ENGINEERING PROPERTIES AND MICROSTRUCTURE OF BRICKWORK UNDER AGGRESSIVE ENVIRONMENT

by

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D_v	Pore size distributiom
r_i	Pore size
P_{conc}	Connected porosity
P	Pressure generated by a growing crystal in atmosphere
C	The saturation concentration in the pore
C_s	The saturation concentration in bulk solution
V_c	The molar volume of solid salt ($m^3 .mol^{-1}$)
R	The molar gas constant (8.3 $J.K^{-1} mol^{-1}$)
T	Absolute temperature
E_m	Elastic modulus of masonry
f_k	Characteristic compressive strength of masonry
E	Modulus of elasticity of masonry
f_b	Mean compressive strength of unit
f_m	Compressive strength of mortar
b_y	Depth of brick unit
C	Number of course
H	Height of masonry
A_w	Cross-sectional area of masonry
$W_{x, z}$	Lateral dimensional of masonry
A_b	Total cross-sectional area of unit
$b_{x, z}$	Total lateral dimension of unit

SIFAT-SIFAT KEJURUTERAAN DAN STRUKTUR MIKRO KERJA BATA DI BAWAH PERSEKITARAN AGRESIF

ABSTRAK

Kajian ini melaporkan pengaruh persekitaran agresif terhadap sifat-sifat mekanikal dan prestasi sistem batu-bata. Kajian ini melibatkan pengukuran ubahbentuk lembapan, kekuatan dan modulus keanjalan dinding batu-bata selapis yang telah dibina dengan bata tanah liat bakar dan kalsium silika menggunakan mortar gred (iii) dengan nisbah 1: 1: 6 (OPC: kapur: pasir). Selepas dibina, dinding-dinding batu-bata telah diawet dengan menggunakan plastik "*polythene*" selama 14 hari dalam bilik kawalan suhu 20±5ºC dan lembapan 80±5%. Dinding-dinding batu-bata kemudian telah didedahkan dengan sodium sulfat, sodium klorida dan sodium sulfat-sodium klorida dengan kepekatan 5%, 10% dan 15%. Kekuatan mampatan dan modulus keanjalan telah diuji pada usia 28, 56 dan 180 hari. Manakala ubahbentuk dinding batu-bata telah dipantau sehingga usia 210 hari. Ubahbentuk lembapan, kekuatan dan modulus keanjalan unit batu bata dan prisma mortar juga telah diuji dan membolehkan peranannya terhadap sebarang perubahan bentuk dinding-dinding batu-bata dapat ditentukan. Selain daripada itu, sifat-sifat dinding batu-bata, unit-unit batu-bata dan mortar kawalan juga diuji agar kesan-kesan terhadap persekitaran agresif dapat diukur. Selanjutnya, analisis XRF juga telah dijalankan bagi menentukan kandungan elemen yang sediada wujud dalam batu-bata dan mortar. Manakala, analisis XRD, SEM dan EDX telah dijalankan selepas usia 180 hari bagi menentukan sebatian-sebatian yang wujud selepas didedahkan terhadap garam-garam terlarut. Hasil ujikaji menunjukkan berlakunya pengembangan dan pengurangan kekuatan dan modulus keanjalan dinding batu-bata terutama dalam kes dedahan di dalam sulfat. Ia berkait dengan pembentukan kristal-kristal "*ettringite*" dalam mortar yang mengakibatkan pengembangan, keretakan dan penguraian mortar yang seterusnya menyebabkan penguraian dinding-dinding batu-bata. Pembentukan "*thenardite*" telah ditemui dalam batu-bata tanah liat bakar dan kalsium klorida disebabkan oleh pendedahan terhadap sulfat, manakala "*halite*" dalam batu-bata kalsium silika dan mortar yang disebabkan oleh kehadiran klorida, tetapi ia tidak menyebabkan kesan yang ketara terhadap dinding batu bata. Model-model komposit telah menganggar kurang dari nilai sebenar terhadap modulus keanjalan dan ubahbentuk lembapan dinding-dinding batu-bata yang telah didedahkan terhadap persekitaran agresif. Dinding-dinding batu-bata tanah liat bakar dan kalsium silika menunjukkan prestasi yang baik dalam persekitaran klorida tetapi lemah dalam persekitaran sulfat dan gabungan sulfat-klorida disebabkan oleh pembentukan kristal-kristal "*ettringite*".

