

Fracture Strength

A New Approach to Assessing the Salt Attack Resistance of Fired Clay Bricks

By

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BACKGROUND

The resistance of fired clay bricks (FCB) including bricks, pavers and roof tiles to salt weathering is determined on a long time scale and has historically been difficult to predict. Improvements to material testing and analysis allow the manufacturer to provide reassurance about their bricks' durability after many years of service. Salt attack is a damaging process to FCBs in sub-tropical and tropical climates. Frost attack is an analogous process that is regarded as the more damaging to FCBs in temperate climate in which the temperature drops below the freezing temperature of water. Surface damage appears on a small scale on FCBs during attack from either salt or frost. The mechanisms of salt attack are not well known. As a result of this lack of fundamental knowledge test methods for salt attack have been long and inaccurate. This project set out to investigate better methods that can be used to determine the resistance of FCBs to salt attack in a variety of saline conditions.

PHILOSOPHY OF THE RESEARCH

Most of the written literature on this topic concentrates on assessing the type of microstructures that lead to the fastest development of stress by a number of salts. The author acknowledges there is a necessity to know how different salts can crystallise to create varying amounts of stress within FCBs. However, equally important is the determination of how stress at the crystal surface creates macroscopic damage through cracking inside the microstructure of FCBs.

Accelerated aging tests are the most commonly used test method for determining the resistance to weathering from either salt or frost. The reduced time scale in many accelerated aging tests has invoked mechanisms that would not normally occur during natural weathering time scales. The usefulness of accelerated aging tests has been questioned when the mechanisms of decay in real environments are different to those of the accelerated test.

A material approach was taken to study the resistance of FCBs to salt attack. Salt attack was categorised in terms of the porous and solid microstructure of FCBs. The mechanical properties of FCBs were also categorised with respect to their material properties. An understanding of the linkages between material properties and resistance to salt attack and mechanical properties would increase the knowledge for designers of masonry elements as well as helping manufacturers identify elements of their processes that need to improve the microstructure of FCBs to make them stronger and more durable.

PROCESS OF RESEARCH

This project was performed in three stages using eight different fired clay bricks and pavers.

Stage 1. Material property characterisation: The solid density, porosity, rate of water absorption and the pore size distribution were measured for each FCB.

Stage 2. Resistance to salt cycle tests: Sodium chloride and sodium sulfate decahydrate were used in three different concentrations as test media in cycle tests. The rate of uptake of salt and solution and the rate of damage was measured as a function of cycle number.

Stage 3. Mechanical property characterisation: FCBs were tested for their stress-strain properties under uniaxial compression and spherical indentation. Indentation tests were also performed to obtain the surface area of indentation (SAI) hardness and Weibull distributions of each sample. Indentation tests are non-destructive and more tests can be performed on each sample compared to compression tests. This produces an average result that has less uncertainty.

RESULTS OF THE STUDY

Table 1 Water absorption values, porosity, solid density, saturation coefficients, compressive strength and SAI hardness for samples in the study.

	M0	Q3	Q4	N5	M6	M7	M8	M9
5min WA %m/m	4.65	6.80	6.90	9.21	3.23	5.73	5.05	4.16
1hr WA %m/m	4.93	7.31	7.48	9.64	3.86	6.07	5.40	4.68
4hr WA %m/m	5.40	7.89	8.10	10.02	4.18	6.27	5.63	4.87
1day WA %m/m	5.99	8.95	9.20	10.88	4.62	6.70	5.93	5.12
8day WA %m/m	6.95	10.73	10.86	12.41	5.63	7.91	7.11	6.14
15day WA %m/m	7.24	11.59	11.77	12.83	6.03	8.31	7.61	6.67
Porosity %v/v	16.25	27.48	27.28	28.00	17.90	20.07	19.31	17.16
Solid Density g/m³	2.60	2.58	2.54	2.68	2.57	2.65	2.68	2.67
Saturation Coefficient 24hr/15day	0.83	0.77	0.78	0.85	0.77	0.81	0.78	0.77
Number of Cycles to Failure from Sodium Sulfate Decahydrate Attack	38.0	23.3	22.0	8.0	45.0	22.7	36.0	37.0
Number of Cycles to Failure from Sodium Chloride Attack	>40.0	>40.0	>40.0	36.0	>40.0	>40.0	>40.0	>40.0
Elastic Modulus (GPa)	11.4	4.9	5.0	4.7	24.5	8.5	8.6	9.5
Compressive Strength (MPa)	43.5	12.3	15.7	20.5	32.9	47.1	46.4	54.0
SAI Hardness (MPa)	61.9	38.5	39.9	33.1	57.5	67.3	69.4	77.8
Weibull Modulus	12.9	8.15	4.11	12.4	8.26	19.7	14.5	10.4

