Effects of water on mortar-brick bond

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The quality of bond in masonry is, to a large extent, a function of the (i) the hydration conditions and (ii) the mortar composition of the mortar-brick interface. For insight into the effects of these parameters on bond performance it is essential to dispose of quantitative information about water content changes and flow rates, occurring immediately after brick laying. This quantitative information is preferably to be obtained by means of a non-destructive testing. The paper describes the test set-up, the potentiality and the limitations of two measuring methods, using thermal neutrons, with which the required data can be acquired. Furthermore, an attempt is made to explain differences in bond performance of various brick-mortar-brick combinations, using the results from neutron transmission measurements and X-ray diffraction testing.

Keywords: **mortar-brick bond, masonry, non-destructive testing, neutron transmission techniques**

Introduction

For some decades now good quality of mortar-brick bond in masonry is not always evident. Cases of serious deterioration in relatively new masonry structures were reported. Property changes of mortars, due to the use of air-entraining agents and fillers, are believed to be a major reason for the decrease of bond performance.

Evaluating the bond problems and analysing the complex nature of the bond phenomenon, it was clear, that more fundamental knowledge on mortar-brick bond should be gathered in order to obtain a better understanding of the problems.

From the literature (e.g. Goodwin & West (1980); Grandet (1973); Lawrence & Cao (1988); Opperman & Rudert (1983); Sneck (1978)) it was concluded, that mortar-brick bond performance is determined, to a large extent, by
(i) the degree of hydration of the cementitious mortar material,
(ii) the composition of the mortar,
in the interfacial zone of mortar and brick.

Insight into the phenomenon of mortar-brick bond is, up to now, almost entirely based on the study of bond performance and material characteristics after hardening of the binder in masonry assemblies. Very little is known about the effects of water flow in the mortar immediately after brick laying, whereas the influence of these effects on the hydration conditions and the mortar composition in the interfacial zone are assumed to be considerable.

Therefore, the present study was focused on the acquisition and interpretation of detailed qualitative information on water content changes in fresh masonry mortars.

Important flow effects related to the evaluation of the mortar-brick bond development are the following:
- the change of the water content distribution in the mortar as a result of brick suction, compared with a known initial distribution: analysis of changes in water/cement ratio.
- the water flow rate in the mortar during suction: estimation of transport of fine particles.

Measuring techniques

Introduction

Changes of water content in mortars, as a result of brick suction, are commonly determined gravimetrically.
The test specimen usually consists of two units with a mortar joint in between (Högberg (1967); Kjaer (1991)). The water loss of the mortar can then be measured by the determination of the weight increase of the adjacent units after a definite absorption period. To this end the specimen has to be destructed. Therefore, sheets of gauze are often placed between mortar and brick to facilitate the splitting of the test specimen. With this technique it is possible to quantify mean water content changes of the mortar joint.
Another method is used in order to obtain information about water gradients in the mortar bed (Anderegg (1942); Davison (1961)). In this case the mortar is cut in slices after a definite period of mortar-brick contact. Next, the water content of each layer can be determined.
The destruction of the test specimen is a serious drawback in assessing water content changes. The monitoring i.e. the determination of the water content values as a function of time, calls for a very large number of test specimens and is, therefore, very time-consuming. Moreover, monitoring during the first important minutes of mortar-brick contact is even hardly possible. Consequently, non-destructive testing techniques are to be preferred. Non-destructive methods proposed to monitor the internal water content distribution in porous inorganic materials are γ-ray attenuation and nuclear magnetic resonance (NMR) imaging (Gummerson et al. (1979)). Neutron radiography offers another promising non-destructive technique in this field. It was decided, after consideration of the available facilities and possibilities at the TU-Delft, to develop non-destructive measuring techniques using neutron radiography.

Neutron Transmission Techniques

General

For the study of water transport phenomena in ceramic materials neutron transmission may be applied as a research probe (Neumann and Reppmann (1988)).
Thermal neutrons with energies in the order of 25 meV can be used for this purpose. During transmission these neutrons are either scattered or absorbed by the atoms the material is composed of. This phenomenon is physically characterized by the scattering and absorption cross-sections of the elements concerned. In Table 1 the cross-sections pertinent to bricks and mortars are given:

Table 1. Scattering (σ_s) and absorption (σ_a) cross sections of elements normally present in brick or mortar (Sears (1986)).

