The influence of water flow (reversal) on bond strength development in young masonry

Caspar Groot
Joe Larbi

Water loss from the fresh mortar is believed to be related to mortar-brick bond strength development in masonry. Recent research on mortar-brick bond has shown that, particularly, effects of water flow on the composition and the hydration conditions of the mortar-brick interface have to be taken into account to explain bond strength development. However, many cases of unexpected bond behaviour are still registered, and apparently the insight into this complex phenomenon is still incomplete.
In this paper an attempt is made to increase the understanding by analysing in more detail the hydration conditions of the mortar at the interface. To this end, models of capillary water pressure and water transport for cylindrical capillaries (bricks) and water-containing particle systems (mortars) are analysed and applied to the evaluation of a series of bond strength tests. To enhance the potential for a more extensive analysis of the test results much attention is paid to the 'hygric' characterisation of bricks and mortars of the test series.
It is concluded, that not only the water flow from mortar to brick (which takes place immediately after mortar-brick contact) but also a reversed water flow from brick to mortar (occurring after compaction and initial hydration of mortar) may significantly influence the bond strength development.

Keywords: **masonry, bond strength, moisture transport, porosity, polarising and fluorescent microscopy.**

1 Bond strength estimation through the IRA

A great number of investigations carried out in the field of mortar-brick bond, consisted of experiments to establish a relationship between the suction of the brick and the mortar-brick adhesion. After an extensive evaluation of the literature, Goodwin and West [1980] arrived at the conclusion that the rate of absorption has to be considered for fired clay bricks, as the most important single factor affecting bond. According to them this conclusion holds for both bond strength and extent of contact (permeability).

The rate of absorption considered by Goodwin and West is, in fact, the initial rate of absorption (IRA). The IRA is the measure of brick suction accepted in masonry practice and very simple to determine. It represents the weight of water absorbed in 1 minute by the bed face of the brick (the face of the brick that is in contact with the mortar) when immersed to a depth of 3 mm in water (water suction from a free water surface). The IRA values are generally expressed in $kg/m^2/min$.

HERON, Vol. 44, No. 2 (1999) ISSN 0046-7316

The IRA values of fired clay bricks may vary significantly between low suction rate brick (IRA : ~0.5 kg/m^2/min) and high suction rate brick (IRA: 3–4 kg/m^2/min). Bricks with exceptionally high IRA values up to 10–12 kg/m^2/min are used in masonry as well.

The most desirable value of the initial rate of absorption, according to Goodwin and West, to achieve maximum tensile bond strength turns out to be in the range of 0.8 –1.2 kg/m^2/min. This result was derived from an analysis of test results showing maximum values of strength with bricks having absorption rates of about 1.0 kg/m^2/min and lower bond strength values for both lower and higher IRA.

This recommendation was contested in other studies. Yorksdale [1982], for instance, concluded from an examination of comparable test data on the bonding ability of structural clay units that there is no justification for including recommendations on the initial rate of absorption in the body of specifications, thereby making them part of the qualifying requirements.

2 Theoretical considerations

2.1 *Introduction*

The supposed connection between the IRA and bond strength stems from the notion that the IRA is thought to be related to water absorption of the brick out of the mortar. The degree of water loss is subsequently supposed to be an indication of bond strength development. The reasoning is then that

(i) a very low water loss from the mortar will create unfavourable bond conditions at the mortar-brick interface as a result of "floating" of the brick on a thin layer of water squeezed out of the mortar; this causes a very porous interface.

(ii) a very high water loss from the mortar may cause unfavourable hydration conditions of the mortar at the interface of the mortar impairing the bond development as well.

(iii) in between an optimum will be reached (see figure 1).

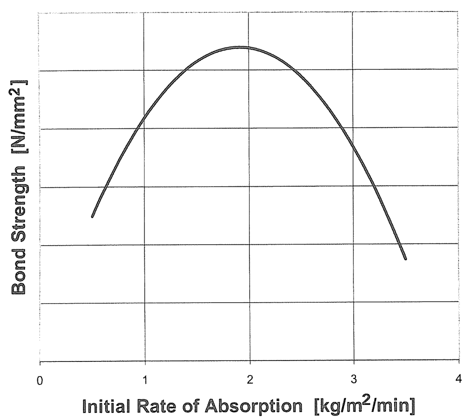


Fig. 1. Trend Curve for the Bond Strength / IRA relationship.

This reasoning, however, is inadequate to explain the many exceptions (in practice) to the general trend as presented in figure 1.

Using the results of qualitative capillary water transport modelling, characterisation data on mortars and bricks, mechanical testing and microscopic observation some examples of unexpected bond strength development are evaluated.

2.2 *Capillary pressure theory for bricks*

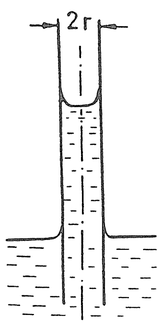
For the application of this theory the brick is assumed to consist of a system of open, parallel, cylindrical capillary pores of different diameters perpendicular to the water surface. Water absorption of a brick from a free water surface can now be described as the total water uptake by individual capillaries.

