EFFECTS OF WATER ON MORTAR-BRICK BOND
EFFECTS OF WATER ON MORTAR-BRICK BOND

PROEFSCHRIFT

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SUMMARY

Bond between mortar and brick is essential to ensure the structural soundness and water tightness of masonry structures. For some decades now good quality of mortar-brick bond is not always evident. Property changes of mortars are believed to be a major reason for the decrease in bond performance.

Having considered the complex nature of the bond phenomenon it was concluded that more fundamental knowledge had to be gathered in order to understand problems in this field and to propose improvements.

From the literature review it is clear that water plays a key role in the process of bond development, since bond primarily originates from mechanical interlock of hydrated cement in the mortar to the brick surface (pores). Therefore this study was focused on the effects of water on mortar-brick bond.

In order to develop and to validate ideas about the influence of water on bond, it is necessary to have at one’s disposal detailed and quantitative information about water content changes in the mortar resulting from suction exerted by the brick. Up to now very little is known about water content changes in the mortar, especially immediately after brick laying. For this reason novel non-destructive neutron transmission measuring techniques were developed for the determination of water distributions and flow rates in fresh mortars and relevant parts of the vicinal bricks.

Test results of the water content distribution over the cross section of brick-mortar-brick specimens (neutron transmission measurements) showed a good predictability of the occurrence of hydration products (X-ray diffraction measurements) in the middle of the joint. This was not the case for the mortar interface.

Other test results showed the considerable influence of the absorption characteristics of the brick and the water retention of the mortar on the water distribution and flow rates in the mortar. The absorption behaviour of calcium silicate bricks turned out to differ significantly from that of fired clay bricks.

The most significant decrease in flow rate was measured during the period of 100 to 200 sec immediately after brick laying.

In test specimens of high absorption fired clay bricks it was observed that the initial flow rates in a mortar type do not vary significantly for different initial water contents of the applied brick type. From this it has been concluded that possible transport of fine material from the bulk to the interface in the mortar is not prevented by prewetting of the brick.

The test results regarding the water distributions and flow rates in the mortar were subsequently related to the tensile bond behaviour of the test specimens. From the comparison
of the test results it was concluded, that (i) transport effects in the mortar resulting in unfavourable mortar composition in the interfacial zone and (ii) absorption effects, unfavourably influencing the hydration conditions in the interfacial zone, may effect mortar-brick bond behaviour.

The occurrence of transport effects was studied, using X-ray diffraction techniques. It was demonstrated, that the phase composition in the middle of the joint and in the interface region of mortars usually differ significantly. An enrichment with fine grained material was observed in the interface region. This enrichment is a function of the flow rate and the composition of the mortar.

The possible influence of absorption effects in the interfacial zone was studied by analysing test results of water distributions and flow rates with the help of capillary absorption theories, which are applicable to porous media. It was shown, that the experimentally determined interactive effects of capillary pressures in mortar and brick on the water distribution and flow rate can, for the greater part, be explained if mortar and brick are adequately modelled.

The analysis of the mortar composition and the hydration conditions in the interfaces of test specimens resulted in the following conclusions:
- low bond strength between high absorption fired clay bricks (high flow rates of water) and modern mortars (containing a high content of fine inert material) is primarily caused by an unfavourable cement/fine inert material ratio in the interfacial zone.
- low bond strength between calcium silicate bricks and mortars is primarily caused by unfavourable hydration conditions in the interfacial zone.

In the last chapter it is indicated which measures can be considered to improve mortar-brick bond in the observed problem cases.
SAMENVATTING

Hechting tussen mortel en steen is van essentieel belang voor de constructieve kwaliteiten en de waterdichtheid van metselconstructies. Sinds enige decennia is een goede kwaliteit van de hechting tussen mortel en steen niet altijd vanzelfsprekend. Verondersteld wordt dat veranderingen in de eigenschappen van metselmortels de belangrijkste reden zijn voor de achteruitgang in hechtingedrag.

Gezien de complexiteit van het verschijnsel hechting werd geconcludeerd dat meer fundamentele kennis verkregen zou moeten worden om problemen op dit gebied te begrijpen en verbeteringen voor te stellen.

Het literatuuronderzoek maakte duidelijk dat water een sleutelrol speelt bij het ontstaan van hechting; hechting wordt vooral bepaald door haakweerstand tussen uitgehard cement in de mortel en de aanliggende steen. Dit was de reden het onderzoek te richten op de effecten van water op de hechting tussen mortel en steen.

Om ideeën over de invloed van water op hechting te kunnen ontwikkelen en te toetsen is het noodzakelijk te kunnen beschikken over gedetailleerde en kwalitatieve gegevens betreffende veranderingen in watergehalte, die in de mortel optreden als gevolg van wateropzuiging door de steen. Tot op heden is er bijzonder weinig bekend over veranderingen in watergehalte van de mortel. Dit geldt in het bijzonder voor de periode onmiddellijk na vermetselen. Daarom werden nieuwe meetmethoden ontwikkeld om waterverdelingen en watersnelheden in voegen en gedeelten van aanliggende stenen niet-destructief te bepalen. Hierbij werd gebruik gemaakt van transmissietechnieken met thermische neutronen.

Met de resultaten over de waterverdeling in de dwarsdoorsnede van voeg en aanliggende stenen (transmissiemetingen met neutronen) bleek de aanwezigheid van hydratatie produkten in het midden van de voeg goed voorspelbaar te zijn (verificatie met behulp van röntgendiffractie). Dit was niet het geval voor de hechtzone.

Uit andere proeven kwam de aanzienlijke invloed van de absorptie-eigenschappen van de steen en de watervalshoudendheid van de mortel op de waterverdeling en de transportsnelheden van water in de mortel naar voren. Het absorptiegedrag van kalkzandstenen vertoonde aanzienlijke verschillen met dat van bakstenen.

De grootste afname in transportsnelheden van water in de mortel werd gemeten gedurende de eerste 100 à 200 seconden onmiddellijk na het vermetselen van mortel en steen.

Bij proefstukken met sterk zuigende bakstenen werd waargenomen dat de initiële transportsnelheid van water per morteltype weinig wordt beïnvloed door het initiële vochtgehalte van de steen. Hieruit kan worden geconcludeerd dat een mogelijk transport van fijne delen vanuit het midden van de voeg naar het hechtvlak niet wordt voorkomen door voorbevochtiging van dit soort stenen.
samenvatting

De beproevingresultaten betreffende waterverdeling en transportsnelheden van het water werden vervolgens gerelateerd aan het hechtgedrag van de proefstukken. Na vergelijking van resultaten werd geconcludeerd, dat (i) transporteffecten in de mortel resulterend in een ongunstige samenstelling van de mortel in de hechtzone en (ii) absorptie-effecten, resulterende in ongunstiger hydratatiecondities in de hechtzone, het hechtgedrag ongunstig kunnen beïnvloeden.

De aanwezigheid van transporteffecten werd bestudeerd met behulp van röntgendiffractie technieken. Aangetoond werd dat de fasensamenstelling in het midden van de voeg gewoonlijk duidelijk verschilt van die in de hechtzone. In de hechtzone werd een toename van fijn materiaal waargenomen. Deze toename is een functie van de transportsnelheid en de samenstelling van de mortel.

De mogelijke invloed van absorptie-effecten in het hechtvlak werd bestudeerd door de testresultaten over waterverdelingen en transportsnelheden te analyseren met behulp van capillaire absorptiethoorieën die toegepast kunnen worden op poreuze media. Daarbij bleek dat experimenteel bepaalde interactieve effecten van capillaire spanningen in mortel en steen op waterverdeling en transportsnelheid, voor een groot deel, verklaard kunnen worden indien mortel en steen adequaat worden gemodelleerd.

De analyse van de compositie van de mortel en de hydratatiecondities in de hechtzones van proefstukken leidde tot de volgende conclusies:

- lage hechtsterkte tussen sterk zuigende bakstenen (hoge transportsnelheden van water) en moderne mortels (met een hoge hoeveelheid fijn/inert materiaal) wordt op de eerste plaats veroorzaakt door een ongunstige cement-inert materiaal verhouding in de hechtzone.

- lage hechtsterkte tussen kalkzandsteen en mortels wordt op de eerste plaats veroorzaakt door ongunstige watergehalte condities (onvoldoende hydratatie) in de hechtzone.

In het laatste hoofdstuk wordt aangegeven welke maatregelen overwogen kunnen worden om tot een verbetering van het hechting te komen in de gesignaleerde probleemgevallen.
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introduction

1 INTRODUCTION

1.1 Scope of the problem

For some decades now good quality of mortar-brick bond is not always evident. Cases of serious deterioration in relatively new masonry structures were reported, dealing with frost damage of mortars and problems on bond between mortar and brick.

Focusing on the mortar-brick bond, the following developments may play a role with respect to this question:

(i) changes in brick and mortar properties;
(ii) alterations in structural concept of walls;
(iii) execution conditions.

(i) Brick properties are influenced by the applied production process, due to different requirements with respect to raw materials, shaping techniques and firing cycles. The new production techniques may affect the absorption characteristics and the surface properties of bricks.

The property changes of mortars over the past decades are believed to be more pronounced than those for bricks. The application of air-entaining agents (a.e.a.) has to be mentioned in this context. Essential consequences of the use of a.e.a. as to the mortar composition are a lower water and a higher air content (compared with non-air-entrained mortars). The effects of these changes on bond characteristics are insufficiently understood. This also goes for the application of ground lime stone in masonry cement.

