WATER PERFORMANCE OF VENEER WALLS

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ABSTRACT
The hypothesis that will be tested in this project is whether it is possible to reduce the thickness of masonry cladding or redesign masonry units to be lighter and use less material and still maintain acceptable durability and water penetration performance. According to the Canadian masonry standard S304.1, the minimum thickness of exterior veneer wall is 90 mm for non-engineered walls. This project will focus on issues of durability and resistance to water penetration of wind-driven rain and will specifically investigate the impact of changes in thickness on water penetration into the wall cavity. More specifically it will focus on 89 mm and 76 mm deep units with different void configuration. The increase in water penetration should not be an issue with the rain-screen principle, but it means there is an additional demand on the water resistance of the backup system and primarily on the drainage from the cavity. The drainage provisions are already rather demanding and very much dependant on the workmanship. This paper will report results of 42 tests of veneer walls in accordance with ASTM E 514, and extensive testing to determine properties of clay bricks used in this study. Parameters such as wind pressure and amount of rain will also be addressed.

KEYWORDS: clay brick, veneer wall, water penetration, water absorption

INTRODUCTION
The series of tests reported on below was carried out in response to the hypothesis that it is possible to reduce the thickness of masonry yet still maintain acceptable durability and water penetration performance. The need for testing is in response to the current standard S304.1-04, which does not allow the use of bricks less than 90 mm thick in non-engineered applications.

This paper focuses on issues of resistance to water penetration and durability, and specifically investigates the impact of changes to veneer thickness on water penetration into the wall cavity and water absorption by the wall. The increase in water penetration should not be an issue in the rain-screen design, although it will result in an additional demand for water resistance from the backup system and for drainage from the cavity.

Other benefits from this change will include reduction in embodied energy and decreases in the attachment forces of veneer to the structural support for seismic loads resulting from the reduced weight. Lighter units will facilitate easier handling by masons and will decrease loads on lintels and scaffolding. However, there are a number of potential disadvantages besides loss of strength and increased water penetration: namely the reduction in thermal mass and R-value, sound transmission, fire resistance, and stability.

LITERATURE REVIEW – TESTING

The testing of water penetration through masonry veneer wall has been standardized by ASTM in E 514 – 09 *Standard Test Method for Water Penetration and Leakage through Masonry*. It provides an excellent framework for the design of the testing chamber and the selection of the equipment. The standard defines the specimen size (1.08 m^2 test area), the method of water delivery (one sprinkler pipe delivering 149 litres per hour (2.3 litres/m^2/min)), the pressure difference (50 Pa), and the test duration (four hours).

Another standardized test method has been developed by ASTM E331-96 *Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference*. Its principle is very similar to the masonry test; however, air pressure maintained across the test surface is a much more important variable, and it consists of smaller tests samples with a shorter test period of 15 minutes (as opposed to the four-hour duration for the proposed testing). Water pressure for the test standard is set at a higher rate of 3.4L/m^2/min and water is sprayed from a grid pipeline system instead of a single pipe.

The review indicated that besides the ASTM tests, researchers varied the parameters and the testing protocol to study impact of wind-driven rain on masonry veneer walls. More recent tests at Concordia [1,2] studied wetting patterns and needed to consider surface absorption of materials and vapour diffusion. These tests require more sophisticated instrumentation, using analogue data acquisition as well as ability to monitor the weight of the specimen during the testing.

LITERATURE REVIEW – WATER PENETRATION THROUGH MASONRY WALL

The interest in water penetration through masonry wall and its impact on wall performance began around the 1930s, intensified in 1950s and ’60s with the significant increase in housing construction, and became even more significant with the adoption of rain-screen principles. The test were performed by the US National Bureau of Standards [3] and similarly in Canada [3,4], Great Britain, France, Germany, and South Africa. During rain storms, moisture can penetrate through the masonry veneer as the external pressure is greater than the pressure in the cavity.

From the literature review, it can be concluded that there are various factors that affect the water penetration performance. These factors include physical properties of brick (thickness, material, void area), width and type of mortar joints, IRA, bond formed between brick and mortar, workmanship, air pressure, and flow rate.

