EFFECTS OF PRODUCTION METHOD, KILN SIZE, AND SPECIMEN SIZE ON THE PROPERTIES OF FIRED CLAY BRICK

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ABSTRACT

Experimentation with fired clay brick is subject to certain limitations. Due to the size of experimental facilities and testing apparatus, as well as the cost associated with full scale production of multiple compositional variations for experimental purposes, it is often desirable to produce small scale specimens within a laboratory for use in large experimental programs. The properties of small scale fired clay brick specimens prepared in a laboratory vacuum extruder and fired in a small kiln are compared to the properties of full scale bricks produced in a large, automated plant. The effects of both the specimen production and firing method are investigated. The specimens are compared through testing of mechanical and physical properties including compressive strength, absorption, durability, and mercury intrusion porosimetry. Results indicate a significant effect of both production and firing method. The specimen size influenced the absorption, extrusion influenced porosity and durability, and firing location influenced the pore distribution and absorption.

KEYWORDS: brick; masonry; scale; firing; laboratory; extrusion; plant

INTRODUCTION

Fired clay brick is an ancient yet still widely used building material. In order to remain relevant and competitive in today's market, the cost of production as well as the sustainability of resources must be optimized. This is achieved in several ways; through development of alternative raw materials, use of alternative fuel sources, and increased energy efficiency. In testing new methods and materials, the challenge of producing, storing, and testing full sized specimens becomes apparent. It is therefore ideal to be able to use small scale specimens, produced in a laboratory, for determining the properties of full scale brick without requiring the use of production facilities and large storage areas. This paper will present the results of an experimental program that was carried out to study the effects of producing bricks extruded and fired in a lab and automated plant.

EXPERIMENTAL PROGRAM

Specimens were produced in two settings; a laboratory and an automated plant. The laboratory was equipped with a small batch mixer (10 kg), a vacuum extruder, and an electric kiln. The plant operated with a large mixer, extruded through a vacuum extruder, dried in a gas oven and fired in a continuous gas kiln. All specimens were produced with crushed shale from the same source. The composition of the shale is given in Table 1. Details of the specimen dimensions and production locations are given in Table 2. The laboratory specimens were produced in 20 kg batches, which resulted in approximately 30 lab specimens per batch. The specimens were mixed and extruded in the lab. They were air dried for 24 hours followed by 24 hours in an oven at 100°C. Specimens marked X were then transferred to a full plant kiln car to be fired in the plant kiln with specimens FX. The full scale specimens FL were obtained from the same kiln car following mixing and extrusion in the plant. The bricks were dried in the lab and fired in an electric kiln with specimens L.

Table 1: Shale Composition by X-Ray Fluorescence

Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	MnO	SO_3	LOI
%	46.83	0.77	16.33	5.83	9.90	2.96	4.00	0.25	0.07	0.11	0.20	12.50

Table 2: Specimen Dimensions and Production Details

Identification	Size (mm)	Extrusion	Firing
L	152.4x50.8x25.4	Lab	Lab
X	152.4x50.8x25.4	Lab	Plant
FL	247x75.7x90	Plant	Lab
FX	247x75.7x90	Plant	Plant

Table 3: Heating Schedule for Lab Kiln

Ramp Rate (°C/hr)	Dwell Temp. (°C)	Dwell Time (hr)
120	475	0.5
90	850	1
60	1035	3.5
-600	25	END

The laboratory kiln followed the heating schedule in Table 3. The firing temperature of the continuous plant kiln ranges between 1040°C and 1060°C, which is slightly greater than that of the laboratory kiln. The difference in heating and cooling rates between the two kilns can result in the formation of different minerals that will affect strength, colour, and pore size distribution. The testing program included compressive strength, freeze-thaw durability, absorption, and porosity. For each type of brick, five repetitions were used for each test in order to allow statistical significance in the analysis.