The practical significance of a.e.a. consists in a substantial improvement of the workability of the mortar, meaning a better and longer lasting appropriate consistency. Therefore the use of a.e.a. must be considered as an irreversible development.

The above mentioned uncertainties about the effects of mortar changes underline the need for quality control. The rapid growth of the ready mix mortar market is, in this respect, a favourable evolution (estimated developments of the Dutch market are (1987-97): increase of the prefab mortar volume, from 40 to 80%; decrease of volume of hand-made mortars, from 60 to 20%).

(ii) In modern structure the inner veneer of the usually applied cavity wall often consists of a prefab timber structure. As a consequence the stiffness of the outer masonry veneer is higher than that of the inner panel (which was not the case in former times, when both veneers were made of brick masonry). At wind loads this results in higher tension in the masonry veneer.

(iii) Labour productivity requirements are often a threat to good quality. The risks of poor quality of mortars are to be located especially in the sector of hand-made ones. Non-qualified use of a.e.a. may easily lead to extremely high air and low water contents of the mortar. Another recent development is the transport of bricks and their storage on site in plastic sheet material. The laying of brick, nearly oven-dry not rarely occurs. The effect of
this practice on the quality of mortar-brick bond can be very negative.

Also abroad considerable attention has been paid to bond in masonry over the past years. The main reason was and is the concern of the building industry whether the mortars produced, using commercially available masonry cements, are equivalent to portland cement lime mortars with respect to masonry assembly performance. This equivalence has to be proved by means of tests in order to acquire the permission for the application of a new mortar in one of the mortar classes as specified in the Masonry Standards.

Evaluating the bond problems and analysing the complex nature of the bond phenomenon, it may be concluded, that more fundamental knowledge on mortar-brick bond should be gathered in order to ensure good quality of masonry.

1.2 Aim of the research programme

The foremost objective of the research programme is to acquire more insight into the role of water with respect to the quality of mortar-brick bond (the justification for this choice is given in chapter 2).

To this end the attention has been focused in particular on the quantitative determination of water transport during the first hours of mortar-brick contact. Quantitative knowledge of phenomena like water movement in the mortar during the first period of contact with the brick, changes of water contents in the mortar from an initial to an equilibrium value, differences in water contents of mortar and brick, the influence of the initial water content of the brick on the water absorption, is considered to be important to further the understanding of the hydration conditions of the binding agent(s) and variation in mortar composition over the cross-section of the joint.

Wishing to obtain quantitative information on water transport phenomena means at the same time choosing for an important component of experimental work in this study. This is due to the current state of the art as to the modelling of water transport in porous media (Unsaturated Flow Theory). Up to now model parameters corresponding to restrained water and the limited availability of water (which is the case in mortars) did not find their formulation in this theory.

As all the investigated phenomena are time-dependent, this study is aimed at developing non-destructive testing techniques, allowing a detailed study of water profiles with, possibly, sharp moisture gradients.

Some of the theoretical aims of the study are (i) to evaluate the test results on water transport with respect to pore diameter characteristics of brick and mortar and (ii) to attempt to apply the Unsaturated Flow Theory to water flow results.

As to the mechanical bond performance the aim is to find relationships between effects of water transport on water distribution and mortar composition and the bond development.
introduction

This study is markedly influenced by the idea that the efforts made should contribute to the solution of practical problems in the field of mortar-brick bond. Therefore, the search for more fundamental insight is linked to questions originating from the masonry practice. The employed research methodology and techniques and the choices with respect to the composition and dimensions of the test specimens are influenced as well by the wish to produce test results applicable to the masonry practice (see chapter 3).

The main practical aims of the study are:
- to advance insight into the differences in bond behaviour between traditional and modern mortars.
- to contribute to the understanding of interactive behaviour of mortar and brick in order to promote the compatible use of mortar and brick.
- to evaluate the bond strength test results in the light of quality requirements.
2 REVIEW OF THE LITERATURE ON MORTAR-BRICK BOND

2.1 Review methodology

The number of parameters related to the phenomenon of mortar-brick bond is considerable. A distinction can be made between composition parameters of brick and mortar and the effects of these on properties influencing bond in masonry (see Table 2.1).

Table 2.1 Composition-parameters of mortar and brick and their relations with properties influencing bond in masonry (Groot, 1988).

<table>
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<th>Composition parameters</th>
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4
As the bond phenomenon is very complex, it is of paramount importance to analyze it carefully. The analysis should result in assessing the influence of the relevant parameters and their interrelations. Therefore, the following points have been considered:

- as a result of detailed analysis of the hydration products in the interfacial zone (Grandet et al. (1972); Oppermann and Rudert (1979); Lawrence and Cao (1987)) a relationship between bond strength and the extent of cement hydration has been suggested. The degree of hydration is highly dependent on the occurrence of water during the hardening process; therefore, water in mortar and brick is an important factor for the study of bond. From Table 2.1 it is clear that quite some parameters are linked with water: brick porosity (absorption behaviour), mortar composition (water requirement, water retention, water/cement ratio). In other words the study of hygric behaviour allows a study of interrelationships of parameters as well.

- it can be noted that the hygric (relating to water or moisture) properties of mortar and brick are interactive (decrease of consistency and water/cement ratio of the mortar due to brick suction; distinct absorption effects of the bricks depending on the water retention of the mortar).

Up till now quite some bond research has been focused on the study of separate properties of mortar and brick. An example in this respect is the determination of mortar characteristics by means of test specimens cast in steel moulds. The effects of brick suction on the mortar properties are ignored in this approach. This may result in significant misinterpretation of the bond performance of the combination of brick and mortar. Therefore, special attention will be paid to those references in which test results on assembly behaviour are presented.

- 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. This observation refers to the difference between mechanical strength and water tightness (permeability) of masonry constructions. A dense morphology in the interface may result in low joint leakage; however, favourable bond strength is not guaranteed. The inverse may occur as well. Parameters related to the morphology are mortar composition (cement 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 of the mortars in relation to these composition parameters.

Taking into account the above mentioned considerations the literature review has been focused on:

- the analysis of the bond mechanism in the light of the hygric behaviour and the composition parameters of the assembly constituents.

- the evaluation of the effects of the hygric interactivity of mortar and brick.
2.2 The microstructure of the interface

2.2.1 Fired clay-cement paste interface

Investigations of the interface microstructure are rare in masonry research. Since the early seventies only a limited number of investigations have been carried out to study the chemical and physical characteristics of the bond between brick and mortar. Grandet (1972, 1973) was the first to set up experiments to examine the hydration products formed by cement pastes on fired clay substrates with different porosities and water contents, using X-ray diffraction and electron microscopy techniques.

His major observations were the following:
- a layer of ettringite is formed on the surface of the porous fired clay (the concentration of ettringite decreased to a normal level in the bulk of the cement paste),
- the concentration of calcium hydroxide is very low in the vicinity of the interface compared with that in the body of the cement paste.

Grandet attributed the mechanical bond of the brick-mortar combination to the anchorage (mechanical interlock) of the needle-like ettringite crystals in the pores of the brick. From micro-photographical data he concluded that the ettringite crystals generally occur with diameters of about 0.05 μm. Mechanical bond was found to be low with substrate pore radii smaller than or about 0.05 μm. A substantial improvement of bond was achieved for substrates with coarser pores, if the cement was properly hydrated behind the ettringite layer. If the brick is dry and has a high suction rate, there may be a partially hydrated zone in the cement paste, to a depth of several millimetres, possessing poor mechanical strength. From tensile bond tests it is known that rupture often occurs in the mortar some millimetres from the interface, when high-suction bricks are applied. The same rupture mode was found by Grandet using combinations of cement paste and brick.

Goodwin and West (1980) questioned the applicability of Grandet's results to mortar-brick combinations with low-suction rate bricks, where the cement is well hydrated but the joint material may be pulled from the brick easily.

It may be assumed that in this case there is hardly any transport of colloidal materials from the mortar or the cement paste into the brick. This may result in the development of a poor bond because of a lack of mechanical interlocking as hydration products have not penetrated into the brick pores. At the same time the cement hydration in the mortar may be well advanced.

Recent results of experimental studies by Lawrence and Cao (1987, 1988) seem to point to the occurrence of a different type of microstructure morphology than that found by Grandet. Brick-mortar interfaces were investigated using SEM (scanning electron microscopy) and associated techniques. The samples consisted of combinations of one type of fired clay brick with plain cement and lime-cement pastes.

The morphology developed in the brick-paste interface (for both paste types) was found to
be characterized by a dual layered structure. The first layer was a Ca-rich film (this layer was more predominant when lime-cement paste was used). C-S-H particles and Ca(OH)₂ crystals growing on this film formed the second layer. The products formed at the interface were similar for saturated and dried bricks, with the only difference that the crystals tended to be coarser for saturated bricks. Quantities of C-S-H gel as well as partially unhydrated cement particles were found inside the brick pores. Hydration products occurred much deeper in dried brick than in saturated brick.

2.2.2 Interface studies in concrete research

The interpretation of the interface morphology observed in paste-fired clay combinations can be evaluated in comparison with the test results obtained in the field of interface research of normal weight (non-porous aggregates) and lightweight (porous aggregate) concrete.

The dual layered interface found by Lawrence and Cao for the paste-fired clay specimen appeared to correspond with an interfacial morphology reported by Barnes, Diamond and Dolch (1978, 1979). This morphology was the result of the interaction between a non-reactive silicious aggregate and a cement paste. It is noted that such a microstructure occurs in the interfacial zone of a nearly non-porous aggregate and cement paste. Hence, it can be assumed that the hydration conditions in the vicinity of the fired clay substrate were essentially comparable with those of a non-porous material: (very) low suction rates of the bricks.