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ABSTRACT

The influence of aggressive environmental exposures on the mechanical properties and performance of masonry systems has been investigated. The investigation involved the measurement of moisture movement, strength and modulus of elasticity of single leaf masonry walls which were built from fired-clay and calcium silicate bricks in conjunction with designation (iii) mortar with proportions of 1: 1: 6 (OPC: lime: sand). After being constructed, the masonry walls were cured under polythene sheet for 14 days in a controlled environment room with temperature of 20±5ºC and 80±5% relative humidity. They were then exposed to sodium sulphate, sodium chloride and sodium sulphate-sodium chloride solutions at different concentrations of 5, 10 and 15%. The strength and elastic modulus of the brick walls were determined at the ages of 28, 56, and 180 days. At the same time, the moisture movement of the brick walls was monitored up to 210 days. The moisture movement, strength and modulus of elasticity were also measured on the unbonded bricks and mortar prism so that the contribution of brick types and mortar on the deformation of the masonry walls could be quantified. In addition, the properties of companion control walls, brick units and mortar were also assessed so that the effects of the aggressive exposure conditions could be quantified. XRF analysis was also carried out to determine the actual elements in the masonry materials before being exposed to soluble salts. XRD, SEM and EDX analysis were conducted after 180 days to observe the compounds developed after the exposure the soluble salts. As a result, after the period of exposure to the soluble salt conditions, large expansion and reduction in strength as well as elasticity of masonry wall were observed in particular for the case of sulphate exposures. These are mainly associated with the formation of ettringite crystals in the mortar, inducing expansion, cracking and disintegration of the mortar which led to the disintegration of the masonry walls. The formation of thenardite was observed in the fired-clay and calcium silicate brick due the exposure to sulphate, whereas halite formation was observed for the case of calcium silicate brick and mortar, due the exposure to chloride, but they did not cause any significant effect on the masonry walls. The composite model underestimated the modulus of elasticity and moisture movement of masonry wall which were exposed to the aggressive environments. Both the fired-clay and calcium silicate masonry walls exhibited better performance in chloride environment than in sulphate exposure and sulphate – chloride exposure due to the formation of expansive ettringite crystals.

CHAPTER 1

INTRODUCTION

1.1 General

Masonry walls are composite structures defined as macroscopic combinations of two or more distinct materials having a finite interface between them. The quality of raw materials and the method of brick manufacturing can influence the strength and durability of brickwork. Surej et al. (1998) revealed the various factors that may adversely affect the performance of a material during the course of time, such as material properties, masonry structures, environmental conditions and maintenance.

Considering the factors affecting durability is very important because these properties can influence brick/mortar compatibility. The durability properties of bricks should also be evaluated for the proper selection of building materials in construction to ensure that the strength and performance of brick walls are maintained when subjected to an aggressive environment during their service life.

Khalaf and DeVenny (2002) found that the main factor influencing the durability of masonry is the degree to which it becomes saturated with water. Saturation can occur in three ways: directly through rainfall, indirectly when water moves upward by capillary action from foundation, or laterally from retained material. However, Zsembery (2001) suggested that the most important factors are the severity of the environmental conditions to which the units are exposed, such as moisture and the availability of soluble salts. These two are the main factors for the salt attacks. The salt attack occurs when the soluble salt drawn into *its pores* cannot be evaporated with the moisture. As a result, the salts build up as crystals underneath the wall surface and the expansion pressure develops could be sufficient to deteriorate and rupture the masonry structure, causing crumbling, even for strong masonry materials.

Masonry structure design is focused mainly on the ability of the structure to resist applied loads, however deformations that arise from other effects such as variations in temperature and moisture content (Bremner, 2002). The design and subsequent use of these structures are therefore limited by the properties of the material. The material properties are depends on the manufacturing process which would influencing the microstructure of the materials.

Fernandes and Lourenco (2007) noted that mechanical characterization is a fundamental task for safety assessment and structural work, where the compressive strength is a key parameter in the case of masonry structures. In fact, Kaushik et al. (2007) believed that the strength and stiffness of the masonry lies between the strength of the bricks and that of mortar. Furthermore, in the case of fired-clay bricks, the mechanical properties of the brick are very relevant because the resistance and durability of the masonry depend significantly on the characteristics of the bricks (Fernandes and Lourenco, 2007).

The ability to resist salt attacks is one of the main considerations because salt attacks cause damage to masonry materials in sub-tropical and tropical climates (Philips and Zsembery, 1982). Malaysia experiences hot and moist conditions with heavy rains; therefore, it has the potential to encounter the same problems. The lack of consciousness among Malaysians in the salt attack problems in the brickwork hinders the government from solving the problems efficiently and at the same time causes the increase in the cost of brickwork maintenance. Therefore, the aim of this study is to investigate the influence of aggressive environments, such as sodium sulphate and sodium chloride, on the engineering properties and microstructure of masonry walls.

