Materials and Structures/Matériaux et Constructions, Vol. **34**, August-September 2001, pp 438-445

TECHNICAL REPORTS

Sorptivity: a reliable measurement for surface absorption of masonry brick units

M. M. Reda Taha[1], A. S. El-Dieb[2] and N. G. Shrive[3]

(1) Stantec Consulting Ltd , Calgary, Canada, T2R 1M1

(2) Structural Engineering Department, Ain Shams University, Cairo, Egypt

(3) Department of Civil Engineering, The University of Calgary, Calgary, Canada, T2N 1N4.

Paper received: July 27, 2000; Paper accepted: January 9, 2001

ABSTRACT

An inherent weakness of masonry structures is low bond and bond strength. Although masonry bond is a result of many interrelated factors (*e.g.* surface texture, surface absorption and mortar composition, etc.), surface absorption of masonry units has a significant effect on masonry bond. Following a critical review of the current measurements of the surface absorption of masonry units, the theoretical bases of sorptivity as a measurement of surface absorption are presented. The limitations of sorptivity measurement are discussed through a review of the application of the concept of sorptivity to different porous building materials. An experimental programme to examine the surface absorption of masonry units is described. Analysis of the results showed sorptivity to be a simple and reliable measurement of surface absorption for masonry units that could be used in building standards.

RÉSUMÉ

L'une des faiblesses inhérentes des ouvrages en maçonnerie réside dans le manque de lien et le manque de solidité du lien. Malgré le fait que le lien de maçonnerie soit le résultat de plusieurs éléments mis en corrélation (par exemple, l'état de la surface, le degré d'absorption de la surface, la composition du mortier, etc.), le degré d'absorption de la surface des unités de maçonnerie a un effet important sur ce lien. À la suite d'un examen critique des méthodes actuelles de mesure du degré d'absorption de la surface des unités de maçonnerie, les bases théoriques de la sorptivité comme méthode de mesure du degré d'absorption de la surface sont présentées. Les limites de la mesure de la sorptivité sont discutées en réexaminant l'application du concept de sorptivité à divers matériaux de construction poreux. Un programme expérimental ayant pour but d'examiner le degré d'absorption de la surface des unités de maçonnerie est décrit. L'analyse des résultats a démontré que la sorptivité est une méthode simple et fiable de mesure du degré d'absorption de la surface pour les unités de maçonnerie, et devrait être introduite dans les nouveaux codes de construction des bâtiments.

1. INTRODUCTION

Good interface bond between the masonry unit and mortar constitutes an important criterion for any masonry structure. Factors affecting the interface bond include, mortar composition, mortar water retentivity, unit surface texture, unit moisture content and unit surface absorption. The latter has a major role in the development of masonry interface bond as explained by many researchers and reviewed in detail by Goodwin and West [1]. Masonry bond is primarily achieved by mechanical interlocking of cement hydration products growing in the masonry pores on the brick surface and connected to the mortar matrix [2]. Water absorption can significantly affect interface bond strength because it determines, in conjunction with mortar retentivity, the amount of water transmitted from the mortar to the brick. This in turn controls the degree of hydration of the mortar and the amount of hydration products that will be transported and deposited in the masonry pores [3]. This interplay was demonstrated by quantitative analysis of the amount of Ettringite in the masonry-mortar interface and its relation to the masonry unit absorption criteria [4].

Water suction in masonry units represents a restrained water movement through which capillary forces, chemical binding forces and physical adsorption forces affect water movement. Numerous trials were carried out to explain the basis of water suction of masonry units and its

Editorial Note
Dr. Mahmoud M. Reda Taha is a RILEM Affiliate Member.

role in the development of bond between unit and mortar. Early studies by Voss [5] recommended the use of 48-hour total absorption time to represent water absorption of masonry units. Anderegg [6] noted the importance of knowing the rate of absorption rather than the total amount of water absorbed and showed how early water absorption affects mortar hydration and consequently bond strength. The initial rate of absorption (IRA) is therefore used as a measure of initial brick suction.

IRA measures the weight of water absorbed in 1 minute by the bed face of the brick unit when immersed in 3 mm deep water. Using the unit's IRA and the water retentivity of mortar, it is possible to select combinations of mortar and brick type to achieve good bond. There is considerable difference between the IRA of clay bricks and concrete blocks and this has been attributed to the ability of the pores of the materials to exert capillary suction forces over a short time period [7].

Extensive research work has been aimed at relating IRA to masonry bond strength in order to recommend limits for IRA to guarantee an acceptable level of bond strength. McGinley [3] showed that there is a range of optimum IRA to obtain the highest bond strength. IRA values lower and higher than this range are expected to reduce bond strength. Lawrence and Cao [8] came to a similar conclusion after showing that there is a limit beyond which increasing IRA results in reducing bond strength. This is because low IRA will not allow enough hydration products to migrate towards the unit surface, while high IRA will reduce the degree of hydration and the amount of hydration products deposited in the pores of the unit. High IRA will also induce shrinkage cracks that will weaken the masonry/mortar interface.

