The Effect of Na_2SO_4 and NaCl Solutions on the Moisture Movement of Fired Clay Masonry Wall

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ABSTRACT

The influence of sodium sulphate and sodium chloride exposures on the moisture movement of masonry systems has been investigated. The investigation involved the measurement of moisture movement of single leaf masonry wall which were built with fired clay bricks in conjunction with grade (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 room with temperature of 25 ± 2ºC and 80 ± 5% relative humidity. They were then exposed to sodium sulphate and sodium chloride solutions at different concentrations of 5, 10 and 15%. The moisture movement was monitored up to 210 days. The moisture movement was also measured on the unbonded bricks and mortar prism so that the contribution of brick and mortar on the moisture movement of the masonry walls could be quantified. As a result, after the period of exposure to the soluble salt conditions, large expansion was observed in particular case of sulphate exposure. The composite model underestimated the moisture movement of fired clay masonry walls which were exposed to the soluble salts.

Keywords: *Fired clay brick, Sodium sulphate, Sodium chloride, Moisture movement*

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1.0 INTRODUCTION

Salt attack is one of the major causes of decay to masonry wall materials such as brick and mortar which requires a combination of permeable masonry, moisture, soluble salt and evaporation. This physical phenomenon occurs when evaporation take place below the surface, leaving the salt to grow as crystal in the masonry pores. The process normally produces efflorescence or salt crystals. However, efflorescence which deposited as a white bloom does not deteriorate the masonry structure but causes problems in aesthetics.

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 [1]. Malaysia as a tropical conutry 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 [2].

In practice, sodium chloride and sodium sulphate cause most cases of salt attacks [3]. Sulphate is normally present in many bricks and stones, in Portland cements, and in some groundwater. It is also one of the salt types most frequently found and is destructive for masonry materials [4. They are formed from sulfur dioxide and sulfurous acid in the atmosphere [5]. 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. In fact, the source of salts may be one or a combination of the following [6]:

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

The attack of soluble salt especially sulphate and chloride ions should be considered as serious cases because this phenomena would cause change and damage on masonry wall structures as a composite material. 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 sulphate and chloride ions on the moisture movement of fired clay brick masonry walls.

2.0 MATERIALS AND METHODS

2.1 Fired clay brick

Fired clay brick with five perforations were used in the tests. The properties of units which have been determined are strength, water absorption, porosity and initial rate of suction as given in Table 1. The strength of fired clay brick was 32 MPa with water absorption of 13.42% for 24 hours immersion. Meanwhile the initial rate of suction is approximately 1.97 x 10^{-3} kg/m^2/min.

Table 1: Properties of fired-clay bricks

Parameter	Strength (MPa)	Water absorption	Porosity (%)	IRA $kg/m^2/min$
Mean	32	13.42	21.41	1.97×10^{-3}
Standard deviation	3.74	0.91	1.67	0.00014

2.2 Mortar

Mortar designation (iii) i.e. 1: 1: 6 (OPC: lime: sand) was used throughout the test program. This proportion can be considerable benefit to the durability of the final brickwork. The strength of mortar cubes under water curing was presented in Table 2. The strength of mortar cubes were determined using six 75 mm cubes according to BS 4551 [7]. The range of water cement ratio of mortar mix is 1.53 and 1.54.

Table 2: Strength of Mortar Cubes under Water Curing

Mortar batch	Brickwork reference	Strength (MPa)	
		14 days	28 days
1	Water	5.81	8.80
2	Chloride	5.47	6.17
3	Sulfate	6.43	7.71
4	Sulfate-Chloride	6.39	7.72

2.3 Specimens

Single leaf fired clay masonry wall specimens (1.5 units wide x 5 units height) were constructed using one type of fired-clay bricks unit and mortar. 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 of mortar prism were partly sealed after 3 days curing and completed within 7 days according with volume surface ratio (V/S) of 42 mm. The partly sealed of fired-clay brick units also were prepared based on volume surface ratio of 39 mm.

2.4 Exposure and testing procedure

After casting, the all specimens were cured under polyethene sheet for 14 days in control environmental room with temperature of 25 ± 2 °C and 80 ± 5 percent humidity. The unbonded partly sealed fired clay brick units 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 sodium sulphate and sodium chloride by spraying on the surface of the masonry every 24 hours with concentration of 5%, 10% and 15% of soluble salt. Sodium chloride was used to provide chloride ions, while sodium sulphate was used to provide the sulphate ions. This rate of concentration used to develop of missing data to which masonry decays when subject to high level of sulphate ions especially in Malaysia climates. The expansion or shrinkage measurements were taken up to 210 days using Demec gauge.

3.0 RESULTS AND DISCUSSIONS

3.1 Mortar prism

The time-dependent movement curve of the control mortar prisms are shown in Fig. 1. The figure shows that, the moisture movement associated with the shrinkage of the partly sealed mortar prisms was initially fast, with most of the shrinkage occurring within the first 100 days. The average shrinkage of the mortar prism varied between 270 and 400 x 10^{-6} after 210 days.