1.2 Problem statement

Salt attack is one of the major causes of decay to masonry wall materials such as brick and mortar. This phenomenon occurs due to the presence of soluble salt in the material after the evaporation process. The process normally produces efflorescence or salt crystals. The methods of formation of both phenomena have similar chemical reactions.

Efflorescence or flowering on the wall surface normally occurs when the soluble salt transported by the moisture to the surface cannot evaporate during wetting and drying periods. This salt is left behind and is deposited as a white bloom. The point at which the salt appears in solid form is exactly where the majority of the surface evaporation takes place.

Salt crystallization begins when the moisture cannot dissolve all the salt present. Bremner (2002) indicated that when the rate of the migration of the salt solution through the masonry material pores is lower than the rate of evaporation, the drying zone forms below the surface. The salts will grow as minute crystals within the pores and may lead to expansion due to the crystallization pressure. More importantly is a degradation process that leads to the reduction in the strength or ultimately the destruction of the masonry material affected.

In practice, sodium sulphate and sodium chloride cause most cases of salt attacks (Zsembery, 2001). Sodium sulphate is normally present in many bricks and stones, in Portland cements, and in some groundwater. They are formed from sulfur dioxide and sulfurous acid in the atmosphere (Jordan, 2001). Chloride comes from the salt-laden air near the sea through the mixture of water and groundwater. Salts in the masonry wall are either present in the masonry at the time of building or absorbed from the atmosphere or groundwater during the life of the building. The source of salts may be one or a combination of the following (Young, 1995):

(i) Saline soils and groundwater

(ii) Sea spray

(iii) Air-borne salt

(iv) Air pollutants

(v) Biological, such as pigeon poop, microorganism, leaking sewers

(vi) Salt naturally occurring in stone, brick clay, or mortar sand

(vii) Salt water used for puddling brick clay or mixing mortar

(viii) Salts used for de-icing roads in cold climates

(ix) Inappropriate cleaning compounds

In a study on the restoration of a municipal building in Penang, Malaysia, Ahmad (2004) found that the percentage of sulphate exceeded the safe level of 0.020%, with the highest level recorded at 6.27%. The presence of a very high level of sodium sulphate may deteriorate the surface of the brick and mortars, causing the loss of binders and cohesion. In the latest findings, Kamal et al. (2007) indicated that since the 1970s, many of the heritage buildings in Malaysia have been demolished because the defects were not noticed due to the lack of technical knowledge and the high cost of repair and maintenance. Building defects normally occur along the external wall due to chemical action, dampness, salt crystallization, and so on. Malaysia also has many peat soil areas, and according to Wan Ibrahim et al. (2007), the acid level in this area is very high with a water pH of 2 to 4. This clearly indicates that Malaysia, as a tropical country, is highly susceptible to salt attacks.

A number of previous studies have been conducted on salt attacks on masonry materials and these are discussed in Chapter 2. However, most studies did not focus on the influence of the degree of salt attack and the consequence on the structural performance of masonry walls. This issue is very important, because the understanding of the mechanism of deterioration will be useful in the production of more durable materials and determining an effective repair scheme.

1.3 Objectives

This study is primarily focused on the effects of sulphate and chloride attacks on the mechanical properties and structural performance of masonry walls under aggressive conditions. The main objectives of this study are as follows:

(i) To characterize the effects of aggressive salt exposure on masonry walls

(ii) To investigate the effects of aggressive salt exposure on the properties and performance of masonry walls

(iii) To study the influence of aggressive salt exposure on the microstructure of fired-clay and calcium silicate brick.

(iv) To determine the elastic modulus and moisture movement of fired-clay brick and calcium silicate brick masonry walls due to aggressive salt environment

1.4 Scope of the study

This study involves the construction of a single leaf wall combined from two types of bricks, i.e., fired-clay brick and the calcium silicate brick, with the selected mortar ratio of 1:1:6 (Ordinary Portland cement: lime: sand) throughout the investigation. The fired-clay brick selected because it is very famous brick and widely used in the country. Meanwhile, the calcium silicate brick selected because the study on this type of brick in Malaysia is very limited and still lacking the technical information under local saline environment.

This study carried out in three phase. In the first phase, the walls and their corresponding unbonded brick units and mortar prisms were cured under a polythene sheet for 14 days and were then exposed to sodium sulphate and sodium chloride environments, as well as to a double salt environment, which is a combination of sodium sulphate and sodium chloride solution. The compressive strength and elasticity of specimens were measured after 28, 56, and 180 days. The testing carried out only up to 180 days because the overall effect of the solution obviously appears at this age. The basic properties, such as water absorption, porosity, initial rate of suction and etc of the masonry materials were also measured.