Results from Salt cycle tests compared with Material Properties

- ◆ FCBs were found to absorb much larger volumes of sodium chloride than sodium sulfate during salt cycle tests. This occurred because the hydration process of sodium sulfate restricts nuclei from growing within the solution until hydration was completed.
- ◆ Failure due to sodium sulfate decahydrate attack was linearly related to the water absorption properties of FCBs. Primarily the rate of damage was linearly related to the 5-minute and 24-hr volume of water absorbed.
- ◆ Failures due to sodium chloride salt attack were not observed except in sample N5. These failures were observed only using 14% and saturated solutions of sodium chloride. The rate of solid salt uptake was related to the total porosity of FCBs. As such the resistance of FCBs to damage from sodium chloride attack would be expected to be proportional to the total porosity of samples.
- ◆ Sample M7 absorbed an unusually large amount of sodium sulfate during cycle tests. This was attributed to its mono-modal pore size distribution causing the same paths to be used for solution intrusion to extrusion. In addition, the pore size distribution plus the high solid density of sample M7 provided a fast propagation of cracks to the surface where they could combine to exfoliate particles.

- ◆ Fracture patterns of FCBs attack with sodium sulfate decahydrate show there to be two distinctive types of fractures occurring. The first is a short crack growth dusting of the surface of a FCB such as that found in samples Q3, Q4 and N5. The second type of failure was a longer crack formed in samples with lower porosity like that found in samples M0, M6, M7, M8 and M9.
- ◆ Possible theories used to explain salt attack on FCBs include an increase in surface tension between crystals close to each other but separated by pore walls. Excess surface energy due to crystal separation during growth provides the driving force for crystals to induce stress on the pore walls that can cause crack growth within the FCB.

Results from Comparing Mechanical Properties with material properties

- ◆ The bulk elastic moduli of FCBs were found to be proportional to the relative densities (1-porosity).
- ◆ The total porosity of FCBs was related to the SAI hardness number and the compressive strength of FCBs for those samples that had similar solid elastic moduli. Samples M0 and M6 were found to have larger solid elastic moduli compared to the rest of the samples in the study. As a result, their compressive strength and SAI hardness was not linearly related to the total open porosity of the other FCBs.
- ◆ The SAI hardness number correlated linearly with the compressive strength except for when the compressive strength test showed significant lateral expansion of the sample. This occurred in sample N5.
- ◆ Samples Q3 and Q4 had significantly increased hardness at the red coloured surface compared to the black core of the brick.
- ◆ The Weibull modulus of SAI hardness values indicated the spread of hardness through the microstructure of FCBs. A high Weibull modulus relative to the average SAI hardness indicated there was a small distribution of hardness throughout the microstructure. Samples N5, M7 and M8 had high relative moduli thus, a narrow distribution of hardness. Samples M0, Q3, and M9 had a medium distribution of hardness and samples Q4 and M6 had a wide distribution of hardness.
- ◆ The damage in most samples was typical of bend-induced and shear-induced grain crushing and sliding. The porous microstructure appeared to collapse into itself during an indentation. This type of behaviour was consistent with other studies on porous mullite.
- ◆ The stress-strain behaviour of an FCB when indented indicated that resistance increased as the indenter entered further into the sample. FCBs can be best modelled as cellular materials.
- ◆ The analysis of the eight FCBs in this study suggests that sample M0, the red firing pressed brick, contains the best mixture of properties. This is because it has reasonable suction to allow mortar to be absorbed and it has a slightly higher elastic modulus relative to the extruded bricks. This will make it relatively more resistant to all three types of weathering processes.

DISCUSSION OF THE RESULTS AS THEY RELATE TO THE STANDARDS PERTAINING TO THE RESISTANCE OF FCBs TO WEATHERING PROCESSES

There are three distinct types of weathering processes that create a similar type of damage in FCBs. These are frost attack, attack by non-hydratable salts such as sodium chloride and attack from hydratable salts such as sodium sulfate decahydrate. Below is a summary of the properties that are necessary creation during frost, sodium sulfate and sodium chloride attack.

FROST ATTACK

Total (Boiling) water absorption: This indicates the volume of water that can be absorbed by the brick, hence the volume of ice that can be created.

Saturation coefficient: This indicates how much space is left for ice crystals to grow into once the pore water in large pores has crystallised.

Strength of the microstructure: This includes elastic and inelastic strength. Strength indicates how well stress can be dissipated within the microstructure before macrocracks begin to form.