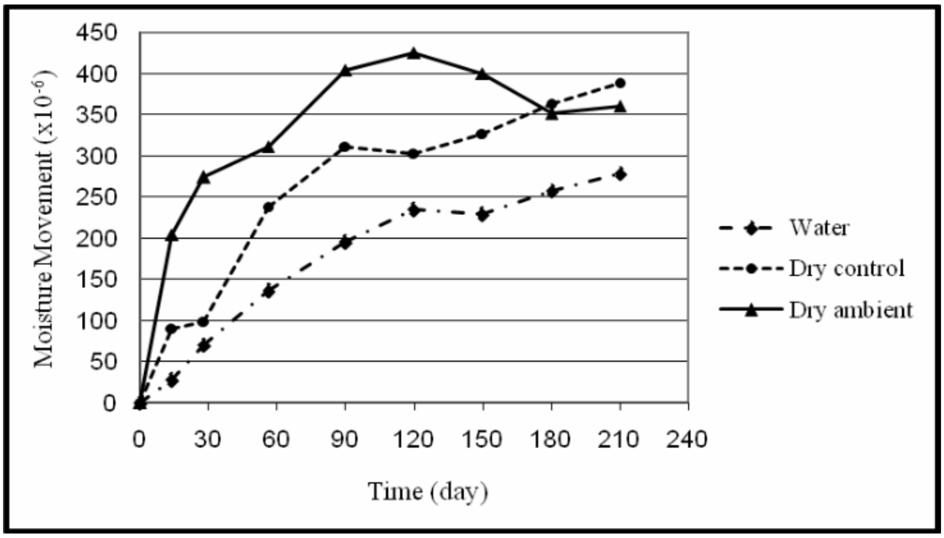

Figure 1: Moisture movement of control mortar prism

The mortar prism experienced expansion after being exposed to sodium sulphate solutions, where the mortar prisms significantly expanded due to the crystallization of sodium sulphate (see Fig. 2). The expansion of the mortar due to the sodium sulphate attack can be considered one of the damaging phenomena. However, in the earlier periods, an initial shrinkage still occurs. Furthermore, the low expansion is also occurs followed by a sudden increase until failure. The initial shrinkage possibly lasts up to 56 days and depends on the sodium sulphate concentrations. However, depending on the concentration of the solution, the service time decreases when the concentrations increase. The figure shows that the maximum expansion of the mortar prisms affected with 5%, 10%, and 15% sodium sulphate concentrations is 10032, -15046, and -7500 x 10^{-6} measured on the age of 210, 150, and 90 days, respectively.

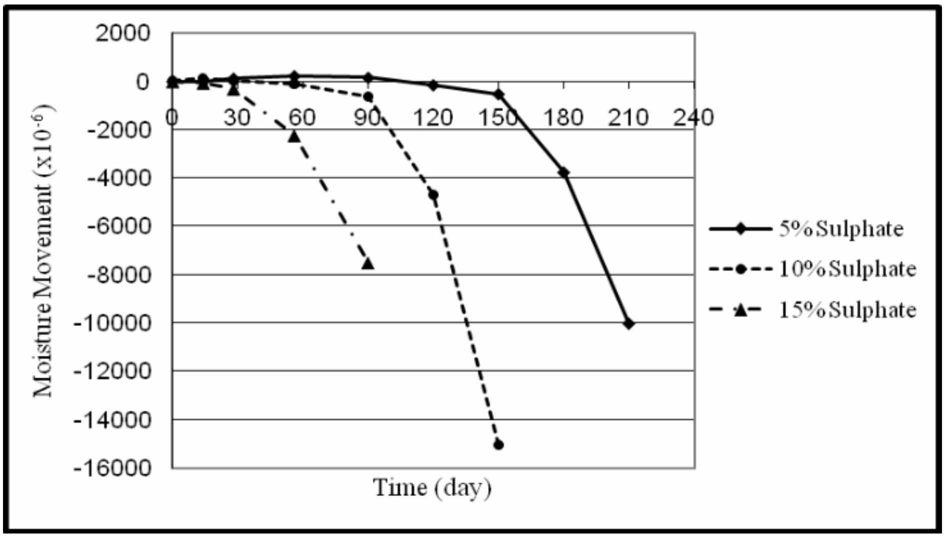

Figure 2: Moisture movement of mortar prism exposed to sodium sulphate

The moisture movement of the mortar prisms exposed to different concentrations of sodium chloride is graphically illustrated in Fig. 3. The figure show that the mortars exhibit shrinkage and the sodium chloride does not cause any large deterioration on the mortar prisms. The average shrinkage of the mortar prism after 210 days exposed to different concentrations of sodium chloride is between 220 and 365 x 10^{-6}.