Water pressure

Water pressure (suction) in an open uniform capillary from a free water surface is governed by capillary force, water/tube friction and gravity. Neglecting the effect of gravity the water pressure is given by

$$p = \frac{2\sigma}{r} \qquad (1)$$

in which, σ it is the surface tension (N/m) of the liquid and r the radius of the capillary (m). From equation (1) it clear that coarse pores exert a low capillary pressure and fine pores a high capillary pressure (see figure 2)



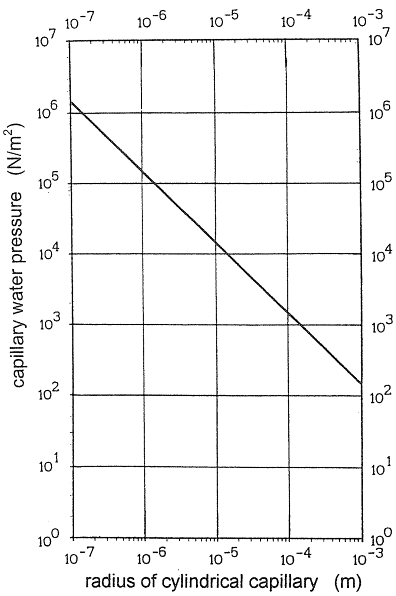


Fig. 2. Capillary pressure in open cylindrical pores as a function of the pore radius.

Water transport

Water transport in an open uniform capillary from a free water surface is governed by capillary force, water / tube friction and gravity. Neglecting the effect of gravity, which is reasonable for a capillary elevation of some centimetres, the mass of water (m) absorbed by the capillary after a period of time t may be given by:

$$m = c \cdot r^{2.5} \cdot \sqrt{t} \cdot \rho \tag{2}$$

in which, m: mass of absorbed water (kg), r: radius capillary (m), t: time (s), ρ: the density of the liquid (in kg/m^3) and c: a constant, $\pi\sqrt{(\sigma/2\eta)}$, with σ is the surface tension (in N / m) of the liquid and η the dynamic viscosity (in Ns/m^2).

From equation (2) the significant influence of the pore radius on the mass of transported water as a function of time is obvious (a factor 10 in pore radius corresponds with a factor 316 for the mass of transported water per period of time, neglecting gravity).

From the equations (1) and (2) it can be concluded that the total mass of absorbed water by a system of capillaries is a function of the pore size distribution and the pore volume. It is clear as well that numerous pore distributions may absorb an equivalent mass of water in a definite period of time. In other words, *equal IRA values may be the result of pore systems with different pore size distributions and pore volumes.*

A system of open capillary tubes as a model of a brick is, of course, an idealization. The pore structure is far more complex (pore shape, varying pore diameter, pore orientation, interconnections of capillaries, closed pores etc.). However, it has been observed by many workers, that unidirectional water absorption by porous solids increases as the square root of the elapsed time. In its general form this relation can be formulated as follows:

$$m' = A\sqrt{t} + C \tag{3}$$

in which, m': mass of absorbed water per unit area (kg/m^2), A : water absorption coefficient ($kg/m^2/t^{1/2}$), t : time (s) and C : intercept value (kg/m^2).

2.3 *Capillary pressure theory for fresh mortars*

Important effects of brick suction on fresh mortars are the decreasing water content and the possible movement of particles towards each other (compaction, densification). Both effects may considerably influence the capillary pressure of the water in the mortar.

Schubert (1982) developed models for determining the capillary pressure between particles connected by water. By means of these models it is feasible to estimate the influences of particle dimensions, distances between particles and water content changes on the capillary pressure of the water in the mortar. In this section the models will be used to describe the water pressure of the fresh mortars as a function of water content changes taking place in the mortar. Subsequently, the effects in the mortar will be related to the brick pressure.

Liquid cups

In Schuberts' study much attention is paid to the description of the capillary pressure of liquid cups between particles (liquid cup: accumulation of water between particles). The particles are modelled as spheres. From the numerous examples shown in his study, the case of two spheres with equal diameter is chosen in order to demonstrate the effects of water loss and compaction on the water liquid pressure.

Using the data of figure 3a, the relation between the capillary pressure of water cups and the sphere radius of two identical particles can be found, see figure 3b. In addition the effects of water loss and compaction on the capillary pressure of a water cup between two identical spheres (with radii of 3 μm) is presented (see dotted lines).

