms involved in the deformation and failure are not fully explained and it is believed that the development of a theoretical model of universal application is a tedious task. However, the failure mechanism of masonry depends on the difference of elasticity modulus between unit and mortar. Therefore, deeper studies are currently under preparation, based on the assumption of a preliminary hypothesis that the behaviour of masonry is governed by the characteristics of bed joint (Mohamad et al., 2005)



### 2.14.1 Typical Failure Modes

**Figure 2.13:** Masonry prism (Mohamad et al., 2005)

Figure 2.13 shows the failure of brick masonry prism and the cracks after put brick masonry prism under loading, the calculation of masonry module elasticity using following equation

$$E'_m = \frac{(1+\gamma_t)}{\left(1+\frac{\gamma_t}{\gamma_m}\right)} \; E_b \tag{2.23}$$

$$E'_m \approx 550\, f'_m$$

Where

$f_b$ Compressive strength of brick

$f_m$ Compressive strength of mortar

$f'_m$ Compressive Strength of masonry prism

$t_b$ Thickness of brick

$t_m$ Thickness of mortar

$t'_m$ Thickness of masonry prism

$E_b$ Module elasticity of brick

$E_m$ Module elasticity of mortar

$E'_m$ Module elasticity of masonry prism

Figure 2.14 show the stresses applicant on the brick, mortar and masonry prism

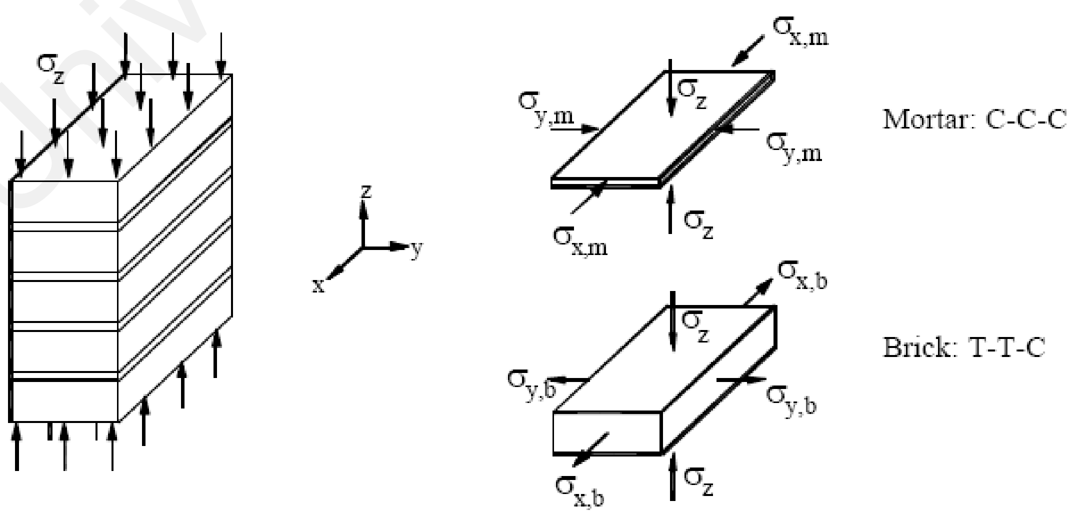



**Figure 2.14:** Mechanic compression of masonry prism (Kaushik et al., 2007)

Kaushik et al., (2007) diescribed the stress-strain curve of masonry prism as presented in Figure 2.15.

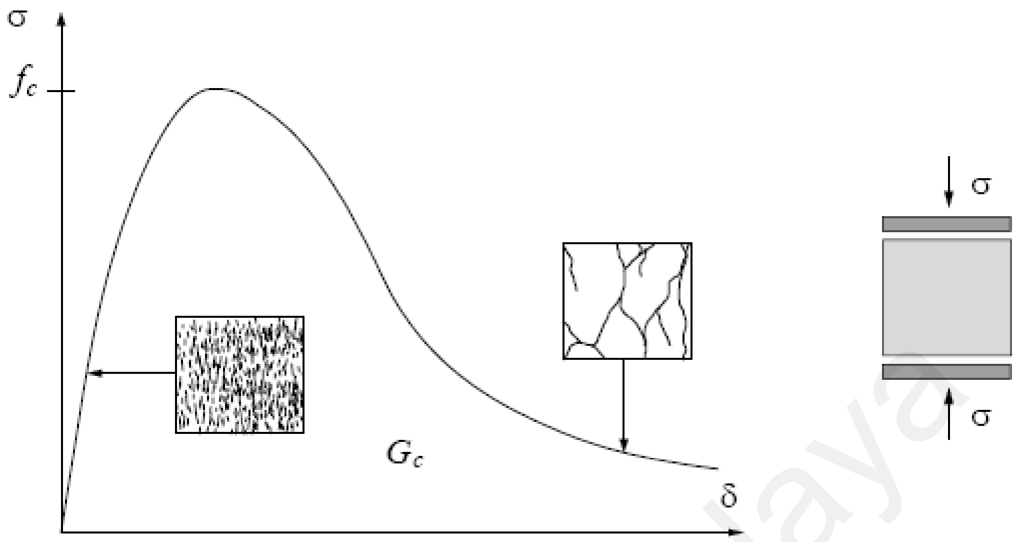



**Figure 2.15:** Masonry stress-strain curve (Kaushik et al., 2007)

### 2.14.2 Compressive Strength of Masonry Prism

Table 2.16 showed some researches results strength of masonry prism

**Table 2.16:** Compressive strength of brick and masonry prism. (Gumaste et al., 2006).

| Source | Brick Strength MPa | Mortar | | Prism size mms | h/t | Prism strength MPa | Corrected prism strength MPa | Masonry efficiency μ |
|---|---|---|---|---|---|---|---|---|
| | | Type | Strength MPa | | | | | |
| Varghese &Ashok Kumar 1965 | 8.330 | CM 1:6 | 5.70 | 254x254x1020 | 4.00 | 3.60 | 3.42 | 0.410 |
| | 14.29 | CM 1:6 | 5.70 | 254x254x1020 | 4.00 | 3.90 | 3.70 | 0.260 |
| | 17.14 | CM 1:6 | 5.70 | 254x254x1020 | 4.00 | 4.00 | 3.80 | 0.220 |
| Bhandari 1982 | 22.0 | *CLM 1:1:6 | 2.27 | 725x713x107 | 6.70 | 3.15 | 3.15 | 0.140 |
| Elangonmani 1983 | 8.80 | CM 1:6 | 3.10 | 225x225x445 | 1.98 | 2.28 | 1.66 | 0.190 |
| Matthana 1996 | 6.40 | CM 1:6 | 3.90 | 225x105x435 | 4.10 | 1.83 | 1.76 | 0.275 |
| | 6.40 | CLM 1:1:6 | 5.60 | 225x105x435 | 4.10 | 1.91 | 1.84 | 0.290 |
| Raghunath 2003 | 6.25 | CM 1:6 | 4.50 | 225x105x430 | 4.10 | 2.67 | 2.56 | 0.410 |
| | 6.25 | CM 1:6 | 4.50 | 225x225x610 | 2.71 | 2.05 | 1.66 | 0.200 |
| Cumaste 2004 | 5.70<br>5.70 | CM 1:6<br>CM 1:6 | 7.30<br>7.30 | 230x105x460<br>230x230x460 | 4.38<br>2.00 | 1.83<br>1.38 | 1.773<br>1.01 | 0.311<br>0.177 |
| | 23.0 | CLM 1:5:4 | 12.2 | 235x115x460 | 4.00 | 10.0 | 9.50 | 0.413 |
| | 23.0 | CM 1:6 | 7.30 | 235x115x460 | 4.00 | 6.70 | 6.365 | 0.277 |
| | 23.0 | CLM 1:5:4 | 12.2 | 235x235x460 | 1.96 | 13.6 | 9.85 | 0.428 |
| | 23.0 | CM 1:6 | 7.30 | 235x235x460 | 1.96 | 6.70 | 4.85 | 0.211 |

***CLM:** Cement-Lime-Morta

### 2.14.3 Mortars

Mortar is a homogenouse mixture of cementitious material; inter material particles and water that is produced at site for joining the masonry units. Mortar influences the strength, durability and resistance to rain penetration of masonry.

Jagadish et al (2003) reported that some properties of mortar for masonry construction, should gain enough strength and harden in a reasonable time so that further courses of masonry can be laid without excessive racking movements also, the fresh mortar should have sufficient workability so that the mason can easily fill the joints and it should have ability to retain water preventing its escape into masonry units.

Depending on the type of cementitiouse material used mortars can be broadly classified as:

Lime mortar, cement mortar, composite mortar, lime- pozzolana mortar, and soil-cement mortar.

## 2.15 Summary

This chapter presented the related literature for bricks and blocks. The expression of engineering properties, effects of sound insulation and fire resistance in bricks is proposed. It was established through the literature review that different types of brick and blocks for the main properties include compressive strength, water absorption, densities and volume porosity, sound insulation and fire resistance rate for different materials. It was noted minimum strength, density, water absorption and porosity of bricks are important aspects to be considered. Discussion also concentrated on standards used for sound insulation and fire resistance. It was further noted that stabiliser types, compaction pressure and curing periods are the main effective ways to improve properties of bricks and blocks. It was also discussed in this Chapter that chemical action is related to deterioration mechanisms in bricks and blocks which remains the least investigated and documented of all deterioration modes. The reactions are potentially possible in bricks due to the various minerals found in raw material and stabiliser hydrates. It will not be possible to experimentally examine these chemical actions in this study.

Many studies have looked into peat and other soil stabilisation in laboratory using various binders. It has been well recognised that organic content retard proper hydration of binders. In general, it has been found that the cement and lime content contributed to the strength gain of cement treated soils.

Based on the above conclusion, it is worth investigating the parameters of compressed stabilised peat bricks. The investigation should look into engineering properties as well as the characteristics of sound insulation and fire resistance on compressed stabilised peat brick wall.

# CHAPTER 3

# RESEARCH METHODOLOGY

## 3.1 General

The purpose underlying this study is to gain understanding of stabilisation of peat soil for brick as construction material. The experiment was focused mainly on laboratory testing. The investigation was started by reviewing related literature to provide rationale for the research work and to study modified peat as brick and determine engineering properties of compressed stabilised peat bricks; sound insulation and fire resistance, and maximum strength and deformation for stabilised peat masonry prism under axial loading. The soil sampling was carried out at a site in Banting village, Klang, Selangor state, Malaysia.

Chemical stabilisation involves the addition of a binder or bonding agent to a soil. The binder modifies the soil properties through cementation or linkage of its particles (Houben & Guillaud, 1994). Both cementation and linkage are a result of chemical reactions involving the binder and water. Cementation creates a strong and inert matrix that can appreciably limit movement in a soil. The voids in the soil are also filled with insoluble by-products of the hydration reaction while some soil particles are coated and firmly held together by the binder (Ingles, 1962). The key binder that acts in this manner is PFA cement or Ordinary Portland cement and lime. It is generally reported in compressed soil block and brick literature that the effect of chemical stabilisation is more permanent, and may take several years or even decades to partially reverse. For this reason, chemical stabilisation of soil is so far considered to be the superior method of choice. It is also well established that the effects of chemical stabilisation is significantly increased by improving the soil grading and compacting the mix (Dunlap, 1975; Gooding, 1994). From the related literature, the important engineering properties of brick and block is compressive strength, water absorption and porosity were aspects investigated in this study.

### 3.2 Laboratory Testing

The program involved basic engineering properties of untreated and stabilised peat soil for compressed brick (specific gravity, sieve analysis, Atterberg limit, linier shrinkage and pH), wet and dry compressive strength, water absorption, porosity, bulk density and dry density. This Chapter also describes the method employed for sound insulation, fire resistance of stabilised peat brick masonry wall and stress- strain of load bearing and deformation of stabilised peat masonry prism.

The results were analysed and compared with the published data, the results of the axial load bearing stabilised peat brick prism were validated and analysed numerically using finite element software, SAP2000. The methodology of the research is summarised in the flowchart as shown in Figure 3.1. All laboratory test procedures were based according to the British (BS), (EN ISO) and U.S. (ASTM) standards.

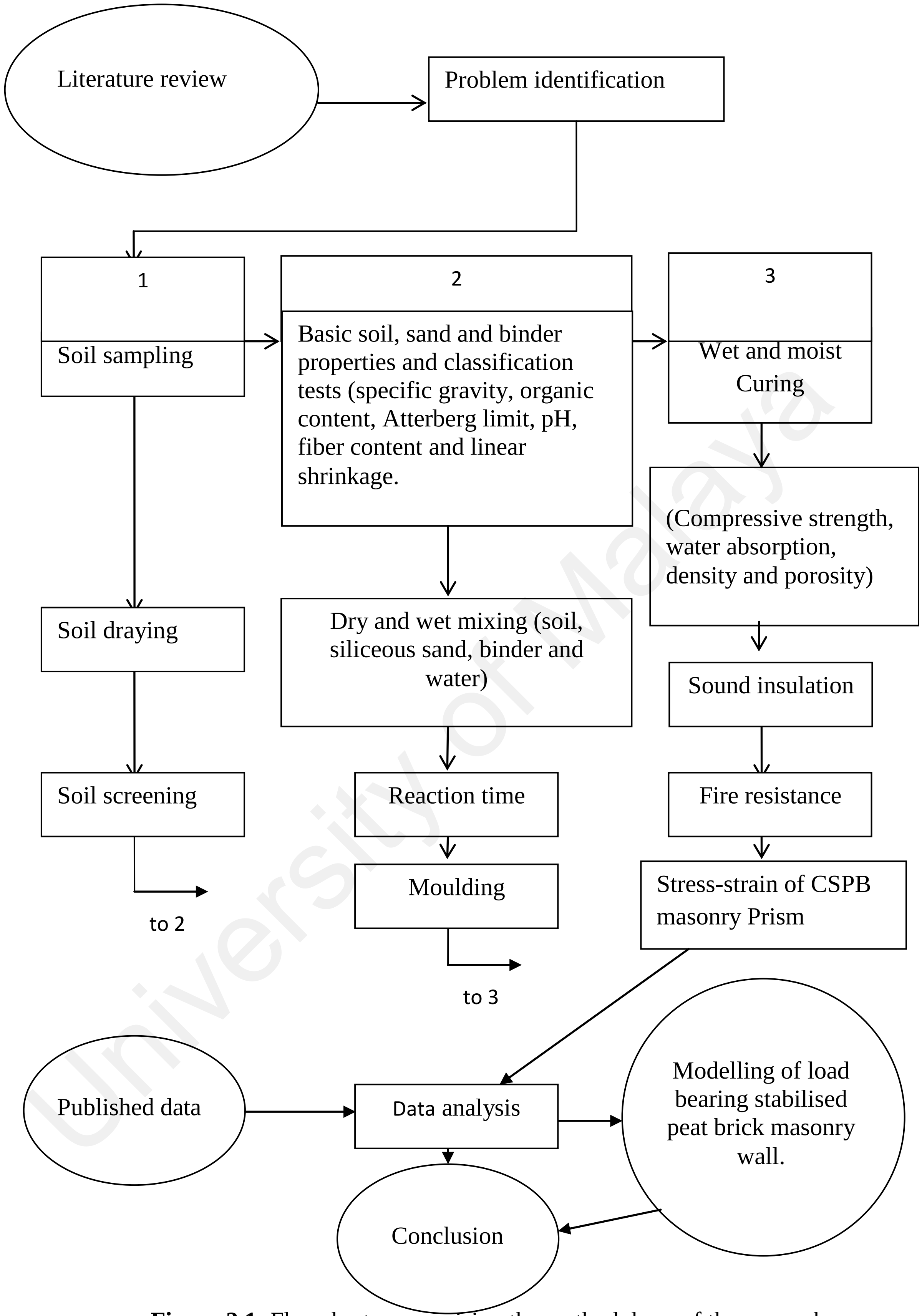



**Figure 3.1**: Flowchart summarising the methodology of the research

### 3.3 Materials Used for Manufacturing Bricks

#### 3.3.1 Peat

Peat soil samples were collected from the site, and excavated to a depth of 0.5 to 1 m below the ground surface. The selection of peat soil as raw material in this study is based on previous investigation of stabilised peat ground. Visual observation of the peat indicated that the soil was dark brown in colour and very high in moisture content. Properties of peat soil is presented in Tables 3.1 and 3.2

The soil characterisation test which was performed to the soils included moisture contents; unite weight, particle size analysis, classification organic content, specific gravity, pH and mineralogy analysis. The peat soil used in this study was obtained from Banting, state of Selangor. This study used dried peat through 2 mm sieving size with 13% to 14% moisture content. PFA cement, Ordinary Portland Cement, hydrated lime and siliceous sand were used as additives. The mineralogical analysis of this materials used in this study were tested using X-Ray fluorescence test, which is presented in this Chapter.



##### 3.3.1.1 Basic Properties of Peat Soils

Peat soil usually contains organic material with normal depth of 0.5 meter. Peat is known for its high organic content which could exceed 75 percent. The organic contents classified as peat are basically derived from where the plant rate of accumulation is faster than the rate of decay. The content of peat soil differs from location to location due to the factors such as temperature and degree of humification. Decomposition or humification involves the loss of organic matter either in gas or in solution, the disappearance of physical structure and change in chemical state (Huat, 2004).

Basic properties of peat investigated in this research are summarised in Tables 3.10 and 3.11. It was discovered that the screened soil had initial void ratio, specific gravity and pH, 9.99, 1.49 and 4.65, respectively. The soil was dark brown colour and spongy in nature. The soil could be classified as $H_4$ according to Von Post degree of himification because upon squeezing and extruding it between fingers, it was found to be somewhat pasty and the plant structure was hardly identifiable (Wong, 2010). The screened peat had bulk density, dry density and Linear Shrinkage of 1.098 Mg/$m^3$, 0.196 Mg/$m^3$ and 5.78% respectively.

**Table 3.1** Properties of in-situ peat soil

| **Property** | **Value** |
|---|---|
| **Physical Properties** | |
| Bulk density ($\gamma_b$), Mg/m$^3$ | 1.059 |
| Dry density ($\gamma_d$), Mg/ m$^3$ | 0.112 |
| Moisture content (w), % | 700-850 |
| Void ratio, (e) | 9.99 |
| Fiber content, % | 84.99 |
| Degree of saturation, (Sr) | 100 |
| Specific gravity, Gs | 1.343 |
| Classification /Von Post | $H_4$ |
| Linear Shrinkage, % | 5.58 |
| BET specific surface area, m$^2$/g | 87.77 |
| **Engineering properties** | |
| Cc | 8.5637 |
| Cv, (m$^2$/year) | 5E+01 |
| Cs | 0.347 |
| k (m/sec) | 3.5E-8 |
| P yield (kPa) | 12 |
| **Chemical properties** | |
| pH | 4.6 |
| Loss on Ignition | 98.46 |

**Table 3.2**: Properties of screened peat soil

| Property | Value |
|---|---|
| **Physical properties** | |
| Bulk density ( $\gamma_b$ ), Mg/m $^3$ | 1.098 |
| Dry density ( $\gamma_d$ ), Mg/ m $^3$ | 0.196 |
| Void ratio, (e) | 7.050 |
| Fibre content, (%) | 80.36 |
| Specific gravity, Gs | 1.494 |
| Linear Shrinkage, (%) | 5.780 |
| Organic content (%) | 92.00 |
| BET specific surface area, m $^2$ /g | 76.34 |
| pH | 4.65 |
| Liquid limit, % | 173.75 |
| Plastic limit, % | 115.8 |
| Plastic Index, % | 57.95 |
| **Chemical properties** | |
| $CO_2$ | 93.40 |
| $Na_2O$ | 0.045 |
| MgO | 0.150 |
| $AL_2O_3$ | 0.850 |
| $SiO_2$ | 3.150 |
| $P_2O_5$ | 0.033 |
| $SO_3$ | 0.790 |
| $K_2O$ | 0.040 |
| CaO | 0.375 |
| $T_iO_2$ | 0.025 |
| $M_nO$ | - |
| $F_{e2}O_3$ | 0.690 |
| $Z_nO$ | 0.003 |

### 3.3.2 Binders

Two types of binder were used to fabricate peat bricks, namely Ordinary Portland Cement and Portland Pluverised Fuel Ash Cement, the later is rapid setting Pulveried Fuel Ash cement with high fineness and manufacturing by adding a superplasticiser as a cement-dispersing agent.

The binder used mostly for soil stabilisation is Ordinary Portland Cement and some special cement like PFA to gave high strength and rapid hydrate. When the pore water of soil interacts with Ordinary Portland Cement, hydration of the cement occurs rapidly, and the major hydration (primary cementation) products are hydrated calcium silicates. A Portland cement particle is a heterogeneous substance, containing minute tri calcium silicate ($C_3S$) dicalicum ($C_2S$), tricalcium ($C_3A$), and solid solution described as tetra calcium alumino-ferrite ($C_4A$) (Lea, 1970).

The presence of chemically combined water (water crystalisation) in cement gel and its porous nature indicates that the volume of cement gel is greater than that of cement particle prior to hydration, Hence, during the reaction between cement and water in the soil, the cement gel would gradually fill the void spaces between cement and soil particles. The cement gel would bind the adjacent cement grains together during hardening and form a hardened skeleton matrix, which encloses unaltered soil particles (Bargado et al., 1996).

Portland Pulverized fuel ash (PFA) is captured from the flue gases by electrostatic precipitators and consists in the main spherical, fine glassy particles with a high silica and alumina content. Stabilisation with PFA cement (intensive mixing and compaction of dry soil with dry cement powder and water) provides good. Cement treatment has been used extensively for construction purposes resulting in increasing the strength. Together with surface compaction, soil improvement can be intensified by a strong admixture of PFA cement or lime.

All mixtures of natural soil and PFA cement, sand and compaction are generally termed "compressed stabilised peat brick. Soil – cement is a mixture of pulverized soil material or aggregates, measured amounts of PFA cement, and water that is compacted to high density. Enough cement is added to produce a hardened material with strength and durability. Chemical and physical properties of PFA and OPC cement are showed in Table 3.3.

**Table 3.3**: Properties of PFA and OPC cement

| Properties | Values | |
|---|---|---|
| | **Ordinary P Cement** | **PFA Cement** |
| **Physical properties** | | |
| Bulk density ($\gamma_b$), Mg/m$^3$ | 1.420 | 1.370 |
| Specific gravity, Gs | 3.020 | 2.980 |
| **Chemical properties** | | |
| MgO | 0.890 | 0.710 |
| $AL_2O_3$ | 6.280 | 6.430 |
| $SiO_2$ | 21.60 | 18.60 |
| $P_2O_5$ | 0.090 | 0.474 |
| $SO_3$ | 0.020 | 3.710 |
| $K_2O$ | 0.720 | 0.924 |
| CaO | 66.23 | 64.24 |
| $T_iO_2$ | 0.220 | 0.452 |
| $M_nO$ | 0.080 | 0.119 |
| $F_{e2}O_3$ | 3.700 | 4.098 |
| $Z_nO$ | 0.010 | 0.039 |
| **Total weight (%)** | **99.93** | **99.68** |

### 3.3.3 Pozzolanic Materials

Small amount of pozzolanic materials were added to the stabilised peat to promote secondary pozzolanic reactions, which were responsible for the long-term strength of the stabilised soil as construction materials, one of secondary pozzolanic was added to the mixture. Hydrated lime is formed from the calcinations of limestone at high temperature above 850°C. The importance of the lime comes from the possibility of producing a strong material in combination with other natural materials.

The effects of lime can be seen in three different stages:

- During mixing, the very fine lime particles occupy the empty spaces between the cement grains and limit the flow of water, thus helping to increase water retention in the fresh mix. The smallest particles with high specific surface can absorb on the surface of cement grains, thus acting as a dispersing agent that prevents flocculation and increases mix plasticity.

- At early age, the lime helps increase material packing, because the small lime grains with size between 1 and 30 μm that have yet to be completely dissolved fill the gaps between cement and sand grains. The structure of hydrated lime consists mainly of amorphous calcium oxide, CaO, and when slaked, heat is evolved and calcium hydroxide Ca $(OH)_2$ is formed.
- Soil stabilisation by lime means the admixture of this material in the form of calcium oxide or calcium hydroxide to the soil, and the compaction of the mixture at the optimum water content. Lime addition will reduce soil plasticity, increase strength and durability, decrease water absorption and swelling. Chemical characteristics of lime are presented in Table 3.4.

**Table 3.4:** Properties of hydrated lime

| **Chemical Properties** | **Values** |
|---|---|
| MgO | 4.420 |
| $AL_2O_3$ | 0.111 |
| $SiO_2$ | 0.200 |
| $P_2O_5$ | 0.320 |
| $SO_3$ | 0.474 |
| $K_2O$ | 0.067 |
| CaO | 94.19 |
| $T_iO_2$ | - |
| $M_nO$ | 0.018 |
| $F_{e2}O_3$ | 0.111 |
| $Z_nO$ | 0.011 |
| **Total weight (%)** | **99.92** |

### 3.3.4 Siliceous Sand

Siliceous sand material was used in this study. Fine sand with a maximum diameter of 2 mm was used to increase solid matrix to the peat. Use of sand for this study has specified grain size distribution to give uniformity of standard material in the mix design. The physical and mechanical properties of siliceous sand are given in Table 3.5.

Well graded siliceous sand was used as a filler to increase the account of solid particles in peat and cement mixture. The siliceous sand added to the peat and cement should be well graded, to ensure the well grading of the sand. The sand composition was formulated in such a way that out of the 100 % proportion of the sand, 5%, 10%, 15%, 25%, 20%, 15%, and 10 % should be rationed at 2 mm, 1.18 mm, 600 µm, 425 µm, 300 µm, 150 µm, and 75 µm sieve sizes, respectively. The sand yielded insignificant chemical reactions in cement hydrolysis due to large size of the sand grains. Addition of sand to the stabilised peat reduces the voids by filling the void spaces within the loss peat during the cementation process of the soil.

**Table 3.5**: Properties of siliceous sand

| Properties | Values (%) |
|---|---|
| **Physical properties** | |
| Bulk density ($\gamma_b$), Mg/m$^3$ | 1.600 |
| Specific gravity, Gs | 2.550 |
| **Chemical properties** | |
| MgO | 0.390 |
| $AL_2O_3$ | 19.20 |
| $SiO_2$ | 70.04 |
| $P_2O_5$ | 0.731 |
| $SO_3$ | 0.160 |
| $K_2O$ | 3.750 |
| CaO | 2.150 |
| $T_iO_2$ | 0.045 |
| $M_nO$ | 2.125 |
| $F_{e2}O_3$ | 0.033 |
| $Z_nO$ | 0.041 |

### 3.3.5 Gypsum

Gypsum was used for finishing CSPB wall as plaster; this material is also aconstituent of boulders which are grained to be granulated materials in the cement industry manufacture. The material used in natural case without sieve. The physical and chemical properties of these materials are given in Table 3.6

**Table 3.6:** Physical and chemical properties of gypsum

| **Chemical Properties** | **Values (%)** |
|---|---|
| **Physical properties** | |
| Bulk density ($\gamma_b$), Mg/m$^3$ | 1.310 |
| Specific gravity, Gs | 2.700 |
| **Chemical properties** | |
| $CO_2$ | - |
| $Na_2O$ | - |
| MgO | - |
| $AL_2O_3$ | 0.540 |
| $SiO_2$ | - |
| $P_2O_5$ | - |
| $SO_3$ | 46.57 |
| $K_2O$ | 0.045 |
| CaO | 30.77 |
| $T_iO_2$ | - |
| $M_nO$ | 0.020 |
| $F_{e2}O_3$ | 0.220 |
| $Z_nO$ | - |
| LOI($H_2$O) | 20.90 |

## 3.4 Laboratory Tests

Variation of any of the several production input variables could influence the quality and performance of bricks. These variables include:

- Soil
- Stabiliser (type and content)
- Water amount
- Compaction pressure
- Curing conditions

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

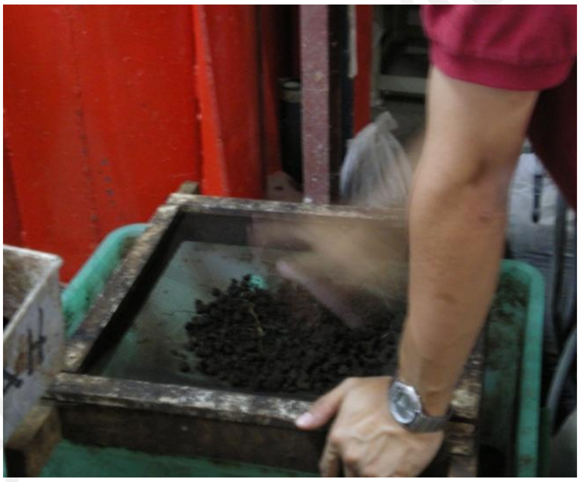


**Figure 3.2:** Dry peat soil being sieved through a 2 mm sieve

A total of 41 mixtures were prepared in the fabrication of bricks (designated CSPB 1-CSPB 41). The material proportions used in the designs of these mixes are presented in Tables 3.2 These designs were further categorised into three series; Series I, II and III. Four mixtures in series I (CSPB 1 - CSPB 4) compacted at 10 MPa. Series II mixtures (CSPB 5 – CSPB 13) were compacted at 10 MPa and (CSPB 14 – CSPB 22) compacted at 6 MPa, and series III mixtures (CSPB 23 – CSPB 31) were compacted at 10 MPa and

(CSPB 32 – CSPB 40) were compacted under 6 MPa and the last mix for hollow brick compacted in mould under 10 MPa. Table 3.7 presents the mix design of this study.

### 3.4.1 Preparation of Brick Specimens

The compressed stabilised peat brick was fabricated in two types of steel mould with internal dimension of 70 mm x 70 mm x 70 mm and 220 mm x 100 mm x 70 mm which is typically used in a laboratory test. The hollow brick was fabricated in a steel mould with internal dimension 220 mm x 100 mm x 70 mm with two holes (diameter for each one 35 mm) as shown in Figure 3.4.

The electric hydraulic machine was connected with a load cell and data-logger to control the pressure. This equipment was used to cast bricks. After 3 to 5 minutes under pressure, the sample was removed from the hydraulic machine which was then subsequently covered with plastic bags for 1 day. When the specimens had attained sufficient strength for handling; these specimens were transferred to the water filled tanks at 23 ± 2℃ for different periods of curing.

**Table 3.7:** Mix design

| Specimen number | Peat Soil % | Binder composition % | Sand % | Compaction pressure MPa | Code |
|---|---|---|---|---|---|
| Series 1 | | | | | |
| 1 | 10 | 30 PFA cement | 60 | 10 | CSPB1 |
| 2 | 15 | 30 PFA cement | 55 | 10 | CSPB2 |
| 3 | 25 | 30 PFA cement | 45 | 10 | CSPB3 |
| 4 | 40 | 30 PFA cement | 30 | 10 | CSPB4 |
| Series 2 | | | | | |
| 5 | 20 | 30 PFA cement | 50 | 10 | CSPB5 |
| 6 | 20 | 25 PFA cement | 55 | 10 | CSPB6 |
| 7 | 20 | 20 PFA cement | 60 | 10 | CSPB7 |
| 8 | 20 | 30 PFA cement + 4 Lime | 46 | 10 | CSPB8 |
| 9 | 20 | 25 PFA cement + 4 Lime | 51 | 10 | CSPB9 |
| 10 | 20 | 20 PFA cement + 4 Lime | 56 | 10 | CSPB10 |
| 11 | 20 | 30 PFA cement + 2 Lime | 48 | 10 | CSPB11 |
| 12 | 20 | 25 PFA cement + 2 Lime | 53 | 10 | CSPB12 |
| 13 | 20 | 20 PFA cement + 2 Lime | 58 | 10 | CSPB13 |
| 14 | 20 | 30 PFA cement | 50 | 6 | CSPB14 |
| 15 | 20 | 25 PFA cement | 55 | 6 | CSPB15 |
| 16 | 20 | 20 PFA cement | 60 | 6 | CSPB16 |
| 17 | 20 | 30 PFA cement + 4 Lime | 46 | 6 | CSPB17 |
| 18 | 20 | 25 PFA cement + 4 Lime | 51 | 6 | CSPB18 |
| 19 | 20 | 20 PFA cement + 4 Lime | 56 | 6 | CSPB19 |
| 20 | 20 | 30 PFA cement + 2 Lime | 48 | 6 | CSPB20 |
| 21 | 20 | 25 PFA cement + 2 Lime | 53 | 6 | CSPB21 |
| 22 | 20 | 20 PFA cement + 2 Lime | 58 | 6 | CSPB22 |
| Series 3 | | | | | |
| 23 | 20 | 30 OPC cement | 50 | 10 | CSPB23 |
| 24 | 20 | 25 OPC cement | 55 | 10 | CSPB24 |
| 25 | 20 | 20 OPC cement | 60 | 10 | CSPB25 |
| 26 | 20 | 30 OPC cement + 4 Lime | 46 | 10 | CSPB26 |
| 27 | 20 | 25 OPC cement + 4 Lime | 51 | 10 | CSPB27 |
| 28 | 20 | 20 OPC cement + 4 Lime | 56 | 10 | CSPB28 |
| 29 | 20 | 30 OPC cement + 2 Lime | 48 | 10 | CSPB29 |
| 30 | 20 | 25 OPC cement + 2 Lime | 53 | 10 | CSPB30 |
| 31 | 20 | 20 OPC cement + 2 Lime | 58 | 10 | CSPB31 |
| 32 | 20 | 30 OPC cement | 50 | 6 | CSPB32 |
| 33 | 20 | 25 OPC cement | 55 | 6 | CSPB33 |
| 34 | 20 | 20 OPC cement | 60 | 6 | CSPB34 |
| 35 | 20 | 30 OPC cement + 4 Lime | 46 | 6 | CSPB35 |
| 36 | 20 | 25 OPC cement + 4 Lime | 51 | 6 | CSPB36 |
| 37 | 20 | 20 OPC cement + 4 Lime | 56 | 6 | CSPB37 |
| 38 | 20 | 30 OPC cement + 2 Lime | 48 | 6 | CSPB38 |
| 39 | 20 | 25 OPC cement + 2 Lime | 53 | 6 | CSPB39 |
| 40 | 20 | 20 OPC cement + 2 Lime | 58 | 6 | CSPB40 |
| 41 hollow Brick (with 2 holes ) | 20 | 30 OPC cement | 50 | 10 | CSPB41 |

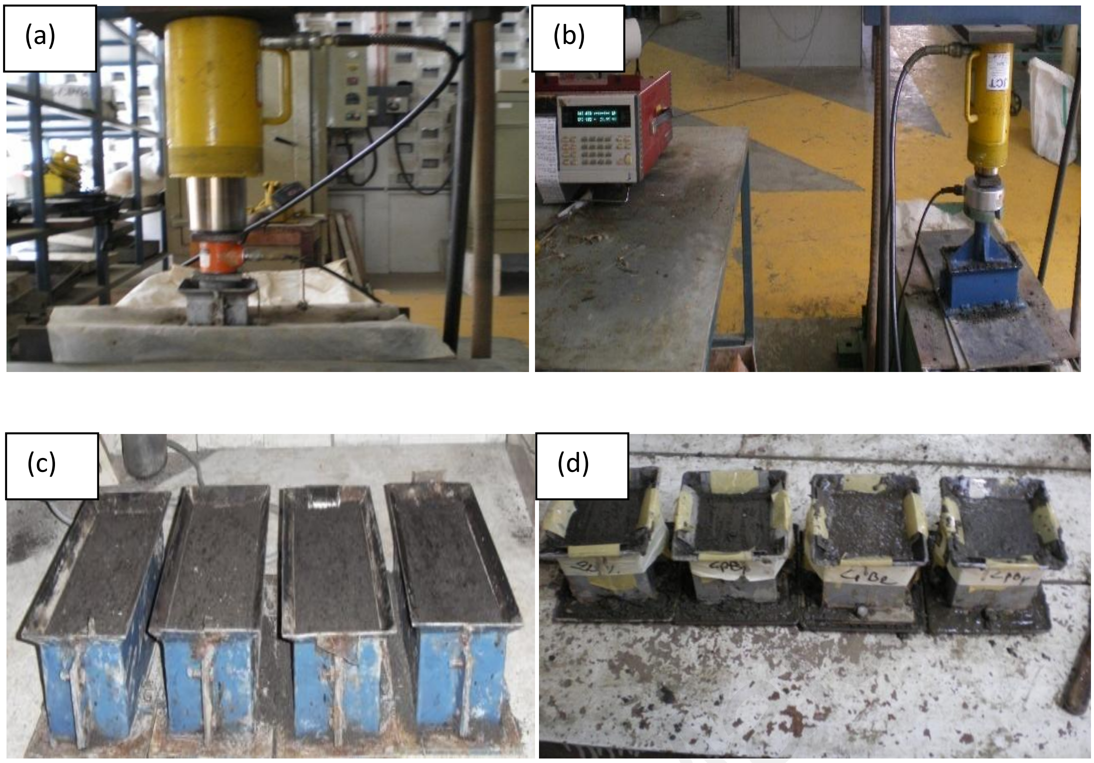



**Figure 3.3:** Steps involved in the preparation of brick specimen**:** (a) small size mould under loading, (b) big size mould under loading, (c) big size of brick after compacted, (d) small size of brick after casting.

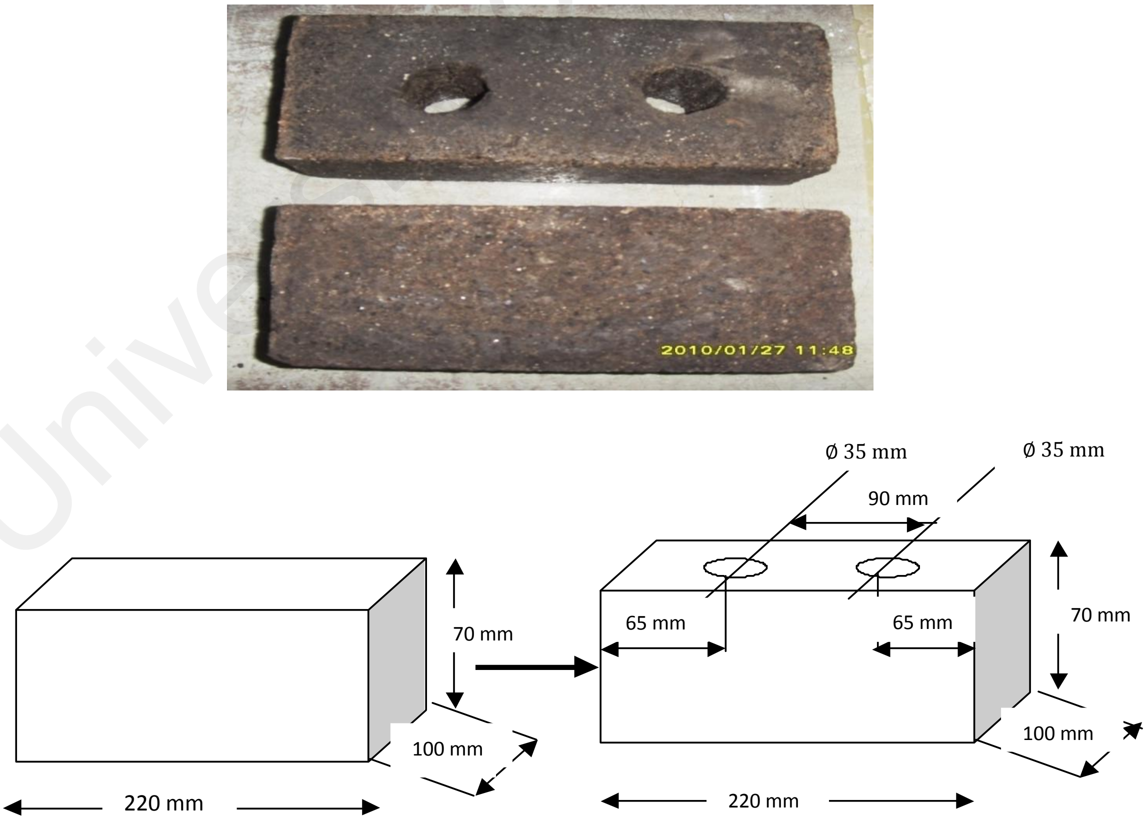



**Figure 3.4:** Solid and hollow bricks after curing periods

**Table 3.8** Summary of the actual input variables used in the design of the experimental samples.

| S/N | Input Variable | Units | Amount | Experimental Design | |
|---|---|---|---|---|---|
| | | | | Fixed | Varied |
| | Screened Peat Soil | % | 10,15,20, 40 | * | |
| A | Sand | % | 30 to 60 | | * |
| | Stabilisers | | | | |
| B | OPC | % | 20, 25, 30 | | * |
| | PFA | % | 20, 25, 30 | | * |
| C | Lime | % | 2, 4 | | * |
| D | Water | % | 24 | * | |
| | Compaction Pressure | | | | |
| | High | MPa | 10 | * | |
| | Medium | MPa | 6 | * | |
| E | Curing time | Days | 3, 7,14, 28 | * | |
| | Temperature | ℃ | 23 ± 2 | * | |

Peat soil varied from 10% to 40 %, the amount of 10%, 15%, 25% and 40 % was used only for a few samples to determine strength; 10% and 15% obtained high strength but was not economic. Were 25% and 40% of peat soil the results obtained for strength less than 1 Mpa. Literature review suggests that purpose brick was at a minimum of 2 Mpa. Therefore, for this study the fixed amount of peat soil was 20% by total weight of admixture for all samples.

### 3.4.2 Experimental Plan

The experimental testing of this study started with the moisture content, plasticity index, pH and linear shrinkage tests. The details of the tests are shown in Tables 3.10 to 3.18. The purpose was to determine moisture content of peat soils and sand after drying, the chemical addition (cement and lime) used at dry condition. When natural sun was used to dry peat soil during the one week in the laboratory, the average moisture for 10 samples was at 14%. However, the moisture content of sand after drying at 110 ℃ for 24 hours was 0.8%.

Dry peat soil sieved through a 2.00 mm, were dried under natural temperature of sun in the laboratory, the moisture content of peat soil after drying was 13% to 14 %. The purpose of saving the dry peat soil was to remove the coarse materials such as roots, stones and large fibres greater than 2 mm size. Peat soil was then mixed with chemical binder, sand and distilled water using the electric mixer for 5 to 10 minutes. The amount of water added to each admixture was 24% by the total weight of admixture which was obtained from the plasticity test. When added more than 24% of water to the mixture and pressure was used to compact the materials in the mould, the materials came out from the mould. Thus addition of water if less than 24% the strength become very low which means there is inadequate hydration of chemicals with soil and sand.

Table 3.12 shows several chemical and physical tests on raw materials and stabilised peats as detailed. Electronic method tests curved out in order to determine the alkalinity or acidity of materials. While the organic and ash contents of natural peat were determined in organic tests, X-Ray Fluorescence tests were done in order to determine the chemical elements of the materials used to modified peat soil as construction materials. Energy Dispersive X-Ray and scanning electron microscopy analyses were required in order to examine the development of chemical elements of natural peat and stabilised materials and investigate the microstructures of research materials.

Details of the compressive strength, density, water absorption and porosity of the bricks are summarised in Tables 3.10, 3.11, 3.12, 3.13, 3.14, 3.15 and 3.16 as well as the tests investigation of the effects of compaction pressure, binder content and curing periods. Sound insulation and fire resistance, details are shown in Tables 3.17 and 3.18. Similar to ASTM, BS and EN fabricate small scale of compressed stabilised peat brick walls in laboratory.

The three samples of sound transmission loss curves were calculated from the measurement of the control wall. The sound transmission loss curves showed high, medium and low frequency. The high frequency or superior sound proofing was construed as sounds limited from musical instrument, the medium sounds as loud or even any sounds speech audible such as a murmur and low sounds such as normal speech which can be understood quite easily.

Three sample dimensions of 80 cm x 80 cm x 12 cm and details of masonry wall mix design are presented in Table 3.9. The objective of this test was to determine the rating time of fire resistance for compressed stabilised peat brick masonry wall.

**Table 3.9**: Properties of stabilised peat brick and mortar at 28 days used for sound insulation and fire resistance tests

| Sample | Mix design | Wet Strength at 28 days for solid bricks and Mortar | Density | Water absorption |
|---|---|---|---|---|
| **Sample 1** | 30% OPC + 20% Peat soil + 50% Sand | 6.33MPa | 1869 $Kg/m^3$ | 2.6 % |
| **Sample 2** | 30% OPC + 4% Lime+ 20% Peat soil + 46% Sand | 7.66MPa | 1895 $Kg/m^3$ | 4.4 % |
| **Sample 3** | 25% OPC + 4% Lime + 20% Peat soil + 51 % Sand | 5.88 MPa | 1775 $Kg/m^3$ | 6.2 % |
| **Mortar** | 20% OPC +80% Sand | 32.0 MPa | 2264 $Kg/m^3$ | - |

**Table 3.10**: Moisture content and particle size tests

| Type of tests | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Moisture content | Balance weight and drying oven | 1 | 9 specimens of dry screened peat soils and sand.<br>18 specimen for stabilised peat | Recording to Table 3.7 | Binder composition for all mix design presented in Table 3.7 | None | The test aimed to determine the moisture content of row materials and stabilised peat material |
| Particle size | Particle size equipment | 2 | Dry peat through 2 mm and siliceous sand | None | None | None | The test aimed to determine the particle size of sand and peat |

**Table 3.11**: Plasticity index and linear shrinkage tests

| Type of tests | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Plastic limit test | Casagrande liquid limit apparatus & drying oven | 3 | 18 specimens | Recording to Table 3.7 series II and III (10 MPa ) | 20%, 25%, 30% PFA cement.<br>20%, 25%, 30% OPC<br><br>2 to 4 % Lime | None | The purpose of the Atherberg tests was to evaluate the trend of limits of stabilised peat at different binder quantities. |
| Liquid limit test | Casagrande liquid limit apparatus & drying oven | 4 | 18 specimens | Recording to Table 3.7 series II and III (10 MPa ) | 20%, 25%, 30% PFA cement.<br>20%, 25%, 30% OPC cement<br>2 to 4% lime | None | |
| Linear shrinkage test | Linear shrinkage apparatus and drying oven | 5 | 18 specimens | Recording to Table 3.7 series II and III (10 MPa ) | 20%, 25%, 30% PFA cement.<br>20%, 25%, 30% OPC cement | None | Linear shrinkage test gives the percentage of linear of a soil and estimate plasticity index of the soil. |

**Table 3.12**: Chemical and physical tests

| Type of tests | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Electronic method test | Electric pH Test | 6 | 18 specimens | Recording to Table 3.7 and Appendix A | 20%, 25%, 30% PFA cement.<br>20%, 25%, 30% OPC cement<br>2 to 4% lime | None | The purpose of the test was to evaluate the pH of untreated and stabilised peat. (appendix A) |
| Organic content test | Muffle furnace and porcelain cups | 7 | 10 specimens | None | None | None | The test objective was to identify the % of organic and ash contents of natural peat. |
| X-Ray Fluorescence test | Bruker S4-Explorer X-Ray Fluorescence (1 Kw) | 8 | 5 specimens (Nature peat, Lime ,Cement and Sand )<br>4 specimens for CSPB | None | None | None | The objective of the test was to determine the chemical contents of untreated peat, chemical binders, siliceous sand, and stabilised peat bricks samples |
| Energy Depressive X-Ray and Scanning Electron Micrographs Analysis | XL 40 Philips Scanning Electron Microscope | 9 | 12 specimens | None | Best binder compositions of laboratory mix design from Table 3.7 | None | The objective of the test was examine the microstructure of the untreated and stabilised peat |

**Table 3.13:** Wet compressive strength

| Type of tests | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Wet Compressive strength | Compression Test machine | 10 | 432 specimens of stabilised peat, 3 times for every mix design cured in water for 3,7,14 days and 14 days moist cured | Recording to Table 3.7 | 20%, 25%, 30% PFA cement.<br><br>20%, 25%, 30% OPC cement<br><br>2 to 4% lime | Relationship between strength and curing time<br><br>Relationship between wet compressive strength and cement content | The test aimed to establish wet compressive strength of stabilised peats of different mix designs |
| Compressive strength (mortar) | Compression Test machine | 11 | 9 specimens of mortar | Recording to Table 3.9 | OPC | Relationship between wet compressive strength and curing time | The test aimed to determine the compressive strength of mortar using in lying brick wall and plaster of stabilised peat wall |

**Table 3.14:** Dry compressive strength

| Type of test | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Dry compressive strength | Compression Test machine | 12 | 12 specimens for stabilised peat brck, 3 times for each best mix design | Recording to Table 3.7 | (30% OPC)<br><br>(30% OPC + 4% lime), | Relationship between wet compressive strength and dry compressive strength | The test aimed to establish dry compressive strength of stabilised peat brick of different mix designs at 28 days |
| Dry compressive strength | Compression Test machine | 13 | 9 specimens for hollow brick | Recording to Table 3.7 | 30% OPC | Relationship between wet compressive strength ,dry compressive strength of hollow brick with curing time | The test aimed to establish dry compressive strength of stabilised peat hollow bricks at 28 days |

**Table 3.15**: Bulk and dry density

| Type of test | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Dry and bulk density | Balance Weight and drying oven | 14 | 36 specimen for stabilised peat bricks | Recording to Table 3.7 | 20%, 25%, 30% ( PFA cement). 20%, 25%, 30% (OPC) 2% to 4% lime | Relationship between dry and fresh density for different mix design | The test aimed to determine the fresh density and dry density of stabilised peat brick |

**Table 3.16**: Total water absorption and porosity

| Type of test | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Water absorption test | Drying oven and water tank curing | 15 | 36 specimen for stabilised peat bricks | Recording to Table 3.7 | 20%, 25%, 30% PFA cement. 20%, 25%, 30% OPC 2 to 4% lime | Relationship between water absorption and curing time, strength | The test aimed to determine the water absorption of stabilised peat bricks |
| Porosity | Drying oven and curing water tank | 16 | 36 specimen for stabilised peat bricks | Recording to Table 3.7 | 20%, 25%, 30% PFA cement. 20%, 25%, 30% OPC 2 to 4% lime | Relationship between porosity and curing time<br><br>Relationship between porosity and strength ,density | The test aimed to determine the porosity of stabilised peat bricks |

**Table 3.17**: Sound insulation

| Type of test | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Sound insulation | Sound system | 17 | 3 specimens<br>Small scale of stabilised peat brick wall dimension 80 x 80 x 80 $cm^3$<br>The first specimen 30% PFA with 2 sides gypsum plaster<br>The second with one side gypsum plaster and another side mortar plaster<br>The third sample with two sides mortar plaster | 30% PFA +4% lime<br>25% OPC+ 4% lime<br>30% OPC +4% lime | PFA, OPC and lime | Relationship between reduction sound losses and frequency | The test aimed to determine the sound reduction index of stabilised peat wall and compare with reference curve of sound ASTM E 90 and ASTM 413 |

**Table 3.18**: Fire resistance of stabilized peat brick wall

| Type of test | Type of equipment | Set | No. of specimen | Binder content | Binder composition | Graphical relationship | Description |
|---|---|---|---|---|---|---|---|
| Fire resistance | Flames fire testing | 18 | 3 specimens<br>Small scale of stabilised peat brick dimension<br>80 x 80 x 80 $cm^3$<br><br>The first specimen with one side gypsum plaster and another side mortar plaster<br><br>The second specimen with two sides mortar plaster.<br><br>The third specimen with 2 sides gypsum plaster | 30% PFA<br><br>30% OPC +4% lime<br><br>25% OPC+4% lime | PFA, OPC and lime | Relationship between fire rating and time | The test aimed to determine the rating of fire resistance for stabilised peat bricks masonry wall And compared with ASTM E119 and ISO 834 |
| Compressive strength and deformation of load bearing stabilised peat masonry prism | Compression machine Testing | 19 | 1 specimen<br>Small scale of stabilised peat brick masonry prism<br>Dimension 400 x 220 x 100 cm | 30% OPC +4% lime | OPC and lime | Relationship between stress and strain, vertical displacement | The test aimed the maximum axial load, stress-strain curve and displacement |

### 3.5 Testing Procedures

A series of laboratory tests were carried out on stabilised peat to test brick for construction materials. Various content of binders were used in the stabilised peat such as PFA cement, OPC cement and lime. Laboratory tests were conducted to obtain physical and mechanical properties of cemented peat bricks, as moisture content, particle size analysis, Atterberg limit, organic content of peat soil, pH, specific gravity, wet and dry compressive strength, bulk and dry density, water absorption and porosity. Moreover, the sound insulation and fire resistance of stabilised peat brick masonry. Were also investigated chemical analysis using X-Ray Fluorescence spectrometer (XRF), Scanning Electron Microscopy (SEM), compressive strength, and deformation of load bearing on compressed stabilised peat masonry wall were also tested.