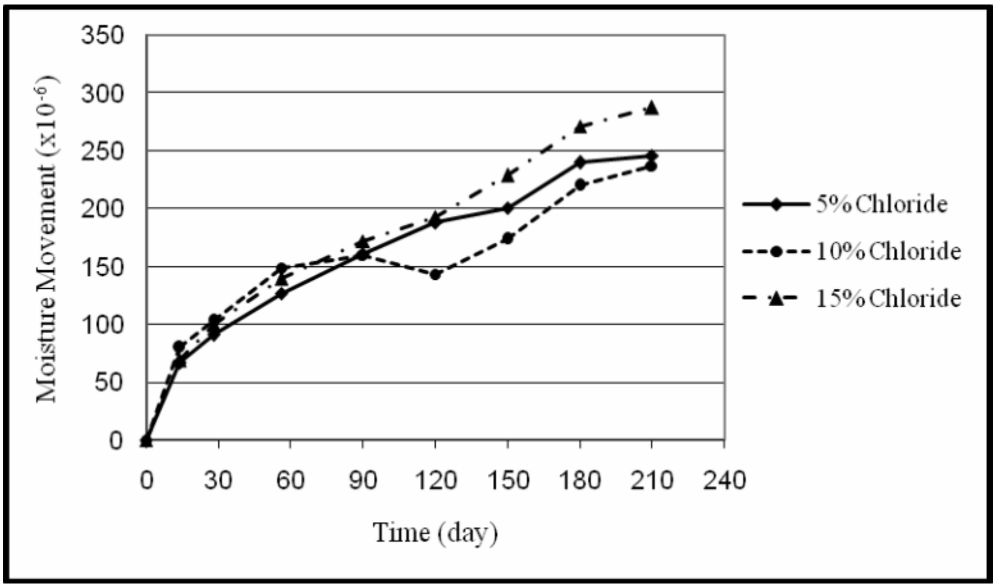

Figure 3: Moisture movement of mortar prism exposed to sodium chloride

3.2 Fired clay brick

The expansion time curves for all the partly sealed unbonded fired clay bricks under control, sodium sulphate and sodium chloride, are presented in Fig. 4, 5 and 6, respectively. Fig. 4 shows that for control purposes, the moisture movement of the partly sealed fired clay brick can be of shrinkage or expansion. The expansion occurred at about -462 and -300 x 10^{-6} for the specimens exposed to moisture condition. Under ambient dry conditions, the shrinkage recorded was about 312 x 10^{-6}.

For the specimens exposed to sodium sulphate and sodium chloride conditions, Fig. 5 and 6 shows that all the partly sealed fired clay brick units had long-term expansions. The expansion was typical of the irreversible moisture expansion with movement consisting of a slow continual growth of units over time. The expansion measured for the specimens exposed to 5%, 10%, and 15% concentrations of sodium sulphate at 210 days was -690, -843, and -979 x 10^{-6}, respectively. For the specimens exposed to sodium chloride solutions, the expansion recorded was -323, -411, and -391 x 10^{-6}, respectively. However, the results indicate that the expansions occurring under sodium sulphate conditions were higher than those of the fired-clay bricks under sodium chloride conditions.