Porous lightweight aggregate-cement paste interfaces often show a different microstructure. Zang and Gjørv (1990) examined the interfacial microstructure of different types of lightweight aggregates and cement pastes. For porous lightweight aggregates without dense shells, a material comparable with fired clay brick with respect to its absorption behaviour, almost no Ca(OH)₂ rich zone was observed near the aggregate particle. Meanwhile, paste and aggregate were bonded rather well. The good bond was attributed to mechanical interlocking between paste and aggregate, due to cement paste penetration into the surface pores. This type of microstructure seems to be more similar to the interfacial structures observed by Grandet.

2.2.3 Different brick-paste interfacial microstructures

For a further analysis of the test results of Grandet and Lawrence/Cao it may be useful to compare the composition of the specimens more closely. Grandet et al. (1972) used fired clay cylinders of 2 cm in diameter and 2 cm in height. On top of polished cylinders he placed the pastes (layer thickness unknown). The water/solid ratio of the cement pastes was 0.25-0.30. The applied bricks ranged from low-suction to medium-suction rate with mean pore radii from 0.05 μm to 2.9 μm. Lawrence and Cao (1987) cut slides of 10 mm thickness out of bricks. The slides were ultrasonically cleaned prior to the application of the cement paste (thickness of the paste layer
review of the literature on mortar-brick bond

unknown). Cement paste and cement-lime paste (lime/cement ratio: 1/4) were used with a water/solid ratio of 1.0. The applied bricks were of a low-suction rate type as could be deduced from bond strength test results (Lawrence and Cao, 1988). The most important difference between the test series turns out to be the water/cement ratio of the applied pastes. Investigations carried out by Larbi and Bijen (1990) on the forming of calcium hydroxide in set portland cement systems brought to light the influence of the water/cement ratio and the presence of aggregate particles. Increasing the water-cement ratio from 0.30 to 0.50 caused an increase of the Ca(OH)$_2$ content in both portland cement pastes and mortars at all ages of hydration. Moreover, at the same water/cement ratios the calcium hydroxide content of the mortars was found to be significantly higher than that of the pastes. It was also observed that the Ca/Si values in the aggregate-paste interfacial zone were materially higher than in the bulk paste.

Relating these results to the microstructure detected by Grandet and Lawrence and Cao it is assumed that the established differences can be attributed to the variations in water-cement ratio. Different types of microstructures may occur in masonry as well, since the final water/cement ratio at the interface may vary substantially as a function of brick suction and mortar properties.

_Cement paste bond versus mortar bond_

The paste-aggregate microstructure seems less complicated to evaluate with regard to bond than the mortar-brick microstructure. The reason for this is that for mortar-brick bond a number of supplementary parameters have to be considered. Mentioned are: compaction of the mortar, sand/cement ratio, water/cement ratio, water quantity, water retentivity, sand grading etc.

For this reason direct extrapolation of findings on paste-brick microstructure development to mortar-brick combinations is not possible.

2.2.4 Brick-mortar interface

_Fired clay_

Lawrence and Cao (1987) compared brick-paste interfaces with a sample of a brick-mortar interface collected from an internal wall about four years of age. C-S-H type I and ettringite were found to grow on sand particles and brick surfaces, indicating a limited degree of cement hydration.

They also reported a gradation of sand particles retained in the capillary pores, the finer particles transported deeper into them than the coarser ones. This implies, according to their interpretation, that a mortar with a coarser sand grading should provide a higher bond strength than a mortar with a very fine sand grading. In the first case a large portion of brick pores would be filled with hydration products instead of sand particles.

It may be assumed that a certain degree of sand gradation in the brick pores only occurs under quite specific conditions: the mortar must contain extremely fine sand and the brick pores must be very coarse. Normally, the transport turns out to be restricted to water and very
review of the literature on mortar-brick bond

fine particles of hydrated lime, ground lime stone and (hydrated) cement. Very probably the greater thickness of the hydrated cement layer on the sand grains explains the better bond strength performance, since coarsely graded sand has a smaller specific surface area. Also, the lower w/c ratio of the mortars containing that type of sand may favour hydration if it is combined with a low suction rate brick.

Calcium silicate
Oppermann and Rudert (1979, 1983) carried out an extensive programme on calcium silicate brick-mortar bond using SEM techniques as well. The applied calcium silicate bricks showed a rough and open surface texture with pore diameters > 100 μm. A series of very different mortars were used: cement, hydrated lime and cement-hydrated lime mortars. The air content in these mortars varied from 3 to 20%; the water retentivity differed considerably as well. Consequently, the microstructure in the bulk of the mortar showed significant variation: open pore structures, systems with isolated pores, air bubbles (entrained by a.e.a.) ranging from 100 to 350 μm in diameter, differences in hydration products etc. With respect to the microstructure of the brick-mortar interface the authors reported the following:
- the mortar did not penetrate into the pores of the rough brick surface if the pore diameter ranged from 100 to 500 μm; no hydration products were found inside the finer brick pores. Oppermann and Rudert concluded that bond through pore anchorage did not take place (hence, surface anchorage).
- bond only developed at the outer rims of the brick surface; the mortar formed dome-like structures spanning the pores of the brick surface; surveying the surface they observed mortar pattern of different geometry, representing point-like, curved linear and plane-like bond areas. However, circular and randomly distributed hexagonal patterns occurred most frequently.

Surface texture
Several workers (Kampf, 1963; Thornton, 1953; McBurney et al., 1946) studied the effects of surface texture of bricks on bond. Their results were not conclusive at all. It may be assumed that the surface roughness will influence the mechanical interlock of the mortar to the brick. However, the degree to which variations in surface texture affect bond is not clear (Goodwin and West, 1980).

2.2.5 Nature of bond

Introduction
Physical and chemical forces may occur if two different materials get sufficiently close to one another for interaction. From concrete research it is known (Bijen et al., 1993) that the bond between hydration
and normal (non-calcareous) aggregate particles results from a combination of physical forces (the influence of chemical forces can be neglected). These physical bonds are: the van de Waals force of attraction and mechanical interlock. Consequently, the distance between hydration products and aggregate (van der Waals forces) and the entering of hydration products into the pores of the aggregate (mechanical interlocking) are important factors with respect to the bond development.

Some important aspects regarding the physical bond mechanisms are:
- the surface roughness of the aggregate resulting in an increase of contact area may favour the development of van der Waals forces,
- the micromechanical interlocking between two phases are affected by (i) the microtopography of the surface on the one hand and (ii) the size of the covering or penetrating molecules on the other hand (Sasse and Friedrich, 1983).

These principles may also apply to bond between mortar and brick.

**Masonry research**

Kampf (1963) performed tensile bond strength tests (cross-brick couplets) on specimens of mortar between glass plates and concluded that keying (interlocking) is the principal force bonding mortar to brick. He found that, regardless of the type of portland cement mortar, the bond strength was less than 10% of a good mortar brick bond. Then he argued that factors as brick absorption, brick pressure, water retention and workability affect only keying. So this phenomenon is essential for mortar-brick bond.

However, Högberg (1967) observed that the bond strength between mortar and glass may be equal to a good mortar-brick bond for low water/cement ratio of the mortar. In fact, the results of both workers are, apart from being controversial, difficult to link with (a degree of) interlocking, since no information is given on the surface roughness (and/or the influence of a possible chemical attack resulting in increased roughness) of the applied glass plates.

It was, finally, with the help of X-ray and SEM-techniques (in combination with mechanical testing) that the importance of interlocking could be proved. Grandet et al. (1972) and Lawrence and Cao (1987) showed that the bond properties of the brick-cement paste interface stem from the interlocking of hydration products formed in pores and on the brick surface that are connected with the bulk of the cement paste. Lawrence and Cao (1987) emphasized that not only the mechanical interlock, but also the type of hydration product has to be considered. For example, C-S-H contributes more to the mechanical properties than Ca(OH)$_2$ crystals.

For the mortar-brick combinations there is less evidence for the penetration of hydration products into the pores (Oppermann and Rudert, 1979). It is more likely that in many cases of mortar-brick contact the interlock is restricted to the brick surface with its numerous voids, cracks and fissures.

Grandet concluded from comparative mechanical testing, performed 7 days and 6 months after specimen production, that no gradual chemical reaction between fired clay and cement occurred. This conclusion is supported by concrete research results as to interfacial microstructures with related materials combinations. The absence of chemical reactions
supports the idea that mechanical interlock is the only significant contribution to bonding at the brick-mortar interface.

2.3 Brick-mortar interaction and bond

2.3.1 Brick suction

2.3.1.1 Initial Rate of Absorption (IRA)

Goodwin and West noted in their "Review of the Literature on Brick-Mortar Bond" (1980) that a great number of investigations, carried out in this field, consisted of experiments to establish a relationship between the suction of the brick and the adhesion of the mortar. After an extensive evaluation of the literature they 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. This conclusion holds, in their point of view, for both bond strength and extent of bond (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. It represents the weight of water absorbed in 1 minute by the bed face of the brick when immersed to a depth of 3 mm in water (water suction from a free water surface). The IRA-values are expressed in kg/m²/min. Other units are:
- g/dm²/min, known in Western-Europe under the name Haller value.
- g/30 sq in./min applied (decreasingly) in the English speaking world.

The relation between the units are:
1 kg/m²/min = 10 gr/dm²/min (Haller value 10) = 20 gr/30 sq in./min

The IRA-values of fired clay bricks may vary significantly. Between low-suction rate and high-suction rate brick the initial rate of absorption of a dry brick may range from ~0.5 to 4-5 kg/m²/min. However, bricks with IRA-values up to 10-12 kg/m²/min are used in masonry as well.