The applicability of IRA is questionable as different pore distributions with different water flows may result in the same IRA values [9]. Although it is true that the first few minutes have a significant effect on the amount of water transfer from the mortar to the unit, the process does not stop completely until the cement sets. The one minute time is an arbitrary choice. Thus while many researchers have correlated bond strength to IRA, there are usually limitations to these correlations [7, 10]. Hence, the debate as to whether IRA or total water absorption is the more useful measure has been going on for more than 60 years. While the Australian and the Canadian standards indicate IRA can be a useful indicator for bond strength, the British standard considers the total water absorption to be more suitable than IRA. Both measurements showed different limitations in judging the absorption performance of brick masonry units. A reliable engineering measurement that can accurately describe the absorption performance of brick units within the critical period of bond development is still required. Sorptivity may be such a measure.

2. THE THEORY OF SORPTIVITY

Sorptivity is a material property that describes the tendency of porous material to absorb and transmit water by capillary suction. The application of the sorptivity principles to masonry units and the interpretation of experimental data require some understanding of the theoretical basis of unsaturated flow and its physical limitations. Hence, a brief explanation of the theory of sorptivity follows [11 and 12].

2.1 Theoretical basis

The energy form of any saturated flow is governed by Equation (1):

$$\Phi = \Psi + Z \tag{1}$$

where Φ is the total hydraulic potential, Ψ is the non-gravitational hydraulic potential including capillary suction and Z is the gravitational potential. Defining K as the hydraulic conductivity and u as the flow velocity then:

$$u = K\nabla\Phi \tag{2}$$

Neglecting the effect of gravitational potential, Equation (2) can be re-written as:

$$u = -K\nabla\Psi \tag{3}$$

Extending Darcy's equation to unsaturated flow by considering $K(\theta)$ as the moisture content dependent hydraulic conductivity gives:

$$u = -K(\theta)\nabla\Psi(\theta) \tag{4}$$

where θ is the moisture content. The boundary conditions of θ equals θ_1 at saturation and zero for oven dried samples. Defining the hydraulic diffusivity $D(\theta)$ as:

$$D(\theta) = K(\theta)\left(\frac{d\Psi(\theta)}{d\theta}\right) \tag{5}$$

simplifies Darcy's equation for unsaturated flow [11 and 12] to:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(-D(\theta)\frac{\partial\theta}{\partial x}\right) \tag{6}$$

Philip [11] solved Equation (6) using the Boltzmann transformation:

$$x = \phi(\theta)t^{-1/2} \tag{7}$$

The differential equation of unsaturated flow thus becomes dependent on the time function $\phi(\theta)$ as shown in Equation (8):

$$2\frac{d}{d\phi}\left(D(\theta)\frac{d\theta}{d\phi}\right) + \phi(\theta)\frac{d\theta}{d\phi} = 0 \tag{8}$$

The solution to this differential equation was introduced by Philip [11] who determined the integration of $\phi(\theta)$ as:

$$i = t^{1/2}\int_{\theta_i}^{\theta_1}\phi(\theta)\,d\theta \tag{9}$$

where i is the cumulative volume of water absorbed per unit volume.

$$i = \frac{\Delta Mass}{A \cdot \rho} \tag{10}$$

ρ is the specific gravity for water, A is the area exposed to the water and i is determined experimentally. Defining θ_1 as the saturation level and θ_i to be zero for oven dried specimens, the value of the integration can also be derived experimentally over any time period t. This integration is defined by Philip [11] as the "sorptivity" S as shown in Equations (11) and (12):

$$S = \int_{\theta_i}^{\theta_1} \phi(\theta) d\theta \tag{11}$$

$$i = S\, t^{1/2} \tag{12}$$

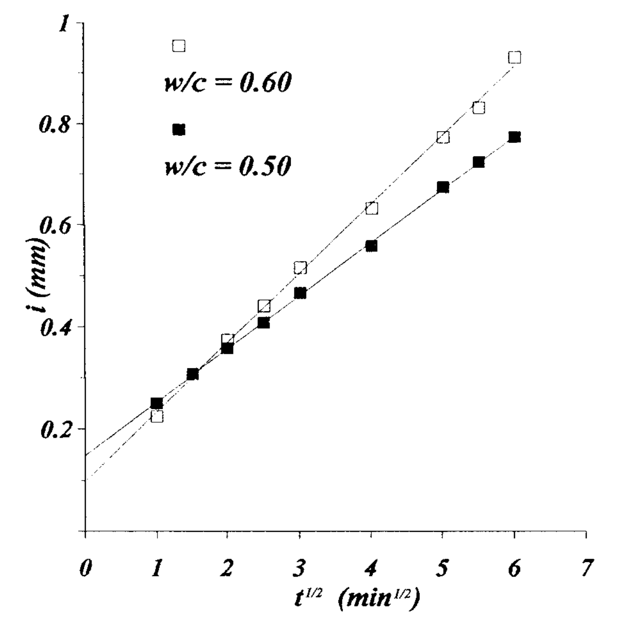

Fig. 1 – Typical sorptivity plot for two types of concrete [13].