Element	σ_s [10^{-24} cm^2]	σ_a(0.1308nm)* [10^{-24} cm^2]
H	38	0.242
O	4.235	0.00014
Na	3.28	0.386
Mg	3.708	0.46
Al	1.504	0.168
Si	2.178	0.124
S	1.026	0.39
Ca	3.05	0.31
Fe	11.83	1.86

* The absorption cross-sections are noted for the neutron wavelength at which the experiments have been conducted.

It is clear that the hydrogen scattering cross-section is by far the largest of all the presented elements. So the thermal neutrons are scattered by hydrogen atoms substantially more strongly than by any other chemical element usually present in bricks or mortars. Consequently, water in masonry can be accurately detected by this technique.

Moreover, the penetration depth of thermal neutrons in most materials (e.g. brick) is in the order of centimetres. Therefore, a beam of thermal neutrons is a unique probe to study the distribution of water (either absorbed or chemically bound) in bricks and mortar.

Neutron transmission

The transmission of a neutron beam by a sample of thickness l is given by:

$$I = I_0 \exp \{-l\Sigma_i \mu_i\} \tag{1}$$

I is the number of neutrons counted per unit of time with sample in the beam and I_o with empty beam; μ_i is the attenuation coefficient due to element i expressed by:

$$\mu_i = n_i (\sigma_i^s + \sigma_i^a) \tag{2}$$

with n_i the particle number density of element i, and σ_i^s and σ_i^a the cross sections for scattering and absorption. Rewritten this yields,

$$\Sigma_i \mu_i = \mu_d + \psi \mu_w \tag{3}$$

with μ_d the attenuation coefficient of dry brick or dry mortar, μ_w the attenuation coefficient of water and ψ the volume fraction of water in brick or joint; $0 \leq \psi < 1$. It is not possible to discriminate between absorbed and chemically bound water. From eqs. (1) and (3) follows:

$$\psi = \frac{l}{\mu_w l} \ln\left(\frac{I_o}{I_w}\right) - \frac{\mu_d}{\mu_w} \qquad (4)$$

where $\varphi = 100\ \psi$, the water content in % by volume, and I_w the intensity of neutrons transmitted by the wet brick or mortar.

Instrumental test set-up

At the Interfaculty Reactor Institute (IRI) of the Delft University of Technology a 2 MW swimming-pool type nuclear reactor is equipped with various thermal neutron facilities. For the transmission experiments described in this study, a monochromatic beam was used with a wavelength of 0.1308 nm (selected by means of a zinc crystal (002) reflection). Using a monochromatic beam one is dealing with only one value of the attenuation coefficient for each element present in the sample. The data on the neutron beam are given in Table 2.

Table 2. Neutron beam data.

Wave length [nm]	Neutron Flux [$cm^{-2}s^{-1}$]	Intensity [s^{-1}]
0.1308	$1.3\ 10^6$	$2.8\ 10^4$

The neutron beam was monitored with a low efficiency monitor-detector (M) and the cross section restricted to $25 \times 10\ mm^2$ behind the monitor, in order to reduce background scattering. It is common practice to conduct measurements against a fixed number of monitor counts. In this way fluctuations of the neutron beam intensity are implicitly corrected for, and measured intensities can be judged directly.

The transmitted neutrons were counted by means of a ^3He proportional neutron detector with an efficiency of nearly 100%. The influence of scattered neutrons on the test results was negligible due to the use of a detector collimator, which is positioned perpendicular to the horizontal diaphragms. The restricted beam was applied in two different test set-ups, a scanning technique and a monitoring technique. These techniques were used to study various aspects of water transport.

Scanning technique (lift facility)

In this test set-up (see Figs. 1 and 2) water distribution profiles were scanned over the cross-section of the joint (joint thickness about 12 mm) and parts of the adjacent bricks (about 20 mm each).

For this purpose the test specimen was vertically transported past a pair of fixed horizontal restrictions of the neutron beam (diaphragms) by means of a lift. The two diaphragms were situated just in front of and behind the specimen-lift (L). The dimensions of the diaphragms were 40 mm wide by 1 mm high. With this width a horizontal zone of sufficient reach is covered to facilitate the determination of representative mean water content values; with a height of 1 mm a satisfactory spatial resolution is expected to be achieved. The test specimen was prepared out of range of the neutron beam and subsequently placed in the lift.

The aim of this test set up is to study effects of brick suction on the water distribution in the brick-mortar-brick combinations.

