EFFECTS OF TIME-DEPENDENT DEFORMATION ON THE STRENGTH OF MASONRY

by

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This thesis is dedicated to the people very dear to my heart:

my late caring father *Said Ismail* and my lovely mother *Che Eshah Che Man*

my supporting siblings

Samira Said, Sudirman Said, Syamsul Said and Sulyza Said

and my loving husband

Izwan Johari

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ABBREVIATIONS

A	Cross-sectional area
b	Depth of unit
C	Creep or Specific creep, and number of courses
E	Modulus of elasticity
E'	Effective modulus of elasticity
f	Compressive strength
g	Volumetric content
H	Height of mortar
m	Thickness of mortar
t	Time
R	Ratio of maximum load strain
S	Shrinkage
W	Lateral dimension of masonry
σ	Stress
ε	Strain

KESAN UBAHBENTUK BERSANDAR MASA KE ATAS KEKUATAN MASONRI

ABSTRAK

Pengaruh jenis unit terhadap ubah bentuk struktur dinding bata adalah penting disebabkan terdapat pelbagai jenis bata tanah liat bakar dalam pasaran tempatan. Kebanyakan penerbitan kajian bata tanah liat bakar ini, terutamanya berhubung ubah bentuk jangka panjang, dihasilkan dari negara lain seperti United Kingdom dan jarang ditemui di Malaysia. Oleh itu, kajian ini adalah penting untuk dijalankan disebabkan kurangnya maklumat dan salah tanggapan terhadap bata di Malaysia, yang dikelaskan dalam kualiti rendah dan menjadi bahan pembinaan yang kurang popular berbanding konkrit. Maka, kajian terhadap kesan ubah bentuk iaitu keanjalan, rayapan dan pergerakan lembapan ke atas kekuatan dinding bata dijalankan dalam dua keadaan, iaitu, persekitaran tidak dikawal dan persekitaran terkawal pada suhu 25 ± 2ºC dan kelembapan relatif 75 ± 5%. Kajian yang dilakukan melibatkan pengukuran ke atas dinding tunggal yang dibina dari tiga jenis bata tanah liat bakar Malaysia menggunakan mortar jenis (ii) dengan nisbah campuran simen : kapur : pasir pada 1 : ½ : 4½. Selepas diawet selama 14 hari, dinding kemudian dikenakan tekanan 1.5 N/mm^2 pada arah menegak dan pada masa yang sama dinding kawalan digunakan untuk mengukur perubahan terikan kelembapan. Unit bata dan prisma mortar yang tidak terikat juga diukur bagi membolehkan ramalan dibuat menggunakan model komposit terdahulu. Sebagai tambahan, struktur mikro dan mineralogi bata turut dikaji. Hasil kajian mendapati keanjalan, rayapan dan pergerakan kelembapan dinding bata adalah mempengaruhi kekuatan dinding

tersebut. Peningkatan dan penurunan rayapan di dalam dinding bata ini dipengaruhi oleh kelembapan relatif dan suhu sekitar. Komposisi kimia dan struktur mikro juga mempengaruhi sifat mekanikal dan fizikal, yang bergantung kepada kaedah penghasilannya seperti jenis tanah liat yang digunakan dan suhu proses pembakaran.

EFFECTS OF TIME-DEPENDENT DEFORMATION ON THE STRENGTH OF MASONRY

ABSTRACT

Influence of unit type on the deformation of masonry structure is very important owing to different type of fired-clay brick available in the local market. Most of research published on fired-clay brick, especially on time-dependent movement, were from other countries, mostly in the United Kingdom and rarely be found in Malaysia. Therefore, it is necessary to conduct the study due to a lack of information and misleading perception that local bricks are of low quality and are becoming unpopular building materials as compared to concrete. Thus, the effects of deformation behaviour, viz. elasticity, creep and moisture movement on the strength of masonry in two conditions, ambient and controlled environment at temperature of 25 ± 2ºC and 75 ± 5% relative humidity were studied. This investigation involved the measurement of single-leaf wall built from three types of Malaysian fired-clay bricks using mortar designation (ii) with cement : lime : sand in the proportion of 1 : ½ : 4½. After curing for 14 days, the wall was then loaded to a stress 1.5 N/mm^2 in the bed direction and at the same time the controlled wall was used in the measurement of moisture strain. Bonded and unbounded masonry units and mortar prisms were measured to incorporate the previous composite model for prediction. In addition, microstructure and mineralogy of the masonry unit were also investigated. It was observed that elasticity, creep and moisture movement of masonry walls were affected the strength of masonry wall. Creep in masonry wall increases and decreases with the influence of relative humidity and temperature. The chemical compositions

and microstructure also affected the mechanical and physical properties and these highly depend on the method of manufacture, including clay types and firing temperature.

CHAPTER 1

INTRODUCTION

1.1 History and development of masonry

Masonry is a traditional material for the construction industry and has been used all over the world for thousands of years. Masonry systems are the preferred walling material in many countries. Between the different types of masonry units, fired-clay bricks have been the most popular and widely used structural material since the previous decades. The most effective use of masonry is for load bearing structures, wherein it performs a variety of functions, namely, supporting loads, subdividing space, providing thermal and acoustic insulation, as well as for protection against fire and weather (Rai, 2005).

The Romans introduced brick buildings in Britain and brick was used extensively in the dwellings of the British middle class in the 17th and 18th centuries. Following the great fires in London in 1666 and in Chicago in 1891, laws were created that mandated the use of bricks and blocks to rebuild the cities. Besides for housing, new forms of structures such as the arches with flying buttresses, the vaulted roofs and the domes emerged. For several centuries, masonry became the principal construction material (Abdullah, 2009).