The one-dimensional absorption of water is thus linearly related to the square root of time. The slope of the line, from a plot of the volume of absorbed water per unit area of suction surface versus the square root of the absorption time, as shown in Fig. 1, is used to define the sorptivity (S) of the material. The linearity of the relationship is checked by the value of the correlation coefficient of linear regression. If the value of the correlation coefficient (r) is less than 0.98 ($r^2 < 0.96$) the relation is considered not to be sufficiently linear and the sorptivity of the specimen should not be determined from those data. Sorptivity testing of different porous building materials showed the flow to be generally one dimensional, and the values of the correlation coefficient to be greater than 0.98 for all test time durations up to 8 hours [13]. The results demonstrate that surface absorption is directly proportional to the square root of time. Using the method of least squares, the data points produced a relationship as follows in Equation (13):

$$i = a + S\, t^{1/2} \tag{13}$$

The intercept (a) has a very low value. Hall [13] and Hall and Yau [14] attributed the existence of the intercept to the filling of the open porosity on the inflow surface.

2.2 Sorptivity applications to different building materials

In a different approach to examining the brick suction phenomenon Jansson [15] and Sneck [16] measured the rate of water suction for a period of time. They showed that straight line relationships between the square root of time and the rate of water absorption exist over time periods longer than the 1 minute commonly used for IRA. This pioneering work was the first showing IRA is not necessarily the most suitable measure of masonry surface absorption. Later, Morgan [7] showed that IRA is misleading when applied to calcium silicate bricks as the rate of water absorption of this type of brick changes significantly with time. In a series of publications in the late 1970s and through the 1980s Gummerson *et al.* [12] and Hall *et al.* [17-19] successfully applied the principles of water sorptivity developed for water transport in soils by Philip [11] to different porous building materials including brick units. In 1987, the sorptivity test was introduced as a test which measures the rate of capillary water absorption through dry or partially dry materials [14, 20]. Since then, the sorptivity test has been widely used to evaluate the effect of curing regimes on the different properties of concrete, as well as to evaluate the durability of concrete: sorptivity was found to correlate well with water permeability through concrete [13, 21-25]. Groot [26] showed that IRA represents only one point of a linear relationship between the square root of time and the rate of water absorption and proposed using the square root of time versus specific mass increase to measure water absorption of brick units. Examining water equilibrium in the interface using thermal neutron quantitative analysis, Groot [9, 26] proved that testing times of about 15 minutes rather than one minute are required to simulate water equilibrium in the masonry-mortar interface. Although sorptivity was shown to be a reproducible measurement with a reliable theoretical basis, it has not been proposed as a measurement for masonry absorption in any specification.

2.3 Sorptivity testing

The main reason for the wide use of the sorptivity test that it is an inexpensive, quick and simple one. ASTM Committee C09.03.12 Task Group on Permeability Testing drafted a standard sorptivity test method based on that of Hall [13] in 1996. Recalling Equation (11) for the definition of sorptivity, it is clear that sorptivity is dependent on the initial moisture content of the testing material. Therefore, correction factors to account for the difference between the initial testing moisture and the ideal zero moisture were introduced [18].

Recent research on sorptivity [27] has shown conditioning (*i.e.* drying) the test specimen to be a critical part of the test. If the specimens are randomly conditioned, the test results will be a function of the conditioning process rather than the material quality. Several conditioning methods have been examined for concrete [27]. Oven drying at 110°C was found to introduce microcracking which will influence the test results. Other methods of drying include; using a solvent replacement for 3 days followed by oven drying at 50°C for 4 days, oven drying the specimen at 50°C for 7days, or finally drying at 50°C for 3 days followed by placing the specimen inside a sealed container inside the oven for another 4 days. The reason for placing the specimen in the container is to redistribute the moisture in the specimen. The last method was found to yield moisture contents similar to those encountered in the field.

Drying the specimens to achieve a certain change in mass per day, such as 0.1%, rather than drying the specimen for a fixed period of time was found to yield more consistent moisture content such that conditioning does not become a variable [24]. Drying specimens through a fixed period will not achieve equal degrees of saturation or moisture content for different concrete qualities. High performance concretes (HPC) for example dry so slowly that they need long periods for conditioning [24].

Once the specimen is conditioned, the sorptivity test is conducted by placing one surface of the specimen in contact with water. Different test rigs to allow the uni-directional water flow through the specimen have been introduced by different researchers [13, 28, 29]. Fig. 2 shows a schematic diagram of the test configuration provided by ASTM draft [28]. The sides of the specimens are sealed with a bituminous coating or vinyl electrician's tape in order to have one-directional flow through the specimen. The mass of the specimen is determined at fixed intervals of time with the stop watch being stopped during each weighing.

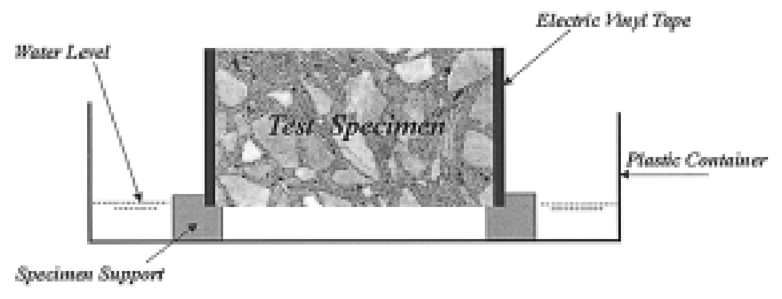

Fig. 2 – Schematic diagram of sorptivity test configuration [31].

