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Influence of Sulfate and Chloride on The Mechanical Properties of Fired Clay Masonry Wall

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Abstract: This paper presents the influence of aggressive environment on the mechanical properties of masonry systems. The investigation involved the measurement of strength and modulus of elasticity of single leaf brick masonry wall which were built from fired clay bricks in conjunction with designation (iii) mortar with proportions of 1: 1: 6 (OPC: lime: sand). After being constructed, the specimens were cured under polythene sheet for 14 days in a controlled environment room with 80 ± 5% relative humidity and temperature of 25 ± 2ºC. The specimens were then exposed to the solution containing sodium sulfate and sodium chloride. The strength and modulus of elasticity of the brickworks were determined at the ages of 28, 56 and 180 days. The strength and modulus of elasticity of the brickworks, unbonded bricks, and mortar prisms were determined at the ages of 28, 56 and 180 days to quantify the contribution of bricks and mortar on the deformation of the masonry walls. As a result, fired clay brickwork is not durable and deteriorate in the environment containing sodium sulfate but durable in sodium chloride. The deterioration of the brickwork clearly influenced by the deterioration of mortar joint. The present of sodium chloride also retarding the attack of sodium sulphate.

Keywords: fired clay brick, sodium sulfate, sodium chloride, strength, modulus of elasticity

1. Introduction

Salt attack is a process that needs a combination of permeable masonry, moisture, soluble salt, and evaporation. It is 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 i.e., efflorescence, scaling, cracking, crumbling, and softening. 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.(2008), 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.

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 average annual temperature in the country is about 26°C with high humidity of 80% respectively (Ibrahim, 2008).

In practice, sodium sulfate and sodium chloride cause most cases of salt attacks (Zsembery, 2001). Sodium sulfate 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.

Bucea et al. (2005) studied the effect of sodium sulfate and sodium chloride in the brick-mortar stack. The sulfate and chloride solution used are about 6.2% and 14% by weight volume (w/v). 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 sulfate solution. This situation is mainly due to the crystallization of sodium sulfate 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 sub-florescence usually produces more decay than salt efflorescence.

The attack of sulfate and chloride ions should be considered as serious cases to the country because this situation clearly could cause damage or deterioration of building material when the brickwork material exposed to

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the surrounding environment for certain periods. They could affect the brickwork in terms of performance such as strength and modulus of elasticity. These properties are required by the designers of masonry structures. Any form of change in masonry material may affect the overall structure performance of masonry wall. Therefore the main aim of this paper is to evaluate the effect of sulfate and chloride ions on the strength and elasticity of fired clay masonry walls.

2. Experimental Work

Masonry Materials

Fired Clay Brick

One type of fired clay bricks with five perforations was chosen to construct single leaf masonry walls. The properties of brick units which have been determined are strength, modulus of elasticity, water absorption, porosity and initial rate of suction as given in Table 1. Table shows that the mean strength and elasticity of the unsealed units was 32 MPa and 8.54 GPa, respectively. Although the units tested were selected from the same batch and type of bricks, the strength showed variations in strength and modulus of elasticity with a standard deviation of about 3.74 and 1.42. The porosity and water absorption for 24 hours immersion was 21.46% and 13.42%, respectively. Meanwhile the initial rate of suction is approximately 1.97 x10^{-3} kg/m^2/min.

Table 1: The properties of unsealed fired clay brick units

Parameter	Strength (MPa)	Elasticity (GPa)	Water absorption (%)	Porosity (%)	IRA kg/m^2/min
Mean	32	8.54	13.42	21.46	1.97x10^{-3}
Standard deviation	3.74	1.42	0.91	1.67	0.00014

Mortar

The walls were constructed using 1: 1: 6 (Ordinary Portland cement: lime: sand) design mortars. This mix design of mortar used in order to produces a well filled mortar but with the extra adhesion and flexibility given by lime, balance by the strength of cement. This proportion also can be considerable benefit to the durability of the final brickwork.

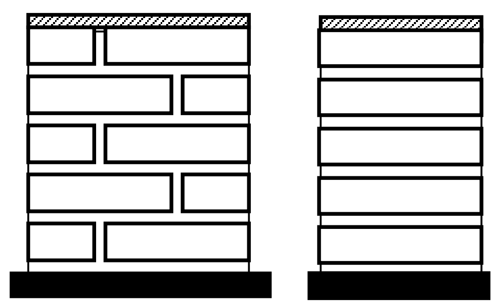
The strength of cement-lime mortar cubes under water curing was presented in Table 2. The strength of mortar cubes were determined using 75 mm cubes according to BS 4551: 2005. The range of water cement ratio of mortar mix is 1.50 and 1.56. The strength of the mortar prism ranged from 5.40 to 8.80 MPa between the age of 14 and 28 day.