The history of masonry application in Malaysia dated back more than 350 years ago with the construction of the Stadthuys in Malacca, built by the Dutch in 1650. A more modern form of masonry construction was initiated by the British during the colonial era of Malaya. Brickwork buildings were at that time built specially for government offices, quarters and middle-class residential. The administrative block of the Sultan Abdul Samad Building, built in 1894 and given a face-lift during the Fourth Malaysian Plan (1981 – 1985), is an example of a masonry heritage, which stands as a remarkable landmark of Kuala Lumpur (Arman Ali, 2005). Other examples of the early distinguished buildings using load bearing brick masonry are Hospital Tun Aminah and Bangunan FMS Railways (Abdullah, 2009).

Due to the importance and benefits offered by fired-clay bricks in construction, factors affecting the strength, stability and performance of masonry structures have to be identified, and need to be considered in design. Earlier, masonry is known as a material of great antiquity, originally built by instinct rather than design (West, 1977). Until the 19th century, there were no proper engineering methods of masonry design and the only design method used was based largely on the 'Rule of Thumb' as given in Building Codes and Regulations (Rai, 2005). As a result, the structural stability was achieved by using massive thickness of walls, of which there were less movement and the forms of construction were less susceptible to damage arising from it. Such construction concepts continued for centuries. Only in 1948, a proper design rule was introduced in Great Britain and subsequently improved equivalent emerged with the development of the construction industry.

The evolution of the construction industry has created a significant feature of modern brickwork construction that is designed based on sound engineering principle. In contrast with the previous method of design, the design of new structures lead to greater movements for the following reasons; working stresses have resulted in an increase in the elastic modulus of the materials, prefabrication has led to greater use of articulated construction as opposed to continuous construction; taller building with slender construction have increased the problems of movement; finally, modern heating and insulating techniques have tended to exaggerate thermal moisture movement (Lenczner, 1971). There is no doubt that the knowledge of brickwork behaviour under load becomes important matter in the new design methods of construction. Because of the increasing demand placed on the building industry, it is important to improve some of the existing methods of construction. In order to achieve that, the behaviour of the individual materials must be investigated and understood as well as their composite interaction and in particular the deformation characteristics of brickwork under a sustained load.

1.2 Research background

Masonry can consist of artificial or natural units that are jointed together with mortar, whereby each part of the components possesses different deformation characteristics. All building materials including masonry tend to deform when they are subjected to a sustained applied load. The states of stress in units and mortar are different under sustained load, i.e. the units are compressed in the direction of load together with tension in perpendicular. When subjected to a uniaxial compressive force, the mortar has a tendency to expand laterally more than the brick. Because the mortar and brick are bonded together chemically and mechanically, the mortar is confined laterally by the brick (**Figure 1.1**). This is called deformation of two different types of materials that may result in a reduction in strength and stiffness, eventually leading to cracking. In that case, it is important to understand the effects of deformation in both masonry unit and mortar to be considered in design and construction of masonry structures.

Failure to allow for long term movements in the design of unreinforced masonry may cause serviceability problems i.e. spalling and buckling, or cracking in the case of restraint to movement (Abu Bakar, 1998).

Changes in building materials and technology have affected the design and behaviour of many building components, including masonry walls. Long term movements in masonry structures, are of interest mainly in connection with cracking resulting from stresses generated by restraint to these movements (Brooks, 1985). Although stronger units and mortars increase the compressive strength of the masonry, they do so at the expense of other important properties. Thus, masonry walls today tend to be thinner and more brittle than their massive ancestors (Brick Industry Association, 2006).

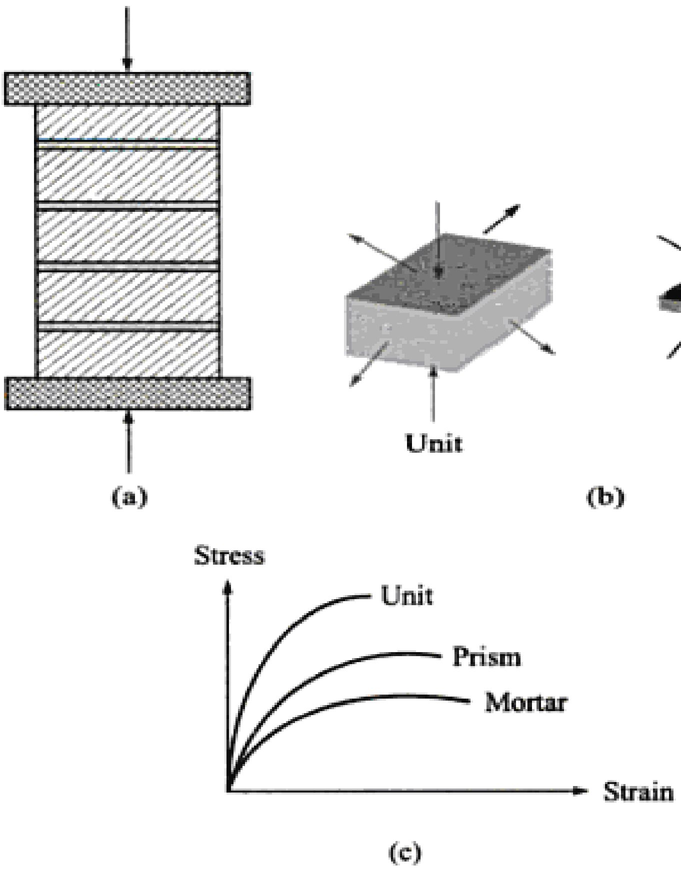


Figure 1.1 a) Prism under axial compression b) states of stress of units and mortar c) stress relationship for materials and prism (McNary and Abrams, 1985)

Elasticity can be defined as an instantaneous deformation immediately after load is applied. It is the ability of a material to deform under a load, without a permanent set or deformation upon the release of the load (Somayaji, 2001). Masonry continues to deform if it is subjected to constant load and this phenomenon is called “creep” which is described as the permanent movement or deformation of a material in order to relieve stresses in the material (Marzhan, 2000). The moisture movement of masonry unit is described as being in two conditions, either expansion or shrinkage. Clay masonry tends to expand due to adsorption of moisture or shrink with a loss of water.