Thomas Hines [5] concluded that neither the brick unit nor the mortar are responsible for leakage. The water penetrates through the wall mainly along hair line cracks typically present between the mortar and the unit. Similarly Sandra Roller [6] stressed that the performance of masonry wall depends on bond, and quality and type of joints. She was particularly concerned about the head joints, as she observed that most of the leakage occurred through these joints, and about the importance of tooling of joints. Both agreed that the IRA of clay units, mortar type, and workmanship are controlling the performance of a masonry wall. Roller also investigated the effect of wind pressure on water penetration. She conducted this by using another test method called the Rilem tube method in addition to the ASTM E514 to compare the variations in water leakage. It was concluded that, in general, increased pressure resulted in increased water penetration. It was also observed that the effects of pressure were more pronounced in panels with lower-quality workmanship, such as use of dry mortar, moving of brick once it was laid, etc. From retesting these walls, Roller noticed that the results were not static, as various factors could differ among tests. The points that showed leakage in one test did not show leakage in subsequent tests. The leakage rate, wetting patterns, relative order of leak appearance, and point of origin changed with different tests and could not be predicted.

Straube and Burnett's [7] study came up with important conclusions on the performance of masonry walls subjected to driving rain penetration. Firstly, all brickwork can be expected to absorb the majority of driving rain initially. Secondly, once saturated, a significant portion of imposed driving rain will penetrate through the veneer. Thirdly, almost all the penetration rates are in the range of 1 to 3 $L/m^2/hr$, and lastly, the application rate does not play a strong role in penetration but strongly affects the time for the wall to saturate. In addition, rain penetration at the bottom of the wall is always higher, and temperature variance has a high impact on drying times. Straube and Burnett's study concluded that the following four important elements contribute to how water behaves on a surface of a building: the rate at which water is deposited, the amount of moisture accumulated on the surface, the duration of the water deposition, and any previous wetting and drying history of the cladding.

A study by Sanders [8] on the effect of void area on wall system performance determined that an increase in the void area of brick masonry units did not significantly affect moisture penetration. Also, a reduction in face shell thickness did not appear to negatively affect flexural bond strength or moisture penetration. Sanders and Brosnan [9] investigated seven sets of bricks from seven different manufacturers. These bricks were of varying physical properties (i.e., material, void area, and dimensions). Flexural bond strength and compressive strength tests were conducted to determine physical properties of brick walls, which would then be used to compare water penetration test results of different kinds of bricks. From the tests it was concluded that increasing void volume or decreasing the face shell thickness did not have any major effect on water penetration and flexural bond strength. Sanders tracked an account of the mortar consumption during the wall construction. He found that increasing the void area percentage from 25% to 31% increased the mortar consumption by 17% due to mortar falling into voids.

El-Dakhakhni [10] conducted a series of water penetration and leakage tests on brick veneer test panels. During testing, water was observed leaking from cracks in the mortar and water was often observed to bubble from cracks in the mortar. El-Dakhakhni (2011) mentioned that water would drip and bubble from the mortar while the brick appeared dry. Ou (2011) found that water would appear in the mortar and run down the brick test panel before the brick appeared wet from penetration through the brick itself.

TESTING – MASONRY UNITS

This study involved four types of bricks. All brick samples (five bricks of each type) were measured, and the volume of voids was determined. Table 1 gives dimensions and percentage of voids for all brick types used in this study. The general range of results is in agreement with information provided by manufacturers; the maximum variation is less than 5%. Other tests on individual bricks were to determine their absorption characteristics. ASTM C67: *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile* sets the framework for the IRA test, which was followed for the brick specimens used in this research. The IRA test is a short-duration test (one-minute absorption) and is based on absorption into the bed area of the brick. This test is important to predict the potential quality of the bond between the unit and the mortar. An absorption coefficient assessment by means of partial immersion of the brick face was also investigated. The method employed in this experiment is in accordance with the International Standard ISO 15148: *Hygrothermal Performance of Building Materials and Products – Determination of Water Absorption Coefficient by Partial Immersion*. This test describes longer-term characteristics (24 hours) of units and identifies when saturation point is reached. The fundamental difference between the two tests is the submerged surface: the IRA test uses bed area while the absorption coefficient test uses face area. For all these tests, five specimens of each brick type were tested. Table 2 summarizes the results.