3. EXPERIMENTAL WORK

3.1 Materials

Five different groups of masonry bricks were examined. The geometry and manufacturing processes are listed in Table 1.

Table 1 – Description of the examined brick units

Group	Type	Dimensions
A	Pressed units	190 x 90 x 57 - 3 cores (Φ 35 mm diameter)
B	Extruded units	190 x 90 x 57 - 10 cores (Φ 20 mm diameter)
C	Extruded units	190 x 90 x 57 - 10 cores (Φ 20 mm diameter)
D	Extruded units	190 x 90 x 57 - 2 square cores (40 x 40 mm) + 2 cores (Φ 20 mm)
E	Extruded units	190 x 90 x 57 - 10 holes (20 mm diameter)

3.2 Testing programme

The experimental programme included four different tests for masonry units. These are the initial rate of absorption test (IRA), the total water absorption test, the compressive strength test, and the sorptivity test.

3.2.1 Initial rate of absorption, total water absorption and compressive strength tests

All the specimens were dried in 110°C oven for 24 hours and then left to cool for the following 24 hours in dry conditions. The initial rate of absorption (IRA) test, the total water absorption test, and the compressive strength test were carried out in accordance with ASTM C 67 -86 [30]. Five dry units of each group were tested for each test.

3.2.2 Water sorptivity test

Water sorptivity tests were carried out using the guidelines provided by the ASTM draft [28] for measuring the initial rate of absorption of hydraulic cement mortars and concretes. The specimens used were the whole brick units. The specimens were oven dried in 110°C for different drying periods so that all the specimens showed similar change in mass per day (0.5%) and then the specimens were left to cool in dry conditions for the following 24 hours. The test was carried out by allowing one surface of the specimen to be in contact with water of 5 mm depth using a rectangular aluminum support with two side holes as shown in Fig. 2. Using the supporting frame and keeping the outside water level at 1-3 mm above the hole level allows continuous contact between the specimen surface and the water without changing the water depth during the testing time.

The sides of the test specimens were sealed with strips of electric vinyl tape to create uni-directional flow through the specimen. The weight of the specimen was recorded at fixed time intervals with a total time of 25 minutes. The time intervals used are provided by the ASTM draft [28] and are also recommended by other researchers [24, 29]. The timing device was stopped, the surface water was blotted off with a dampened cloth, the specimen weight was determined and the specimen was returned back to its place in the testing frame. The time of the weighing operation did not exceed 20 seconds for any specimen.

Table 2 – IRA, Total absorption and compressive strength brick units test results

Specimen	A	B	C	D	E
			IRA (gm/cm²/min)		
1	67.5	32.9	14	37.2	13.2
2	47	33.3	18	37	5.4
3	55.6	34.3	23.3	41.7	6.5
4	68.8	35.1	23.4	41.9	5.7
5	47.7	33.1	20	39.8	1.7
Average	57.3	33.7	19.8	39.5	6.5
Std. Dev.	10.5	0.9	4.0	2.3	4.2
			Absorption %		
1	7.1	9.7	6.5	9.2	6.7
2	6.6	7.8	6.6	9.6	8.5
3	6.4	7.9	7.2	9.4	6.5
4	7.6	8.1	7.0	9.3	6.3
5	6.7	8.1	6.8	9.8	6.4
Average	6.9	8.3	6.8	9.5	6.
Std. Dev.	0.5	0.8	0.3	0.2	0.9
			Compressive Strength (MPa)		
1	45.6	40.2	47.5	43.4	49.7
2	45.2	38.6	52.5	27.2	51.1
3	49.8	37.3	60.7	32.8	52.3
4	47.6	44.8	47.1	44.8	53.9
5	45.3	33.0	50.5	39.5	48.6
Average	46.7	38.8	51.6	37.5	51.1
Std. Dev.	2.00	4.32	5.55	7.44	2.09

4. RESULTS AND DISCUSSION

The test results for IRA, total water absorption and compressive strength are presented in Table 2. Although the IRA results show the pressed brick units (group A) to have the highest rate of surface absorption, less total water is absorbed. Unpublished research data examining the porosity of both extruded and pressed clay bricks did not show any significant difference in porosity or pore size distribution between bricks manufactured by the different methods.

The compressive strength results showed groups (B and E) to have the lowest compressive strength of all the groups and groups (C and D) to have the highest compressive strength. These four groups are extruded clay bricks. The wide scatter of the compressive strength of extruded clay bricks might be an effect of the manufacturing process on the direction of internal flaws. The direction and size of flaws can significantly affect the fracture toughness and strength of units. The extrusion process may align flaws with the direction of compression, whereas the pressing process would align flaws perpendicular to the subsequent compression.