#### 3.5.1 Materials Properties

Soil identification tests were conducted in order to evaluate the basic properties of the soil and raw materials proposed for research. The classification of a soil is the first requirement needed to identify it. Knowledge of the soil type and properties can facilitate the optimisation of its use in brick production. According to literature sources, soil classification is performed on particles nominally less than 60 mm (Dunlap, 1975). Soil classification methods are based on either one or a combination of the following: particle size distribution, plasticity, compactability, cohesion, and organic matter content (Casagrande, 1947; Fitzmaurice, 1958; Head, 1980).

Unfortunately, soil classification systems are not yet uniformly applied internationally. At the moment, the two classification systems widely used are based on the particle size distribution and on the plasticity of a soil (Lunt, 1980). In order to relate soil behaviour to its physical properties, it is convenient to have standard procedures for testing and reporting of results (Schroder et al., 2004). The moisture content tests were conducted by oven drying method (BS 1377: 1975. Test 1(A)) for sand using oven 110℃ for 24 h and peat soil dried by natural sun, because peat cannot be dried at high temperature it will burn organic matter in peat. Also for the purpose of this study, low temperature was used to dry, but for the big amount of soil which takes time to dry inside a small oven was used. When using the natural sun for one week to reduce the high water the sample was then put in oven at 50℃ so that it will dry quickly. Atterberg limit tests were conducted following BS 1377: 1975, 2(A), 2(B), and 2(C). Determining specific gravity of the soil was made using density bottle method following BS 1377: 1975, 6(B). Organic and ash contents of the peat were determined from the loss of ignition test whereby the oven dried mass of soil was further heated in a muffle furnace to a temperature of 400℃ (BS 1377: 1975, Test 8). According to ASTM D (1997-91), the fibre content of peat was determined from dry weight of fibres retained at sieve No. 100 (> 0.15 mm opening size) as a percentage of oven dried mass. Electrometric method using digital pH meter was employed in this study to measure the pH of raw materials and stabilised peat soil. The pH values of the sample were measured using a calibrated pH probe. Tests for the raw materials and stabilised peat pH were done in accordance with BS 1377: 1985 Test 1(A).

#### 3.5.1.1 Linear Shrinkage

The linear shrinkage test was determined according to BS 1377: (Part 2: 1990). The method covered the determination of the linear shrinkage of the fraction of natural peat and modified peat soil, the sample was passed through a 425 μm test sieve form linear measurement. The mixture was prepared at a value of liquid limit and levelled into the mould. Hydration of the chemicals took some time as the sample was naturally dried for 8 hours and then transferred to a dried oven at 105 ℃ for 24 hours.

**Figure 3.5:** Apparatus of linear shrinkage

### 3.6 X-Ray Fluorescence, X-Ray and Scanning Electron Micrograph Analyses

X-Ray Fluorescence tests were done on raw materials of the modified peat using equipment known as Bruker S4-Explorer X-Ray Fluorescence (1 KW). The raw materials tests using the equipment were the Portland Pulverised Fuel Ash Cement, Ordinary Portland Cement, Lime, siliceous sand and dried peat; details of equipment are shown in Figure 3.6. Using pressed pellet method of specimen preparation, each specimen of 400 mm diameter was tested using the equipment and the data obtained was interpreted using semi-quantitative analyses.

Chemical element and microstructures of dried peat and modified peat specimens were examined using XL40 PHILIPS scanning electron microscope. The Energy Dispersive X-Ray analyses provided evidence on the existence of calcium, silicon and Oxide, which were the major elements of the modified peats materials. The scanning electron micrographs gave visual evidence of the modified peat products, which were the chemical compounds that formed a system of interlocking crystals that bond the organic and soil particles together in the peat process of modified peat as brick products. The XL 40 PHILIPPS scanning electron microscope and Bruker S4-Explorer X-Ray Fluorescence (1 KW) are shown in Figure 3.6.

**Figure 3.6:** XRF and SEM Apparatus

### 3.7 Wet and Dry Compressive Strength

The compressive strength of the brick is perhaps one of its most important engineering properties. It was established from the literature that the durability of block increases with increase in its strength (Stulz & Mukerji, 1988; Houben & Guillaud, 1994). The nominal dimension 70 x 70 x 70 $mm^3$ for major samples, and 220 x 100 x 70 $mm^3$ for several samples used for sound and fire resistances specimens tests bricks and dry strength, the details of compressive strength are presented in Tables 3.13 and 3.14. Failure of specimen in the test normally indicated by machine by decreasing the load and is shown on the screen of the machine.

For each mix design, three specimen samples were made and the average results were taken. For this test, a compression machine was used as shown in Figure 3.7.

**Figure 3.7:** Wet and dry compressive strength apparatus

**3.8 Bulk and Dry Density of Brick**

The density of a brick is a value of its quality. It can be expressed in a number of different ways. The first way brick dry density was tested through the oven-dried value when desiccated to 105 ± 5℃ for 24 hours.

The dry density is commonly used in building specification (BS 6073: Part 2, 1981). When both air and water are driven out by oven drying to constant mass, the brick dry density values are obtained. The density also depends on the degree of compaction, constituent of materials, the size and grading of materials and the form of brick. Densification following the stabilisation of soil with cement can ensure that the close packing achieved is maintained through the mechanical interlock of the grains. It is this interlock which limits excessive movements more than it would have been possible if the stabiliser had not been used. The density of a block can have implication on most of its other bulk properties (Markus, 1979).

Determination of the density value of a brick or block is provided for in most standards. The method used is as described in BS 3921, 1985 and BS 6073: Part 2, 1981.

### 3.9 Total Volume Porosity

Porosity is an important characteristic of brick. In contrast to other moulded or pre-cast building materials, the porosity of brick is attributed to its fine capillaries. By virtue of the capillary effect, the rate of moisture transport in the brick is ten times faster than in other building materials. Moisture is released during day-time and re-absorbed during night-time. The ability to release and re-absorb moisture by capillary effect is one of the most useful properties of brick that helps to regulate the temperature and humidity of atmosphere in a building. This distinctive property makes brick an admirable building material, particularly suitable for building in the tropics. On the other hand, all porous materials are susceptible to chemical attacks and liable to contamination from weathering agents like rain, running water and polluted air. Porosity of building material is an important factor to consider with respect to its performance and applications. In this study, further details on compressed stabilised peat brick are presented in Table 3.14. The samples in this study were immersed inside a water tank for 24 hours and then dried at 105℃ for 24 hours.  The total porosity in brick was then determined directly. This can be done by measuring the weight gain on saturation with water of the initially dried brick after evacuation to remove air from the pore network (Jackson & Dhir, 1996).

## 3.10 Sound Insulation of Compressed Stabilised Peat Wall Masonry

### 3.10.1 Preparation of Compressed Stabilised Peat Brick Walls

The compressed stabilised peat brick was fabricated in steel moulds with internal dimension of 220 x 100 x 70 $mm^3$ in the laboratory as shown in Figure 3.4. An electric hydraulic machine was connected with a load cell and data-logger to control the pressure which was used to cast bricks. After 3 to 5 minutes under 10 MPa pressures, the sample removed from the moulds were covered with plastic bags for 1 day. When the specimens had attained sufficient strength for handling; these specimens were transferred to the water filled tanks at 23 ± 2℃ for 14 days and then transferred to a moist cured room for 14 days. After curing, the samples of bricks were ready for use. The best three mix designs were chosen as shown in Table 3.9, sound transmission loss was measured in a laboratory (according to ASTM E 90). The specimens were constructed in the opening between two small reverberation rooms; the size of each specimen was 80 cm x 80 cm x 12 cm, the plaster of first specimen was made from gypsum plaster used on both sides as presented in Figure 3.10.

The second specimen was plastered used cement mortar on both sides and as for the third specimen, plastered with gypsum on one side and cement mortar on the other side. The thickness of the each plaster was 10 mm, while the thickness of mortar used between the bricks was between 8 mm to 10 mm. The characteristics of mortar are presented in Table 3.9. Curing and plastered specimen of stabilised peat bricks wall are as shown in Figures 3.8 and 3.10.

**Figure 3.8**: Compressed stabilised peat brick

**Figure 3.9**: Curing of compressed stabilised peat brick wall

**Figure 3.10**: Compressed stabilised peat brick with gypsum plaster

### 3.10.2 Measurement of the Sound insulation

#### 3.10.2.1 Preparation of the Rooms

The experimental work entailed studying the sound insulation through stabilised peat brick wall. The dimension of these compartments was defined so that they were similar to small rooms inside a laboratory (1.2 x 0.9 x 1 $m^3$) as shown in Figure 3.11. The materials for source and receiving room were made using two layers of plywood; each layer was of 10 mm thickness, where the cavity between the plywood layers was filled with 75 mm thick polystyrene insulated materials. The total wall and floor thickness of each room was 100 mm. In the opening side of the rooms, 25 mm thickness of insulate rubber was used.

Then, the sound transmission loss of each common wall was measured. The sound loss of the designed control wall was measured 5 times. The sound transmission loss of the wall was measured in accordance with ASTM E 90, and the results were then compared with the reference curve found in ASTM E 90 and ASTM E 413. The sound pressure level was measured in the source room using a third octave band real-time analyser using PAA3 software analysis of results, with a microphone placed at different positions. The sound pressure level was also measured in the receiving room with a microphone placed at different positions. From the measured data, the field sound transmission loss of each wall was calculated with third octave bands from 50 Hz to 4000 Hz using the equation:

$$R = L_s - L_r + 10\log_{10}\left(\frac{S}{A}\right). \qquad \text{Eq } 3.1$$

Where $L_s$ is the sound pressure level in the source room (dB), $L_r$ is the sound pressure level in the receiving room (dB), S is surface area of the common wall ($m^2$) and A is total absorption of the receiving room surface area ($m^2$).

The whole system of sound transmission through the cemented peat brick is shown diagrammatically in Figure 3.12. Measurement took into account three essential aspects: application of high, medium and low frequency in source room and readings of the sound transmitted in receiving room.


**Figure 3.11:** Small scale of transmission sound measurement

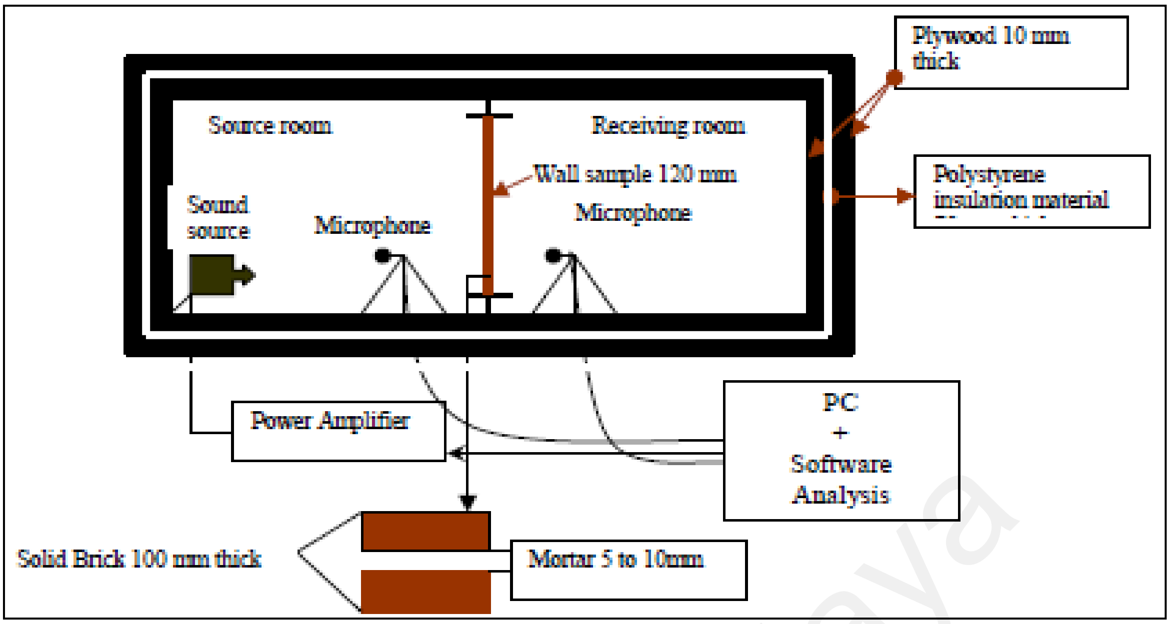



**Figure 3.12:** Setup for a transmission sound measurement

### 3.11 Fire Resistance Rating of Non-Load Bearing CSPB Wall

There has been a large amount of researchs into the open-air burning of flammable liquids and solids objects. The rate of heat released from a pool or solid item burning in the open depends on the rate at which heat from the flames can evaporate or paralyse the remaining fuel, and the rate at which oxygen can mix with the unburned fuel vapour to form diffusion flames.

In this study, fire resistance testing facilities include -scale flames. As for the expertise and accreditations to test a variety of applicable industry standards including ASTM E-119 and UL. The temperature distribution tests were conducted in the fire-testing laboratory. The total of three compressed stabilised peat brick walls have been conducted to investigate the temperature distributions in different mix design and plastered walls and cracking of materials wall burning under high temperature. The dimension of each wall was 80 cm x 80 cm x 12 cm, two flames installed in the middle of the wall specimens using cocking bottle gas for flames as shown in Figure 3.13. Two

Digital thermometers were used in this test one in the front and the second one behind the wall, installed on a steel frame vertically and horizontally on the specimen shown in Figure 3.13. A watch timer was used to observe time of starting of the deformation and cracking of specimen. The flames, heat temperatures were at the centre of wall was more than 1200℃. The characteristics of three cemented peat brick are presented in Table 3.9.

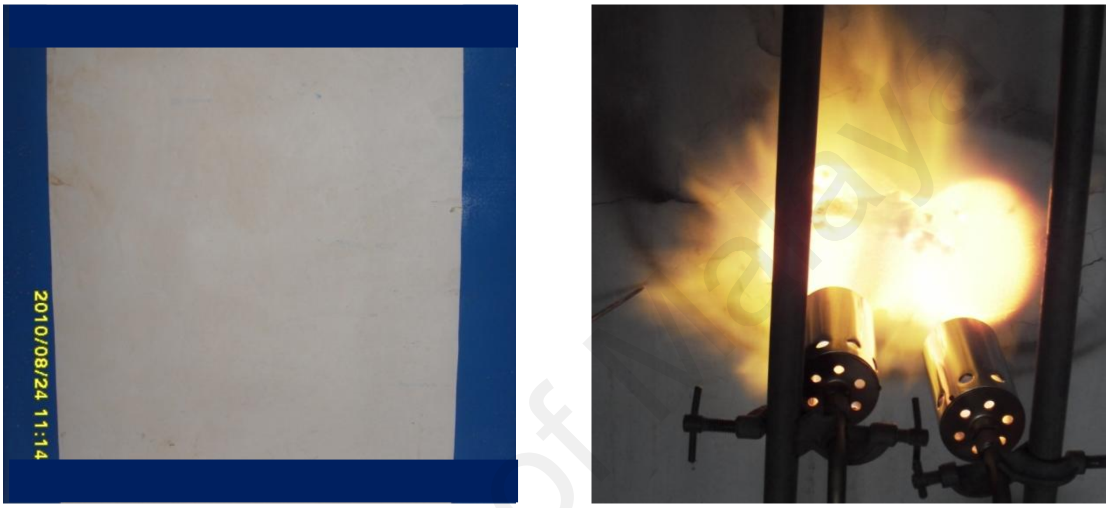



**Figure 3.13**: Flames for burning of CSPB masonry wall

## 3.12 Compressed Stabilised Peat Brick Masonry under Axial Compression

Science masonry is an assemblage of bricks and mortar, it is generally believed that the strength and stiffness of masonry would lie somewhere between bricks and mortar (Hemant et al., 2007).

Masonry is a composite material with brick as the building units and mortar as joining material, which are bonded together at an interface. The basic mechanical properties of the masonry are strongly influenced by mechanical properties of its constituents, namely, brick and mortar. Utilising the material parameters obtained from experiments and using actual geometric details of both components and joints, it is possible to reproduce the behaviour numerically (Lotfi and Shing, 1994). The masonry prism consists of 40 cm high, 22 cm width and 10 cm thickness. 12 mm thickness of mortar, stabilised peat brick masonry age is 28 days. The testing setup is represented in Figures 3.14 and 3.15. The deformation of the prism was measured using a transducer which was connected to a data-logger.


**Figure 3.14**: Stabilised peat masonry prism under axial loading

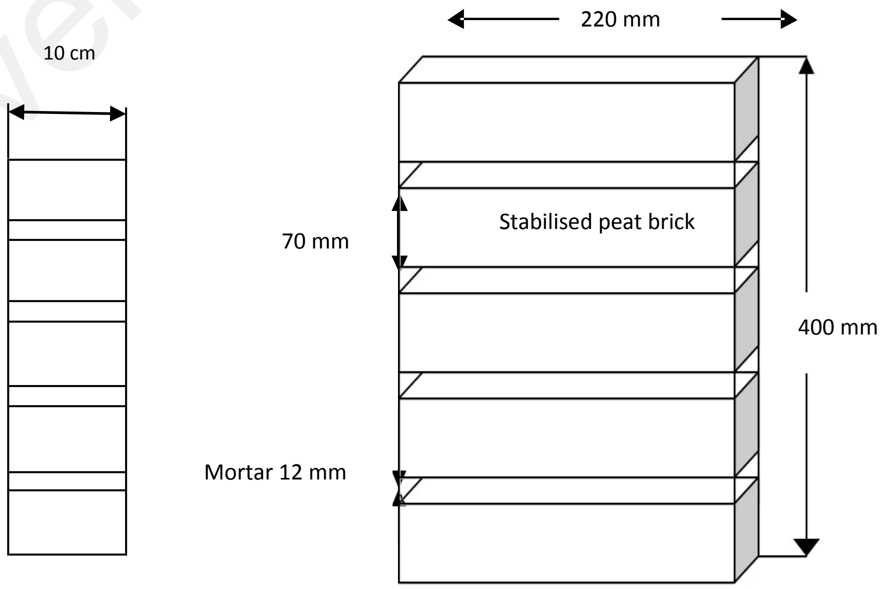



**Figure 3.15**: Compressed Stabilised Peat Masonry Prism

### 3.13 Numerical Analysis

SAP2000 software is one of the most popular finite elements for civil engineering structures. This software is used for two and three dimensional elements. It is a finite element package used mainly by civil engineers. It can analyse general structures, such as bridges, buildings, dams, solids etc. In this study SAP2000 was used to analyse compressive stress-strain of compressed stabilised peat masonry prism, internal forces, and vertical displacement and then results were compared using the experimental method. comparing the vertical displacement of compressed stabilised peat brick masonry prism and clay brick masonry prism.

### 3.14 Summary

Experimental design, tests procedures, brick specimen production, and the total number of specimens provided. The experimental design was based on identifying the main composition and processing variables involved in the production of CSPB: Peat soil, stabiliser type and content, siliceous sand, mix-water content, compaction pressure, and curing conditions. Stabiliser type and content were varied: OPC or PFAcement content was varied from 20% to 30%. Lime content was varied from 2% to 4%. Peat soil fixed at 20%. And mixed water was fixed at 24% by total weight of admixture, siliceous sand ranged between 46% and 60%. Compaction pressure was fixed at 6 MPa for half of mix designs. Other mixes were produced using a compaction pressure of 10 MPa. Curing time all the specimens was 14 days immersed in water and 14 days in moist cured conditions. Small scale for sound insulation and fire resistance were tests similar to ASTM and ISO standards.

# CHAPTER 4

# ENGINEERING PROPERTIES OF COMPRESSED STABILISED PEAT BRICKS

## 4.1 General

In this study, peat soil was investigated in tandem with the production of lightweight bricks. Peat soil, siliceous sand, cement and hydrated lime mixtures were steam autoclaved under different test conditions to produce brick samples.

A new design and methodology of improved peat soil was introduced from modifying the original peat soils with the introduction of additives and loading values in this study. Masonry is one of the most popular materials in many countries for construction of houses due to useful properties such as durability, relatively low cost, wider availability, good sound insulation, heat insulation, and acceptable fire resistance. The conventional types can be identified as burnt clay bricks or cement sand blocks (Jayasinghe and Mallawaarachchi, 2009).

The alternative type's comparable performance and appearance can be identified as compressed stabilised peat consisting of solid and hollow bricks. Hence, there is a necessity of ensuring adequate performance in strength, water absorption, porosity, density, stress-strain characteristic of compressed stabilised peat masonry prism.

A laboratory test was conducted for determination of modifying properties of stabilised peat as solid and hollow bricks. The additives used in this research were Ordinary Portland Cement, Portland Pulverised Fuel Ash Cement, hydrated lime, and also siliceous sand. The addition of solid matrix in the peat produced a good bounding between binders and sand during hydration process. The addition of siliceous sand to the stabilised peat improved the properties of peat by increasing the density and strength. The objectives of this chapter are to identify the main properties of compressed stabilised peat bricks, stress-strain of CSPB masonry prism.

CSPB properties can be influenced by the properties of the main constituents that form brick and by processing methods used to produce the compaction pressure, stabiliser curing, etc. Different input variables are presented in Table 8 (Chapter 3). The durability properties are identified as following:

- Wet and dry compressive strength
- Brick bulk and dry density
- Total water absorption
- Total volume Porosity

The results obtained from the tests are analysed with a view identifying general trends as well as comparing the performance of conventional brick and compressed stabilised peat bricks. The results are used to validate or query theoretical assumptions made in the Chapter 2 of the thesis.



## 4.2 Mineralogical Composition of Stabilised Peat Materials Determined From X-Ray Fluorescence Tests

There is no previous research for stabilised peat as construction material. When the chemical binders and siliceous sand were added to dry peat, different chemical reactions took place that enable the stabilised peat to become hard and achieve high strength and durability. There are many analytical techniques to identify the chemical reactions, such as X-Ray Diffraction (XRD), X-Ray Fluorescence Spectrometer (XRF), Scanning Electron Microscopy (SEM), etc.

Peat is representative of high content of organic matter of soils, including acidic materials, and the organic matter in peat comprise of humic substances which is usually referred to as humus. In the tropical regions, the organic matter is predominantly developed from lignin group. Normally, humic substances formed as polyhydroxipholic with the hydroxil group is bonded to fenol group. The other substance is the carboxil group. The hydroxil and carboxil groups absorb more water through hydrogen bonding (Alwi, 2008). The organic soils can retard or prevent the proper hydration of binders such as cement in soil mixture. Previous investigation of untreated peat and stabilised peat done by Clare and Shrwood (1954); Meclean and Sharwood (1962), show that there will be retardation to the cement hydration with hardening of the organic matter of the calcium ions which are librated during the hydrolysis of the cement grain.

In this study an X-Ray Fluorescence spectrometer (XRF) was utilised to analyse the raw materials presented in Tables 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6. The chemical composition of stabilised peat brick materials is evident in Table 4.1.

**Table 4.1:** Chemical analysis of Stabilised Peat brick at 28 days (using XRF)

| Element | Concentration (%) | | | |
|---|---|---|---|---|
| | CSPB8 | CSPB9 | CSPB23 | CSPB24 |
| MgO | 0.890 | 0.800 | 1.200 | 1.200 |
| $AL_2O_3$ | 7.040 | 8.030 | 5.550 | 6.770 |
| $SiO_2$ | 24.60 | 29.40 | 22.80 | 23.40 |
| $P_2O_5$ | 0.680 | 0.700 | 0.680 | 0.690 |
| $SO_3$ | 2.630 | 2.470 | 2.660 | 2.590 |
| Cl | 0.070 | 0.060 | 0.080 | 0.070 |
| $K_2O$ | 1.090 | 1.110 | 0.710 | 0.960 |
| CaO | 57.50 | 51.78 | 61.92 | 58.67 |
| $T_iO_2$ | 0.560 | 0.540 | 0.380 | 0.490 |
| $M_nO$ | 0.120 | 0.130 | 3.710 | 0.130 |
| $F_{e2}O_3$ | 4.530 | 4.710 | 0.080 | 4.780 |
| CuO | 0.040 | 0.040 | 0.020 | 0.010 |
| $Z_nO$ | 0.110 | 0.080 | 0.030 | 0.090 |
| **Total weight (%)** | **99.87** | **99.83** | **99.90** | **99.96** |

It is clear from the literature review that in general, reactivity of the materials to water is dependent on the lime to silica ratio (CaO, $SiO_2$). The higher ratio, the more hydraulically reactive is the material. It is evident from Table 3.3 that the Ordinary Portland Cement consists of 66.23% CaO and 21.60% $SiO_2$and Portland Pulverized Fuel Ash Cement is composed of 64.24% CaO and 18.60% $SiO_2$. Therefore, both cement types have $AL_2O_3$ 6.38% and 6.24% respectively, and can be classified as hydraulic materials. The hydraulic materials as well as cement reaction with water would develop rapid initial strength gain.

It is also can be seen from Table 3.5 that siliceous sand has major oxide compounds of 70.04% $SiO_2$, 19.20% of $AL_2O_3$ and 2.15% of CaO. Table 3.4 showed that lime composite consists 94.19% CaO and 4.42% MgO. This shows that lime can be classified as a hydraulic material.

Although the major silica (70.04% $SiO_2$) and alumina (19.20% $AL_2O_3$) from 89.24% of the total oxide compound of siliceous sand, the sand cannot be considered as a pozzolanic because of its chemical inertness and the sand particles are too large to enter into secondary pozzolanic reaction. Rather, siliceous sand functions as fillers for the void spaces in the stabilised soil providing sufficient solid particles in the stabilised soil to enable cementation bonds to form and unite. It is shown in Table 3.2 that peat consists of mainly 94.30% $CO_2$, 2.76% $SiO_2$ and 0.850% $AL_2O_3$. While carbon dioxide forms the majority of the peat compound, the low amount of silica and alumina in the soil simply shows that very low amount of clay particles are available in peat soils.

## 4.3 Compressive Strength on CSPB

The compressive strength of a brick is perhaps one of the most important engineering properties. In the basis of the value of the strength of a brick it's mechanical and other valuable qualities are judged (Rigassi, 1995; Young 1998).

Higher compression reduces the amount of voids and increases inter-particle contact within a brick. Higher density always has been associated with higher strength (Spence, 1975; Gooding, 1994).

As sand particles from the bulk of a brick and block, by preserving their own integrity through their own internal bonds, the cement hydrates that intertwine sand particles in a block are known to be porous aggregation of interlocking fibres (Herzong & Michell, 1963). The bonds within OPC hydrate fibres are however, chemical in nature of ionic and covalent types (Taylor, 1998). Such bonds are stronger than the physical ones. These bonds are strong enough to resist any unlimited thixortropic expansion that might normally occur, the bond between clay particles in a soil and the OPC hydrates is thought to be of the chemical type (Herzog & Metchell, 1963; Ingles & Metcalfe, 1972).

Highlight of the test method and factors considered during compressive strength evaluation of compressed stabilised peat brick specimen were discussed. Brick specimen was produced as discussed in Chapter 3 (Section 3.4.1). The compressive strength of a brick is the failure stress measured normal to its face. Two sizes of brick were tested for compressive strength (70 mm x 70 mm x 70 mm and 220 mm x 100 mm x 70 mm), for all specimens tested, standard methods of test were used throughout (BS 3921: 1985).

### 4.3.1 Effects of Varying the Stabiliser Content and Moulding Pressure on the Wet Compressive Strength of CSPB

#### 4.3.1.1 Effect of Varying Peat Soil on Wet Compressive Strength

In this study, the content of peat soil was chosen on the admixture according to the effect of peat on strength. The low content of peat soil achieved high strength but it was found to be not economic as a new material, more than 25% of peat on admixture obtained very low strength which was not sufficient for the purpose of this study. Finally 20% of peat soil was chosen on the admixture of compressed stabilised peat brick. Figure 4.1 shows the relationship between peat content and wet compressive strength at 28 days.

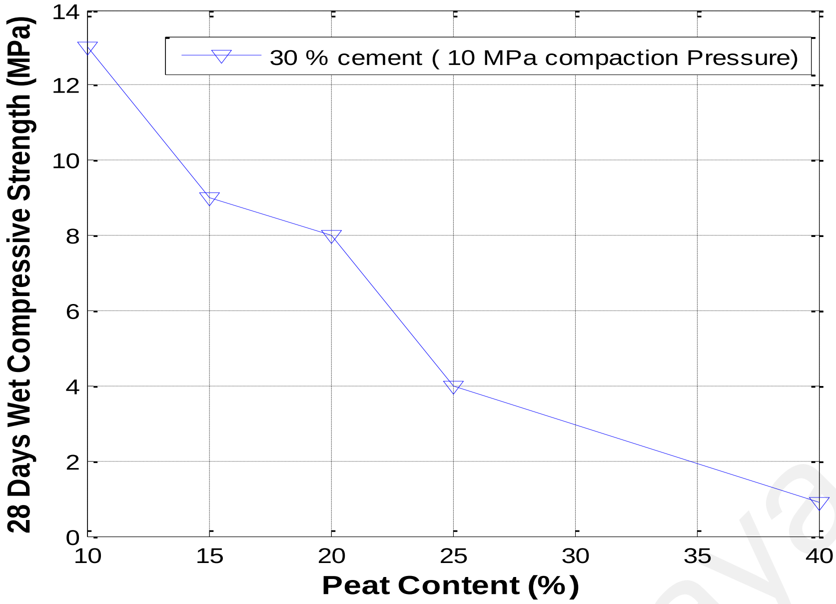


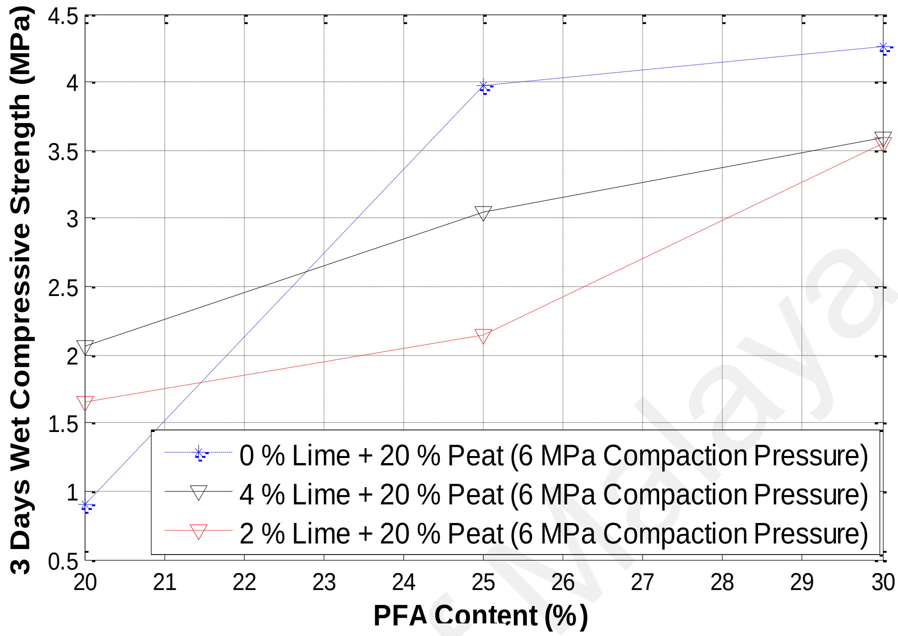

**Figure 4.1:** Effect of peat soil variation content on the wet compressive strength of CSPB

**Note**: All the samples the addition of sand content to the mixture by volume weight from 100% (eg. 20% Peat + 30% cement + 4% lime, means content of sand 46%)

The values of the 28 days of wet compressive strength of variation of peat soil, for 10%, 15%, 25% and 40% of peat soil, stabiliser was fixed at 30% of OPC or PFA cement, for 20% mix design are presented in Table 3.7 (Chapter 3). Figure 4.1 shows that the wet compressive strength achieved 13 MPa for 10% peat and 0.9 MPa for 40%, from the previous research of stabilised ground of peat soil achieved the maximum wet compressive strength 0.7 MPa to 0.9 MPa. Finally for this study, 20% content of peat for all types of mix design was chosen because from the above discussion the content of peat soils less than 20% was not economic for the purpose this study and not sufficient results for more than 20% of peat soil in the mixture.

#### 4.3.1.2 Effects of PFA Cement Content and Lime on CSPB (6 MPa Compaction Pressure).

Figures 4.2 (a), (b), (c), and (d) indicate that the effect of varying PFA cement and lime content with different curing period on wet compressive strength under 6 MPa compaction pressure, 20%, 25% and 30% content of PFA cement were added to the peat soil and siliceous sand.

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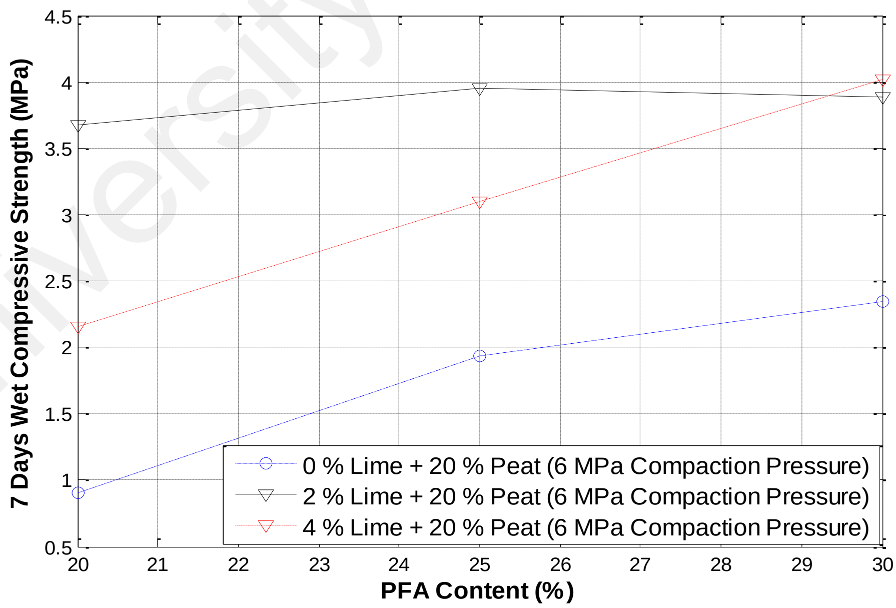


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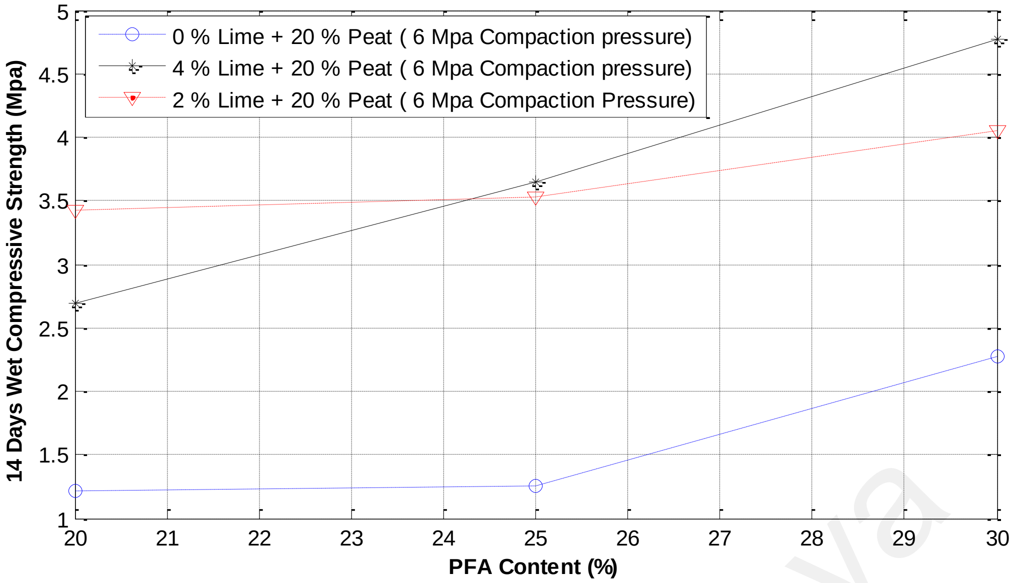


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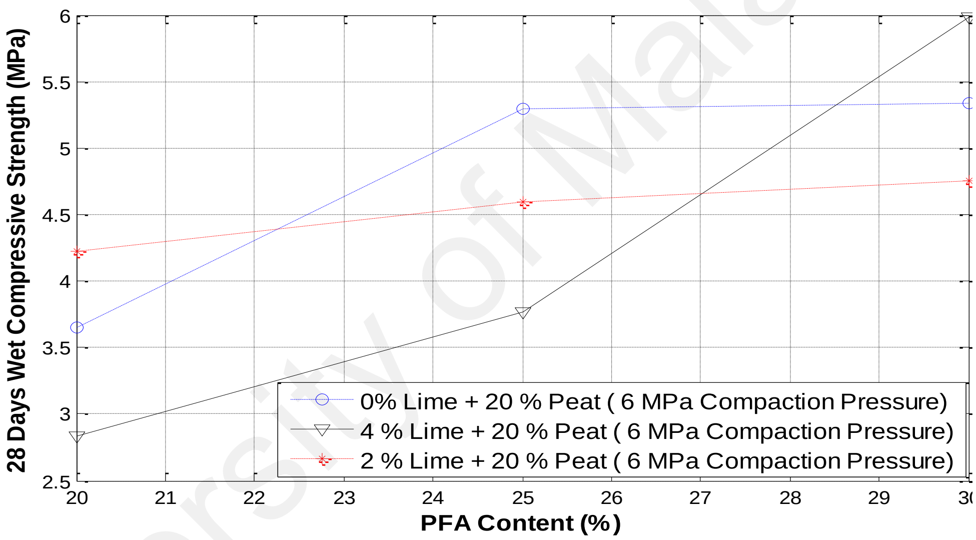



(d)

**Figure 4.2:** Effects of varying PFA and Lime content on the wet compressive strength of CSPB (a) at 3 days, (b) at 7 days, (c) at 14 days, and (d) at 28 days.

Figure 4.2 plotted the average of three specimens under 6 MPa moulding pressure of the wet compressive strength of CSPB incorporating 30%, 25% and 20% PFA cement and 4% lime was 3.75 Mpa, 3.2 MPa and 2.73 Mpa at 3 days respectively, and 5.34 MPa, 4.29 MPa, and 3.65 MPa at 28 days. The addition of lime to stasbilised peat obtained showed that the wet compressive strength of CSPB increased. Increase of wet compressive strength was about 78.87%, 42.6%, and 53.52% with 0%, 4%, and 2% lime respectively at 3 days, 31.15%, 52.67%, and 11.58% with 0%, 4% and 2% lime at

28 days. When the cement content, curing period increased, the strength significantly increased as well. Compressed products gained strength when the curing period was increased because of the pozzolanic reaction in the binder which consolidates the materials progressively. When the proportion of lime in the binder was increased, compressive strength of finished product also increased. To activate the pozzolanic reaction, water was required. In this study, content of water was estimated at 24% by weight of admixture. The results, obtained for 6 MPa compaction pressures where the strength was higher than 2.3 MPa, which is minimum strength, indicated by the standards (Inorpi, 2004; Anfor, 2003); and also according to Australian standard (AS 1225, 1984). Compressive strength of brick was between 3.6 to 6 MPa under 6 MPa compaction pressure. However, the effect of hydrated lime was not effective at 3 and 7 days for wet compressive strength, but at 28 days, as normally lime requires longer time to attain high strength.

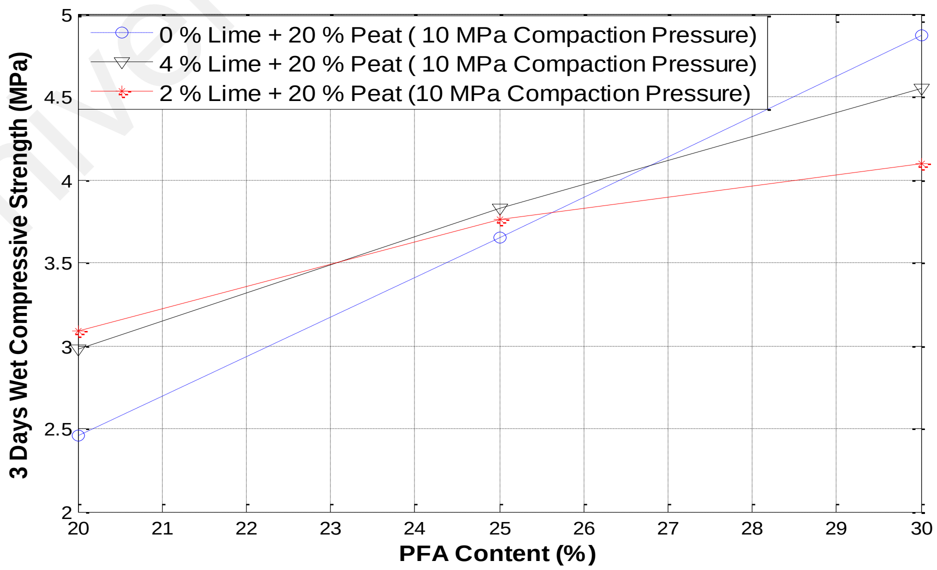
#### 4.3.1.3 Effects of PFA Cement Content and Lime on CSPB (10 MPa Compaction Pressure)

Plotted results in Figure 4.3 show the variation of PFA cement and lime content under 10 MPa, compaction pressure on the wet compressive strength of compressed stabilised peat bricks with different curing period.

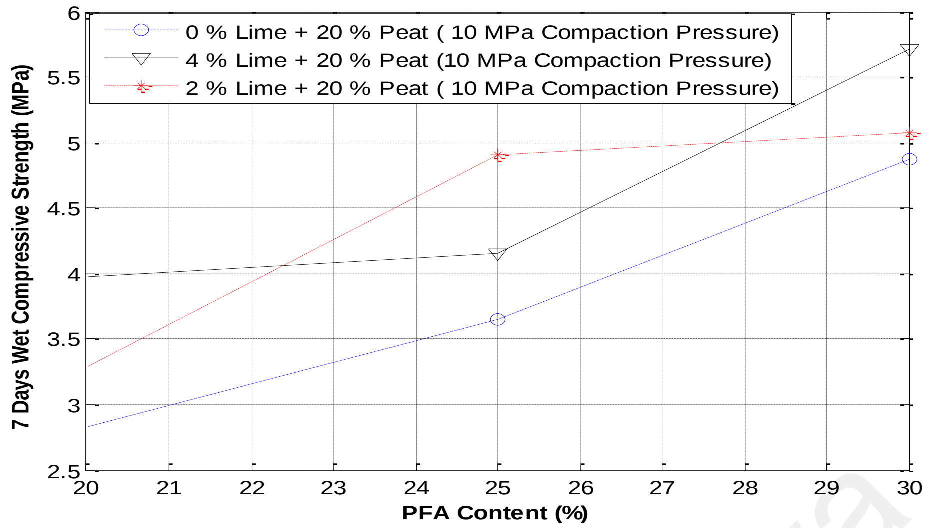
The test conducted to obtain, the values of the average 3, 7, 14 and 28 days wet compressive strength for compressed stabilised peat brick, in this case the stabiliser was PFA cement varied from 20% to 30% and variation of lime ranged between 0% and 4% under 10 MPa compaction pressure as indicated in Figure 4.3. The results obtained showed that the wet compressive strength increased with increased PFA and lime content, however with curing periods, at 3 days the wet compressive strength was 4.87 MPa, 3.65 MPa, and 2.46 MPa with 30%, 25% and 20% PFA content respectively at 7, 14 and 28 days ranged between 4.97 MPa to 7.66 MPa with 30 % PFA, and 2.83 MPa to 3.6 MPa with 20% PFA. The results also revealed from Figures 4.3(a) and 4.3(b), the effect of lime on stabilised peat brick, in fact lime had no effect for short time curing; at 3 days the results showed the value of wet compressive strength for admixture without lime higher than the admixture with lime, but for 28 days the results showed that the wet compressive strength increased with content of addition lime to the admixture of compressed stabilised peat brick.

Tayfun and Mehmet (2006) reported that the production of the construction materials like sand/lime or silica/lime bricks is based on mainly CaO- $SiO_2$-$H_2O$ (C-S-H) formation. Investigation obtained that the compressive strength of lime fly ash brick with 12% content of lime gave the highest compressive strength which was 4.75 MPa.

The phenomenon of reaction of lime with other particles of soil was studied in the most minute details by Brand (1962). He pointed out that certain reactions will take place between calcium hydroxide and elementary soil particles.




(a)

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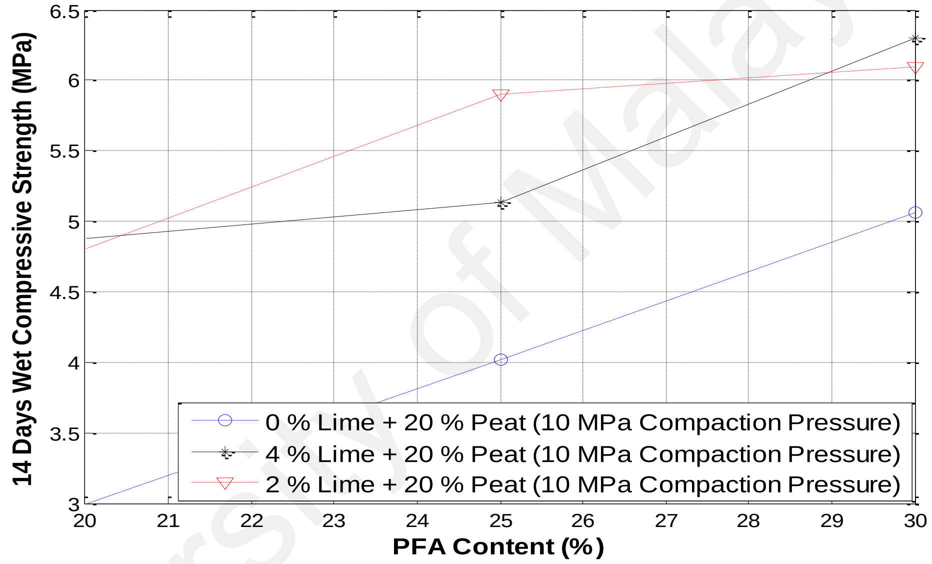


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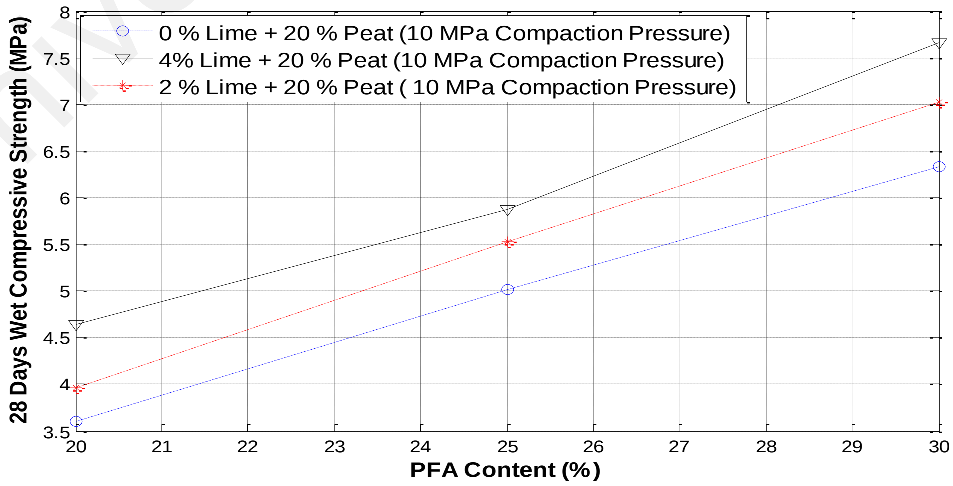
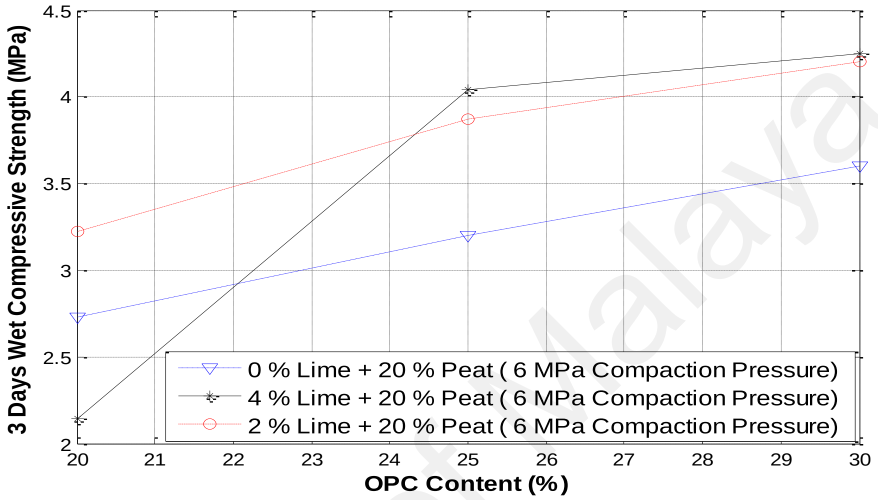



(d)

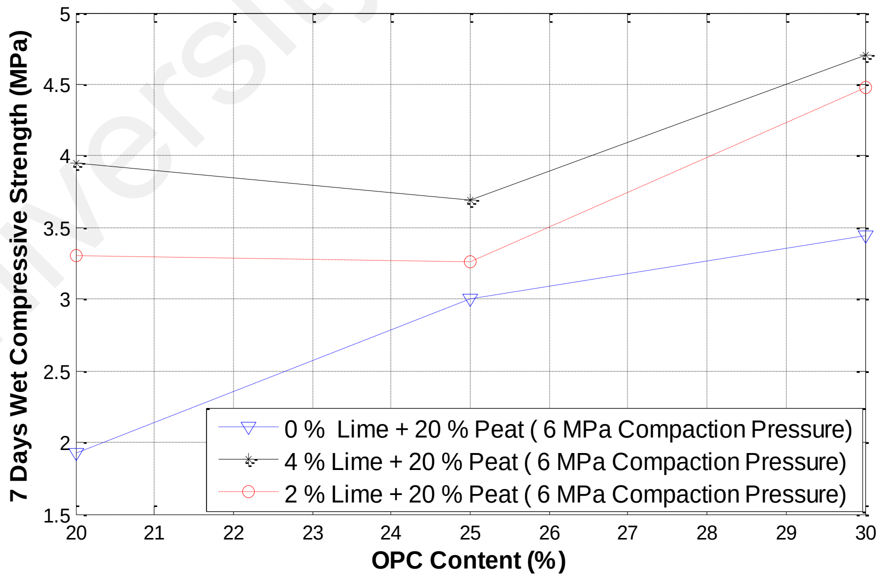
**Figure 4.3:** Effects of varying PFA and Lime content on the wet compressive strength of CSPB. (a) at 3 days, (b) at 7 days, (c) at 14 days, and (d) at 28 days

#### 4.3.1.4 Effects of OPC Content and Lime on CSPB (6 MPa Compaction Pressure)

Variation of Ordinary Portland Cement and hydrated lime under 6 MPa moulding pressure on wet compressive strength of cemented peat bricks are presented in Figure 4.4.