In the second phase, the shrinkage or moisture movement of the masonry walls and unbonded mortar prisms and units were monitored up to seven. Measurement to determine the modulus of elasticity and shrinkage or moisture movement were made and compared with the prediction data using an existing model. Finally, in the third phase the deteriorated parts of the broken samples tested after 180 days were chosen for microstructure observation. Scanning electron microscopy (SEM) was carried out to identify the element or compound formed by the soluble salts solution. X-ray powder diffraction (XRD) was used to support the SEM observation result in determining the mineralogical compositions of the fired-clay brick masonry.

1.5 Masonry materials

Bricks, especially fired-clay bricks, have been used as building materials for thousands of years; they comprise about 15% to 17 % of building materials. Currently, the method of production is modern and more advanced. Calcium silicate or sand lime bricks are produced in Malaysia but only constitute a small percentage of the total demands in the market. Calcium silicate bricks are also not as popular as fired-clay bricks. In Malaysia, the standard size is similar with the British Standard, which is 215 mm long x 102.5 mm wide x 65 mm high, and is bonded with a 10 mm mortar thickness. Fired-clay bricks and calcium silicate brick were selected because no literatures in terms of their performance in local saline environments were discussed in-depth locally from previous researchers.

1.5.1 Fired-clay brick

Fired-clay brick is made from selected clay and is produced by shaping it to the standard shape and size. The brick is then fired for 10 to 40 hours in a kiln at a temperature of 750 to 1300 ºC. The time and firing temperature vary, depending on the raw material used and the type of kiln. However, if the brick is under-fired, the brick produced will be weak due to the poor bonding between the clay particles. According to Lynch (1993), under-burnt brick is generally softer than its counterparts, whereas an over-burnt brick is harder, darker, and often smaller. Nevertheless, fired-clay bricks still have a similar size, shape, and function compared with other types of bricks such as cement sand bricks and calcium silicate bricks but may possess different deformation characteristics.

BS 3921:1985 classifies fired-clay brick into three classes with different advantages and appearances: the engineering brick for situations demanding high strength and durability, the common brick for general building work, and the facing brick for interior work. Fired-clay bricks are also classified according to their resistance to soluble salt content and frost; however, due to the climatic conditions in Malaysia, MS 76: 1972 did not consider frost resistance in the design.

The classification of fired-clay bricks depends on compressive strength and water absorption. However, the most important property of the masonry unit is compressive strength, which is relevant to the strength of a masonry wall. The compressive strength depends on the dimensions and types of units. Bingel (1993) reported that the clay used in brick production is a very variable material and as a result, the properties of brick, such as water absorption, elastic modulus, and strength, can vary widely even if the bricks come from the same batch of units. Wild et al. (1997) analysed the chemical composition of the four fired-clay brick types from Britain, Denmark, Lithuania and Poland (Table 1.1). There found that the chemical composition of the four fired-clay brick types are similar.

Table 1.1: Chemical composition (wt%) of the four fired clay brick types (Wild et al.1997)

Oxide content	Denmark	Lithuania	Britain	Poland
SiO_2	74.09	58.02	54.83	72.75
TiO_2	0.66	0.77	0.97	0.84
Ae_2O_3	12.73	15.28	19.05	15.89
Fe_2O_3	4.74	6.26	6.00	4.97
MnO	0.07	0.08	0.06	0.02
MgO	1.34	3.80	1.17	1.20
CaO	1.19	8.07	9.39	0.87
Na_2O	1.29	0.71	0.50	0.27
K_2O	3.08	4.12	3.15	2.17
BaO	0.055	0.056	0.039	0.050
P_2O_5	0.12	0.15	0.20	0.10
Cr_2O_3	0.015	0.022	0.029	0.022
SrO	0.014	0.016	0.053	0.012
SO_3	0.006	0.139	2.90	0.070
LOI	0.25	2.11	1.48	0.36

1.5.2 Calcium silicate brick

Calcium silicate bricks are considered advanced building materials manufactured by mixing silica sand, lime, and water. Aggregates such as crushed rocks or flints may be incorporated to alter the performance and appearance. According to Nurdeen (2011) indicated that the main oxide that comprised the highest mass was silica (SiO_2) with a mass about, 84%; lime (CaO), 5 to 10%; alumina and oxide of iron, 2%; water, magnesia and alkalis, 7%, respectively. The mixture is then pressed with a high pressure and undergoes autoclaving, which involves curing in high pressure steam about 400°F for several hours.

In the autoclave, the lime reacts chemically with the silica to produce calcium silicate hydrate, which acts as the binding medium. They are also available in several colors, depending on the pigment added at the mixing stage. In contrast to that of fired-clay bricks, the strength of calcium silicate bricks is lower, and its size also shrinks with time. Its dimensional control is also better than that of fired-clay brick.