The most desirable value of initial rate of absorption to achieve maximum tensile bond strength is, according to Goodwin and West (1980), 0.8 - 1.2 kg/m²/min. This was derived from test results showing maximum values of strength with bricks having absorption rates of about 1.0 kg/m²/min and lower bond strength values for both lower and higher IRA.

This assertion has been 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.

One of his relevant observations was that the mortar type appeared to have a far greater effect on the tensile bond strength than the initial rate of absorption. In fact, this observation shows the basic drawback of the use of the IRA in view of predicting bond strength: it does not include the interaction between brick and mortar.
review of the literature on mortar-brick bond

Flexural bond testing of walls built of calcium silicate bricks (West et al., 1979) resulted in serious doubts about the value of the initial rate of absorption as an indication of expected bond strength in the case of calcium silicate bricks. It has been observed that the absorption behaviour of calcium silicate bricks markedly differs from that of the fired clay bricks. This may be caused by differences in pore size distribution and pore structure of both brick types. The capillary suction force is believed to play an important role in the noted differences in suction behaviour and its effects on bond strength. This parameter is not covered by the IRA characterization. The problem of suction behaviour in relation to porosity will further be elaborated in Chapter 4, Theoretical Considerations.

2.3.1.2 Water suction out of pastes and mortars.

The brick suction from a free water surface turns out to be different from water suction out of a paste or a mortar. Grandet and Thenoz (1971) measured the mass of absorbed water from a cement paste by fired clay specimens of different porosities. The porosity, characterized by the mean pore diameter, ranged from 0.05 μm to 2.9 μm. The pore content of all specimens was about 16%. The water loss of the cement paste was found to be a function of the mean pore diameter and initial water content of the brick.

![Diagram showing water loss of paste as a function of degree of saturation of brick](image)

<table>
<thead>
<tr>
<th>mean pore diameter</th>
<th>fired clay</th>
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<tbody>
<tr>
<td>A: 0.05 μm</td>
<td></td>
</tr>
<tr>
<td>B: 0.1 μm</td>
<td></td>
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<tr>
<td>C: 0.4 μm</td>
<td></td>
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<tr>
<td>D: 1.7 μm</td>
<td></td>
</tr>
<tr>
<td>E: 2.9 μm</td>
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*Fig. 2.1 Variation in water loss from a cement paste as a function of brick porosity and the degree of saturation of the brick (Grandet and Thenoz, 1971).*
Grandet and Thenoz concluded from their data presented in Fig. 2.1 that,
- the dry fine porous brick (mean pore diam. ca 0.05 μm) absorbs significantly more water from the cement paste than the dry coarsely porous brick (mean pore diam. ca 2.9 μm).
- the suction of the coarsely porous brick drops to about zero at a degree of saturation of ca 35%.
- at 100% of saturation the finely porous brick shows an important absorption as well (tests executed at 70% RH, resulting in moisture loss of the brick by evaporation).

Davison (1961) quantified the difference between water absorption from a free water surface (IRA) and water loss of a fresh mortar due to brick suction. In a test series he studied the water loss of three fresh mortar types during a 5 min. period of contact with bricks in six IRA ranges. He observed that the moisture content losses of each mortar increased as the IRA of the bricks increased up to a certain value and subsequently dropped for further increasing IRA values (Fig. 2.2). Hence, the total uptake by very high IRA brick was lower than the uptake by intermediate IRA brick. It can be noted as well that moisture losses of mortars decreased as the mortar retentivity increased.

**Fig. 2.2** Moisture loss of fresh mortar versus brick suction (contact time 5 min.), (Davison, 1961).
Figs 2.1 and 2.2 show a clear difference between moisture loss of pastes and mortars. It may be assumed that a low IRA of fired clay corresponds with a low mean pore diameter (hence, in Fig. 2.1 brick type A will show a low IRA and brick type E a high IRA). The IRA values of Fig. 2.2 were determined on dry bricks. Consequently, water losses of cement pastes presented in Fig. 2.1 (with a degree of saturation of 0%) can be compared with the water losses of the mortars of Fig. 2.2. The differences may be attributed to variations in initial water content and water retentivity.

2.3.2. Mortar composition

2.3.2.1 Changes in mortar due to brick suction.

Effects of compaction.
As a result of the brick suction changes take place in the mortar. Anderegg (1942) reported variation in compaction over the cross-section of the mortar after brick suction. He found that the higher the initial absorption rate, the greater was the tendency to form a highly congealed layer of mortar on the brick surface. The layer showed a permeability varying inversely with the initial suction of the brick. Anderegg suggested that the layer may act as a barrier which decreases the water suction from a mortar.

A stratification in compaction was also found by Détriche (1981, 1985). He studied the effects of brick suction on mortar stiffening by means of measuring the shear resistance at different positions in the mortar with a modified needle of Vicat. The one-sided suction tests (simulation of rendering layer on walls) were performed with (non-)porous substrates and pastes/mortars.

In brick-mortar combinations Détriche observed two effects as a result of the brick suction:
- an increase of the mortar stiffness. This phenomenon was found to be caused by compaction only (decreasing distances between grains due to water uptake by bricks). The increase in stiffness occurred during the period immediately after brick-mortar contact. The degree of stiffening was the same over the whole cross-section of the mortar if the mortar thickness was small compared with the brick thickness. At a high mortar-brick thickness ratio a stratification in compaction over the cross-section of the mortar was observed: high stiffness in the vicinity of the absorbing brick, the stiffness decreasing with the distance from the contact surface brick-mortar.
- the early set of the cement starts significantly earlier if the mortar is well compacted.

The tests indicate that the degree of compaction, the stratification of compaction and the effects on cement binding are a function of the suction rate of the brick and mortar properties like initial water/cement ratio and water retentivity.

The compaction of the mortar, caused by brick suction, may have important effects on the ability of the mortar to flow (plasticity) and, as a consequence, to adhere to a maximum of brick surface. The decrease in plasticity may be influenced by lime and additives like air-entraining agents and viscosity modifiers. These components improve the water retentivity of
the mortar.

Brick suction and water retentivity are interactive parameters. That is why they have to be adapted to each other:
- if the water retentivity is too high in relation to the brick suction, the brick may "float" on the mortar, resulting in slowing down of brick laying and impaired bond.
- if the water retentivity is too low in relation to the brick suction the brick layer may have difficulty in spreading the mortar, and an insufficient amount of water may be available at the brick-mortar interface for hydration of the cement.

The addition of retentivity improving components to the mortar does not only influence the plasticity during brick laying but affects other mortar properties as well (composition, water/cement ratio etc.). This is probably an important reason why it turned out to be impossible to establish relationships between water retentivity and bond strength.

**Effects of drying shrinkage**

Mortar deformation is also influenced by drying shrinkage. The drying shrinkage of mortars is normally determined by means of test cubes cured under controlled conditions. The measured values are then \( (9-14) \times 10^{-4} \) (Baker, 1979; Brouns, 1983). It is difficult to relate these values to masonry, as (i) the water/cement ratio of mortar between bricks is not the same as in the tested cubes (ii) the drying conditions over the cross-section of mortar and brick may vary significantly. Due to the varying drying conditions the shrinkage will differ locally. This may cause shrinkage cracking: an example is the often observed cracking at the outer portions of the brick-mortar interface. A comparable way of shrinkage cracking, also caused by unfavourable local drying conditions, may occur at the mortar-brick interface (Lawrence and Cao, 1988) of high-suction rate bricks in contact with mortar. Consequently, drying shrinkage may result in impaired bond. The negative effects of drying shrinkage may be reduced by favourable curing conditions and compatibility of mortar and brick properties.

**Effects of changing water/cement ratio.**

For mortars normally used in masonry practice, the initial water/cement ratio is about 1.0. The brick suction causes a reduction of the water/cement ratio of the mortar.

Kjaer (1991) showed that brick suction has a great influence upon the strength of the hardened mortar in the mortar joints. Comparing compressive strength of mortars hardened between bricks and mortars hardened in steel moulds (hence, without suction losses) the first were found to be significantly higher (in a number of cases twice as high) than the latter. More and more it is recognized that the brick suction influences the mechanical properties of the mortar. This finds its reflection in attempts made to include the compressive strength of mortar from joints (Schubert, 1988; Wohln and Riechers, 1990) in new masonry codes.

Little is known about the water-cement ratio distribution over the cross-section of the mortar joint. It may be assumed that the water distribution will be influenced by water retentivity, compaction effects and brick suction. As a consequence water gradients are believed to occur
review of the literature on mortar-brick bond

at the transition zone between mortar to brick. This will result in variation of water-cement ratio in the interface and in the mortar body. It is to be stressed that bond may strongly be influenced by a rather large number of local effects at the brick-mortar interface.

**Transport effects in the mortar**

Due to water movement from mortar to brick fine particles in the mortar may be transported to the interface. Habib and Leeds (1957) suggest that the bond is affected by the flow of water carrying cementitious particles from the body of the mortar to the mortar-brick interface.

Dekker (1987) concludes from SEM-observations that for a good mortar-brick bond cement particles have to precipitate from the mortar on the brick surface causing bond between brick and mortar by means of hydration. These observations are in agreement with the findings of Grandet and Lawrence/Cao (Grandet et al., 1972; Lawrence and Cao, 1987).

Another effect of brick suction is assumed to be the concentration of air bubbles at the interface, when air-entrained mortars are used. The transport effects may cause changes in sand/binder ratio and water-cement ratio at the interface and as a consequence influence the local bond capacity and hydration conditions. Hence, mortar-brick bond may be affected by this phenomenon.