(a)

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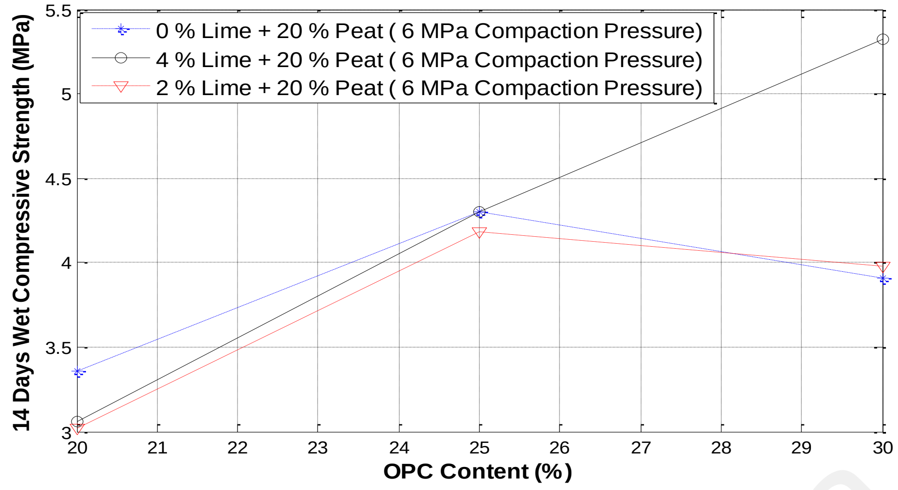


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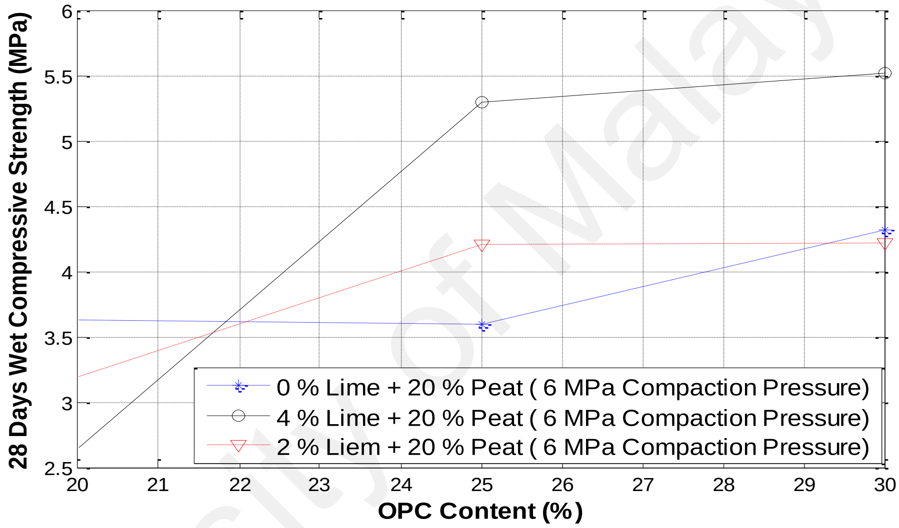



(d)

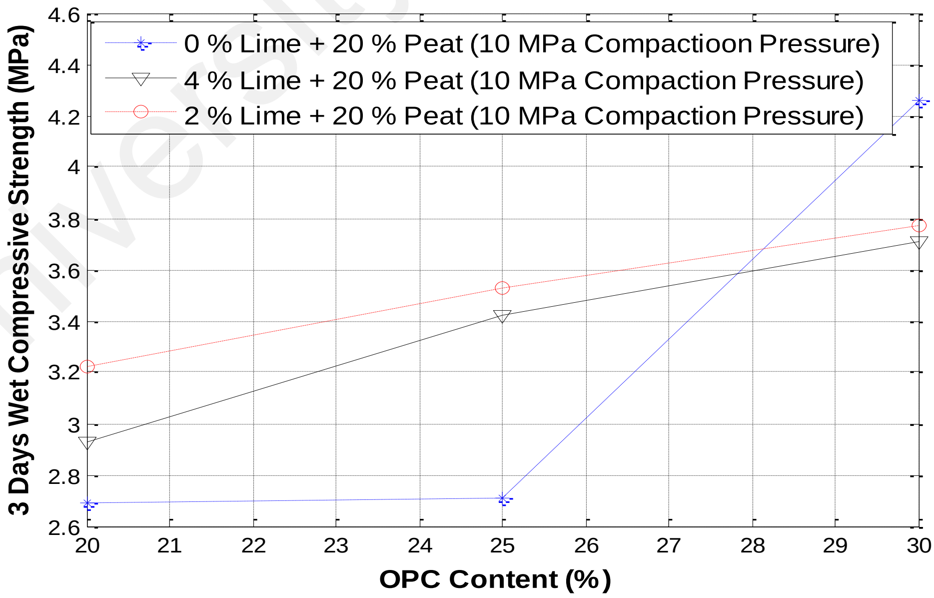
**Figure 4.4:** Effects of varying OPC and lime content on the wet compressive strength of CSPB. (a) at 3 days, (b) at 7 days, (c) at 14 days, and (d) at 28 days.

Results plotted in Figures 4.4 obtained that the wet compressive strength of compressed stabilised peat bricks with OPC as stabiliser under 6 MPa moulding pressure achieved 4.32 MPa without lime and 5.62 MPa with lime at 28 days . It was also observe that the wet compressive strength with PFA cement was higher than compressive strength with OPC.

Increase in wet compressive strength was about 34.17%, 49.6%, and 23.22% with 0%, 4% and 2% lime respectively, at 28 days the wet compressive strength increased about 14%, 42.5%, and 24.13% with 0%, 4% and 2% lime respectively. According to literature sources (Chapter 2 Section 2.8.1), wet compressive strength values are quite wide-ranging, varying from country to country, and from author to author. The experimental values obtained here however, compared well with most current standard. Some recommended minimum values are: 1.2 MPa (Lunt, 1980), 1.4 MPa (Fitzmaurice, 1958) and 2.8 MPa (ILO, 1987). The ratio of the wet compressive strength increased from 3 days to 28 days which was 1.48.

#### 4.3.1.5 Effects of OPC Content and Lime on CSPB (10 MPa Compaction Pressure)

Figure 4.5 shows the variation of Ordinary Portland Cement and lime on wet compressive strength of stabilised peat brick under 10 MPa moulds pressure. The results of varying compaction pressure under 10 MPa over the same range of cement content for CSPB presented in Figures 4.5 and 4.6. Wet compressive strength increased at 30% OPC content 11.8%, 13.45%, 14.4%, and 11.8% at 3, 7, 14, and 28 days respectively.

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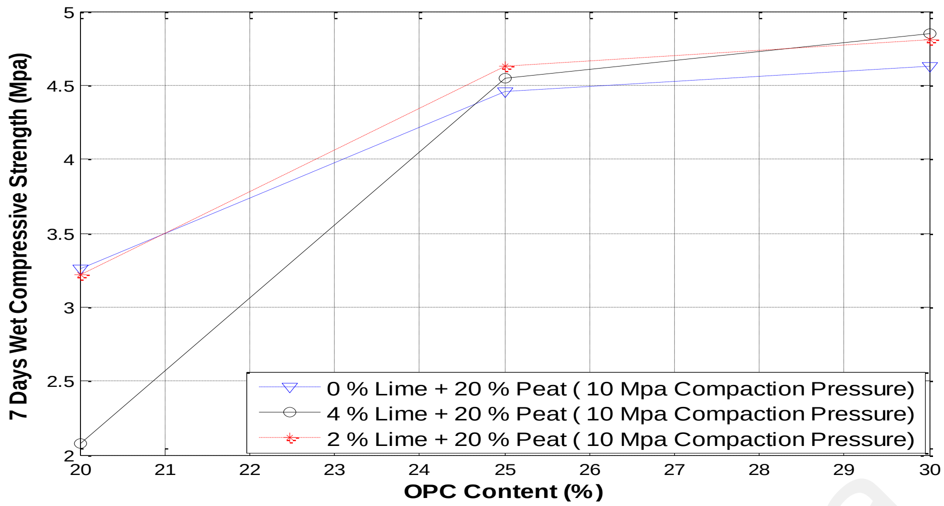


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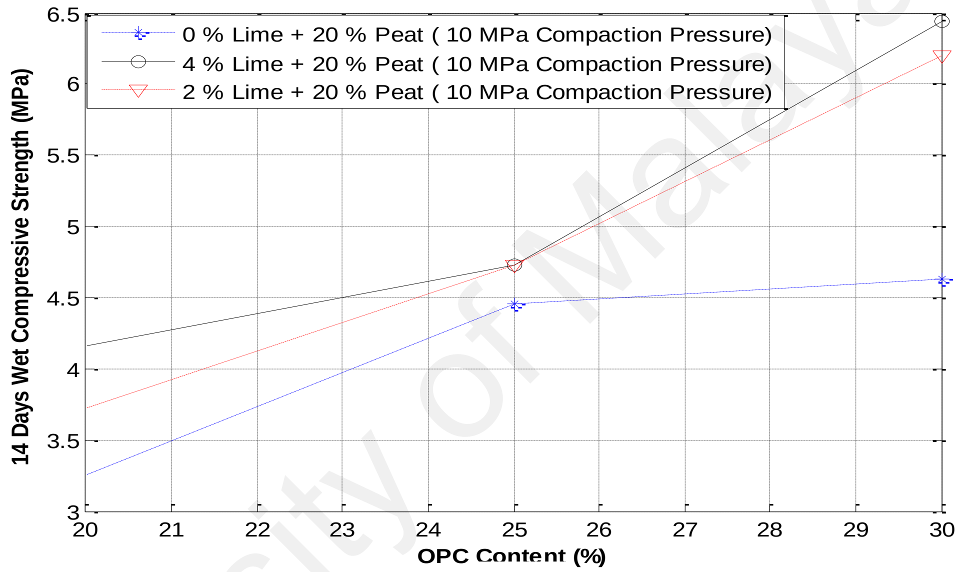


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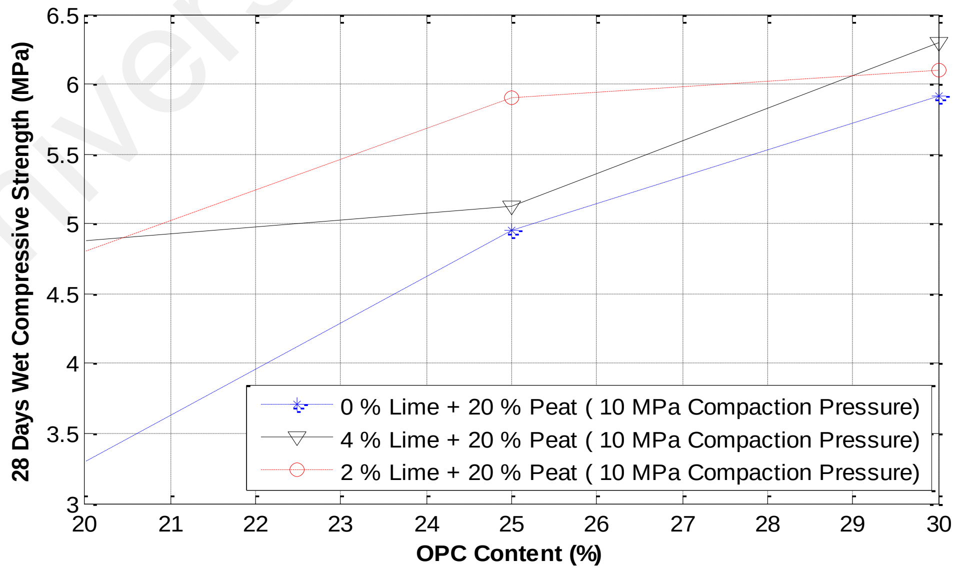



(d)

**Figure 4.5:** Effects of varying OPC, Lime content and curing on the wet compressive strength of CSPB. (a) at 3 days, (b) at 7 days, (c) at 14 days, and (d) at 28 days.

Compressive strength with 10 MPa pressure increased about 36.85%, 21%, and 14.58% with 0%, 4%, and 2% lime respectively at 3 days. It increased at 28 days about 44%, 43.72%, and 27.69% with 0%, 4%, and 2% lime respectively. These findings confirmed earlier work by other researchers that increase in stabiliser content is a more economic way to increase the wet compressive strength in blocks (Lunt, 1980). The wet compressive strength of a CSPB appears to be more sensitive to changes in cement content than compaction pressure (Anthony, 2001). Higher compression reduces the amount of voids and increases inter-particle contact within a brick. Higher density always has been associated with higher strength (Spence, 1975; Gooding, 1993).

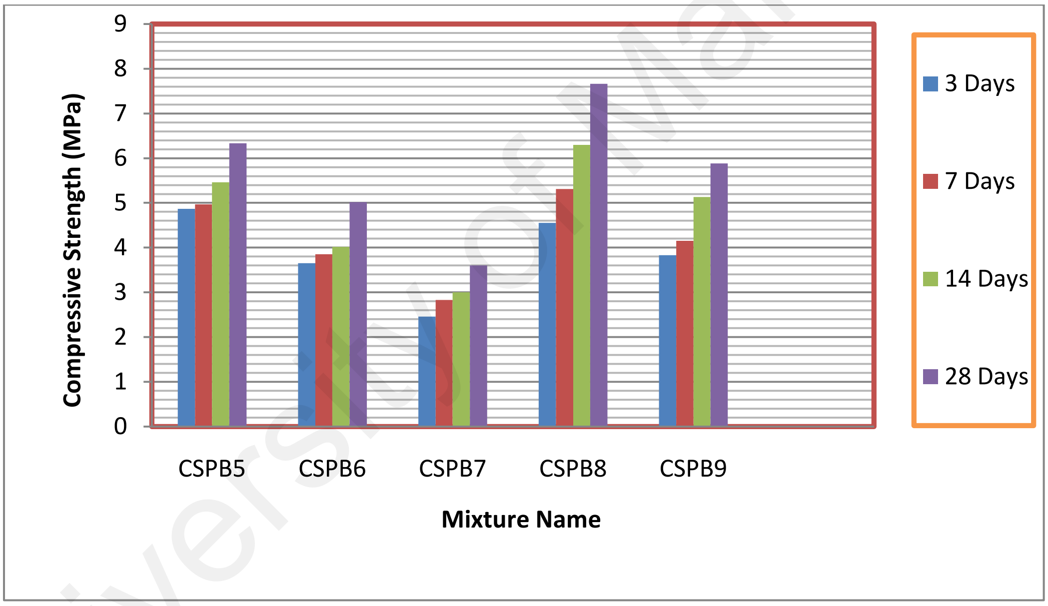
The results also show that although improved performance can be achieved by increasing compaction pressure, the degree of improvement diminishes as this pressure is increased.

#### 4.3.1.6 Effect of Curing on Wet Compressive Strength of CSPB

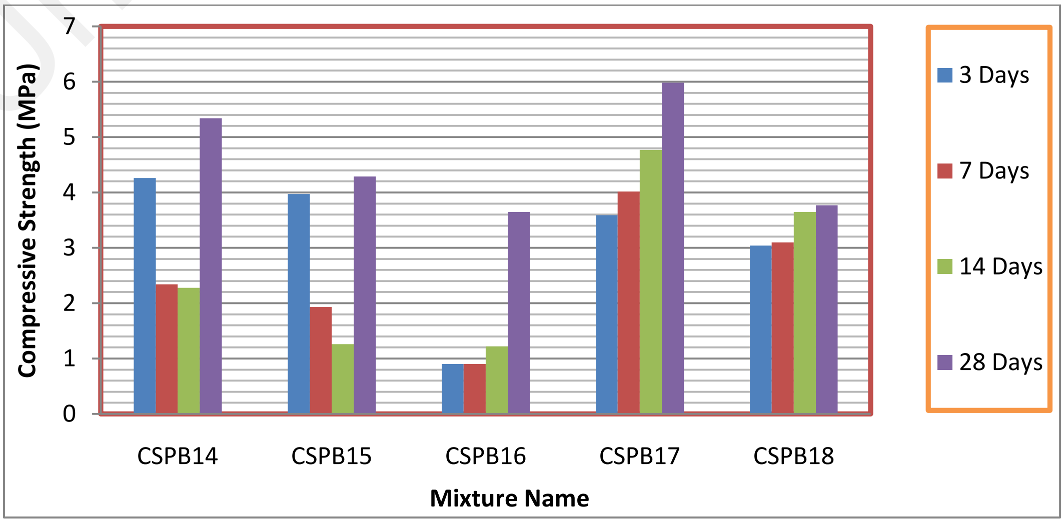
Curing of compressed stabilised peat brick under different conditions was carried out to evaluate the effect of varying this parameter on the properties of bricks. The primary curing periods of the specimen was covered with plastic bag for 1 day, and then transferred to a water tank for 14 days. After this period, the specimen become hard when transferred to the moist cured room for another 14 days. Different mix designs of stabilised peat brick are presented in Figure 4.6.

The effect of varying curing on brick strength was investigated experimentally on brick strength whereby CSPB specimen was stabilised with 20%, 25% and 30% cement and compacted at 6 MPa and 10 MPa. As the test was meant to indicate the OPC; PFA cement and lime were varied. The progressive increase in wet compressive strength of the stabilised soil from 3 to 28 days of curing 14 days in water and 14 days moist cured was attributed to the chemical reactivity of OPC or PFA cement and lime, superplasticiser and the binder with water, and the role of siliceous sand as filler in the stabilised soil.

Increases in compressive strength from 3 to 28 days ranged from 29% to 32.5%, with admixture compacted under 6 MPa pressure and ranged between 32.7% and 51.66% with mixture compacted under 10 MPa.




**(a)**

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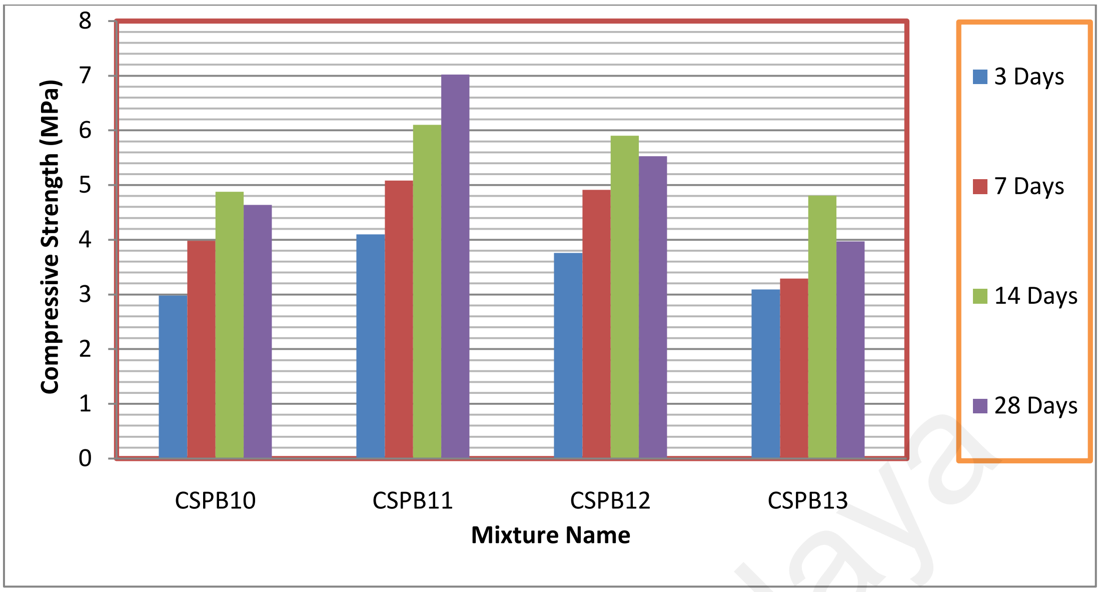
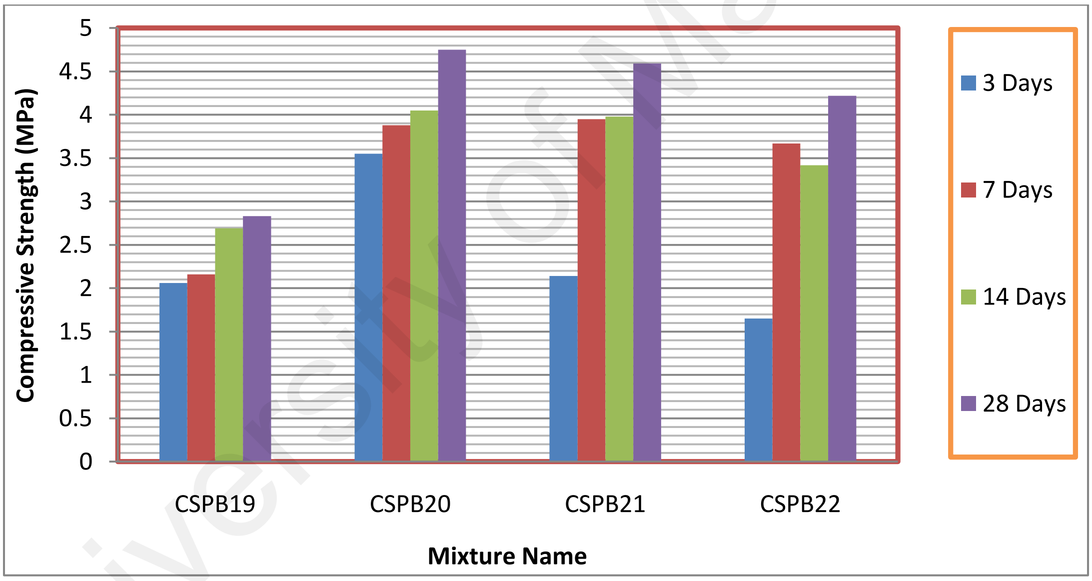



**(c)**




(d)

**Figure 4.6:** Relationship between wet compressive strength and curing. (a) and (b) PFA cement and lime as stabiliser under 10 MPa compaction pressure, (c) and (d) PFA cement and lime as stabiliser under 6 MPa compaction pressure.

#### 4.3.1.7 Effect of OPC and PFA Cement on CSPB

According to Table 3.7 in Chapter 3, different mix designs were chosen for comparison of the effect of OPC and PFA cement on wet compressive strength between compressed stabilised peat bricks. The results obtained are shown in Figures

4.7 and 4.8. Figures 4.7 and 4.8 show the compressive strength determined at the ages of 3, 7, 14, and 28 days for each mixture under 10 MPa pressure. Three specimens were tested and average of three results was reported as compressive strength. Mixtures of 30% PFA cement and 30% OPC cement achieved the best compressive strength at all ages ranging from 4.26 to 6.33 MPa. The lowest strength reflected in those mixtures with less cement ranged from 2.69 to 3.6 MPa.

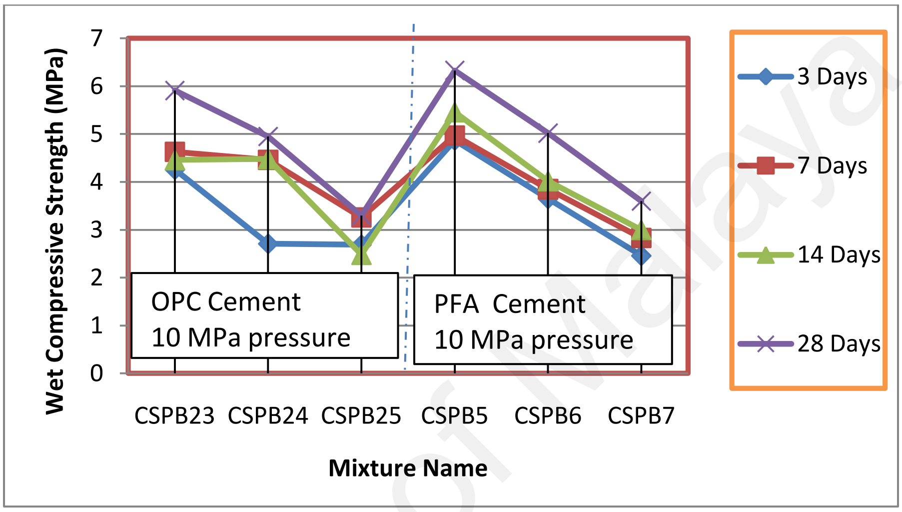



**Figure 4.7:** Effect of stabiliser on wet compressive strength under 10 MPa compaction pressure.

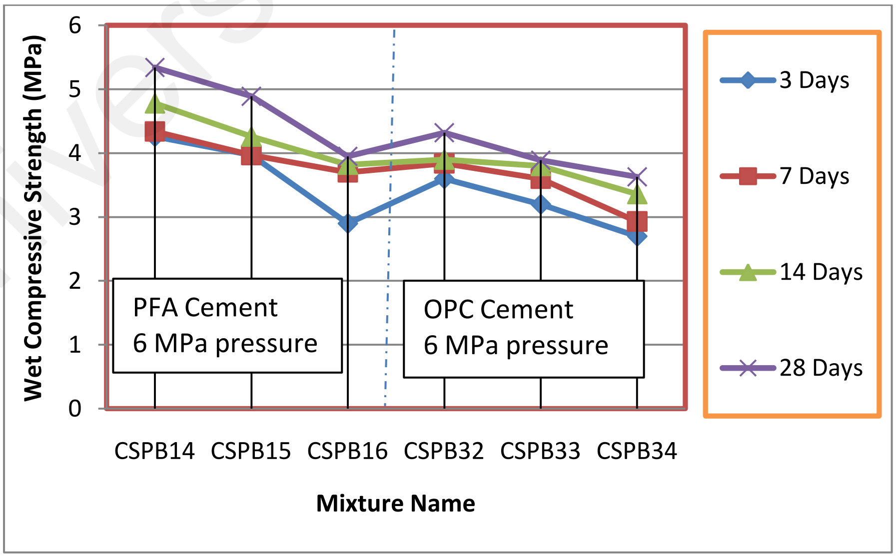



**Figure 4.8**: Effect of stabiliser on the wet compressive strength under 6 MPa compaction pressure.

The compressive strength was valued by the strength of brick incorporating 30% OPC cement was 4.26 MPa and 5.34 MPa at both 3 and 28 days, respectively. However, with 20% OPC or 20% PFA cement, the strength ranged from 2.79 MPa to 3.95 MPa. Wet compressive strength with 30% PFA cement was higher about 15% more than mixture with 30% OPC.

#### 4.3.1.8 Comparison between Wet and Dry Compressive Strength of CSPB and Hollow CSPB.

The effect of varying the stabiliser type and content on the gap between dry and wet compressive strength was investigated experimentally. The values obtained are plotted as shown in Figures 4.9 and 4.10.

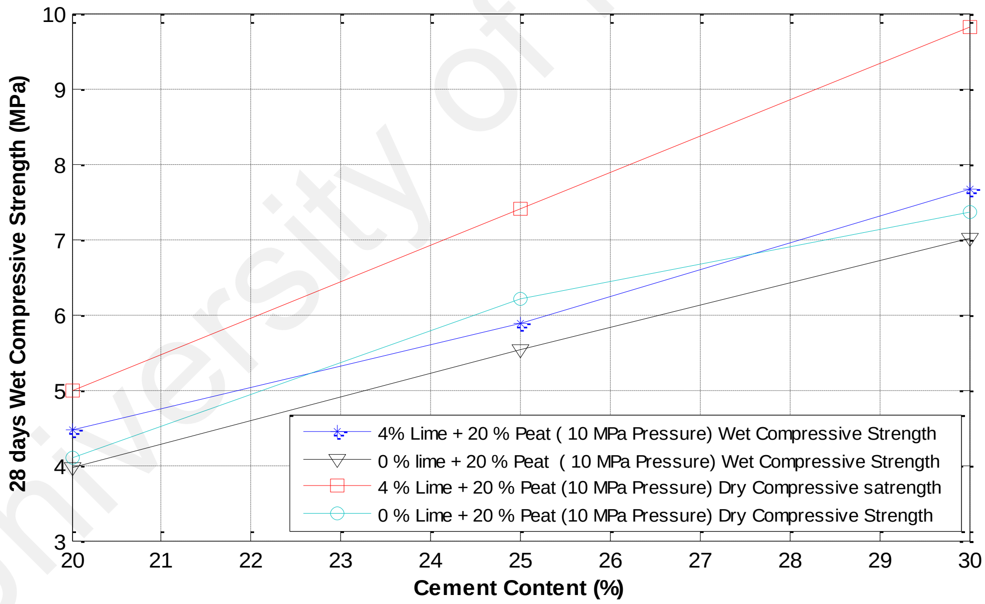



**Figure 4.9:** Variation of stabiliser on the dry and wet compressive strength of CSPB

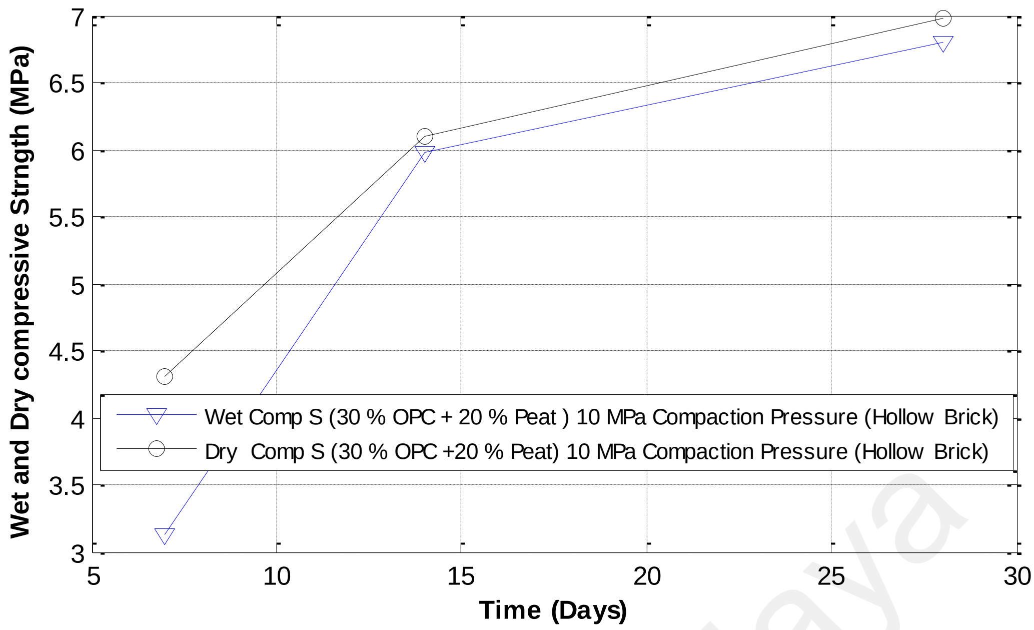



**Figure 4.10:** Variation of stabiliser on the dry and wet compressive strength of hollow CSPB

The values of the wet compressive strength of compressed stabilised peat bricks at 28 days ranged between 4 MPa and 7.66 MPa. The equivalent values of their dry compressive strength ranged between 4.5 MPa and 9.88 MPa. The difference between wet and dry compressive strength was about 20% (for 20 % cement) and 29% (for 30% cement). This shows that the higher cement content, the higher difference between the wet and dry compressive strength in compressed stabilised peat brick. The results for improved bricks compared well with values reported in concrete research where the difference between wet and dry compressive strength ranged between 9% and 21% (Neville, 1995). It has also been recently recommended that the ratio of the mean dry and wet compressive strength in CSBs should not be greater than 2 MPa (Houben et al., 1996). From Figure 4.10 it can be obtained that the ratio between dry and wet compressive strength ranged between 1.25 and 1.4. The upturn in strength is a consequence of its pozzolanic reaction with freed lime from the hydration reaction of OPC with water, and also due to its ability to effectively between the OPC grains (Weidemann et al, 1990; Illston, 1994; Young, 1998; Taylor, 1998).

Figure 4.10 indicates that the difference between wet and dry compressive strength of hollow bricks. The values of wet compressive strength of hollow compressed stabilised peat brick was 3 MPa at 7 days, 6 MPa and 6.6 MPa at 14 days, and 28 days respectively. The dry compressive strength was 4.6 MPa, 6.3 MPa and 7 MPa at 7, 14, and 28 days. The ratio between wet and dry compressive strength ranged between 1.05 and 1.5.

According to Meukan et al. (2004) compressive strength of stabilised laterite soil bricks ranged between 2 MPa to 10 MPa with 3% to 10% cement content, and investigations revealed that the compressive strength increased with increase in cement content and curing period.

Solomon, (1994) indicated from his investigation of compressive strength of stabilised laterite blocks with 8% of cement varied between 2 and 6 MPa. In the present study, the compressive strength varied between 0.9 MPa to 7.66 MPa.



## 4.4 Total Water Absorption

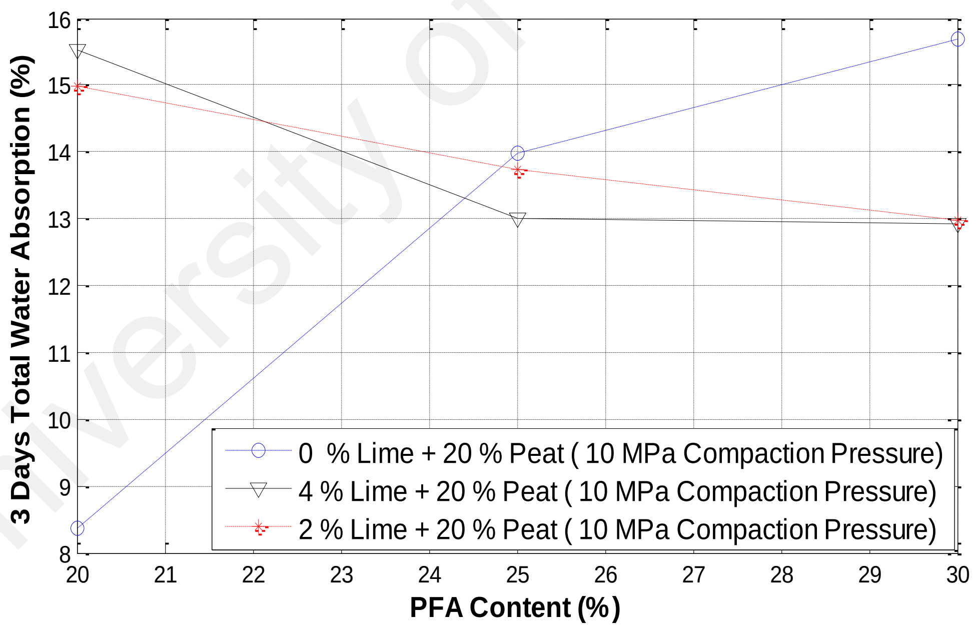
Almost all bricks and blocks can absorb water by capillarity (Keddi & Celghorn, 1980). The total amount of water absorbed is a useful measure of bulk quality. The total volume of voids in a brick can be estimated by the amount of water it can absorb.

Knowledge of the total water absorption of a brick is important because it can be used for various purposes such as:

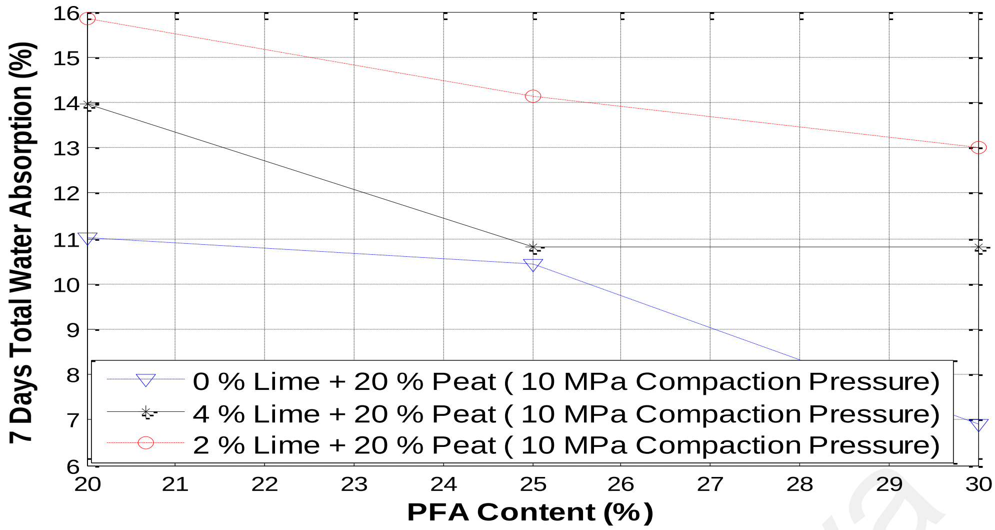
- Quality checks on bricks.
- Comparison purpose with set standards and values for other similar materials.
- Classification of bricks according to required durability and structural use.

The total water capacity of a block can usually be measured by determining the amount of water it can take in (ILO, 1987). The amount absorbed is influenced by the pre-existing moisture condition of a brick; hence it is advisable that the brick is first dried to keep the mass constant before further testing (BS: 3921, 1985).Various procedures can be carried out to determine total water absorption capacity of a brick (BS 3921: 1985). For the purpose of this thesis, the method used for total water absorption is cold immersion in water 24 hours after oven drying to constant mass. Three specimens for each mix design were examined for this thesis, also testing of total water absorption on different curing time.

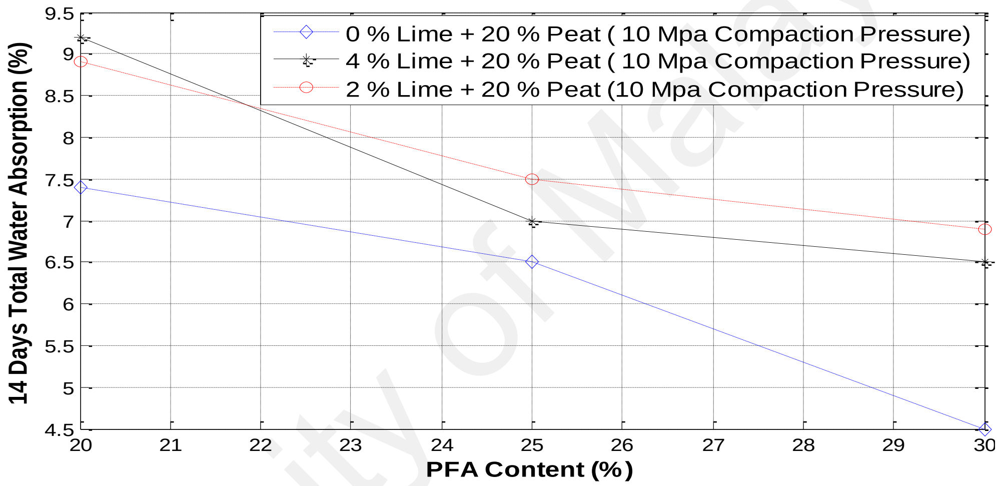
1. Mixtures under 10 MPa moulding Pressure: casting of stabilised brick specimen was under 10 MPa for 10 minutes.



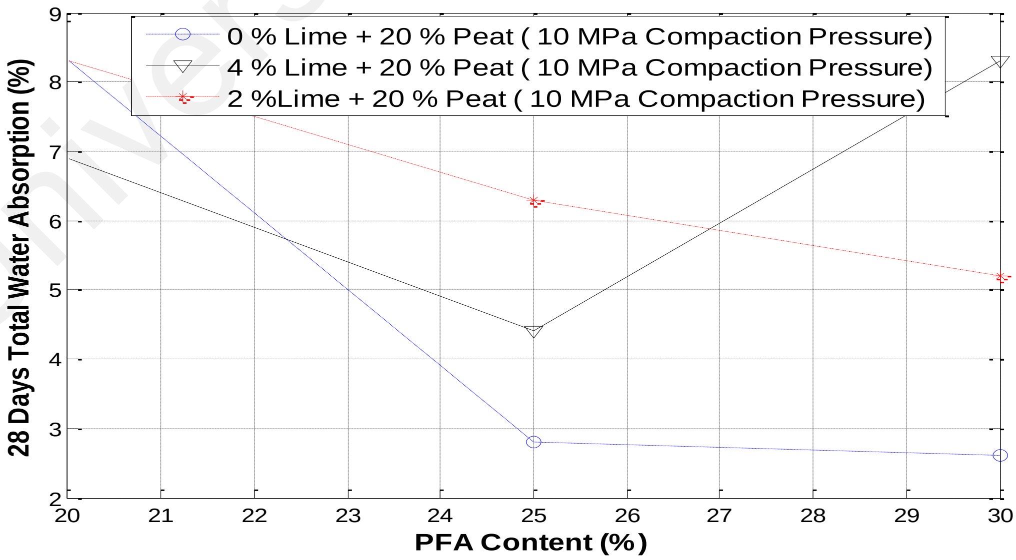

(a)




(b)



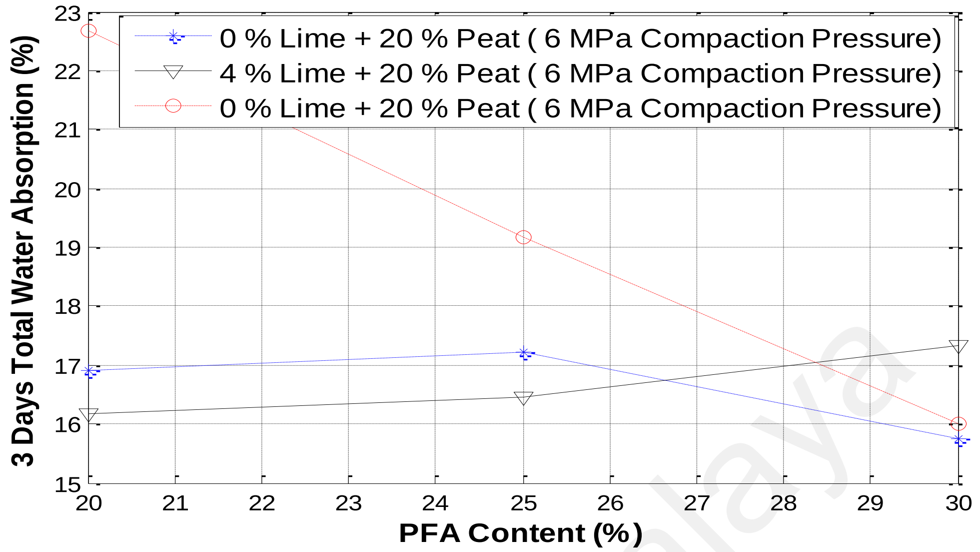

(c)



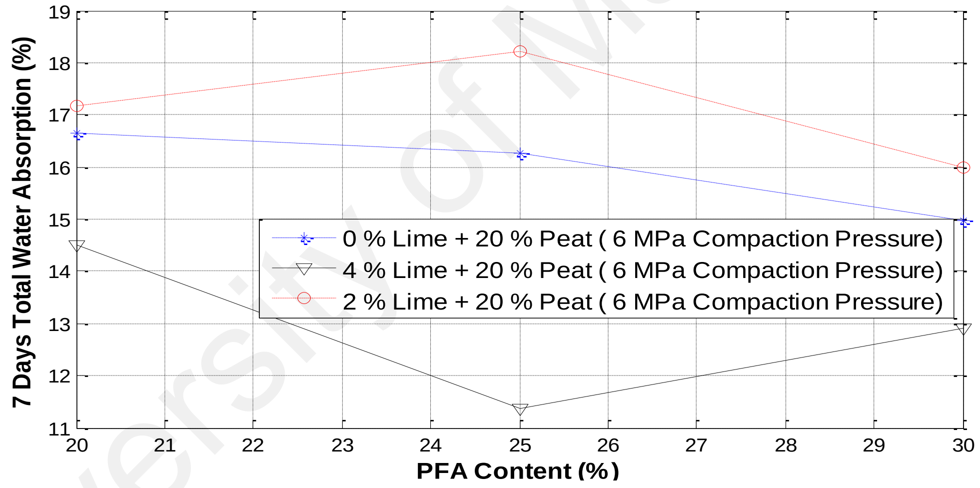

(d)

**Figure 4.11:** Effects of varying PFA content and curing on the total water absorption under 10 MPa compaction pressure.(a): at 3 days, (b) at 7 days, (c) at 14 days and (d) at 28 days

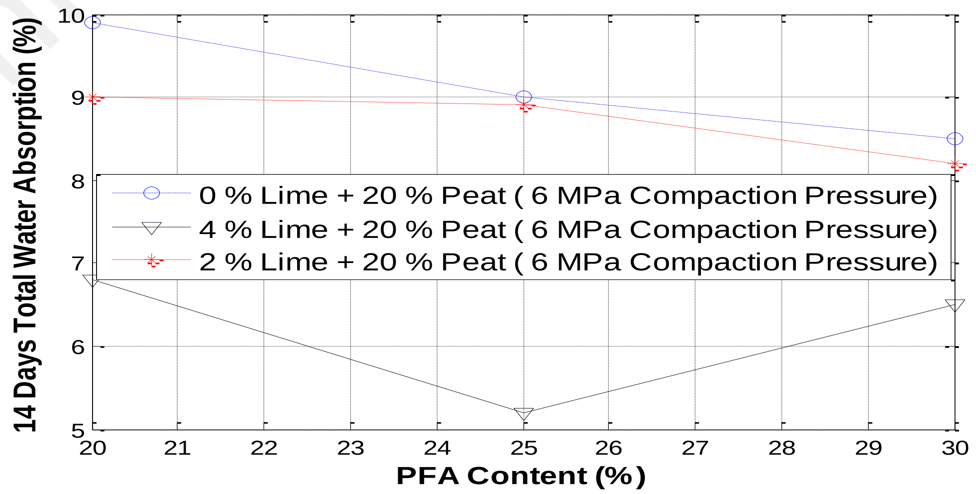
2. Mixtures under 6 Mpa compaction pressure:



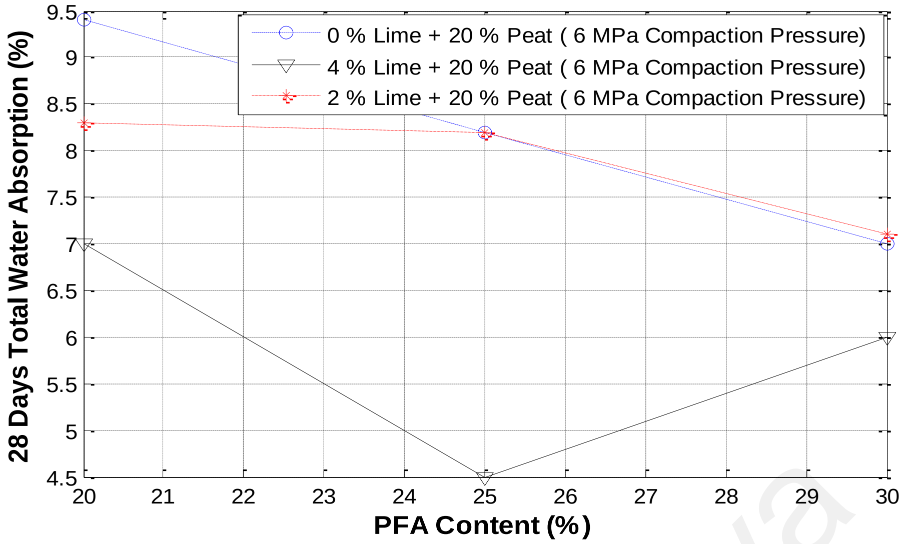

(a)




(b)




(c)




(d)

**Figure 4.12:** Effects of varying PFA and content and curing period on the total water absorption under 6 MPa compaction pressure in CSPB: (a) at 3 days, (b) at 7 days, (c) at 14 days and (d) at 28 days

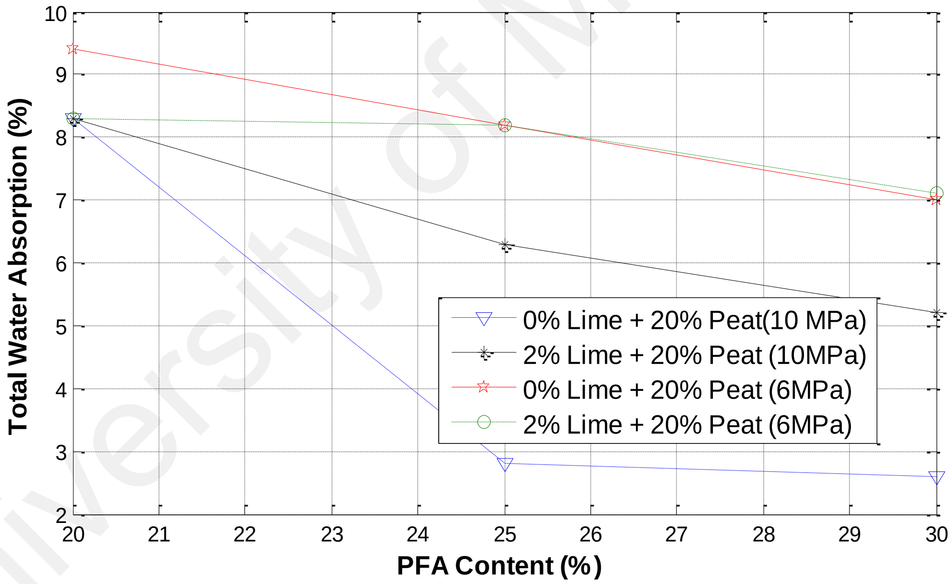



**Figure 4.13**: Effects of varying the stabiliser content and type, and compaction pressure on the total water absorption in CSPB.

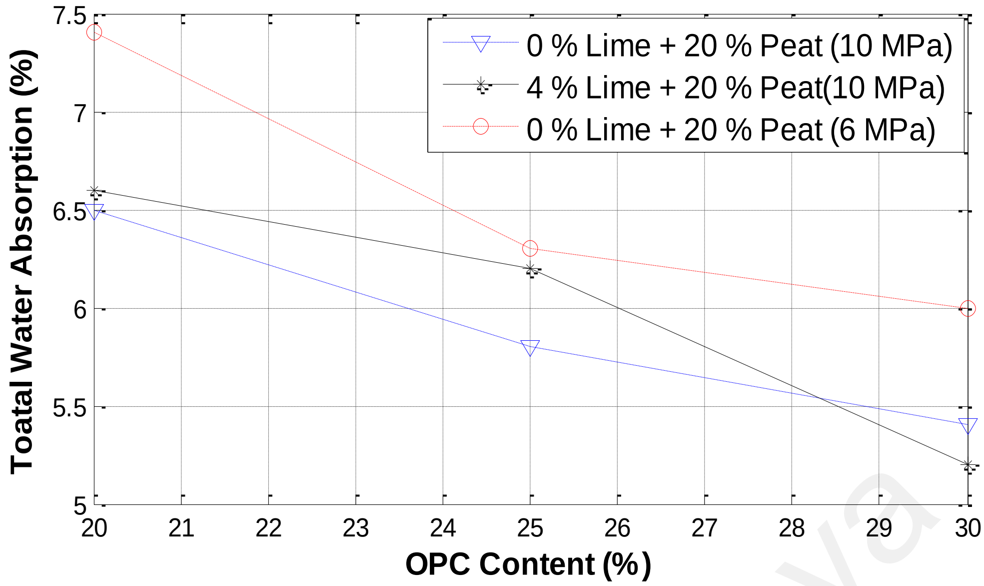



**Figure 4.14:** Effects of varying OPC and lime content, and compaction pressure on the total water absorption in CSPB

Figure 4.11 shows that relation between stabiliser (PFA and lime) and curing at 3, 7, 14 and 28 days under 10 MPa compaction pressure and the total water absorption in CSPB. The results obtained that the total water absorption in CSPB decreased with increased cement content and curing period. The decrease was generally under 10 MPa 4%, 37%, 32% and 68% at 3, 7, 14, and 28 days with variations in PFA content from 20% to 30%.