Table 2: The strength of mortar cube

Mortar batch no	Brickwork reference	Strength (MPa)	
		14 days	28 days
1	Water	5.81	8.80
2	15% Chloride	5.47	6.17
3	5% Sulfate	6.43	7.71
4	5% Sulfate + 15%Chloride	6.39	7.72

Specimen

Single leaf masonry wall specimens (1.5 unit wide x 5 unit heights) were constructed using one type of fired clay brick and mortar (see Figure 1[a]). In construction of masonry wall, the need for highest accuracy and good practice on the part of the brick layer was stressed prior to the commencement of bricklaying. Furrowing of bed joints was to be avoided whilst all perpends needed to be filled with mortar. This was to ensure avoidance from strength reduction due to incomplete bed joint. After construction complete, the masonry wall specimens were immediately covered with polythene sheet until 14 days to prevent moisture loss from the mortar. From each batch of brickwork, cement-lime mortar prisms, 75 x 75 x 300 mm, were prepared at the same time as the masonry construction. The specimens were partly sealed after 3 days curing and completed within 7 days according with volume surface ratio (V/S) of 42 mm for the mortar prism and 39 mm for the partly sealed of fired-clay brick units. The masonry prisms were also constructed using different thickness of mortar i.e. 10 mm, 15 mm and 20 mm as shows in Figure 1[b].



(a) (b)

Figure 1: Specimens of (a) masonry wall with 1.5 unit width x 5 unit height (b) masonry prism with 1 unit width x 5 unit height

Exposure and Testing Procedure

After casting, the all specimens were cured under polyethene sheet for 14 days in control environmental room with temperature 25 ± 2 °C and 80 ± 5 percent humidity. The unbonded partly sealed fired clay brick and mortar prism also were prepared and initially cured under same condition so as to maintain the same exposure condition as the corresponding bricks and mortar in the wall. After curing process, the specimens were exposed to the 5% Na_2SO_4 (sulfate environment), 15% NaCl (chloride environment), 5% Na_2SO_4 + 15% NaCl (sulfate-chloride environment) by a spraying on the surface of the masonry every 24 hours. This rate of concentration used to develop of missing data to which masonry decays when subject to solution containing sodium sulfate and sodium chloride especially in Malaysia climates. The strength and modulus of elasticity tests were conducted at the age of 28, 56 and 180 day after exposed to sulfate ions. The magnitude of modulus of elasticity was obtained using a tangent value from stress strain graph at an elastic region.

3. Results and Discussion

Compressive Strength

Mortar prism

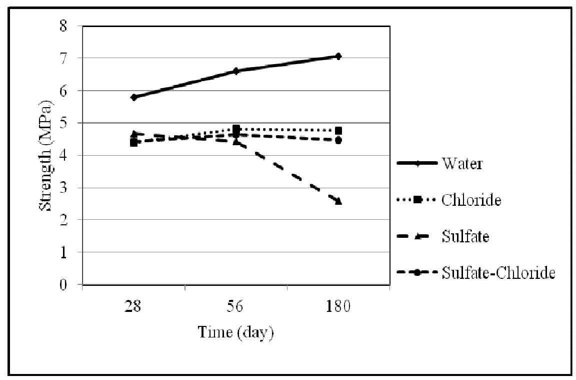
The partly sealed mortar prisms were cast at the same time as the building of the masonry walls. The strength development of 75 x 75 x 300 mm partly sealed mortar prism in the fired-clay brickwork tested on the age of 28, 56, and 180 day is shown in Figure 2. Before the tests were carried out, the mortar prism was initially cured under a polythene sheet for 14 days and then exposed to moisture and soluble salt to maintain the same exposure conditions as the corresponding mortar in the wall.

From the result obtained it is found that the strength of mortar prism was increased with time after exposed to water moisture condition. The strength of the mortar prism at the age of 28, 56 and 180 day was 5.79, 6.59 and 7.05 MPa, respectively. Meanwhile, the strength of mortar prisms after exposed to sulfate condition found being decrease in strength. Figure 2 explained that the strength of the mortar prisms under sulfate condition is only about 4.67 MPa after 28 days. The strength reduction explained that the mortar prism being affected by the sulfate ions. Moreover, after 56 days, the mortar prisms continuing showed a reduction in strength. For instance, the strength on the age of 56 day slowly decreased to 4.41 MPa, and at the age of 180 day, the strength of mortar has decreased rapidly to 2.58 MPa. The failure can be characterized by a few cracks followed by severe cracking. These phenomena occurred due to the crystallization of sulfate ions in the micro-structure of mortar, generating sufficient pressure to rupture the material micro-structure.

The chloride ions do not show large effects on the mortar prisms, and cracking does not appear on the mortar prism surface. Although a reduction in strength occurs, as shown in Figure 2, due to the change in the density of the mortar prism, the strength recorded still fulfills the minimum standard requirement. The strength of the mortar prism after affected with chloride ions on the age of 28, 56, and 180 day was 4.40, 4.81, and 4.76 MPa, respectively.