**2.3.2.2 Mortar constituents**

**Sand**

In masonry research relatively little attention has been paid to the role of sand in mortars with regard to bond. Sand grading, grain form, type of material, sand content are known to influence the water requirement and water retention of a mix. That is why effects on mortar-brick interaction are assumed to occur.

The significant influence of sand on the water requirement of masonry mortars was emphasized by several workers:

- van Balen (1990) found that mortars with very fine sand (often used in Belgium) require, for a defined consistency, up to 50% more water than similar mortars containing 'normal' sand (grading within the recommended envelope of the code). The fine sand mortars showed also a substantially better water retention.
- comparison of the water content of mortars (with similar consistencies) composed of different sand types (river sand, quartz and dorsilit) showed differences ranging from 30 to 50% for the same grading (Groot, 1987(b)).
- Schneider (1977) carried out an extensive evaluation of the effects of sand with regard to the water requirement of masonry mortars. He arrived at the conclusion that a characterization of sand by means of the grading curve or the grain size index does not provide a reliable comparative indication of the water requirement. This coincides with
the established influence of the grain form (which can not be covered through a grading description). For the characterization of sand he introduced the so-called water requirement coefficient, being the water requirement in weight % of a mortar mix of 250 g Portland cement 350F and 1000g of dry sand with a slump of 19 ± 0.5 cm. Compression tests showed, according to Schneider, that the evaluation of sands as to their applicability to masonry mortars using the water requirement coefficient was more reliable (and less expensive) than by means of a sand grading curve or the grain size index number. The coefficient should not exceed a value of 30.

*Hydrated lime and ground lime stone*

Calcium hydroxide (hydrated lime) and calcium carbonate (ground lime stone) are important components in a number of mortar types. Hydrated lime has been applied since centuries in masonry mortars. Ground lime stone is often used in modern masonry cement. Both play an important role with regard to the water retentivity of the mortar. The hydrated lime is chemically active in triggering the cement hydration; as a long-term effect relevant to durability carbonation has to be mentioned. The ground lime stone is believed to act mainly as an inert admixture. Consequently, the effects of lime and lime stone on bond may be different. Also, the traditional lime-cement mortar varies in other respects from the modern masonry cement mortar:

- the cement/binder ratio (in which the binder is cement + lime) of a 1:1:6 (by volume) lime-cement mortar is about 0.66 (by mass), while lower ratios, 0.50-0.55, are often observed in masonry cement mortars.

- the addition of a.e.a in masonry cement diminishes the quantity of water in a mortar, needed for a required consistency; this results in a lower water-cement ratio than that of the traditional lime-cement mortar (modern lime-cement mortars contain a.e.a. as well).

*Binder:sand ratio*

The binder/sand ratio of a mortar may markedly influence the mechanical properties of masonry. However, a simple relationship between binder/sand ratio and bond strength does not exist. The reason is that an increase of bond strength is not only a function of cement quantity but depends on the availability of water for hydration. This may be illustrated by comparing the hydration conditions in the interface of a high-suction rate brick brought in contact with a 1:3 mortar and with a 1:6 mortar (Högberg, 1967). Both mortar types require roughly the same amount of water for a similar consistency, hence the water/cement ratio of the 1:6 mortar will be twice as high as that of the 1:3 mortar. The final water/cement ratio of the mortar, after suction of the high suction brick, may be significantly more favourable as to cement hydration for the 1:6 mortar than with the 1:3 mortar. However, the opposite will hold if these mortars are combined with a low suction-rate brick. Water requirement, water/cement ratio and water retentivity are affected as well by the type of binder used. This is due to differences in specific surface and physical absorption of the binders.
review of the literature on mortar-brick bond

Air-entraining agents
The use of air-entraining agents (a.e.a.) has become common practice in masonry. Some effects of a.e.a. on the mortar are:
- improvement of the workability by better plasticity and water retentivity, elimination of bleeding, decrease of water content and improvement of frost resistance.

Investigations on bond strength show that air-entrainment has a negative effect on the development of bond (Högberg, 1967; Lawrence and Cao, 1988).
The microstructural reasons for this effect may be:
- the reduction of bond area at the interface; several workers (Högberg, 1967; Oppermann and Rudert, 1983; Kreijger et al., 1983) observed a concentration of bubbles at the interface; as to bond not only the reduced bond area but also the stress intensifying effect of voids is believed to decrease the strength. The air bubbles are sometimes connected, forming air-slits at the interface. Kreijger, Bijen and Wiebenga (1983) suggested that the size of the air bubbles (Opperman and Rudert, 1983) and hydrophobic action of the brick surface might explain the origin of the air-slit development. The occurrence of increased hydrophobic action was verified by means of preliminary testing (marked effect of a.e.a. on calcium silicate bricks, limited effect on fired clay bricks).
- a change of the hydration conditions at the interface as a result of the occurrence of air bubbles; according to Lawrence and Cao this is due to a limited formation of the Ca-rich base on the brick surface before subsequent deposition of cement hydrates. The Ca-rich film was found to form around the bubble surfaces rather than the brick surface.

Oppermann and Rudert (1983) and Gosh (1990) noted that regarding the occurrence of air in mortars, not the air content alone does influence bond strength. Gosh compared the bond strength of a number of air-entrained Type M mortars (similar air content) composed with different a.e.a. and mixed by means of different techniques. The measured bond strengths varied substantially. From the analysis of the test results he suggested that a fine, uniform bubble structure would favour strength, while an irregular structure would harm strength. Oppermann and Rudert arrived at the same conclusion for silicate brick-mortar combinations. The better bond performance of mortars containing fine bubbles may be attributed, in their opinion, to the higher amount of contact surface found at the interface than with mortars containing coarse bubbles.

2.4 Bond strength.
As discussed previously, brick characteristics and mortar composition will affect the microstructure of the interface and consequently influence the development of bond between brick and mortar. The evaluation of the effects of brick suction on (i) the hardening conditions of the mortar (degree of cement hydration) (ii) local variations in mortar composition, may help to explain the substantial differences in bond development observed for the various brick-mortar combinations used in masonry.
2.4.1 Brick-cement paste bond strength

Grandet et al. (1972) correlated observations on interfacial microstructures of brick-paste combinations with tensile bond strength values obtained from testing of similar combinations. Attributing the mortar-brick bond strength first of all to the mechanical interlock of ettringite crystals penetrated into the brick pores, he arrived at the conclusion that the tensile bond strength should increase with the increase of the mean pore radius of the brick. This conclusion seems to be confirmed by the test results presented in Fig. 2.3.

![Graph showing tensile bond strength between cement paste and brick as a function of the mean pore diameter and initial moisture content conditions of the brick](image_url)

**Fig. 2.3** Tensile bond strength between cement paste and brick as a function of the mean pore diameter and the initial moisture content conditions of the brick (presentation as a graph of Fig. 1 (Grandet et al., 1972)).

Comparing the tensile bond strength values of Fig. 2.3 with the brick-paste suction data from Fig. 2.1, however, it is clear that not only the mean pore-diameter but also the degree of hydration may play an important role as to the development of bond strength. This can be illustrated by evaluating the changes in water/cement ratio in the paste caused by brick suction.

The initial water/cement ratio of the cement paste was, according to Grandet, 0.27. The water loss of the paste caused by the suction of the finely porous brick (mean pore diam. 0.05 μm) will halve the water/cement ratio of the paste (see Fig. 2.1), while only a slight decrease of water/cement ratio is to be expected for the combination paste/coarsely porous brick (mean...
pore diam. 2.9 μm). Consequently, the conditions for cement hydration are more favourable for the paste in contact with coarsely porous brick. The better performance of the saturated combinations may be explained as follows: no water loss or less water loss of the mortars may be expected if saturated substrates are used (see Fig. 2.1). This implies an improvement of the hydration conditions of the pastes for all combinations under these low initial water-cement ratio conditions.

2.4.2 Brick-mortar bond strength

2.4.2.1 Low-suction rate fired clay bricks

Lawrence and Cao (1988) studied the bond strength development for low suction rate bricks with four types of mortar. They varied the initial water content of the bricks (6, 11, 14 %). Flexural bond strengths were determined after 7 days of air curing (bond wrench test procedure). For all combinations bond strength decreased with increasing initial water content of the brick (see Fig. 2.4).

![Graph showing flexural bond strength as a function of mortar composition and initial water content of a low-suction rate brick](image)

<table>
<thead>
<tr>
<th>Mortar Comp.</th>
<th>W/C Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:0.6</td>
<td>1.01</td>
</tr>
<tr>
<td>1:1.6</td>
<td>1.17</td>
</tr>
<tr>
<td>1:0.6*</td>
<td>0.81</td>
</tr>
<tr>
<td>1:1.6**</td>
<td>1.36</td>
</tr>
</tbody>
</table>

* cement : lime : sand (by vol.)
* AEA : 0.7% on weight of cement
** AEA : 1.5% on weight of cement

Fig. 2.4 Flexural bond strength as a function of mortar composition and initial water content of a low-suction rate brick (Graph representation of Table 1 from (Lawrence and Cao, 1988)).
review of the literature on mortar-brick bond

Lawrence and Cao explained the differences in bond strength development by evaluating the effects of brick suction (saturated and dry) on the interfacial microstructure development:
- the water suction by the saturated bricks will be low; consequently, the penetration of the mortar into the brick will be minimal and there will be a high porosity at the interface due to the high local water/cement ratio; both effects will contribute to low bond strength. The high mortar porosity at the interface was confirmed by the examination of the microstructure of the saturated brick-plain cement interface which showed coarse, hydrated crystals).
- the bond strengths for the lime-cement mortars were believed to be lower due to the higher water/cement ratio of the mortar and a possible excess of calcium hydroxide at the interface.
- it was assumed from the evaluation of paste-brick interfaces that the microstructures of lime-cement mortars should be denser and more continuous than that of cement mortars.
- the air-entrainment appeared to have a detrimental effect on the bond strength.