Figure 4.12 shows that the total water absorption under 6 MPa were decreased by about 7%, 10%, 14% and 25% at 3, 7, 14, and 28 days respectively with variation in PFA content from 20% to 30%. The reduction in absorption with increase in stabiliser content is progressive. Figure 4.13 evidently indicates that the total water absorption decreased with increased PFA content. However, from Figure 4.14 it is clear that the total water absorption of CSPB decreased about 17% under 10 MPa pressure and 19% under 6 MPa with increase in content of OPC from 20% to 30%. The results also show that the total water absorption values obtained compared well with those of other similar materials and with current recommended maximum values for bricks and blocks.

Hago et al. (2007) recommended that the water absorption of cement stabilised compressed bricks ranged between 2% to 11.2%. According to Ajam et al. (2009), the water absorption of PG fired bricks ranged between 15.84% and 19.67%. Kumar (2000); IS: 3952 (1988) reported that the water absorption of ordinary burnt clay bricks or blocks should not be more than 20 % by weight. BS: 3921, (1985) defined the limits of water absorption in order to categorise engineering bricks. The standard specifies low water absorption for category A. ≤ 4.5% and ≤ 7% for category B.

The above results confirm that CSPB have the potential to absorb appreciable amounts of water and possibly retain it too. Moreover, they confirm earlier findings that improvement the quality of a brick is easily achieved by variation in stabiliser content and type. However, the improvement quality of compressed stabilised peat bricks is dependent on the curing period.

### 4.4.1 Correlation Between Total Water Absorption and Wet Compressive Strength of CSPB

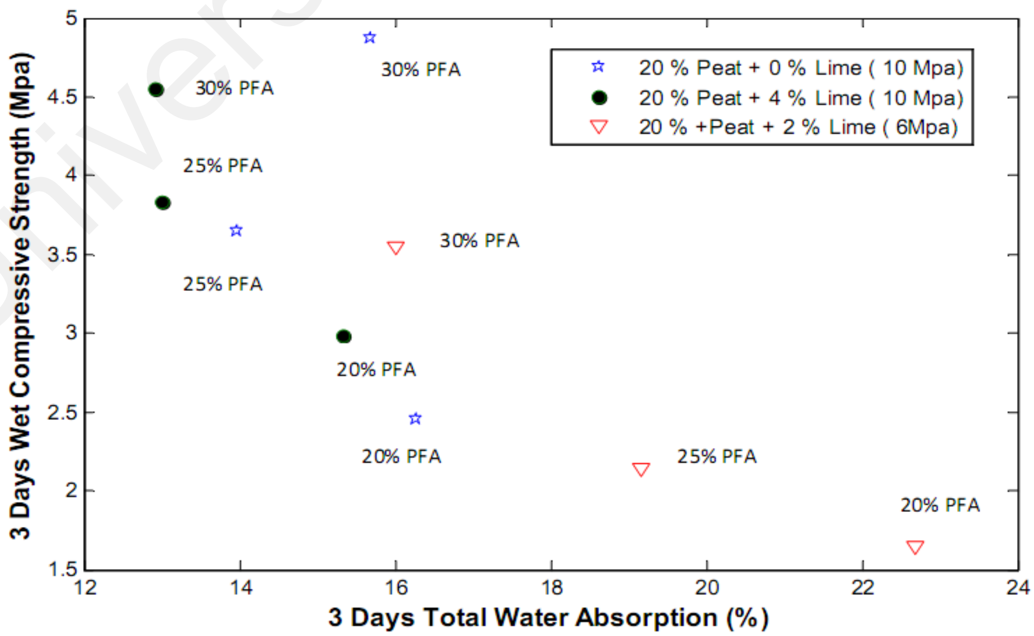



**Figure 4.15**: Correlation between total water absorption and wet compressive strength of CSPB at 3 days (PFA)

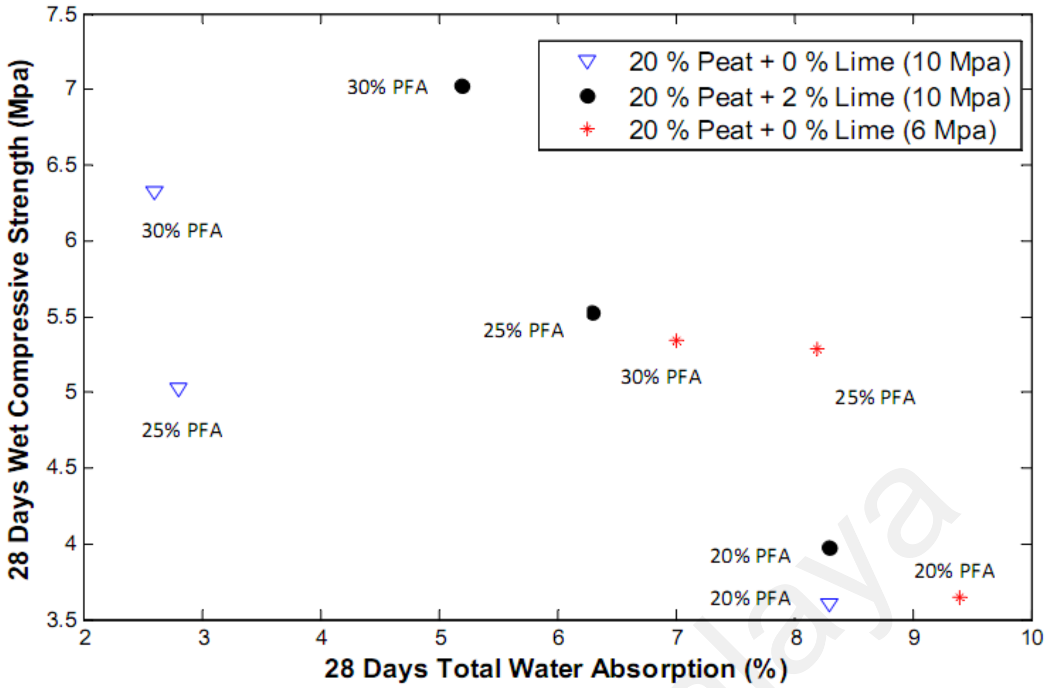



**Figure 4.16**: Correlation between total water absorption and wet compressive strength of CSPB at 28 days (PFA)

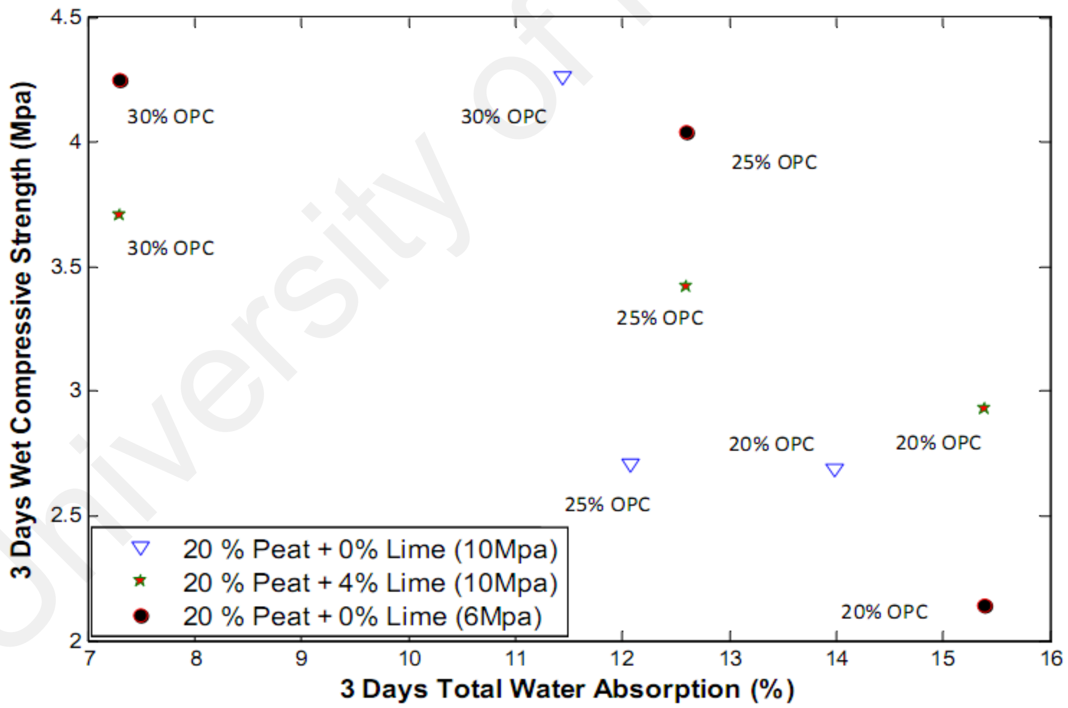



**Figure 4.17**: Correlation between total water absorption and wet compressive strength of CSPB at 3 days (OPC)

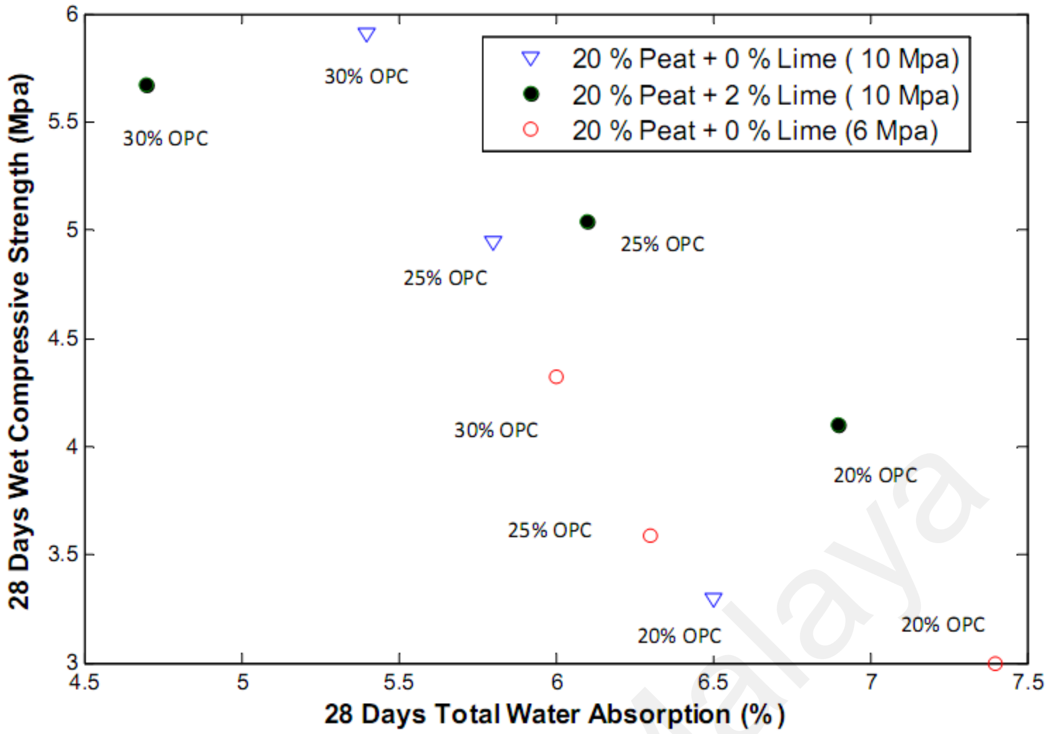



**Figure 4.18**: Correlation between total water absorption and wet compressive strength of CSPB at 28 days (OPC)

In this section, the correlation between total water absorption and wet compressive strength is discussed. The experimental results obtained for total water absorption are plotted against those for 3 and 28 days wet compressive strength shown in Figures 4.15, 4.16, 4.17 and 4.18. These Figures show that a general negative correlation between total water absorption and wet compressive strength. The graphs show that a decrease in water absorption is accompanied by a corresponding increase in strength. The negative coefficient of correlation found, varied between -1.09 to -0.705 at 3 days with OPC as stabiliser and -0.999 to -0.612 at 28 days. However it varied between - 0.956 to - 0.269 at 3 days with PFA cement and - 0.994 to - 0.891 at 28 days. The water absorption at 3 days was higher with lower strength, as less curing period means less hydration of cement and lime with soil and sand particles, however less strength means more voids and more water absorption for compressed stabilised peat bricks. As mentioned previously, the total water absorption capacity of a block and brick can usually be measured by determining the amount of water it can take in (ILO, 1987).

### 4.4.2 Correlation between Total Water Absorption and Dry Density

The correlation between total water absorption and dry density values was plotted values from the measured points for both properties. As shown in Figures 4.19, 4.20, 4.21 and 4.22 a negative correlation exists between total water absorption and dry density of CSPB. Increase in density with variation of PFA cement from 1600 kg/$m^3$ to 1694 kg/$m^3$at 3 days and from 1645 kg/$m^3$ to 1895 kg/$m^3$ at 28 days decreased water absorption for about 29% at 3 days and 72% at 28 days. Similar increase in density over the same or different range of PFA contents and compaction pressure in improved bricks results in a decrease in total water absorption. However effects of OPC on CSPB, increased in density from 1633 kg/$m^3$ to 1758 kg/$m^3$ at 3 days and 1685 kg/$m^3$ to 1858 kg/m3 at 28 days decreased water absorption by about 25.6% at 3 days and 41.5% at 28 days.

The results also show that for some samples tested, beyond a certain density values, no appreciable reduction in total water absorption could be found. The results obtained here, shows that further increase in bricks, dry density would necessarily lead to continued reduction in total water absorption. The relation between strength, dry density and total water absorption is negative, when increased strength subsequently increases density and decreases water absorption. Kumar (2002) reported that the increase in density of Fal.G brick was from 1172 kg/$m^3$ to 1230 kg/$m^3$, while water absorption decreased by about 19%.

From Figures 4.19 to 4.22 the values of coefficient of correlation using statistical method found negative values of coefficient for all samples studied. At 3 days, coefficient of correlation varied between -0.956 and -0.269 with PFA cement and between -1.03 and -0.931 with OPC. The coefficient of correlation at 28 days varied between -1.04 to -0.913 with OPC and -0.994 to -0.891 with PFA cement.

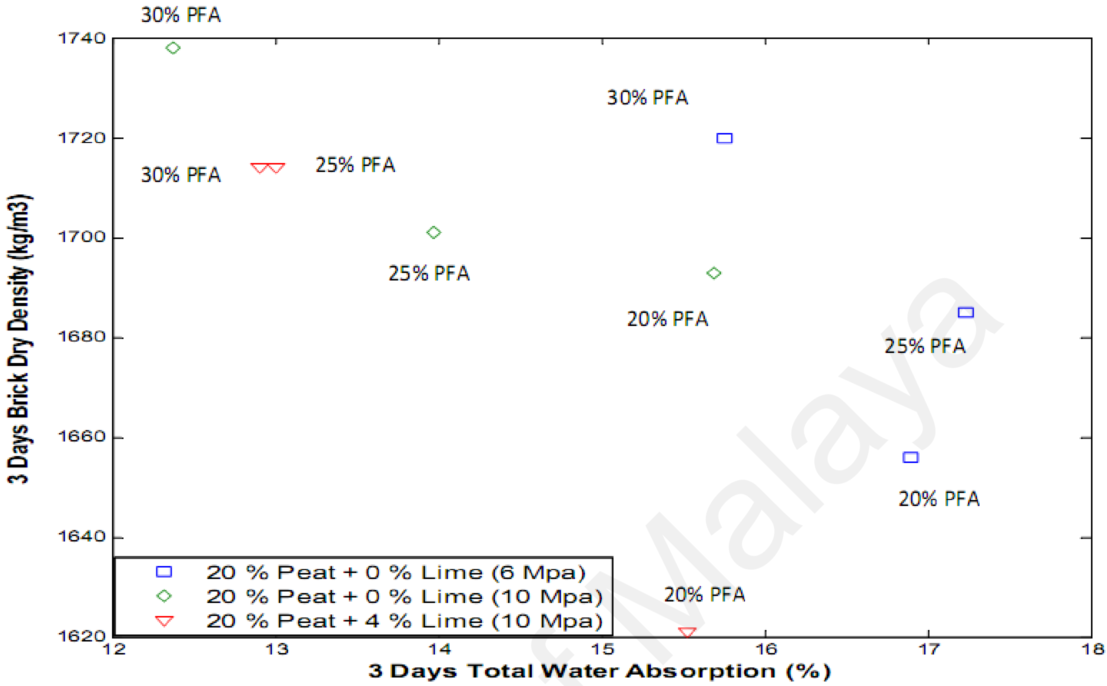



**Figure 4.19**: Correlation between total water absorption and brick dry density at 3 days

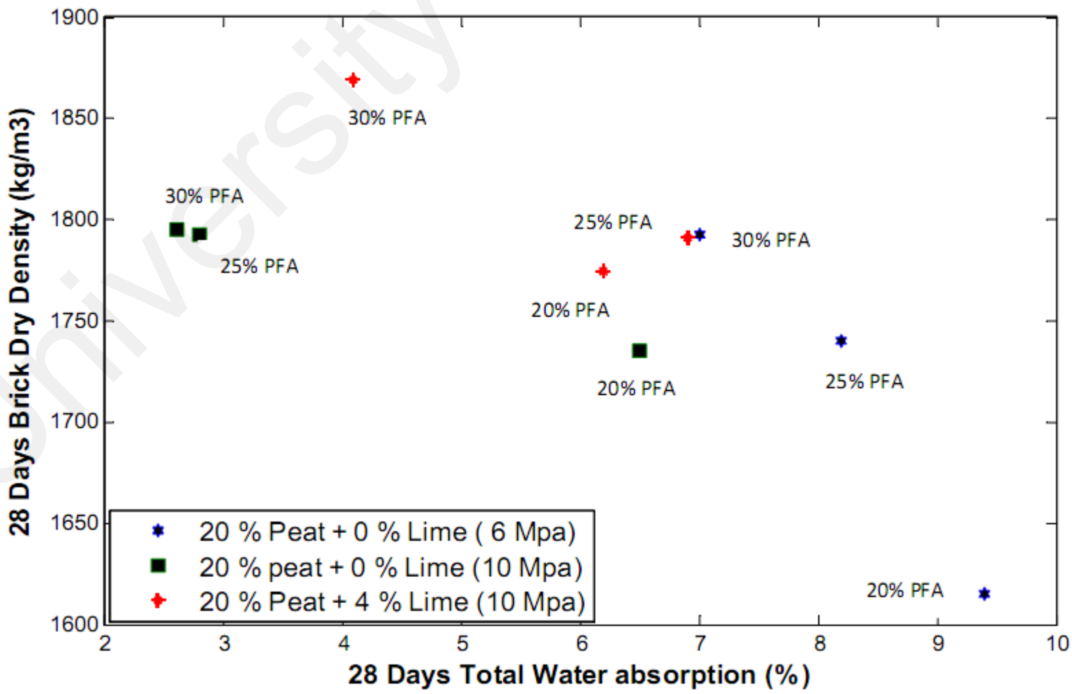



**Figure 4.20**: Correlation between total water absorption and brick dry density at 28 days

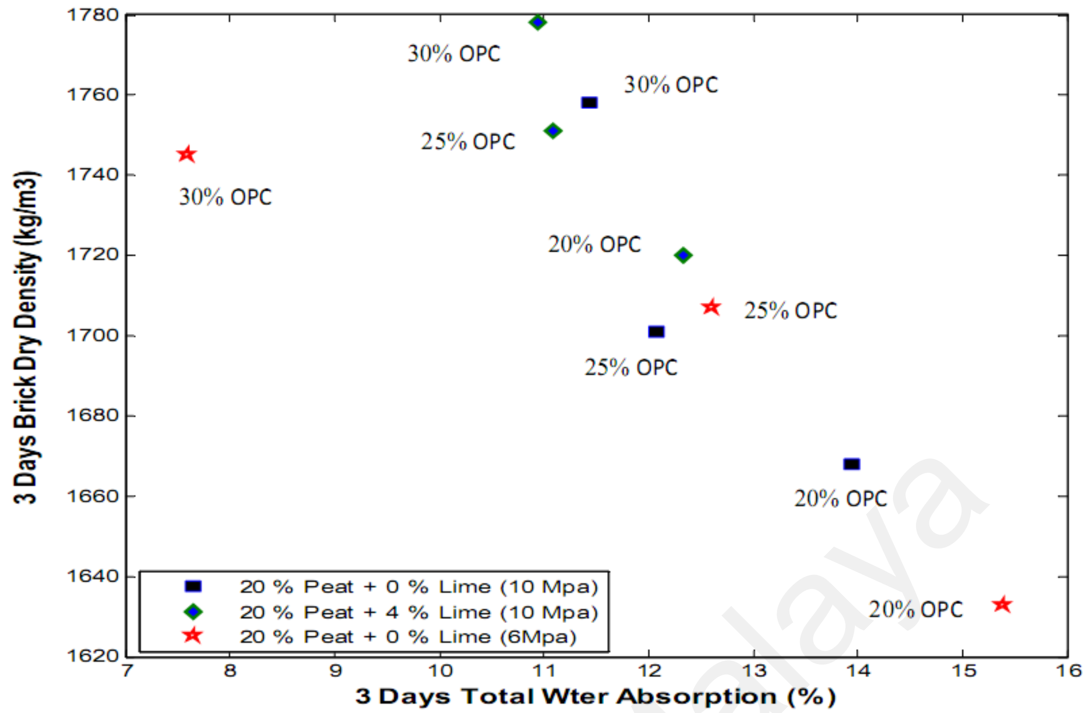



**Figure 4.21**: Correlation between total water absorption and brick dry density at 3 days

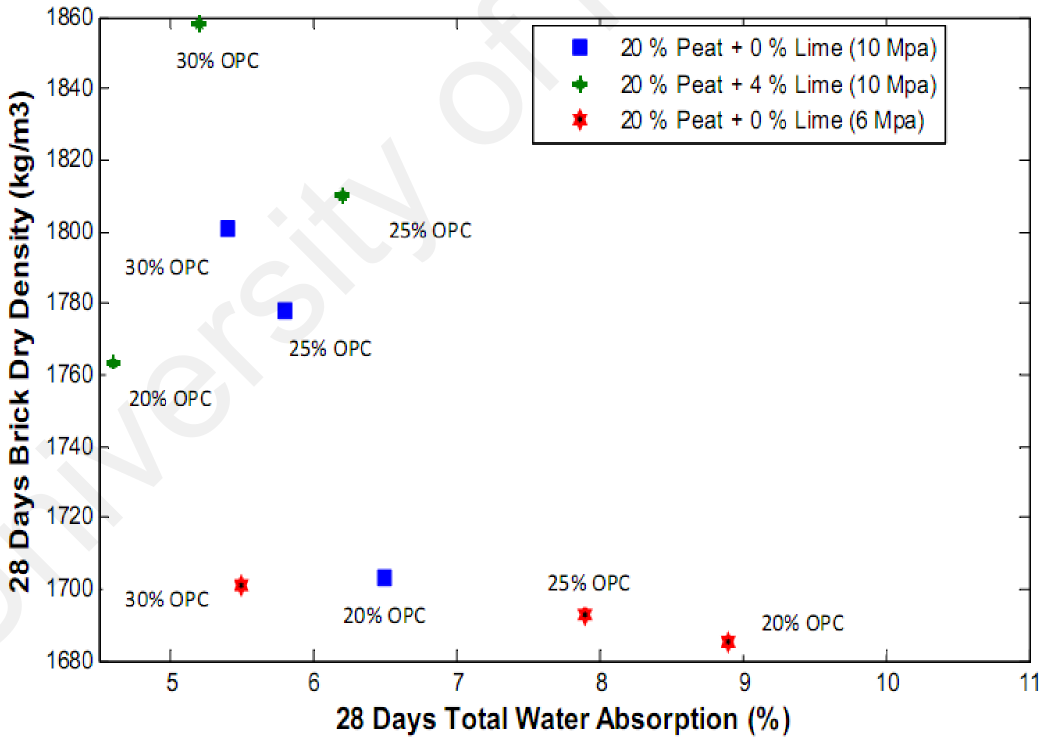



**Figure 4.22**: Correlation between total water absorption and wet compressive strength of CSPB at 28 days

### 4.5 Brick Bulk and Dry Density

The density of a brick is a valuable aspect in terms of its quality. It can be expressed in a number of different ways. The first way Brick dry density is usually indicated by the oven-dried value when desiccated to 105 ± 5℃ for 24 hours.

The brick bulk density based on the pre-existing state of moisture usually soon after demoulding. The methodology of testing is discussed in Chapter 3. For all brick specimens, three samples were tested in each mixture. The compaction pressure varied from 6 MPa to 10 MPa. The plotted results are shown in Figures 4.23, 4.24, 4.25, 4.26, 4.27 and 4.28. Figures 4.23 and 4.24 show the relationship between variations of PFA cement and dry density of compressed stabilised peat brick. The results indicate that the increase of PFA content from 20% to 30% improved density of brick at 3 and 28 days. However, for matching amount of PFA amount, improved brick density was about 3.4% with 0% lime under 6 MPa compaction pressure, 5.2% and 2% with 0%, 2% lime, respectively under 10 MPa compaction pressure at 3 days. Increase in density at 28 day was about 9.92%, 3.3% and 3.6% with 0%, 2 %, and 4% lime, respectively. Increase in density was also found to occur when compaction pressure was increased from 6 MPa to 10 MPa about 5.4% at 28 day.

Using OPC as a stabiliser on compressed stabilised peat brick found improvement in dry density at 3 days and 28 days with increased content of OPC from 20% to 30%. Figures 4.27 and 4.28 obtained that increase was about 6.4% and 5.12% under 10 MPa and 6 MPa compaction pressure respectively at 3 days. An increase in dry density of brick at 28 day was about 5.4% and 1.46% under 10 MPa and 6 MPa compaction pressure respectively.

The increase of cement content replacement material appears to be an economic alternative to achieving higher densities in bricks. Anthony, (2001) reported that the marked increase in density witnessed in improved bricks and blocks could have been due to four factors associated with the inclusion of microsilica: Pore filling effects, increased homogeneity, improved bounding and reduced voids.

Hago et al. (2006) investigated the characteristics of concrete block containing petroleum-contaminated soils and found a variation of dry density between 1300 $kg/m^3$ to 1480 $kg/m^3$. Laurent et al. (2000) reported that the density of lateritic soil bricks varied between 1640 $kg/m^3$ and 1660 $kg/m^3$. In this study, the dry density varied between 1633 $kg/m^3$ and 1895 $kg/m^3$. Many previous researches for different types of bricks and blocks produce evidence on dry density as found in this study that it is necessary for good quality of bricks. However, the bulk density of compressed stabilised peat bricks indicated that increase of bulk density of bricks increased with stabilisers content and compaction pressure. Figure 4.28 shows that the bulk density varied between 1945 $kg/m^3$and 2029 $kg/m^3$for PFA stabiliser and between 1915 $kg/m^3$and 2043 $kg/m^3$ for OPC. These results obtained indicate that the bulk density of CSPB with OPC or PFA is almost the same.

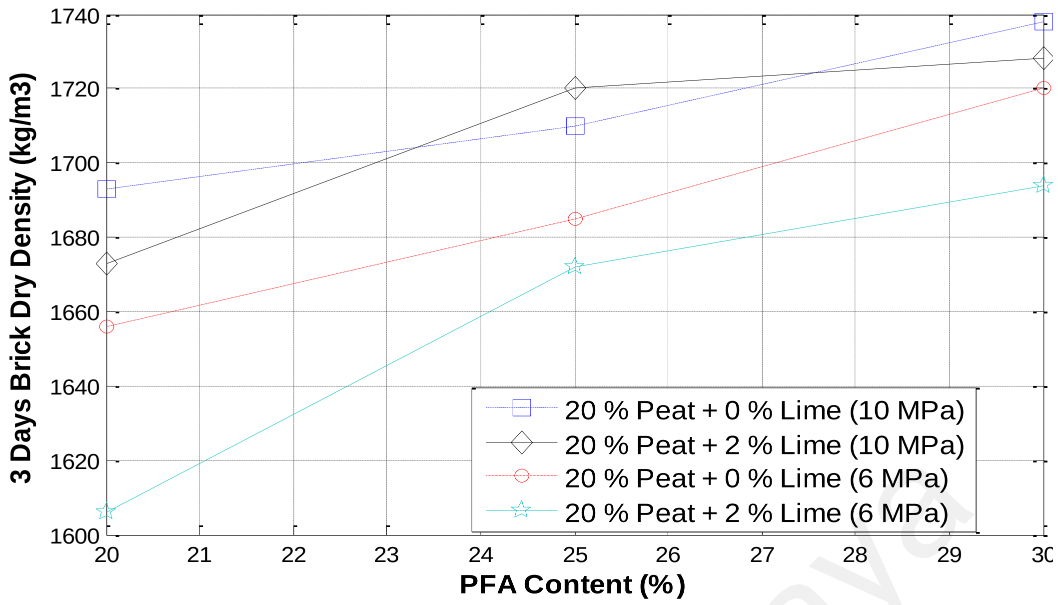



**Figure 4.23:** Effects of varying PFA cement content, Lime and compaction pressure and compaction pressure on brick dry density at 3 days

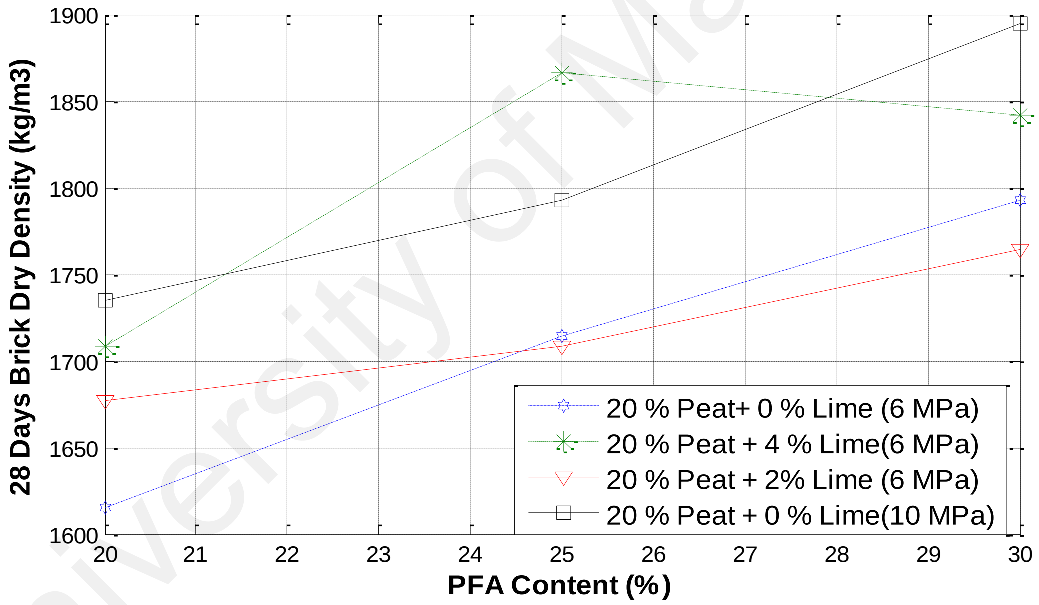



**Figure 4.24:** Effect of varying PFA cement content and compaction pressure on brick dry density at 28 days.

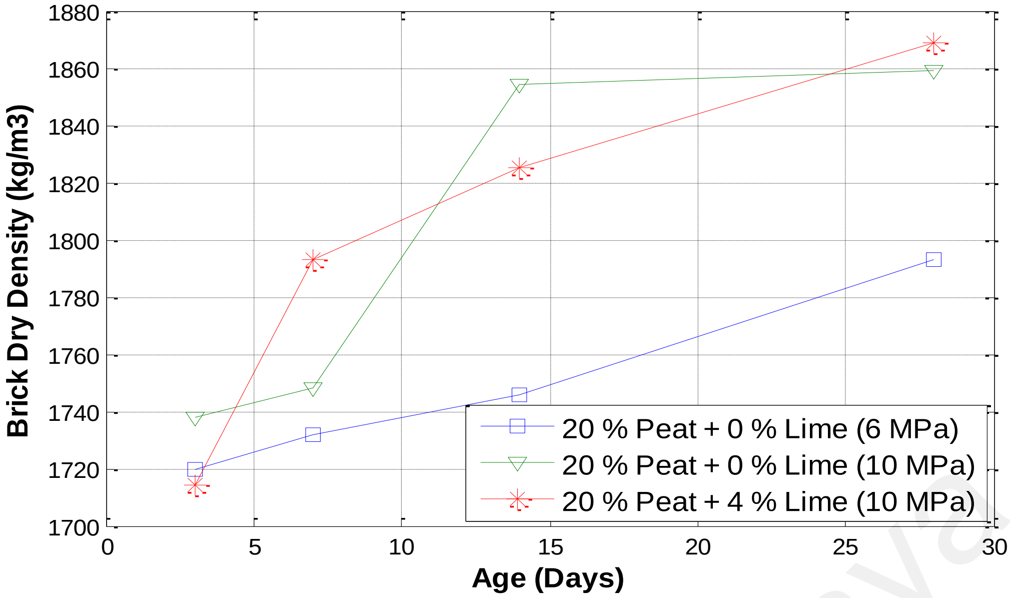



**Figure 4.25:** Effects of varying curing period and compaction pressure on brick dry density

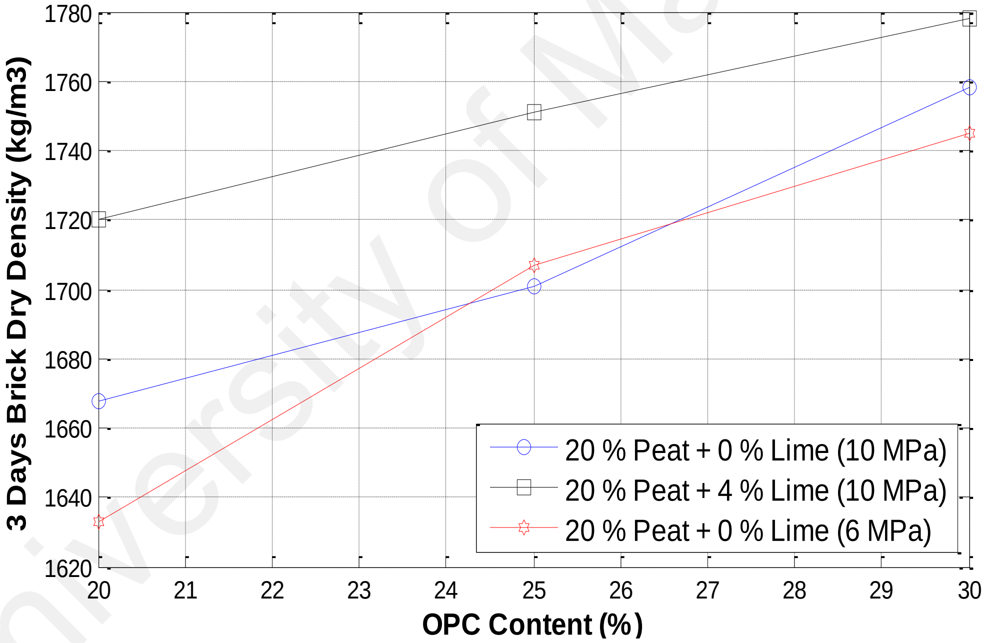



**Figure 4.26:** Effects of varying OPC content and compaction pressure on brick dry density at 3 days.

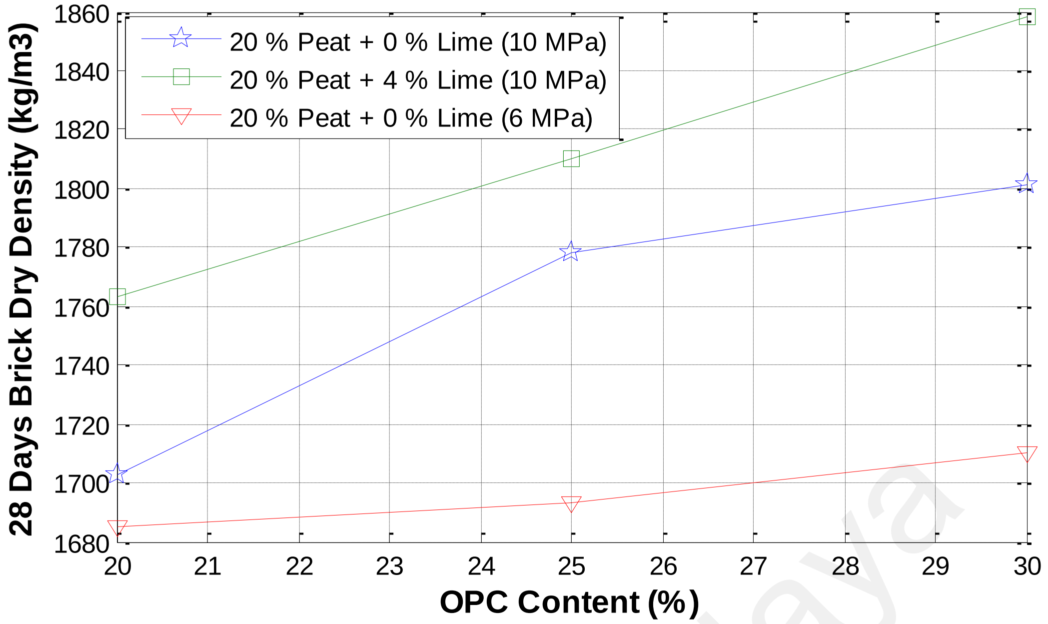



**Figure 4.27:** Effects of varying PFA cement content and compaction pressure on brick dry density at 28 days

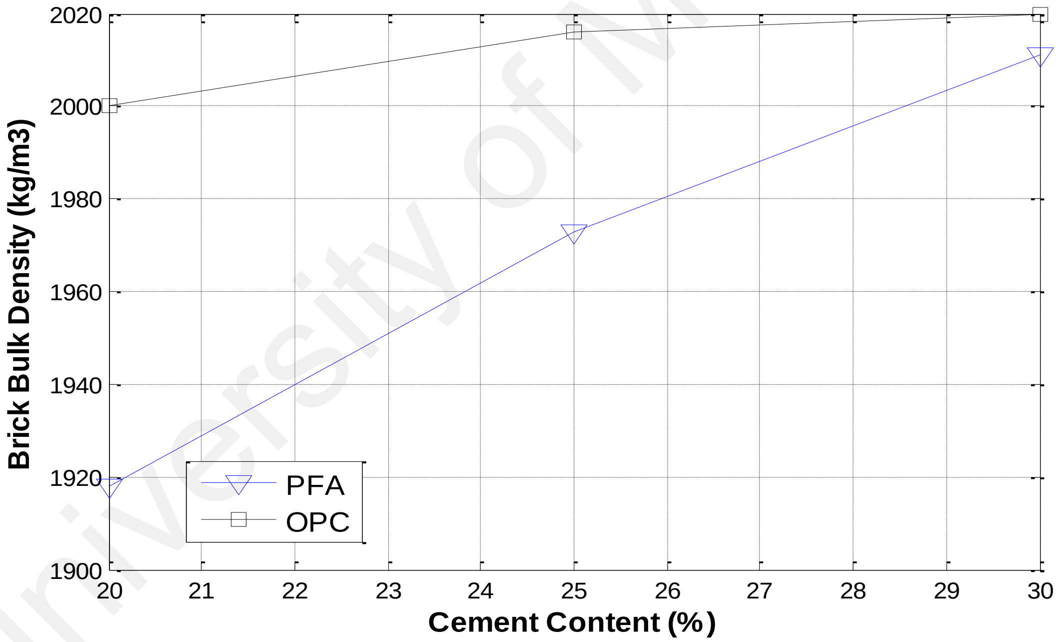



**Figure 4.28** Effects of varying PFA and OPC content on brick bulk density

### 4.5.1 Correlation Between Dry Density and Wet Compressive Strength

The experimental results obtained a correlation between brick dry density and wet compressive strength plotted as shown in Figure 4.29. The results indicate that a positive correlation exist between dry density and wet compressive strength of CSPB for different stabiliser content and compaction pressure. The graph shows that an increase in density is accompanied by a corresponding increase in strength. The positive coefficient of correlation values between strength and density was 1.08 with samples of CSPB compacted 6 MPa pressure at 28 days, ranging between 0.184 to 0.924 with samples of CSPB compacted 10 MPa at 28 days. The correlation between density and strength has also been widely reported in comparable materials (Jackson & Dhir, 1996; Ruskulis, 1997). The dry density values for more usage of materials are fired clay bricks dry density which is between 2250 kg/$m^3$ and 2800 kg/$m^3$, calcium silicate bricks which is between 1700 kg/$m^3$ and 2100 kg/$m^3$and concrete blocks between 500 kg/$m^3$and 2100 kg/$m^3$.

These values are definitely comparable compared with those obtained experimentally in this study. It is widely known that fired clay bricks are most popular material in the most part of the world, but are deemed environment problematic. Many countries are trying to find new materials which are more environmentally friendly compressed stabilised earth bricks and blocks. Current research findings show that dry density for bricks and blocks are between 1300 Kg/$m^3$and 2100 Kg/$m^3$. Lighter materials which are easier for transportation and laying walls in buildings, and also by reducing reinforced concrete like columns and beams dimension are viable cost reduction methods for building purpose.

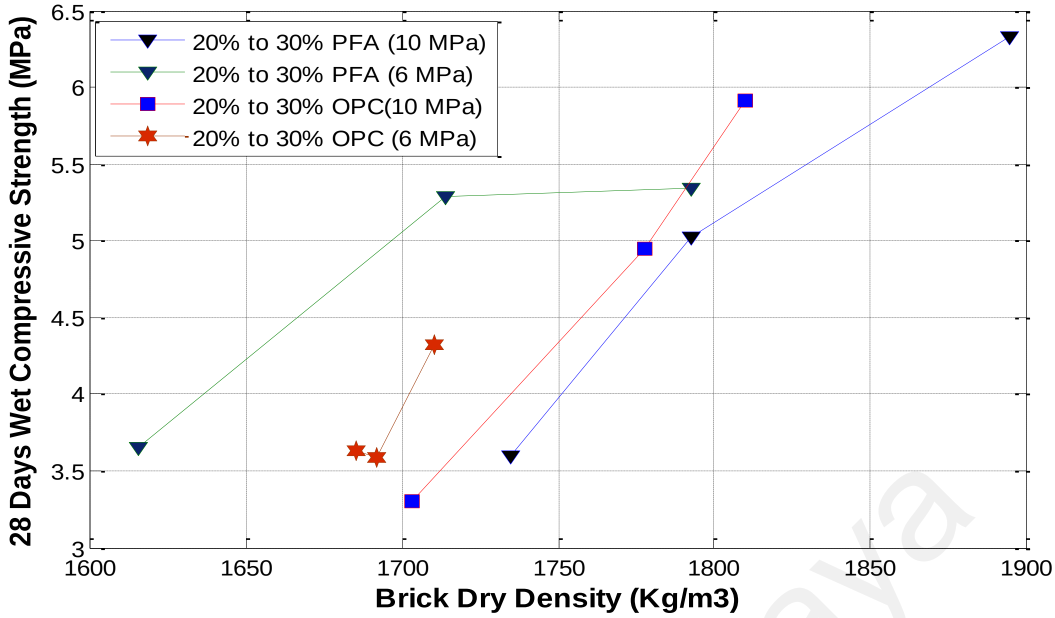



**Figure 4.29**: Correlation between brick dry density and wet compressive strength of CSPB at 28 days

### 4.6 Total volume porosity

In this test, porosity is an important characteristic of brick. In contrast to other moulded or pre-cast building materials, the porosity of brick is attributed to its fine capillaries. By virtue of the capillary effect, the rate of moisture transport in the brick is ten times faster than in other building materials. Moisture is released during day-time and re-absorbed during night. Porosity of building material is an important factor to consider with respect to its performance and applications. In general, link between porosity and quality has been widely reported in concrete literature (Neville, 1995). The capillary porosity which is often the most predominant aspect is believed to be function of the water-cement ration and the degree of hydration achieved (Sjostrom et al., 1996).

The total volume porosity in CSPB can be determined directly. The value of the water absorption may be converted to volume basis porosity by using the following relationship:

$$n = \frac{(WA)\rho}{100\,\rho_w} \qquad \text{Eq. 4.1}$$

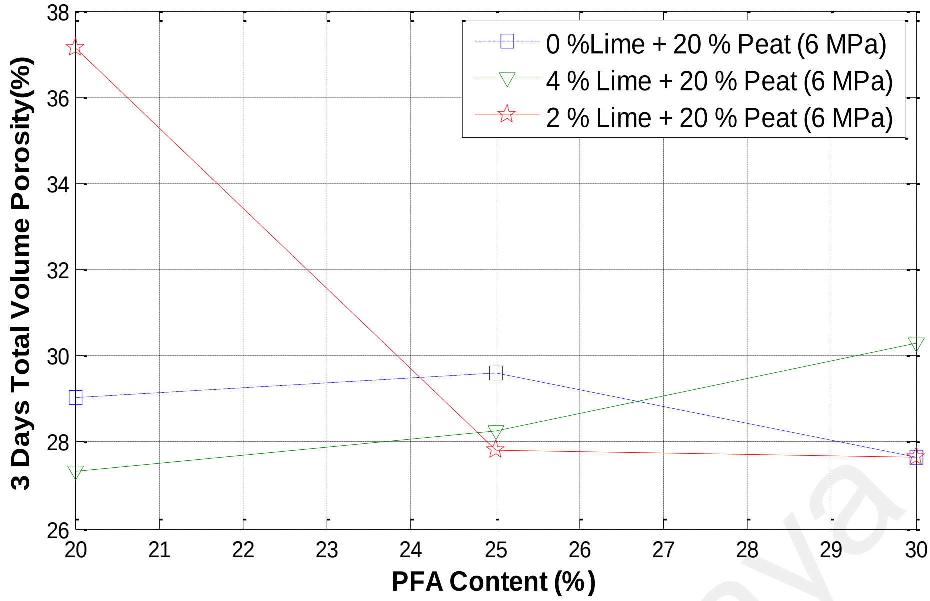
Where n = volume porosity

$\rho$ = brick dry density ($kg/m^3$)

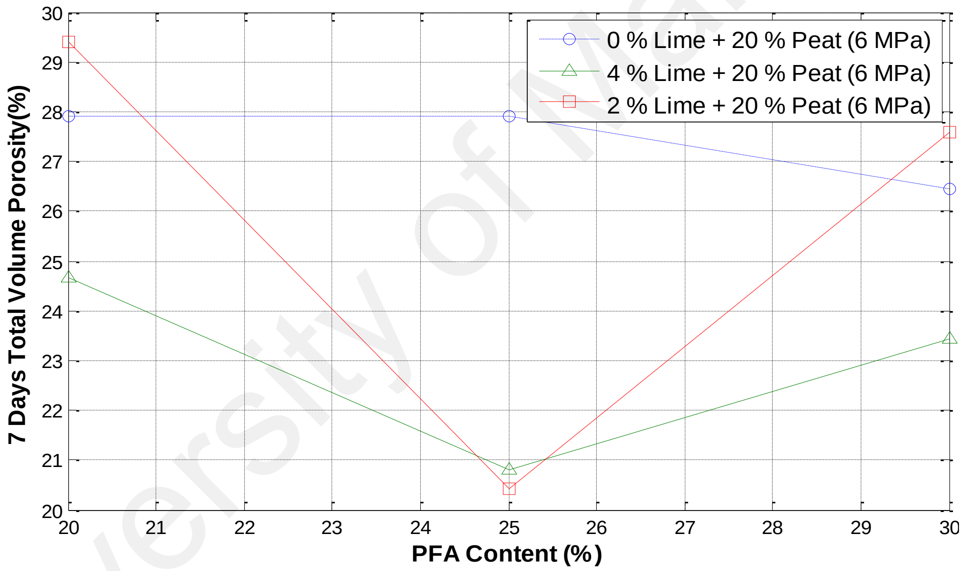
$\rho_w$ = density of water ($kg/m^3$)

WA = water absorption (%)

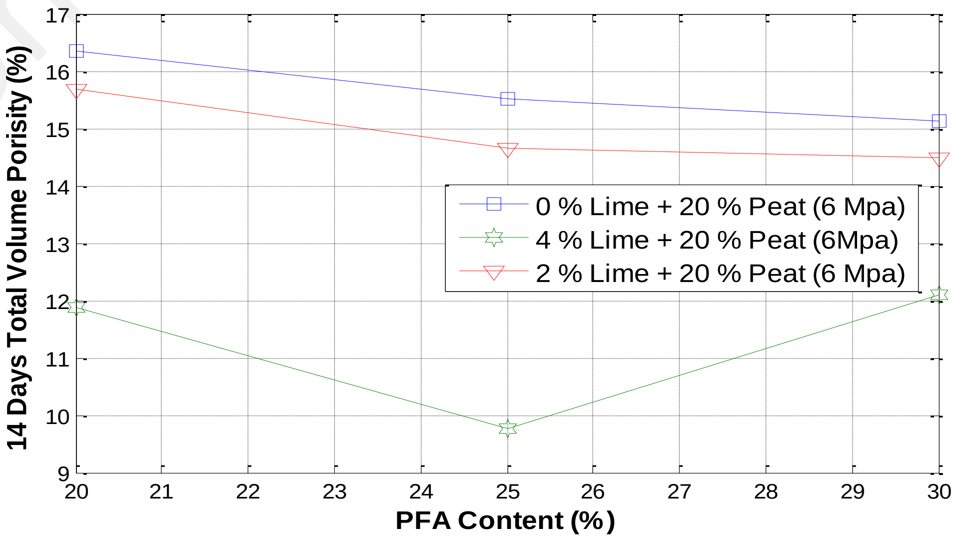
The results of volume porosity in CSPB are presented in Figures 4.30 and 4.31. The results obtained indicate that the porosity with 6 MPa compaction pressure ranged between 27% and 37% with 20% PFA content and 28% to 31% with 30% PFA at 3 days curing period, at 7 days curing the porosity decreased by about 3.75% without lime, 9.66% with 4% lime and 20.5% with 2% lime. Hydration of lime improved with longer curing period, whereby the results indicate that for three days with lime this was still no effect. Porosity of brick at 28 days decreased by about 53.7% without lime, 62.83% with 4% lime and 59.29% with 2% lime. Decrease in porosity when PFA increased content from 20% to 30%, however decreased with increased content of lime from 2% to 4%. Casting the brick under 10 MPa compaction pressure showed that the porosity of that brick improved better than 6 MPa compaction pressure. Figure 4.32 presented the porosity at 28 days which decreased by about 82.5%. Materials with total volume porosity above 30% are considered to be of high porosity (Jackson & Dhir, 1996). All the bricks examined during this research can therefore be considered to be of low porosity.