The volume of water absorbed per unit area of the brick (*i*) is determined using Equation (13). (*i*) is plotted against $t^{1/2}$ and regression analysis performed for each specimen. The coefficient of correlation (*r*) was determined for each regression. As previously mentioned the validity of the method for regression is limited to correlation coefficients greater than 0.98 ($r^2 > 0.96$) [28]. This is because lower regression coefficients violate the assumptions of unsaturated flow conditions for the sorptivity measurement. Figs. 3 and 4 show the sorptivity graphs of all the tested masonry groups.

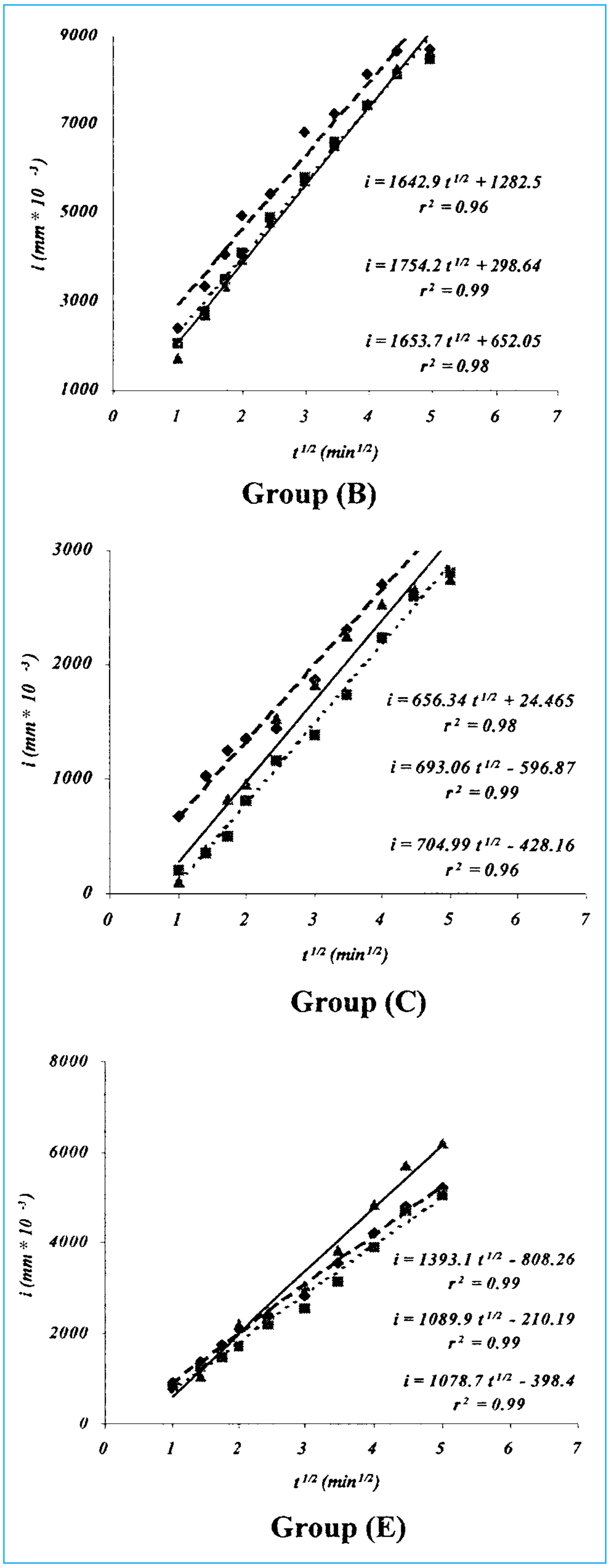

Fig. 3 – Sorptivity plots for masonry brick units (groups B, C and E).

Fig. 3 shows the typical sorptivity plot of masonry brick units as observed for groups B, C and E. The sorptivity plot of groups A and D are shown in Fig. 4 where