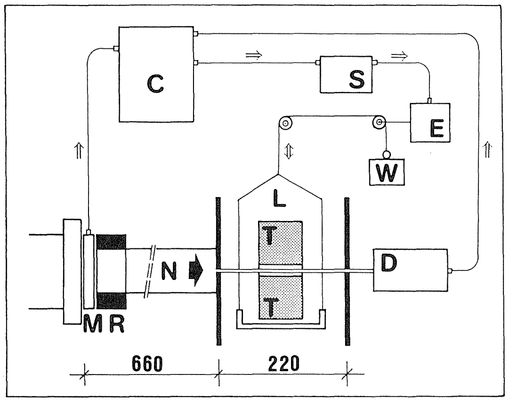
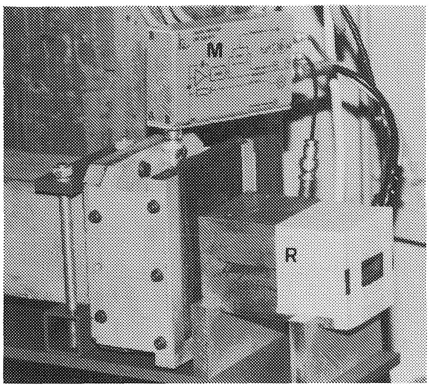


Fig. 1. Diagram of scanning test set-up. M: monitor, R: restriction, N: neutron beam, T: brick-joint-brick specimen, L: lift, D: detector, W: counter weight, E: motor, S: drive unit, C: computer (drawing P. van der Ende, IRI).



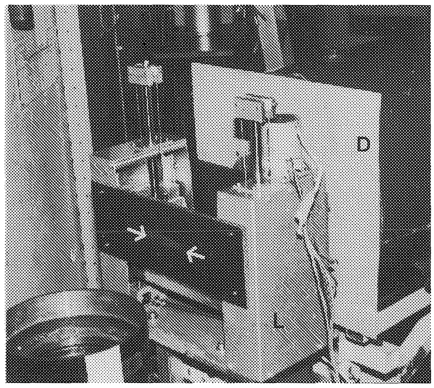


Fig. 2. On the left-hand side view of monitor (M) and restriction (R). On the right-hand side view of lift (L) with front diaphragm (see arrows) and detector (D).

Some advantages of the experimental set-up are the following:
- the lift-facility allows water distribution measurements over an important zone of the test specimen and,
- tests under controlled conditions, in aluminium containers, can easily be conducted: long-term testing without evaporation problems.

However a major drawback is that considerable changes in water content during the first period of absorption cannot be assessed because of the lapse of time between the preparation of the specimen and the start of the measurement.

Monitoring technique (brick laying device)
Information on water loss of the mortars during the first minutes after preparation (mortar-brick contact) is considered of paramount importance for the interpretation of transport phenomena, which may influence bond. In this case it is essential to monitor changes in neutron transmission at some well-defined positions of the test specimen, right from the first moment of mortar-brick contact after brick laying.

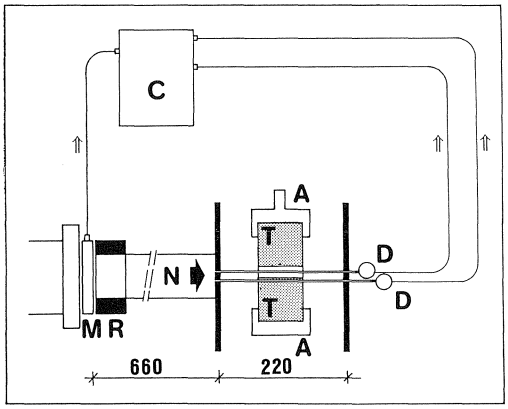


Fig. 3. Diagram of monitoring test set-up. M: monitor; R: restriction; T: test specimen; A: brick laying device; D: detector; C: computer.

To obtain this information preparation of the test specimen in the neutron beam is required. To this end a brick laying device has been designed and constructed enabling the brick laying to be carried out in the neutron beam (see Figs. 3 and 4) and, at the same time, avoiding beam contact with the investigator.
The water changes were measured at two positions of the specimen: in the middle of the joint and at 2 mm from the upper surface in the lower brick. In order to avoid the influence of scattered neutrons the beam is reduced, in this test set-up, by means of two diaphragms, 40 mm wide and 1 mm high, placed in front of and behind the specimen. The transmitted neutrons are counted with two detectors (D).