In the sulfate- chloride ions, strength reduction in the mortar prism was observed, although it increased in the early ages (Figure 2). The reductions clearly occurred after the 180th day of exposure. For example, the strength of the mortar prism for the period up to 56 days increased after exposure to the sulfate-chloride ions. However, after 180 days, the specimens exhibited strength reduction to 4.45 MPa. This phenomenon occurred is due to the micro-cracking induced by the crystallization of sulfate-chloride ions in the mortar prism. In addition, based on the results discussed above, micro-cracking was largely induced by the crystallization of sulfate ions. However, comparing the strength of mortar under sulfate ions exposure with the strength of mortar under sulfate-chloride ions exposure found that the strength of mortar exposed to sulfate-chloride ion was not too severe because the presence of chloride ions retarding the attack of sulfate ions. These findings were confirmed by Al Amoudi (2002) who indicated that the presence of chloride ions in the sulfate environment could reduce the sulfate attack in plain and blended cements.

Figure 2: Compressive strength of mortar prism



Fired clay brick

The strength of the fired clay brick units was tested for the partly sealed units. The aim of the partly sealed units test was to investigate the effect of salt condition on the strength of unbonded brick units. The partly sealed units were tested at the same period as the partly sealed mortar prism and masonry wall specimens. Before the test was carried out, the specimens were also cured under a polythene sheet for 14 days before being exposed to water and salt conditions to maintain the same exposure conditions as the corresponding bricks in the wall.

The strength of the partly sealed fired clay brick units is shown in Figure 3. In comparison, the figure shows that the strength performance of fired-clay brick under water and soluble salt conditions is not largely different. Meanwhile, the strength of fired-clay bricks affected with all salt conditions shows variety in the strength properties. The variations in strength made determining the actual effect of salt solution on the final strength of brick units such as the rate of reduction difficult. Figure 3 portraits that the strength of the fired-clay brick unit under water exposure condition is between 24 and 25 MPa. The range of strength for the specimens affected with the all conditions on the age of 180 day is 22 to 24 MPa, 23 to

25 MPa, and 22 to 24 MPa for chloride ions, sulfate ions, and sulfate-chloride ions conditions, respectively.

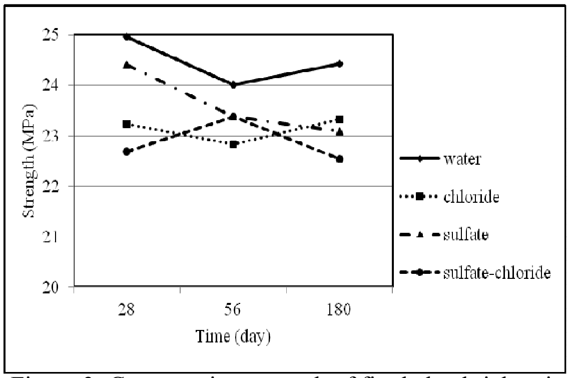


Figure 3: Compressive strength of fired clay brick units

Masonry wall

The strength of the brickwork depends on the types of unit or mortar, or both. The environmental exposure should also be considered. In theory, the mode of failure of the masonry wall under compressive stress is mainly a tensile splitting failure in a direction perpendicular to the applied load.

The strength of fired clay brickworks is presented in Figure 4. In determining the strength of the brickwork, the variation in brick units and mortar strength as well as the uniformity of moisture or soluble salt absorption should be considered because they affect the final strength of the brickwork.

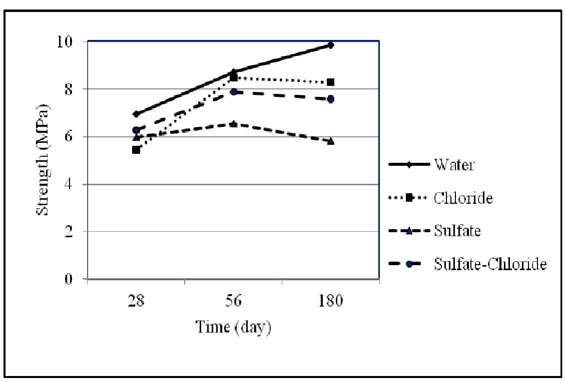


Figure 4: Compressive strength of fired clay brick masonry wall

For the control specimens which is the specimen exposed to water condition, an increase in strength similar to concrete was recorded for the masonry wall. Figure 4 shows that, the strength of the control fired clay brickwork at the age of 28, 56 and 180 day was about 6.95, 8.72 and 9.86 MPa, respectively. The strength of brickwork can be associated with the strength of the brick unit and the mortar strength and thickness. They can be verified by referring to Figure 5, which shows that the strength of fired clay brickwork was increase with time but reduced when the mortar thickness increased; i.e., the strength of the fired-clay brickwork with a mortar thickness of 10 mm at the age of 28 days was 12.18 MPa, respectively. However, when using a 15 mm mortar thickness, the strength was reduced to 10.54 MPa, respectively. The strength of the fired-clay brickwork using 10, 15, and 20 mm mortar thickness also increased up to 50% with time at the age of 28 days. Furthermore, the strength of the fired clay brick masonry wall was significantly lower than that of the masonry unit but higher than the strength of the mortar.