0 %Lime + 20 % Peat (6 MPa)
4 % Lime + 20 % Peat (6 MPa)
2 % Lime + 20 % Peat (6 MPa)
3 Days Total Volume Porosity(%)
PFA Content (%)
38
36
34
32
30
28
26
20
21
22
23
24
25
26
27
28
29
30

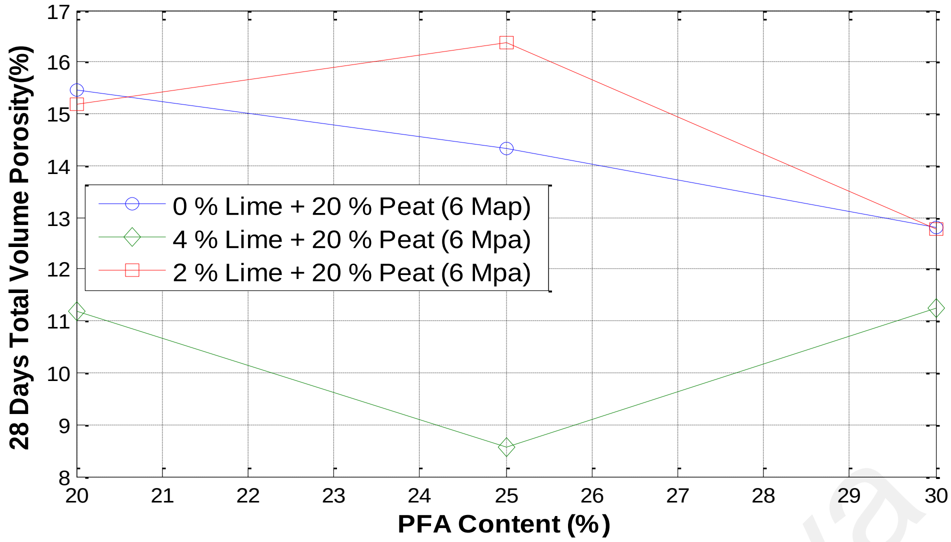
(a)


0 % Lime + 20 % Peat (6 MPa)
4 % Lime + 20 % Peat (6 MPa)
2 % Lime + 20 % Peat (6 MPa)
7 Days Total Volume Porosity(%)
PFA Content (%)
30
29
28
27
26
25
24
23
22
21
20
20
21
22
23
24
25
26
27
28
29
30

(b)

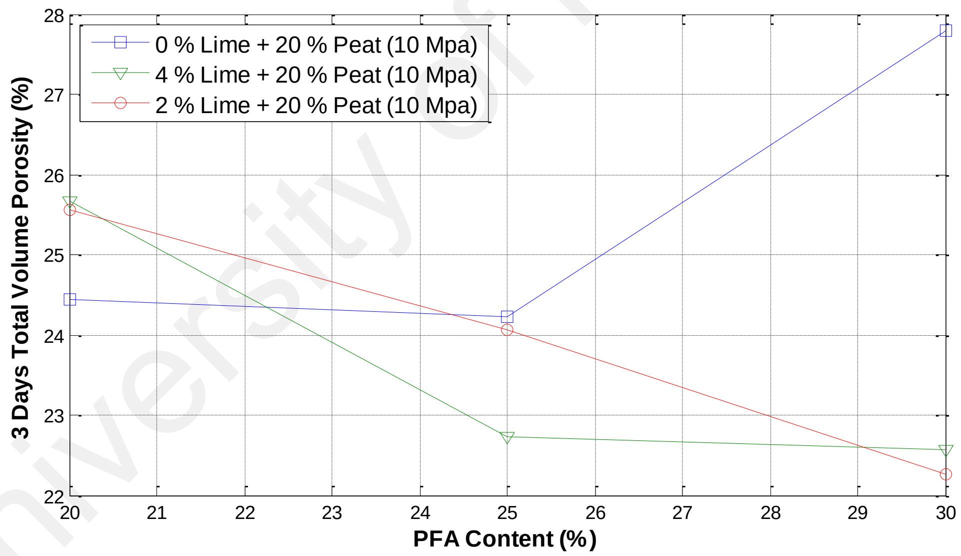

0 % Lime + 20 % Peat (6 Mpa)
4 % Lime + 20 % Peat (6Mpa)
2 % Lime + 20 % Peat (6 Mpa)
14 Days Total Volume Porisity (%)
PFA Content (%)
17
16
15
14
13
12
11
10
9
20
21
22
23
24
25
26
27
28
29
30

(c)

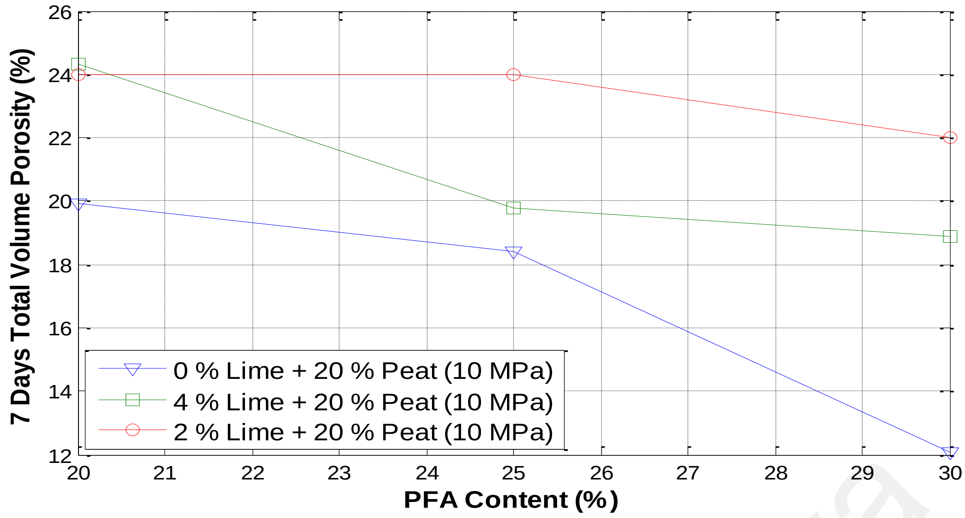



(d)

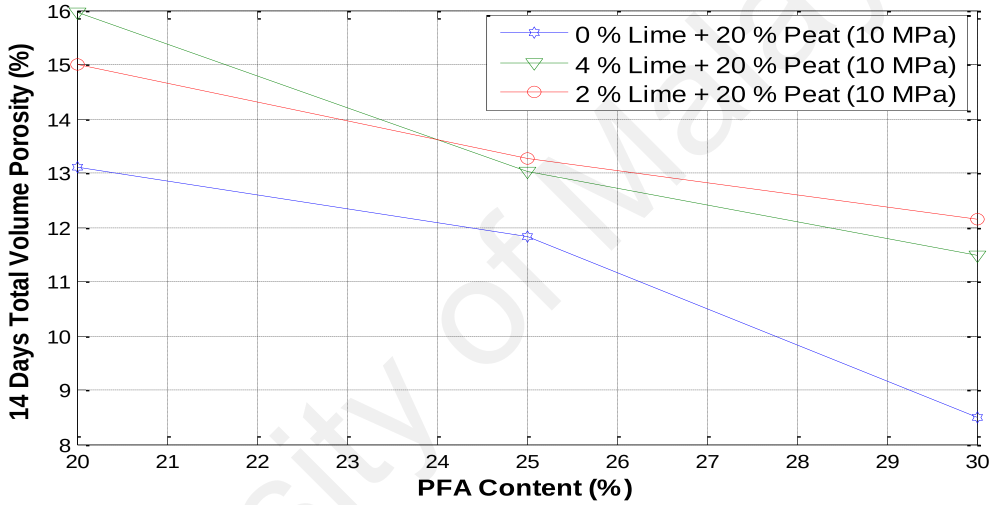
**Figure 4.30**: Effects of varying PFA cement content on brick porosity (a) at 3 Days, (b) at 7 Days, (c) at 14 Days and (d) at 28 days under 6 MPa compaction pressure



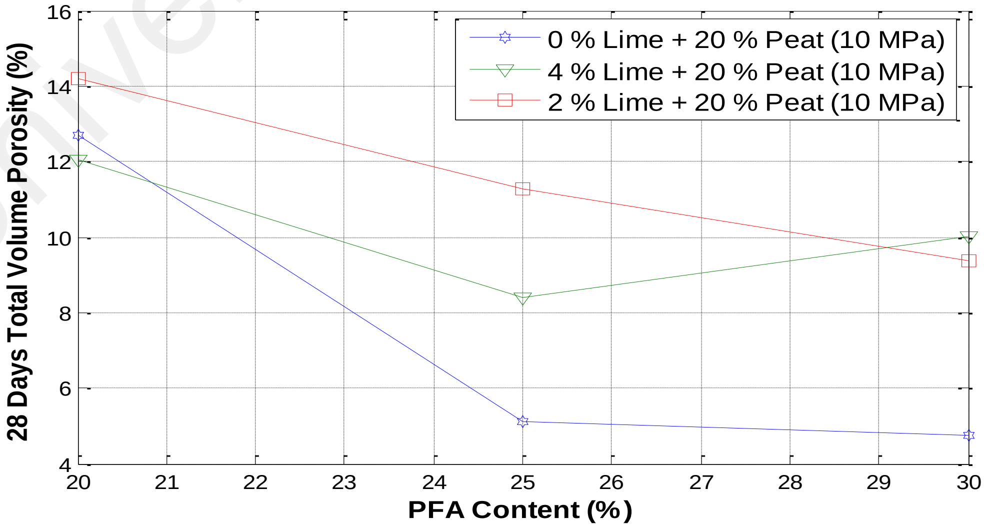

(a)




(b)




(c)




(d)

**Figure 4.31**: Effects of varying PFA cement content on brick porosity (a) at 3 Days, (b) at 7 Days, (c) at 14 Days and (d) at 28 days under 10 MPa compaction pressure.

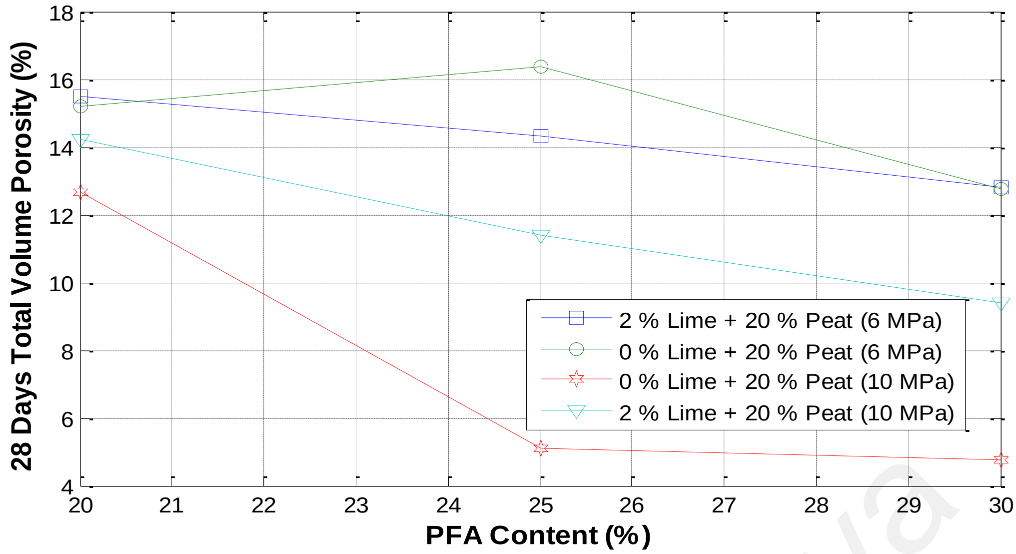



**Figure 4.32**: Effects of varying PFA cement content and compaction pressure on brick porosity at 28 days.

Figure 4.32 indicate that the porosity variation improvement with different pressures and different stabilisers content, that porosity decreased about 62.5% and 33.87% under 10 MPa compaction pressure with 0% and 2% lime, respectively. High compaction pressure gives lesser voids to improve density and strength.

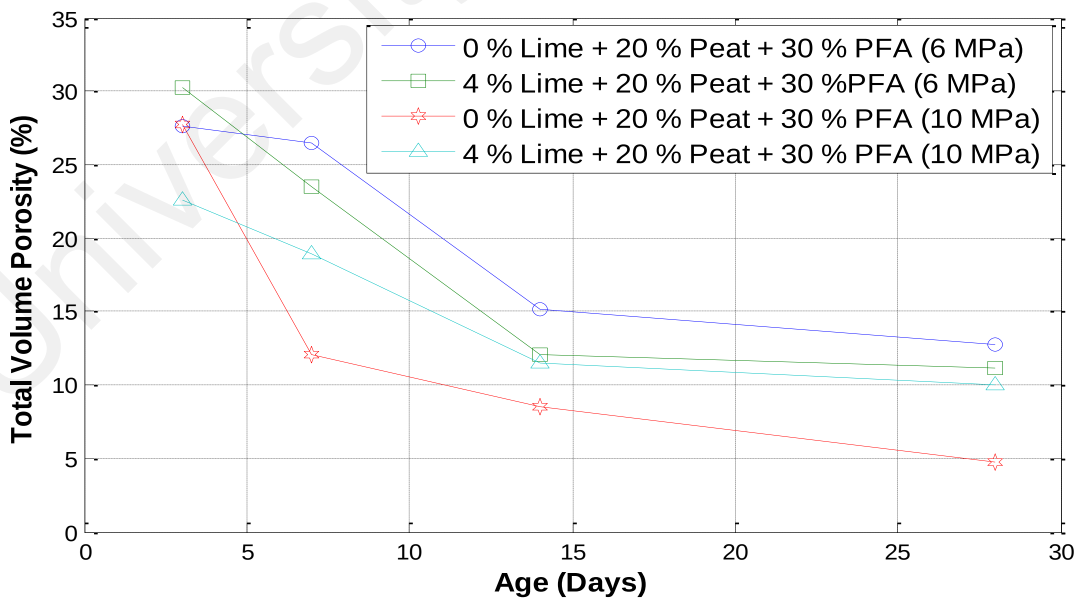



**Figure 4.33**: Effects of curing period, stabiliser content and compaction pressure on brick porosity.

Figure 4.33 shows that the porosity on CSPB decreased with increased curing period. Cement and lime with water created good bounding of soil and sand particles, the hydration of cement and lime with curing period increased strength and reduced voids between particles of samples. This reaction formed combinations of Tri-calcium silicate and Di-calcium silicate referred to as $C_3S$ and $C_2S$ in the cement literature, (Akroyd, 1962; Lea, 1970; Neville, 1995). The chemical reaction eventually generated a matrix of interlocking crystals that cover any inert filler and provide a high compressive strength and stability.

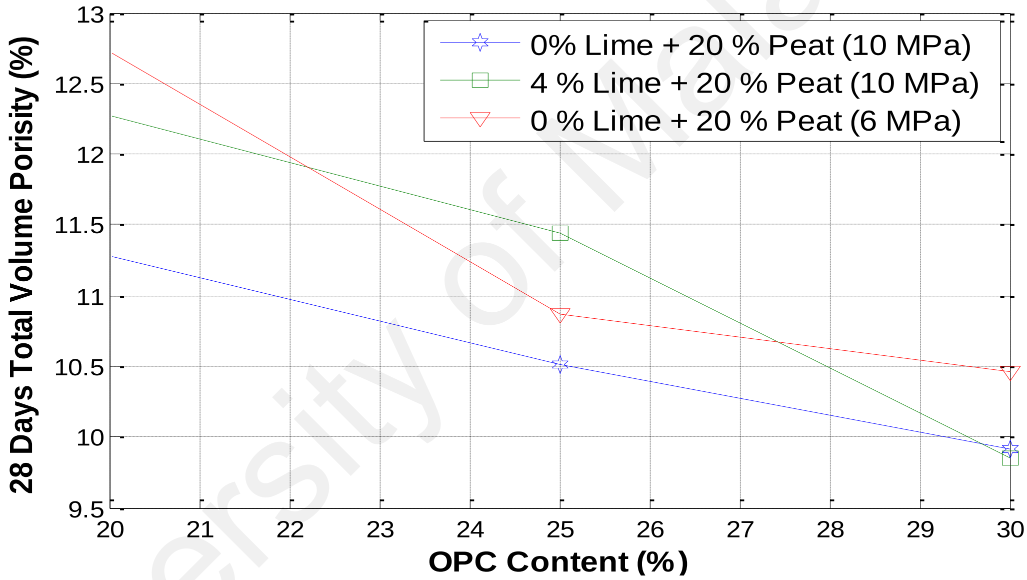



**Figure 4.34:** Effects of varying OPC content and compaction pressure on brick porosity at 28 days

Figure 4.34 and 4.35 show the effects of varying OPC content, lime and curing period on total volume porosity of compressed stabilised peat bricks. The results indicated that using OPC cement to stabilise peat soil as brick can achieve higher strength and lower porosity. Increasing content of OPC decreased the total volume porosity of brick. However the strength and durability improved, OPC content was increased from 20% to 30%, while volume porosity decreased by about 17.7% without lime under 6 MPa compaction pressure, 13.82% and 6.76% with 4% and 0% lime under 10 Mpa compaction pressure respectively. The effect of curing period from 3 to 28 days on total volume porosity indicated that the porosity decreased about 51.65% with (30% OPC and 0% lime) under 10 MPa compaction pressure, 49% with (30% OPC and 4% lime) under 10 MPa compaction pressure and 57.6% with (30% OPC and 2% Lime) under 6 MPa compaction pressure.

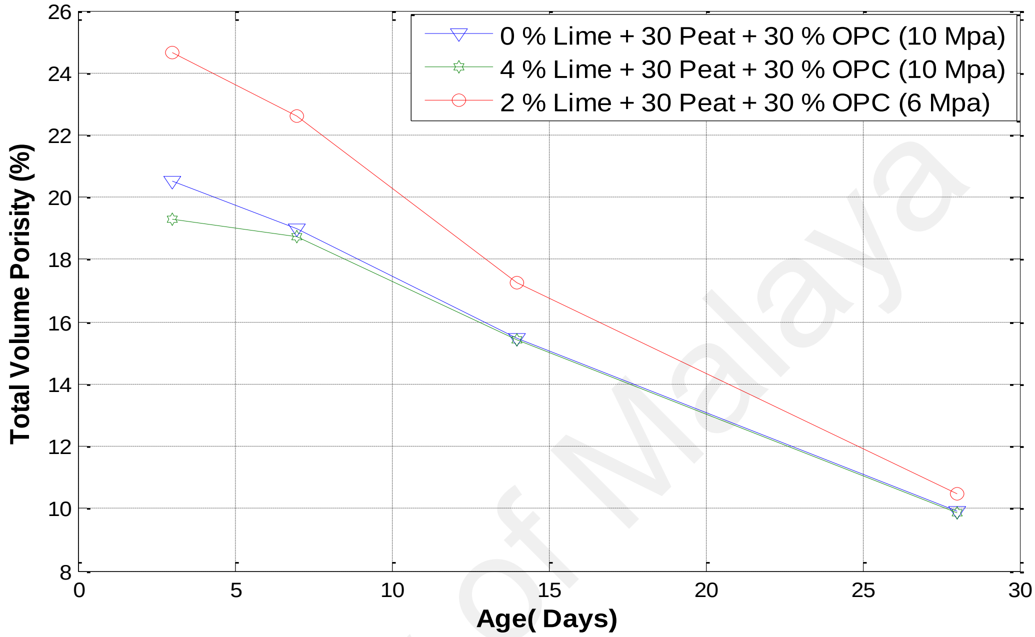



**Figure 4.35**: Effects of curing period and compaction pressure on brick porosity

### 4.6.1 Correlation Between Wet Compressive Strength and Volume Porosity

According to Figure 4.36, wet compressive strength and total volume porosity are negatively correlated. Increased porosity is accompanied by a decrease in strength. The coefficient of correlation for CSPB without lime under 6 MPa compaction pressure was -0.835 and -0.889, -0.467 without lime and 4% lime under 10 MPa respectively. A strong negative correlation coefficient therefore exists between the two variables. The effect of stabiliser and compaction pressure, 10 MPa compaction pressure and 30% PFA cement exhibited the lower porosity between 4.75% and 12.68%, 6 MPa compaction pressure and 30% PFA exhibited highest porosity between (12.79% and 15.47%). The coefficient of correlation varied between -0.994 to -0.839. Materials with total volume porosity above 30% are considered to be of high porosity (Jackson & Dhir, 1996). All the brick samples examined during this study can be therefore considered to be of low porosity.

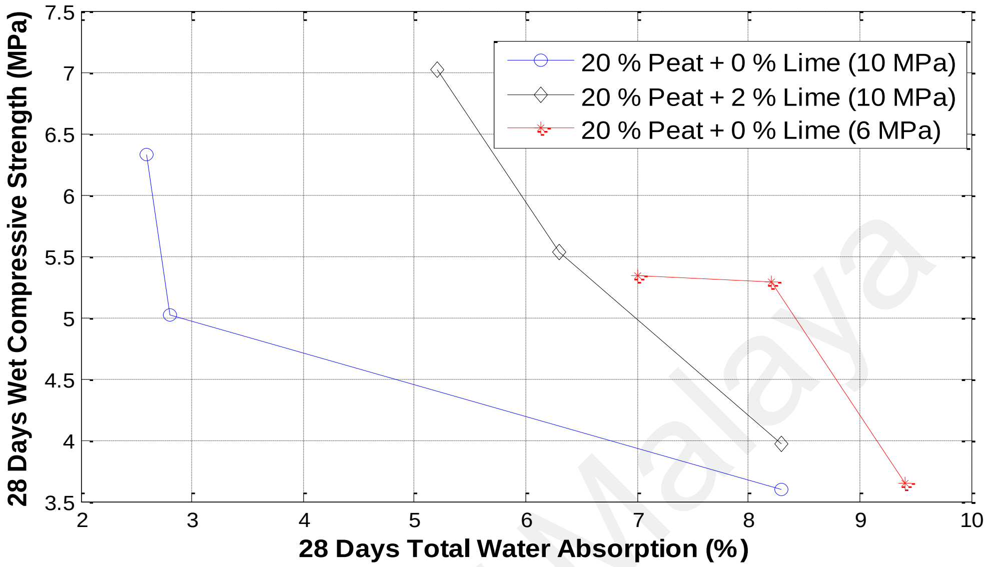



**Figure 4.36:** Correlation between wet compressive strength and total volume porosity with cement variation in CSPB

According to Anthony (2001), the decrease in compressive strength with increase in porosity can be partly explained as the compressive strength of a block or brick is limited by brittle fracture. Therefore it is sensitive to individual flaws in the block sample under test, and discontinuities between solid phases in a block (due to the presence of voids and pore structure) constitute in it. The higher the amount of voids, the weaker the block is to be. Large coarse soil fractions in a block can also create flaws in it. The combination of such large particles and voids in a block can make it more susceptible to brittle fracture failure.

### 4.6.2 Correlation Between Dry Density and Volume Porosity

The relationship between dry density and volume porosity was examined using the results obtained previously as presented in Figure 4.37. The results indicate that the increase in density decrease total volume porosity. The coefficient of correlation was -0.398 on mixture without lime and 20% to 30% cement under 6 MPa compaction pressure, -0.551 on mixture without lime and 20% to 30% cement content under 10 MPa pressure, and -0.323 on mixture with 4% lime and 20 to 30% cement. These statistical values confirm that a very strong negative correlation exists between the two properties. In this study, almost all brick samples examined showed that the increase in dry density is associated with a decrease in porosity. Increased density is accompanied by closer packing of the solids in a brick.

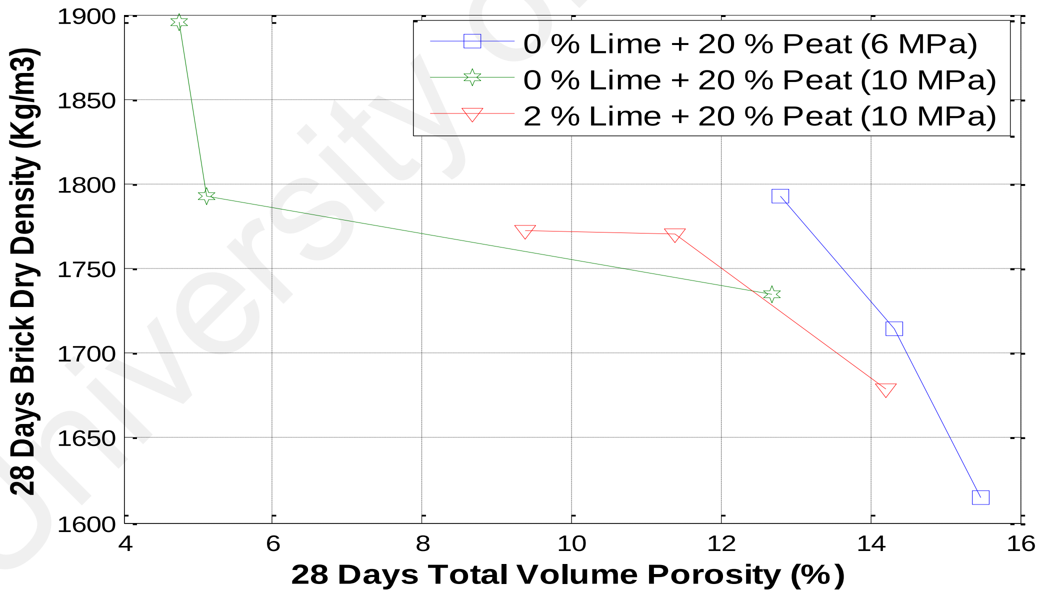



**Figure 4.37:** Correlation between brick dry density and total volume porosity with variation of stabilisers in CSPB.

## 4.7 Scanning Electron Micrographs of Untreated Peat and Compressed Stabilised Peat Brick

The Scanning Electron Microscope analysis of untreated peat was carried out and results are provided in Figures 4.38. Figure 3.39 shows the effect of curing of stabilised peat brick at 7, 14 and 28 days. The scanning micrographs of test specimens with the binder compositions of 20%, 25% and 30% of cement is presented in Figure 4.40. The results obtained indicate that the composition of untreated peat is vegetal fibre and organic matters. The organic coarse particles were typically hollow spongy. Such finding complements the idea of Kogure et al. (1993) regarding the multiphase system of peat in which the soil is divided into two major components, namely organic bodies and organic spaces. In the multiphase system of peat, pore opening not only occupies the outer space of the organic bodies but also their inner space (Wong, 2010).

Changes in microstructures with much reduced void spaces were evident in the stabilised peat brick samples after 7, 14 and 28 days of curing; it is evident from the Figures that significant flocculating effect of cement particles is visible with cementation products formed which were mainly calcium silicate hydrate crystals, that hardened as a result of cement setting. Formation of the cementation products was mainly attributed to the addition of 2% to 4% lime by mass of admixture of stabilised peat brick. Scanning Electron Microscopy of peat soil with 30% cement and 50% sand, it is evident that the flocculation and aggregation produced C-S-H gel as a result of pozzolanic reaction. Figure 4.39 clearly shows the effect of curing on compressed stabilised peat brick. On the 7$^{th}$ day the specimen indicated that the duration was not enough to bond sand and other particles of peat, the cement and lime needed more time to complete hydration. More curing time shows fewer voids between stabilised peat brick particles. Curing time reduces the voids and higher strength means compressed stabilised peat brick becomes more durable with curing time. Figure 4.40 shows compressed stabilised peat brick with different content of cement form 20% to 30%. From the results it is evident that increasing cement content on admixture significantly reduced the pore sizes caused by flocculation and aggregation due to the hydration process of the materials. One reason why organic matter retarded the hydration of cement was because it preferentially absorbed calcium ions and therefore, the addition of binder with high of calcium, such as hydrated lime, may often enable the soil to the treated (Ingles and Metcalf, 1972). Another aspect for consideration is rapid hardening cement which contains hydrated lime which may be useful. Siliceous sand graded particle was another contributing factor for high strength and much reduced voids of the compressed stabilised peat bricks.

Hydrated lime and siliceous sand, inclusion of a small quantity of superplasticiser in the cement of the stabilised peat brick mixture actually enhanced the cement dispersing performance. Good cement dispersing capability of the superplasticiser enabled water held in cement particle agglomerations to be released, thus improving workability of stabilised peat brick mixture and allowed more cement particles to react with water to produce the required cementations bonds (Wong, 2010). This reduced porosity and increased hydration in the stabilised peat brick mixture resulting in the formation of the stabilised soil of high early strength.

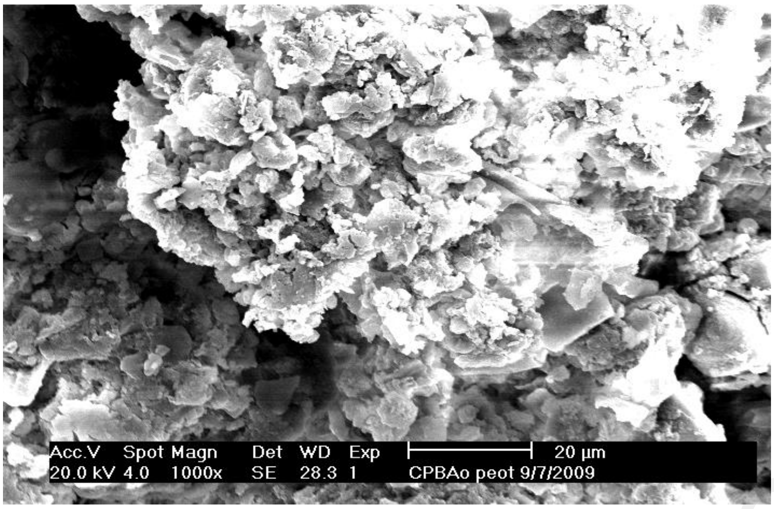
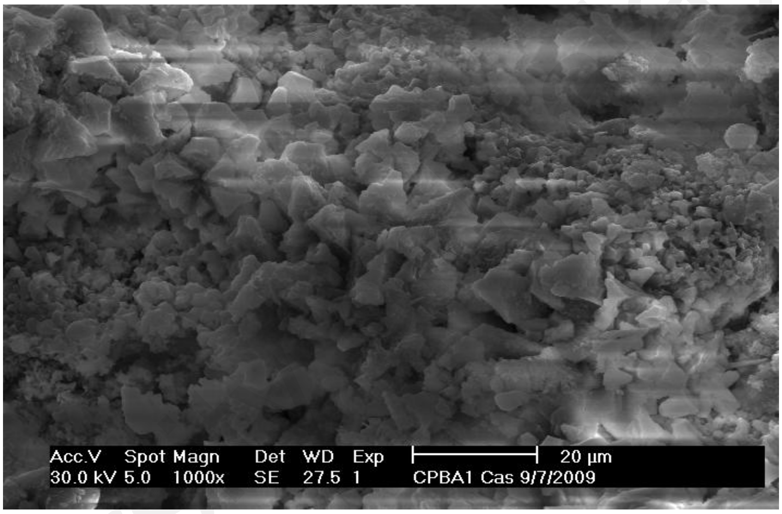
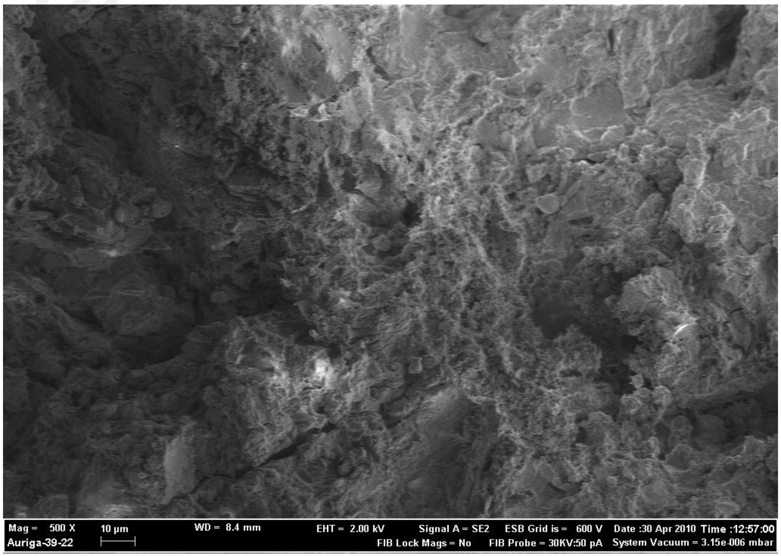


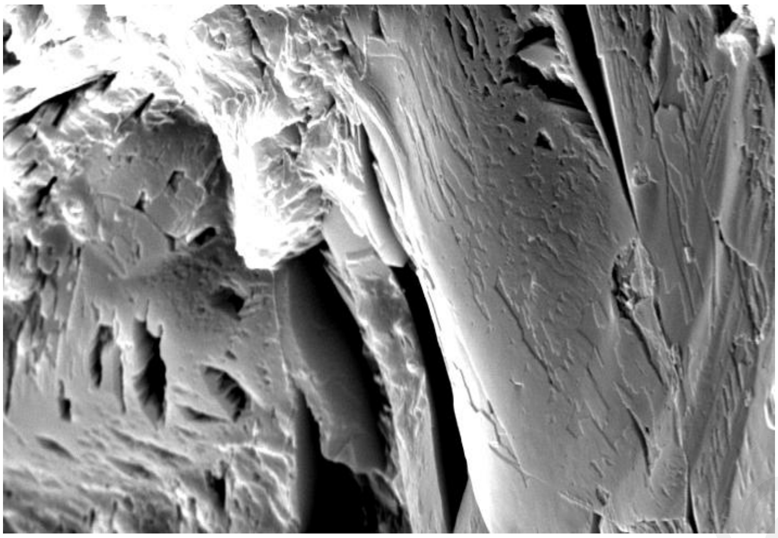

**Figure 4.38**: Scanning Electron Microscopy of untreated peat




**(a)**

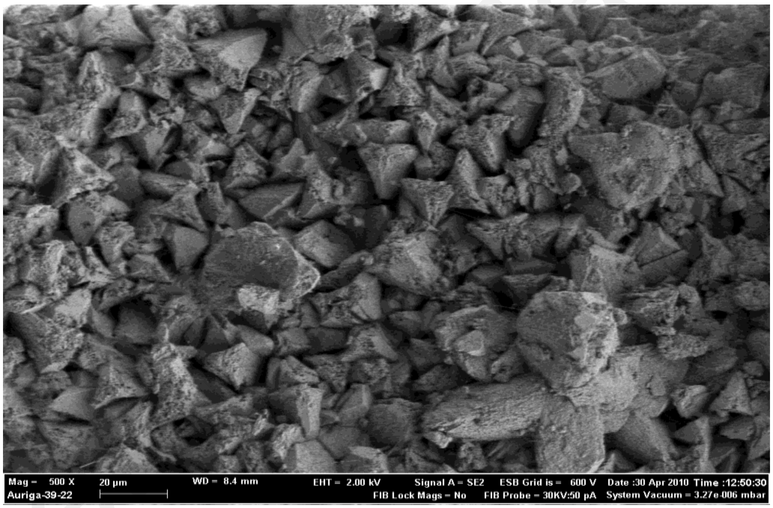



**(b)**

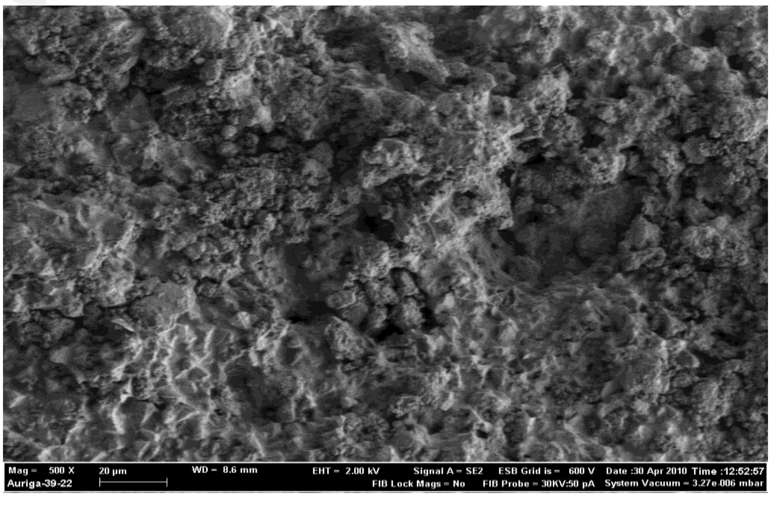


**(c)**

**Figure 4.39**: Scanning Electron Microscopy of stabilised peat. (a), at 7 days; (b) at 14 days and (c) at 28 days




**(a)**

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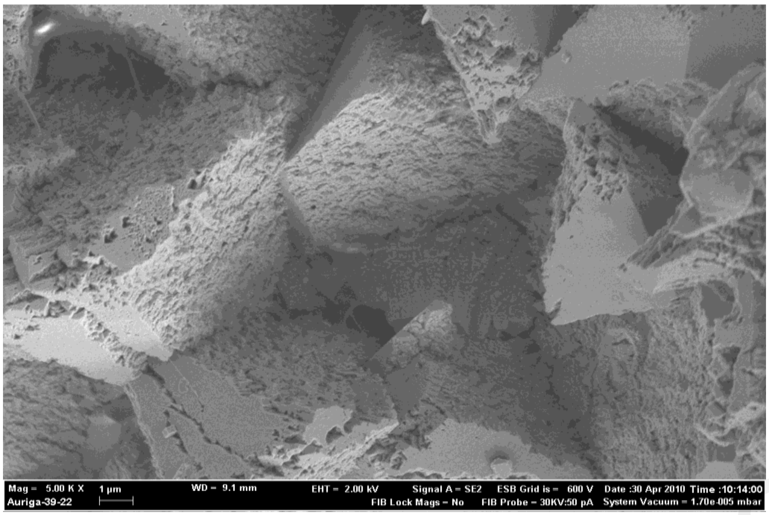



**(c)**

**Figure 4.40:** Scanning Electron Microscopy of stabilised peat brick at binder of composition (a) 20 % PFA cement, (b) 25 % PFA cement and (c) 30% PFA cement

## 4.8 Consistency Limit and Shrinkage of Compressed Stabilised Peat Brick

### 4.8.1 Linear Shrinkage on CSPB

Linear shrinkage tests were performed using standard semicircular linear shrinkage moulds of 25 mm diameter x 140 mm length. The tests aimed to examine the reduction in linear shrinkage of stabilised peat brick specimen. The tests were also performed to estimate the plasticity index (PI) of the stabilised peat brick, since the peat was stabilised by cement, lime and siliceous sand. For soils with very small clay content, the liquid and plastic limit tests may not produce reliable results (Whitlow, 2004). Hence, linear shrinkage (LS) can be used to approximate the soil plasticity index (PI) with the following equation:

$$PI = 2.13 \times LS \quad \text{Eq 4.2}$$

Linear shrinkage of stabilised peat brick specimen, drying of organic coarse particles causes shrinkage of thin-walled tissues and collapse of cell structure, thereby decreasing particle porosity and water holding capacity (Terzaghi et al., 1996). Analysis of Figure 4.41 shows that the average linear shrinkage of stabilised peat bricks specimen was significantly reduced to 49%, 35.85% and 36.8 with variation of cement from 20% to 30% and variation of lime from 0%, 4%, and 2% respectively.

The effects of stabiliser on compressed stabilised peat brick, PFA, OPC and lime used for stabilise peat brick were investigated. Figures 4.41 and 4.42 describe the variation of linear shrinkage of stabilise soil with cement and lime contents. The addition 20% to 30% content of PFA cement reduced the linear shrinkage by about 49%, 35.85% and 36.8% with 0%, 4% and 2% lime respectively. Increase from 20% to 30% of OPC to peat soil and sand decreased the linear shrinkage by about 78%, 7.78% and 17.34% with 0%, 4% and 2% lime respectively. The results also indicated OPC on CSPB caused lower shrinkage than PFA cement, but perhaps the ash in PFA cement led to high shrinkage. Ajam et al. (2009) and Alviset (2002) investigated the shrinkage of phosphogypsum clay bricks and reported that the firing shrinkage should lie between 0.5% and 3%. In this study, linear shrinkage for all samples was lower than 3%.

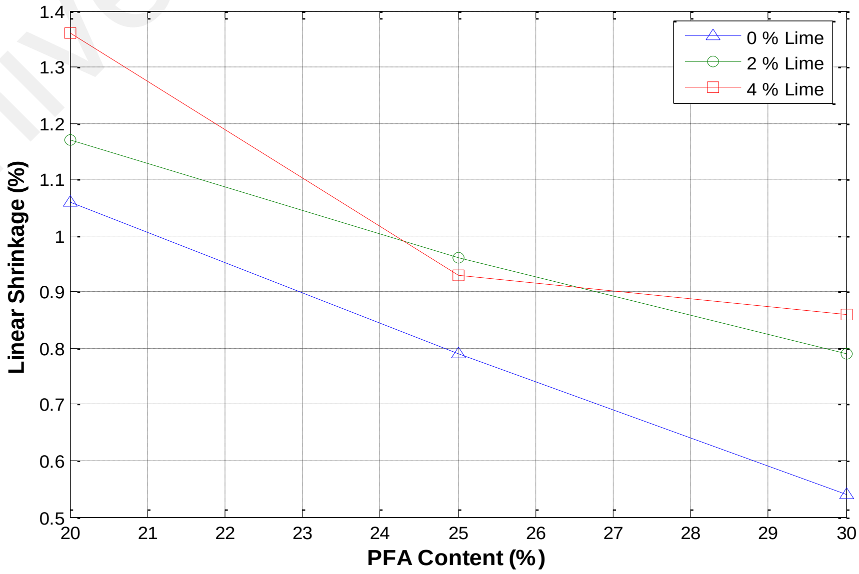



**Figure 4.41:** Effects of stabiliser (PFA and Lime) content on linear shrinkage of CSPB

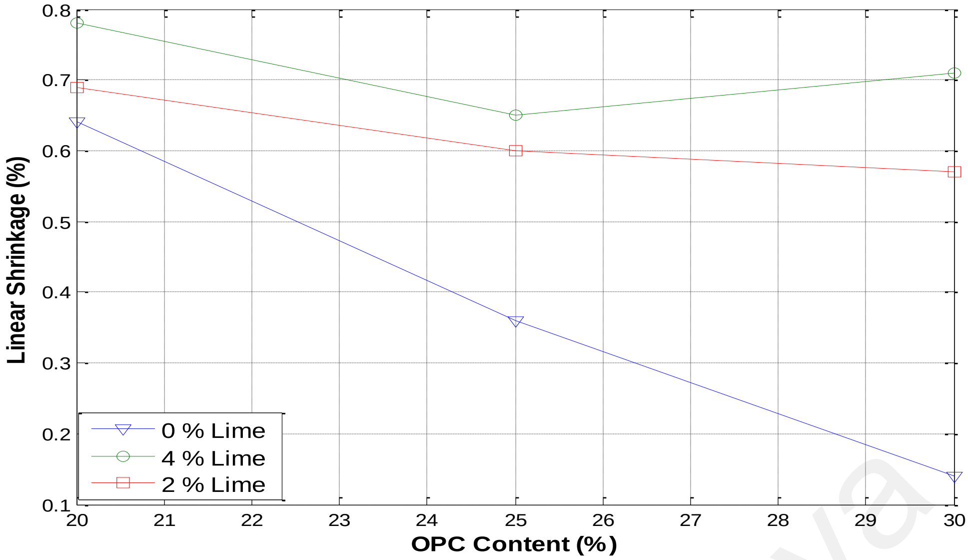



**Figure 4.42:** Effect of stabiliser (OPC and Lime) content on linear shrinkage of CSPB

### 4.8.2 Plasticity Index on Compressed Stabilised Peat Brick

The plasticity index of stabilised peat brick with different content of cement and lime can be noted from Figure 4.43. The average plasticity index of the soil with additives was significantly reduced between 49%, 37% and 32% with 30%, 25%, 20% PFA cement content and 0%, 4%, 2% lime respectively. Drastic reduction in the average linear shrinkage and plasticity index of the stabilised peat brick specimen indicated that the mixture had less moisture sensitivity and better volume stability after stabilisation with the binder and siliceous sand. Ajam et al. (2009) reported that the dry shrinkage of PG brick was 1.85%.

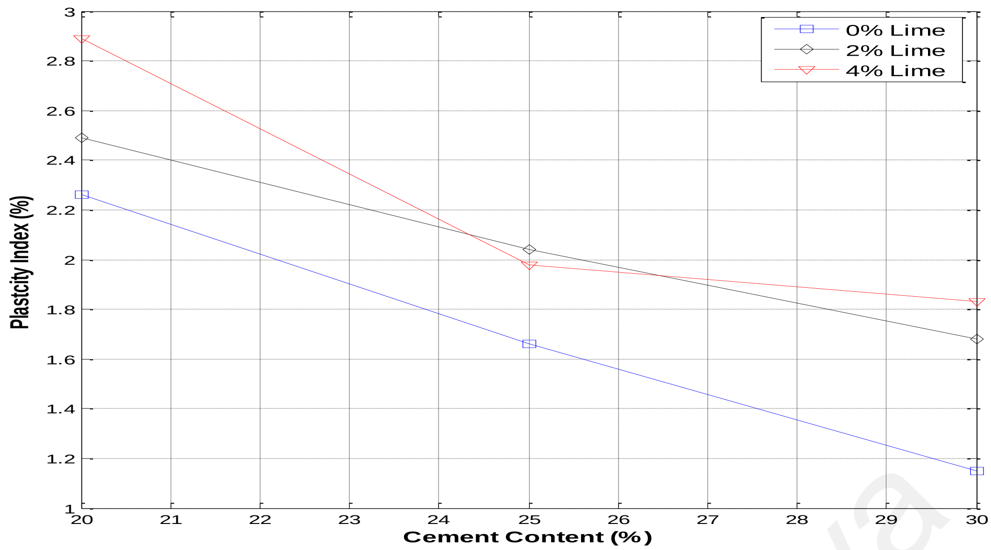



**Figure 4.43:** Effects of cement content and lime on plasticity index of CSPB

### 4.9 Stress Strain Characteristics of Solid CSPB Masonry under Axial Loading

Masonry walls are used in almost all types of building construction in many parts of the world because of its low cost, good sound insulation, fire resistance rating, easy availability, and locally available materials and skilled labour. Masonry is typically a nonelastic, nonhomogeneouse and anisotropic material composed of two materials of quite different properties: stiffer bricks and relatively cost effective mortar. Masonry is very weak in tension because it is composed of two different materials distributed at regular intervals and the bond between them is weak. Therefore, masonry is normally provided and expected to resist only the compressive forces.

During compression of masonry prism constructed with stiffer bricks, mortar of the bed joint has a tendency to expand laterally more than the bricks because of lesser stiffness. However, mortar is confined laterally at the brick-mortar interface by the bricks because of the bond between them; therefore, shear stresses at the brick-mortar interface result in an internal state of stress which consists of triaxial compression in mortar and bilateral tension coupled with axial compression in bricks. This state of stress initiates vertical splitting cracks in bricks that lead to failure of the prism (McNary and Abrams, 1985; Atkinson and Noland, 1983; Drysdale et al., 1994). Since masonry is assemblage of bricks and mortar, it is generally believed that the strength and stiffness of masonry would lie somewhere between that of bricks and mortar.

In order to evaluate the effect of the axial load on the CSPB masonry resistance and collapse mechanism, and with the aim of extending the classical approach to masonry collapse, in this study a test was performed on small prism of 400 x 100 x 220 $mm^3$ solid compressed stabilised peat brick and four 12 mm thick mortar at 28 days of age; which was intended to represent typical brick work. The global height of the stack was 400 mm. The testing setup is represented in Figures 3.13 and 3.14.

The vertical displacement of the upper part of machine is controlled and locked by means of mechanical device. The displacements between the specimen ends are measured by related to data logger. The axial load reading transferred directly to the machine window. The moving end of the machine is displacement controlled, while the load is measured automatically, reading of load is presented in screen window of machine.

Masonry prism was constructed using combination of five bricks and four mortar grades, and stress-strain curves were obtained by averaging the three specimens of each combination. Compression testing was done following ASTM C 1314-00 a (ASTM 200b) and (IS 1905, IS 1987). The summary of results including prism strength ($f'_m, f_b, f_m$), failure strain, and modulus of elasticity ($E_b$, $E_m$, and $E'_m$) are given in

Table 4.2. Failure of the majority was due to the formation of vertical splitting cracks along their height.

Determination of the states of stress-strain, the experimental method can be replaced with the formulation recommended by Uniform Building Code (UBC, 1991) of America. The modulus elasticity of masonry prism ( $E'_m$) in compression can be calculated using the following equation:

$$E'_m = \frac{(1+\gamma_t)}{(1+\frac{\gamma_t}{\gamma_m})} E_b \qquad \text{Eq. 4.3}$$

$$\gamma_t = \frac{t_m}{t_b}$$

$$\gamma_m = \frac{E_m}{E_b}$$

**Table 4.2**: Summary results of brick, mortar and masonry prism

| **Properties** | | **Values** |
|---|---|---|
| Compressive strength of brick | $f_b$ | 7.18 MPa |
| Compressive strength of mortar | $f_m$ | 32 MPa |
| Compressive strength of masonry prism | $f'_m$ | 2.59 MPa |
| Thickness of brick | $t_b$ | 70 mm |
| Thickness of mortar | $t_m$ | 12 mm |
| Thickness of masonry prism | $t'_m$ | 100 mm |
| Module elasticity of brick | $E_b$ | 2500 N/$mm^2$ |
| Module elasticity of mortar | $E_m$ | 3500 N/$mm^2$ |
| Module elasticity of masonry prism | $E'_m$ | 2578 N/$mm^2$ |

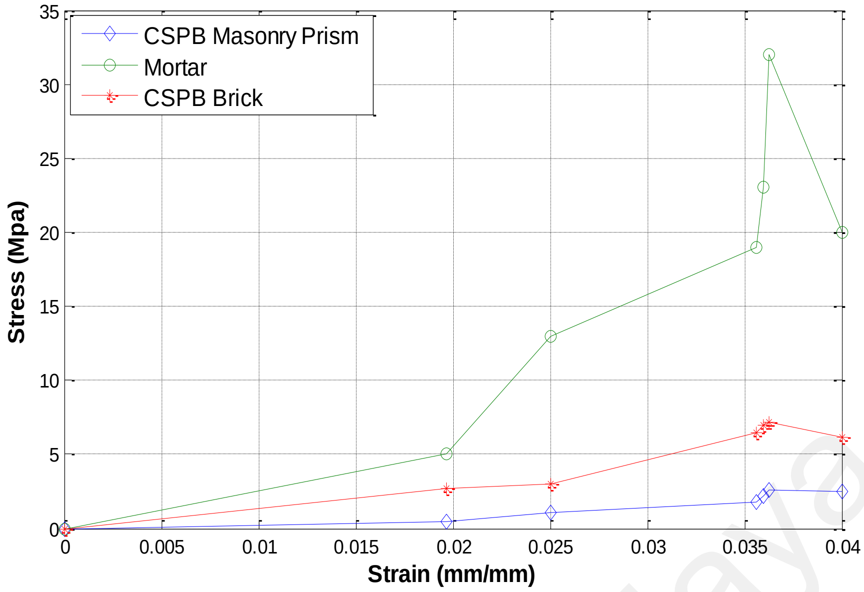



**Figure 4.44**: Compressive stress-strain curve

Figure 4.44 shows the compressive stress of mortar which was higher than the brick and masonry prism, preparation of mortar gives high compressive strength at 28 days.

Experimental results show that $E'_m$ can be directly correlated with $f'_m$ and it was found 2580 $N/mm^2$.

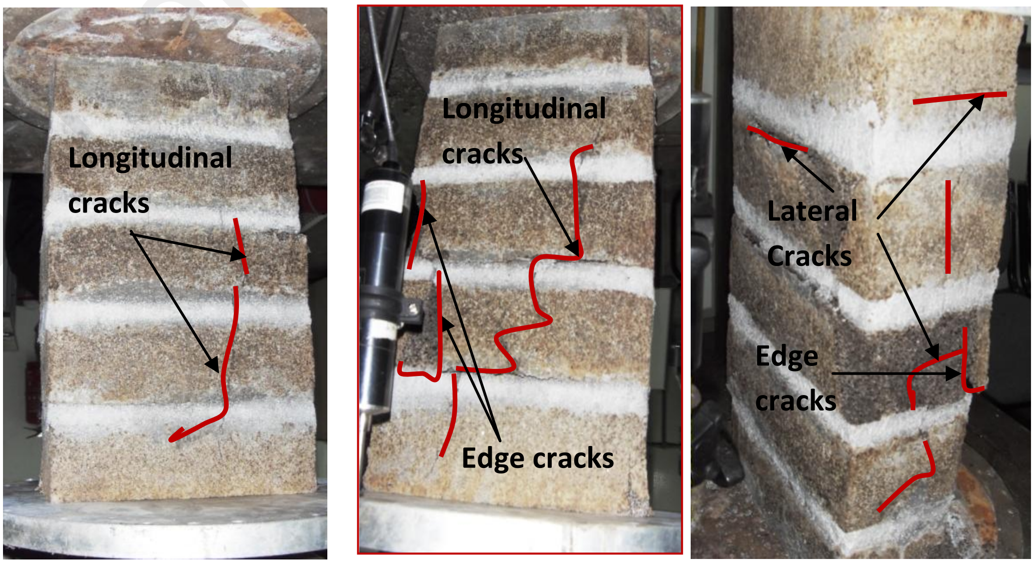



**Figure 4.45**: Cracks pattern evolution of axial loading

The masonry prism with cement-sand mortar found that the module elasticity $E'_m$ 2580 N/$mm^2$ was higher than the module of elasticity of compressed stabilised brick which was 2500 N/$mm^2$.