Calcium silicate bricks are also suitable for use in both external and internal walling. They are available as common or facing bricks. As for fired-clay bricks, the calcium silicate bricks also are available in a solid or a frogged units and are made to a standard size of 216 x 102.5 x 65 mm.

1.5.3 Mortar

Mortar is the second component in brickwork, accounting for as little as 7 percent of the volume of a masonry wall. Good mortar is a vital importance in all brickwork because it bonds the units together, to carry the weight placed on the wall and seals the joint to provide a weatherproof wall. However, the role it plays and the influence it has on performance and appearance are far greater than the proportion used (Beningfield, 1999).

BS 5628-3:2001 describes mortar for building to be composed of one part binder, which is cement or lime or both, and three parts sand to give a workable mix; this has been used for a very long time. BS 5628: Part 1 gives the specifications for the various mortar grades used. Sufficient water is added to achieve suitable workability for the bricklayer to spread the mortar smoothly. However the satisfactory mix for most works is one part hydrated lime, one part cement and six parts sand by volume. Lime cement mortar is most suitable because it combines the advantages of good workability with early strength. It should be used up within an hour of mixing, however, it is not suitable for works below the damp course level.

In define the quality of mortar, ASTM C270 focuses on three masonry properties such as water retention, air content and compressive strength. However, these parameters only present a limited view of characteristics of the mortar. Other parameters such as workability, durability and chemical composition of the mortar are also important. In study the chemical composition of the samples from medieval city walss, Franzini et al. (2000) found that, the mortar is mainly composed of SiO_2 and CaO as well as Al_2O_3 and CO_2 (see Table 2).

The cement lime mortars generally have low strength but are able to accommodate large movements without signs of distress. However, cement mortars are not suitable for use with some other types of masonry units. The selection of the mortar mix depends on such factors as consistency, durability, and its ability to bond with the masonry unit (Lawrence, 2008). In addition, although similar mixes are used, the strength of mortar in practice may vary.

Table 1.2: Chemical composition of the mortar (wt%), Franzini et al. (2000)

Type of mortar / Composition	MP 106	MP 111	MP 114
H_2O^+	5.26	4.01	2.96
CO_2	9.95	11.76	14.01
Na_2O	0.68	0.80	1.06
MgO	1.80	2.24	1.58
Al_2O_3	5.55	5.90	5.85
SiO_2	51.20	48.20	46.86
P_2O_5	0.05	0.04	0.05
SO_3	0.02	2.36	0.23
K_2O	1.10	1.11	1.45
CaO	22.84	21.92	23.63
TiO_2	0.19	0.21	0.19
MnO	0.05	0.06	0.09
Fe_2O_3	1.31	1.39	2.04
ΔCaO	10.18	6.95	5.80
(ΔCaO/CaO)*100	44.56	31.72	24.54

1.6 Definition of terms

1.6.1 Durability

Durability is defined as the ability of the material to remain serviceable for an acceptable period without excessive or unexpected maintenance. For brickwork, it refers to the resistance of the masonry wall to attacks by soluble salts. Durability also depends on the environmental condition because the difference in exposure has obvious effects on durability. In general, mortar is less durable than fired-clay and calcium silicate bricks because it contains reactive and binders such as ordinary Portland cement. It also has a high porosity and lower hardness and abrasion resistance.

1.6.2 Evaporation process

Evaporation is a thermal separation process that occurs only on the surface of the specimens. The evaporation rate for the external surface of masonry materials is related to the nature of the wall surface and environmental condition. In most cases, the concentrate resulting from the evaporation process is the final product. For the masonry wall, the final products of evaporation process are efflorescence, which grows on the surface of the masonry walls, and crystal, which grows underneath the surface.

1.6.3 Efflorescence

Efflorescence occurs when soluble salts transported by moisture cannot evaporate and are left behind on the wall surface as white efflorescence. The presence of this compound does not deteriorate the masonry structure but causes problems in aesthetics. Efflorescence depends on the soluble salt content as well as on the wetting and drying conditions.

1.6.4 Moisture movement

Moisture movements in masonry depend on the type of masonry unit and are related to the percentage of moisture absorbed. They also depend on the deformation properties of mortar. They can either shrink or expand and may either be reversible or irreversible. However, the total moisture movement is very dependent on the difference between the shrinkage and the moisture expansion of the masonry wall. In this research, the moisture movements for unloaded masonry are defined, as shown in Figure 1.1.