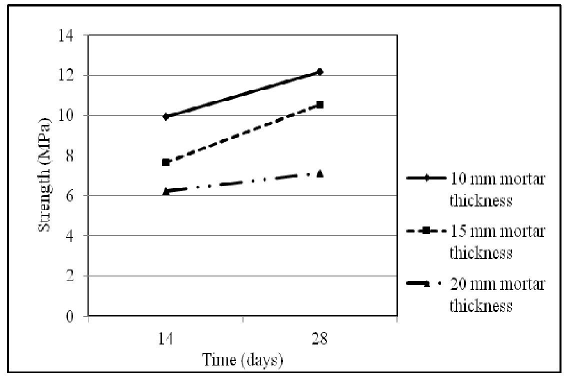


Figure 5: Compressive strength of fired clay brick masonry wall with different mortar thickness

The sulfate ions attack can deteriorate and eventually reduce the strength of the masonry wall. However, this phenomenon depends on the durability of the mortar joint and bonded bricks from the sulfate ions. If the results of the mortar prism and unbonded brick units as discussed above are considered, the reduction in the strength of masonry wall significantly occurs due to the deterioration of the mortar joints. The deterioration occurs because of the crystallization of sulfate ions, and the mortar joint becomes soft, erodes, and crumbles. The deterioration of the mortar joint under sulfate ions can also be associated with the separation of the brick–mortar bond due to the loss of the binder properties. Furthermore, the damage that may occur due to the crystallization of sulfate ions is influenced by the formation of pore structure. The size of the pore structure influences the salt crystallization, including the nucleation and precipitation, the capillary rise of solutions, the evaporation of water, and the effect of the wetting and drying cycles (Benevente et. al, 2004). In this research, the strength of the fired clay brickwork with sulfate ions is shown in Figure 4. The figure shows that at the age of 28 and 56 days, the strength of the fired-clay brickworks increased with time but slowly decreased after 180 days. The strength of the fired-clay brickworks at 180 days was 5.81 MPa, respectively.

The presence of chloride ions did not cause any large effect on the strength of the fired-clay masonry wall, although high concentrations were used. The results presented in Figure 4 shows that after exposure to chloride ions, the strength of the fired-clay masonry wall decreased with time. The strength of the masonry wall after exposure to chloride ions at the age of 180 days was 8.27 MPa, respectively.

The presence of sulfate-chloride ions in the masonry wall was not as severe compared with the sulfate ions condition but was more severe than the chloride ions. The severity of the sulfate- chloride ions depends on the severity of the sulfate ions. However, the severity of sulfate ions could be delayed and reduced due to the presence of chloride ions. Therefore, Figure 4 shows that the strength of the fired-clay brickwork after exposure sulfate-chloride ions slowly reduced from 7.85 MPa after 56 days to 7.50 MPa after 180 days, respectively.

Modulus of Elasticity

The elastic modulus is very important in term of masonry design. As a composite material, the modulus of elasticity of masonry wall is depending on brick units and mortar. When one of the material undergo the deterioration, the reduction in modulus of elasticity could be occur as well as will influence the performance of masonry wall overall.

Mortar prism

Theoretically, the relationship between the strength and the modulus of elasticity is linear, i.e., when the mortar strength is high, the elastic modulus is also high. The modulus of elasticity of the 75 x 75 x 300 mm unbonded partly sealed mortar prisms were measured from the tangent line in an elastic region of the mortar prism stress–strain graph. The elastic modulus of the mortar prisms depends on the strength properties; thus, when the strength decreases, a reduction in elasticity will occur.

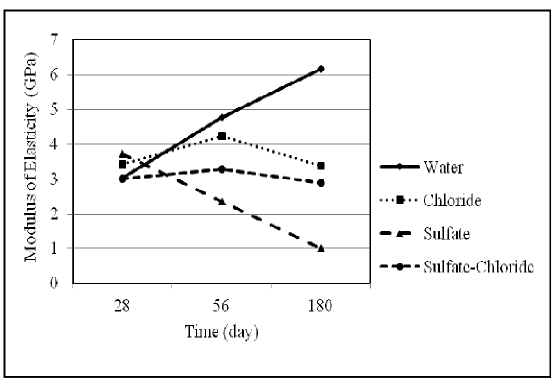


Figure 6: Modulus of elasticity of mortar prism

Figure 6 present the modulus of elasticity of the partly sealed unbonded mortar prism in the fired-clay masonry walls after affected with soluble salts. Different types of salt solutions yielded different effects on the mortar prism specimens. For the mortar prisms affected with the sulfate ions, the modulus of elasticity of the mortar prisms decreased with time. The modulus of elasticity of the mortar prisms after 28 days of sodium sulfate exposure was 3.73 GPa. After 56 days of exposure, the reduction in the modulus of elasticity rapidly declined. As shown in the figure, the modulus of elasticity of the mortar prisms at 180 days was less than 1.0 GPa. At this age, the mortar prisms became soft and the cracking clearly appears.

Sodium chloride is often present in masonry materials (Binda and Baronio, 2006). In a mortar joint, some of the chloride reacts with the aluminate phase in the cement to form chloroaluminates, and as such, free chloride ions are no longer present. These bound chlorides have been considered to be not harmful, but this is no longer believed to be true (DeVekey, 2008). In this study, after exposed to chloride ions, the reduction in the modulus of elasticity of mortar prism was also measured. Nevertheless, the magnitudes were still in the same range as the control samples. Therefore, these findings clearly show that the chloride ions do not induce a severe condition on the cement–lime sand mortar. Figure 6 shows that the elastic modulus of the mortar prisms of the fired clay masonry wall affected with chloride ions on the age of 28 and 56 day slowly increased and was about 3.45 and 4.20 Gpa. However, after 180 days of being exposed to chloride ions, the strength slowly decreased at magnitudes 3.37 Gpa.