1.3 Problem statement

Compared to traditional brickwork, modern masonry structures are design to be slender, spanning longer and utilise stronger materials, reinforcements and prestressing where allowance for creep and shrinkage is important. If masonry design techniques are to be improved, then basic engineering data for the material must be available or predictable. Unfortunately, creep data for use in the design a masonry structures are still limited and this scenario has restricted the development of universal design procedure. Studies on creep of masonry are quite recent (early work by D. Lenczner in early 1960s) compared to concrete that are well documented (discovered by W.K. Hatt in 1907). Therefore, as creep and shrinkage is a long term phenomenon, research on them is time consuming and it take many more years and even decades before enough data can be generated (Abdullah, 2009).

The influence of unit type on the deformation of masonry structure is very important owing to different types of units available in the local market. According to Abdullah and Wan Omar (2007), none of the manufacturers in Malaysia produces bricks with strength less than 5 N/mm^2 and more than 90 percent of the manufacturers produce bricks with more than 10 N/mm^2 strength. More than 5 percent produces bricks of more than 50 N/mm^2. This finding indicates that although most of Malaysian bricks are common bricks, they posses the level of strength to be used as load bearing bricks (Abdullah et al., 1994). Therefore, the perception that local bricks are of low quality is wrong as revealed in the previous research (Abdullah and Othman, 2005).

Besides this misleading perception, the lack of data on bricks could also be the reason why bricks become unpopular load bearing building materials as compared to reinforced concrete. Most of the published research on bricks, especially in deformation behaviour was carried out in other countries, and mostly in the United Kingdom, and rarely to be found in Malaysia. Even though the design procedure method is well documented by other country, due to lack of knowledge and experience on the system has results in poor adoption of load bearing (LB) system in our country. As a consequences, fired-clay brick is only popular as a non load bearing material instead of load bearing and hence dominance of reinforced concrete (RC) system in construction industry. For that reason, this research can be as a fundamental research in order to promote the load bearing brick system in Malaysia.

Not many this kind of research done in Malaysia using our own materials such as fired-clay brick, sand and cement that tested in local environment condition. Due to these factors, it is important to investigate and understand the mechanical properties of the local bricks, so that the effect of deformation behaviour on the strength of masonry can be studied further. The findings of this research will help develop better understanding of fired-clay brick unit and masonry structures constructed with different types of fired-clay brick produced by local manufacturers and finally, contribute a data base for Malaysian Standard development of masonry deformation design procedure.

1.4 Objectives of the research

The main objectives of the research have been specified into three subjects to obtain realistic plans in ensuring an achievement of the intended goal:

1. To determine the effects of elasticity, creep and moisture movement on the strength of masonry structures constructed from different unit types of fired-clay brick.
2. To study the deformation behaviour of fired-clay brick masonry walls under ambient condition and controlled environment.
3. To investigate the influences of microstructural and mineralogical characteristics on the mechanical properties of fired-clay bricks.
4. To compare the results of experimental work with the prediction method using empirical and composite modeling.

To fulfill the first objective, three types of fired-clay brick have been used to investigate the effects of deformation characteristics on the strength of masonry walls constructed from units with different mechanical properties.

This study has been divided into two series where tests have been conducted in ambient condition and in a controlled laboratory. In the second objective, both conditions were tested to investigate the effects of temperature and humidity in Malaysia on the deformation of single-leaf walls. The purpose of testing the walls in ambient condition was to simulate the actual environment on site.

In the third objective, the microstructure and mineralogical compositions of each type of fired-clay brick unit was tested to investigate their relation with the mechanical properties particularly the unit strength.

Finally, the results obtained from the experimental work will be compared with the prediction method using empirical and composite modeling.

1.5 Scope of work

This research dealt with the investigation of deformation behaviour of Malaysian fired-clay bricks and their effect on the masonry strength. The work has been divided into two series. In Series 1, the specimens were subjected to a constant stress level and were allowed to creep under fluctuating conditions or ambient temperature and humidity. In Series 2, the specimens were also loaded with a constant stress level but in a controlled environment under a constant temperature of 25 ± 2 ºC and a relative humidity of 75 ± 5 %.

Three types of fired-clay bricks have been used in this research i.e. solid brick (Brick type 1) and perforated brick (Brick type 2 and Brick type 3) in the form of single-leaf wall. The same type of mortar with mix designation of 1 : ½ : 4½ (cement : lime : sand) by mass was used in both series of walls. Prior to the construction of the walls, the properties of materials were determined to obtain the characteristics of each type of brick and also the properties of mortar. In both series, three single-leaf walls were constructed in 5-stack course with the same batch of mortar. Wall 1 has been used to test for the compressive strength at the age of 14 days, Wall 2 as a controlled wall (unloaded) used for shrinkage/moisture expansion and Wall 3 as a loaded wall for elasticity and creep. From each batch of mortar, six cubes of 100 mm x 100 mm x 100 mm and two prisms of 75 mm x 75 mm x 300 mm (only in Series 2) were prepared and tested at 14 days. Mortar cubes were tested for compressive strength, while prisms that were partly sealed were used to estimate the modulus elasticity and shrinkage of mortar. As a specific study, the relationship between porosity and mechanical properties of units especially strength were investigated. Therefore, each type of fired-clay bricks was tested for their chemical composition, microstructure and also crystalline phases.

1.6 Outline of the thesis

This thesis is divided into six chapters; Chapter I focuses on introduction that generally explains the overall view about the research, including the detailed explanation on problem statement and objectives of the research.

Chapter II includes the review of properties of masonry component materials and also discusses the previous research work related to deformation behaviour and the strength of masonry walls. A specific review on brick microstructure and mineralogy were also discussed at the end of this chapter.

Chapter III discusses the modeling proposed by previous researchers and also the relevant Code of Practice to predict deformation in masonry wall design.