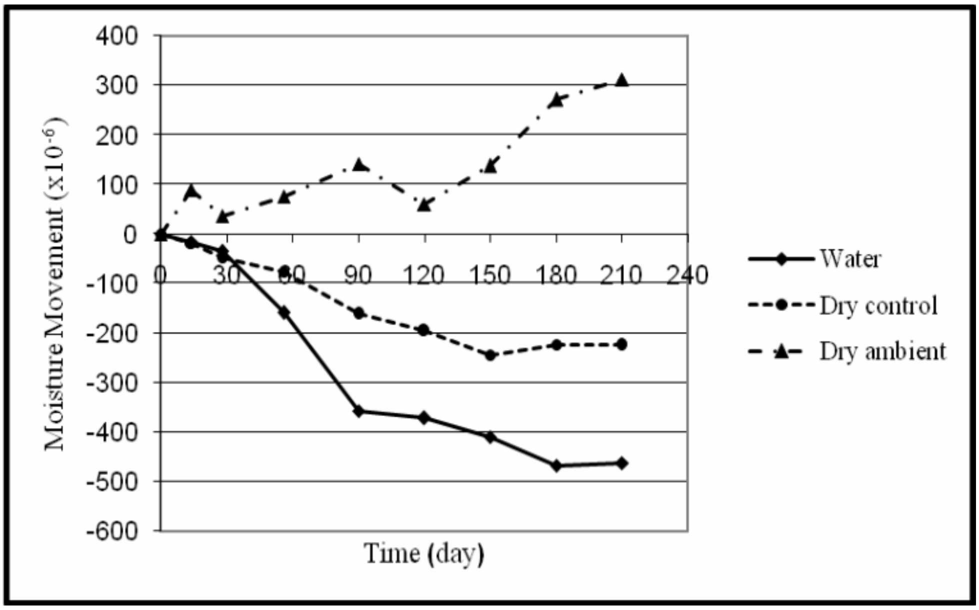

Figure 4: Moisture movement of control fired clay bricks

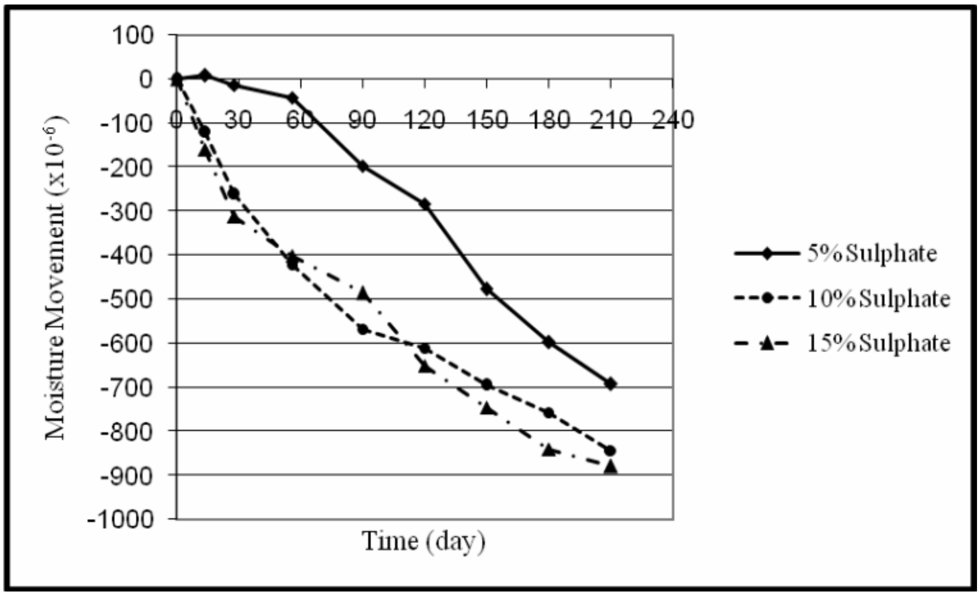

Figure 5: Moisture movement of fired clay brick exposed to sodium sulphate

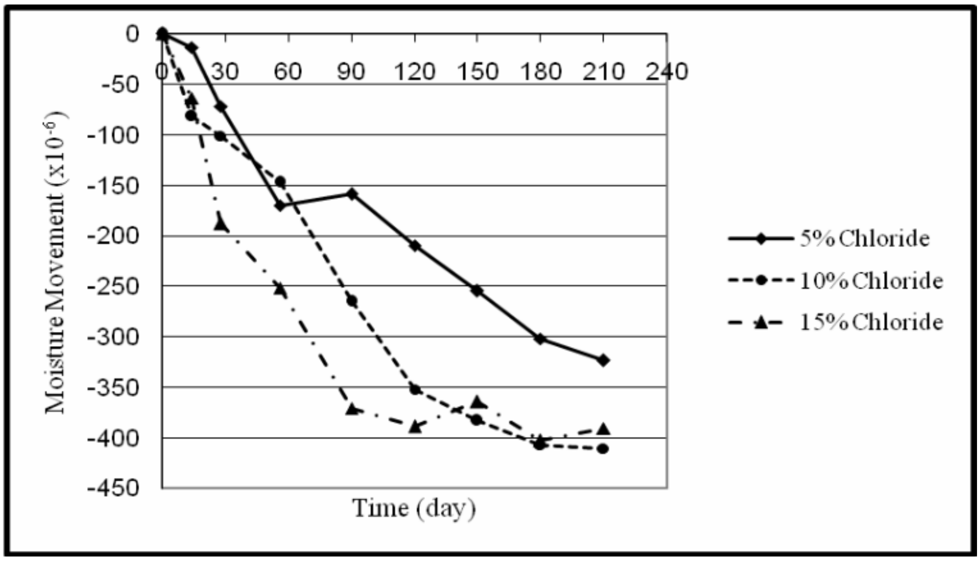

Figure 6: Moisture movement of fired clay brick exposed to sodium chloride

3.3 Masonry wall

The movements of the brickwork normally depend on the movement characteristics of the mortar or brick unit. The time-dependent movement curve in the vertical and horizontal direction of the control fired-clay brickwork is plotted in Fig. 7 and 8, respectively. In these figures, the graph shows that the fired clay brickwork expriences expansion after exposure to wet and dry control conditions and shrinkage in dry ambient conditions. This expansion gradually decreases with time and eventually stabilizes to a constant value. However, the brickwork exposed to dry ambient conditions exhibited a continuous long-term shrinkage. The curve fluctuated due to the inconsistency in temperature and humidity. The shrinkage of the fired clay brickwork after 210 days was 196 and 150 x 10^{-6} in the vertical and horizontal directions, respectively. Under wet conditions, the vertical and horizontal expansions were -841 and -491 x 10^{-6}, respectively.