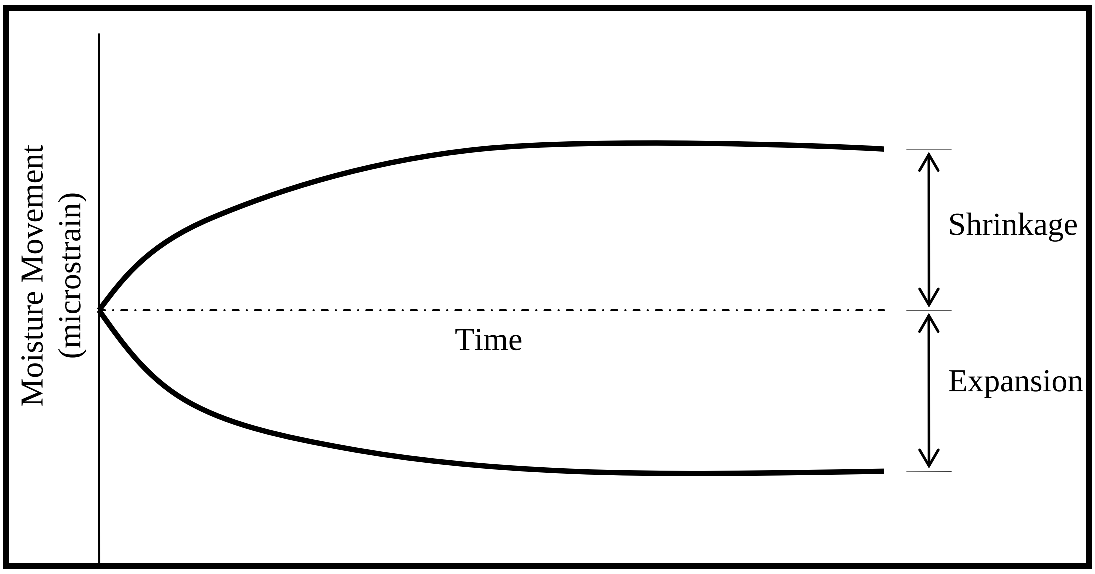

Figure 1.1: Moisture movement of unloaded specimen

1.6.4.1 Expansion

Moisture expansion is the main cause of volume instability in masonry materials. The moisture expansion is generated by the fired-clay brick. After removal from the kiln, the fired-clay units exhibit a small growth due to its exposure to water vapor or water. The fired-clay units start to expand from the time they begin to cool after firing.

1.6.4.2 Shrinkage

Shrinkage is defined as the time-dependent strain generated due to moisture loss through evaporation at a constant temperature without load. The shrinkage is generated by the mortar and calcium silicate bricks. It is a volumetric effect and is expressed as a linear strain because it is normally measured on a structural element by the determination of length change.

1.6.5 Compressive strength

The strength of a material is its ability to resist force, which is equal to the stress that the material can resist. It is the most important property and can be used to assure the engineering quality in the application of building materials. Strength is also normally proportional to the modulus of elasticity; thus, when strength decreases, a reduction in elasticity occurs. Mortar has a tendency to influence the strength of masonry wall. Although bricks have high strength and elasticity, when combined with the mortar, they can resist the vertical load. If the strength of the mortar joint is low, the masonry wall strength is not reduced, but if the thickness varies, the strength could be inconsistent. Furthermore, incomplete mortar bed joints give rise to stress concentration, which causes the failure of the masonry under relatively low strength.

1.6.6 Modulus of elasticity

The modulus of elasticity is defined as the ratio of stress to a corresponding strain below the proportional limit of a material. The stress-strain relationship of masonry is classified as non-elastic and non-linear. There are four different definitions of elastic modulus for masonry: secant modulus, chord modulus, initial tangent modulus, and tangent modulus (Figure 1.2). In this report, the elastic modulus cited the tangent moduli at the elastic range of the stress-strain curves as shown in curve 2 in Figure 1.2.