Whilst in Figure 4.45 where a typical crack pattern is evident, thus the specimen is applied with axial load and after which there was failure of masonry prism. Figure 4.45 shows that crack was almost longitudinal to the specimen. Many other cracks indicate that such a phenomenon took place also in the central and edge of bricks. The cracks extended to the mortar joint, only when some parts of the brick tended to detach. Many failure theories were used to foresee the compressive strength of masonry. Table 4.3 summarises the estimates of the compressive strength according to some of these theories.

**Table 4.3**: Comparison between experimental results and previous results on masonry prism

| **Compressive strength of masonry prism** | | |
|---|---|---|
| **Reference** | **Experimental values MPa** | **Present results MPa** |
| Sarangapani et al. (2002) clay prism | 2.5 | 2.59 |
| Tomaževič (1999) clay prism | 1.6 | 2.59 |
| Sarangapani et al. (2005) clay prism | 3.2 | 2.59 |

## 4.10 Experimental and Numerical Modelling of Compressed Stabilised Peat Brick Masonry Prism.

Recent advancement in mathematical modelling structurally has seen the development of numerous research work of masonry prism of compressed stabilised peat brick through experimental and numerical methods. However to date, there is no experimental and numerical solutions that have solved the analysis of compressed stabilised peat brick masonry prism. This is mainly because there has been no previous research for compressed stabilised peat bricks. Following the success of producing compressed stabilised peat brick used for walls as masonry prism, there is dire need to test the effects of stabiliser types and content, compaction pressure, curing period, and siliceous sand content. The test was carried out in order to evaluate the axial compressive stress-strain and vertical displacement of compressed stabilised peat brick masonry prism constructed with five units of compressed stabilised peat bricks and four layers of mortar with thickness 12 mm (1 cement : 4 siliceous sand). The masonry having approximate length, width and height as 220 mm, 100 mm, and 400 mm, the top vertical load was 30 KN, 45 KN, and 57 KN. Properties of compressed stabilised peat bricks, mortar and clay brick are presented in Tables 4.4 and 4.5.

Masonry walls are used in almost all types of building construction in most parts of the world because of low cost, good sound and heat insulation properties, easy availability, and locally available raw material. Numerical analysis of masonry walls requires the material properties and constitutive relationships of masonry and its constituents. In this study, the main concern is with axial compressive stress-strain behaviour of solid compressed stabilised peat brick masonry prism. The basic mechanical properties of the masonry are strongly influenced by the mechanical properties of its compositions, namely, brick and mortar. Using the material parameters obtained from experiments and actual geometric details of both components and joint, it is possible to reproduce the behaviour of masonry numerically (Lotfi and Shing, 1994).

In the present study, models with two different material assumptions are presented as one; both phases of the material are replaced with an equivalent material property, assuming it to be a homogenous material. It proposes a failure criterion for masonry in which, the ultimate behaviour of masonry is described by the classical linear elastic relation. To demonstrate the applicability of such models, the results of the experimental investigation performed earlier will be used. The equation for homogenous material module elasticity is presented in Eq. 4.3.

**Table 4.4**: Properties of CSPB masonry prism

| **Properties** | | **Values** | |
|---|---|---|---|
| Thickness of brick | $t_b$ | 70 | mm |
| Thickness of mortar | $t_m$ | 12 | mm |
| Thickness of masonry prism | $t'_m$ | 400 | mm |
| Module elasticity of brick | $E_b$ | 2500 | $N/mm^2$ |
| Module elasticity of mortar | $E_m$ | 3500 | $N/mm^2$ |
| Module elasticity of masonry prism | $E'_m$ | 2578 | $N/mm^2$ |
| Dimension of masonry prism | (X, Y, Z) | 220 x 100 x 400 $mm^3$ | |

**Table 4.5**: Properties of clay brick masonry prism (Hemant et al., 2007)

| **Properties** | | **Values** | |
|---|---|---|---|
| Thickness of brick | $t_b$ | 70 | mm |
| Thickness of mortar | $t_m$ | 12 | mm |
| Thickness of masonry prism | $t'_m$ | 100 | mm |
| Module elasticity of brick | $E_b$ | 2630 | $N/mm^2$ |
| Module elasticity of mortar | $E_m$ | 3592 | $N/mm^2$ |
| Module elasticity of masonry prism | $E'_m$ | 3750 | $N/mm^2$ |
| Dimension of masonry prism | (X, Y, Z) | 220 x 100 x 400 $mm^3$ | |



### 4.10.1 Numerical Analysis

Using eight node isoparametric brick elements, the model had been discretised into 26 elements using homogenised material (brick and mortar) for analysis of compressive stress-strain. Figure 4.46 presents dimension of a typical five compressed stabilised peat bricks and four layers of mortar. The boundary condition adopted was that all nodes at the base of the model were assumed to be fixed.

Each solid element has its own local coordinate system for defining material properties and interpreting output. Stresses in the element local coordinate system are evaluated at the integration points and approximated to the joints of the element. Each solid element has six rectangular faces, with a joint located at each of the eight corners as shown in Figure 4.46.

### 4.10.2 Analysis of Model as a Homogenous Material

In this analysis, the compressed stabilised peat brick, which was compressed stabilised peat and cured 28 days (14 days in water and 14 days in the moist cured), the brick compressive strength at 28 days was 7.18 MPa. The mortar composition is 1:4 (cement, siliceous sand), the compressive strength was 32 MPa at 28 days. Determination of vertical displacement and stress-strains was carried out with the aid of finite element analysis. The equivalent material properties can be determined by experimental method.

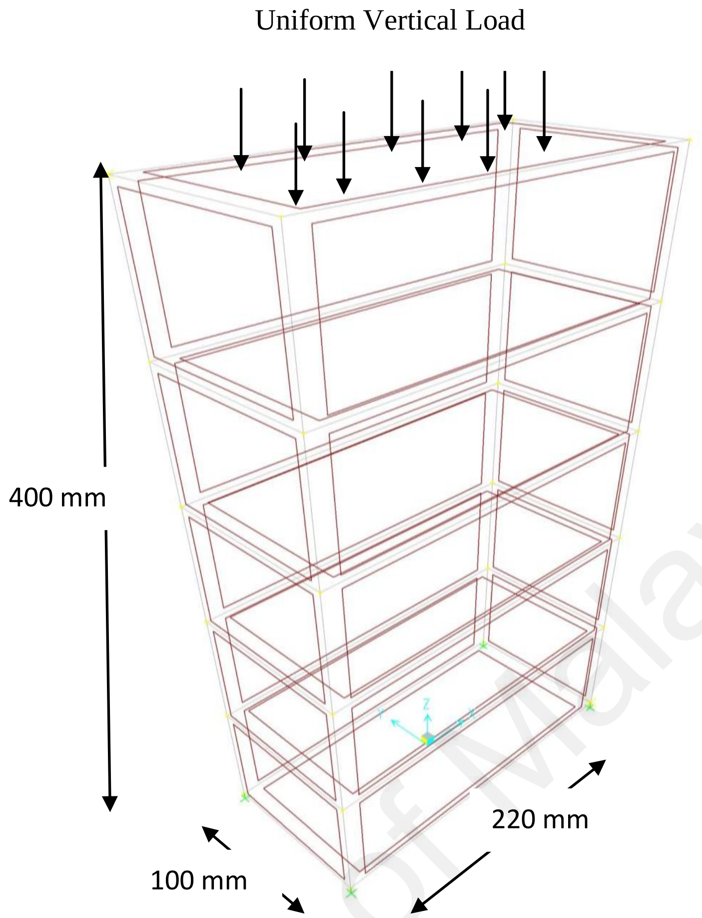



**Figure 4.46:** Prism constituent into five bricks and four layers of mortar

The aim of analytical modeling is to represent the behaviour of a real structure in mathematical terms. Because of this reason, before any analysis, a model should be developed in order to understand the effects of loads, understand the load transfer mechanism within the structure and to determine the load capacity etc. The need for a simple model arises from the complexity of the nature of historical masonry construction materials. Under this circumstance, some idealisations are needed. The most important idealisations through analytical modeling are;

- Idealisation of geometry
- Idealisation of material behaviour

However, a good analysis should be as simple as possible as long as it adequately represents the effects of loads on the structure.

#### 4.10.2.1 Idealisation of the Geometry

Lourenço (2002) reported that one of the basic principles of creating an analytical model is creating a geometrical model. However, it is difficult to distinguish between the structural and decorative elements in case of historic masonry structures. As a general rule, the geometric idealisation should be as simple as possible providing that the model is adequate for the problem being analysed.

The geometrical representation can be made by using frame, shell or solid elements. No element type is superior to the other. The decision of the element type is completely dependent on the complexity of the problem. For example, it would be unnecessary to use solid elements for the out of plane investigation of a masonry wall. Instead of solid elements, it would be enough to use shell elements for such investigation.

#### 4.10.2.2 Idealization of the Behaviour

The basic idealisations for the analysis of masonry are elastic behaviour (linear), inelastic behaviour (non-linear) and plastic behaviour. The basic assumption of elastic analysis is that the material obeys Hooke's law. The increase or decrease of strain is directly proportional to the decrease or increase of stress. The deformations are fully recovered when the applied actions are removed. Linear elastic behaviour is mostly valid for the masonry under tensional loading. Plastic analysis methods are usually performed for determining the load at failure. However, the application of plastic analysis is not practical for large structures (Lourenço 2002; Lourenço 2001). When plastic analysis methods are concerned, the main assumption is that masonry has no tensile strength and infinite compressive strength. The most powerful and realistic idealisation method for the analysis of masonry is the non-linear material assumption. The behaviour of the structure can be observed through elastic range up to the time of failure. The cracks through loading can be simulated by redistribution of stresses were cracks occur.

The method for numerical representation depends on the scale of the problem and the intended calculations. A detailed micro-element represents the behaviour of mortar and masonry separately. Simplified micro-element represents the bricks as a continuum, however the mortar interface is assumed to be a lumped interface. The macro models are used for plastic analysis and they represent the mechanical properties of masonry as a homogeneous material (Lourenço, 1998). The analysis results of compressed peat brick masonry prism are presented in Tables 4.6, 4.7 and 4.8 and Figures 4.46 to 4.56.

**Table 4.6**: Maximum displacement of masonry prism with different load case (12 mm Mortar thickness)

| Load case | Load values | Maximum displacements (mm) |
|---|---|---|
| 1 | 30 kN | 4.2 mm |
| 2 | 45 kN | 6.3 mm |
| 3 | 57 kN | 7.9 mm |

**Table 4.7**: Maximum stress- strain of masonry prism with different load case(12 mm Mortar thickness)

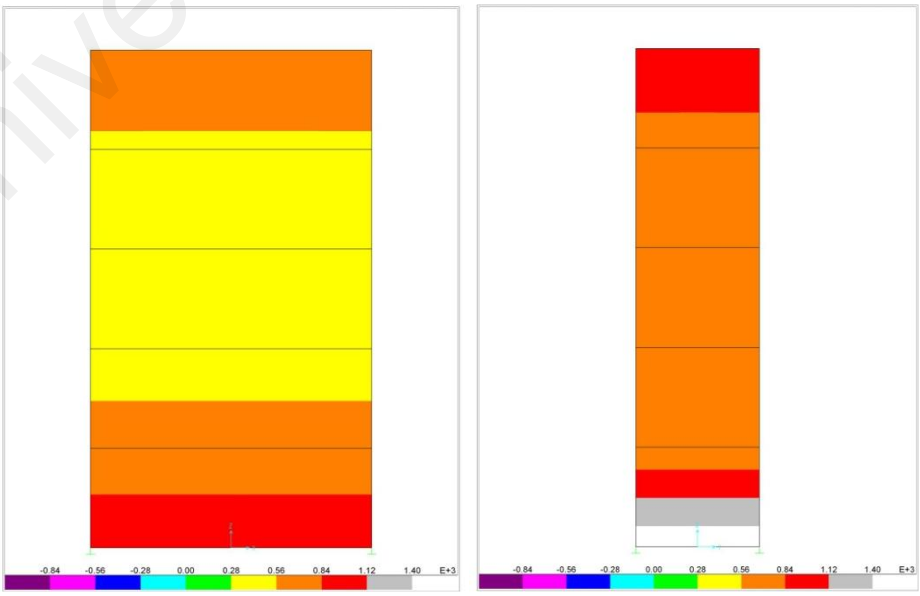
| Load case | Load values | Maximum stress MPa | Maximum strain |
|---|---|---|---|
| 1 | 30 kN | 1.40 | 0.0105 |
| 2 | 45kN | 2.25 | 0.0157 |
| 3 | 57 kN | 2.75 | 0.0362 |

**Table 4.8**: Maximum internal forces of masonry prism with different load cases (12 mm Mortar thickness).

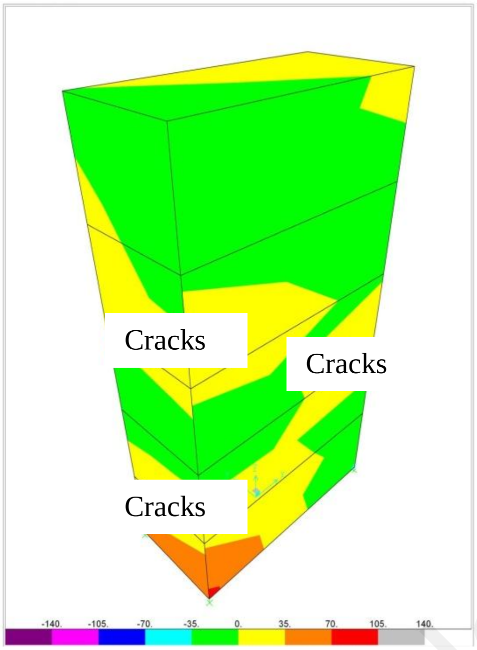
| Load case | Load values | Maximum internal forces (kN) |
|---|---|---|
| 1 | 30 kN | 0.250 |
| 2 | 45 kN | 0.375 |
| 3 | 57 kN | 1.75 |

Figure 4.47 presents the maximum stresses of masonry prism under the first case of load. It was observed that the stress is very strong in the bottom as the left and right sides were greater than 1.40 MPa and very weak in the middle of the masonry prism which varied between 0 and 0.5 MPa. It was observed from Figure 4.47 (b) that the stress was stronger at the bottom of the small face of masonry prism. Figure 4.47 (c) shows evidence of the most cracks in the masonry prism was in the middle and bottom.

When the load displacement diagram was investigated, it was observed that a very brittle failure occurs when the inertial force is 0.250 kN as presented in Figure 4.48. The maximum deformation observed is 4.20 mm.

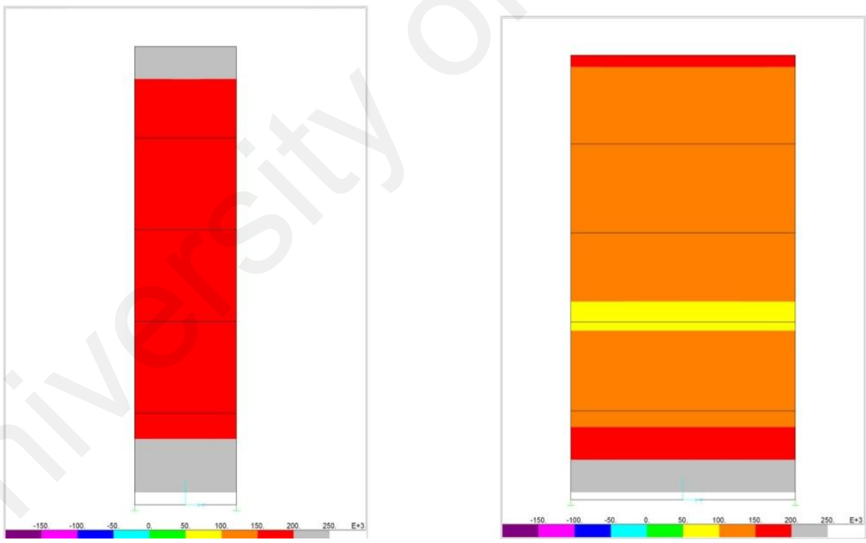



(a) (b)




(c)

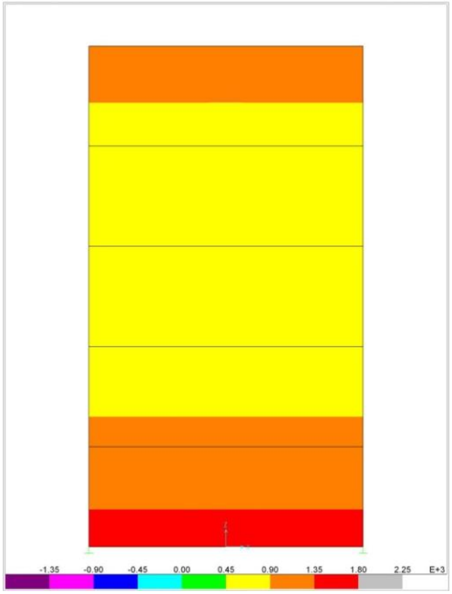
**Figure 4.47**: Load case 1: Stress for masonry prism: (a) Stress in the left side, (b) Stress in the right side, and (c) Evaluation of cracking at masonry prism



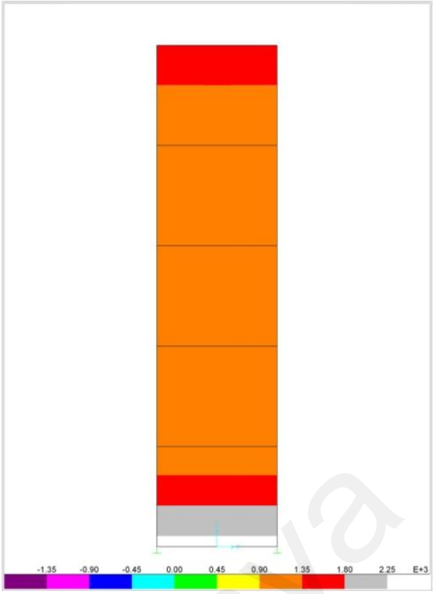
(a) (b)

**Figure 4.48**: Load case 1: Internal forces for masonry prism: (a) Forces in the left side, (b) Forces in the right side

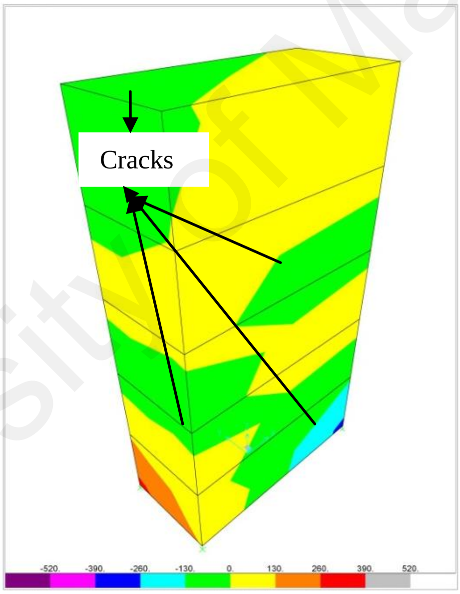
The higher displacement of masonry with 30 kN was in the middle of masonry prism because in middle of masonry prism the stresses and internal forces obtained from Figure 4.47, 4.48(a) and 4.48 (b) were very small or negative values.




(a)

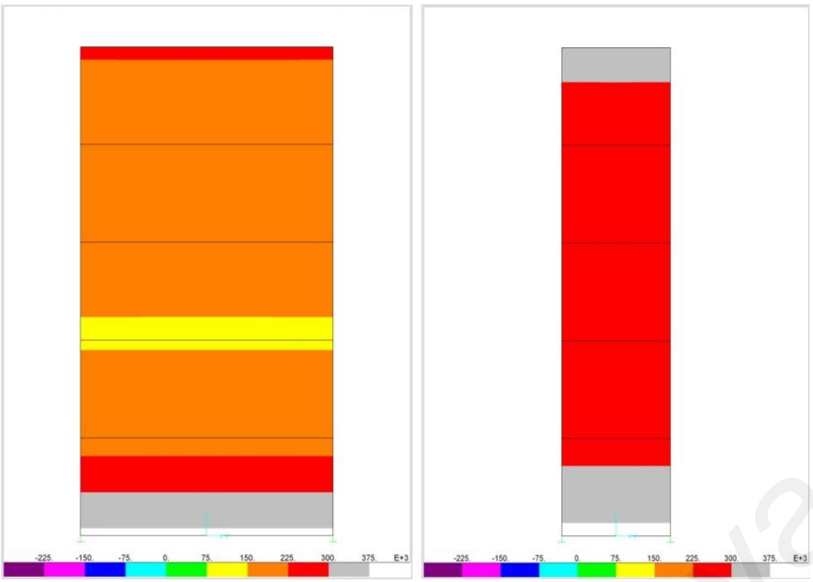



(b)




(c)

**Figure 4.49**: Load case 2: Stress for masonry prism: (a) Stress in the left side, (b) Stress in the right side, and (c) Evaluation of cracking of masonry prism




(a) (b

**Figure 4.50**: Load case 2: Internal forces for masonry prism: (a) Forces in the left side, (b) Forces in the right side

For the second case of load (45 kN) the stresses and internal forces presented are as found in Figures 4.49 and 4.50. Figure 4.50 obtained that the limit load reached by the FEM model with a 2.25 N/mm$^2$. From the results, it showed that increasing the vertical loading for masonry increases the stresses; however the internal forces also increase with increase load. Figure 4.50 (a) and 4.50 (b) obtained the great internal forces in the bottom of masonry prism as well as in the bottom and top in the small side of masonry. Figure 4.49 (c) shows the cracks in the top edge and middle of the masonry prism. The vertical displacement for second case of load (45 kN) was 6.3 mm.

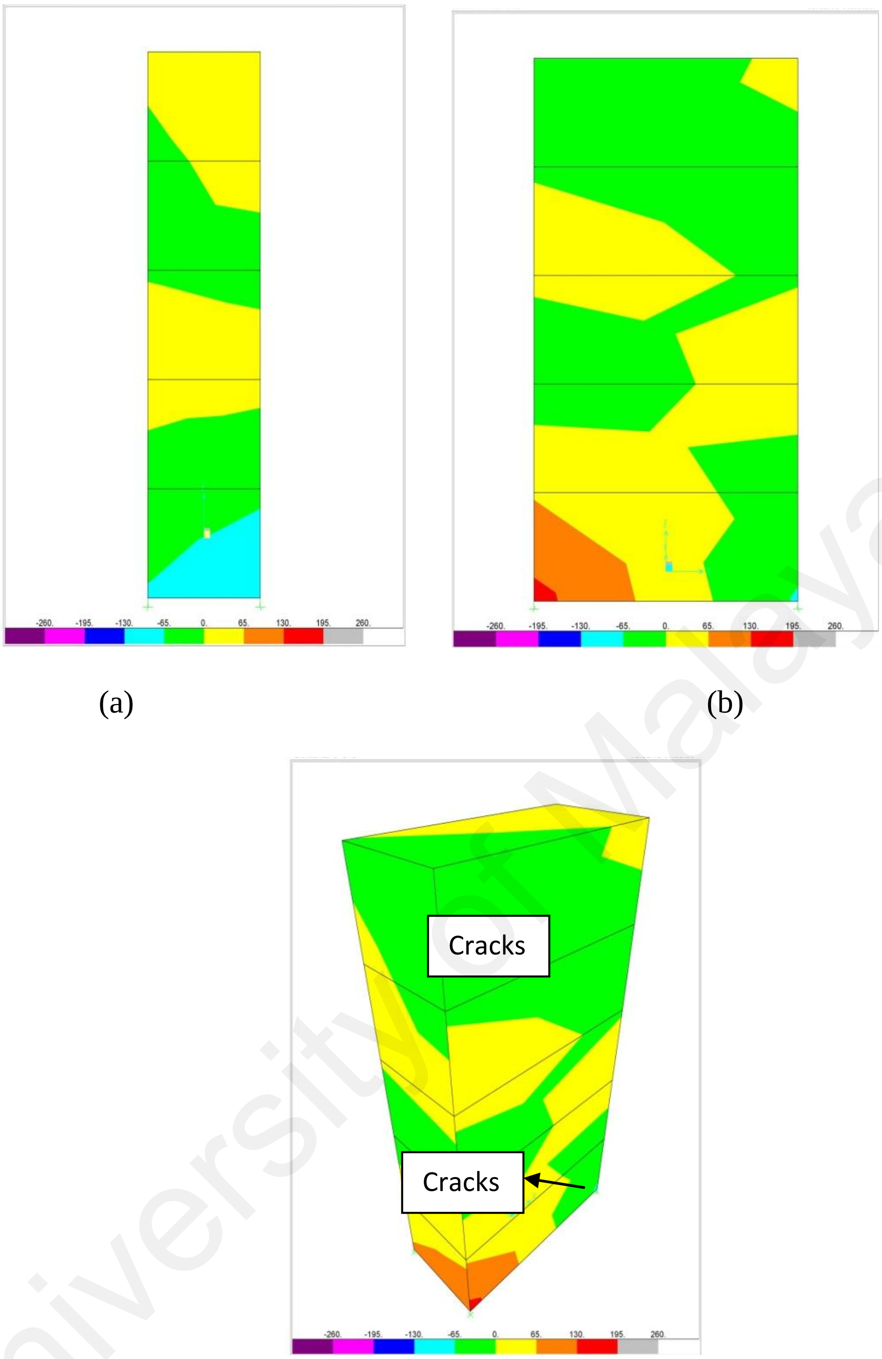
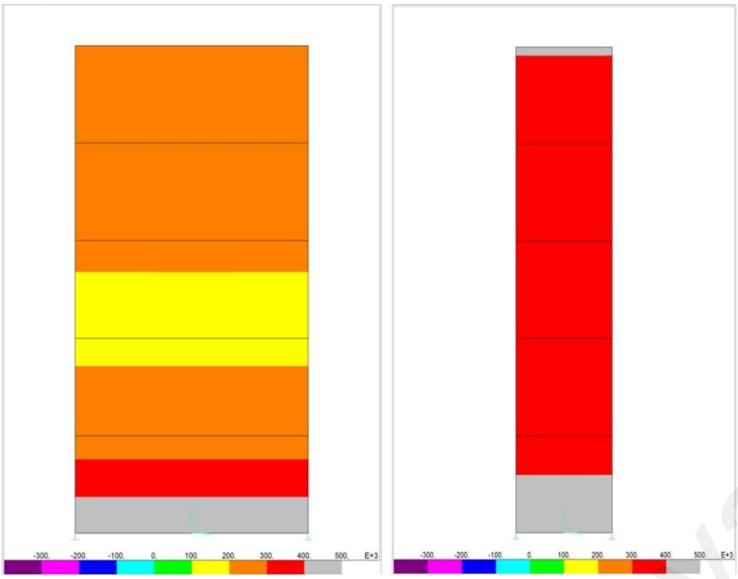



**Figure 4.51**: Load case 3: Stress for masonry prism: (a) Stress in the left side, (b) Stress in the right side, (c) Evaluation of cracking of masonry prism



(a) (b)

**Figure 4.52**: Load case 3: Internal forces for masonry prism: (a) Forces in the left side, (b) Forces in the right side.

For the third case of load (57 kN) the stress increased to 2.75 N/mm$^2$ presented in Figure 4.51, the stress increased with increased loading and was higher in the bottom of the masonry prism. The cracks shown in Figure 4.51 (c) were found in the top and middle of masonry prism when the stress was almost zero or negative. The internal forces for this case increased to 1.75 kN as presented in Figure 4.52 (a) and 4.52(b). From these Figures it also can be observed that the internal forces were greater at the bottom of masonry. The maximum displacement of the third case of load was 7.9 mm. The limit load reached by the FEM model with a 2.75 N/mm$^2$ tensile strength for third case load. This value is very close to experimental value 2.59 N/mm$^2$

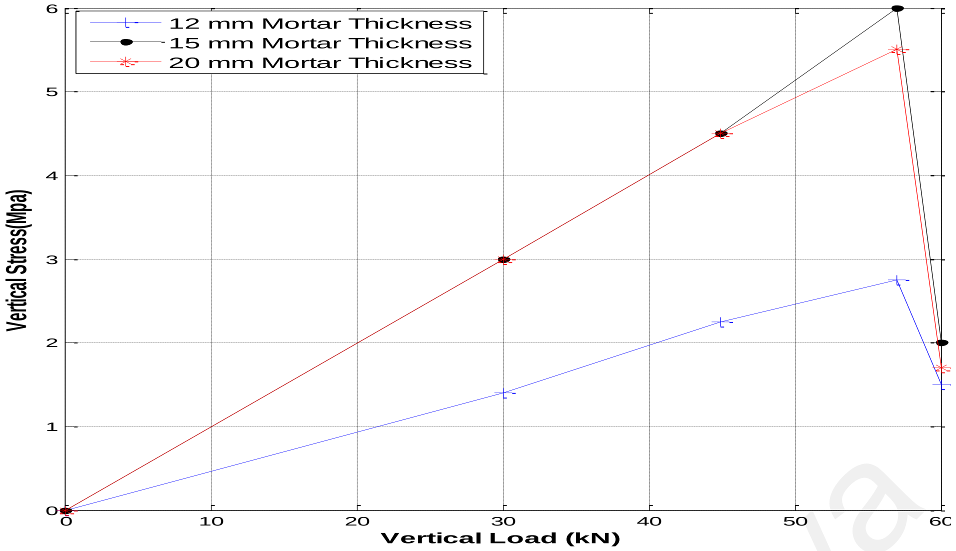
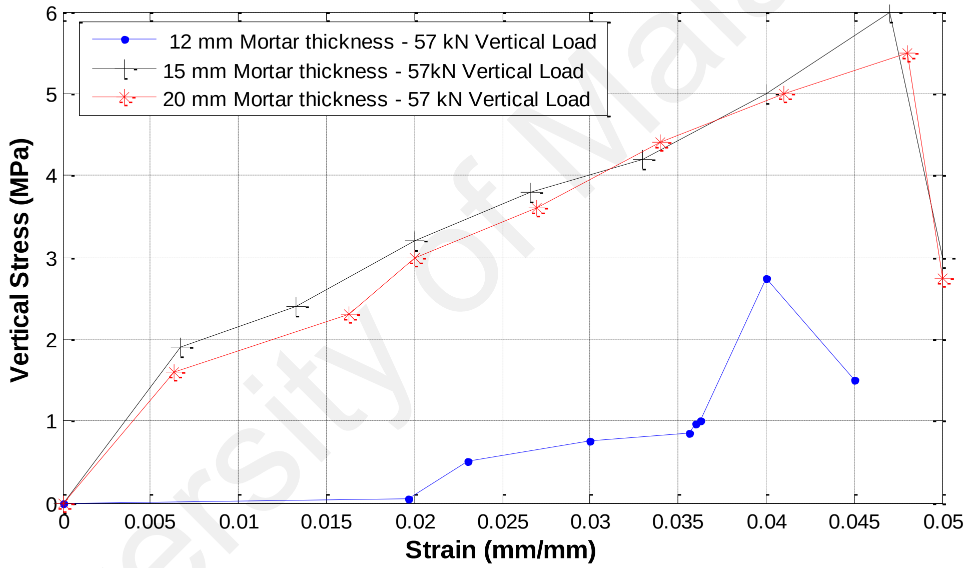
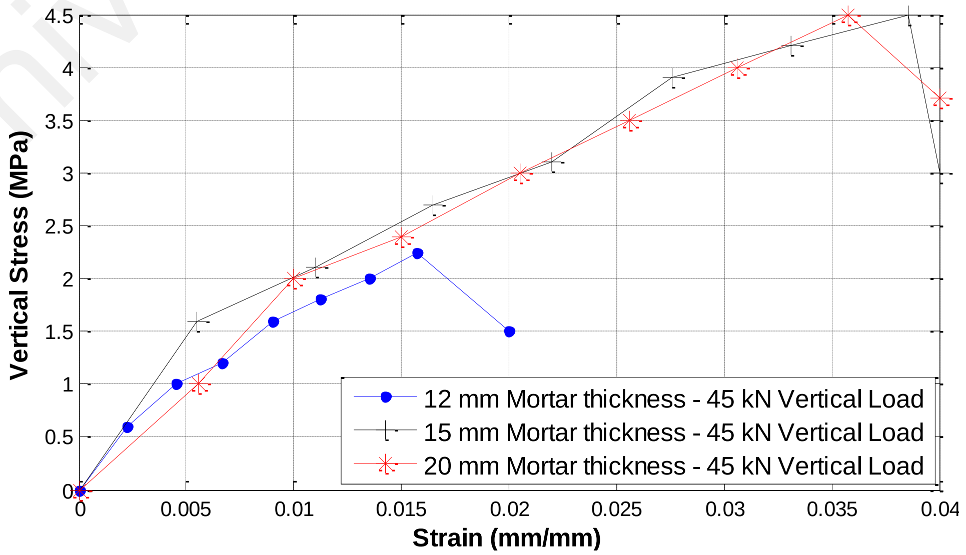


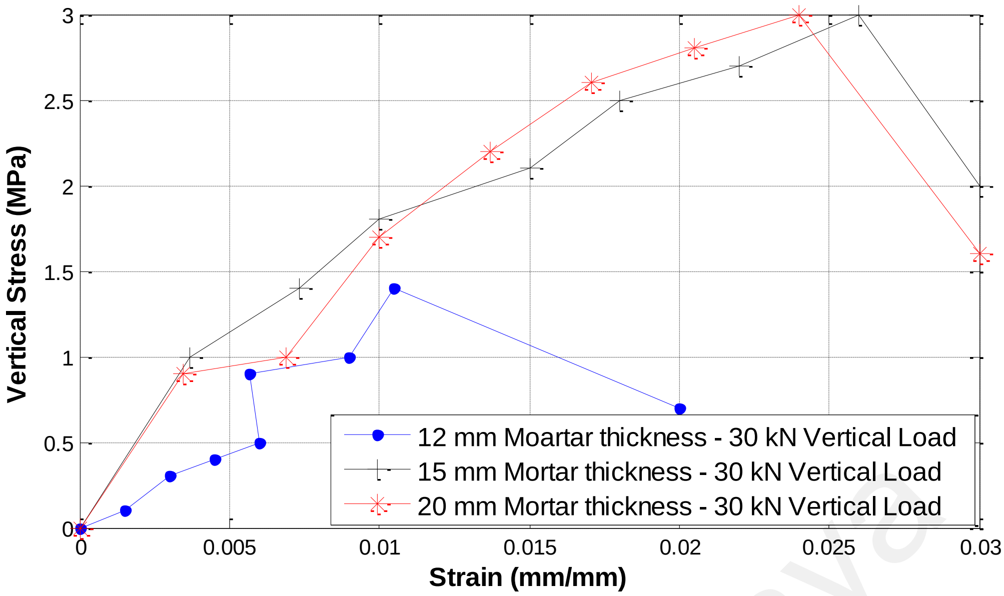

**Figure 4.53**: Relationship between stress and vertical load




(a)




(b)




(c)

**Figure 4.54**: CSPB masonry prism stress-strain curves with different thickness of mortar and load: (a) vertical load 57 kN, (b) vertical load 45 kN and (c) vertical load 30 kN

From Figures 4.53 and 4.54, it can be observed that the increasing of load and thickness of mortar increased stresses. The stress strain curves obtained that the stress for 12 mm mortar thickness was increased about 49% when the vertical load increased from 30 kN to 57 kN. Figure 4.54 also obtained the maximum stresses of CSPB masonry prism with 15 mm and 20 mm mortar thickness increased by about 50% and 45% respectively. However from Figures 4.53 and 4.54 can be observed that the maximum stress decreased when increased mortar thickness more than 15 mm about by 8%.

The measured displacement by experimental method was slightly higher than the numerical method by about 1.8%. The characteristics of clay brick and mortar used for clay masonry are presented in Table 4.5, observed from Figure 4.55 the vertical displacement of clay masonry prism was much higher than displacement of compressed stabilised peat brick, because the type of mortar and brick used in the investigation was of very high strength. (Hemant et al., 2007).

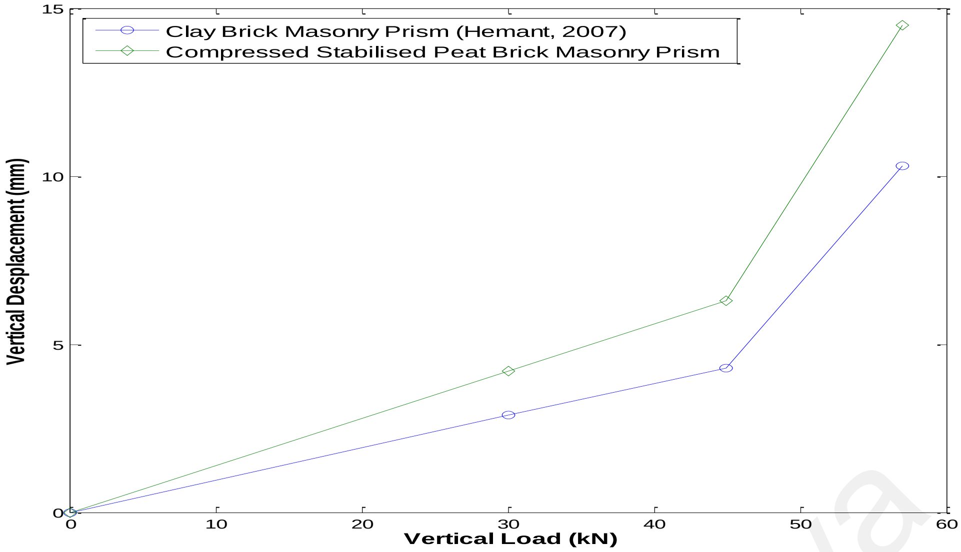



**Figure 4.55**: Vertical displacement curves of masonry prism model (12 mm Mortar thickness)

### 4.10.3 Comparison of experimental and finite element stress-strain of CSPB masonry prism

In this study, the comparisons of results were only for the first case of load (57 kN). Figure 4.46 shows the shape of model with 12 mm mortar joint thickness, and contour of stresses which are shown in Figure 4.47 (c). The comparison of stress-strain curve and vertical displacement from both analysis experimental and FEM are shown in Figure 4.56. The strength of mortar is higher than strength of brick, which will cause reduction in the compressive strength of masonry prism. The actual compressive strength of the masonry is determined by experimental method as presented in Section 4.7 which in the fact was higher than strength obtained by numerical method. Only the last point of numerical method was higher than the experimental value which was about 5.8 %.

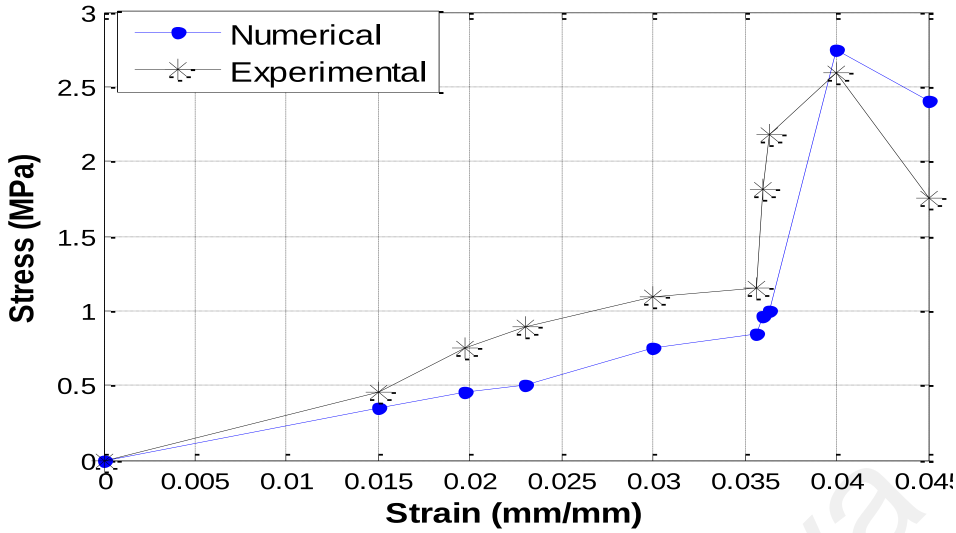



**Figure 4.56**: Stress-Strain curve of masonry prism model

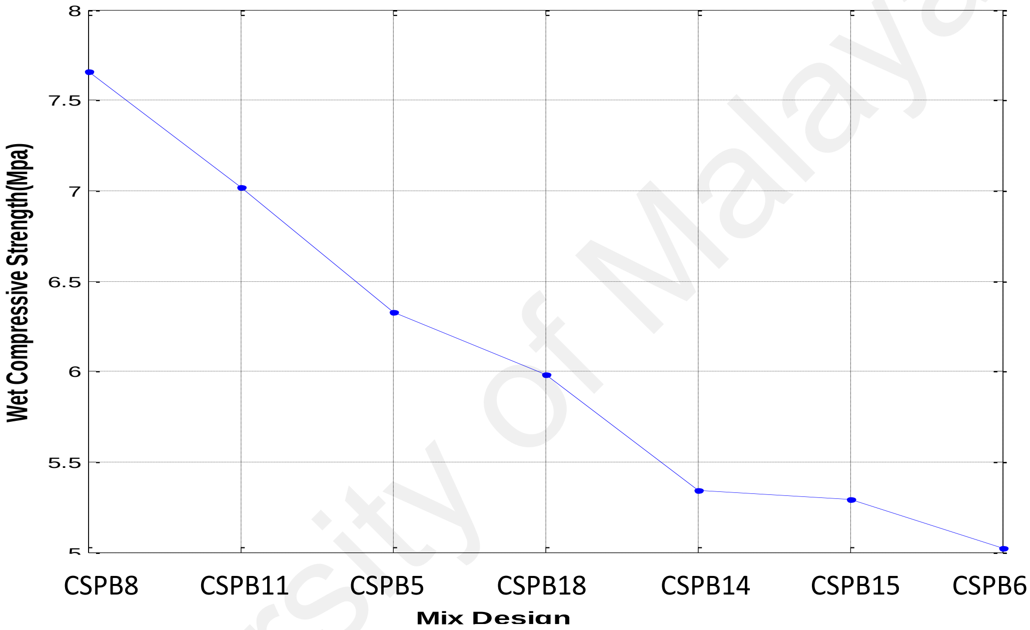
## 4.11 Cost Analysis

The strength of the seven mix designs of compressed stabilised peat brick were the minimum compressive strength and compaction pressure requirement of CSPB and cost per unit production of them is shown in Table 4.9.

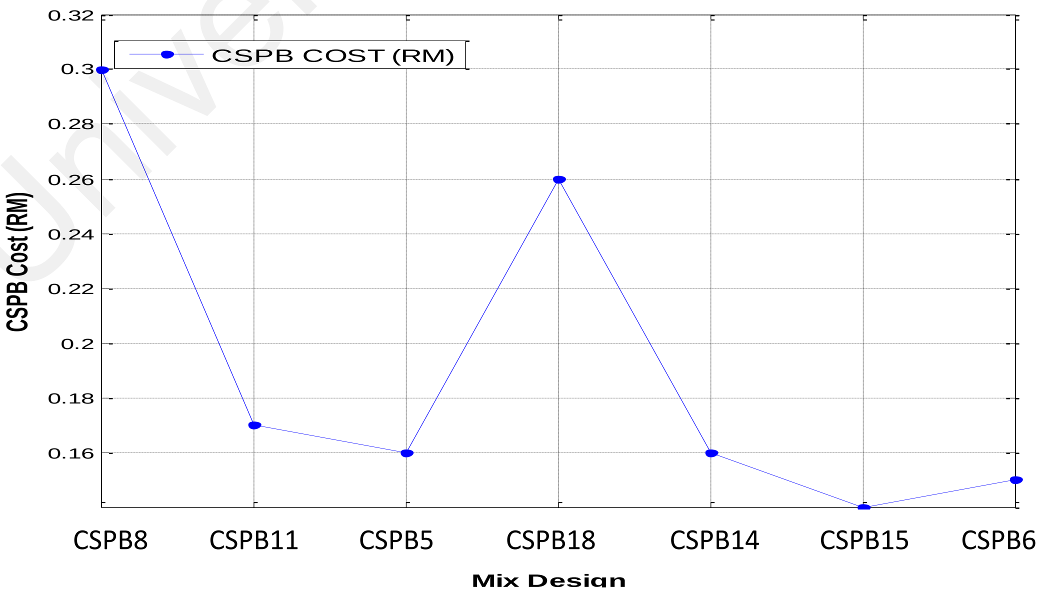
**Table 4.9**: Cost of compressed stabilised peat bricks

| No. | Mix design | 28 Days compressive strength(MPa) | Cost (RM/Unit) |
|---|---|---|---|
| 1 | CSPB 5 | 6.33 | 0.16 |
| 2 | CSPB 6 | 5.02 | 0.15 |
| 3 | CSPB 8 | 7.66 | 0.30 |
| 4 | CSPB 14 | 5.34 | 0.16 |
| 5 | CSPB 15 | 5.29 | 0.14 |
| 6 | CSPB 18 | 5.98 | 0.26 |
| 7 | CSPB 11 | 7.02 | 0.17 |

The comparative graph of strength and cost of CSPB with different content of cement, lime and different pressure presented in Figure 4.57 provide evidence that the compressive strength increased sharply with the increase of cement content and lime. Table 4.9 and Figure 4.56 provide the effect of increasing strength increase the cost. However the addition of lime to the admixture increases the cost. The cost of CSPB compared to traditional clay brick was lower. From above discussion, it can be concluded that the mix design: CSPB8, CSPB5, CSPB18, CSPB9, CSPB14, CSPB15 and CSPB6 were in the range of compressed stabilised peat bricks, strength required. The cost for compressed stabilised peat brick ranged from 0.14 RM to 0.30 RM from pore to good quality of brick. The reduces cost ranged from 25% to 65% compared to the good quality of clay bricks or cement brick and about 20% compared to the pore clay brick.




(a)




(b)

**Figure 4.57**: Comparative strength and cost: (a) wet compressive strength of CSPB, (b) Cost of CSPB per unit (RM).

## 4.12 Summary

The compressive strength of compressed stabilised peat brick using PFA or OPC cement and lime is highest compared to the compressive strength of CSPB without lime. However, the higher compaction pressure obtained higher compressive strength. This Chapter described the findings from the main engineering or durability properties tests which included basic properties, wet compressive strength, brick bulk and dry density, total water absorption and total volume porosity.

It was found that the wet compressive strength value at the 30% cement content level was about 3.5 times greater than the recommended minimum value of 2 MPa. Even the cement content of 20% the strength was lower. The wet compressive strength was surprisingly about 2 times higher than the minimum recommended value. The trend of the graph showed that where lime is used, only 3 days curing would be required to achieve greater than the minimum recommended value.

The effect of increase in cement and lime content with strength in CSPB was found to closely correspond in all cases. There is no previous record prior to this thesis to show that similar spectacular gains in strength and other properties have ever been achieved in compressed stabilised peat brick.

It was also established that increase in compaction pressure resulted in an increase in wet compressive strength. A 40% increase in compaction pressure resulted between 15% and 32% in wet compressive strength. The effect of curing period with strength in CSPB was found to increase strength by about 52% from 3 days to 28 days. It can be concluded that increase in stabiliser content, compaction pressure and curing period is a more effective way to increasing the wet compressive strength.

Form investigation of effects of varying the stabiliser type and content on the CSPB total water absorption, it was found that the cement content increased and lime decreasing the water absorption of brick. By increasing cement from 20% to 30%, it was found water absorption reduced from 5.4% to 16.4%. There was negative correlation between total water absorption and dry density, coefficient of correlation varied between -1.04 to -0.913 with OPC as stabiliser and varied between -0.994 to -0.891 with PFA cement as stabiliser.

In this Chapter, the density of CSPB was also investigated by varying of stabiliser content, compaction pressure and curing period. The results found that the density increased by about 10% with increased cement from 20% to 30%. A 40% compaction pressure increase improved dry density by about 5.38%, also increased density by about 9.5% when curing period was increased from 3 to 28 days. Dry density can be a valuable quality in a brick. It was also found that a strong positive correlation exists between density and the 28 days wet compressive strength of bricks, the coefficient of correlation was 1.08 with 6 MPa compaction pressure and 0.924 with 10 MPa compaction pressure.

The total volume porosity was also evident in this chapter. It was found the volume porosity varied between 4.75% and 14.20% when the compaction pressure was 10 MPa and ranged from 8.56% to 15.79% when the pressure was 6 MPa. Moreover, the negative correlation between porosity and wet compressive strength was indicated where, coefficient of correlation varied between -0.889 and -0.467.

Linear shrinkage of CSPB presented in this Chapter ranged between 0.5% and 1.36%. The plasticity index indicated in this chapter ranged between 1.8% and 2.85%.

In this chapter compressive behaviour of CSPB masonry and its constituents were also investigated numerically to develop the stress-strain curves, internal forces and vertical displacement; it was also to gain insights of comparison between experiment and numerical methods. Numerical analysis results showed that, by increasing the load, the strength, internal forces and displacement of the masonry will increase. The comparison between numerical and experimental analysis obtained several different results between both methods.  The results for numerical methods obtained that almost all points of strength were lower than strength from experimental methods. Only for the last point the strength from the numerical method was higher than the strength from the experimental method.

# CHAPTER 5

# CHARACTERISTICS OF SOUND INSULATION AND FIRE RESISTANCE OF COMPRESSED STABILISED PEAT BRICKS WALL

## 5.1. General

To protect a building against exterior and between rooms noise, the airborne sound transmission is of primary importance. An effective means for reduction sound transmission is to place some form of sound insulation between the source and listener. By their very definition, acoustically absorbent materials will allow sound energy to enter the material, and perhaps allow it to pass through, but will severely reduce the amount of sound reflected (James and Jeffrey, 1995).

The STC rating of a sound barrier is established by a standard test that measures the airborne sound transmission drop through the barrier at various frequencies. These performance data are displayed on a graph along with a standard noise reduction performance criterion curve.

The great progress of fire research during the last decades of the $20^{th}$ century has made it possible to treat fire as a phenomenon governed by the same laws of nature as other physical and chemical phenomena. The art of fire has been transformed to science of fire. Recent research results have been turned into design tools with which engineers can assess the consequences of fire in different scenarios. Recent changes in building regulations in many countries have begun to allow a performance-based approach to fire safety design.

The aim underlying this study is to seek a better alternative for insulation of building noise. The laboratory experiments were performed placing the specimens between two relatively small rooms. However, for the purpose of this study a small scale of flames for fire resistance of compressed stabilised peat bricks in opening air, used simulated to ASTM E 119 and ISO 834 standards.