COMPRESSIVE STRENGTH

The full scale specimens were tested according to CSA CAN3-A82.2-M78 [1], where loading was applied in the direction of extrusion. In order to test the small scale specimens in the direction of extrusion, loading was applied on the smallest face. Compressive strength results shown in Figure 1 reveal that the average strength values for specimens extruded and fired in a plant are greater than those extruded and fired in a lab. However, statistical evaluation of the results using the t-test has yielded no significant difference between the production methods. The lower observed compressive strength of the lab extruded specimens may partially result from a large difference in the aspect ratio of the two extrusion methods when tested in compression. The ratio of height to minimum cross sectional width for the laboratory specimens is 3 while that of the plant specimens is 0.84. Adjustments for aspect ratio based on work by Krefeld [2] shown in Figure 1 indicate that when the aspect ratio is accounted for, the compressive strength of the specimens extruded in the lab may actually be slightly higher, but not by a statistically significant margin. The failure pattern shown in Figure 2 was found to be similar for both production methods, with a splitting at the perimeters of the extrusion core holes.

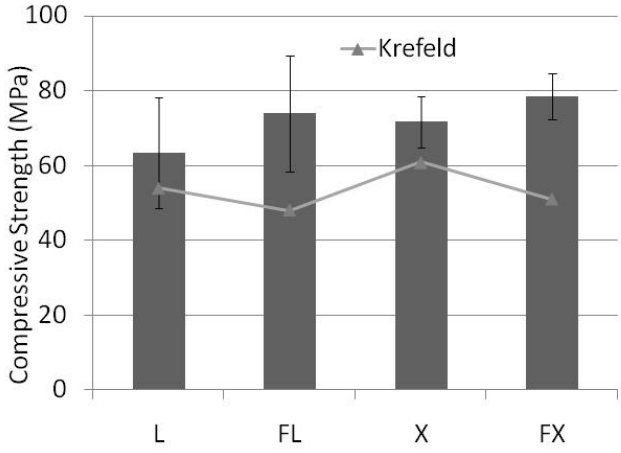

Figure 1: Average Compressive Strength and Aspect Ratio Adjustment

a) **b)**

Figure 2: Failure in Compression for a) Laboratory and b) Plant Produced Specimens

INITIAL RATE OF ABSORPTION AND ABSORPTION RATIO

The initial rate of absorption (IRA), which is a measure of pore refinement and connectivity, is a rate of capillary suction for a known surface area in a given time, and can serve as an indication of field bond performance [3]. A statistical comparison of the IRA results in Figure 3 reveals that there is a significant increase in the IRA of small scale specimens in both firing locations. In addition, firing in the small electric laboratory kiln decreased the initial rate of absorption for both large and small specimens.