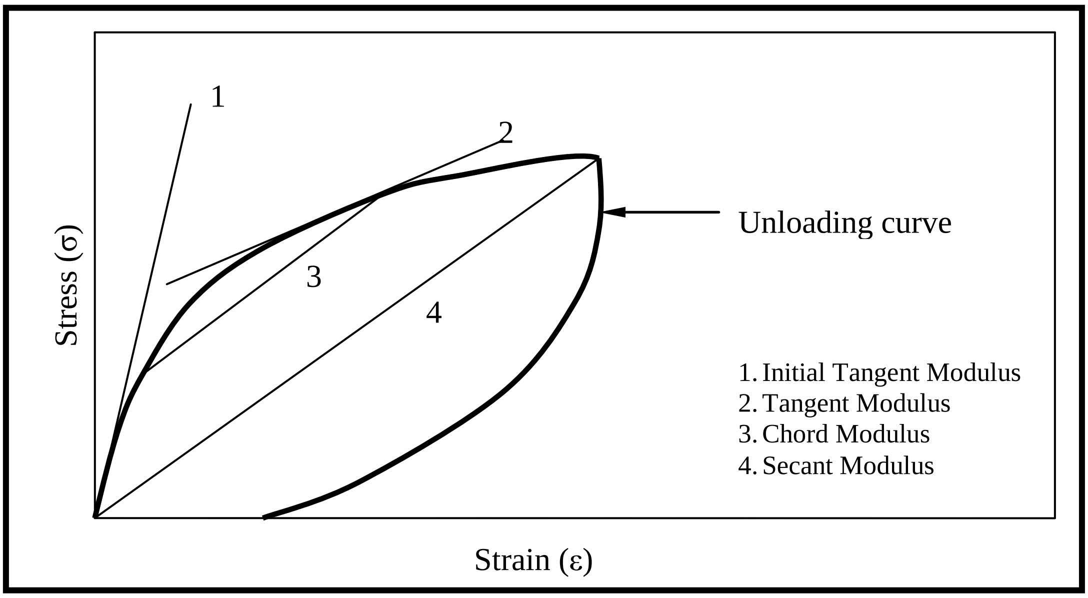

Figure 1.2: Types of elastic modulus measurement for masonry

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the effect of salt attack and the factors that influence the formation of the crystallizing salt in masonry structures. A general literature review of research carried out on elasticity and moisture movement affecting masonry structures is also presented.

2.2 Salt attack in masonry material

Salt attack is a process that needs a combination of permeable masonry, moisture, soluble salt, and evaporation. The effect of salt attack on masonry material and structures can present in different forms, i.e., efflorescence, scaling, cracking, crumbling, and softening.

Salt attack is also one of the physical phenomena that is strictly controlled and prevented to make the material more durable. This phenomenon can cause the decay and deterioration of masonry material. Decay and deterioration occur when evaporation process takes place underneath the surface, leaving the salts to grow as crystals in the masonry pores. In addition, the growth pressure of developing crystals is sufficient to deteriorate masonry materials. However, this occurrence depends on the physical properties of brick unit and mortar joint. Espinosa et al. (2008a), Rijniers et al. (2005), and Buchwald and Kaps (2000) agreed that the cause of decay and deterioration is due to the influence of the existence and movement of water and damaging salt. In Australia, salt attack has been the primary mechanism of more severe masonry decays (Young, 1995). Espinosa et al. (2008b) noted that a significant part of the damage of building material is due to the salts contained in the pores of the material caused by the hygroscopic properties of soluble salts solutions.

Zsembery (2001) revealed that not all salts that exist in moisture can cause damage, more so are liable to attack. In addition, Zsembery (2001) indicated that, in practice the most common case of salt attack are due to the existence of sodium sulphate and sodium chloride. It contrast, Young (1995) found that the types of salt commonly presence in masonry walls are sodium chloride and calcium sulphate. Binda and Molina (1990) revealed that sulphate is one of the salt types most frequently found and is destructive for masonry materials. The nature of the masonry is very important because it is influence the amount of salt required to cause damage. However, more than 0.5% by weight is considered a cause for concern.

Bucea et al. (2005) studied the effect of sodium sulphate and sodium chloride in the brick-mortar stack. The sulphate and chloride solution used are about 6.2% and 14% by weight volume (w/v) as recommended by AS4456.10. These are then exposed to seven cycles with seven days wet and seven days dry for each cycle. After one cycle, the salt appeared on the surface of the brick, and the mortars deteriorated, causing the binder to lose its cohesion. However, after seven cycles, the mortars became soft especially in sodium sulphate solution. This situation is mainly due to the crystallization of sodium sulphate and sodium chloride. According to Benevente et al. (2004), who studied salt crystallization in porous stone, efflorescence is produced if salt crystallization in porous stone occurs on the surface of the stone, whereas subflourescence is produced if salt crystallization occurs in the porous media of the stone. Salt subflorescence usually produces more decay than salt efflorescence.

Salt resistance on fired-clay brick was studied by Phillips and Zsembery (1982) using a cycling test method. The bricks were exposed for 2 hours to sodium chloride and sodium sulphate, both having a concentration of 14% (w/v). These were then dried for 22 hours at 110 ºC. The number of cycles ranged from 1 to 80 cycles, depending on the type and quality of the brick such as firing temperature. The study reported that less sodium chloride cycles with an average of 4 to13 cycles are needed to cause failure in specimens fired at a lower temperature ranging from 900 to1000 °C compared with the case with sodium sulphate with an average of 8 to15 cycles. In specimens fired at 1050°C, sodium sulphate caused failure in a limited number of cycles, whereas many of the specimens survived a large number of sodium chloride cycles. This is parallel with the study conducted by Van Hees and Brocken (2004), which also reported that sodium sulphate provides more severe conditions than sodium chloride because with sodium sulphate, brick masonry showed intensive brick spalling and scaling and was pushed out of the mortar joints. However, when the masonry was treated with siloxane after contamination with salt, the damage of the masonry exposed to sodium chloride was more serious than that exposed to sodium sulphate.