2.4.2.2 High-suction rate fired clay bricks

There are frequent references in the literature to poor bond quality between fired clay with a high initial rate of absorption and mortar (Palmer and Parsons, 1934; Anderegg, 1942; Haller, 1958; Albrecht and Schneider, 1964). This may be attributed to a lack of water available for cement hydration at the interface.

The bond strength of high-suction rate bricks may be increased in several ways:
- prewetting of the bricks was found to have a positive effect: the cement hydration in the case of high-suction bricks (contrary to low-suction bricks) is favoured by the decrease of capillary suction. Reservations about the effectiveness of prewetting in site practice (seldom done, wetting never uniform) are quite realistic. Therefore it is considered to be wiser to solve the problem by means of changing the mortar composition.
- adaptation of the mortar to the high-suction conditions can be aimed for. Palmer and Parsons (1934) showed that an increase of the water retentivity may improve bond. The better bond is then attributed to the higher final water-cement ratio in the mortar favouring cement hydration. Högberg (1967) advocates the use of lean mortars (binder-sand ratios of from 1:5 to 1:6) in combination with high absorption bricks. These mortars show a high initial water content and low retentivity. The extra available water is assumed to contribute to the bond. The favourable influence of a high initial water content of the mortar, if applied with high IRA bricks, was observed by Kampf (1963) and Baker (1979) as well. Baker found for 4 mortar types, brought into contact with a fired clay brick (IRA: 3.2 kg/m²/min), a marked increase of bond strength by increasing the flow of the mortar. Baker concluded that (with rather high suction rate bricks) maximum bond strengths were attained with mortars of wettest workable consistency. Högberg (1967) concluded from experimental data that a reduction of bond was especially noticeable on strong absorbent materials when air-entraining agents were used.

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2.4.2.3 Calcium silicate bricks

Oppermann and Rudert (1979, 1983) carried out shear bond strength tests on brick-mortar combinations accompanied by SEM observations of mortar, brick and interface. Four calcium silicate brick types and two fired clay brick types were used in combination with portland cement (1:4), cement-lime (1:2:8) and lime (1:3) mortars. They arrived at the following conclusions:

- masonry mortars with particularly good bond behaviour are characterized by: early set, high water retentivity and small air voids (air-entrained mortars) with a narrow range of size distribution.
- the mortar type appeared to have an important effect on the shear bond strength: the portland cement mortars performed significantly better than the lime-(portland cement) mortars.
- no relation could be established between the IRA of the calcium silicate bricks and the shear bond strength. West et al. (1979) arrived at the same conclusion for flexural bond strength of calcium silicate brickwork.
- from the test results they concluded, that a relationship between the internal specific surface of calcium silicate brick and shear bond strength may exist. However, more research has to be carried out to establish the assumed relationship.
- the shear bond strength between fired clay and mortar was found to be always higher than that of comparable calcium silicate combinations.
- the shear bond strengths were higher for the low-suction (IRA: 0.71 kg/m²/min) clay brick than for the medium-to-high suction rate (IRA: 2.74 kg/m²/min) brick.

In an attempt to relate water absorption of calcium silicate bricks over a long period, instead of the initial rate of absorption, to bond strength, Anstotz (1990) compared the 24 hours’ water absorption coefficient (kg/m²/√h) of a number of bricks with tensile bond strength values. For combinations of 6 types of calcium silicate bricks and 3 mortar types he found:

- the lower the water absorption of the brick the higher the tensile bond strength between mortar and brick.
- a significant effect of the mortar type on the tensile bond strength.

2.4.2.4 Sand grading and bond strength

Anderson and Held (1986) investigated the influence of sand grading on the bond strength of lime-cement mortars (1:1:6) in contact with three types of brick. Four sand gradings were used with specific surface areas ranging from 8.7 to 17.1 m²/kg (calculated values from grading curve data). The three brick types were a low-suction rate wire cut brick (IRA: 0.46 kg/m²/min), a medium-suction rate semi-pressed brick (IRA: 2.03 kg/m²/min) and a low-suction rate calcium silicate brick. The initial water content of the bricks was varied in the test series. Some of the test results are shown in Fig 2.5.
review of the literature on mortar-brick bond

![Wire cut brick (IRA 0.46)](image)

<table>
<thead>
<tr>
<th>Sand</th>
<th>Spec.Surf.Area [m²/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.7</td>
</tr>
<tr>
<td>2</td>
<td>13.2</td>
</tr>
<tr>
<td>3</td>
<td>10.4</td>
</tr>
<tr>
<td>4</td>
<td>17.7</td>
</tr>
</tbody>
</table>

All mortars 1:16 [by vol.]

![Semi-dry pressed brick (IRA 2.03)](image)

![Calcium silicate brick](image)

**Fig. 2.5**  Bond strength as a function of brick type, sand grading and initial water content of the brick. (Anderson and Held, 1986).

Anderson and Held concluded, among other things, that (see Fig. 2.5)
- sand gradings can have a marked influence upon the properties of mortar and tensile strength of mortar to bricks: the greater the fines content, the lower the bond strength.
- sand 1 which had the coarsest grading invariably gave the highest bond strengths. This, however, may have been influenced by the fact that the mortar containing this sand had the lowest water-cement ratio at the required consistency.
- both the clay brick types (low and medium IRA) showed lower bond strength with increasing initial water content whereas the calcium silicate brick gained strength with increased initial water content of the bricks.
The test results of Anderson and Held on calcium silicate brick-mortar bond as a function of the sand fineness and initial water content are contested by other test results (de Dreu, 1982). Substantial differences in brick characteristics (suction behaviour) and mortar properties (initial water/cement ratio, air content) essentially hamper the comparative interpretation of the test results of both investigations.

Sneck (1978) studied the influence of sand grading on the bond strength between a clay brick type of a rather high suction rate (IRA: 3 to 4 kg/m²/min) and a lime-cement mortar (35/65/500 by mass). Using a very fine, a standard and a very coarse grading he found that the mortar with the coarse sand was clearly inferior as to interaction characteristics like bond strength and column compressive strength (the coarse mortars performed well in prism testing: high prism bending strength and prism compressive strength). Snack assumed that the high initial water content of the fine-sand mortar was advantageous when this mortar was brought into contact with the rather high-suction rate bricks (sufficient water remains available for hydration of the cement after brick suction). Tests performed by Gérard, Dugnoli and Wattiez (1985) showed that no bond strength at all developed between clay bricks of very high suction rate (IRA 10 - 12 kg/m²/min!) and cement mortars (300 kg cement/m³ sand) containing very fine sand (more than 45% of the sand passing φ 0.150 mm). This total lack of bond could not be attributed to an excessive water loss of the mortar. Microstructural effects at the interface like local changes in mortar composition might explain this phenomenon. The bond strength with the very high suction brick increased with coarser sand grading. An increase could be noted as well for all combinations when the bricks were wetted.

2.4.2.5 Conditions in situ

Curing

Temperature, humidity and air movement may considerably influence the hardening conditions of the mortar. Effects of temperature and humidity were studied by Isbener (1969). He pointed out that the hydration of cement continues only as long as the environmental relative humidity of the mortar exceeds about 85%. He found that the relative humidity at a depth of 1/8 of the thickness of the brickwork reduced to 80% after three days of drying at 28 °C and 50% relative humidity. Hence, hydration in the outer portion of the joint ceased after three days. Other measurements showed that hydration at the quarter-points and centre of the brickwork proceeded for 12 and 15 days, respectively. Moreover, shrinkage cracking in the outer part of the joints may reduce the section of the bond surface. Both tensile and flexural bond strength are affected by these phenomena: as flexural strength is largely determined by the strength of the material in the outer fibres, the drying rate at the outer portion of the mortar joints is most important.

The effect of the curing conditions on bond strength was verified by laboratory testing: Baker (1979) observed that air-cured test specimen showed a marked increase in bond strength when they were water-cured. Goodwin and Saunders (1988) reported, for calcium silicate bricks, a significant improvement in flexural bond strength with increased time of initial cover (28 days compared with 3 days) when tested at an age of 1 year.
review of the literature on mortar-brick bond

Environmental conditions like low temperature, low relative humidity, dry air, violent air movement are believed to influence considerably the hardening conditions on site.

Workmanship
It has been appreciated for a long time already that the quality of workmanship can have a marked effect on the bond between brick and mortar. Many workmanship factors affect bond achieved in practice (Baker, 1979): pressure applied to the joint while laying, area of contact, thickness of joint, movement of brick after initial placement, laying conditions, elapsed times between mixing, spreading and laying.
These factors may be influenced substantially, as explained previously, by non-compatibility of brick and mortar properties.