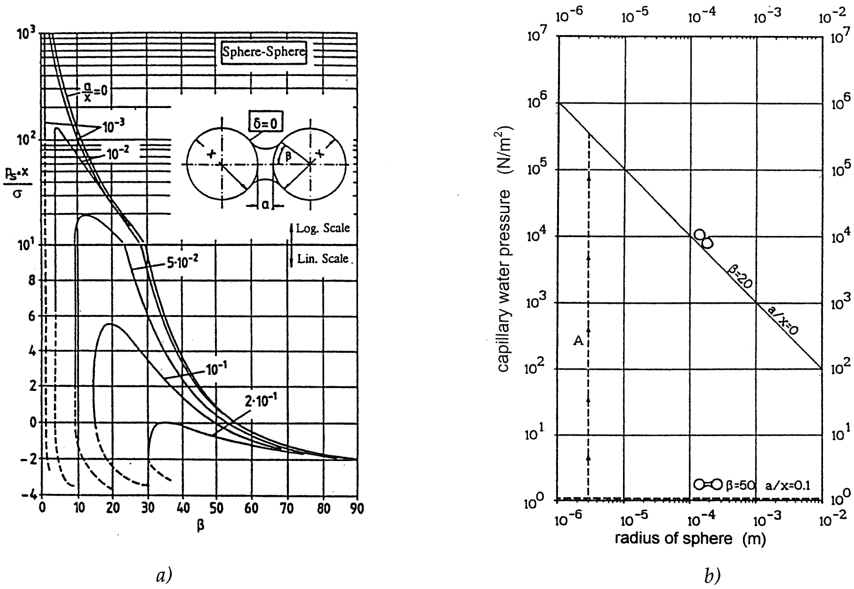


Fig 3. a) Relative capillary pressure of a liquid cup between two identical spheres (a) as a function of the cup angle (β), contact angle (δ) and distance (a/x ratio) (Schubert, 1982).

b) Capillary water pressure (change) as a function of changing distance (a) and cup angle (β) for water between two identical spherical particles (sphere radii 3 μm).

The graphs clearly depict that,

- with decreasing distance between the spheres (compaction) the capillary pressure increases,
- as a result of water loss of the mortar the capillary pressure will increase (lower β):
  - in case of surface contact ($a = 0$) continuously,
  - in case of $a > 0$ up to a certain value and subsequently decrease to nil due to collapse of the cup,
- with decreasing sphere diameter the capillary pressure increases.

The changes in water pressure as a function of water loss and compaction of particles can be understood analysing figure 3b. Line A in this figure represents the increase of the capillary pressure of a water cup between two spherical particles with radii of 3 μm; it is assumed that the cup angle (β) reduces from 50 to 20 degrees and the a/x ratio diminishes from 0.1 to 0 (in other words, in the final situation the spheres touch each other).

Further analysis of the capillary pressure between spherical particles (Schubert, 1982) shows that in case of different particle dimensions, the particle with the smallest diameter determines, to a large extent, the value of the capillary pressure.

2.4 *Particle pressure theory applied to mortars*

The water needed for masonry mortars to ensure a good workability is relatively high. Depending on the type of mortar the initial water-fines (cement + additions, such as hydrated lime and/or ground limestone) ratio may range from 0.8 to 1.3. As a result of brick suction the young mortar looses water. This process starts immediately after laying of the brick (the first mortar-brick contact), and lasts, for fired clay brick, from about 15 to 60 minutes, depending on the absorption characteristics of the brick. The water loss of the mortar may range from 10 to 80 %!
The effects of water transport from mortar to brick can be better understood using Schubert's capillary pressure theory. As can be concluded from this theory, the distance between the particles and the dimensions of the particles significantly influence the generated water pressures, see figure 3.

To apply this theory to masonry mortars an approximation can be made of the average distance between the mortar particles using the composition data of the mortar. Likewise, the particle dimensions can be derived from the mortar constituents.
The distance between the particles can be estimated through the determination of the water film thickness around the particles. The average values for the film thickness may be calculated using the water-fines ratio of the mortars and the specific surface values of the fines.

Example:
For a portland cement mortar, a cement is used with specific surface of 310 m^2/kg. The water cement ratio (no other fines present) is 0.8. Neglecting the specific surface of the aggregate (which is very low) 0.8 kg (= 0.8 E – 3 m^3) of water is available to form a film around 310 m^2 of particles. The average thickness of the film is then 2.6 μm. Taking into account the water needed to fill the voids between the particles an average water film thickness of about 1.3 μm (half the calculated 2.6 μm) may be left. Assuming a mean particle diameter of the cement of about 30 μm the a/x (see figure 3a) is about 1/10 ($a = 2 \cdot$ film thickness).
If a masonry cement or lime cement mortar is applied the average thickness of the water film will be half of that of the portland cement mortar as the specific surface of these binders is about twice as high. From this it can be concluded (see figure 3) that *the initial water pressure in the mortar is so low that the initial water uptake of the brick can be compared with water absorption from a free water surface.*

Consequently, the coarse brick pores will significantly contribute to the *initial* water loss of the mortar. High absorption bricks (high IRA) generally contain more coarse pores than low absorption bricks. So it may be expected (see equation 2,under section 2.2) that the *initial* mass of water absorption *as well as* the *initial flow* rate will be higher for high absorption bricks than for low absorption bricks.