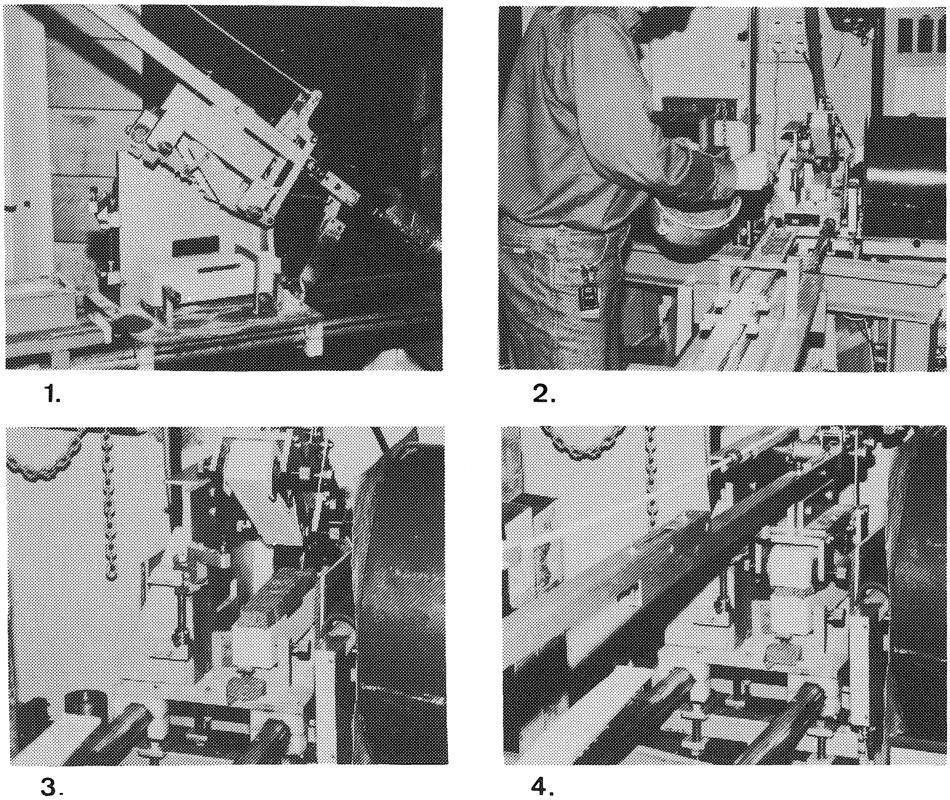


Fig. 4. Preparation of test specimen.

1. *Placing of bricks in the grips of the brick laying device (out of beam),*
2. *After transport of brick laying device to beam, pouring of the mortar in a separate container (out of beam),*
3. *Starting the test programme by means of the computer, next: placing of the mortar on the lower brick,*
4. *Finishing the specimen*
   (brick laying device designed and constructed by J. Lanser)

Attenuation coefficients

The attenuation coefficients of the bricks (dry), water and the dry mortars (mass of the dry components: sand, binding agent(s) and / or admixtures, additives) are experimentally determined by means of transmission measurements (eq. (1)). To this end specimens of different thickness were prepared (see Fig. 5). The measured data were corrected for background intensity.

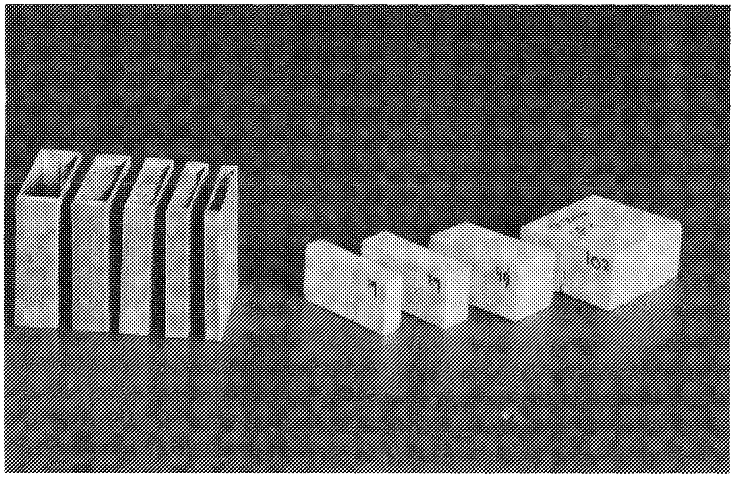


Fig. 5. Test specimens for the determination of attenuation coefficients: on the left-hand side containers for granular materials and water, on the right-hand side brick specimens of different thicknesses.