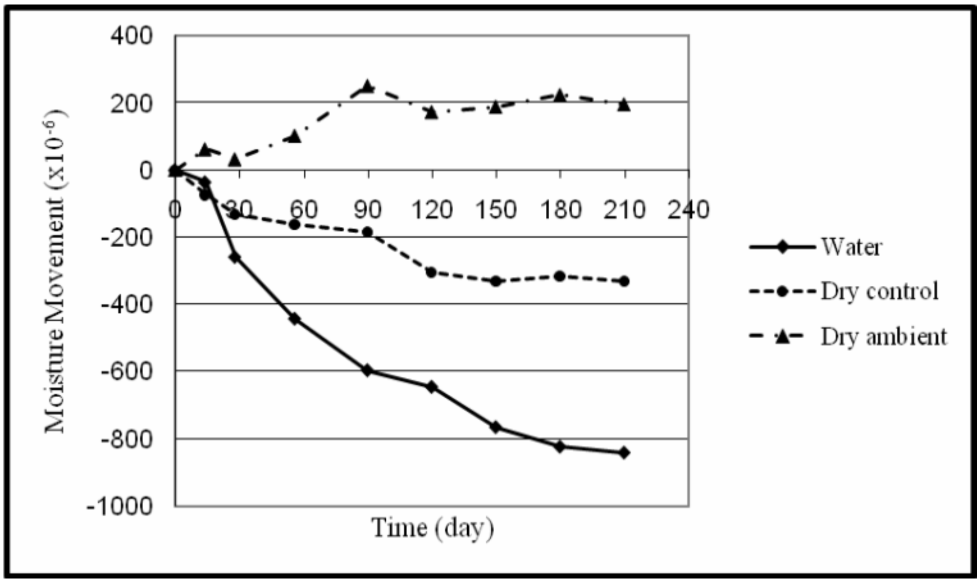

Figure 7: Vertical moisture movement of control fired clay masonry wall

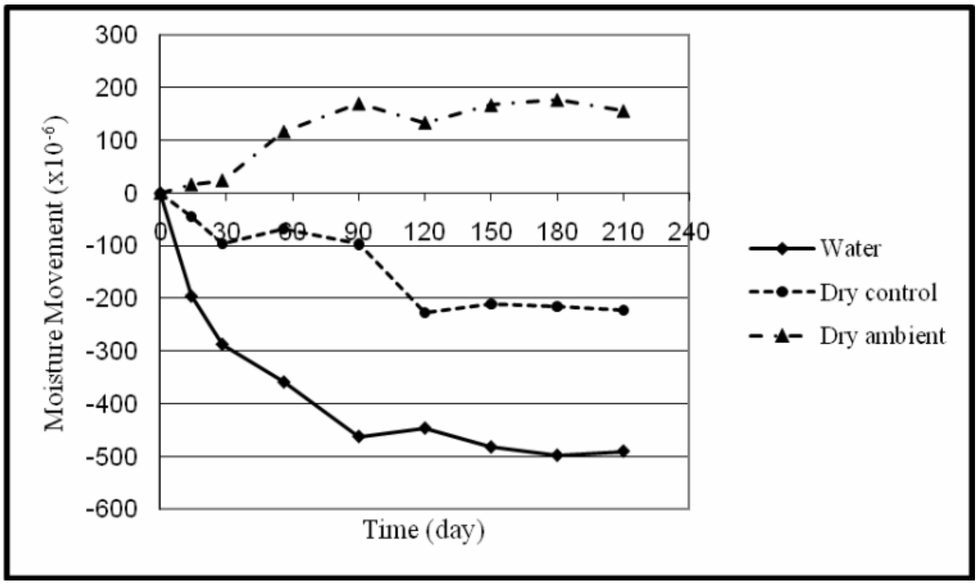

Figure 8: Horizontal moisture movement of control fired clay masonry wall

The time-dependent movement curves of the fired clay masonry wall in both directions after exposure to different concentration of sodium sulphate are plotted in Fig. 9 and 10. The fired-clay masonry wall exhibited continuous long-term expansion after being exposed to sodium sulphate, and the expansion of the brickwork increased with the increase in sodium sulphate concentrations. However, in the early stages, for the brickwork exposed to 5% and 10% concentrations of sodium sulphate, the panels exhibited shrinkage because of the fresh mortar undergoing shrinkage within the first 28 days, followed by a continual long-term expansion. This expansion gradually declined from 28 to 120 days before rapidly expanding.

For the brickwork exposed to 15% concentration of sodium sulphate, the expansions occurred immediately after being exposed to the sodium sulphate solutions. The average expansion for the fired-clay brickwork exposed to 5%, 10%, and 15% concentrations of sodium sulphate in the vertical and horizontal directions at 210 days was approximately -14655,-17896, and -20986 x 10^{-6} and -4142, -4771, and -6930 x 10^{-6}, respectively. The expansion of the fired clay masonry wall due to the sodium sulphate attack exceeded the expansion in the unbonded brick units. This expansion significantly occurred due to the expansion of the mortar joints because of the crystallization of sodium sulphate. The crystallization of sodium sulphate within the mortar joints also caused local disruptions in the mortar beds and induced stress in the brickwork. These results agree with those of Bucea et al. [8] who found that the mortar deteriorates and becomes soft after exposure to sodium sulphate.