2.5 Extent of bond (water permeability of masonry)

The research on the water permeability of masonry walls was extensively reviewed by Grimm (1982).
A summary of the damage caused by insufficient water tightness may explain the interest in this phenomenon:
Water damage may include dimensional change, corrosion, decay, efflorescence, freeze-thaw spalling or splitting, increased heat transmission, condensation, deterioration of interior finishes and building contents, and tenants inconvenience (Robinson and Baker, 1975). The mode of water entry into the face of masonry focuses the attention on the importance of the extent of bond:
Leakage may take place through masonry units, but more usually it occurs through channels at the unit-mortar interface. As a consequence the density of the interfacial microstructure and the continuity of mortar-brick contact will be important parameters with regard to water permeability (a complete extent of bond does not necessarily imply a high bond strength: this depends on the type of hydration products formed at the interface). Lawrence and Cao (1988) concluded from interfacial mortar-paste examination that lime may play an important role in achieving dense and continuous microstructures.

Workmanship and compatibility of masonry unit and mortar are assumed to influence water permeability of walls more than other factors.
With respect to the material properties Grimm recommended:
- to specify low-lime mortars in winter and with low-suction bricks,
- to use Type III (high-early strength) portland cement in winter,
- to specify high-lime mortar with high-suction bricks in summer,
- to avoid the use of mortar materials containing air-entraining agents, unless the air content of the mortar is known to be less than 14 percent,
- to wet bricks having an IRA greater than 1.29 kg/m²/min prior to laying.

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2.6 Concluding remarks

The present knowledge of mortar-brick bond is based principally on mechanical and permeability experiments, supported by characterization methods to describe brick and mortar properties.

The prediction of the bond strength and permeability is found to be hampered by an incomplete understanding of the interaction effects of the great number of parameters (see Table 2.1), insufficient property characterization of brick and mortar and micro-effects, difficult to quantify (mortar compaction, transport of fines and air-bubbles). The examination of the mortar-brick interface by means of micro-level techniques (X-ray diffraction, SEM and related techniques) provided a beginning insight into the nature of the bond mechanisms (there are still many problems left due to the limited number of test programmes performed in this field).

The micro-level test results confirmed the ideas obtained from phenomenological testing that water plays a key role with regard to bond. It may be assumed, evaluating the interfacial microstructure, that the hydration of cement (conditions and effects) and the composition of the hardened material at a micro scale determine to a large extent mortar-brick bond.

A common characteristic of mechanical and micro-level testing methods is that both are focused on the study of properties of masonry assemblies after hardening of the binder. These test methods are up to now insufficiently linked with what is happening (effects of water flow) in the mortar immediately after mortar-brick contact.
3 RESEARCH METHODOLOGY

3.1 Introduction

Mortar-brick bond may be studied in different ways depending on the objective of the investigation. Many studies are concerned with property verifications of masonry assemblies. Examples in this field are the determination of bond strength and water permeability. The results of these determinations provide most valuable information about important characteristics of assembly behaviour in masonry practice. An important restriction of this type of tests is, however, that they only characterize aspects of final bond performance. Consequently, the contribution to the understanding of bond mechanisms is of a rather indirect nature.

Investigations focused on gaining a better insight into the phenomenon of bond are believed to be more effective by studying the processes occurring in the masonry assembly from the first moment of mortar-brick contact after brick laying up to complete hardening of the binding agent. The reason is that information may be obtained on changes in the mortar effecting the final bond development.

Changes in mortar and brick may be investigated by means of various techniques, ranging from micro to macro level. It is clear that with each of the applicable methods specific aspects of the bond problem can be investigated. Therefore, it may be assumed that an interrelated use of techniques and methods will be the most effective way to study the mechanisms of mortar-brick bond.

3.2 Effects of water on bond and outline of research methodology.

From the literature review it is to be concluded that water plays a key role in the process of bond development. Substantial gaps in knowledge of the influence of water have been noticed.

These are the main reasons to focus this study on the effects of water on bond.

Most of the workers assume that the hydration conditions of the mortar are of great importance for the development of a good mechanical interlock between mortar and brick. However, quantitative data about the hydration conditions in the mortar are barely available.

As a consequence, the evaluation of bond development has been, up to now, more or less limited to deductive and comparative interpretations of the effects of water on the hydration of mortars.

In order to validate ideas about the influence of water on bond it is essential to have at one’s disposal detailed and quantitative information about water content changes in the mortar during the setting and hardening period of the binder.

A problem in this respect is the lack of suitable experimental methods to monitor water content changes in test specimens.

That is why a first priority of this study will be the development of an appropriate testing technique.

The next step will be the evaluation of the hydration conditions of the mortar by means of
the obtained water content data, followed by the development of hypotheses on expected bond behaviour. These hypotheses have to be compared with the results of mechanical testing (bond strength) and, eventually, permeability testing (water tightness). It must be expected, as was shown in the literature survey, that relationships between water content and bond are influenced by air content, sand grading, changes of the mortar composition, micro suction effects etc. in the interfacial zone of mortar and brick. Consequently, the application of other experimental methods such as SEM-techniques, X-ray analysis and micro-hardness tests may be necessary to explain the effects of water in relation to the mechanical performance.

3.3 Experimental approach

Water flow

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, starting from a known initial distribution: analysis of changes in water/cement ratio.
- the (change of the) water content gradient at the interface mortar-brick: analysis of changes in water/cement ratio.
- the water flow rate in the mortar during suction: estimation of transport of fine particles.

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 (Neumann and Reppmann, 1988). It was decided, after consideration of the available facilities and possibilities at the TU-Delft, to develop a non-destructive measuring technique using
research methodology

neutron radiography.

*Test specimen.*
It was found before that research on bond, directed to establish relationships between the individual properties of mortar and brick, had been quite unsuccessful. Hence, the study of the effects of water on mortar-brick bond is believed to be most effective if masonry assemblies (combinations of brick and mortar) are used. For this reason brick-joint-brick combinations will be applied as specimens in the test programmes. Choices with regard to composition and dimensions of the test specimen will notably be influenced by the objective to relate the results to masonry practice. For this reason,
- the bricks and mortars have to represent types normally used in masonry structures,
- no special arrangements will be made to optimize the brick surface (e.g. by means of grinding or polishing),
- the production of the specimen will take place as much as possible according to normal brick laying procedures. However, measures will be taken to ensure plan parallelism of the bed faces and constant joint thickness.

**3.4 Modelling of water transport**

*Aim of modelling*
The aim of modelling of water transport in the case of mortar-brick bond should be, the development of methods for the calculation of water flow from mortar to brick in order to quantify the initial flow rates and the final water content of the mortar after suction. Approximations on the initial flow rates may then be useful regarding the interpretation of possible transport effects in the mortar and data on the final water content of the mortar may be practical with respect to the evaluation of the hardening conditions of the binder. The advantage of modelling is that from a limited number of experimentally determined data, water transport for different suction conditions of the brick (depending on its initial water content) and different retentivity of the mortar may be calculated.

*Unsaturated flow theory (UFT).*
Water flow in soils has been studied in agro-hydrology since some decades. The results are used for the prediction of water rise from ground water levels (crop growth conditions: water uptake by roots) and for the evaluation of infiltration problems (flood irrigation and inundation).
The soil can be considered as an unsaturated porous medium in which water flow can be modelled by the so-called Unsaturated Flow Theory (UFT), an extended Law of Darcy. Hall et al. (1977) proved that the UFT theory is also applicable to porous building materials such as fired clay bricks.
At the present state of the art it is theoretically possible to calculate the water absorption of a brick (for different initial water contents) from a free water surface by means of the UFT.
However, data needed for the calculation of the moisture dependent diffusivity \( D(\psi) \) of a material, an essential parameter in the flow equation, are difficult to determine. Simple measuring techniques for the determination of the diffusivity would considerably facilitate the use of the UFT.

In order to determine the diffusivity of soils gravimetric sampling is widely used in laboratory practice. However, this is a destructive method, which interferes with water flow processes and, in any case, it is not easy to apply accurately to solid materials. It may be assumed that neutron radiography can be used as a non-destructive method for the determination of diffusivity as well. Fundamentally, it must be possible to describe the process of water loss of a mortar by means of the UFT. The first steps in this field can be taken by applying this theory to experimentally determined data on the water loss of mortars, as a function of time, in brick-mortar-brick specimens.

**Limitations of modelling.**

Water transport calculation through the unsaturated flow theory may become an interesting tool to predict water loss of mortars caused by brick suction. Its use, however, will be limited to suction processes of short duration, due to the influence of cement hydration on the flow process.

As only mean values of the water content of the mortars can be determined, assessment of the hydration conditions at the mortar-brick interface remains a problem. Therefore, it may be assumed that the prediction of the effects of suction through UFT on the water content of the mortar is more promising for the evaluation of the compressive strength of masonry than for that of the mortar-brick bond strength.

### 3.5 Micro techniques

The effects of water on bond are of particular interest with respect to the hydration conditions and the mortar composition in the interfacial zone of mortar and brick.

In order to establish relationships between the test data on

(i) the interfacial water-cement ratio during hydration,

(ii) the expected influence of the flow rate on the interfacial mortar composition,

and the mortar-brick bond strength, the micro studies will be focused on the analysis of composition gradients of the interfacial zone.
4 THEORETICAL CONSIDERATIONS

4.1 Introduction

A number of models have been developed to describe water transport from mortar to brick just after brick laying. These models are based on capillary pressure theory and unsaturated flow theory. The advantages and drawbacks of these models are discussed in this chapter. The theories will be compared to the test results (see Chapters 7 and 8).

4.2 Initial rate of absorption (IRA) and capillary pressure theory

The initial rate of absorption (IRA) is used in masonry practice as a characterization of absorption behaviour of the masonry unit (see Chapter 2). The determination of the IRA is extremely simple and, for this reason an attractive characterization method. Unfortunately, the IRA is essentially a single point measurement. Data about the rate of water uptake over extended periods of time provide normally more reliable information on suction behaviour. This is due to the fact that initial suction irregularities can be corrected for quite simply with more test data. The relevance of the IRA-characterization stems from the assumption that relationships exist between IRA-values and mortar-brick bond strengths. Several workers established relationships, which, subsequently, were contested by others. As a consequence, this item has been under discussion up to these days.