Details of experimental work and methodology are presented in Chapter IV. Descriptions of each type of material used in this research were also discussed in this chapter together with the results of materials properties that have been characterized in the preliminary work. In addition, it also contains the general description on special test equipment used.

In Chapter V, details of data analysis of experimental work are presented. The discussions are focused on the effects of time dependent deformation on the strength of fired-clay brick masonry. Results of microstructure and chemical composition of three types of fired-clay brick tested in this research were presented. The correlation between brick microstructure and mineralogy with the engineering properties of units was also included in this chapter.

Prediction results using established models by previous researchers were presented in Chapter VI. Furthermore, the comparison of results from experimental and prediction methods for both series are also presented here.

Finally, Chapter VII provides the overall conclusion based on experimental and analytical findings of deformation behaviour of masonry. The recommendations for further research are also provided for future studies.

1.7 Definition of terms

1.7.1 Total deformation

When subjected to a sustained applied load masonry undergoes an instantaneous or elastic deformation followed by a time-dependent deformation i.e. creep and moisture movement which is the combination of these can be determined as total deformation. Total deformation of masonry can be determined from total strain calculation. Hence;

Total strain = elastic strain + creep strain + [shrinkage (+ve) or expansion (-ve)]

1.7.2 Elastic modulus

When a load is imposed on a masonry member, the stress-strain relationship is classified as non-elastic and non-linear. If a structural member such as single-leaf wall is subjected to a vertical compressive load, it will tend to decrease in height by a small amount. If upon removal of the load, the wall returns to its original height, it is said to have behaved elastically. Elasticity can also be described as that property of a material by virtue of which deformations from a load or stress disappear after the removal of the load. An elastic material behaves inelastically when the stresses exceed the elastic limit, beyond which changes in the volume, shape and form are permanent.

In addition to the characteristics of the material, the elasticity depends also on the type of load: tensile, compressive or shear (Somayaji, 2001). Consequently, there can be four definitions for the elastic moduli for masonry, the initial tangent modulus, tangent modulus, secant modulus and chord modulus (**Figure 1.2**). For the masonry creep tests carried out during this research the secant modulus of elasticity was used, which corresponds to the instantaneous strain (ε_o) generated by the applied stress (σ_o).

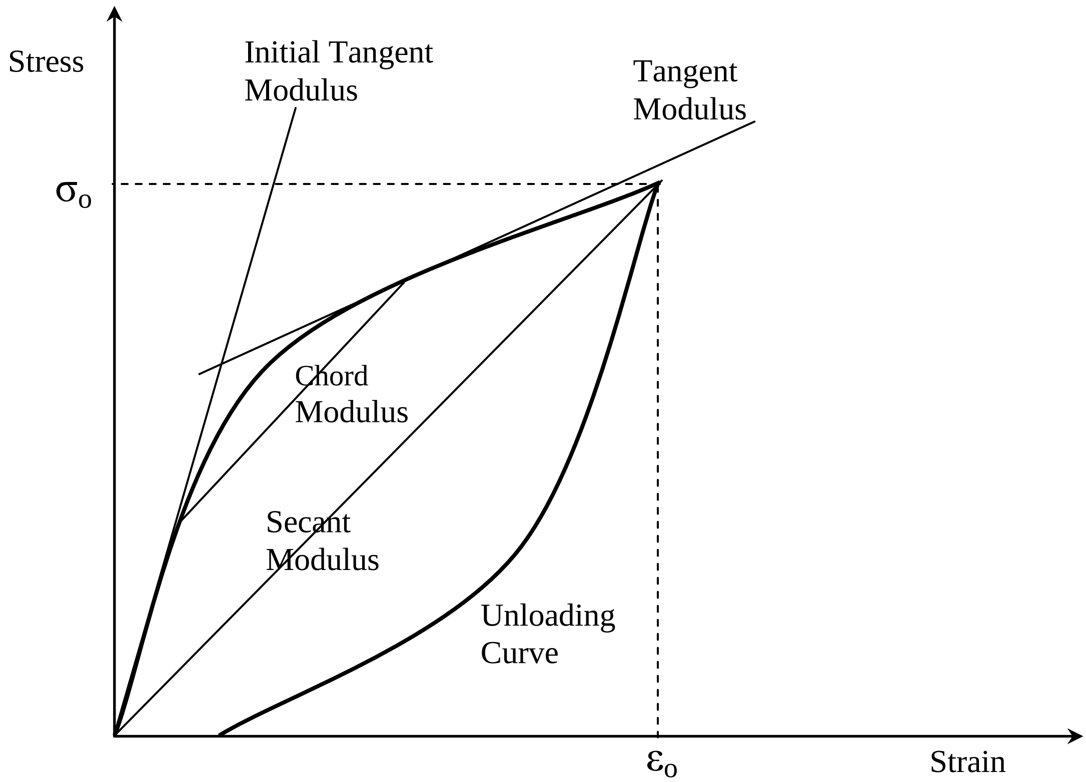


Figure 1.2 Elastic moduli for masonry (Neville et al., 1983)

1.7.3 Creep

Creep is known as a time-dependent movement that could be defined as a progressive movement with time in a material under a sustained load. When a brickwork member is subjected to a sustained load it undergoes an instantaneous (elastic) strain and this is followed by time-dependent strain which is called creep (Lenczner, 1980). Based on the graph illustrated in **Figure 1.3**, during the early stages of loading the creep rate is quite rapid but slows down gradually, except for a temporary acceleration during a transitional stage. Creep ceases after a period of time, which is varies from a few months to a year or more.

The general form of strain-time curve for a material subjected to creep shows the three definitive stages, primary, secondary and tertiary. Muller (1986) elaborated the three characteristic regions as depicted in **Figure 1.3**, primary creep region in which the rate of creep decrease continuously with time. Although the strain accumulated during the first creep stage is small, it is important if the load duration is short or if the load becomes greater. The primary creep interval will be active for all load levels. If the material exhibits a minimum creep rate, the secondary creep range (sometimes called stationary creep) designates the range of steady state creep. The straight line relation of secondary creep may be a convenient approximation when the magnitude of this creep is large compared with primary creep. Secondary creep region in which the creep rate is constant is a dominant interval of a creep curve.