Table 1: Physical Properties of Brick Samples

Brick	Weight	Length	Width	Height	Void Area	Contact Area	Void Volume	Net Volume	% of Voids
	kg	cm	cm	cm	cm^2	cm^2	cm^3	cm^3	%
Type A	2.57	25.60	8.96	8.00	52.74	204.80	421.92	1413.1	22.99
Type B	2.07	25.70	7.46	8.00	45.45	205.60	364.32	1169.5	23.75
Type C	1.38	18.96	8.94	5.62	37.65	106.56	211.62	741.02	22.21
Type D	2.19	24.92	7.52	7.00	24.61	174.44	172.27	1139.5	13.13

TESTING – WALL SPECIMENS

Wall specimens were made from the above brick units following ASTM E514 recommendations. A standard 90mm thick clay brick wall specimen of brick types A and C and a thinner 75mm clay brick specimen of brick types B and D were constructed. Test wall specimens of types A and B bricks measured 6 units long (1.602m) by 16 units high (1.424m). Test wall specimens of types C and D brick specimens measured 8 units long (1.582 m) by 21 unit high (1.376 m) and 6.5 units long (1.634 m) by 18 units high (1.438 m) respectively. The exposed area of the wall inside the test chamber is approximately 1.14 m^2; the surface area of the wall outside the test chamber was parged using the same mortar mix as for the masonry joints. The parging results in a flat surface, which allows for better seal and helps to reduce water penetration outside of the test chamber. Mortar was mixed from pre-bagged mix for type N for all brick walls. Wall specimens of brick types A and B were also constructed using type S mortar. Mix proportions were as recommended by the manufacturer. A qualified mason was used to lay bricks in order to ensure that workmanship of the tested specimen is similar to the quality of walls on construction sites. Mortar sample cubes for quality control (compression test) were taken in accordance with CSA A179-04 and ASTM C67. According to CSA A-179, the minimum strength for type S is 12 MPa and 5 MPa for type N. All mortar cubes tested exceeded these minimum values except one cube of S-type mortar (used for one-third of joints in A3 and B2). Absorption test results for mortar are given in Table 2.

One objective of the overall research about water penetration through brick veneer was to identify whether bond strength between mortar types and different brick types has an impact on the amount of rainwater penetration in masonry veneer. The methods performed in this experiment are in accordance to the ASTM Standard E518: *Standard Test Methods for Flexural Bond Strength of Masonry*, third-point loading test. Five brick prisms were constructed for each brick type as recommended by ASTM E518. (See Table 3.)

Table 2: Absorption Test Results

Brick/Mortar Samples	**Water Absorption Coefficient**	**Initial Rate of Absorption**	
	$g/m^2/s^{1/2}$	$g/min/193.55\ cm^2$	$g/m^2/min$
Brick Type A	23.0	13.16	679.93
Brick Type B	70.6	36.55	1888.4
Brick Type C	55.6	20.84	1076.72
Brick Type D	113.3	33.76	1744.25
Mortar Type S	29.4	–	–
Mortar Type N	46.2	–	–

Table 3: Specifications and Results of Flexural Bond Strength Test

Sample	Mortar Type	No of courses	Length	Width	Depth	Weight	Max. Load	Modulus of Rupture
			mm	mm	mm	N	N	N/mm^2
Type A	S	7	620	256	90	235.8	230	0.185
Type B	S	7	620	257	75	192.4	Failed prior to testing	
Type C	N	10	650	189	90	192.4	335.9	0.2
Type D	N	10	790	249	75	245.8	219.05	0.265

The wall test panel is shown in Figure 1, and the test chamber attached to the wall specimen is shown in Figure 2.

RESULTS

Table 4 summarizes tests carried out on wall constructed of four different clay bricks. When results are presented, the labelling from Table 4 will be used. All tests carried out on walls from four different unit types using type N mortar are presented in Figures 3 and 4, representing water that penetrated through the wall and water that was absorbed by the wall respectively.

Figure 1: Wall Sample

Figure 2: Wall Sample with Attached Test Chamber

Table 4: Summary of All Water Penetration Tests

TEST	Brick A			Brick B			Brick C			Brick D			Mortar Type	Pressure in Pascals	Flow Rate in l/hr	Date
	1	2	3	1	2	3	1	2	3	1	2	3				
I	✓	✓	✓	✓	✓	✓							N	500	155	July, Aug. 2008
II	✓	✓	✓	✓	✓	✓							N	500	155	July, Aug. 2010
III	✓	✓	✓	✓	✓	✓							N	120	155	Aug. 2010
IV	✓	✓	✓	✓	✓	✓							N	500	78	Aug. 2010
V[1)]		✓ ✓			✓ ✓								N	500	155	Aug. 2010
VI	✓	✓	✓	✓	✓	✓							S	500	155	Sept., Oct. 2010
VII							✓	✓	✓	✓	✓	✓	N	500	155	Sept., Oct. 2010

1) The initial water penetration test on dry wall was followed with two tests shortly after.