This phenomenon is experimentally demonstrated by several workers using non-destructive testing techniques such as neutron transmission (Groot, 1993) and nuclear magnetic resonance (Pel (1995), Spiekman (1995) and Brocken (1998)), see figure 4.

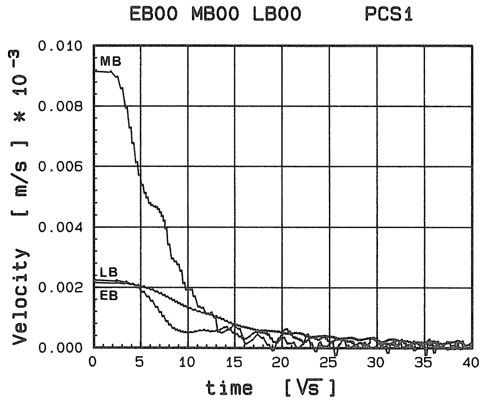


Fig. 4. *Differences in initial water velocity (related to the total brick surface) from mortar to brick for different brick-mortar-brick samples, measured using neutron transmission techniques (Groot, 1993). PCS1: portland cement mortar; EB00: dry medium-absorption brick (IRA, 1.5 kg/m²/min); MB00: dry high-absorption brick (IRA, 4.4 kg/m²/min); LB00: dry calcium silicate brick.*

During the period of high initial flow rate fine particles (cement, lime, ground limestone) may move with the flow from mortar to brick.

As a result of the initial water loss, the particles will move to each other and the cup angles will decrease causing higher water pressures in the mortar; *from this moment on also the finest particles are immobilised in the dense packing of the mortar.*
In the final stage of the transport process, air present in the mortar may cause very high capillary pressures in the mortar (for intact water cups). According to Luikov (1966), this pendular state corresponding with the withdrawal of water from a porous particle system, will cause for a system of equal sphere diameter capillary pressures of $p_s = 12.9\ \sigma / r$.

Since masonry cement and lime-cement mortars show (i) lower initial distances between the particles and (ii) finer particles, the initial flow rates as well as the water loss will be lower than in portland cement mortars.

3 A Case Study

3.1 *Introduction*

A test series was carried out to compare bond strength behaviour of a number of mortar-brick combinations with the IRA-Bond Strength approach discussed in section 1. The aim was to find explanations for cases where apparent divergent bond development takes place.

To enhance the potential for a more extensive analysis of the test results, and the interpretation of unexpected results much attention was paid to the characterisation of the bricks and the mortars.

3.2 *Test specimens*

Bricks

The test specimens consisted of brick-mortar-brick combinations. Six types of fired clay bricks, ranging from low-absorption to high-absorption were used in the tests. Some absorption and porosity characteristics of the bricks are collected in table 1, while figure 5 provides information about the pore size distribution.

Table 1. Absorption and porosity characteristics.

	Absorption		Porosity	
Brick Type	IRA *) [kg/m^2.min]	Free Water Absorption [vol. %]	Mercury Pore Volume [vol. %]	Average Pore Diameter #) [µm]
A	0.29	2.50	12.5	2.3
B	1.39	13.7	18.0	3.1
C	2.90	27.5	33.5	2.3
D	3.04	23.1	29.3	8.5
E	3.34	19.5	22.3	8.4
F	3.71	33.3	40.0	1.4

*) IRA: Initial Rate of Absorption

#) determined using mercury porosimetry

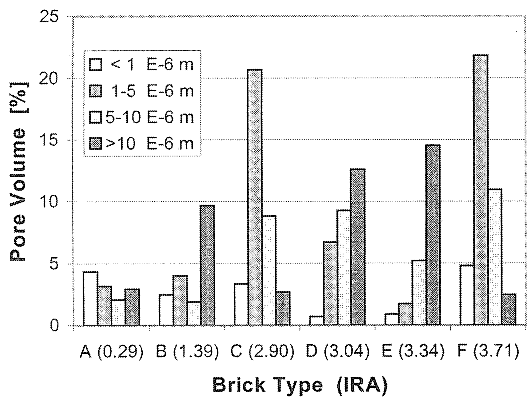


Fig. 5. Pore size distribution (in pore diameter) of the bricks through mercury porosimetry.

The data under the heading 'absorption' provide information about the Initial Rate of Absorption (IRA) and the free water absorption behaviour of the bricks. The porosity data of table 1 provide information on the mercury pore volume and the average pore diameter of the bricks.
From table 1, it can be deduced that more pores contribute to the pore size distribution than to the free water absorption (the gap between mercury pore volume and free absorption pore volume of brick A, for example, is striking).
Linking of pore size distribution to water absorption behaviour requires a well-balanced interpretation, as no clear relationships are established. However, it seems to be reasonable to conclude from the pore size distribution data of figure 5 that more or less equal IRA (compare the brick types C and D or E and F) can be obtained with very different pore size distributions (see the theoretical consideration of section 2.2). Furthermore, it is clear from figure 5 that brick types B, D and E contain a relatively high quantity of coarse pores (pore diameter >10 μm) and C and F a relatively high amount of finer pores (pore diameter 1–5 μm).