## 5.2 Airborne Sound Transmission Through Single Compressed Stabilised Peat Bricks Partition Wall.

Sound transmission in domestic housing is a problem that exists in many countries thus many different solutions is being adopted to achieve acceptable levels of sound insulation. At a national level, there are two basic approaches that a government body (or other regulatory body) can take to ensure that the national housing stock achieves an appropriate standard of sound insulation. One method is to specify the types of construction that are acceptable, usually after they have been tested in national testing laboratories. While the other approach is to carry out sound insulation tests on the actual constructions to establish whether or not, the construction fulfills the requirements of satisfying performance criterion (Craik and Smith, 2000).

Measurement of sound reduction index for three types of cemented peat brick walls commonly used in partitions are presented. The results show that sound reduction index ($R_w$) is smaller under low frequencies and larger under high frequencies. Measurement of sound transmission index is in concurrence with the international standard ISO 140-3, ISO 140-4 and ASTM E- 90. The results have been compared with reference values found in ASTM E-90 and ASTM E-413, for all samples studied. The methodology of testing is discussed in Chapter 3.

From the measured data the field sound transmission loss of each wall was calculated with third octave bands from 50 to 4000 Hz using the equation:

$$R_w = L_s - L_r + 10 \log_{10}(S/A) \, . \qquad \text{Eq: 5.1}$$

Where $L_s$ is the sound pressure level in the source room (dB), $L_r$ is the sound pressure level in the receiving room (dB), S is surface area of the common wall ($m^2$) and A is total absorption of the receiving room surface area ($m^2$).

Figure 5.1 and 5.2 show measurements of sound reduction index for first specimen of satbilised peat bricks wall; three levels of sound were applied in the source room; the first was high sound proofing such as a musical instrument, the second similar to a loud speech sound audible enough to be recognised as a murmur and the third similar to normal speech which can be understood rather easily. The results show that the wall built with compressed stabilised peat bricks produced sound transmitted loss at 500 Hz achieved 44 dB, 44 dB and 24 dB for higher, medium and lower frequencies respectively. The comparison with ASTM reference curve gives deficiency of 30.4 dB, 23.37 dB and 3.1 dB with high, medium and low frequency respectively. From related literature, it is found that the maximum deficiency is 32 dB and variation between each point is maximum 8 dB. The total deficiency for first sample was 30.4 dB and a maximum value between each point was 7.7 dB.

It is evident from Figure 5.3, the variation of sound from lower to higher frequency produced sound reduction index from higher to lower. Figure 5.4 shows measurement of sound reduction index for the second specimen of stabilised peat bricks wall. Results show that the sound transmission class was 24 dB with high frequency, 24 dB with medium and low frequency. From Table B1 in the Appendix B, the total deficiency for the second specimen testing was 30.6 dB, 13.1 dB and 1.6 dB with high, medium and low frequency respectively. The maximum difference between each point was 6.3 dB, 3.1 dB and 6 dB with high, medium and low frequency respectively. The variation of sound reduction index of high, medium and lower sound applied for second specimen is presented in Figure 5.4.

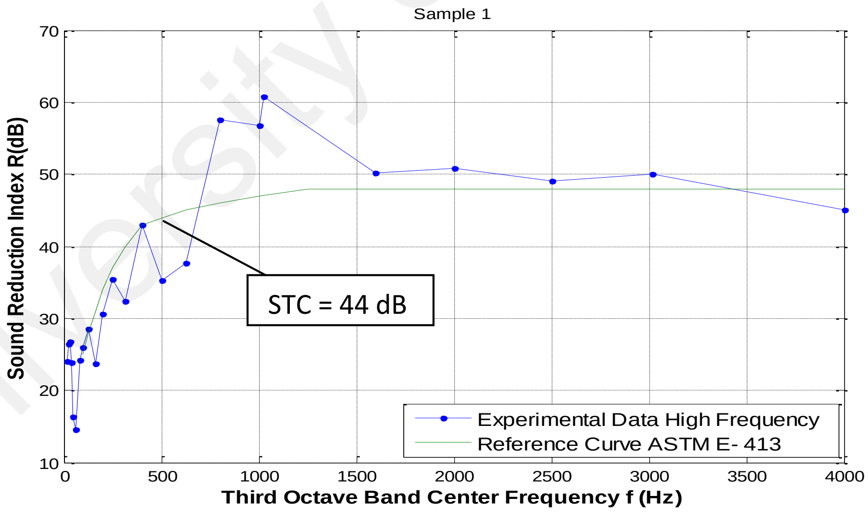
Figure 5.5 presented measurement of sound reduction index of the third specimen of compressed stabilised peat bricks wall. Results show that the sound transmission loss was 44 dB at high frequency, 44 dB and 24 dB at medium and low frequencies respectively which were produced in the source room. The total deficiency presented in Table 2 in the Appendix shows that deficiency was 28.6 dB, 27.7 dB, and 1.6 dB with high, medium and low frequency. However, the maximum variation between each point was 7.3 dB, 5.6 dB, and 1.4 dB with high, medium and lower frequency respectively. The variation of sound reduction index of third specimen with high, medium and low frequency are presented in Figure 5.6.

The results showed that the sound insulation property results of each specimen. It can be concluded from the study that sound reduction index ($R_w$) increased when the frequency rose from 20 Hz to 4000 Hz for high frequency and a range of 20 Hz to 630 Hz contributed to the sound transmission loss for medium and low frequency. Many studies of variation in sound transmission loss showed that various factors may influence measured sound transmission loss. Factors commonly identified included receiving and source room size and geometry, common new material walling and size as well as measurement procedures.

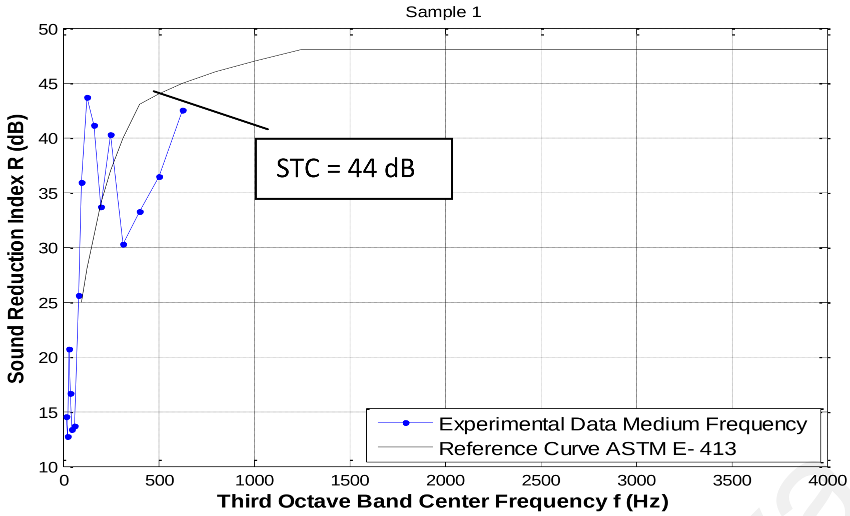
From Figures 5.2, 5.4 and 5.6**,** the measured sound reduction index for the three walls of compressed stabilised peat brick indicated that there are no significant differences on sound reduction index curves between the walls with different type of plastering and mix design; in fact it gives almost the same sound reduction index at 500 Hz frequency.

In compliance with ASTM E- 90 and ASTM E- 413, the sound transmission of a wall is determined by comparing its transmission loss curve with a set of standard curves. The standard curve is superimposed over a plot of actual sound transmission loss curve, and shifted upwards or downwards relative to the test curve until some of measured values of the test specimen fall below those of the sound transmission contour.

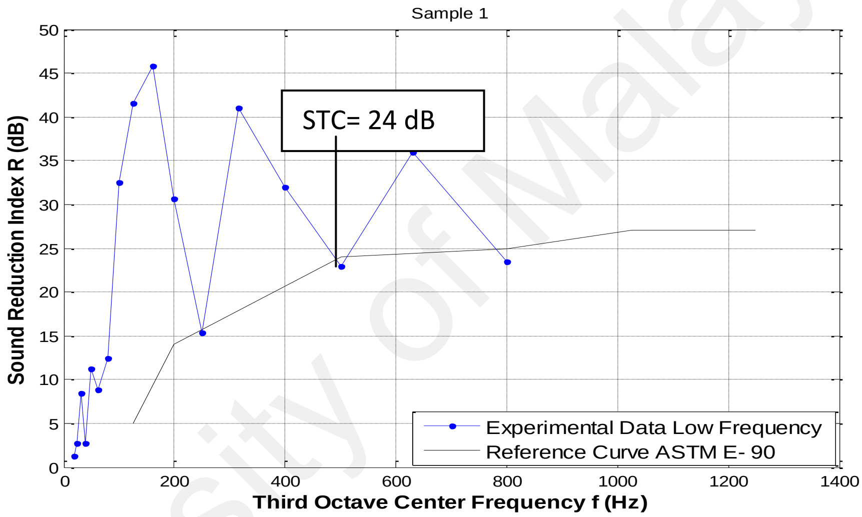
From the results in this study, it can be concluded that compressed stabilised peat partition wall was an effective condition for construction insulation.




**(a)**




**(b)**




**(c)**

**Figure 5.1:** Sound Transmission of CSPB wall partition. (a) high frequency, (b) medium frequency and (c) low frequency

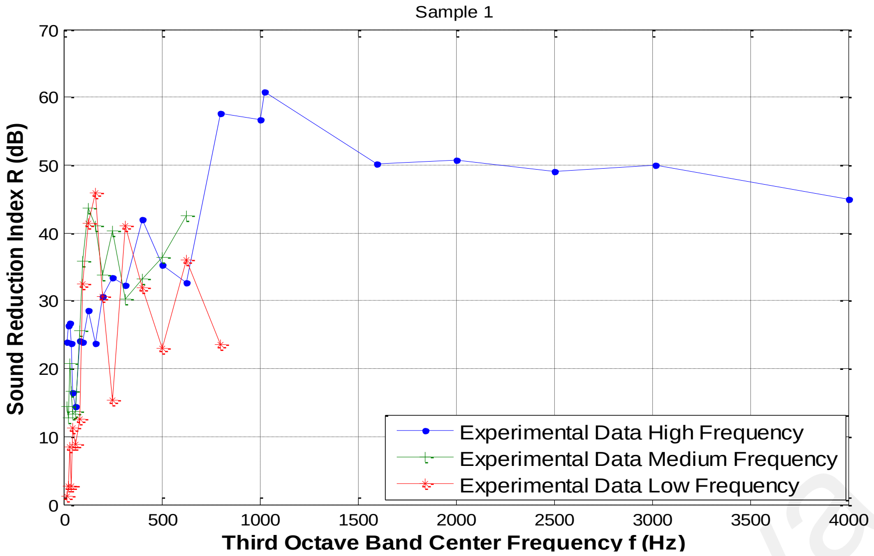



**Figure 5.2:** Comparison of Sound Transmission of CSPB wall partition between high frequency, medium frequency and low frequency

**Table 5.1:** Measured Sound Transmission loss.TL and values of the chifted reference curve for STC = 44 ( High frequency sample1)

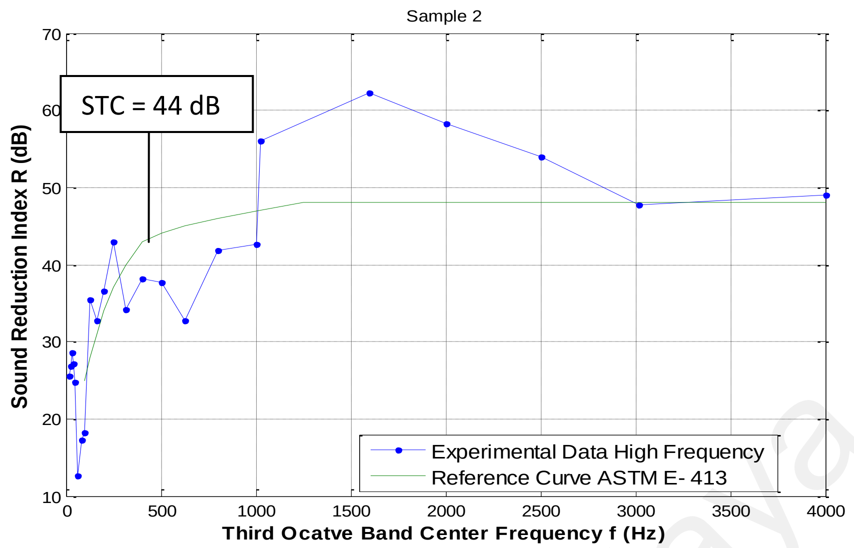
| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) High frequency | Shifted Reference Curve ASTM E- 413 STC= 44 | Deficiency |
|---|---|---|---|
| 20 | 24.0 | - | - |
| 25 | 26.4 | - | - |
| 31.5 | 26.7 | - | - |
| 40 | 23.8 | - | - |
| 50 | 16.4 | - | - |
| 63 | 14.5 | - | - |
| 80 | 24.2 | - | - |
| 100 | 25.9 | 25 | 0.0 |
| 125 | 28.6 | 28 | 0.0 |
| 160 | 26.7 | 31 | 4.3 |
| 200 | 33.6 | 34 | 0.4 |
| 250 | 35.4 | 37 | 1.6 |
| 315 | 32.3 | 40 | 7.7 |
| 400 | 42.9 | 43 | 0.1 |
| 500 | 36.0 | 44 | 8.0 |
| 630 | 37.6 | 45 | 7.4 |
| 800 | 57.6 | 46 | 0.0 |
| 1000 | 56.7 | 47 | 0.0 |
| 1250 | 60.7 | 48 | 0.0 |
| 1600 | 50.2 | 48 | 0.0 |
| 2000 | 50.8 | 48 | 0.0 |
| 2500 | 49.0 | 48 | 0.0 |
| 3150 | 50.0 | 48 | 0.0 |
| 4000 | 47.0 | 48 | 1 |
| Total deficiency (100 Hz- 4000 Hz) | | | 30.4 |

**Table 5.2:** Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44 (Medium frequency sample 1)

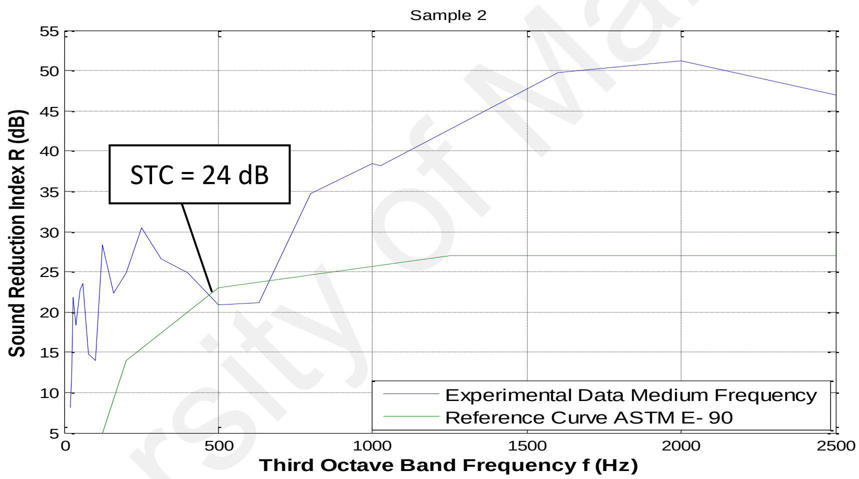
| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) Medium frequency | Shifted Reference Curve ASTM E-413 STC= 44 | Deficiency |
|---|---|---|---|
| 20 | 14.5 | - | - |
| 25 | 12.7 | - | - |
| 31.5 | 20.7 | - | - |
| 40 | 16.7 | - | - |
| 50 | 13.3 | - | - |
| 63 | 13.3 | - | - |
| 80 | 25.6 | - | - |
| 100 | 35.9 | 25 | 0.0 |
| 125 | 34.7 | 28 | 0.0 |
| 160 | 41.1 | 31 | 0.0 |
| 200 | 33.7 | 34 | 0.3 |
| 250 | 40.3 | 37 | 0.0 |
| 315 | 32.7 | 40 | 6.3 |
| 400 | 36.2 | 43 | 6.8 |
| 500 | 36.4 | 44 | 7.8 |
| 630 | 42.5 | 45 | 2.5 |
| Total deficiency (100 Hz- 630 Hz) | | | 23.73 |

**Table 5.3:** Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44 (Low frequency sample 1)

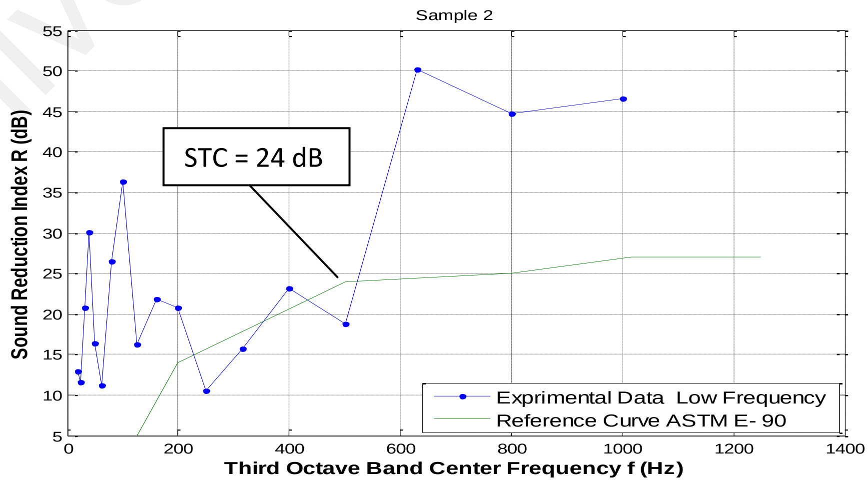
| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) low frequency | Shifted Reference Curve ASTM E- 90 STC= 24 | Deficiency |
|---|---|---|---|
| 20 | 1.20 | - | - |
| 25 | 2.70 | - | - |
| 31.5 | 8.50 | - | - |
| 40 | 2.70 | - | - |
| 50 | 11.3 | - | - |
| 63 | 8.90 | - | - |
| 80 | 12.5 | - | - |
| 100 | 32.5 | - | - |
| 125 | 41.5 | 5.00 | 0.0 |
| 160 | 41.8 | 10.0 | 0.0 |
| 200 | 30.7 | 14.0 | 0.0 |
| 250 | 15.4 | 16.0 | 0.6 |
| 315 | 41.0 | 17.5 | 0.0 |
| 400 | 32.0 | 21.0 | 0.0 |
| 500 | 23.0 | 24.0 | 1.0 |
| 630 | 36.0 | 24.5 | 0.0 |
| 800 | 23.5 | 25.0 | 1.5 |
| Total deficiency (125 Hz- 8000 Hz) | | | 3.1 |




(a)




(b)




(c)

**Figure 5.3:** Sound Transmission of CSPB wall partition. (a) high frequency, (b) medium frequency and (c) low frequency

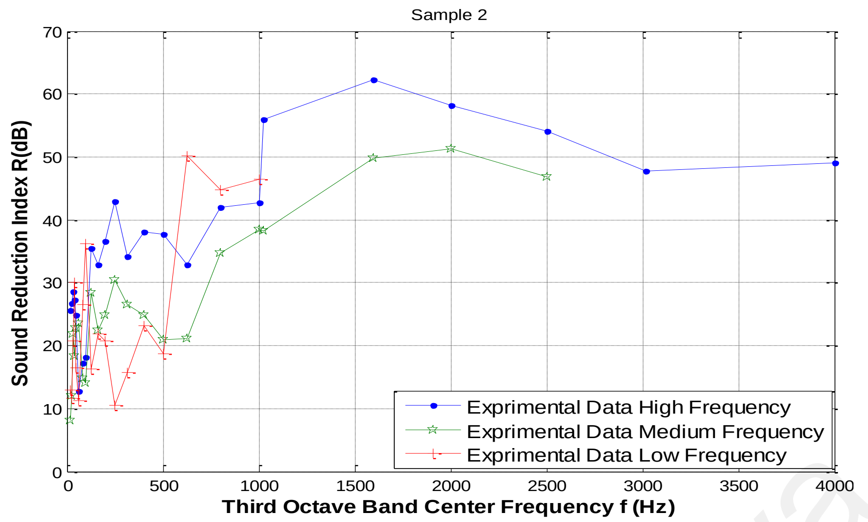
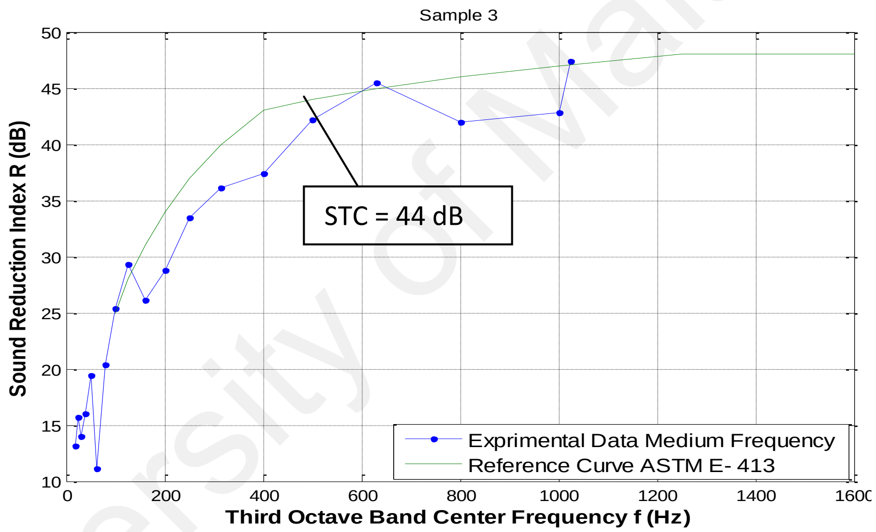
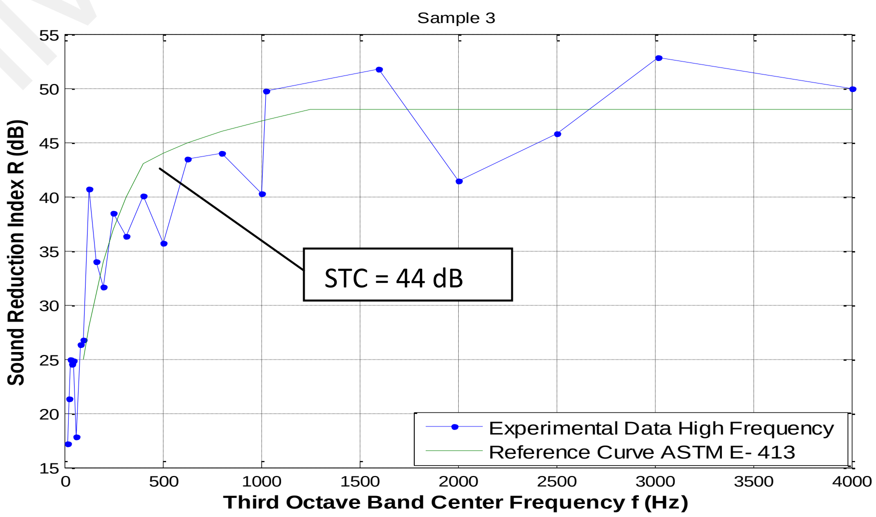



**Figure 5.4:** Comparison of Sound Transmission of CSPB wall partition between high frequency, medium frequency and low frequency




(a)

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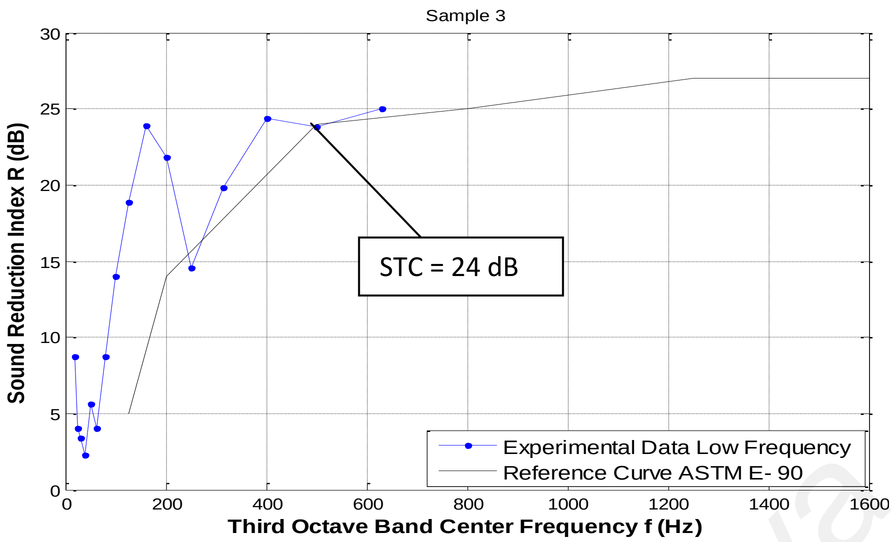



(c)

**Figure 4.5:** Sound Transmission of CSPB wall partition. (a) high frequency, (b) medium frequency and (c) low frequency

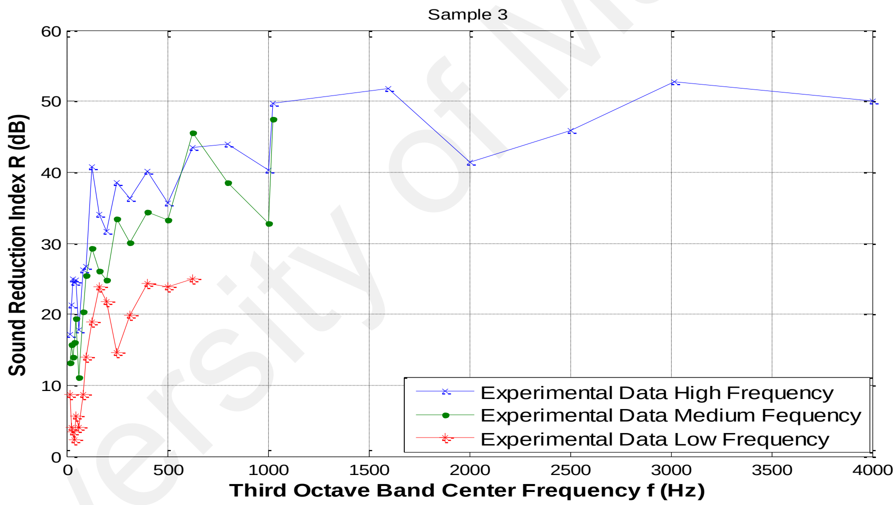



**Figure 5.6:** Comparison of Sound Transmission of CSPB wall partition between high frequency, medium frequency and low frequency

## 5.3 Fire Resistance Rating on Compressed Stabilised Peat Brick Non- Load Bearing Wall

Despite the general trend towards rational design for fire safety, the regulatory systems in most countries do not encourage calculation of fire resistance, which is most often assessed only by standard tests. The fire resistance requirements for parts of buildings vary significantly and non-systematically between different countries, being based on historical development rather than science.

Fire resistance requirements often influence construction costs significantly. Excessive fire resistance is an unnecessary cost. The recent development of fire safety engineering and the trend toward performance based fire regulations open up new possibilities for optimising building design without compromising safety.

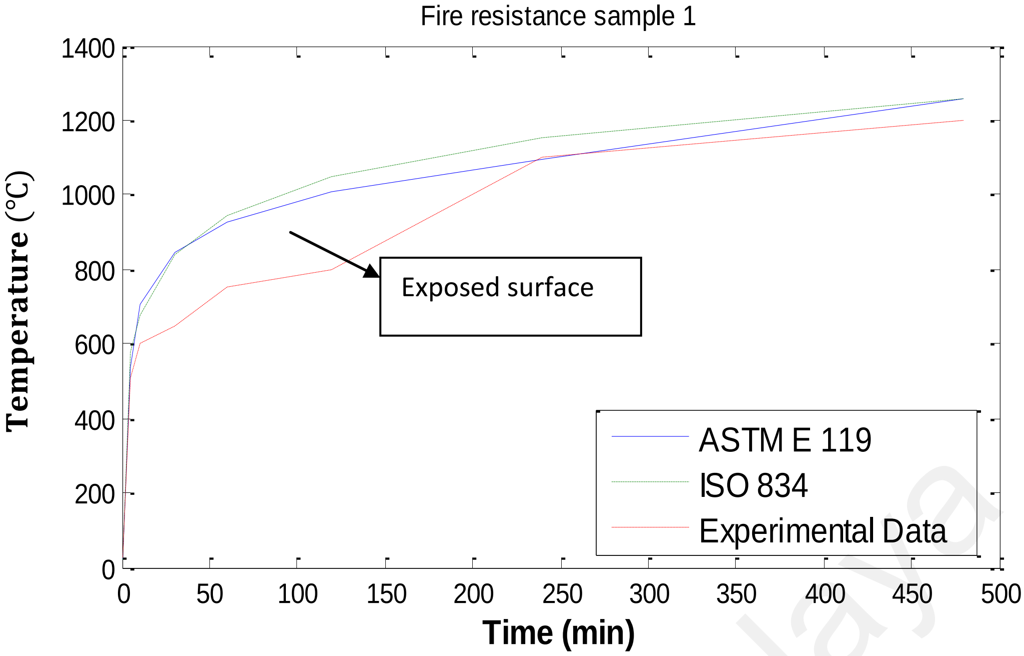
Many people involved in the process of design, construction, or maintenance of buildings, view compliance with fire safety legislation merely as an obstacle to be overcome with minimum cost and effort. Legislation for fire safety in buildings varies greatly from country to country, and is sometimes not effectively monitored or controlled due to lack of resources. The scope of the legislation also varies greatly, with some jurisdictions having inadequate allowance for important matters such as property protection, safety of fire fighters, or evacuation of disabled people. It is strongly recommended, therefore, that the interpretation made from views and opinions expressed here is in the context of local building practices and relevant local legislation.

The history of fire resistance testing was reviewed by Babrauskas (1976). In general, specimens must conform to criteria in three different performance aspects: stability, integrity, and insulation. Stability means that the assembly must not collapse.

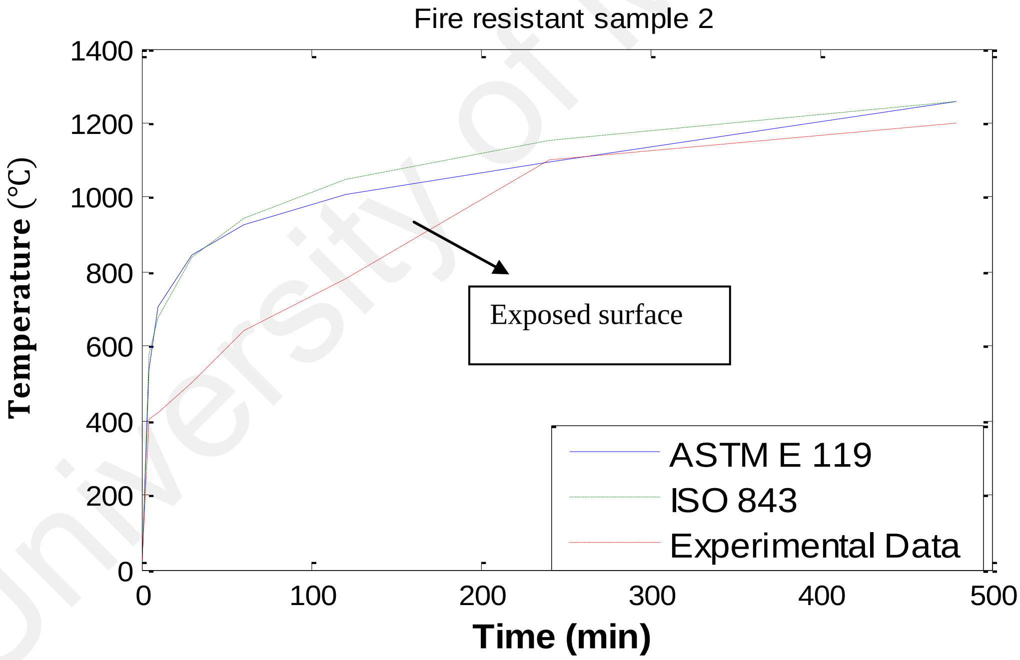
Integrity means that the specimen must not pass or flame hot gases through any holes or cracks that may appear. Insulation means that the unexposed face of the specimen must not get so hot as to be able to ignite combustibles put in contact with it. The earliest thermal transmission criterion used in fire resistance tests was simply that the floors or walls shall not pass flame or fire (Barbrauskas, 2009). The surfaces of walls are especially subjected to attack by fire, both because of their vertical orientation and because of their large surface (John, 1996).

A fire characterised by flame is the most common type. Here, the flame actually is the fire, the production of gaseous reaction products with the evolution of heat and light. The colour of light emitted is determined by the element in the reacting mixture. The gaseous flame is made more visible when carbon and other solid or liquid by products resulting from incomplete combustion are raised to incandescent temperatures and glow, red, orange, yellow , or white, depending on their temperature.( John, 1996).

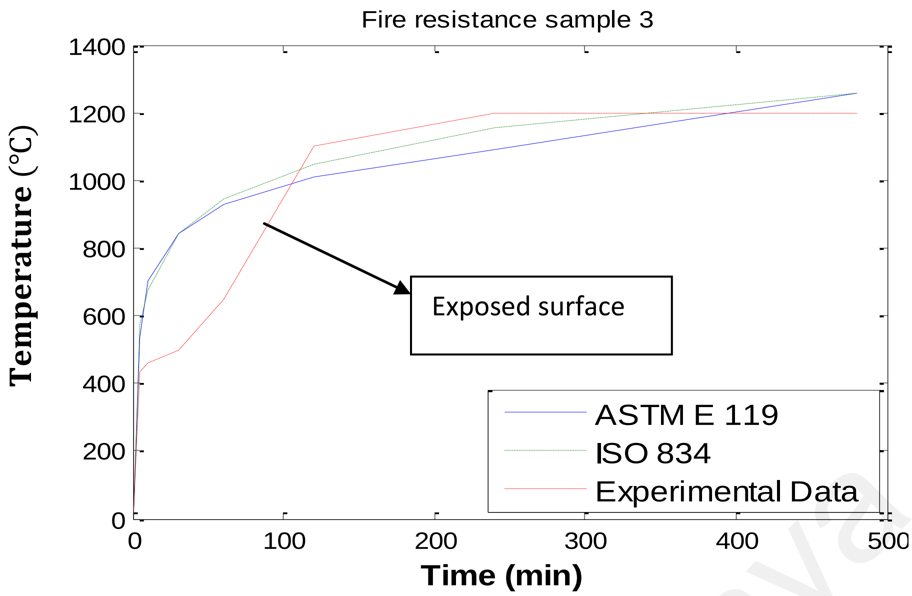
Most fire-resistance of walls using furnaces methods, full–scale testing for this method very expensive, for the purpose of this study a small scale of flames in opening air, used simulated to ASTM E 119 and ISO 834 standards. The methodology of this test is discussed in detail in Chapter 3.


Fire resistance sample 1
Temperature (°C)
Time (min)
Exposed surface
ASTM E 119
ISO 834
Experimental Data


(a)


Fire resistant sample 2
Temperature (°C)
Time (min)
Exposed surface
ASTM E 119
ISO 843
Experimental Data


(b)




(c)

**Figure 5.7**: Exposed surface Temperature-time curve (Comparison between laboratory results and standards). (a) First sample, (b) Second sample, (c) Third sample

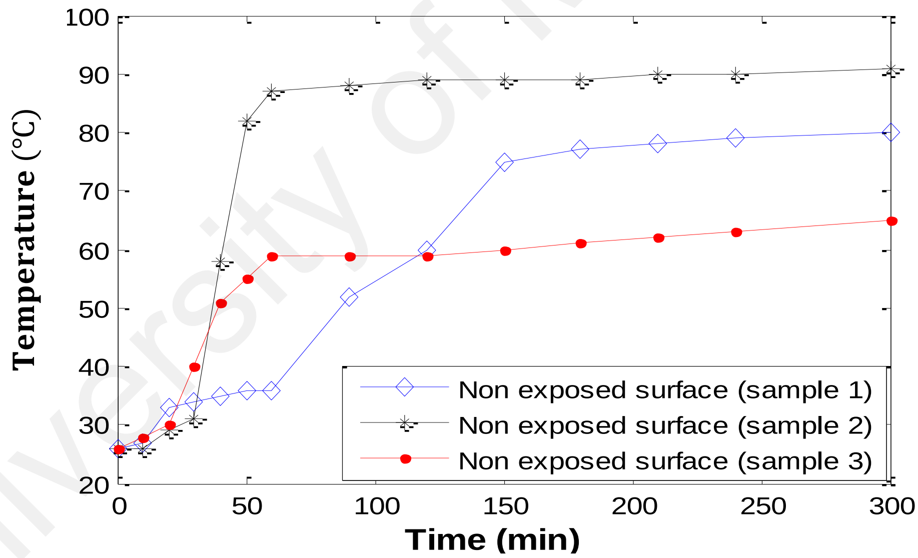


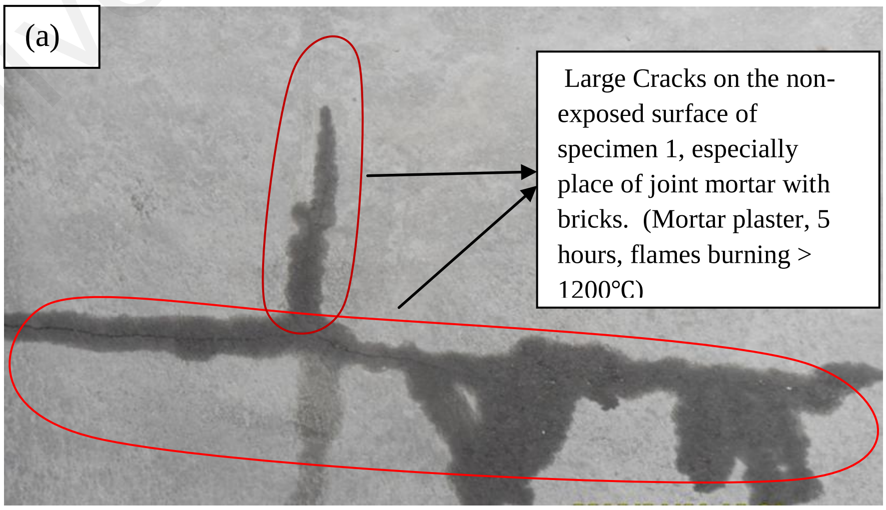

**Figure 5.8:** Non-exposed surface Temperature-time curve

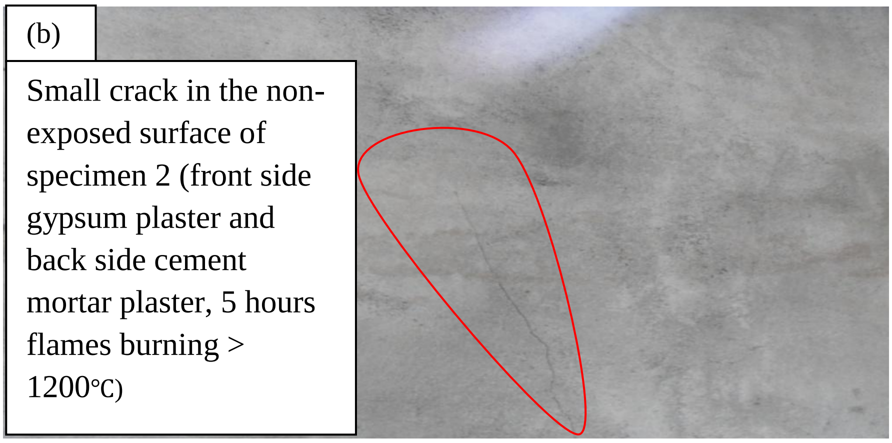


Figure 5.7 shows that the laboratory results are very similar to ASTM E 119 and ISO 834 standards. For the first and the second sample, the curve was below the standard curve, as for the third sample the values were at numerous points up the standard curve. Hence, from these results obtained it is evident that the third sample has more fire resistance, because the plaster used for this sample was gypsum for both sides. Gypsum material gives high resistance against fire. Figure 5.8 shows that the temperature transferred from the first specimens was 80°C and 91°C, 65°C for the second and third specimen respectively, it clearly form this results the compressed stabilised peat brick wall has good resistance for fire, from 1200°C applied transferred only 65°C to 91°C. Moreover, when used gypsum plaster for both sides very low temperature transferred through the specimen.

### 5.3.1 Observation of Walls Cracks During Five Hours Burning

Figures 5.9 and 5.10 show that the flame burning on compressed stabilised peat brick walls gives more cracks for masonry wall plastered with cement mortar, and it was also observed that water came out from the edge of cracks, small cracks for the second specimen plastered with one side cement and the other side gypsum and no cracks appeared for the third specimen wall plastered both sides with gypsum. Results indicated that gypsum there was not much difference between mix design with 25% cement and 4% lime, 30% cement and 30% cement with 4% lime. The plaster type was effective for fire resistance; but gypsum was the best for increase rate of fire resistance of CSPB masonry wall.





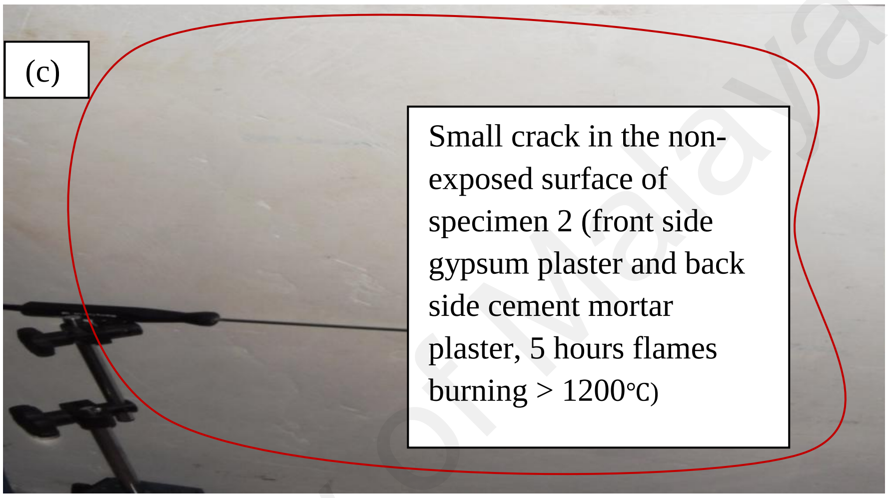
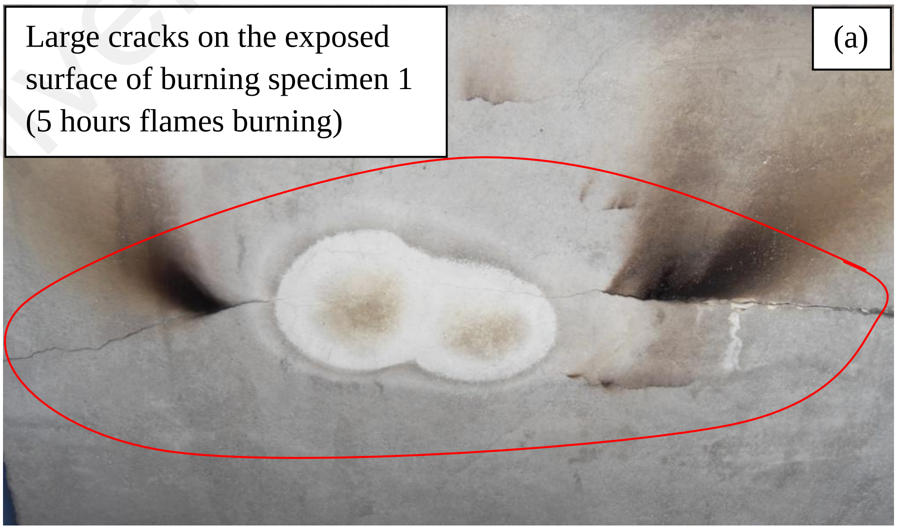
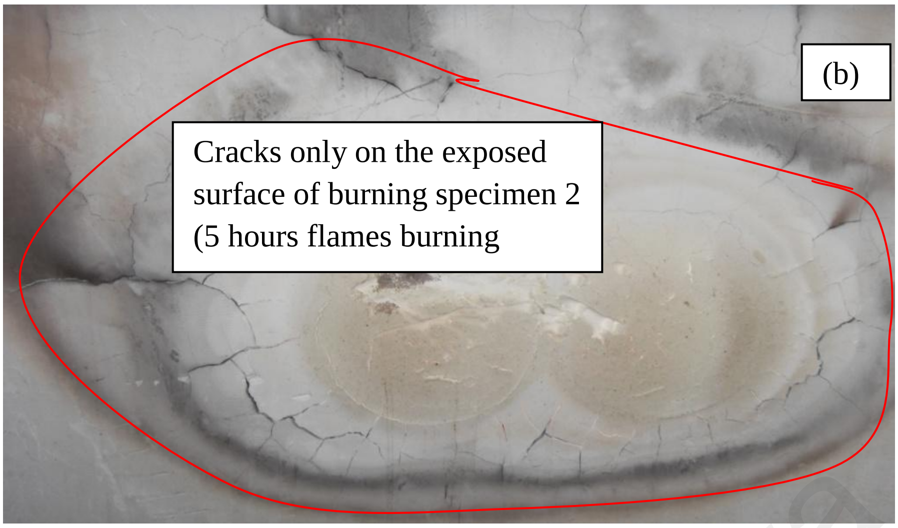




**Figure 5.9:** Cracks on the non-exposed surface of samples. (a) sample 1 with 2 sides mortar plaster , (b) sample 2 in the front side gypsum plaster and back cement mortar plaster, (c) sample 3 with two sides gypsum plaster







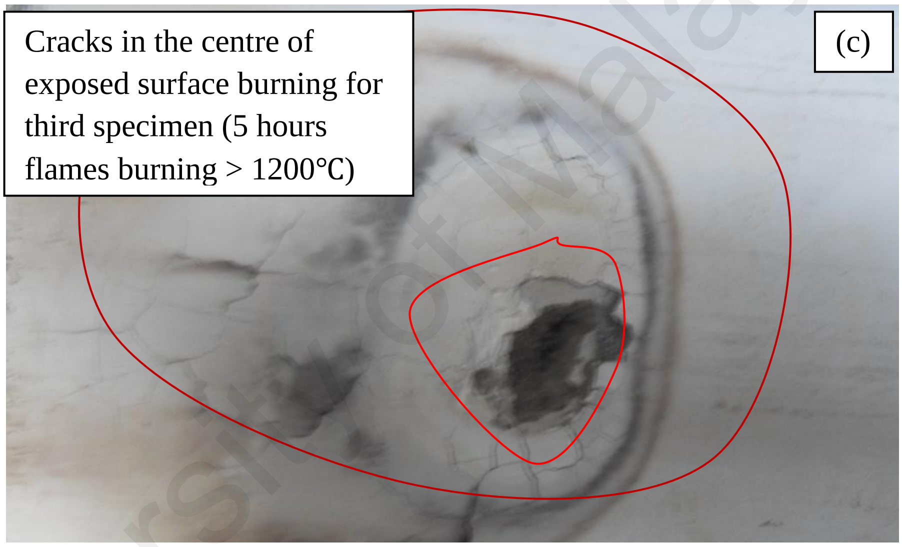




**Figure 5.10**: Cracks on the exposed surface of samples after five hours burning. (a) sample 1 with 2 sides mortar plaster , (b) sample 2 in the front side gypsum plaster and back cement mortar plaster, (c) sample 3 with two sides gypsum plaster



For finishes on the fire exposed side of the wall, a time is assigned to the finish as in Chapter 2, which is the length of time to the finish toward the fire resistance rating of the exposed side of the wall. The thickness of gypsum and cement plaster used for this test was 12 mm. according Table 2.15 (Chapter 2). The period of fire resistance rating of gypsum plaster is 15 minutes and 25 minutes for cement mortar plaster.

There is no previous published data for compressed stabilised peat brick; hence, for this reason the researcher compared the CSPB with the solid clay brick and concrete blocks. As pointed out in Chapter 2, the fire resistance rating for 4 inch lightweight (1600 kg/m$^3$) was 2 hours. The result of fire resistance rating for each specimen is presented in Table 5.4.

### 5.3.2 Calculation of CSPB Wall Fire Resistance Rating

The calculated fire resistance formulas are based on the temperature rise on the unexposed side of wall. Equivalent thickness of individual compressed stabilised peat brick was calculated with the following equation

$$T_e = V_n/LH = Ps \times W \qquad \text{Eq. 5.2}$$

where: W = specified width of the masonry unit, in.

Ps = percent solid of the masonry unit

In our case Ps = 100%, width of brick is 4 inch

$T_e$ = 1 x 4 = 4 inch

Fire resistance calculated by following formulas

$$R = (cV)^n \qquad \text{Eq. 5.3}$$

where:

R = fire resistance period, hr

c = coefficient depending on the material, design of the wall, and the units of measurement of R and V

V = volume of solid material per unit area of wall surface and n exponent depending on the rate of increase of temperature at the exposed face of the wall.

**Table 5.4**: Fire resistance rating of CSPB masonry wall

| Fire resistance rating | | | |
|---|---|---|---|
| | **Sample 1** | **Sample 2** | **Sample 3** |
| **CSPB masonry wall** | 2 h | 2 h | 2 h |
| **Finished plaster** | 25 minute | 15 minute | 15 minute |
| **Total** | 2.25 h ≅ 2 h | 2.15 h ≅ 2 h | 2.15 h ≅ 2h |

The CSPB masonry wall has small deformation and cracks after 5 hours flames burning under > 1200℃. The objective of this test is to find the right time for CSPB masonry wall so that it does not collapse after 5 hours burning and small temperature transformed to non exposed surface of wall.

### 5.4 Summary

In this chapter, the effects of sound insulation and fire resistance of CSPB masonry wall were investigated. The results found that the CSPB partition wall has good sound insulation compared to ASTM standard the maximum sum deficiency, 32 dB and for each point 8 dB. Three samples tested in this research found the maximum deficiency 30.6 dB and between each point was 7.7 dB. At 500 Hz, the losses sound transmission when applied had a high frequency which was 44 dB. This value acquired is good for wall insulation. The fire resistance rating of CSPB wall has good resistance when applied more than 1200℃, the results found the rating more than 5 hours if compared to the standard where the minimum fire rating of same dimension of wall used in this study for 2 hours.

# CHAPTER 6

# CONCLUSION AND RECOMMENDATION FOR FURTHER RESEARCH

## 6.1 Conclusion

The principal objective of this thesis was to investigate the engineering properties, sound insulation and fire resistance of compressed stabilised peat bricks. It can be concluded that the addition of chemical binders and siliceous sand into peat resulted with positive effects on the production of compressed stabilised peat bricks. This significantly improved the strength and density of new material.

Findings from bulk properties tests included wet and dry compressive strength, brick dry density, total water absorption and volume porosity. Other aspects investigated were the effects of sound insulation, fire resistance and stress-strain characteristic of CSPB masonry prism. It was found that the wet compressive strength using Ordinary Portland Cement or Portland Pulverised Fuel ash Cement and hydrated lime can be an effective way of increasing strength, and by implication the durability of compressed stabilised peat bricks.

It was found in the case of lower cement content and higher compaction pressure, the wet compressive strength was higher than the recommended minimum value of 2 MPa. The effect of increase in cement content with strength in bricks was found too closely correspond in all cases. It can be concluded that with increase in cement content from 20% to 30%, the wet compressive strength increased by 40%. It can be therefore concluded that the use of cement contents when increased from 20% to 30% was more suitable for compressed stabilised peat brick. It was also established that increase in compaction pressure resulted in increase of wet compressive strength. A 40% increase in compaction pressure resulted in wet compressive strength which increased between 15% to 32%. It was also found that the mean dry compressive strength was higher than the mean wet compressive strength between 20% and 29%. Another aspect which was found is that the wet compressive strength when using PFA cement was higher than the wet compressive strength by using OPC.