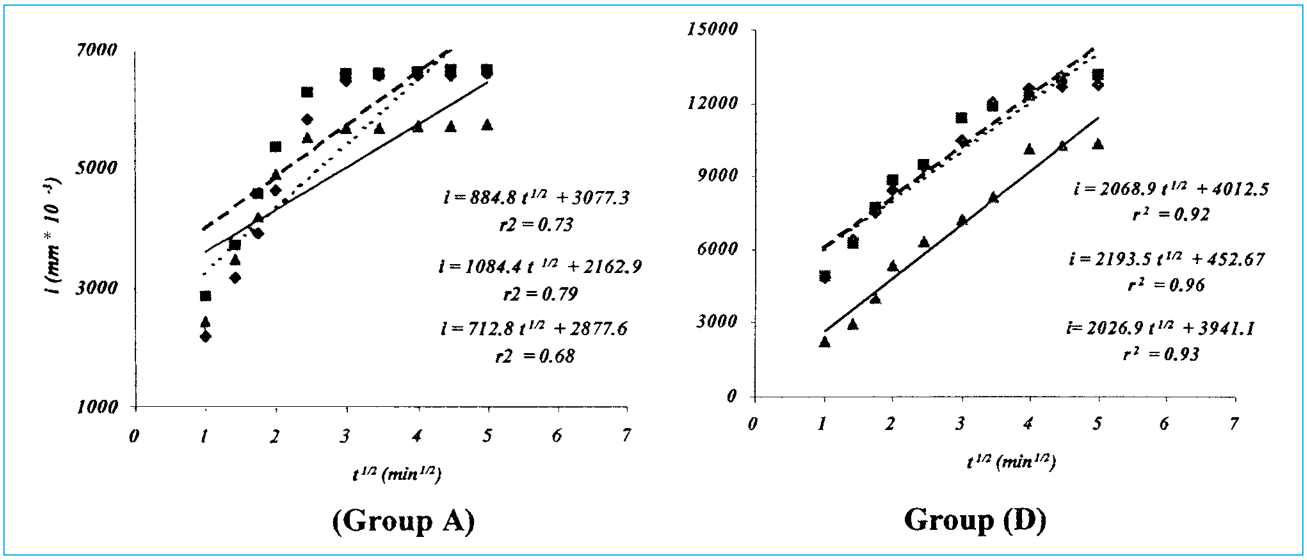

Fig. 4 – Sorptivity plots for masonry brick units (groups A and D).

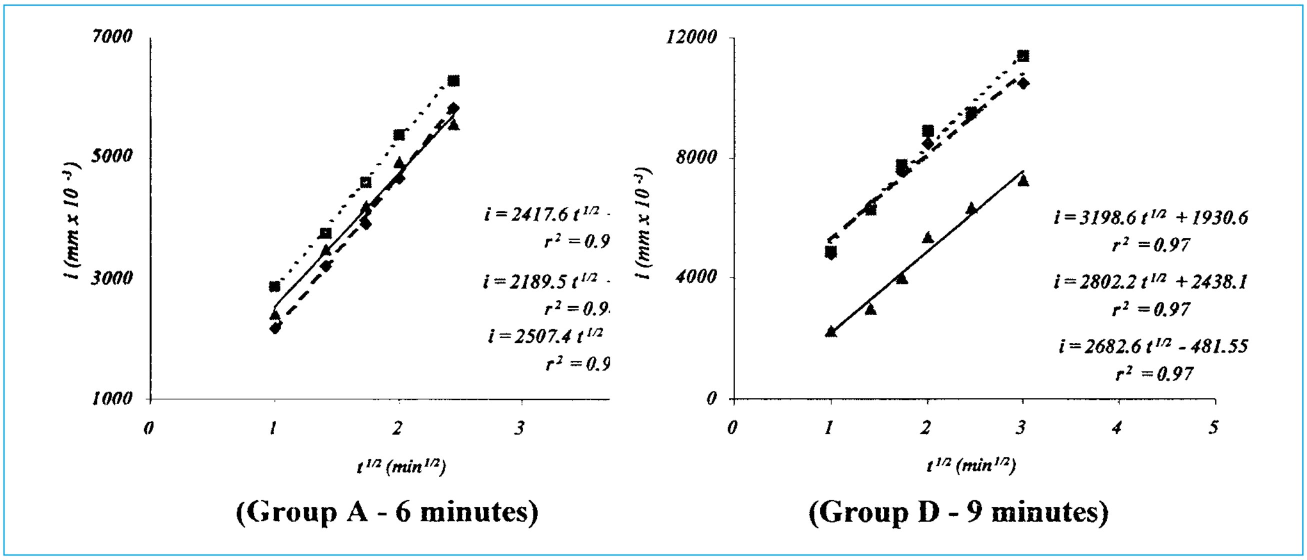

Fig. 5 – Modified sorptivity plots for masonry brick units (groups A and D).

the unsaturated flow conditions are not fulfilled over the total testing time. The bricks become saturated within the 25 minutes of the test and the curves flatten off. There is thus a low coefficient of correlation associated with linear regression. Therefore, the complete sets of data shown in Fig. 4 can not be used to calculate the sorptivity for groups A and D. The points constituting the horizontal portions of the curves must be removed so that an acceptable linear regression can be established with the sloping parts. A t_{total} must be found where t_{total} is the time to saturation. t_{total} was determined from repeated regression analyses, and found to be about 6 and 9 minutes for groups A and D respectively.

The data prior to these times meet the regression requirements. Data from groups A and D are plotted in Fig. 5 for the times up to saturation. These results reflect accepted practice for concretes where the sorptivity of concrete is frequently determined from the slope of the early time periods up to 9 minutes [28].

With the time adjustment above, the experimental data show sorptivity to be a reproducible measurement for masonry brick units with relatively low standard deviations. A comparison between the three surface absorption criteria of the brick examined showed some agreement between sorptivity and total water absorption. This comparison is shown in Table 4. On the other hand, the IRA gave a much different rank order. This

Table 3 – Sorptivity (S) of the brick units

Property	A		B		C		D		E	
t_{total} (mins)	6		25		25		9		25	
Water sorptivity (S)										
	S	r	S	r	S	r	S	r	S	r
1	2.42	0.99	1.64	0.98	0.66	0.99	2.8	0.98	1.09	0.99
2	2.19	0.99	1.75	0.99	0.71	0.98	2.68	0.98	1.39	0.99
3	2.51	0.99	1.65	0.99	0.69	0.99	3.2	0.99	1.08	0.99
Average	2.37		1.684		0.685		2.894		1.187	
Std. Dev.	0.165		0.061		0.026		0.27		0.178	