Test results and observations

Test specimens

The test specimens consist of brick-mortar-brick combinations.

The bricks

The three brick types with explicitly divergent absorption behaviour are:

- an extruded clay brick (EB), fine pores, low suction rate brick
- a machine moulded clay brick (MB), coarse pores, high suction rate brick
- a calcium silicate brick (LB), combination of very fine and coarse pores

The mortars

In the mortars sand grading, type of binding agent and, consequently, the water requirement as a function of the workability, are varied. The three basic mortars are

- a portland cement A mortar (PC), cement/sand ratio 1:4.5 (v/v), air-entrained
- a lime-portland cement A mortar (LC), cement/lime/sand ratio 1:1:6 (v/v), not air-entrained
- a masonry cement mortar (MC), masonry cement/sand ratio 1:3 (v/v), air-entrained

The masonry cement contains portland cement A (55% by mass) and ground limestone (45% by mass).

Sand grading: S1, S4, S5

S4 and S5 are a finely graded and coarsely graded sand, respectively. S1 differs from S4 in the sense that 30% of the finest fraction ($0.125 < d < 0.250$) of S4 is replaced by very fine quartz flour.

The S1-grading is choosen to facilitate the study on the influence of fine inert material on the bond strength development.

For further details on brick and mortar properties, see Groot (1993).

The abbreviations used in the graphs are:

EB00	: extruded clay brick, dry
MB00	: machine moulded brick, dry
MB15	: machine moulded brick, prewetted (~ 15 mass %)
LB00	: calcium silicate brick, dry
LB07	: calcium silicate brick, prewetted (~ 7 mass %)
PC	: portland cement A mortar
LC	: lime-portland cement A mortar
MC	: masonry cement mortar
S1, S4, S5	: sand grading type

Example: MB15LCS4, abbreviation used for a brick-mortar-brick specimen, consisting of prewetted (~ 15 mass %) machine moulded bricks and a lime-portland cement A mortar containing S4 graded sand.

Results from scanning technique

By means of the scanning technique water distribution profiles were determined over the cross-sections of joints and relevant parts of vicinal bricks. An example of the test results obtained from a series of measurements is presented in Fig. 6. The mortar-brick interfaces are marked by means of horizontal, dotted lines. The initial water content in the mortar is marked by a vertical, dotted line. The analysis of the test results of a series of 45 brick-mortar-brick combinations resulted in the following observations regarding the interpretation of the hydration conditions of the mortar bulk and mortar interface:

Mortar bulk

Comparison of the hydration conditions (neutron transmission measurements) and the occurrence of hydration products (X-ray diffraction measurements) in the mortar bulk showed, a good predictability of the occurrence of hydration products as a function of the experimentally determined hydration conditions of the cementitious material. Moreover, a negligible or very small variation in the occurrence of hydration products as a function of the sand grading was observed.

Mortar interface

It is concluded that the interpretation of the hydration conditions at the mortar interface is hindered by uncertainties about the water content values at micro-level (the outer hundred μm of the mortar interface) due to (i) the spatial resolution of 1 mm of the measuring technique and (ii) micro suction effects (funicular, pendular water state) in the outer zone.
Uncertainties about the mortar composition, due to possible transport of fine material to the interface are important as well.

The final water content in the mortar bulk of the calcium silicate combinations are significantly lower than those of the fired clay brick combinations of comparable mortar types.

Comparison of tensile bond strength test results with water content profiles showed that no relation can be established between water content values at the interface and mortar-brick bond strength values.