Last stage denominated as tertiary creep region in which the creep rate increases quickly until creep failure of the material may occur at higher loads. In addition, creep may also be expressed in terms of specific creep (creep per unit stress) and creep coefficient (the ratio of creep to elastic strain). The tertiary creep may not exist, depending whether or not there is an increase in stress. For instance, in concrete this may arise from an increase in creep due to microcracking at high stresses i.e. at stresses greater than the typical range of working stress that is generally 25 to 40 per cent of the short term strength (Neville et al., 1983).

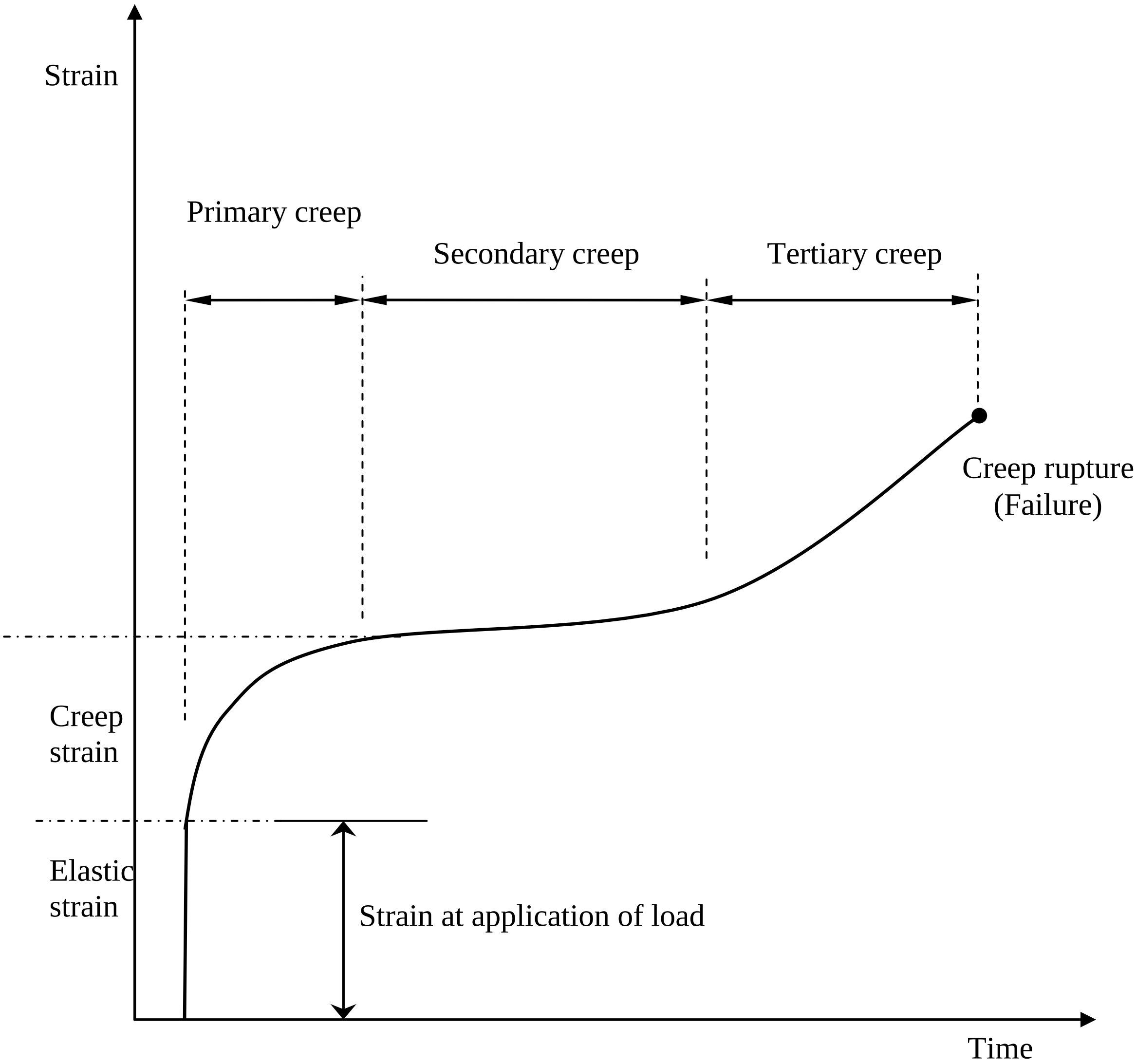


Figure 1.3 Creep characteristic (Neville et al., 1983)

1.7.4 Moisture movement (expansion or shrinkage)

Moisture movement can affect the dimensional changes of all normal building materials except for metals. Many building materials tend to expand with an increase of moisture content (expansion) or shrink with a loss of water (shrinkage). The moisture movements are complicated in the case of masonry structures, because mortar tends to shrink but clay brick units experience irreversible expansion slowly over time upon exposure to water or humid air. This behaviour is also known as time-dependent movement. The composite effects of these movements can manifest themselves in three different patterns of moisture movement strain as illustrated in **Figure 1.4** (Bremner, 2002). **Figure 1.5** shows that creep commences after the elastic strain resulting from the application of the load, but there may be an accompanying shrinkage or moisture expansion depending on the type of masonry, which has to be measured separately on the controlled wall (unloaded) (Edgell, 2005).