Table 4 – Comparing surface absorption criteria for the masonry groups in a descending order

Rank	1	2	3	4	5
IRA	A	D	B	C	E
Absorption	D	B	A	E	C
Sorptivity	D	A	B	E	C

Table 5 – IRA ($gm/cm^2/min$) values of brick units measured at first and second minutes respectively

Masonry group	A	B	C	D	E
IRA (Over one minute)	48.3	39.9	6.3	77.3	16.9
IRA (Over two minutes)	33.6	28.5	5.7	50	11.8

limited agreement between the sorptivity and the total water absorption of masonry bricks shows the ability of sorptivity to predict long term absorption performance. However, considering the difference in the physical meaning of the three criteria compared and the limited number of tested specimens, a general conclusion needs to be confirmed or negated by additional tests. Sorptivity has an advantage over total absorption in that it fully describes the absorption performance of the masonry brick units during the most critical period of interaction between the units and the mortar.

The water surface absorption values through the sorptivity test were then used to determine the initial rate of water absorption (IRA) over different testing time (1 minute and 2 minutes). Average one minute and two minutes IRA values extrapolated from the sorptivity testing data are presented in Table 5. All the units showed higher rates of absorption within the first minute than the average over two minutes. This is attributed to the microstructural difference between the brick skin (surface layers) and the inside of the unit and also to the change of the initial water content with time.

Statistical analysis using the student t-test with 5% level of significance was applied to examine the difference between the one and two minutes IRA values. The two values were significantly different. This significant difference between the values confirms that the 1 min limit, as an arbitrary choice, is not necessarily the best for providing an accurate engineering evaluation of brick suction. The real interaction of the masonry unit and the adjacent mortar depends on the absorption performance of the units over a much longer time period. Further research is clearly required to examine possible correlation of sorptivity with bond strength of masonry prisms. An experimental programme correlating the sorptivity data to masonry bond strength is currently underway.

5. CONCLUSIONS

1- During the last 50 years, different research work has revealed that IRA is an inconsistent measure of the surface absorption of masonry units.

2- The theory of sorptivity of water in porous materials was reviewed together with its recent application to different porous building materials. An experimental programme was undertaken to examine the sorptivity of masonry brick units. A simple test set arrangement and procedure was utilized.

3- Comparison between the total water absorption, the IRA and sorptivity of brick units showed that IRA was not consistent with the other two measurements. There may be qualitative agreement between sorptivity and total water absorption. However, sorptivity has the advantage of being able to describe fully the water surface absorption performance of masonry bricks over the most critical time period in the development of interface bond strength.

4- When sorptivity is used to determine the surface absorption performance of masonry brick units, there may be a need to reduce the total testing time. The 25 minutes testing time defined by ASTM draft [28] and recommended by many researchers for concrete and mortar may not always be applicable to masonry brick units due to the possible violation of the assumptions of unsaturated flow. The total testing time should be limited to the time of saturation (6 and 9 minutes for two brick types here).

5- A comparison between the IRA values measured for one and two minutes total testing time showed a significant change of the IRA values measured at two minutes compared to those values measured at 1 minute. This demonstrates the arbitrary nature of the one minute testing time used in the IRA test causing the measure to be inconsistent with other measures.

6- Sorptivity is a reliable, reproducible, engineering measurement for predicting the surface absorption performance of brick units.

7- Research examining the relationship between sorptivity and masonry bond strength is required.

ACKNOWLEDGMENT

This work is financially supported by Natural Sciences and Engineering Research Council of Canada (NSERC): we gratefully acknowledge this support. Thanks for IXL-Industries, Medicine Hat, Alberta for donation of the brick units. Special thanks to Miss Roxanne Pierre for providing the French translation of the abstract. Finally, the help of the technical staff, Department of Civil Engineering, The University of Calgary especially Mr. Terry Quinn should not go without special thanks.

REFERENCES

[1] Goodwin, J. F. and West, W. H., 'A review of the literature on brick/mortar bond', *Proceedings of the British Ceramic Society* **30** (23) (1982) 23-37.

[2] Sugo, H. O., 'Strength and microstructural characteristics of brick/mortar bond', Ph.D. Dissertation, Department of Civil, Surveying and Environmental Engineering, The University of

Newcastle, (Newcastle, Australia, 2001).

[3] McGinley, W. M., 'IRA and the flexural bond strength of clay brick masonry', in 'Masonry : Components to assemblages', Matthys, J.H., Ed., ASTM STP 1063. 1990 (American Society for Testing and Materials, PA, USA) 217-234.

[4] Lange, D. A., Deford, H. D. and Ahmed, A., 'Microstructure and mechanisms of bond in masonry', Proceedings of Seventh North American Masonry Conference, University of Notre Dame, (South Bend, Indiana, USA, 1996) 167-174.

[5] Voss, W. C., 'Permeability of brick masonry walls - A hypothesis', *ASTM Proceedings* **33** (1933) 670 p.