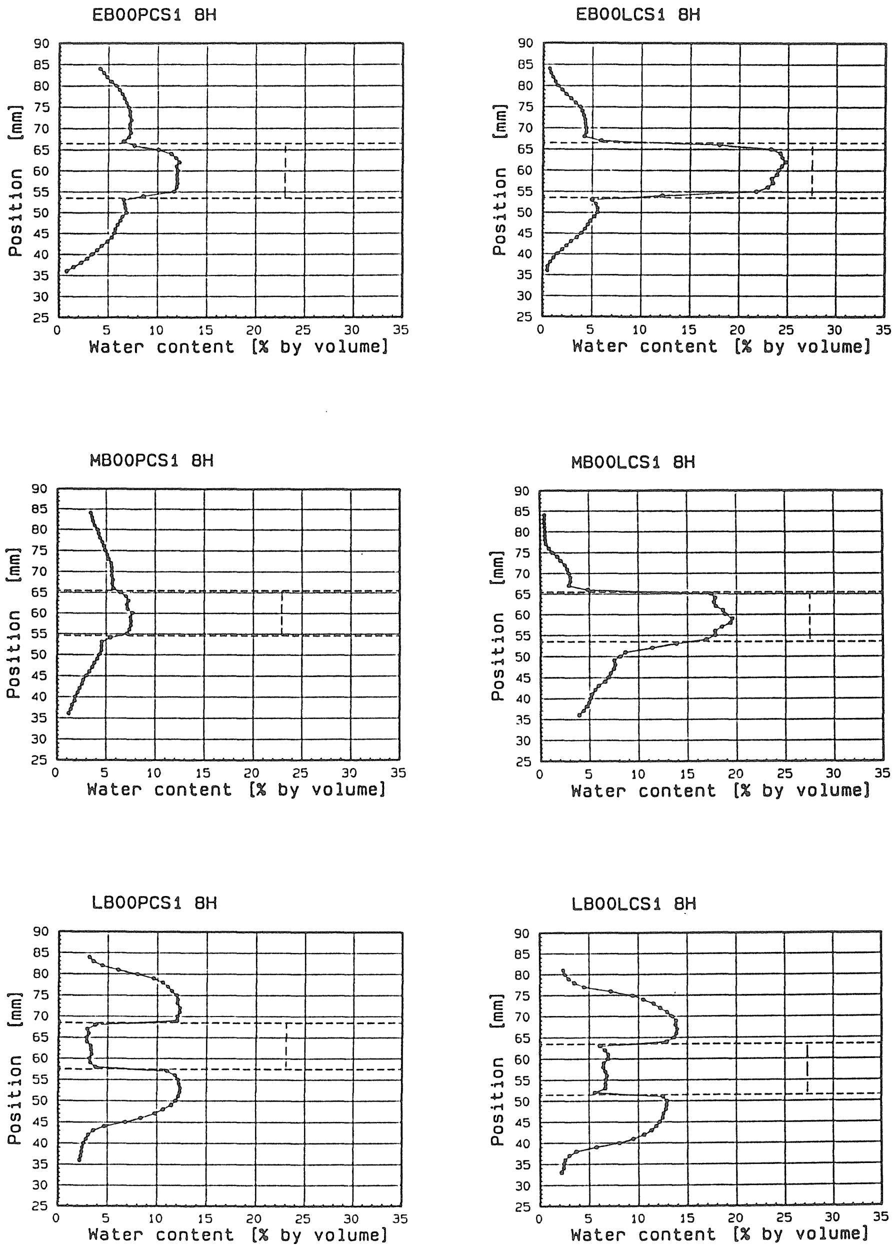


Fig. 6. Different absorption behaviour of dry EB, MB and LB in contact with PCS1 and LCS1 mortars. Profiles scanned 8 hours after preparation of the test specimens. Test conditions: RH 95%, 20°C.

Results from monitoring technique
Information about the water flow rates during the period of time immediately after brick laying is supposed to be essential for the evaluation of the possible transport of fine particles from the mortar core to the interfaces. The transport effects on the composition of the interfacial zone may determine the development of bond strength to a large extent. An example of the test results, obtained from a series of monitoring measurements, is presented in Fig. 7.

From the transmission measurements can be derived, that the moisture flow rates from mortar to brick may vary significantly, depending on the absorption characteristics of the brick and the water retention of the mortar. The most significant differences in flow rates are measured during the period of 100 to 200 s, immediately after brick laying.

In most cases, the initial flow rates in the high absorption MB-combinations are, per mortar type, significantly higher than in the low absorption EB- and the LB-combinations.

The influence of the type of sand grading on the flow rates can be studied by comparing one with another the flow curves of the complete test series. The flow rates after 25 seconds of mortar-brick contact are presented in graphical form in Fig. 8.

The most important conclusion to be drawn from Fig. 8 turns out to be that the brick type has a far greater effect on the flow rate at $t = 25$ s. than the sand grading applied in the mortars.