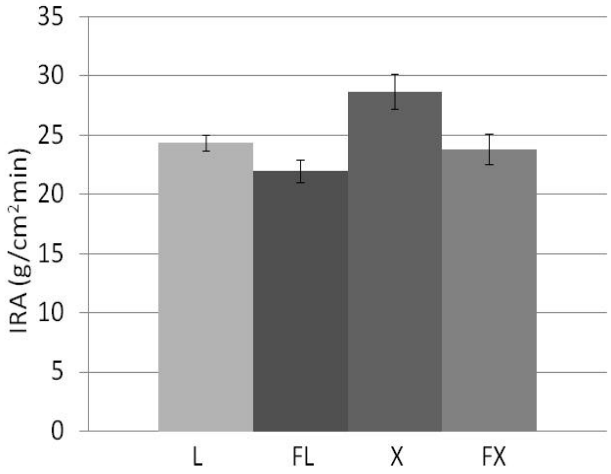

Figure 3: Average Initial Rate of Absorption

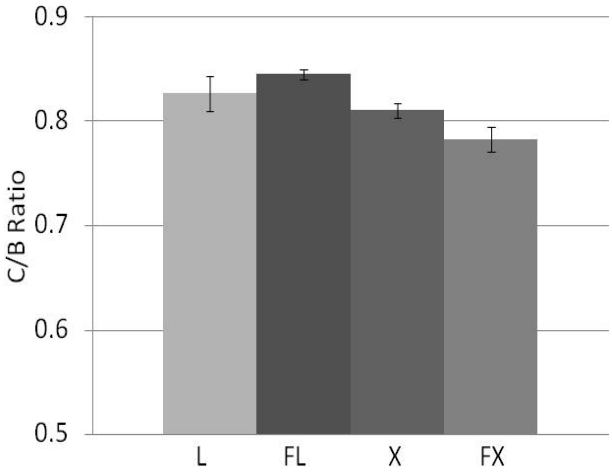

Figure 4: Average C/B Ratio

The 24 hour cold water absorption and 5 hour boiling water absorption values were measured and the ratio of the values is shown in Figure 4. The C/B ratio can be used as an indication of expected durability, as the ratio indicates the ability of the small pores to accommodate pressure from freezing water in the large pores. Thus the C/B ratio is actually the proportion of the pores that are easily saturated versus the total pore volume. Statistical evaluation reveals no significant effect due to size. The type of kiln does influence pore refinement, where specimens fired in the laboratory electric kiln tended to have a larger C/B.

FREEZE-THAW DURABILITY

Durability testing was performed using a modified method which was derived from ASTM 1262-98, Standard Test Method for Evaluating the Freeze-Thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units [4]. This method was adopted to track the specific mass loss of each specimen over the course of the experiment and the results are intended for comparative evaluation of the freeze-thaw resistance. Freeze-thaw testing was performed with two solutions; water and 3% sodium chloride. Both laboratory extruded and plant extruded specimens were tested with the finished face parallel to the direction of extrusion. Mass loss was recorded after 5 cycles of freezing and thawing to a total of 100 cycles.

There was an increased mass loss for the plant extruded specimens in the first 50 cycles, as shown in Figure 5a. Small pop outs formed on the surface of L specimens after 30 freeze-thaw cycles. In the final half of the test, the small scale specimens fired in the lab experienced very rapid mass loss, while the small scale specimens fired in the plant continued to perform well, see

Figure 5b. The plant extruded specimens also continued to experience mass loss at an increasing rate. Similar to the laboratory extruded specimens, the plant extruded specimens fired in the plant had significantly less mass loss than those fired in the lab.

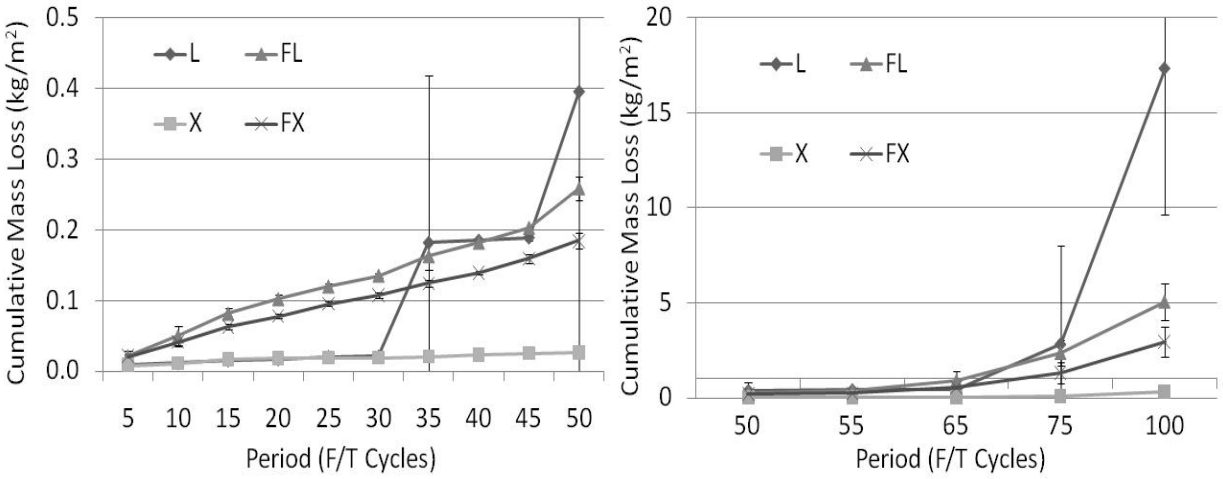

Figure 5: Average Cumulative Mass Loss in Water a) First 50 Cycles b) Last 50 Cycles