[6] Anderegg, F. O., 'The effect of brick absorption characteristics upon mortar properties', *ASTM Proceedings* **42** (1942) 821 p.

[7] Morgan, J. W., 'Brick absorption', *Architecture Science Review* **20** (3/4) (1977) 66 p.

[8] Lawrence, S. J. and Cao, S., 'The influence of some factors on the tensile bond strength of masonry', Proceedings of the 10th International Brick and Block Masonry Conference (IB2MaC) , Shrive, N. G. and Huizer, A., Ed., (Calgary, Canada, 1994) 929-938.

[9] Groot, C. J. W. P., 'The characteristics of brick and mortar considering mortar/brick bond', Proceedings of the 11th International Brick/Block Masonry Conference (IB2MaC), Tongji University, (Shanghai, China, 1997) 50-58.

[10] Lawrence, S. J. and Page, A. W., 'Bond studies in masonry', Proceedings of the 10th International Brick and Block Masonry Conference (IB2MaC), Shrive, N. G. and Huizer, A., Ed., (Calgary, Canada, 1994) 909-917.

[11] Philip, J. R., 'The theory of infiltration: 4. Sorptivity and algebraic infiltration equations', *Soil Sciences* **84** (1957) 257-264.

[12] Gummerson, R. J., Hall, C. and Hoff, W. D., 'Water movement in porous building materials - II. Hydraulic Suction and Sorptivity of Brick and Other Masonry Materials', *Building and Environment* **15** (1980) 101-108.

[13] Hall, C., 'Water sorptivity of mortars and concretes: a review', *Magazine of Concrete Research* **41** (147) (1989) 51-61.

[14] Hall, C. and Yau, M. H. R., 'Water movement in porous building materials -IX. The water absorption and sorptivity of concretes', *Building and Environment* **22** (1) (1987) 77-82.

[15] Jansson, I., 'Testing the rate of water absorption', Proceedings of the RILEM/CIB Symposium on Moisture Problems in Building, (Helsinki, Finland, 1965), 2, 10 p.

[16] Sneck, T., 'Dependence of masonry properties on the interaction between masonry units and mortar', Proceedings of North American Masonry Conference, Noland, J. L. and Amrhein, J. E., Ed., (Colorado, USA, 1978) 21.1 - 21.12.

[17] Hall, C., 'Water movement in porous building materials - I. Unsaturated flow theory and its applications', *Building and Environment* **12** (1977) 117-125.

[18] Hall, C., Hoff, W. D. and Skeldon, M., 'The sorptivity of brick: dependence on the initial water content', *Journal of Physics, D: Applied Physics* **16** (1983) 1875-1880.

[19] Hall, C., Hoff, W. D. and Nixon, M .R., 'Water movement in porous building materials: VI. Evaporation and drying in brick and block materials', *Building and Environment* **19** (1) (1984) 13-20.

[20] Ho, D. W .S. and Lewis, R. K., 'The water sorptivity of concretes: the influence of constituents under continuous curing', *Durability of Building Materials* **4** (3) (1987) 241-252.

[21] Kelham, S. A., 'A water absorption test for concrete', *Magazine of Concrete Research* **40** (143) (1988)106-110.

[22]Hooton, R. D. and Beal, D., 'Sorptivity: measure of concrete durability', *Physical Infrastructure Center, The Latest in Civil Engineering Research from QUT*. **1** (4) (1992) 6-7.

[23] Bentur, A. and Jaegermann, C., 'Effect of curing and composition on the properties of the outer skin of concrete', *Journal of Materials in Civil Engineering* **3** (4) (1991) 252-262.

[24] Hooton, R. D. and El-Dieb, A. S., 'Permeability and permeability measurement - Are we any further ahead?', Advances in Cement and Concrete, Proceedings of an Engineering Foundation Conference, (Durham, New Hampshire, USA, 1994) 24-29.

[25] Hooton, R. D., Mesic, T. and Beal, D. C., 'Sorptivity testing of concrete as an indicator of concrete durability and curing efficiency', Proceedings of the Third Canadian Symposium on Cement and Concrete, (Ottawa, Ontario, Canada, 1993) 264-275.

[26] Groot, C. J. W. P., 'First minutes water transport from mortar to brick', Proceedings of the 9th International Brick/Block Masonry Conference (IB2MaC), (Berlin, Germany, 1991) 71-78.

[27] DeSouza, S. J., Hooton, R. D. and Bickely, J. A., 'Evaluation of laboratory drying procedures relevant to field conditions for concrete sorptivity measurements', *Cement, Concrete, and Aggregates* **19** (2) (1997) 59-63.

[28] American Society for Testing and Materials, Standard Test Method for Measurement of Initial Rate of Absorption of Hydraulic Cement Mortars and Concretes, ASTM draft # 9, 1996, 8 p.

[29] Sabir, B. B., Wild, S. and O'Farrell, M., 'A water sorptivity test for mortar and concrete', *Mater. Struct.* **31** (1998) 568-574.

[30] American Society for Testing and Materials, Standard Methods of Sampling and Testing Brick and Structural Clay Tile, ASTM C 67-86, 1986, 51-61.