Mortars
Two types of mortars were applied: a cement mortar and a masonry cement mortar. The cement applied was always a portland cement. The two mortars were air-entrained up to an air content of 15 %. The masonry cement consisted of a mixture of portland cement [55 % by mass] and ground limestone [45 % by mass]. Some characteristics of the mortars are given in table 2.

Table 2. Fresh Mortar Characteristics.

Characteristics		Cement *) Mortar	Masonry Cement *) Mortar @)
Composition (masonry)cement: sand	[v/v]	1 : 4.5	1 : 3
Water/Cement Ratio	[m/m]	1.03	1.38
Water/Fines #) Ratio	[m/m]	1.03	0.76
Cement content	[mass %]	12.7	8.8
Air-Content	[vol. %]	15	15

*) air-entrained
@) masonry cement containing 55% cement and 45% ground limestone [m/m]
#) Fines, being <cement> in cement mortar and <cement + limestone> in the masonry cement mortar; specific surface cement 307 m^2/kg, specific surface masonry cement 638 m^2/kg

The sand used in the mortar consists of a river sand with a rounded grain form, resulting in a relatively low water requirement to achieve the desired workability. The grading, by mass %, is as follows: grain size $0.125 < d < 0.250$ mm, 30%; grain size $0.250 < d < 0.500$ mm, 30 %; grain size $0.500 < d < 1$ mm; 30 %, grain size $1 < d < 2.$ mm, 10%.

3.3 *Test results and discussion*

3.3.1 Mortar core

To evaluate the supposed relationship between water loss from the mortar and the mortar-brick bond strength, the following tests were performed:

- determination of the water loss of the fresh mortar (after 45 min.); if the water loss is known an estimation can be made of the hydration conditions (water-cement ratio) of the mortar: assuming that after 45 minutes the water transport from the fresh mortar to brick is finished, this situation may represent the hydration condition of the mortar under the curing conditions: 20 °C and 65 % RH.

  The hydration conditions after 45 min. were approximated through the determination of the *w-c* ratio; therefore, a sample was taken from the mortar; this sample was weighed and subsequently dried, the remaining water content was compared to the initial water content and expressed in the water-cement ratio of the mortar during hardening.
- determination of the bond strength, after 28 days of hardening (conditions 20 ^{0}C, 65 % RH); this test was performed according to ASTM C952.

Water loss out of the mortar

The relationship between the (i) the Initial Rate of Absorption of the six brick types and (ii) the water-cement ratio of the mortars, 45 minutes after production of the brick-mortar-brick combinations is given in figure 6.

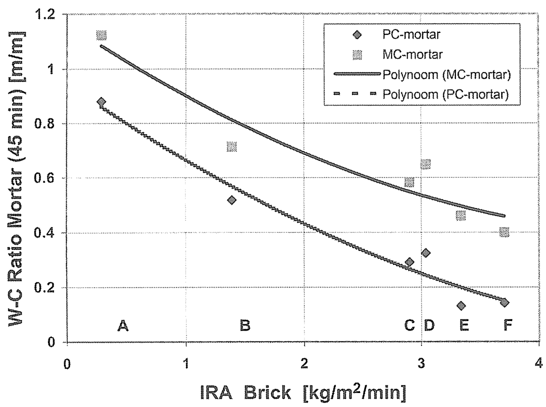


Fig. 6. Effect of suction behaviour (IRA) of the (dry) bricks on the water-cement ratio in the mortar core 45 minutes after manufacturing of the test specimen (after first mortar-brick contact).

Bond Strength

For the 12 combinations (6 brick types and 2 mortar types) cross-couplet bond strength tests (10 specimens per combination) were carried out according to ASTM C952.
In figure 7 the trend curves for the IRA / Bond Strength relationships are presented.

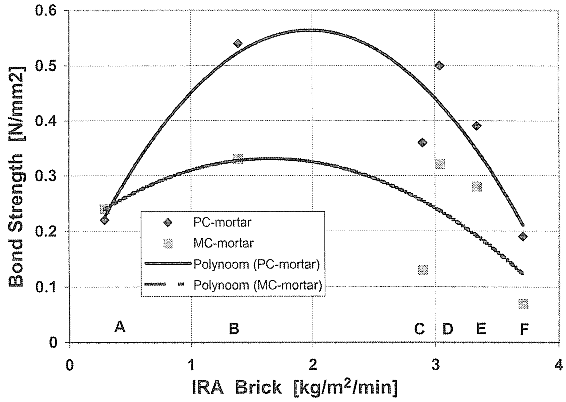


Fig. 7. Trend curves for the IRA / Bond Strength relationship.