From the Figs. 7 and 8 can be concluded as well that the initial flow rates in a mortar type do not vary significantly for different initial water contents per brick type. Consequently, transport effects are not prevented by prewetting.

X-Ray diffraction
Tensile bond strength testing showed very poor bond between mortars, containing relatively high quantities of fine inert materials (masonry cement mortar (MCS1), containing high amounts of ground lime stone of the masonry cement and quartz flour) and high absorption, fired clay bricks (MB) and calcium silicate bricks (LB). Prewetting of the bricks did not result in a better bond performance.

In order to find explanations for differences in bond behaviour, the composition of portland cement (PC) and masonry cement (MC) mortars, hardened between fired clay bricks (MB and EB) and between calcium silicate bricks (LB), was studied using X-ray diffraction techniques.

From the analysis of the test results it was derived that, the phase compositions in the bulk and in the surface region of mortar joints are different, and that more hydration products are formed in the surface region of the joints of PC-mortars than in that of MC-mortars.

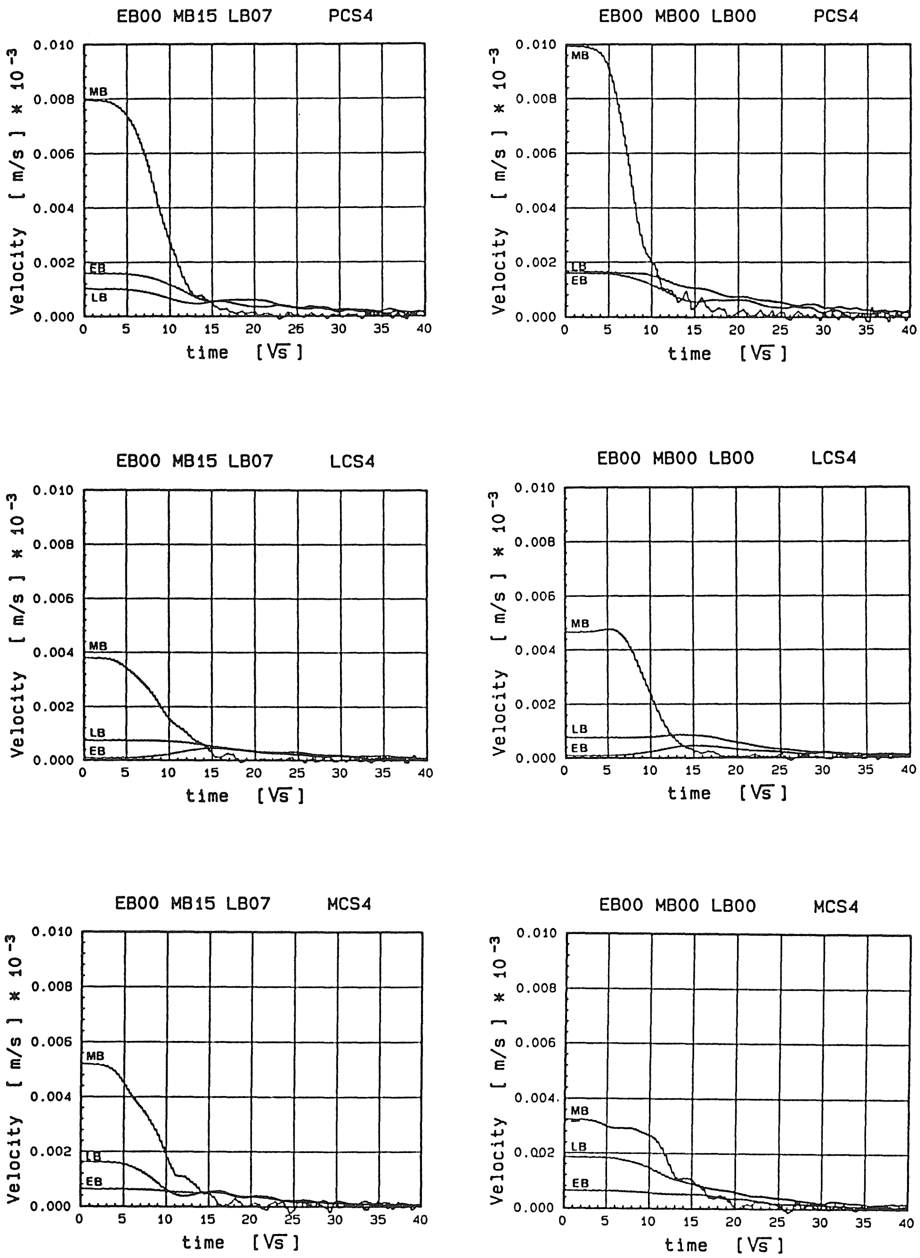


Fig. 7. Flow rates from mortar to brick for EB-, MB- and LB-combinations with mortars containing S4-graded sand.