SODIUM SULFATE ATTACK:

24hr (Cold) Water absorption: This indicates how much salt solution can enter the microstructure during normal service life.

Strength of the microstructure: As previously explained.

SODIUM CHLORIDE ATTACK:

Total Porosity: This indicates the total volume of sodium chloride that can be absorbed into the microstructure of an FCB.

Strength of the microstructure: As previously explained.

The most cited standard relating to durability of FCBs is the ASTM C62-2001 for frost resistance [1]. Using the criteria in ASTM 62-2001 the FCBs in this study achieved different categories of weathering to those that could be achieved for sodium sulfate and sodium chloride resistance according to results from accelerated aging tests (see Table 2).

Table 2. Ratings for each FCB according to frost, sodium sulfate and sodium chloride attack.

FCB	Frost Rating	Sodium Sulfate Rating	Sodium Chloride Rating
M0	Severe Weathering	Severe Weathering	Severe Weathering
Q3	Negligible Weathering	Moderate Weathering	Severe Weathering
Q4	Moderate Weathering	Moderate Weathering	Severe Weathering
N5	Moderate Weathering	Negligible Weathering	Moderate Weathering
M6	Severe Weathering	Severe Weathering	Severe Weathering
M7	Severe Weathering	Moderate Weathering	Severe Weathering
M8	Severe Weathering	Severe Weathering	Severe Weathering
M9	Severe Weathering	Severe Weathering	Severe Weathering

ASTM 62-2001 suggests that resistance increases with a higher compressive strength and lower boiling water absorption and lower saturation coefficient. A frost index can be mathematically expressed using these three values (see Equation 1).

$$\text{Frost Index} = \text{Compressive Strength} / [\text{BWA} * \text{Saturation Coefficient}] \quad \text{— Equation 1}$$

The saturation coefficient is an indication of the spread of the pore size distribution within the microstructure. The Weibull modulus is an indication of the spread of the hardness within the microstructure. Since hardness was related to porosity, it is reasonable to substitute the Weibull distribution for the saturation coefficient and recalculate the frost index and rename it the weathering index (see Equation 2). Table 3 shows each index for the eight FCBs tested in this study.

$$\text{Weathering Index} = \text{Compressive Strength} / [\text{BWA} * \text{Weibull Modulus}] \quad \text{— Equation 2}$$

Table 3. Frost and weathering indices of each FCB and their ratings.

FCB	Frost Index and Rating		Weathering Index and Rating	
M0	7.26	SW	0.466	SW
Q3	1.43	NW	0.136	NW
Q4	1.70	MW	0.324	MW
N5	1.88	MW	0.129	NW
M6	7.12	SW	0.661	SW
M7	7.03	SW	0.287	MW
M8	7.83	SW	0.421	SW
M9	10.55	SW	0.779	SW

The aim of any standard test is provide an accurate guide of the performance of the product. For salt attack and frost attack the mechanisms of stress creation are time dependent and difficult to accurately replicate in an accelerated aging test. As such, accurate material tests are needed to provide a holistic picture of the resistance of FCBs to point stresses. This study leads the way to develop a methodology that tests the important material properties to evaluate FCBs for their resistance to salt attack and other weathering processes. These include water absorption, porosity, density and mechanical properties such as elastic modulus, SAI hardness and Weibull modulus. SAI hardness provides a microscopic measure of material strength and in doing so can provide an indication of the surface porosity if the elastic modulus of the solid material is known. Analysis of the data from 100 SAI measurements will provide a Weibull modulus of each sample, which can be used together with porosity and elastic modulus data to determine an index of resistance to natural weathering processes. This index needs to be compared to the environment the brick is likely to be placed.

CONCLUSIONS

This study investigated the material properties of FCBs and compared them to the resistance to salt cycle tests using sodium sulfate decahydrate and sodium chloride and to the mechanical properties including compressive strength and hardness. The results of this study have indicated that material properties are inherently related to generation of stress during salt crystallisation and the resistance to crack growth through the microstructure of FCBs.

As a footnote, a prototype of an instrument that can automatically measure the indentation stress-strain curve many times across the surface of a FCB is presently under construction. Analysis of data from this instrument will produce information about the indentation stress-strain properties, SAI hardness, Weibull modulus and elastic modulus of FCBs. Therefore, indirect measurements of compressive strength, porosity and resistance to sodium chloride attack can be made using the results from tests using this instrument.

REFERENCES

1. American Society for Testing Materials, "*ASTM Designation 62-01 - Standard Specification for Building Brick (Solid Masonry Units Made From Clay or Shale)*", 2001, American Society for Testing and Materials, West Conshohocken, USA, pp: 1-4.

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