The modulus of elasticity of the mortar prism for both types of brickwork after being exposed to sulfate-chloride ions in the early age increased with time before slowly declining after 180 days. The reduction occurs due to micro-cracking because of crystallization of sulfate ions and chloride ions. The modulus of elasticity of the mortar prism of fired clay masonry wall after being affected with double salt solutions on the age of 180 day was 2.90 Gpa, respectively.

Fired clay brick

The modulus of elasticity of the brick units depend on the strength of the unit. A small change in the density of the brick units will cause a reduction in the modulus of elasticity and other intrinsic properties, which depend on the microstructure properties of the brick units such as the distribution and shape of voids (Shrive and Jessop, 1980).

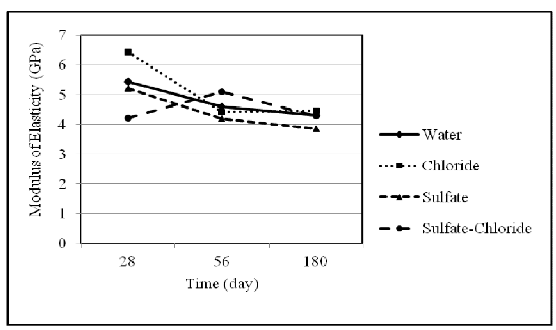


Figure 7: Modulus of elasticity of fired clay brick units

Figure 7 indicates that the modulus of elasticity of the fired clay brick units affected with soluble salt ions shows a variation in the modulus of elasticity and that the values are sometimes inconsistent. The inconsistent of modulus of elasticity might have occurred due to the different rates of adsorption of each unit during curing or the spray process caused by the variety of the material properties used during the manufacturing process. This occurrence cannot be controlled because it is considered the nature of the fired clay brick. The different rates of adsorption cause the percentage of soluble salt adsorbed in the each brick bodies to vary. This situation causes the different rates of defect due to the soluble salt in each fired clay brick. For instance, the high rate of adsorption causes the high and quick effect of reactions due to the soluble salt in the fired clay brick bodies. From Figure 7, for the specimens affected with sulfate ions, the modulus of elasticity at 180 days was 3.85 Gpa. For the specimens affected with chloride ions and sulfate-chloride ions, the modulus of elasticity recorded was 4.46 Gpa and 4.28 Gpa, respectively.

Masonry wall

The modulus of elasticity is linearly related to the ultimate failure of the strength of the masonry. The overall modulus of elasticity of the masonry wall depends on the type of mortar and brick units used in the brickwork. The influence is significant for the fired-clay masonry walls.

The modulus of elasticity of the masonry wall was calculated based on the elastic region from the stress-strain graph. Figure 8 shows the elastic moduli of the fired clay masonry wall under all testing conditions. The modulus of elasticity of the control specimens of fired clay masonry wall was in the range between 10 to12 GPa. According Alexander and Lawson (1982), reported that the initial elastic modulus for normal strength brickwork using 1: 1: 6 design mortars were 5 to15 GPa. As strength, the elastic modulus can also be associated with the effect of mortar thickness. The uniformity of mortar thickness depends on the workmanship or mason skill factor. Figure 9 shows the effect of the mortar thickness on the modulus of elasticity of the fired-clay brickwork. When the mortar thickness increases, the modulus of elasticity of fired clay masonry walls is reduced. However, it is increases with time.

Figure 8 also show the significant effect of sulfate ions on the modulus of elasticity of the fired-clay masonry wall. The reduction in the modulus of elasticity of the fired-clay masonry wall largely occurs due to the deterioration of the mortar joint because of crystallization of sulfate ions. The reduction of the modulus of elasticity also increases with time. The modulus of elasticity of the fired-clay masonry wall affected with sulfate ions after 180 days was 5.56 GPa, respectively.

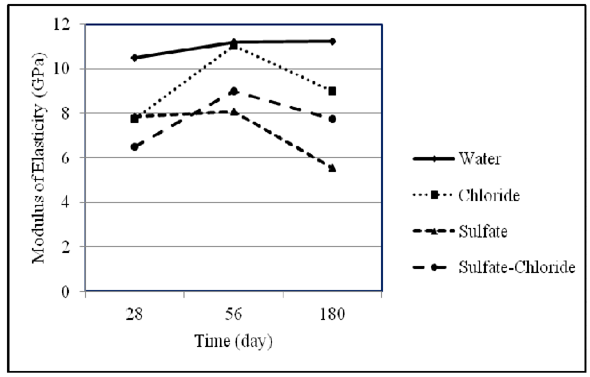


Figure 8: Modulus of elasticity of fired clay brick masonry wall

For the brickwork exposed to chloride ions, some effects of chloride ion on the fired-clay brickwork were observed. Figure 8 shows that, the modulus of elasticity of fired clay brickwork slowly declined after 180 days of exposure to chloride ions. The modulus of elasticity of the fired clay brickwork after 180 days of being affected with chloride ions was approximately 9.00 GPa, respectively.