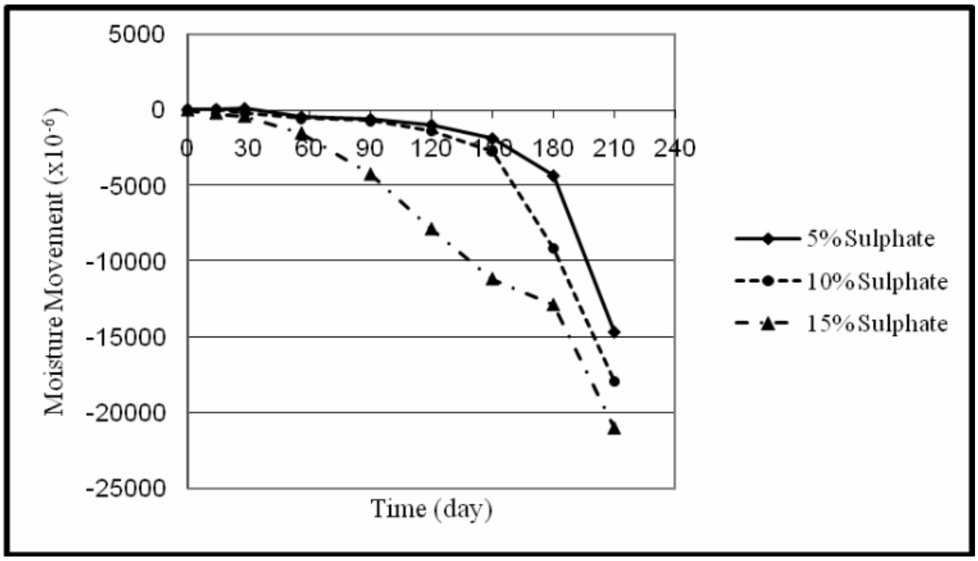

Figure 9: Vertical moisture movement of fired clay masonry wall exposed to sodium sulphate

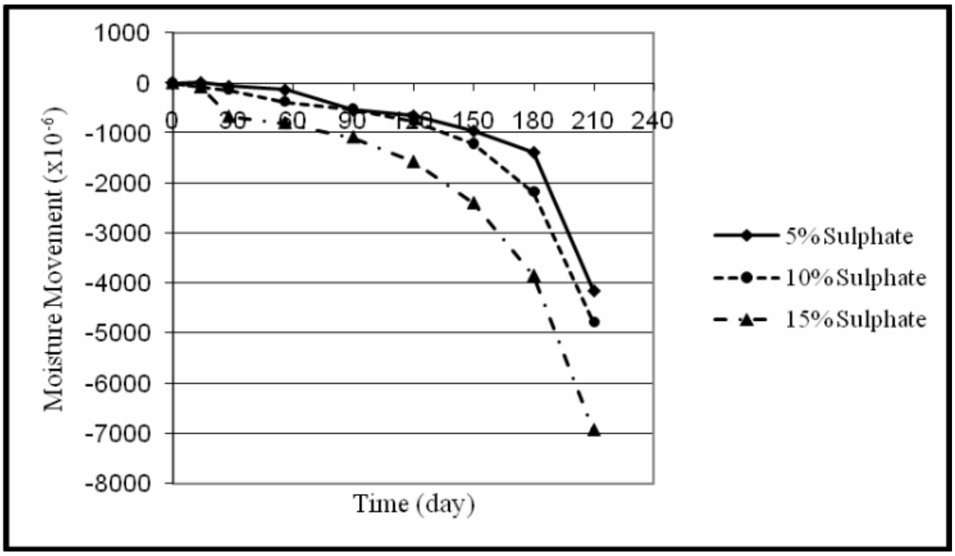

Figure 10: Horizontal moisture movement of fired clay masonry wall exposed to sodium sulphate

The presence of perforation in the brick could also influence the cracking of the bonded bricks due to the large expansion of the mortar joints. In the case of the fired clay brickwork, the mortar could fill up the perforation of the fired clay brick during the construction of the masonry wall. As discussed above, the mortar largely expanded after exposure to sodium sulphate. The expansions occurred due to the crystal growth pressure in the micro-structure of the mortar. In addition, the expansion of mortar was very high and occurred more rapidly than in the fired clay brick units. The reason is that the crystallization pressure that developed in the mortar was higher than that in the brick units. Due to the large expansion of the mortar joint, especially in the horizontal direction, the bonded bricks were then drawn together. This phenomenon causes the cracking on the bonded brick surface in the vertical direction. The schematic diagram of the mechanism of the brickwork subjected to bonded brick-mortar interaction is shown in Fig. 11.