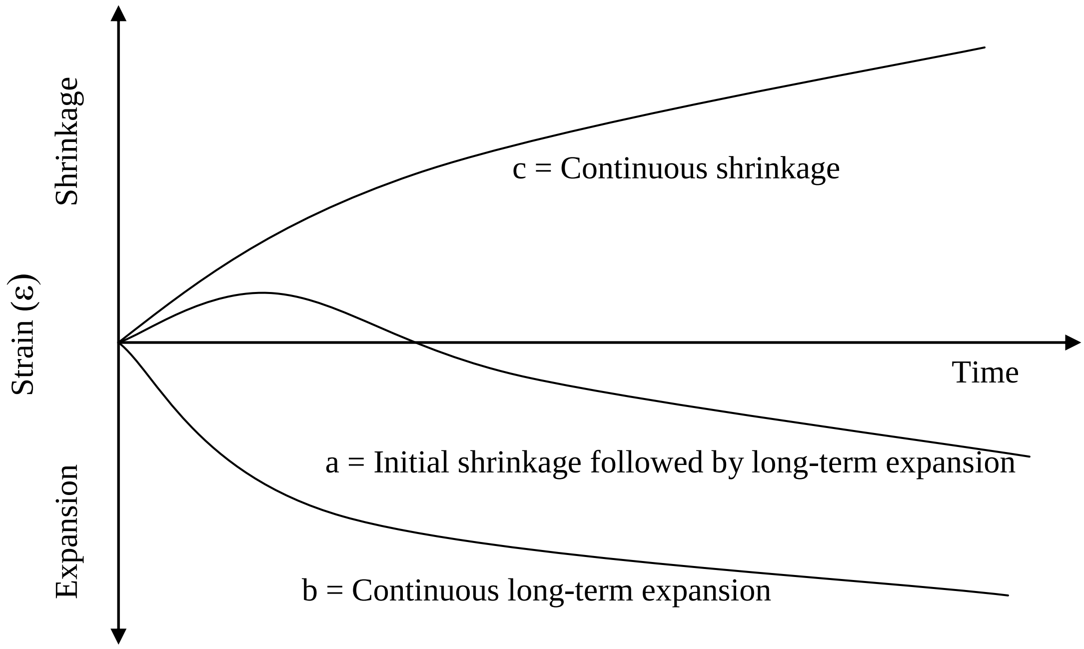
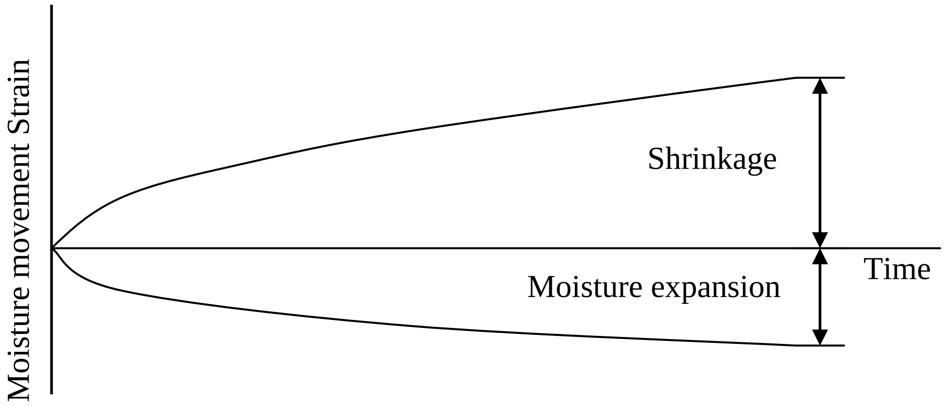
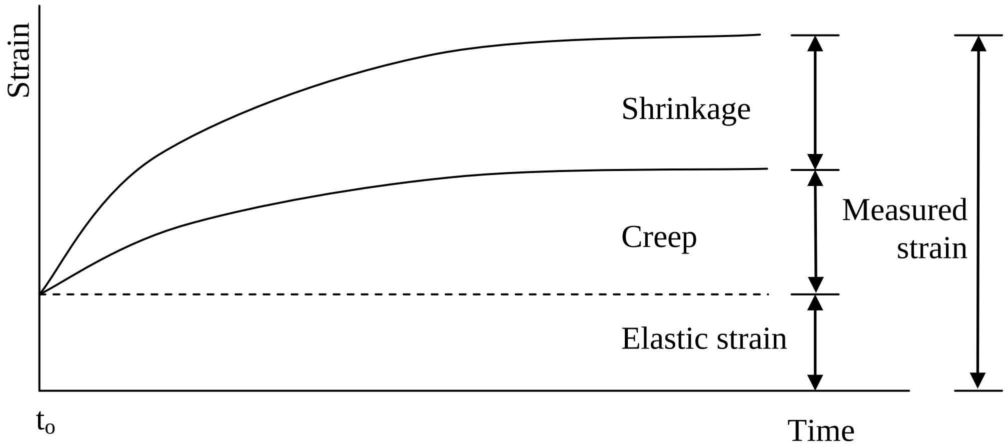


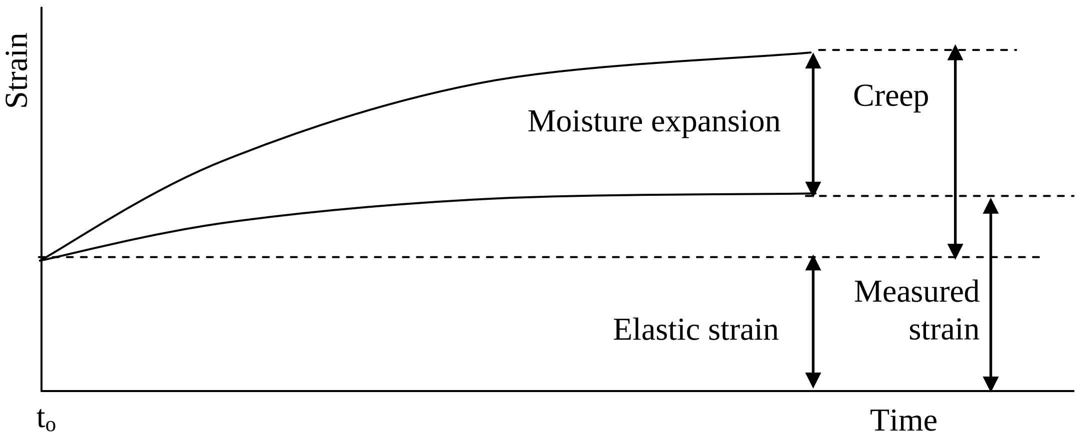
Figure 1.4 Patterns of moisture movement strain in fired-clay masonry (Edgell, 2005)



(a) Moisture movement strain of an unloaded specimen



(b) Elastic strain, creep and shrinkage



(c) Elastic strain, creep and moisture expansion

Figure 1.5 Definition of creep when there is accompanying moisture movement (shrinkage or expansion) from the measured strain (Edgell, 2005)

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The knowledge of time-dependent movements is becoming a significant concern in the design of brickwork and composite structures. For the long term effect, many costly failures have occurred during the last decade because these movements have not been taken into consideration at the design stage (Lenczner, 1986).