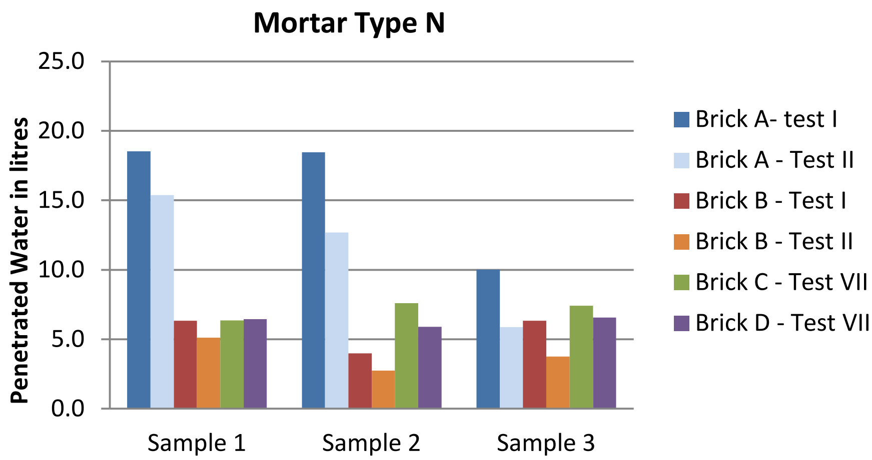

Figure 3: Penetrated Water in Litres

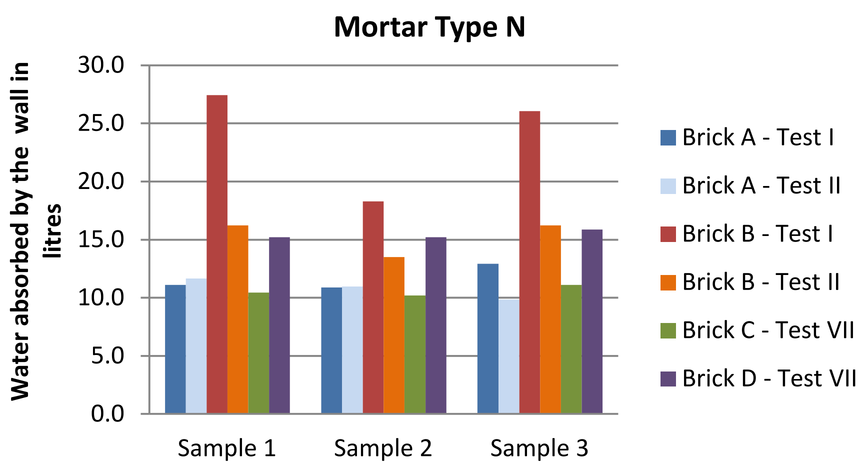

Figure 4: Absorbed Water in Litres

Brick type "B" test series II gives consistently lower water absorption than series I. There is no obvious explanation for this discrepancy; it could be due to a scale error. Indeed, it was identified that when battery power is low, readings are not accurate. However, the consistency of all three wall samples showing the same trend would not support the above argument. Series I results for water absorption were ignored from the results summarized below. The average values of all wall tests carried out on each type of brick are arranged in bar charts shown in Figures 5. It can be concluded that water that penetrated through walls made of type "A" brick is 15 litres, which is almost three times more than for brick type "B" walls (4.7 litres). Type "C" and "D" brick walls allowed 7.1 and 6.3 litres respectively to penetrate through the wall. This would indicate that the decrease in wall thickness does not impact the water penetration through the wall. Two thinner walls ("B" and "D") allowed less water penetration than did the standard veneer walls. The water absorbed by thinner walls "B" and "D" (15.3 and 15.4 l itres respectively) is significantly greater than for standard wall types "A" and "C" (11.2 and 10.6 litres).