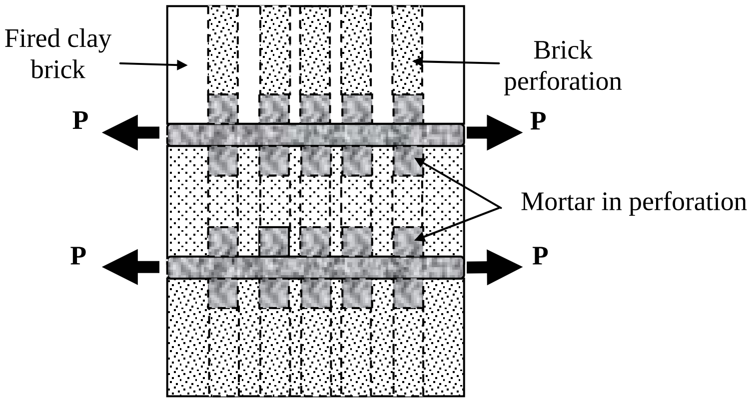

Figure 11: The fired-clay brickwork subjected to bonded brick-mortar restraint

The vertical and horizontal movement-time curves for the fired clay brickwork panels exposed to sodium chloride are plotted in Fig. 12 and 13, respectively. The figures show that the walls experience smaller expansion after being exposed to different concentrations of sodium chloride. For the brickwork exposed to 5% and 10% concentration of sodium chloride, the specimens exhibited shrinkage at an early stage because of the fresh mortar undergoing shrinkage exceeding the expansion in the brick units, but later the contribution of the brick expansion became more influential. For the brickwork exposed to 15% concentration, the specimens instantly expanded after being exposed to sodium chloride. Nevertheless, the expansion was lower than that of the wall panels exposed to sodium sulphate but not obviously different from the controlled wall panels exposed to wet or moisture conditions. This situation influenced by the quality of the clay brick units varied. The expansion of the brickwork exposed to sodium chloride after 210 days was approximately -787, -676, and -960 x 10^{-6} and -356, -319, and -427 x 10^{-6} for both directions of movement, respectively.

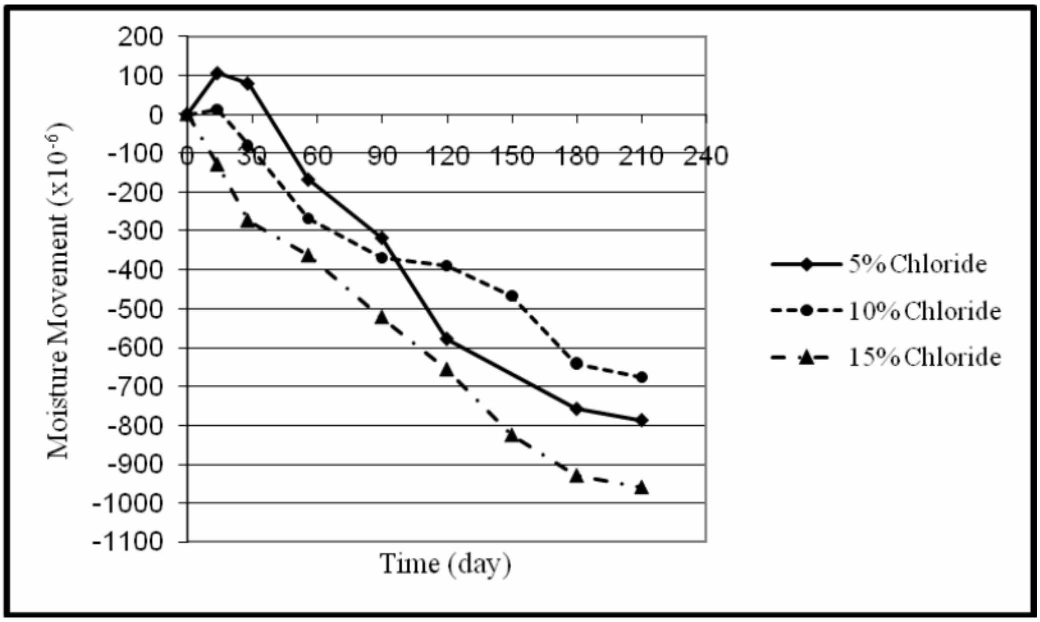

Figure 12: Vertical moisture movement of fired clay masonry wall exposed to sodium chloride

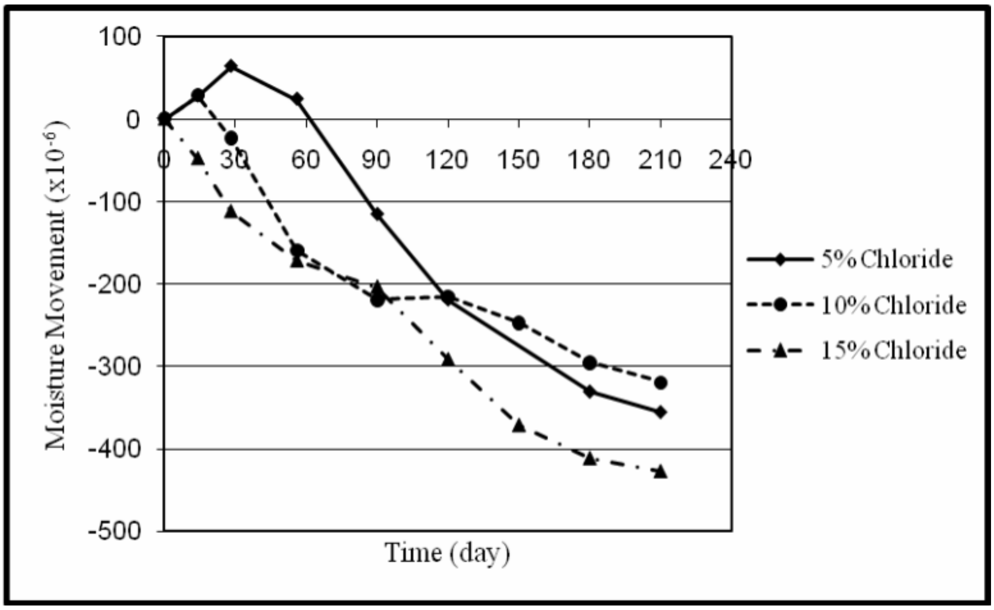

Figure 13: Horizontal moisture movement of fired clay masonry wall exposed to sodium chloride