Chapter Two presents the reviews of published experimental works done by previous researchers on deformation characteristics of masonry, viz. modulus elasticity, creep and moisture movement of masonry. This chapter also covers the overall review of masonry components properties i.e. brick units and mortar. A specific subject on the influence of microstructural and mineralogical characteristics on the properties of different fired-clay bricks will also be discussed at the end of this chapter.

2.2 Masonry

Masonry is a building material with an excellent mix of architectural, physical, physiological and structural properties. The properties of masonry can vary widely given the choices of unit and mortar. The compressive strength and elastic modulus of brick and mortar are the major factors which influence the properties of the brick masonry (Hendry, 1998). Unlike other structural materials, masonry is a composite non-homogeneous structural material, whose mechanical properties depend on the properties of the interaction between the composite components, brick and mortar, their volume ratio and the properties of their bond. The mechanical properties and the behaviour of masonry depend strongly on the orientation of the bed joint towards the applied load and the stress state of the joints (Bosiljkov, 2006). The behaviour of brick masonry is also dependent on other factors including moisture in the brick at the time of laying, thickness of mortar joints and arrangement of bricks.

2.2.1 Fired-clay bricks

The word "brick" comes from the French word *brique*. The term "brick" was used without a qualifying adjective, is understood to mean such a unit or a collection made from clay or shale hardened by heat. Clay brick is the first man-made artificial building material and one of the oldest building materials known. Clay brick is the most extensively used type of masonry units throughout the world. Its widespread use is mainly due to the availability of clay in most countries. Its durability and aesthetic appeal also contribute to its extensive application in both load bearing and non-load bearing structures (Arman Ali, 2005).

Bricks have been extensively used since the time of the Assyrians and Babylonians throughout all ages. The manufacturers of this building material still follow the same ancient procedures. The properties of clay units depend on the mineralogical composition of the clays used to manufacture the unit, the manufacturing process and the firing temperature (Hendry, 1991). The important engineering and mechanical properties of brick include compressive strength, modulus of rupture, modulus elasticity, water absorption, tensile strength, thermal movement and fire resistance (Somayaji, 2001).

Different countries have their own ways for the classification of the bricks. The Malaysia Standard, MS 76 (1972) now in the process of revision was based on the British Standard, BS 3921 (1985), which classifies the bricks into engineering, facing and common bricks. Based on the structural requirements, these bricks can further be categorized into two groups, which are load bearing and non-load bearing. Bricks that have a minimum compressive strength of 7.0 N/mm^2 are considered as load bearing bricks and can be used for building elements that carry loads. The non-load bearing bricks are mainly used as infills (constructed between columns) and other building elements that are not designed to carry loads (Abdullah, 2009). The important qualities of standard bricks are adequate mechanical strength and absorption, well sintered with uniform colour, even surfaces and free of flaws or cracks with sharp and well defined edges, giving clear ringing sound when struck against each other, so hard that no impression is left when scratched with finger nails. Upon breaking, the surface should show a bright homogenous and compact surface free from voids or grit. A brick soaked in water for 24 hours should not show deposits of white salt on drying in shade (Ahmad et al., 2008).

2.2.2 Mortar

Mortar is a plastic mixture of cementitious materials, sand and water, and capable of binding together individual masonry units. Previously, before the existence of mortar, the early Egyptians used a cementing material obtained from burning gypsum in masonry construction. The mortar mainly serves two purposes; to bond individual units together as a single larger unit known as masonry and also to serve as a bedding material to form a cushion to distribute pressure uniformly over the surface. Therefore, bricks should not be merely laid, but should be rubbed and pressed down so as to force the mortar into the pores of the bricks to produce maximum adhesion (Somayaji, 2001).

Even though mortar makes up as little 7 % of the total volume of a masonry wall, it plays a crucial role in the performance of the structure more than this proportion indicates. A workable mortar should have a smooth, plastic consistency that is easily spread with a trowel and readily adheres to a vertical surface.

The most important properties of masonry mortars are workability, water retention, bonding (durability, and strength), weather resistance or durability, strength (tensile and compressive), volume change, efflorescence, extensibility and elasticity and permeability. All mortars have each of these properties to some degree, but one mortar may excel in workability, another in strength and another in bond (Esstech, 2007).

2.3 Strength of masonry

Compressive strength of masonry is one of the important performance characteristic used by engineers in the design of masonry structures. The bonding between brick and mortar is critical for the composite behaviour between the two materials. The failure in compression of masonry depends basically on interaction between unit and mortar joint as a result of their different deformation characteristics (Somayaji, 2001).

2.3.1 Factors affecting strength of masonry

The important factors in determining the compressive strength of brick masonry are strength of unit, strength of mortar, suction of units, deformation characteristics of unit and mortar, water retentivity of mortar, joint thickness, geometry of unit and workmanship.

Basically, increasing the strength of the unit will increase the masonry compressive strength and elastic modulus. The compressive strength of the clay units depends on three main factors, composition of the clay, method of manufacture and degree of burning (Somayaji, 2001). A few studies have been performed on brick masonry in India related masonry strength with brick strength. It was reported that the strength of brick masonry is in the range of 25-50 % of the brick strength (Gumaste et al., 2006).