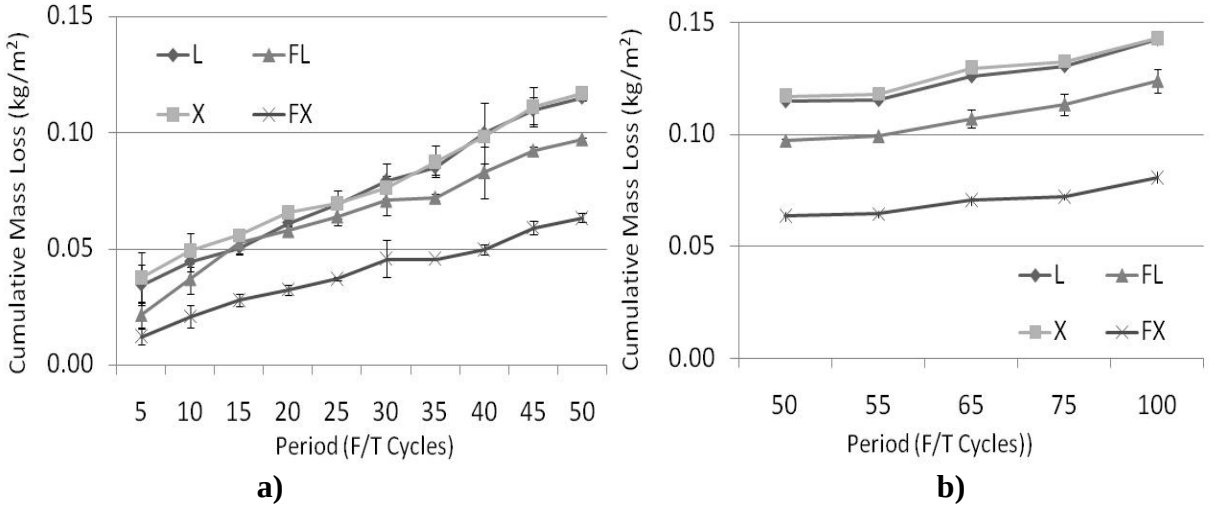

Figure 6: Average Cumulative Mass in 3% NaCl Solution a) First 50 Cycles b) Last 50 Cycles

When tested in a 3% NaCl solution, the mass loss of the specimens is more consistently linear in the first 50 cycles of freezing and thawing shown in Figure 6a. The full scale plant extruded specimens have a lower overall mass loss in the first 50 cycles; however there is a significant increase in mass loss for the laboratory fired specimen in the first 15 cycles of testing. After this point, the rate of mass loss is similar for both large scale specimens. The laboratory extruded specimens have similar mass loss throughout the first 50 cycles. In the final 50 cycles of freezing and thawing shown in Figure 6b, the rate of mass loss decreases for all specimens. The lab

extruded specimens continue to experience similar mass loss, greater than that of the plant extruded specimens. The plant extruded specimens have similar rates of mass loss. Despite the initial increase in mass loss, there is not a statistically significant difference between similarly extruded specimens fired in different locations; however there is a difference in mass loss as a result of extrusion location, where lab extrusion results in increased mass loss due to freezing and thawing.

MICROSTRUCTURE

Mercury intrusion porosimetry (MIP) was performed on the specimens in order to measure their pore structure, which can be related to durability. Figure 7 shows the incremental pore volume for specimens L, X, FL, and FX. With higher peak volume values and a more narrow distribution, the specimens extruded in the lab have a more uniform pore structure and a higher total porosity. Although there is not a significant difference between the overall porosity due to firing location, there is a difference in the pore size distribution. Specimens fired in the plant kiln tend to have a more widely distributed range of pore sizes. There is a greater volume of both larger and smaller pores in specimens X and FX when compared to L and FL.