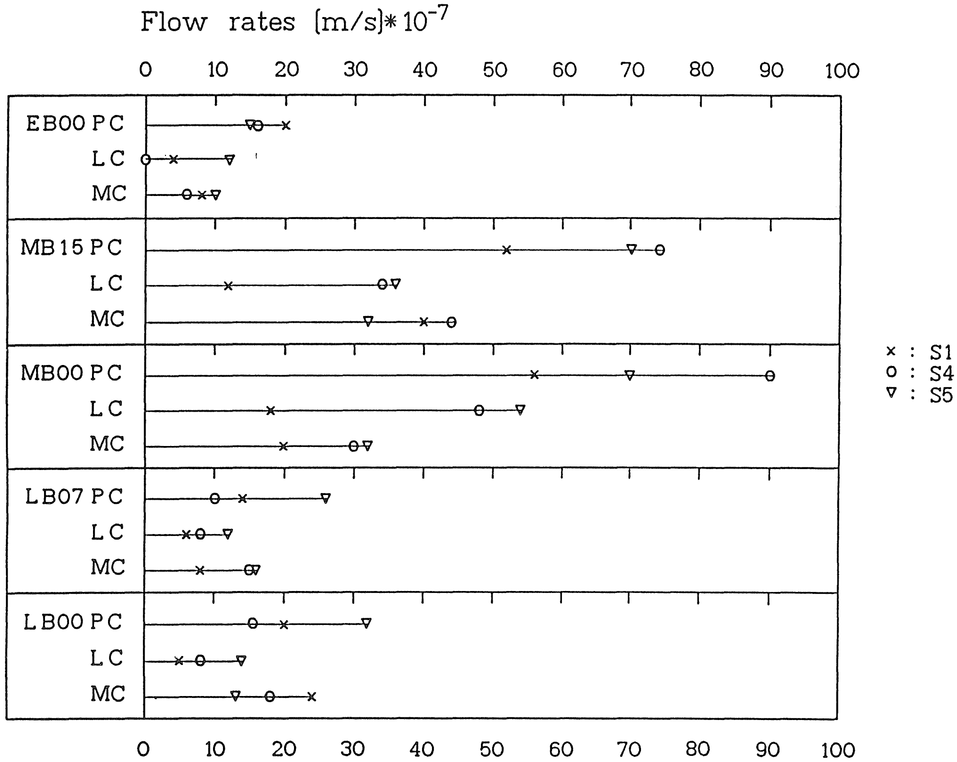


Fig. 8. Flow rates after 25 seconds of mortar-brick contact.

Further analysis of the composition of MCS1-mortars over the outer 2 mm of the joint showed the occurrence of gradients in the phase composition: e.g. the amount of calcite (ground lime stone of the masonry cement) is substantially higher in the surface region than in the bulk of the joint.

The degree of enrichment with very fine grained material in the surface region of the MCS1-mortars was found to correspond with the initial flow rates in the mortar (transport effect).

It was concluded that low bond strengths between masonry cement mortars (MCS1) and high absorption bricks (MB) are likely to be caused, primarily, by unfavourable portland cement A/all fines ratios in the interfacial mortar zones (all fines: all material in the matrix, inclusive cement, of about the same as or smaller grain size than that of the cement).
Moreover, more favourable portland cement A/all fines ratios in the interfacial zones of the MCS1-mortars, hardened between calcium silicate bricks, do not favour the bond strength development significantly. This is attributed to the occurrence of lower water contents at the interfacial zone caused by high capillary pressures in the calcium silicate brick (vapour transport conditions).

Conclusions

With the help of the developed neutron transmission techniques it is possible to obtain precise quantitative information about water content distributions and flow processes in masonry test specimens.
The supposed influence of flow effects on the mortar interface composition (and, consequenly, on the mortar-brick bond performance) is confirmed by the test results of neutron transmission monitoring technique and X-ray diffraction investigation.

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