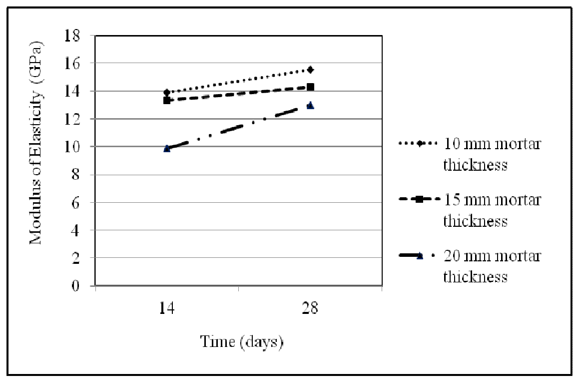


Figure 9: Modulus of elasticity of fired clay brick masonry wall with different thickness of mortar joint

Sulfate-chloride ions also cause the reduction of the modulus of elasticity of fired clay brickwork. The modulus of elasticity of the fired clay brickwork decreased after 180 days of exposure. The modulus of elasticity of the fired clay masonry wall was 7.75 GPa.

The relationship between the brickwork and the mortar joint was observed when the masonry wall was loaded axially with the uniform load. The deteriorated mortar joint was crushed more quickly than the bonded brick and caused the masonry wall to suddenly collapse. However, the crushed mortar closed the cracking and the gap between the bonded brick bed-face and made the brickwork become strong enough to sustain axial load. The reason is that the bonded brick still strong although some reduction in brick strength occurred. In contrast, the vertical deformation associated with the strain was high and caused the lowering of the modulus of elasticity due to the high deformation of the deteriorated mortar joints.

The degree of deterioration of fired clay brickworks due to the soluble salt attack was evaluated by measuring the reduction in the modulus of elasticity. The reduction in the modulus of elasticity of both types of brickworks was calculated after 180 days of exposure to the soluble salt conditions, as shown in Figure 10. This value was evaluated using the following equation:

$$E_R = [(E_w - E_s)/E_w] \times 100 \qquad (1)$$

where

E_R = reduction in the modulus of elasticity,
E_w = the average elastic modulus of the masonry wall under water conditions,
E_s = the average elastic modulus of the masonry wall exposed to the salt solution.

The average elastic modulus of the specimens exposed to the water condition was considered a control specimen because it represents a 0% concentration of the soluble salt solution.

Figure 10 shows a reduction in the modulus of elasticity for the fired clay brick brickworks after 180 days, respectively. After 180 days of exposure to soluble salts conditions, all specimens experienced a reduction in the modulus of elasticity, greatly depending on the quality of the brick and mortar used in the construction of the masonry wall. The reduction occurred due to the crystallization of the soluble salt and the density change in the masonry material. The figure also shows that a higher modulus of elasticity reduction was observed in the specimens exposed to sodium sulfate solutions with 52% of reduction. For the specimens exposed to sodium chloride solutions, the reduction was 32%, respectively. For the modulus of elasticity of the specimens exposed to sodium sulfate-sodium chloride solutions, the reduction that occurred for fired clay was approximately 20%.

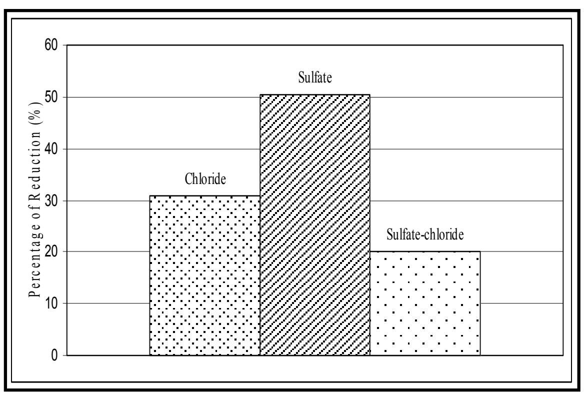


Figure 10: Reduction in modulus of elasticity of fired clay brickwork at the age of 180 days

Composite modeling

Modulus of elasticity

All prediction models estimate the modulus of elasticity of the masonry loaded in the bed face direction. Most of the models are based on the strength of the units, mortars, or both. The estimated values of the modulus of elasticity in this section were only considered at the age of 180 days.

In Eurocode 6, ENV 1996: 2001, the modulus of elasticity of brickwork was also determined from the characteristic compressive strength of the masonry wall as below:

$$E = K_E f_k \qquad (2)$$

where,

E = modulus of elasticity of masonry (GPa)
f_k = characteristic compressive strength of masonry (MPa)
K_E = 1000

The characteristic compressive strength of the masonry can be obtained either experimentally or from the relationship between strength of masonry, strength of the units, and the mortar strength as follows:

$$F_k = K f_b^{\alpha} f_m^{\beta} \qquad (3)$$

where

f_b = mean compressive strength of the unit, (MPa)
f_m=compressive strength of the mortar, (MPa)
β = 0.70
α = 0.30
K = 0.55

Table 3 shows that the predicted modulus of elasticity for all fired-clay brickworks was generally less than the measured values. Table 3 also shows that the predicted modulus of elasticity for the control specimens of fired-clay brickwork was estimated within ±45%. Meanwhile, for the fired-clay brickwork experimented with sulfate ions, chloride ions, and sulfate-chloride ions, the modulus of elasticity was expected within ±46%, ±49%, and ±40%, respectively.