The effects of sodium and magnesium sulphate on the masonry mortar were explored by Lee et al. (2008) and Santhanam et al. (2002). Lee et al. (2008) cured the specimens in the solutions up to 15 month. After 15 months, the mortar specimens deteriorated due to sulphate attack; as a result, surface damage and reduction in compressive strength occurred. Moreover, the expansion of the mortar specimens affected with magnesium sulphate solution was lower than that of the mortar specimens affected with sodium sulphate solution. This situation occurred because in different pH environments, the sulphate expansion properties are significantly related to the stability of products caused by sulphate attack (Al Amoudi et al. 1995).

Brickwork is a composite material made up of a combination of mortars and bricks. When expansion occurs in mortar, the effect is normally on the overall expansion of the brickwork. DeVekey (2008) explained that sometimes, small horizontal cracks are visible in the center of the wall because mortar is typically affected more within the body of the wall than on the surface. Due to the greater expansion in the center of the wall, which remains wetter for longer periods than the outside, axial cracks may appear on the external elevation in thick masonry. However, lateral cracking may occur as well, but it is expected to be less obvious when there is a high axial load stress.

2.3 Factors influencing salt attack in masonry structure

The factors influencing the salt attack are very important and will be discussed in this section. The factors namely, soluble salt, microstructural properties, mortar mixes, moisture, and temperature and humidity must be present for salt decay to occur because if any one factor is removed from the process, salt attack could be prevented (DeVekey, 2008).

2.3.1 Soluble salt

Soluble salt is one of the main factors as if desirable for salt attack. It can be derived from an external source, as discussed in Section 1.2, and can also occur naturally in the material's body, such as fired-clay brick. Soluble salts in fired-clay brick are developed by the reaction between sulfur oxides formed during firing and minerals present in the brick (Edgell, 2005). The common problem associated with soluble salt in masonry wall is the formation of efflorescence on the surface. However, efflorescence is an aesthetic problem and can be removed with water. A more serious effect occurs when a high level of soluble salt is present in the masonry materials, causing the crystallization of salt to occur underneath the surface of the brickwork material, as discussed in Section 2.2.

Bricks are classified according to their resistance to soluble salt content and frost. However, due to humid and warm climates, resistance to frost attack was neglected in the conditions set in Malaysia. The soluble salt limits for fired-clay bricks as given in BS EN 771 Part 1 and BS 3921:1985, is shows in Table 2.1. However, BS EN 771 Part 2 and BS 187: 1978 do not discuss the soluble salt limits for calcium silicate brick.

Table 2.1: Category limits for active water soluble salts

<table>
<tr><th rowspan="2">Soluble ion</th><th colspan="2">BS 3921: 1985</th><th colspan="3">BS- EN 771-1</th></tr>
<tr><th>Low (L)
(%)</th><th>Normal (N)
(%)</th><th>S0
(%)</th><th>S1
(%)</th><th>S2
(%)</th></tr>
<tr><td>Sodium</td><td>0.030</td><td rowspan="3">0.25</td><td rowspan="3">No requirement</td><td rowspan="2">0.170</td><td rowspan="2">0.060</td></tr>
<tr><td>Potassium</td><td>0.030</td></tr>
<tr><td>Magnesium</td><td>0.030</td><td>0.080</td><td>0.030</td></tr>
<tr><td>Sulphate</td><td>0.500</td><td>1.60</td><td>Nil</td><td>Nil</td><td>Nil</td></tr>
</table>

BS EN 771-1 classifies three categories of soluble salt contents, namely, S0, S1, and S2, as presented in Table 2.1. Category S0 comprises bricks not subject to any limit on specified soluble salt. It is intended for use in situations where the total protection against water penetration is provided. However, category S1 gives a limit for bricks on soluble salt, including sodium, potassium, and magnesium contents. In category S2, bricks have a lower limit than those in S1. In contrast, BS 3921:1985 limits the soluble salt content of fired clay brick unit into two categories. The first category is Low (L) class with restrictions on the ions of magnesium, potassium, and sodium as well as on the total amount of sulphate. The second category is the Normal (N) class with limits on the amount of specific soluble salts as a combination of sodium, magnesium, and potassium as well as on the total amount of sulphate. This classification is very important for the durability of the masonry wall aspect because soluble salt can damage and deteriorate the cement mortar if it is continuously exposed to moisture or wet conditions.