Observations

- Figure 6 shows that the water-cement ratio decreases gradually with increasing IRA. It can be observed that the water loss gradient for the cement mortars is steeper than for the masonry cement mortars. This can be explained by the differences in fines, in quantity as well as in particle size, of the two mortar types (see as well section 2.4, 'capillary pressure in fresh mortars').
- Comparing the figures 6 and 7, it is clear that the hydration condition of the *mortar core* is a poor indicator for bond strength estimation; especially the bond strength values of the combinations D (IRA: 3.04) and E (IRA: 3.34), for the cement as well as masonry cement mortars are unexpectedly high.
- The trend curves for the IRA / Bond Strength relationship of the two test series correspond globally with the expectations (see figure 1). However, the deviations particularly for the high IRA combinations (C (IRA 2.9), D (IRA 3.04), E (IRA 3.34) and F (IRA 3.71)) are very significant.
- The observed deviations for the cement mortar combinations are consistent with those of the masonry cement mortars combinations.

3.3.2 Mortar-brick interface

Introduction

Bond between hydration products (in mortars) and non-calcareous substrates (such as bricks) results from a combination of physical forces (the influence of chemical forces may be neglected). These physical bonds are: mechanical interlock and to a lesser extent van der Waals forces of attraction. Consequently, the transport of hydration products into the coarser pores, voids and at the interface of the brick (mechanical interlocking) and the distance between hydration products and aggregate (van der Waals forces) are important factors with respect to the bond development.

As a result of detailed analysis of the hydration products in the interfacial zone of cementitious mortars a relationship between bond strength and the extent of cement hydration has been suggested (Grandet (1971), Lawrence (1987)). The degree of hydration is highly dependent on the occurrence of water during the hardening process.

However, not only the extent of cement hydration, but also the composition and morphology in the interfacial zone are to be considered for the evaluation of bond behaviour. Parameters related to the morphology are mortar composition (binder type, sand grading, water/binder ratio, aggregate/binder ratio, discontinuity due to concentration of fines and air bubbles in the interfacial zone, inhomogeneity of the mortar) and brick characteristics (suction behaviour and surface properties). Hence, it is necessary to evaluate the hardening conditions (at the interfacial zone) of the mortars in relation to these composition parameters.

So, bond characteristics of masonry, in which cementitious binders are used, largely depend on the (i) hydration conditions and (ii) mortar composition *at the mortar-brick interface.*

Mortar composition at the interface

In order to find explanations for the significant differences in bond strength for bricks with more or less similar high IRA (C,D,E and F), thin sections were made of the combinations: cement mortars applied with the brick types E and F; also thin sections were made of combination A, as a contrasting sample to E and F with respect to absorption behaviour. In addition the mortar-brick rupture modes of these combinations were observed.

The mortar-brick interfaces of the combinations E (IRA: 3.34 $kg/m^2/min$) and F (IRA: 3.71 $kg/m^2/min$) show a layer of cement particles at the interface (see figures 8 and 9). Apparently these layers are formed during the first period of mortar-brick contact, when the initial flow rates of water flowing from mortar to brick are high (see figure 4) and as a result of this, fine particles are transported to the interface. The occurrence of layers of fine material (cement, lime, ground limestone) at the interface mortar-brick, if medium and high-suction rate substrates are applied, has been observed by many workers in the past.

Since the *initial* water uptake from a fresh mortar by the brick may be compared to water absorption from a free water surface (section 2.4) and taking into account the differences in pore size distribution of brick E and F (figure 5), it can be understood that the cement layer at the interface of combination E will be thicker than that of combination F. After all, brick E contains significantly more coarse pores than brick F causing a higher *initial* flow rate for the E-combinations. It seems to be presumable, that the first 5 to 10 seconds after the first mortar-brick contact are an important period. During this period the flow rate decreases steeply (see figure 4); only above certain threshold values, depending on the mass of the fines, transport of fines is likely to occur. (Remark: sometimes the drop in flow rate can be "experienced", feeling the direct stiffening of a mortar coming in contact with a high suction rate brick).

Detailed analysis of the thin sections shows a higher degree of hydration of the mortar for E than for F, as well as in the interface as in the bulk of the mortar. This microscopic observation has been confirmed by means of a chemical analysis of the hydration products of the two mortars.

For both combinations tensile bond fracture occurs in the mortar some mm from the interface. Presumably in the region where the cement concentration is lower as a result of cement transport to the interface.