The effect of varying curing conditions on the performance of CSPB was also investigated in this study. Bricks were cured 3,7,14, and 28 days. Bricks were cured fully immersed in water for 14 days and 14 days moist cured in a special room. It can be concluded that the wet compressive strength increased with increased curing time by about 52%. It can be concluded that the fully immersed and moist cured bricks be done in such a manner as to allow the continued presence of moisture to complete the hydration reaction of stabilisers.

From the investigation into the varying stabiliser type and content, compaction pressure on the CSPB dry density, it was found that the density increased with increased content of stabilisers and compaction pressure. Moreover, the density increased with increasing curing periods. Increasing OPC or PFA cement from 20% to 30% and lime from 0% to 4%, it was found that the density in CSPB was increased between 5% and 7%. The conclusion here is that increase in OPC, PFA, lime and curing period's improved dry density of compressed stabilised peat bricks. Dry density can be an indicator of quality in bricks.

It was found that a strong positive correlation exists between density and the 28 days wet compressive strength, the coefficient of correlation was 1.04 with 6 MPa compaction pressure and 0.924 with 10 MPa compaction pressure. It can be concluded that increase in density can result in wet compressive strength. However, very high densities could prove disadvantageous during brick laying and transportation. It was also found the compressed stabilised peat brick was lighter than solid clay or sand bricks which was about 15% to 20%. In this case it can reduce the cost of building by reducing the weight of constructions elements.

Moreover, increase in stabilisers content, compaction pressure and curing periods resulted in decrease in total water absorption. The overall decrease in total water absorption with increase in cement from 20% to 30% which ranged between 14% and 68%. Increase in the compaction pressure and curing periods was about 25% and 83% respectively. Generally, the less water a brick absorbs, the better its performance is expected to be. It can be concluded that total water absorption is a valuable indicator of a brick as it can be used to estimate the volume of pore voids.

From the results it was evident that the total water absorption values obtained were much lower than the recommended maximum value of 20% (IS) standard and 7% BS 3921(1985). The conclusion here is that increase of stabiliser content, compaction pressure and curing periods in CSPB was an effective way of lowering total water absorption.

Negative correlation was also found to exist between total water absorption and density, coefficient of correlation varied between -1.04 to -0.913 with OPC as stabiliser and varied between -0.994 to -0.891 with PFA cement as stabiliser. Moreover, the volume porosity varied between 4.75% and 14.20% when the compaction pressure was 10 MPa and ranged from 8.56% to 15.79% when the pressure was 6 MPa. It was evident that a very strong negative correlation exists between total volume porosity and wet compressive strength, coefficient of correlation varied between -0.889 and -0.467. The conclusion here is that greater the pores, the higher the number of flaws and localised faults within a brick fabric.

It was found that the negative correlation between brick dry density and total volume porosity, coefficient correlation was -0.398 with 6 MPa compaction pressure and -0.551 under 10 MPa compaction pressure. Increase in density was about 8.3% which resulted in the decrease of total volume porosity by about 80%. It can be concluded that increased density can be an effective way to reduce the volume porosity in bricks. It is therefore recommended that proper moist curing be used as a way to reduce the total volume porosity in compressed stabilised bricks.

There was evidence that there is a positive effect in terms of sound insulation in compressed stabilised peat partition wall. Loss sound transmission through CSPB partition wall was 44 dB at high frequency and between 24 dB and 44 dB with medium and lower frequency. Loss sound transmission was 44 dB similar to the recommended value of clay brick. In comparing experimental results curve with ASTM standard curve it was found that the maximum deficiency was 30.6 dB when standard recommendation was 32 dB and maximum differences values between each point was 7.7 dB when ASTM recommended 8 dB. It can be concluded that the compressed stabilised peat bricks used for partition had good sound insulation.

It was found also that compressed stabilised peat masonry wall has a sufficient rating for fire resistance. Burning of CSPB wall was up to 1200℃ , obtained the rating of fire resistance more than 5 hours, when the recommended value with same thickness of wall tested 2 hours. It can be concluded the compressed stabilised peat brick has good fire resistance.

This study also found that the characteristics of stress-strain for CSPB masonry prism, the stress and strain of failure, the maximum stress of failure found was 2.59 MPa. It can be concluded that the analysis of masonry prism for behaviour of stress-strain estimates fairly good stress strain curves when compared with several experimental research works published in literature. Moreover, many types of cracks were found on CSPB masonry prism.

With the evaluation of CSPB masonry prism model in three dimensions analyses was using SAP2000 finite element analysis software. The results showed the stress-strain curves, internal forces and vertical displacement. However, both experimental and numerical results agreed on the comparison of the CSPB masonry prism.

## 6.2 Recommendation for Further Application

Compressed stabilised peat brick has to be further researched. The findings on this type of brick have however flagged up a number of new questions for further future research. The areas for further research include the following:

- Engineering properties of compressed stabilised peat brick proved to be effective and economical. It is recommended that the best results for main engineering properties used brick for different types of construction.

- Life time of this type of brick should be investigated further with a view to understanding the variation of properties.
- In this thesis, the single wall for sound insulation and fire resistance was investigated. However, there should be further research in this area in terms of the double wall without cavity and with cavity.
- Hollow and interlocking bricks should be investigated as ways to reducing costs.
- Compressed stabilised peat bricks should be investigated in the site to get natural data with environmental condition.

Finally, the use of compressed stabilised peat bricks as alternative walling material is likely to increase in the foreseeable future. It is the improvement engineering properties, sound insulation and fire resistance of a bricks, rather than the other properties which are more important.

## REFERENCES


American Society for Testing Materials. (2008). Standard Test Method for Laboratory Determination of the Fibre Content of Peat Samples by Dry Mass. ASTM: D 1997.USA.

American Society for Testing Materials. (2007). Standard Test Methods for Fire Tests of Building Construction and Materials.ASTM:E119. Annual Book of Standards, ASTM International, West Conshohocken,USA.

American Society for Testing Materials. (2009). Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements. ASTM. E 90. USA.

American Society for Testing Materials. (2007). Classification for Rating Sound Insulation. ASTM E 413. USA.

American Society for Testing Materials. (1989). Standard Specification for Building Brick. ASTM C 62. USA.

Ajam, L., Mongi. O., Hayet. S.F., and Rashid, M. (2009). Characterisation of the Tunisian phosphogypsum and its valorisation in clay bricks. J. Const & Build Mater. 23(1). 3240-3247.

Anfor, (2003).Spécification des éléments en maçonneries. EN 777-1 France.

Australian Standard: 1225. (1984). Clay building bricks. Australia.

Anthony, G. K. (2001). Durability of compressed and cement-stabilised building blocks. Ph.D thesis .University of Warwick. UK.

Adam, E.A., and Agib, A. (2001). Compressed Stabilised Earth Block Manufacture in Sudan. Printed by Graphoprint for the United Nations Educational, Scientific and Cultural Organization. France, Paris, UNESCO.

Agarwal, A. (1981). The Potential of Earth-Based Materials for Third World Housing. Earthscan. Mud, London.

Akroyd, T.N.W. (1962). Concrete properties of manufacture, Pergamon Press.

Aksa, Z. (1984). A lime-stabilized soil building materials. Institute of Human Settlement. Bandong, Indonesia.

Al-Temeemi, A.A., and Harris, D. J. (2004). A guideline for assessing the suitability of earth-sheltered mass-housing in hot-arid climates. J. Energy & Build. 63(3). 251-260.

Alwi, A. (2008). Ground improvement of Malaysian peat soils using stabilised peat column techniques. Ph.D Thesis. University of Malaya, Kuala Lumpur (Malaysia).

Alviset, L. (2002) Matériaux de terre cuite. Techniques de l'Ingénieur. C 905-5. France.

Atkinson, R. H., and Noland, J. L. (1983). A proposed failure theory for brick masonry in compression. Proc, 3rd Canadian Masonry Symp. Edmonton, Alta., Canada, 5.1–5.17.

Atkinson, R.H., Noland, J.L., and Abrams, D.P. (1985). A deformation failure theory for stack bond prismin compression. Proc. VIII.B.C. Melbourne, Australia.

Babrauskas, V. (1976). Fire endurance in buildings. National Bureau of Standards (NBS).USA.

Babrauskas, V. (2009). Unexposed-face temperature criteria in fire resistance tests: A Reappraisal. J. Fire Safety. 44(6). 813-818.

Bargado, D. T., Anderson, L.R., Miura, N., and Balasubramaniam, A.S. (1996). Soft ground improvement in lowland and other environments. 1st edn. New York: ASCE Press.

Beamish, A., and Donovan, W. (1993). Village-Level brickmaking. GATE Publications. Braunschweing. Germany.

Bungey, J.H., and Millard, S.G. (1996). Testing of concrete in structures. 3rd Edn. Blackie Acadimic and Professional. Cambridge, England.

British Standards Institution. (1981). Precast concrete masonry units: Part 1. BS 6073. BSI. London, England.

British Standards Institution. (1985). Clay Bricks: BS 3921. BSI. London, England.

British Standards Institution (1990). Stabilised materials for civil engineering purposes. Part 2: BS 1924 Methods of test for cement-, sampling sample preparation and tests on materials before stabilisation. BSI. London, England

British Standards Institution (1990). Stabilised materials for civil engineering purposes. Part 1: BS 1924. General requirements, sampling, sample preparation and tests on materials before stabilisation. BSI. London, England

British Standards Institution (1990). Method of test for soils for civil engineering purposes. General requirement and sample preparation: Part 1: BS 1377. BSI. London, England.

British Standards Institution (1990). Method of test for soils for civil engineering purposes. Part 2: BS 1377. Classification tests. BSI. London, England.

Borchelt, J.G., and Swink, J.E. (2008). Fire Resistance Tests of Brick Veneer/Wood Frame Walls, Proceedings of the 14th International Brick and Block Masonry Conference, University of Newcastle, Callaghan, Australia.

Boardman, D.I., Glendinning, S., Rogers, C.D.F., and Holt, C. C. (2001). In Situ Monitoring of Lime-Stabilised Road Subgrade. Transportation Research Record, No. 1757. pp 3-13.

Bryan, A. J. (1988). Soil-cement as a walling material l & II. Some measures of durability. Buil & Environ. 23(4). 331-336.

Building Research Establishment. (1980). Building in Hot climate; A selection of overseas building notes. Her Majestry's Stationary Office.BRE. Garston, England.

Coffman, R., N. Agnew, G. Austin., and E. Doehne. (1990). Adobe mineralogy: characterisation of adobes from around the world, 6th International Conference On the Conservation of Earthen Architecture ,Las Cruces, NM, 14-19 .

Chen, H., and Wang, Q. (2006). The behaviour of organic matter in the process of soft soil stabilisation using cement. Bull. Eng. Geo Environ. 65(4).445-448.

Craik, R.J.M., and R.S. Smith. (2000). Sound Transmission Through Double Leaf Lightweight Partitions: Part II – Structure borne sound. Applied Acoust. 61(2). 247-269.

Carmen, J., and Ignacio, C.G. (2005). Earth building in Spain. J . Const& Build Mate. 20(9). 679-690.

Clear, K.E., and Sherwood, P.T. (1954). The effect of organic matter on testing of soil-cement mixtures. J. Appl. Chemi. 4(1). 625-630.

Casagrande, A. (1947). Classification and identification of soils. Proceedings of the American Society of Civil Engineerrs (ASCE). PP783-810. USA.

Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies. (2007). ACI 216.1-07 / TMS-0216-07. The Masonry Society, Boulder.

Dunlap, W.A. (1975). US Airforce soil stabilisation index system. Airforce. Weapons Laboratory. New Mexico, USA.

Duraisamy, Y., Huat, B.K., and Aziz, A.A. (2007). Engineering Properties and Compressibility Behavior of Tropical Peat Soil. Amer .J. of Applied Sciences 4(10), pp.768-773.

Dengiz, O., Ozaytekin, H.H., Cayci, G., and Baran, A. (2009). Characteristics, genesis and classification of a basin peat soil under negative human impact in Turkey. Environ. Geol.

Deepthy, R., and Balakrishnan, S. (2005). Climatic control on clay mineral formation: Evidence from weathering profiles developed on either side of the Western Ghats. J. Earth System Sciences 114 (5). 545-556.

Duraisamy, Y., Huat, B.B.K., and Aziz, A.A. (2007). Compressibility Behavior of Tropical Peat Reinforced with Cement Columns, Ame. J. of Appl. Sciences. 4 (10). 768-773.

Drysdal, R.G., Hamid., A.A., and Baker, L.R. (1994). Masonry structures; Behaviour and design, Prentice-Hall, Englewwod Cliffs, N.J. European Committee of Standardisation(CEN), Design of masonry structures. Part 1-1: general rules for buildings–reinforced and unreinforced masonry. ENV 1996, Euro code 6, Brussels, Belgium.

Delbrouck, O., Janssen, J., Ottenburgs, R., Van Oyen, P., and Viaene, W. (1993). Evolution of porosity in extruded stoneware as a function of firing temperature. J. Appl. Clay Sci. 7. 187–192.

Dohud, (1979). Handbook for Building Homes of Earth. Office of International Affairs. US Department of Housing and Urban Development. Washington , DC 20410, USA.

Esbert, R. M., Ordaz, J., Alonso, F. J., Montoto, M., Gonzalez Limo´n, T., and Alvarez de Buergo Ballester, M. (1997). Manual de diagnosis y tratamiento de materiales petreos y cera´micos. Collegi d'Apparelladorsi Arquitectes Te`cnics de Barcelona, Barcelona.

Elbadri, H.A. (1998). The effect of pozzolans in the stabilisation of sulfide tailings. Master Thesis. McGill University, Montreal. Canada.

Easton, D. (1996). The rammed earth house. Vermont: The Chelsea Green Publishing Company. England.

Evans, R. (1980). Mechanics of water erosion and their spatial and temporary controls: an empirical viewpoint: In Soil Erosion. John. Wiley and Sons. Chichester, England.

Fabbri, B., Gualtieri, S., Santoro, S., and L'altenativa. C. (1997). Calcite nella ceramica grezza: prove tecniche. In 1a Giornata di archeometria della ceramica: Il contributo delle analisi archeometriche allo studio delle ceramiche grezze e comuni. Il rapport forma/funzione/impasto, ed. S. Santoro Bianchi and B. Fabbri. University Press, Bologna. pp. 183–190.

Fulletron, R.L, (1979). Building Construction in Warm Climates. Vol 1,2 & 3. Oxford Tropical Handbooks. Oxford University Press. Oxford , England.

Fitzmaurice, R. (1958). Manual on stabilised soil construction for housing. Technical Assistant Programme. United Nations. New York, USA.

Fire Resistance Classifications of Building Constructions. (1942). National Bureau of Standards. NBS. 92, Washington, USA.

Gooding, D.E.M. (1994). Improvement processes for the production soil-cement building blocks. Ph.D Thesis. University of Warwick. Coventry, England.

Gooding, D. E. M., & Thomas, T. (1995). The Potential of Cement-Stabilised Building Blocks as an Urban Building Material in Developing Countries, ODA Report, UK.

Grimm, C.T, (1996) . Clay Brick Masonry Weight Variation. J. Archit. Eng. 2 (4). 135-137.

Greenfiled, (1996). Research methods. Guidance for Postgraduates. Arnold, Hodder Headline Group. London, England.

Gumaste, KS., Venkatarma, B.V. R., Jagadish, K S.,Nand Nanjunda, Rao, K.S (2006). Strength and elasticity of brick masonry prism and wallets under compression. Mate & Struct. 40. 241-253.

Hemant, B. K., Durgesh, C. R., and Sudhir K. Jain. M. (2007). Stress-Strain Characteristics of Clay Brick Masonry Under Uniaxial Compression. J. Mate in Civil. Eng. 19(9). 728-739.

Houben, H., and Guillaud, H. (1994). Earth Construction: A Comprehensive Guide. Intermediate Technology Publications, UK.

Heathcote, K. (1991). Compressive strength of cement stabilised pressed earth blocks. Buid Res & Inform. 19 (2).101-105.

Hooijer, A. (2006). Tropical peat lands in Southeast Asia. In: Rydin H, Jeglum .JK (eds) Thebiology of peat lands. Oxford University Press.

Hall, M. R., and D. Allinson. (2009). Evaporative drying in stabilised compressed earth materials using unsaturated flow theory. J. Buil & Envi. 45(3). 509-518.

Hall, M., and Djerbib, Y. (2004). Moisture ingress in rammed earth: Part 1: the effect of soil particle-size distribution on the rate of capillary suction. Const & Build Mater. 18(4). 269–80.

Higgins, D. (2007). GGBS and sustainability. Proceedings of ICE. J. Const & Build Mater. 160 (3). 99–101.

Habitat, (2001). United Nation Human Settlement: State of world's city. Urban settlements: housing. http://www.unchs.org/documents.

Huat, B.K., Ali, F.H., and Low, T.H. (2006).Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability. J. Geot & Geol Eng. 24(5). 1293-1306.

Huat, B.K. (2004). Organic and Peat Soils Engineering. Serdang, University Putra Malaysia Press. 10.1007/00254-008-1206-3.

Hago, A.W; Hassan, H.F; Rawas, A; Taha, R., and S. Al-Hadidi. (2006). Characterisation of concrete blocks containing petroleum-contaminated soils. J. Const & Build Mater. 21(5). 952-957.

Harrison, A.W., and Sinha, B.P. (1995). A study of alternative building materials and technologies for housing in Banglore, India. Const & Buil Mate. 9(4). 211-217.

Herzong, A., and Metchell, J. (1963). Reactions accompanying the stabilisation of clay with cement. 42nd Annual Meeting of HRB. Washington, USA

Hebib, S., and Ferral. E.R. (2003). Some experiences on the stabilisation of Irish peats. Can. Geotechnic. 40(1). 107-120.

Head, K.H. (1980). Manual of soil laboratory testing, Vol. 1: Soil classification and compaction tests, 1st edn. London. Pentech Press.

Hendry, A.W. (1990). Structural Design of Masonry Buildings. ISBN 0333497481.

Hendry, A.W. (1981). Structural brickwork. John Wiley. New York.

Hendry, A. W. (1998). Structural masonry. 2nd Ed., Macmillan, London. International Code Council. International building code.

Ingles, O.G., and Metcalf, J.B. (1972). Soil stabilisation: principles and practice, 1st edn. Melborn: Butterworths.

Ingles, O.G. (1962). Bonding forces in soils. In the first conference of the Australia Road Research Board. Sydney, Australia.

Illeston, J.M. (1994). Construction Materials. Their nature and behaviour. 2nd Edn. E. & F.N. Spon, Chapman & Hall. London, England.

Inorpi, (2004). Spécification des éléments en maçonneries. NT 21-287. France.

International Standard Organization: (1968). Rating of sound insulation for dwellings. ISO/R 717. 1st Edn. p7.

Indian standard code. (2000). Practice for plain and reinforced concrete, Bureau of Indian Standards. IS: 456. New Delhi. India.

Indian Standard IS: 1905. (1987). Code of practice for structural use of unreinforced masonry. Bureau of Indian Standards, New Delhi, India.

International Building Code. (2006). International Code Council, Inc., Country Club Hills.

International standard organization. (1995). Acoustics – Measurement of sound insulation in buildings and of building elements. ISO 140. Part 3: Laboratory measurements of airborne sound insulation of building elements.

International Labour Office. (1987). Small-scale manufacture of stabilised soil blocks, International Labour Office, Geneva.

International standard organization. (1960). Field and laboratory measurements of airborne and impact sound transmission. ISO/R140, 1st Edn. p 11.

International Standard Organization: (1982). Acoustics – Rating of sound insulation in buildings and of buildings elements. ISO 717: Part 1: Airborne sound insulation in buildings and of interior building elements.

International Standard Organization: (1982). Acoustics – Rating of sound insulation in buildings and of buildings elements. ISO 717: Part 3: Airborne sound insulation of facade elements and facades.

International Standard Organization. (2002). Fire-resistance tests - Elements of building construction. ISO 834: Part 8: Specific requirements for non-load bearing vertical separating elements.

Indian Standard. (1988). Specification for burnt clay hollow bricks for walls and partitions. IS: 3952. India.

Ismail, M.A., Joer, H.A., M.F. Randolph., and Meritt, A. (2002). Cementation of porous materials using calcite. Gotechnique. 52 (5). 313-324.

John, A.P. (1996). Fire safety engineering design structures. Butterworth-Heimemann. Jordon-Hill. Oxford.

James, A., Jeffery, E.O. (1995). Simplified design for building sound control. John Wiley & Sons, New York. USA.

Janz, M., And Johanson, S.E. (2002). The function of different binding agents in deep stabilisation. Linkoping (Sweeden): 9$^{th}$ Report of Swedish Deep Stabilisation research Centre.

Jackson, N., and Dhir, R.K. (1996). Civil Engineering Materials. 5$^{th}$ Edn. McMillan Press Ltd. London, England.

Jagadish, K S., Raghunath S., and Nanjunda, Rao, K.S. (2003) .Behaviour of masonry structures during Bhuj earthquake of January. Proc. Indian Acad. of Sciences, Earth and Planetary Sciences. 112 (3). 431-440

Jordan, M.M., Boix AT., Sanfeliu. C.D., and Fuenta. (1999). Firing transformation of cretaceous clays used in the manufacturing of ceramic tiles. J. Appl Clay Sci. (14). 225–234.

Jayasinghe, C., and Kamaladasa. N. (2007). Compressive strength characteristics of cement stabilised rammed earth walls. Const & Build Mate. 21(1). 1971-1976.

Jayasinghe, C. R.S., and Mallawaarachchi. (2009). Flexural of compressed stabilized earth masonry materials. J. Mater & design. (30). 3859-3868.

Kaushik, H. B., D. C. Rai, S. K. Jain. (2007). Stress strain characteristics of clay brick masonry under uni-axial compression. J. Mat in Civil Eng. (ASCE). 19 (9).728-739.

Keddi, J., Cleghorn, W. (1980). Brick manufacture in developing countries. Scottish Acadimic Press Ltd. Edinburg, Scotland.

Kumar, S. (2000). Fly ash-lime-phosphogypsum cementitious binder a new trend in bricks. J. Mate Struct. 33(1). 59-64.

Kezdi, A. (1979). Stabilised Earth Roads. Published by Amsterdam company- Oxford, New York.

Knutson, H. H. (1993). The Stress-Strain Relationship for Masonry. Masonry International. 7(1). 31-33.

Kaushik, H. B., Rai, D. C., and Jain, S. K. (2007). Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression. J. Mater Eng, ASCE. 19(9). 728-739.

Kaushik, H.B., Rai, D. C., and Jain, S. K. (2009). Effectiveness of Some Strengthening Options for Masonry-Infilled RC Frames with Open First-Storey. J. Struct. Eng, ASCE, 135(8). 925-937.

Kogure, K., Yamaguchi, H., and Shogaki, T. (1993). Physical and pore properties of fibrous peat deposit. Singapore: 11th Southeast Asian Geotechnical Conference.

kumar, S. (2002). A perspective study on fly ash lime-gypsum bricks and hollow blocks for low cost housing development. J. Con & Build Mater. 16. 519-525.

Lunt, M.G. (1980). Stabilised Soil Blocks for Building. Overseas Building Note No. 184. Building Research Establishment. Garston, England.

Lenczner, D. (1972). Elements of Load-bearing Brick work. Oxford. Pergamon Press.

Lea, F.M. (1970). The chemistry of cement and concrete. 3rd edn. Edward Arnold Ltd. London, England.

Laurent, M., Bourriquen, B. (1994). Proprie´te´s thermophysiques-me´thodes flash bilans des moyens francais. Societe´ Francaise deThermiciens, Journees d’etudes . Paris.

Legget, R. F., and Schreiver,W . R. (1960). Site investigations for Canada's first underground railway: Civil Eng. and Pub. Wks. Review. 55. pp73-80.

Little, B., and Morton, T. (2001). Building with earth in Scotland: Innovative Design and Sustainability, Scottish Executive Central Research Unit, Edinburgh.

Lola, C.R. (1981). Research efforts on soil cement stabilisation for low-cost housing in Nicaragua. University of Tennessee. Knoxivill, USA.

Lotfi, H. R., and P. B. Shing (1994). An interface model applied to fracture of masonry structures. J. Struct. Eng., ASCE, 120 (1). 63-80.

Lourenço, P., and A. Feio. (2001). Strutural study of the Boutaca bridge, Report 01-DEC/E-3 (in Portuguese), Universidade do Minho, Guimarães.

Lourenço, P.B. (1998). Possibilities of modelling masonry as a composite softening material: Interface modelling and anisotropic continuum modelling, Proc. 12th Engineering Mechanics Conf., ASCE, San Diego, U.S.A., p. 56-61.

Lourenço, P. J. Martins and L. Ramos. (2002). Structural stability and strengthening design of the Donim Bridge. Part I: Structural stability, Report LEC 27/2001 (in Portuguese), Universidade do Minho, Guimarães.

Minke, G. (1983). Low cost housing. Appropriate construction techniques with loam, sand, and plant stabilised earth. In Colloque L'habitat Economique dans les PED.

Middelton, G.F. (1992). Earth wall construction. 4th edn. Buiietin. North Ryde. Australia.

McNary, W. S., and Abrams, D. P. (1985). Mechanics of masonry in compression. J. Struct. Eng. 111(4). 857–870

Mathuriau, C., and Chauvet, E. (2002). Breakdown of leaf litter in Neotropical stream. J. North. Am. Benthol Soc. 21. 384-396.

Mohamad, G., Lourenço., P.B., and Roman ,H.R. (2005). Mechanical behaviour assessment of concrete block masonry prisms under compression. In: International conference on concrete for structures (INCOS). 261–268.

Middendrof, J. (2001). Properties and methodology of earth structures. Energy and Environment Michell Addington. Harvard Graduate School of Design.

McHenry., and Paul, G. (1984). Adobe and Rammed Earth Buildings. University of Arizona, Press.

McConville, C.J., and Lee, E.W. (2005). Macro-structural development on firing illite and smectite clays compared with that in kaolinite. J. Am Ceram.Soc. 88(8). 2267-2276.

Meclean, D.J., and Sherwood, P.T. (1962). Study the occurrence and effects of organic matter in relation to the stabilisation of soils with cement. In: Proceedings of the 5th international conference on soil mechanics and foundation engineering (ICSMFE). Paris. Dunod. France. pp 269-275.

Markus, (1979). Stabilised soil. University of Strathclyde. Glasgow, Scotland.

Mitchell, J.K., and., EI Jack, S.A. (1978). Presses Ponts et Chaussées. Paris, France.139.

Murad, E., and Wagner, T. (1998). The firing process. Hyperfine Interactions. Clay Miner. 117. 337–56.

Meukan,, P., Jannot, Y.,. Noumowe, A., and. Kofane T.C. (2004). Thermo physical characteristics of economical building materials. J. Const & Build Mate. 18. 437- 443

Norton, J. (1997). Building with Earth, Intermediate Technology Publication London. Zeta potential in colloid science. Academic Press, New York.

Neville, A. M. (1995) Properties of Concrete, Longman.

Oti, J.E., Kinuthia J.M, and BAI, J. (2008a). Using Slag for Unfired-clay Masonry Bricks, Proceedings of ICE. J. Const & Build Mate. 161(4).147-155.

Oti, J.E., Kinuthia J.M, and BAI, J. (2008b). Developing unfired stabilised buildingmaterials. J. Eng. Sustainability. 161(4). 211-218.

Prasertsan, S., and Theppaya T. (1995). A study towards energy saving in brick making, part 1: key parameters for energy saving. J. Energy. 17(2). 145–56.

Portland Cement Association. (1971). Soil-cement Laboratory Handbook. PCA. Chicago, USA.

Portland Cement Institute. (1970). Soil-Cement Series. PCI Publication. Johannesburg, South Africa.

Palmer, L.A. (1935). Mortars Suitable from the Standpoint of Water-Tightness in Unit Masonry. J. America Ceramic Society. 18 (8).

Rigassi, V. (1995). Compressed earth blocks - V 1: Manual of production, GATE.

Rasmussen, B., and Jens, H.R. (2009). Sound insulation between dwelling-Description applied in building regulations in Europe. J. Appli. Acou. 71(3). 171-180.

Reddy, B.V.V., Lal. R,. And Rao K.S.N. (2007). Enhancing bond strength and characteristics of soil-cement block masonry. J. Mater in Civil Eng. 19(2). 164-172.

Ruskulis, O. (1997). The basics of concrete building products. German Appropriate Technology Exchange. GATE Publications. Braunschweing. Germany.

Singapore Institute of Standard and Industrial Research (1974). Specification for burnt clay and shale bricks.(Singapore Standard :103).

Spence, R.J.S., Cook, D.J. (1983). Building Materials in Developing Countries. John Wiley & Sons Ltd. Chichester, England

Spence, R.J.S. (1975). Predicting the Performance of Soil-cement as a Building Material in Tropical Countries. In Building Science. 10. 155-159. Pergamon Press. London. England.

Stevenson, F, and Williams N. (2000) Scottish Homes Sustainable Housing Guide for Scotland HMSO. ISBN 0114972796.

Sudhakar, M. Rao., and P. Shivananda. (2003). Compressibility behaviour of lime-stabilised clay. J. Geotech & Geoleg Eng. 23(3). 309-319.

Sjostrom. (1996). Durability of building materials and components: Testing, Design and Standard. Proceedings of the 7th International Conference on Durability of Building Materialsand components. 7 DBMC held in Stokholm, Sweeden 19-23. Vol.2. E & F.N Spon. London, England.

Sarangapani, G., Venkatarama Reddy, B. V., and Jagadish, K. S. (2002).Structural characteristics of bricks, mortar and masonry. J. Struct. Eng. 29 (2). 101–107.

Sarangapani, G., Venkatarama Reddy, B. V., and Jagadish, K. S. (2005). Brick-mortar bond and masonry compressive strength. J. Mater.Civ. Eng. 17(2). 229–237.

Stulz, R,. and Mukerji, K. (1988). Appropriate Building Materials: A Catalogue of Potential Solutions, Rev. enl. ed., SKAT, St. Gallen, Switzerland.

Singer, S. S., and Singer, F. (1963). Industrial Ceramics. Chapman and Hall, London.

Smith, R.S., Macdonald. R., Lurcock. D. and Mackenzie RK. (2003). Sensitivity analysis of ISO 717-1 spectrum adaptation terms. In: Proceedings of the Institute of Acoustics. (29).

Smith, R.S., Mackenzie, R., Mackenzie, R., Waters-Fuller, T. (2007). The implications of ISO 717 spectrum adaptation terms for residential dwellings. In: Proceedings of the Institute of Acoustics. (25) 5.

Solomon, A.M.D. (1994). Studies of strength of stabilised laterite blocks and rendering mortars. J. Building .Res. Inf. 22(3).

TMS : 216 (2007). Determining Fire Resistance - Concrete and Masonry (ACI 216.1-07) .The Masonry Society.

Tomaževič, M. (1999). Earthquake-resistant design of masonry buildings. Imperial College Press, London.

Tayfun, M.A. (2006). Statistics of nonlinear wave crests and groups. Ocean Eng. 33(11-12), 1589-1622.

Taylor, E. W. (1998). The Theory and Practice of Transformative Learning: A Critical Review. Information Series. no 374. Columbus: ERIC Clearinghouse on Adult, Career, and Vocational Education, Center on Education and Training for Employment, College of Education, the Ohio State University.

US, E.P.A. (2003). National Emission Standards for Hazardous Air Pollutants for Brick and Structural Clay Products Manufacturing; and National Emission Standards for Hazardous Air Pollutants for Clay Ceramics Manufacturing; Final Rule. 40 CFR Part 63, US EPA,Washington, DC.

Underwriters Laboratories. (2007). Fire Resistance Director. Northbrook.

United Nations. (1964). Soil-cement: Its use in building. Sales No. 64. IV.6. United Nations Publications. New York, USA.

Whiteley, P., Russman, H. D., and Bishop, J. D.(1977). Porosity of building materials. J. Oil Col. Chem. Assoc. 60. 142–150.

Whittemore, O. J., and Halsey, G. D. (1983). Pore structure characterization by mercury porosimetry. In Advances in Materials Characterization, ed. D. R. Rossington, R. A. Condrade and R. L. Snyder. Plenum Press, New York, 1983, pp. 147–157.

Warren, J. (1999). Conservation of Brick. Butterworth Heinemann, Oxford. England.

Weidemann, M., Solounlas, N., Drake, R. E. & Curtis, G. H. 1990. Structural Materials, materials Department. Open University. Butterworths. London, England.

Walker, P.J. (2004). Strength and erosion characteristics of earth blocks and earth block masonry. J. Mater in civil Eng. 16(5). 497.506.

Wild, S., 2003. Role of cement science in sustainable development. In: Dhir, R.K., Newlands, M.D., Csetenyi, L.J. (Eds.), International Symposium CelebratingConcrete:

People and Practices, University of Dundee, Scotland, 3– 775. 4th September. Thomas Telford, London, pp. 143–159.

Wong, L.S. (2010). Stabilisation of peat by chemical binders and siliceous sand. Ph.D Thesis. University of Malaya, Kuala Lumpur (Malaysia).

Whitlow, R. (2004), Basic soil mechanics, Prentice Hall.

Valdeo, N, L., Esbert, R. M. and Grossi, C. M., Hydric. (1993). Properties of some Spanish building stones: a petrophysical interpretation. Mater. Issues Art Archaeol. 3. 911–916.

Vazquz, A., Marquz, J. and Macias, E. (2005). Multiple uses of lime in Mixican public housing : Mortars, block, plaster, paint and soils. International Building Lime Symposium. Orland, Florida.

Yule, C.M., and Gomez, L.N., (2008). Leat litter decomposition in a tropical peat swamp forest in Peninsular Malaysia. Wetlands Ecology and Management, DOI 10.1007/ 11273-008-9103- 9.

Young, L.F. et. al. (1998). The Science and technology of civil engineering materials. Practice-Hall, New Jersey, USA.

**APPENDIX A:** ENGINEERING PROPERTIES OF CSPB

**Table A1**: Compressive strength of CSPB (PFA stabiliser)

| Sample | 3 days Compressive strength (Mpa) | 7 days Compressive strength (Mpa) | 14 days Compressive strength (Mpa) | 28 days Compressive strength (Mpa) |
|---|---|---|---|---|
| Stabiliser | PFA | PFA | PFA | PFA |
| CSPB5 | 4.87 | 4.97 | 5.46 | 6.33 |
| CSPB6 | 3.65 | 3.85 | 4.02 | 5.02 |
| CSPB7 | 2.46 | 2.83 | 3.00 | 3.6 |
| CSPB8 | 4.55 | 5.71 | 6.30 | 7.66 |
| CSPB9 | 3.83 | 4.15 | 5.13 | 5.88 |
| CSPB10 | 2.98 | 3.98 | 4.88 | 4.64 |
| CSPB11 | 4.10 | 5.08 | 6.10 | 7.02 |
| CSPB12 | 3.76 | 4.91 | 5.90 | 5.53 |
| CSPB13 | 3.09 | 3.92 | 4.81 | 3.97 |
| CSPB14 | 4.26 | 2.34 | 2.28 | 5.34 |
| CSPB15 | 3.97 | 1.93 | 1.26 | 5.89 |
| CSPB16 | 0.90 | 0.90 | 1.22 | 3.65 |
| CSPB17 | 3.59 | 4.02 | 4.77 | 5.98 |
| CSPB18 | 3.04 | 3.10 | 3.65 | 3.77 |
| CSPB19 | 2.06 | 2.16 | 2.69 | 2.83 |
| CSPB20 | 3.55 | 3.88 | 4.05 | 4.75 |
| CSPB21 | 2.14 | 3.95 | 3.53 | 4.59 |
| CSPB22 | 1.65 | 3.67 | 3.42 | 4.22 |

**Table A2:** Compressive strength of CSPB (OPC satabiliser)

| Sample | 3 days Compressive strength (Mpa) | 7 days Compressive strength (Mpa) | 14 days Compressive strength (Mpa) | 28 days Compressive strength (Mpa) |
|---|---|---|---|---|
| Stabiliser | OPC | OPC | OPC | OPC |
| CSPB23 | 4.26 | 4.63 | 4.46 | 5.91 |
| CSPB24 | 2.71 | 4.46 | 4.48 | 4.95 |
| CSPB25 | 2.69 | 3.26 | 2.48 | 3.30 |
| CSPB26 | 3.71 | 4.85 | 6.44 | 6.77 |
| CSPB27 | 3.42 | 4.88 | 4.73 | 5.33 |
| CSPB28 | 2.93 | 2.08 | 4.16 | 3.81 |
| CSPB29 | 3.77 | 4.81 | 6.20 | 5.67 |
| CSPB30 | 3.53 | 4.63 | 4.73 | 5.04 |
| CSPB31 | 3.22 | 3.22 | 3.73 | 4.10 |
| CSPB32 | 3.60 | 3.44 | 3.91 | 4.32 |
| CSPB33 | 3.20 | 3.00 | 4.30 | 3.59 |
| CSPB34 | 2.73 | 1.93 | 3.36 | 3.63 |
| CSPB35 | 4.85 | 4.70 | 5.32 | 5.62 |
| CSPB36 | 4.04 | 3.69 | 4.30 | 5.30 |
| CSPB37 | 2.14 | 3.95 | 3.06 | 2.65 |
| CSPB38 | 4.20 | 4.48 | 3.98 | 4.22 |
| CSPB39 | 3.87 | 3.26 | 4.18 | 4.20 |
| CSPB40 | 3.22 | 3.30 | 3.02 | 3.20 |
| CSPB41 | - | - | - | 3.57 |

**Table A3**: Total water absorption (PFA stabiliser)

| Sample | 3 days water absorption (%) | 7 days water absorption (%) | 14 days water absorption (%) | 28 day water absorption(%)s |
|---|---|---|---|---|
| Stabiliser | PFA | PFA | PFA | PFA |
| CSPB5 | 15.69 | 6.900 | 4.5 | 2.6 |
| CSPB6 | 13.97 | 10.44 | 6.5 | 2.8 |
| CSPB7 | 16.37 | 11.01 | 7.4 | 8.3 |
| CSPB8 | 12.92 | 10.81 | 6.5 | 8.3 |
| CSPB9 | 13.01 | 10.82 | 7.0 | 4.4 |
| CSPB10 | 15.53 | 13.97 | 7.2 | 6.9 |
| CSPB11 | 15.76 | 14.98 | 8.5 | 5.2 |
| CSPB12 | 17.23 | 16.26 | 9.0 | 6.3 |
| CSPB13 | 16.90 | 16.66 | 9.9 | 7.3 |
| CSPB14 | 15.76 | 14.98 | 8.5 | 7.0 |
| CSPB15 | 17.23 | 16.26 | 9.0 | 8.2 |
| CSPB16 | 16.90 | 16.66 | 9.9 | 9.4 |
| CSPB17 | 17.34 | 12.91 | 6.5 | 6.0 |
| CSPB18 | 16.45 | 11.83 | 5.2 | 4.6 |
| CSPB19 | 16.18 | 14.51 | 6.8 | 7.0 |
| CSPB20 | 16.00 | 16.01 | 8.2 | 7.0 |
| CSPB21 | 19.17 | 18.23 | 8.9 | 8.2 |
| CSPB22 | 22.68 | 17.18 | 9.0 | 8.3 |

**Table A4:** Total water absorption (OPC as stabiliser)

| Sample | 3 days water absorption (%) | 7 days water absorption (%) | 14 days water absorption (%) | 28 days water absorption (%) |
|---|---|---|---|---|
| Stabiliser | OPC | OPC | OPC | OPC |
| CSPB23 | 11.44 | 10.57 | 8.35 | 5.4 |
| CSPB24 | 12.08 | 11.76 | 9.13 | 5.8 |
| CSPB25 | 13.98 | 14.06 | 9.98 | 6.5 |
| CSPB26 | 10.94 | 10.60 | 8.51 | 5.2 |
| CSPB27 | 11.09 | 12.52 | 9.51 | 6.2 |
| CSPB28 | 12.34 | 9.410 | 9.63 | 4.6 |
| CSPB29 | 15.38 | 9.850 | 8.45 | 4.7 |
| CSPB30 | 8.180 | 12.09 | 10.33 | 6.1 |
| CSPB31 | 11.26 | 10.54 | 8.43 | 6.9 |
| CSPB32 | 13.94 | 12.68 | 10.84 | 6.0 |
| CSPB33 | 12.93 | 11.54 | 9.58 | 6.3 |
| CSPB34 | 14.90 | 11.88 | 10.42 | 7.4 |
| CSPB35 | 7.300 | 10.79 | 8.49 | 5.5 |
| CSPB36 | 12.60 | 17.24 | 12.78 | 7.9 |
| CSPB37 | 15.39 | 10.10 | 8.74 | 5.9 |
| CSPB38 | 16.10 | 9.230 | 9.98 | 4.9 |
| CSPB39 | 14.15 | 12.23 | 8.32 | 4.8 |
| CSPB40 | 15.20 | 11.85 | 11.33 | 3.3 |
| CSPB41 | | | | |

**Table A5:** Total volume Porosity ( PFA as stabiliser)

| Sample | 3 days Compressive strength (Mpa) | 7 days Compressive strength (Mpa) | 14 days Compressive strength (Mpa) | 28 days Compressive strength (Mpa) |
|---|---|---|---|---|
| Stabiliser | PFA | PFA | PFA | PFA |
| CSPB5 | 27.79 | 12.04 | 8.50 | 4.75 |
| CSPB6 | 24.22 | 18.43 | 11.82 | 5.12 |
| CSPB7 | 24.44 | 19.92 | 13.10 | 12.68 |
| CSPB8 | 22.57 | 18.89 | 14.49 | 10.01 |
| CSPB9 | 22.73 | 19.77 | 13.02 | 12.03 |
| CSPB10 | 25.66 | 24.32 | 15.97 | 8.38 |
| CSPB11 | 22.27 | 22.02 | 12.16 | 9.39 |
| CSPB12 | 24.07 | 24.01 | 13.26 | 11.38 |
| CSPB13 | 25.55 | 24.02 | 15.01 | 14.20 |
| CSPB14 | 27.63 | 26.44 | 15.13 | 12.79 |
| CSPB15 | 29.59 | 27.91 | 15.51 | 14.33 |
| CSPB16 | 29.03 | 27.90 | 16.34 | 15.47 |
| CSPB17 | 30.29 | 23.45 | 12.11 | 11.26 |
| CSPB18 | 28.25 | 20.79 | 9.77 | 8.56 |
| CSPB19 | 27.31 | 24.67 | 11.88 | 11.19 |
| CSPB20 | 27.63 | 27.60 | 14.48 | 12.77 |
| CSPB21 | 27.79 | 20.41 | 14.65 | 12.36 |
| CSPB22 | 37.13 | 29.40 | 15.69 | 15.19 |

**Table A6:** Total volume Porosity ( OPC as stabiliser)

| Sample | 3 days volume Porosity (%) | 7 days volume Porosity (%) | 14 days volume Porosity (%) | 28 days volume Porosity (%) |
|---|---|---|---|---|
| Stabiliser | OPC | OPC | OPC | OPC |
| CSPB23 | 20.18 | 18.64 | 14.98 | 9.72 |
| CSPB24 | 20.90 | 20.40 | 16.31 | 10.31 |
| CSPB25 | 23.32 | 19.99 | 17.91 | 12.68 |

**Table A7:** Plasticity index, pH and linear shrinkage

| Sample | Plasticity index (%) | pH | Linear shrinkage (%) |
|---|---|---|---|
| CSPB5 | 1.15 | 11.15 | 0.70 |
| CSPB6 | 1.68 | 11.45 | 1.42 |
| CSPB7 | 2.26 | 11.38 | 0.70 |
| CSPB8 | 1.66 | 11.97 | 0.78 |
| CSPB9 | 2.26 | 11.90 | 1.17 |
| CSPB10 | 1.68 | 12.00 | 0.86 |
| CSPB11 | 2.04 | 11.51 | 1.82 |
| CSPB12 | 2.49 | 11.46 | 0.92 |
| CSPB13 | 1.49 | 11.44 | 1.36 |

**APPENDIX B:** SOUND INSULATION

**Table B1**: Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44(high frequency sample 2)

| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) High frequency | Shifted Reference Curve ASTM E-413 STC= 44 | Deficiency |
|---|---|---|---|
| 20 | 25.6 | - | - |
| 25 | 26.8 | - | - |
| 31.5 | 28.6 | - | - |
| 40 | 27.2 | - | - |
| 50 | 24.8 | - | - |
| 63 | 12.7 | - | - |
| 80 | 17.3 | - | - |
| 100 | 28.2 | 25 | 0.0 |
| 125 | 35.4 | 28 | 0.0 |
| 160 | 32.8 | 31 | 0.0 |
| 200 | 36.6 | 34 | 0.0 |
| 250 | 42.9 | 37 | 0.0 |
| 315 | 34.1 | 40 | 5.9 |
| 400 | 38.1 | 43 | 4.9 |
| 500 | 37.7 | 44 | 6.3 |
| 630 | 39.8 | 45 | 5.2 |
| 800 | 41.9 | 46 | 4.1 |
| 1000 | 43.0 | 47 | 4.0 |
| 1250 | 56.0 | 48 | 0.0 |
| 1600 | 62.3 | 48 | 0.0 |
| 2000 | 58.2 | 48 | 0.0 |
| 2500 | 54.0 | 48 | 0.0 |
| 3150 | 47.8 | 48 | 0.2 |
| 4000 | 49 | 48 | 0.0 |
| Total deficiency (125 Hz- 4000 Hz) | | | 30.6 |

**Table B2**: Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44 (Medium frequency sample2)

| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) Medium frequency | Shifted Reference Curve ASTM E- 90 STC= 24 | Deficiency |
|---|---|---|---|
| 20 | 8.10 | - | - |
| 25 | 12.1 | - | - |
| 31.5 | 21.8 | - | - |
| 40 | 18.4 | - | - |
| 50 | 22.8 | - | - |
| 63 | 23.5 | - | - |
| 80 | 14.8 | - | - |
| 100 | 14.0 | - | - |
| 125 | 28.3 | 5.00 | 0.0 |
| 160 | 22.4 | 10.0 | 0.0 |
| 200 | 24.9 | 14.0 | 0.0 |
| 250 | 30.5 | 16.0 | 0.0 |
| 315 | 26.6 | 17.5 | 0.0 |
| 400 | 24.9 | 21.0 | 0.0 |
| 500 | 20.9 | 24.0 | 3.1 |
| 630 | 21.9 | 24.5 | 2.6 |
| 800 | 34.7 | 25.0 | 0.0 |
| 1000 | 38.5 | 26.0 | 0.0 |
| 1250 | 38.2 | 27.0 | 0.0 |
| 1600 | 49.8 | 27.0 | 0.0 |
| 2000 | 51.2 | 27.0 | 0.0 |
| 2500 | 46.9 | 27.0 | 0.0 |
| Total deficiency (125 Hz- 4000 Hz) | | | 5.7 |

**Table B3:** Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44 (Low frequency sample 2)

| **1/3 Octave Band Frequency (Hz)** | **Measured sound Transmission Loss TL (dB) low frequency** | **Shifted Reference Curve ASTM E- 90 STC= 24** | **Deficiency** |
|---|---|---|---|
| 20 | 12.9 | - | - |
| 25 | 11.6 | - | - |
| 31.5 | 20.7 | - | - |
| 40 | 30.1 | - | - |
| 50 | 16.4 | - | - |
| 63 | 11.2 | - | - |
| 80 | 26.5 | - | - |
| 100 | 36.3 | - | - |
| 125 | 16.2 | 5.00 | 0.0 |
| 160 | 21.8 | 10.0 | 0.0 |
| 200 | 20.8 | 14.0 | 0.0 |
| 250 | 10.5 | 16.0 | 6.0 |
| 315 | 15.7 | 17.5 | 1.8 |
| 400 | 23.2 | 21.0 | 0.0 |
| 500 | 18.7 | 24.0 | 5.3 |
| 630 | 50.1 | 24.5 | 0.0 |
| 800 | 44.7 | 25.0 | 0.0 |
| 1000 | 46.5 | 26.0 | 0.0 |
| Total deficiency (125 Hz- 4000 Hz) | | | 13.1 |

**Table B4:** Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44 (high frequency sample 3)

| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) High frequency | Shifted Reference Curve ASTM E-413 STC= 44 | Deficiency |
|---|---|---|---|
| 20 | 17.2 | - | - |
| 25 | 21.3 | - | - |
| 31.5 | 24.9 | - | - |
| 40 | 24.5 | - | - |
| 50 | 24.8 | - | - |
| 63 | 17.8 | - | - |
| 80 | 26.3 | - | - |
| 100 | 26.3 | 25 | 0.0 |
| 125 | 40.7 | 28 | 0.0 |
| 160 | 34.0 | 31 | 0.0 |
| 200 | 31.7 | 34 | 2.3 |
| 250 | 38.5 | 37 | 0.0 |
| 315 | 36.3 | 40 | 3.7 |
| 400 | 40.1 | 43 | 2.9 |
| 500 | 36.7 | 44 | 7.3 |
| 630 | 43.5 | 45 | 1.5 |
| 800 | 44.0 | 46 | 2.0 |
| 1000 | 40.3 | 47 | 6.7 |
| 1250 | 49.7 | 48 | 0.0 |
| 1600 | 51.8 | 48 | 0.0 |
| 2000 | 49.4 | 48 | 0.0 |
| 2500 | 45.8 | 48 | 2.2 |
| 3150 | 52.8 | 48 | 0.0 |
| 4000 | 50.0 | 48 | 0.0 |
| Total deficiency (125 Hz- 4000 Hz) | | | 28.6 |

**Table B5:** Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 44 (Medium frequency sample 3)

| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) Medium frequency | Shifted Reference Curve ASTM E-413 STC= 44 | Deficiency |
|---|---|---|---|
| 20 | 13.1 | - | - |
| 25 | 15.7 | - | - |
| 31.5 | 14.0 | - | - |
| 40 | 16.0 | - | - |
| 50 | 19.4 | - | - |
| 63 | 11.1 | - | - |
| 80 | 20.4 | - | - |
| 100 | 25.4 | 25 | 0.0 |
| 125 | 29.3 | 28 | 0.0 |
| 160 | 29.1 | 31 | 1.9 |
| 200 | 28.8 | 34 | 5.2 |
| 250 | 35.5 | 37 | 1.5 |
| 315 | 36.1 | 40 | 3.9 |
| 400 | 37.4 | 43 | 5.6 |
| 500 | 43.0 | 44 | 1.0 |
| 630 | 45.5 | 45 | 0.0 |
| 800 | 42.0 | 46 | 4.0 |
| 1000 | 43.0 | 47 | 4.0 |
| 1250 | 47.4 | 48 | 0.6 |
| Total deficiency (125 Hz- 4000 Hz) | | | 27.7 |

**Table B6:** Measured Sound Transmission loss. TL and values of the shifted reference curve for STC = 24 (Low frequency sample 3)

| 1/3 Octave Band Frequency (Hz) | Measured sound Transmission Loss TL (dB) low frequency | Shifted Reference Curve ASTM E- 90 STC= 24 | Deficiency |
|---|---|---|---|
| 20 | 8.70 | - | - |
| 25 | 4.00 | - | - |
| 31.5 | 3.40 | - | - |
| 40 | 2.30 | - | - |
| 50 | 5.60 | - | - |
| 63 | 4.00 | - | - |
| 80 | 8.70 | - | - |
| 100 | 14.0 | - | - |
| 125 | 18.9 | 5.00 | 0.0 |
| 160 | 23.9 | 10.0 | 0.0 |
| 200 | 21.8 | 14.0 | 0.0 |
| 250 | 14.6 | 16.0 | 1.4 |
| 315 | 19.8 | 17.5 | 0.0 |
| 400 | 24.4 | 21.0 | 0.2 |
| 500 | 23.8 | 24.0 | 0.0 |
| 630 | 25.0 | 24.5 | 0.0 |
| Total deficiency (125 Hz- 4000 Hz) | | | 1.6 |