As a binding material, the mortar is also partly responsible for the characteristic strength of the masonry. It is known that the weakest part of masonry structure is the mortar, hence a thin layer of mortar is stronger in compression than a thick one because the less mortar, the better the performance of the wall (Hendry, 2001). Samarasinghe and Lawrence (1992) found that the compressive strength of mortar increases with an increase of cement content and decreases with an increase of lime, sand, water or air content. However, mortar is not only used for binding but also acts as a cushion to accommodate any movement due to load. Therefore, mortar should typically be weaker than the masonry units, so that any crack will occur in the mortar joint where they can be repaired more easily.

To achieve optimum masonry strength it has long been realized that the suction of unit should be controlled to prevent excessive removal of water from the mortar. It seems probable that the water absorbed by the bricks leaves cavities in the mortar, which will be filled with air and end up with a weakened material on setting (Hendry, 1998). **Figure 2.1** suggests how a bed joint may become ‘pillow’ shaped if the brick above it slightly rocked as they are laid. If the water has been removed from the mortar by the suction of the brick, it may have become too dry for it to recover its original flat shape. The resulting wall will obviously lack stability as a result of the convex shape of the mortar bed and may be weaker by as much as 50% than should be expected from consideration of the brick strength and mortar mix. Therefore, the remedy is to wet or dock the bricks before laying so as to reduce their suction rate below 2 $kg/m^2/min$, and a proportion of lime in the mortar mix will help retain water in it against the suction of the bricks (Hendry et al., 1997). According to ASTM C 62-04a (2004), they may be wetted immediately before they are laid, but it is preferable to wet them thoroughly 3 to 24 h prior to use so as to allow time for moisture to become distributed throughout the unit.

The failure of masonry in compression depends basically on the interaction of unit and mortar joint as the result of their different deformation characteristics. In particular, the difference in the elastic properties of the component materials strongly influences the failure mode which can cause either tension cracks parallel to the direction of loading or a kind of shear failure along some line of weakness (Hendry, 1998).

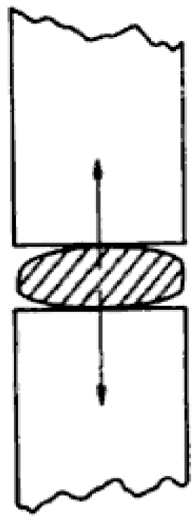


Figure 2.1 Effect of moisture absorption from mortar bed. Movement of brick after laying results in 'pillow shaped of mortar bed.

Water retention is important, not only to enhance workability (plasticity), but also to assure that adequate water is available to hydrate cementitous components of the mortar. Water retentivity allows mortar to resist the suction of dry masonry units and maintain moisture for proper curing. Water retention of the mortar becomes more important as the absorption rate of the masonry increases with the increase of temperature during installation (Palmer and Parsons, 1934). Units with IRS in the range of 0.5-1.5 kg/m^2/min will give reasonable bond, but the best bond occurs if the units have IRS of between 0.8 and 1.2 kg/m^2/min and that mortar are appropriately retentive (Hendry, 1991). Less retentive mixes will "blend" moisture, creating a thin layer of water between mortar and masonry unit and substantially decreasing bond strength. Highly absorptive clay units may be pre-wetted at the job site (Texas Masonry Council, 2003).

From previous investigation, it has been shown beyond doubt that excessively thick bed joints, say 16-19 mm, may be expected to reduce the strength of brickwork by something of the order of 30 per cent, as compared to normal 10 mm thick joints (Hendry, 1998). Hendry (1991) stated that variations in joint thickness can cause variation in strength; thinner joints produce stronger masonry.

The type and geometry of bricks whether solid, perforated, or hollow have an effect on the compressive strength of masonry. Hendry (1998) reported an earlier study conducted on the compressive strengths of highly perforated units, and found that the highest ratio of masonry strength to brick strength was obtained in bricks with perforation ratio of 38-43 %. Hendry (1998) also reported that holes of round shape or slots with round corners have no distinguishable effects on compressive strengths of brickwork.

Masonry has a very long tradition of production by craftsmen, without the engineering supervision associated with reinforced concrete construction. Consequently, it is frequently regarded with some suspicion as a structural material and carries very much higher safety factor. As in the case of other construction materials and techniques, the strength of brickwork is affected by the workmanship at site (Hendry et al., 1997). The primary benefit of prism testing of brick masonry is a more accurate estimation of the compressive strength of the masonry assemblage. Another benefit of prism testing is that it provides a method of measuring the quality of workmanship throughout the course of a project. Low prism strengths may indicate mortar mixing error or poor quality grout (Brick Industry Association, 1992).

In addition, platen restraint is also one of the factors affecting the laboratory measurement of compressive strength. In the compressive strength test, load is normally applied uniformly through two stiff and flat hardened steel platens. As compressive stress increases the test specimen expands laterally; however, due to friction along the interface between the platen and test specimen, lateral expansion of the specimen is confined. This confinement of specimens by platen restraint increases apparent strength of the material (Morel et al., 2007). Due to the above reason the measured compressive strength is found to be higher than the true compressive strength. The platen effect on compressive strength can be reduced by increasing the height/width ratio of the specimens. The plausible reason is, with increase in height the central part will be bigger and may fail through lateral splitting.

2.4 Deformation characteristic of masonry structures

Contrary to popular belief that buildings are inert, they do actually deform quite significantly due to changes in loading and environment. Lenczner (1972) stated that masonry is a visco-elastic material, which when subjected to load, undergoes an instantaneous deformation and is followed by progressive creep the rate of which decreases with time and ceases entirely after a time that varies according to the type of brick and mortar being used. According to Warren and Lenczner (1981), due to lack of reliable information, creep behaviour under sustained load is usually overlooked in the design of load bearing brickwork members. It is known that