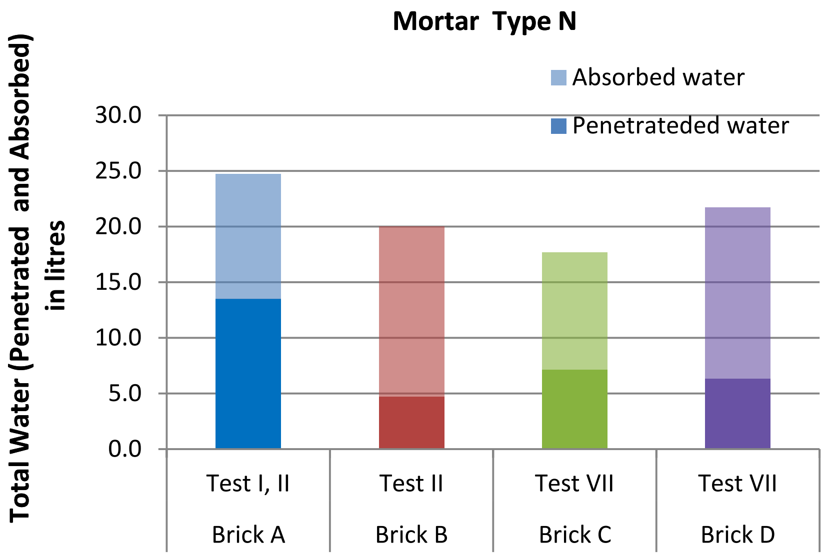

Figure 5: Average Values of Total Water (Penetrated and Absorbed by the Wall)

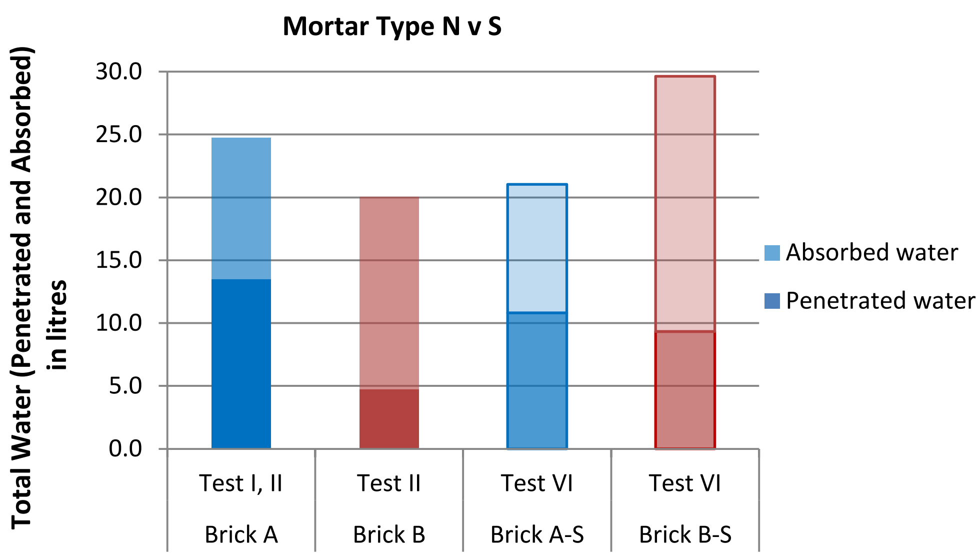

Figure 6: Average Total Water for Wall A & B – Comparing Mortar Type N v S

To investigate the impact of mortar type on bond and resistance to water penetration, brick type A and B wall specimens were constructed using S-type mortar. Figure 6 compares mean results of test series I and II with N-type mortar and test series VI with S-type mortar. The mortar type does not impact the water absorption of the wall. It should be noted that walls of B type brick with S-type mortar exhibited again higher absorption, similar to Test I results. Mortar type S resulted in 30% decrease in the water penetration of type A brick walls. On the other hand S-type mortar resulted in 100% increase in water penetration for brick B walls. It appears that the combination of IRA and mortar may be responsible for this change. Type A brick has 2.75 smaller absorption that type B brick. Higher strength mortar seems to develop better bond with brick of low IRA hence leading to the reduced penetration. The opposite is true for the brick B.