In BS5628: Part 2: 2005 method of prediction, the modulus of elasticity of masonry is based on the characteristic compressive strength of the masonry as show on Equation (4).

$$E_m = 0.9 f_k \qquad (4)$$

where,

E_m = Elastic modulus of masonry in GPa
f_k = characteristic compressive strength of masonry (MPa)

Table 3 shows that the predicted modulus of elasticity of the controlled fired-clay brickwork loaded in the bed face direction was underestimated in the range of ±55% of the measured elastic moduli. These findings are in agreement with Amjad (1990), who found that the variations in the predicted modulus of elasticity are in the range of ±50% of the measured modulus of elasticity because the models are very poor in predicting the modulus of elasticity. For the fired-clay masonry walls affected with soluble salts, the predicted modulus of elasticity was underestimated. The predicted modulus of elasticity for the fired-clay brickwork affected with sulphate ions, chloride ions and sulfate-chloride ions was underestimated approximately by ±12%, ±46% and ±38%, respectively,

ACI 530-92/ASCE 5-92 (1996) method depends on the strength of the brick unit and the type of mortar.

According to the ASTM C270, the type of mortar, i.e., 1: 1: 6, is classified as Type N. Table 3 shows that the predicted modulus of elasticity for the fired-clay brickwork under all conditions was lower than the measured value, except for the brickwork experimented with sulfate ions. For the controlled specimens of the brickwork, the predicted modulus of elasticity was underestimated by ±29%. In contrast, Abu Bakar (1998) reported that the predicted modulus of elasticity of fired-clay brickwork using mortar Type S (1: ½: 4½) is overestimated by 50%. For fired-clay brickwork affected with chloride ions and sulfate-chloride ions, the predicted modulus of elasticity was only underestimated by ±15% and ±5%, respectively. However, for the brickwork experimented with different sulfate ions, the predicted modulus of elasticity was overestimated by ± 37%.

Jessop et al. (1978) suggested the modulus of elasticity of brickwork as below:

$$E_{comb} = \frac{[fE_m(acE_b + dfE_m)(b+e)(a+d)]}{A_{comb}[fbE(a+d) + aceE_b + dfeE_m]} \quad (5)$$

where,

- a – f = masonry unit mortar dimensions
- E_m, E_b = modulus of elasticity of mortar and unit
- A_{comb} = combined area of brick and mortar

This method clearly considers the modulus of elasticity and area of brick units and mortar. Using this method, the predicted modulus of elasticity for the fired clay brickwork in all conditions was underestimated. Table 3 shows that the control specimens were estimated at ±5%, respectively. For the brickworks experimented with chloride ions and sulfate-chloride ions, the modulus of elasticity were underestimated at 36±10% and 50±3%, respectively. In sulfate ions, the prediction for fired clay brickworks was underestimated by ±47%, respectively.

Lenczner (1980) proposed the method of prediction for elastic modulus in brick masonry (E_b) in three categories based on the compressive strength of the brick unit. In this model, the minimum elastic modulus is 5000 N/mm^2 for bricks with a compressive strength of 20 N/mm^2 or less. For bricks with a compressive strength between 20 and 70 N/mm^2, the elastic modulus is given by

$$E_b = 300 f_b - 2000 \quad (6)$$

For units with a compressive strength of 70 N/mm^2 and above, the elastic modulus is considered as follows:

$$E_b = 12750 + 100 f_b \quad (7)$$

The Lenczner model also has an alternative way of obtaining elastic modulus, which is related to the square root of the brick strength. This way, the elastic modulus is given in Equation (8) with a correlation coefficient of 0.96.

$$E_b = 3750[f_b]^{\frac{1}{2}} - 10000 \quad (8)$$

Table 3: Comparison of measured values and predicted values of modulus of elasticity

Condition	Modulus of elasticity (GPa)								
	Measured Value	Predicted values							
		Eurocode[15]	BS5628[16]	ACI 530[17]	Lenczner[20]	Brooks[21]	Jessop et.al [19]	Plowman [23]	Sahlin [22]
Water	11.2	6.1	5.2	8.0	5.3	4.6	6.2	9.0	4.5
Chloride	9.0	4.6	4.9	7.6	5.0	4.3	5.1	8.9	4.2
Sulfate	5.6	3.0	4.5	7.2	5.0	2.7	2.9	8.8	2.8
Sulfate-Chloride	7.8	4.7	4.8	7.4	4.7	4.0	3.9	8.6	4.0

Equations (6) and (7) were recommended for use as well as for in obtaining the upper bound of the elastic movement in brick masonry. However, for the most probable elastic movement, Equation (8) is recommended. However, in this study, Equation (6) was used for the fired clay brick masonry wall because the range of strength was between 20 and 70 N/mm^2. For the fired-clay brick masonry walls, the predicted elastic modulus were underestimated in all exposure conditions. For the brickwork exposed to control condition the modulus of elasticity was estimated at ±52%. In chloride ions and sulfate-chloride ions, the prediction of brickwork estimated about ±40% and ±10% in the sulfate ions condition, respectively.