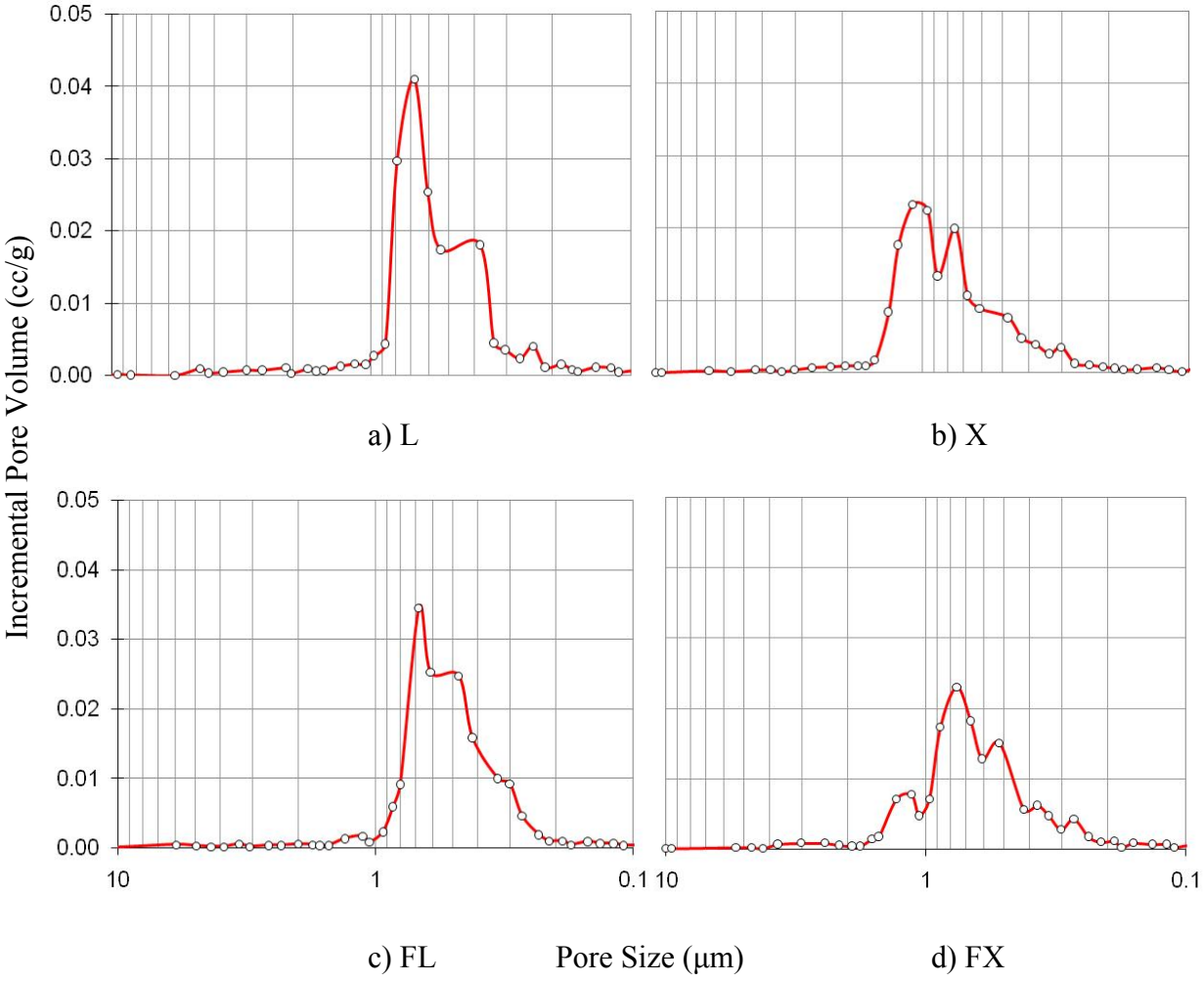

Figure 7: Pore Size Distribution of Specimens a) L, b) X, c) FL, d) FX by MIP

The porosity of the specimens can be used to estimate the durability according to the Maage durability index [5]. According to the index given by Maage in Equation 1, where PV is the intruded pore volume, and P_3 is the percent pores in the intruded pore volume with a diameter greater than 3µm, a value greater than 70 will indicate a durable specimen, while a value below 55 is non durable. According to Table 4, none of the specimens would be expected to be durable in freezing and thawing with respect to their pore distribution. The index values indicate that specimens X, L, FX, and FL would have similar freeze-thaw durability; however, the testing yielded different results.

$$F_c = \frac{22}{PV} + 2.4 * P_3 \quad (1)$$

Table 4: Maage Durability Index

Specimen	PV	P_3	F_c
L	0.180	1.933	22
X	0.173	2.870	25
FL	0.168	2.772	26
FX	0.169	3.186	27

According to the durability index, none of the specimens would be considered durable. The requirements of CAN/CSA-A82.1-M87 state that after 50 cycles of freezing and thawing, no individual brick may lose more than 0.5% mass, and no brick may break [6]. According to this standard, Figure 8 shows that only the specimens extruded and fired in the laboratory experienced failure when tested in water, while none failed in 3% NaCl. The pattern of mass loss did roughly correlate to the durability index given in Table 4, where those specimens with the lowest index lost the most mass. Recognizing that the small sample used may not be representative of the pore size distribution of the materials, the results should be interpreted as indicators or trends.