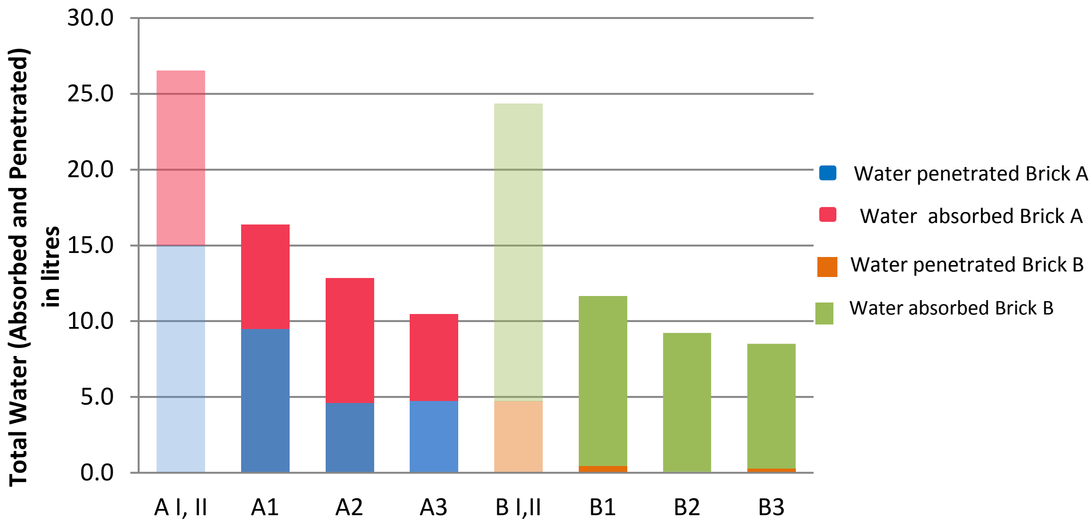

Figure 7: Brick Type "A" and "B" Test Results at 120 Pa Chamber Pressure

The ASTM E514 test calls for the standard wind pressure of 500 Pa. Although this pressure is likely to occur under gusty conditions without a chance for pressure equalization, it will not be consistent over the period of four hours as the test prescribes. For example, the design wind pressure for low-rise buildings in Toronto (Toronto being a very windy place) is 400 Pa pressure and 300 Pa suction on the areas away from building's corners. Therefore it was decided to explore in test series III the impact of reduction in the pressure simulating wind-driven rain, while keeping the prescribed flow rate. In this case, a pressure of 120 Pa was used. The results shown in Figure 7 compare to average values for brick A and B from tests I and II as compared to test at 120 Pa chamber pressure. As expected, the water penetration through both brick types A and B tested with reduced pressure in the test chamber showed significant decrease in both, water absorption and penetration. Walls of type B brick allowed very little water to penetrate (0.27 litres) and type A brick showed 58% reduction. The fact that there is such low water penetration through brick B walls may indicate that the crack width along bed joint may have a significant impact on water penetration.

The ASTM E514 test requires delivery of water at a rate corresponding to hourly accumulation of 138 mm per square meter. This significantly exceeds values in the NBC for one hour of rain (about 100 mm). The test series IV explores the impact of reduction in the rate of water delivery to 78 l/hour. The results of these tests are summarized and compared to the average values for brick A and B from tests I and II in Figure 8. These tests indicated that halving the rate of water delivery results in significant decrease in water penetration for both walls, 45% and 72% for brick walls A and B respectively. The reduction in water absorption is much smaller, 15% and 20% for brick walls A and B respectively.