3.4 Prediction model

The Code of Practice referred to is the BS 5628 [9], Euro-code No. 6 [10], and ACI 530-92/ASCE 5-92 [11]. However, in these methods, no consideration was made for the type of mortar used, and the length of curing as well as the exposure condition. Furthermore, the comparison was made only for the vertical moisture movement. The Code ignores the horizontal movement because the vertical movement is larger and more critical than the horizontal movement. The results of the predictions after 210 days are shown in Tables 3.

BS 5628 [9] ignores the moisture expansion of fired clay brickwork although, in this study, expansions occurred in all conditions and directions. For the controlled fired clay brickwork specimens, the movements in the vertical and horizontal directions were -332 and -223 x 10^{-6} for dry control, 196 and 150 x 10^{-6} for dry ambient temperature, and -841 and -491 x 10^{-6} for the wet control condition, respectively. For the specimens exposed to sodium sulphate and sodium chloride, the expansions measured in the vertical direction were in range of -676 to 960 x 10^{-6}, -14655 to -20986 x 10^{-6}, and -1245 to -1784 x 10^{-6}, respectively. In the horizontal direction, the expansions were -319 to -427 x 10^{-6}, -4142 to -6930 x 10^{-6}, and -432 to -630 x 10^{-6}, respectively.

Eurocode 6 [10] suggested the moisture expansion or shrinkage of fired clay brickwork was between -1000 and 200 x 10^{-6}. In this study, for the controlled fired clay brickwork, the moisture expansion or shrinkgae was less than the design value of -1000 x 10^{-6} and 200 x 10^{-6}. For the wet condition, the estimated shrinkage was higher than that in the range of the suggested final values, which could be influenced by the higher shrinkage of the mortar joint. This situation may be is affected by the aggregate in the mortar joint as well as the humidity and temperature during data measurement. In the case of the fired clay brickwork exposed to different concentrations of sodium sulphate, the estimated moisture expansion was much higher than the design value. In contrast, the estimated expansion was lower than the design value after being affected with sodium chloride.

ACI 530-92/ASCE 5-92 [11] recommends the final value of the irreversible moisture expansion of fired-clay brickwork to be taken as -300 x 10^{-6}. In Tables 3, the method underestimated the moisture expansion of the fired clay brickwork in all conditions of exposure. This situation could be due to the method not considering the effect of aggressive salt exposure on the fired clay brickwork.

Table 3: Moisture movement of control specimens of fired clay and calcium silicate brickwork

Condition/Salt Concentration	Direction of measurement	Measured Data at 210 days (X 10^{-6})	BS 5628 Part 2 (X 10^{-6})	Eurocode 6 (X 10^{-6})	ACI 530-92l (X 10^{-6})
Dry Control	Vertical	-332	0	-1000 to 200	-300
Dry ambient	Vertical	196	0	-1000 to 200	-300
Wet	Vertical	-841	0	-1000 to 200	-300
5% Sulphate	Vertical	-14655	0	-1000 to 200	-300
10% Sulphate	Vertical	-17896	0	-1000 to 200	-300
15% Sulphate	Vertical	-20986	0	-1000 to 200	-300
5% Chloride	Vertical	-787	0	-1000 to 200	-300
10% Chloride	Vertical	-676	0	-1000 to 200	-300
15% Chloride	Vertical	-960	0	-1000 to 200	-300

4.0 CONCLUSIONS

- The resistance and durability of brickwork materials, units and mortar in an aggressive environment are important factors that should be considered to produce durable masonry structures.
- The soluble salt attack especially sodium sulphate solution could result the expansion of the masonry walls which significantly influenced by the deterioration of the mortar joints. However, the rates of failure depend on the types and concentration of soluble salt.
- The sodium sulphate conditions were providing a severe environment conditions on the fired clay brickwork.
- The presence of sodium chloride underneath the fired clay brick and mortar surface did not cause any large effect on the brickwork although expansion was observed.
- The presence of perforation in the fired clay bricks could influence the effects of the soluble salt attack. For instance, the bonded fired clay brick exposed to sodium sulphate was vertically cracked due to the large expansion of mortar joints filling the perforation, attracting the bonded bricks together.
- The predicted value of the moisture movement after exposure to sodium sulphate was overestimated compared with the estimated values due to the large expansion of masonry walls associated with the crystallization process.

5.0 ACKNOWLEDGEMENT

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