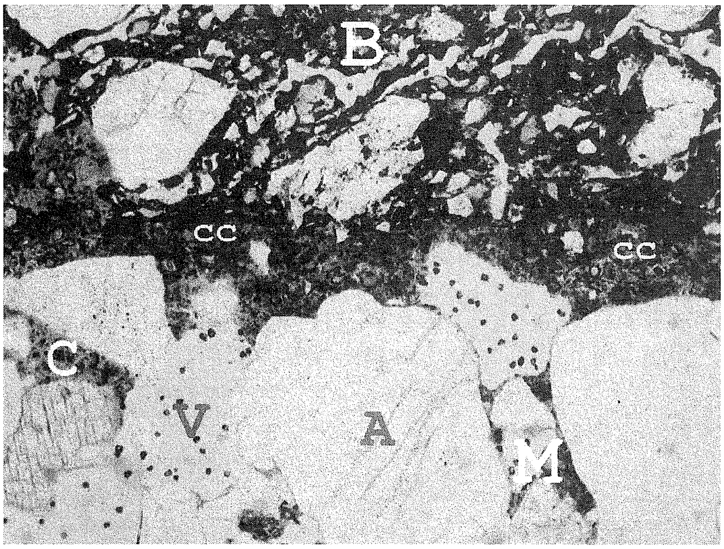


Fig. 8. *Interface brick E / Cement mortar; Layer of cement (cc) at the interface; B: brick; M: mortar; A: aggregate; V: void; cc: partially hydrated cement layer*

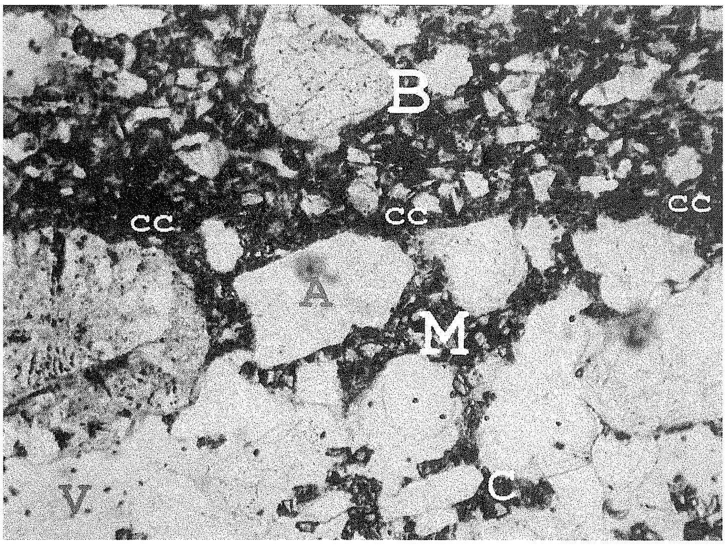


Fig. 9. *Interface brick F / Cement mortar; Layer of (cc) at the interface (thinner than at brick E); B: brick; M: mortar; A: aggregate; V: void; cc: cement concentration*

The bond strength values of the E-combinations are definitely higher than those of the F-combinations (see figure 7). It is remarkable that the degree of hydration of the E-mortars is clearly higher than of the F-mortars, as mortar sampling 45 minutes after brick laying showed more or less similar *w-c* ratios for both E-combinations and F-combinations (see figure 6).

An explanation for the observed differences may be found analysing the conditions with respect to a possible *reversal* of water flow from brick to mortar after (partial) hydration of the mortar (resulting in a finer pore structure). The phenomenon of water flow reversal has been measured earlier by Groot (unpublished test results) using neutron transmission techniques.
At this the differences in pore size distribution of the two brick types E and F have to be considered. Figure 4 shows that the E-bricks contain a considerable amount of coarse pores (pore diameter > 10 mm) while the F-bricks contain a considerable amount of finer pores (pore diameter 1–5 μm). From this it may be concluded that the conditions for water flow reversal from the E-bricks are more favourable than from the F-bricks: lower resistance against mortar suction as a result of lower capillary pressures in coarse brick pores. Also a denser packing at the E-interface (higher initial flow rates), causing an earlier set of the cement (Détriche, 1981) may have contributed to the flow reversal.
Comparing the pore size distributions shown in figure 4 with the Bond Strength / IRA trend line from figure 6 it can be observed that the brick types D and E, containing high amounts of coarse pores (more favourable conditions for water flow reversal) perform better (above the trend line) with respect to mortar-brick bond than the brick types C and F (under the trend line), which show finer pore structures (and consequently unfavourable conditions for water flow reversal).

The thin section of the mortar-brick interface of combination A (bricks A (IRA: 0.29 kg/m^2/min) with cement mortar) shows a lack of binder at the interface (see figure 8).

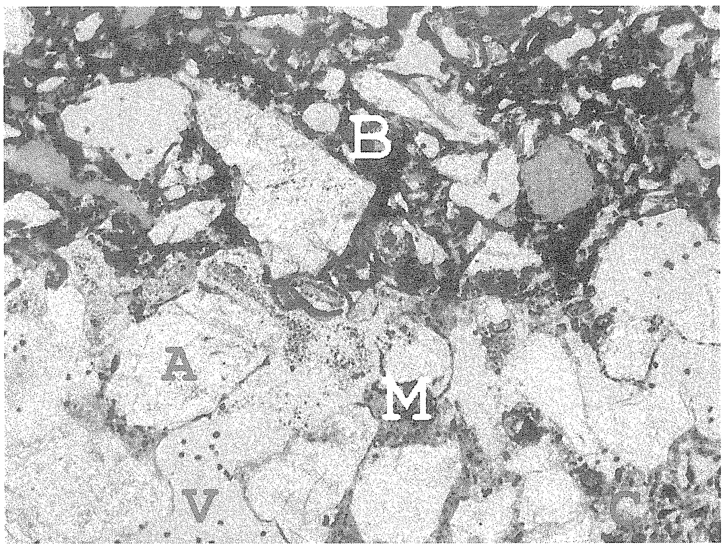


Fig. 10. *Interface brick A / Cement mortar; High void content at the interface; B: brick; M: mortar; A: aggregate; V: void; C: hydrated cement*