In Brook's method of prediction (Brooks, 1990), the modulus of elasticity of masonry materials, such as brick units and mortar, are required. Information was obtained from the partly sealed mortar prisms and partly sealed brick units tested individually. Equation (9) was used to calculate the modulus of elasticity.

$$\frac{1}{E_{wy}} = \frac{b_y C}{H}\left[\frac{A_w}{A_b + \left(\frac{A_m E_m}{E_{by}}\right)}\right] + \frac{1}{E_m}\left[\frac{(C+1)}{H} m_y\right] \quad (9)$$

where,

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
A_m = total cross-sectional area of vertical mortar joints
E_{by} = elastic modulus of unit between bed faces
E_m = elastic modulus of mortar
m_y = thickness of horizontal mortar-bed joint

Table 3 shows a comparison of the measured and predicted modulus of elasticity of fired-clay brickwork in all conditions of exposure. For the control specimens, the predicted modulus of elasticity in the bed direction for fired-clay brickworks was underestimated by ±58% respectively. For the brickwork affected with sulfate ions, chloride ions and sulfate-chloride ions, an underestimation of the values also occurred. For instance, for the brickwork experimented with chloride ions, the modulus of elasticity of fired clay brickwork was estimated by ±52% and ±48% for the brickwork experimented with sulfate-chloride ions, respectively. Furthermore, with sulfate ions, the brickwork was underestimated by ±52% respectively. The main reason for the inaccurate predictions is the lower modulus of elasticity in the wall due to the formation of cracking and the deterioration of mortar joint after affected with different concentrations of soluble salt before loading especially for the masonry wall affected with the solutions containing sulfate ions.

Sahlin's method of prediction is a composite method based on the individual modulus of elasticity of brick and mortar, as well as the depth ratio of brick and mortar (Sahlin, 1971). Using this method, the prediction of the elastic modulus of fired-clay and calcium silicate brick masonry walls in all exposure conditions was underestimated by more than 50% of the measured values of elasticity. Furthermore, the predicted values of elasticity by using Plowman's method in all experimented conditions were overestimated by less than ±20% in the sodium chloride and sodium sulfate-sodium chloride solutions, and up to ±80% for the brickwork exposed to sodium sulfate solutions.

Table 4: Comparison of error coefficient between the measured and predicted modulus of elasticity of fired clay masonry by code of practice and other methods of prediction

Method of prediction by Codes of Practice and other methods	Average of modulus of elasticity (GPa)	Error Coefficient (%)
Measured	6.73	-
Eurocode No. 6	3.46	53
BS 5628 Part 2	4.90	61
ACI 530-92/ASCE 5-92 (1996)	7.60	36
Lenczner	5.03	43
Brooks	3.77	58
Jessop et al	3.38	55
Plowman	8.79	47
Sahlin	2.91	62

The accuracy of prediction was estimated in term of error coefficient as shown in Table 4. The error coefficient was determined as follows:

$$\mathbf{C_e = 100\ X\left(\frac{1}{X_a}\sqrt{\frac{\Sigma(X_p - X_m)^2}{n-1}}\right)}$$

where,

C_e = error coefficient
X_a = average of measured value

X_p = predicted value
X_m = measured value
n = the number of observation

Table 4 shows that, the coefficient error for the fired clay brickworks range from 36% to 62% with ACI 530-92 models give good estimates of the modulus of elasticity.

4.0 Conclusion

(i) The test results presented in this chapter demonstrate the effect of the solution containing sulfate and chloride ions on the strength and elastic modulus of fired clay brickwork. The reduction in compressive strength and modulus of elasticity of fired clay brickworks exposed to aggressive environment are significantly influenced by the mortar joint. Failure and deterioration of the mortar joint causes the brick/mortar bonds to separate and fail.

(ii) The thickness of mortar could affect the overall performance of the brickworks. The strength and modulus of elasticity were reduced when the thickness of mortar joints increased.

(iii) The Lenczner's model is the best prediction model for the fired clay brickwork. For the Code of Practice models, the method recommended by ACI 530-92 gives the best estimation of the modulus of elasticity for the fired clay brickwork.

(iv) Overall, the prediction of the elastic modulus of the fired-clay brickwork under sulfate and chloride ions using Code of Practice and previous research model was underestimated. As a whole, the models recommended by previous researchers gave more accurate estimate of modulus of elasticity than the Code of Practice because the unit and mortar are considered. However, the proposed prediction models did not consider the effects of environmental conditions in predicting the modulus of elasticity and moisture movement. This situation causes the predicted values to be inaccurate. Therefore, for further analysis, the development of a prediction model for the modulus elasticity in aggressive environments is necessary.

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