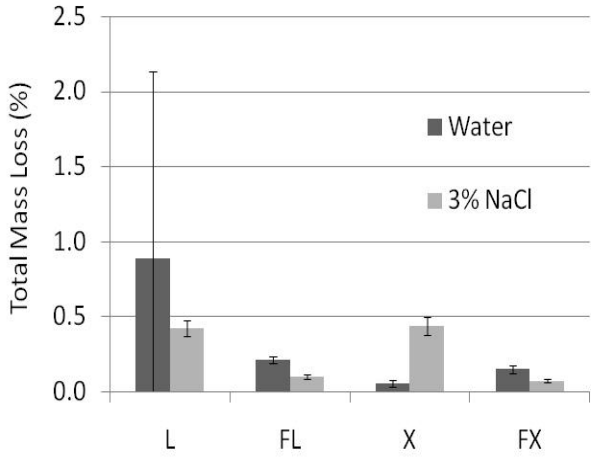

Figure 8: Percent Mass Loss at 50 Cycles of Freeze-Thaw Testing in Water and 3% NaCl Solution

When compared to the durability and porosity results, the C/B ratio appears to reflect the peak volume of pores, which happen to occur at a larger pore size in specimens L and FL, driving up the value of the C/B ratio. The lack of a balance between the large and small pores seems to impact on the durability. Ravagioli proposed a range of particle sizes which uniquely influence durability, where damage was most likely to occur in the range of pore sizes between 0.25μm and 1.4μm [7]. Since the pore size distribution for all of the specimens fell within this range, it cannot be established how the results relate to this theory.

DISCUSSION

The purpose of the tests selected was to assess the performance of the small scale laboratory specimens when compared to the large scale plant specimens in order to correlate the results of further testing carried out at the laboratory scale with expected results in the plant. In addition, it was of interest to identify the more influential of two factors, extrusion and firing, on the resulting strength and durability properties. Regression analysis detailed elsewhere was used to establish the importance of production location [8].

Overall, specimens extruded and fired in the laboratory experienced a decrease in average compressive strength. There was an increase in both the initial rate of absorption and the C/B ratio for specimens produced in the laboratory. When tested in deionized water and 3% NaCl solution for freeze-thaw durability, the specimens produced in the laboratory experienced a much greater mass loss than those specimens produced in the plant. Analysis of the pore structure resulting from the two production methods indicated that laboratory production led to a narrower pore size distribution and an increase in overall porosity. The influence of both extrusion and firing location is not always clear in the results; however the two were statistically similar.

The influence of production method on initial rate of absorption was evident in both extrusion and firing location, where laboratory extrusion and firing led to increased absorption. Porosity and pore size distribution are expected to affect initial rate of absorption however the pore size distributions show that the firing location is significant.

The durability of the specimens was found to be highly related to extrusion method when testing occurred in 3% NaCl, where specimens extruded in the lab experienced higher mass loss. When tested in water, the firing location became the most influential factor.

CONCLUSIONS

A comparison of the methods of production on the absorption, strength, durability and porosity of fired clay brick finds that the results of tests performed on small scale specimens can be expected to be conservative for all properties. Laboratory extrusion followed by firing in the plant kiln may provide more comparable results while still addressing storage and size concerns associated with full scale testing, however this method may still give conservative results, especially with respect to durability testing in sodium chloride solution. This study could not evaluate the effect of the specimen size solely due to restrictions in the equipment available; therefore, it is difficult to make any conclusion. None the less, it is evident that the equipment used to extrude and fire the laboratory specimens must use the same technology as that used in the plant if one is to expect specimens of similar properties.

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