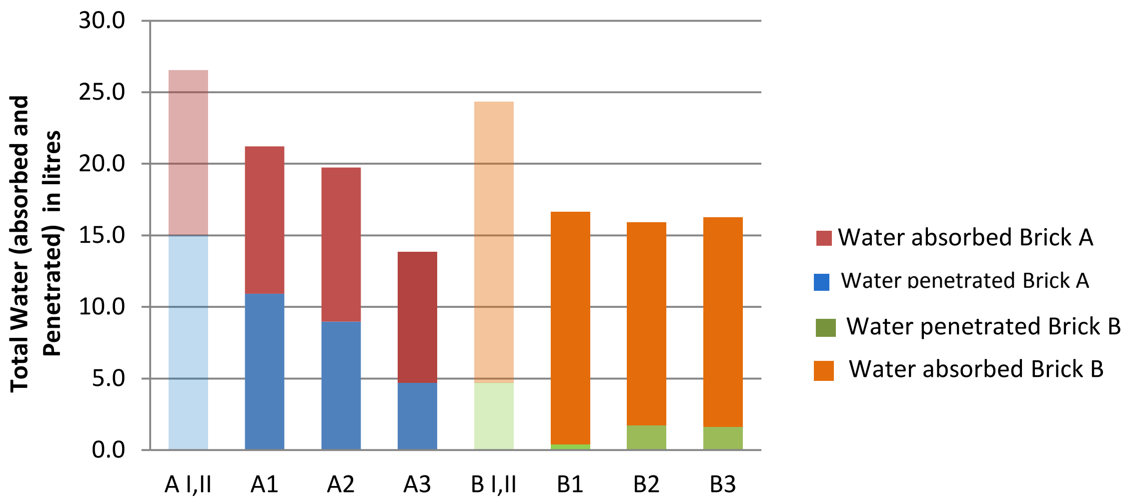

Figure 8: Brick Type A and B Test Results for Water Tate of 78 l/Hour

Table 5: Summary of Results

	IRA in g/m²/min		ASTM 514 test results		ISO 15148
			Water Penetrated in litres	Water Absorbed in litres	4hours absorption in litres
Brick A wall	679.93	Test I, II Test III	13.490 6.3	11.231 6.9	4.122
Brick B wall	1888.4	Test I, II Test I Test III	4.719 3.883 0.3	19.623 15.317 (II only) 9.5	10.765
Brick C wall	1076.72	Test VII	7.130	10.584	8.620
Brick D wall	1744.25	Test VII	6.307	15.422	14.505

CONCLUSIONS

It has been reported by others that there is a significant variation among test results of walls made of the same brick. It also has been confirmed that repeating the same tests using the same equipment and methodology does not lead to exactly the same results. McMaster test used brick type C, and they too observed the significant variation between the tests within each group. However, it is important to note that their average amount of water that penetrated wall C was 7.015 litres, which agrees with 7.13 litres measured in the reported tests.

When comparing the water absorbed by the wall with four-hour absorption under static conditions (ISO 15148), it should be noted that walls of brick type C and D are 23% and 6.5% respectively higher (see Table 5). Similar absorption can be observed for walls of brick type A and B, especially results from reduced pressure tests (Test III). (See Table 5.) ASTM tests indicate increase in water absorption due to water penetration through the masonry beyond the capillary action of partly submerged units, which are measured by the ISO 15148 test. It should be noted that the back of the test area was completely or significantly wet when tested at 500 Pa.

Brick types B and D, which are thinner, are close to saturation in four hours, while types A and C are absorbing water over 24 hours. This explains why walls of brick B and D absorb water like a sponge and allow for very little water to penetrate.

Four bricks, standard A and C and thinner B and D types, all meet the requirements for severe exposure but seem to be at the opposite ends of the acceptable range as set in CSA standards. Common to all water penetration tests is the appearance of wetness on the back of the wall one to two minutes after the commencement of a water penetration test. It appears that the mean total water (i.e., penetrated and absorbed) is significant. It varies from 15.4 $l/m^2/4$ hr (C brick) to 23.0 $l/m^2/4$ hr (A brick) with B and D brick in between. This leads to the conclusion that the amount of water absorbed and penetrated is similar for all tested brick types, and it is significant. Either water has to be drained from the cavity or the wall has to be allowed to dry. The units with low absorption and low IRA (type A) seem to experience a problem with the bond between the unit and the mortar and result in greater penetration. The use of type S mortar seems to improve the bond.

From the durability point of view, smaller absorption is better for severe environments with many freeze/thaw cycles during each winter. The results of the study investigating issues related to water penetration from wind-driven rain for four different brick types indicate that the thickness of veneer wall did not seem as important a variable as the properties of the products and workmanship specifically related to bond between the clay unit and mortar. It can be concluded that the thickness of clay brick veneer does not significantly impact its response to wind-driven rain.

ACKNOWLEDGEMENTS
The author acknowledges financial support of the CMHC through its external research program. The author is grateful for in-kind support of Ryerson University, Hanson Brick, Brampton Brick, and Ontario Masonry Contractors' Association. The author acknowledges participation of her colleague Dr. Mark Gorgolewski and students Hannah Thevapalan, Richy Szeto, Susan Benjamin, Galen Ou, and Benjamin Listerman.

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