Apparently, the (initial) suction of this brick type is so low that no transport of fines from the mortar towards the brick occurs. Further analysis of the mortar shows a high degree of hydration of the mortar all over the joint depth. This is to be expected as the mortar hydrates under high w/c ratio conditions. The interface of A shows a higher porosity than for E and F. This is due to a high water content at the interface during hydration. During the tensile bond strength testing fracture occurred at the interface: the brick face showing only a slight shimmer of cement traces. In fact this represents a case of clear interface rupture.

4 Conclusions

The test results (figure 7) confirm that Bond Strength and IRA can roughly be related to each other through a trend curve as presented in figure 1. Maximum and minimum values depend then on the mortar composition.

The significant deviations from the trend curve for higher IRA-values underline Yorksdale's conclusion that that there is no justification for including recommendations on the initial rate of absorption in the body of specifications, thereby making them part of the qualifying requirements for the bonding ability of structural clay units.

Microscopic analysis of interfaces combined with capillary pressure theory considerations applied to brick and interface porosity showed that the significant differences in mortar-brick bond strength for bricks with more or less similar high IRA's may be caused by *flow reversal* of water from the brick to the mortar. (This phenomenon may occur after (partial) hydration of the mortar, if the bricks contain coarse pores filled with water previously absorbed from the mortar).

Further experimental verification of the flow reversal phenomenon (by neutron transmission techniques or NMR) may support the microscopic findings.

5 References

BROCKEN, H.J.P., (1998), 'Moisture transport in brick masonry: a grey area between bricks'. PhD-Thesis, TU Eindhoven, The Netherlands, ISBN 90-6814-087-6.

DÉTRICHE, C.H. and GRANDET, J. (1981), 'Influence de la suction des supports poreux sur la prise et la résistance au cissaillement des mortiers moulés à leur contact'. Matériaux et Constructions, No 80, pp. 91–102.

DULLIEN, F.A.L., (1991), 'Porous Media, Fluid Transport and Pore Structure'. Academic Press, Inc., New York.

GOODWIN, J.F. and WEST, H.W.H., (1980), 'A review of the literature on mortar/brick bond'. The British Ceramic research Association, Techn. Note No. 308.

GROOT, C.J.W.P., (1993) 'Effects of water on mortar-brick bond'. PhD-Thesis, TU Delft, Delft, The Netherlands, ISBN 90-9006569-5.

GUMMERSON, R.J., HALL, C. and HOFF, W.D., (1981), 'The suction rate and the sorptivity of brick'. Transactions and Journal of the British Ceramic Society. Vol.80, pp. 51 153.

GRANDET, J. and THENOZ, B., (1971), 'Introduction a l'étude de l'adhérence terre cuite pâte de ciment: mesure de l'eau échangé par succion entre les constituants'. Revue Terre Cuite, No 48, pp. 21–28.

LANGE, D.A., DEFORD, H.D. and AHMED, A., (1996), 'Microstructure and Mechanisms of Bond in Masonry'. Proc. Seventh North American Masonry Conference, Un. of Notre Dame, South Bend, Indiana, USA, 1996, pp. 167–174.

LAWRENCE, S.J. and CAO, H.T., 1987, 'An experimental study of the interface between brick and mortar'. Proc. 4th N. Am. Masonry Conf., Los Angeles, pp. 48, 1–14.

LUIKOV, A.V., (1966), 'Heat and Mass Transfer in Capillary-Porous Bodies'. Pergamon Press, Oxford.

PEL, L., (1995), 'Moisture transport in porous building materials'. PhD-Thesis, TU Eindhoven, The Netherlands.

SCHUBERT, F., (1982) 'Kapillarität in porösen Feststoffsystemen'. Springer-Verlag, Berlin.

SPIEKMAN, M., (1995), 'Moisture loss from fresh masonry mortar immediately after brick laying'. (in Dutch) MSc Thesis, TU Delft, The Netherlands.

SUGO, H.O., PAGE, A.W. and LAWRENCE, S.J., "Characterization and Bond Strengths of Mortars with Clay Masonry Units.: Proc. 11th IB^{2}MC, Tongji University, Shanghai, China, pp. 59–68, 1997.

YORKDALE, A.H., (1982) 'Initial Rate of Absorption and Mortar Bond'. ASTM STP 778, pp. 91–98.