Absorption from a free water surface

More insight into the applicability of the initial rate of absorption as a means to predict bond behaviour can be gained by relating the IRA to capillary pressure theory. For the application of this theory the brick is assumed to consist of a system of open, parallel, cylindrical capillaries 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 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 meniscus elevation $H$ as a function of time is given by:

$$H = \sqrt{\frac{\sigma r}{2\eta}} \times \sqrt{t}$$  \hspace{1cm} (4.1)

in which,

$r$ : radius of capillary (m)

$\sigma$ : surface tension of water (N/m)

$\eta$ : dynamic viscosity (Ns/m²)

$t$ : time (s)
theoretical considerations

Hence, the mass of water (m) absorbed by the capillary after a period of time t is given by:

\[ m = \pi r^2 \cdot \sqrt{\frac{\sigma r}{2\eta}} \cdot \sqrt{t} \cdot \rho \]  

(4.2)

in which,
- \( m \): mass of absorbed water (kg)
- \( \rho \): density of water (kg/m³)
- other symbols, see eq. (4.1).

Equation (4.2) can also be formulated as follows:

\[ m = c \cdot r^{2.5} \cdot \sqrt{t} \cdot \rho \]  

(4.3)

From the equations 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 form, varying pore diameter, pore direction, interconnections of capillaries, closed pores etc.). However, it has been observed by many workers, see e.g. Gummerson et al., 1981(a), 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:

\[ m' = A \sqrt{t} + C \]  

(4.4)

in which,
- \( m' \): mass of absorbed water per unit area (kg/m²)
- \( A \): water absorption coefficient (kg/m²/√s)
- \( t \): time (s)
- \( C \): intercept value (kg/m²)

The explanation of the successful application of the \( \sqrt{t} \)-law for porous media lies, according to Gummerson (1981), probably in the fact that the surface effects, as a result of different porosity at the surface than in the bulk of the brick, are of short duration and are 'swept' into the constant intercept value \( C \), whilst air-diffusion from deeper layers depends on \( \sqrt{t} \), just as the capillary absorption process does. It should be emphasized that the \( \sqrt{t} \)-law describes only the one-dimensional case. This may partly explain the contradictory findings of Palmer (1934), Morgan (1977) and Wagner & Niesel (1989).
theoretical considerations

Water absorption from the mortar

The IRA is often thought to be related to water absorption of a brick out of a mortar. Test results of some workers point in the opposite direction,

- Davison (1961) found that, normally, the loss of water is higher in combinations with intermediate IRA bricks than in those with low IRA bricks.
- Sneck (1978) observed that a calcium silicate brick with a high initial rate of absorption absorbed less water from the mortar than one with a lower IRA.

As to this, it turns out to be useful to consider the differences between free and restrained water movement. The free water absorption (IRA determination) is not hindered by several types of forces working in a mortar. To be mentioned are: capillary forces, physical adsorption by the mortar constituents and, in a later stage, chemical binding of water due to hydrolysis and hydration. Brick and mortar must, in fact, be considered as two separate pore systems and the interaction between these systems determines the water flow.

The water movement from mortar to brick can then be approximated as the absorption of water from mortar pores with a certain mean radius by brick pores with smaller pore radii. As a consequence coarse pores (25-50 μm), often found in very high IRA bricks, do not contribute to the water loss of the mortar (while they do contribute to the water absorption from a free water surface).

A similar reasoning can be held on the problem reported by Sneck. Calcium silicate bricks normally show a wide spectrum of pore radii: a considerable number of pores with radii smaller than 0.1 μm (45-65%) and at the same time a percentage of 15-30% of pores with radii of 5-30 μm. Therefore, a high percentage of coarse pores may lead to high IRA and relatively low water loss of mortars, as coarse pores are inactive in this case. From this approach it can be understood that high IRA bricks do not necessarily absorb more water from mortars than intermediate IRA bricks.

Another aspect of capillary behaviour, important with regard to mortar-brick bond, is the capillary suction force. The effect of this force is most clearly expressed by the maximum elevation \( H_o \) of the meniscus in an open capillary. Taking into account the gravity. \( H_o \) is given by:

\[
H_o = \frac{2\sigma}{\rho a}
\]  
(4.5)

in which,

\[ \begin{align*}
\sigma & : \text{surface tension of water (N/m)} \\
\rho & : \text{density of water (kg/m}^3) \\
a & : \text{gravitational acceleration (m/s}^2) 
\end{align*} \]

Hence, the maximum capillary elevation is inversely proportional to the pore radius. Compare e.g. the elevation in open capillary tubes of 0.05 μm and 50 μm: these are 296 m and
0.296 m respectively. From equations (4.5) and (4.3) it is to be deduced that finely porous materials (like calcium silicate bricks) will show a stronger suction and at the same time a slower absorption of water from a mortar than coarsely porous materials (like fired clay bricks). Grandet (1972) assumed that higher capillary suction may impair the reaction of hydration, resulting in weaker bond. The possibly negative effect of higher capillary suction cannot be derived from IRA data.

The main conclusions are:
- the initial rate of absorption, used in combination with pore distribution data of the absorbing unit, may provide a tool to understand in a semi-qualitative way the transport of water from fresh mortar to brick,
- the relationship between the IRA and bond strength turns out to be very dubious.

4.3 Mean Hydraulic Diameter Model

Détriché (1985) proposed, in a study on rendering mortars, to evaluate water transport effects with the help of a mean hydraulic diameter model. Using this capillary permeability model, mean pore diameters of the capillary systems of mortar and brick can be determined. By means of these data Détriché tried to explain differences in water flow from mortar to brick for various combinations and the desiccation of the rendering layer by evaporation etc. In the classical model (Carman-Kozeny theory) the porous medium is assumed to be equivalent to a conduit of a, on the average, constant area, although the cross-section normally has an extremely complicated shape. In analogy with the established practice in hydraulics, the channel diameter \( D(H) \) governing the flow rate through the conduit is assumed to be four times the hydraulic radius (Dullien, 1991), defined as the flow cross-sectional area, divided by the wetted perimeter, that is,

\[
D(H) = \frac{4 \times \text{void volume of medium}}{\text{surface area of channels in medium}} \quad (4.6)
\]

The mean hydraulic diameter of the applied bricks can be calculated from data on pore volume and internal specific surface determined by means of mercury porosimetry. The mean pore diameters of the fresh mortars can be determined from comparable data of the mortars i.e. initial pore volume and specific surface values of the mortar components.

Potentiality and drawbacks of the model

The porosity of the brick as well as that of the mortar are taken into account in this theory. The use of the mean hydraulic diameter model can be considered as a first approach leading to a semi-quantitative characterization of the two distinct pore systems. However, the mean pore radius characterization shows an identical drawback as the IRA, both level out the differences in suction behaviour due to differences in pore distribution.
Another drawback of this theory arises from the fact that the mean hydraulic diameter of the bricks is determined at dry samples. As a consequence the suction behaviour of wet bricks is not covered by the mean pore radius approach. The interpretation possibilities of the mean hydraulic diameter theory with regard to water flow will further be explored by comparing the theory to the test results of the water flow rate measurements (see Chapter 8). Moreover, in Chapter 8 an attempt will be made to model the retention behaviour of the mortar more adequately by applying the capillary pressure theory on a system of particles. By means of this theory it may be feasible to assess the effects of decreasing water content and mortar compaction on the water pressure in the water.

4.4 Unsaturated Flow Theory (UFT)

The dynamic moisture transport in unsaturated porous media can be described (neglecting gravitational effects) by means of equation (4.7) developed by Philip and De Vries (van der Kooi, 1971):

\[
\frac{\partial \psi}{\partial t} = \nabla(D(\psi)\nabla\psi) + \nabla(D(T)\nabla T)
\]  

(4.7)

in which, 
\[
\psi \quad \text{= volumetric moisture content (m}^3/\text{m}^3\text{)}
\]
\[
T \quad \text{= temperature (°K)}
\]
\[
D(\psi) \quad \text{= diffusivity due to a moisture gradient (m}^2/\text{s})
\]
\[
D(T) \quad \text{= diffusivity due to a temperature gradient (m}^2/\text{s})
\]

This equation can be considered as an extended form of Darcy's law. Its validity in describing the flow of water through inert homogeneous soils (agro-hydrology) has been well established since some decades. The UFT is a macroscopic approach (Hall, 1977) of water flow: only average flows across planes whose dimensions are much larger than the pore dimensions are examined. Hence, no attempts are made to relate permeability to pore size distribution and pore structures. The assumption of Darcian behaviour appears to be invalid, according to Hall (1977), at

- high flow velocities (less important in our case),
- the presence of solutes,
- pore blocking by mobile particles (colmatage).

The variation of water flow with temperature is controlled by the temperature dependence of the surface tension (\(\sigma\)) and the viscosity (\(\eta\)) (Gummerson et al., 1980(b)) and proportional to \(v(\sigma/\eta)\). A change in temperature from 10° to 20°C causes an increase of water absorption of about 13%. This means that the temperature effect in the case of water absorption from a free water surface is quite substantial. Gummerson believes that the temperature effect on water flow for brick in contact with fresh mortar will be less significant (Gummerson et al.,

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theoretical considerations

1981(a)). In brick laying practice substantial variation in temperatures may occur, e.g. winter-summer, but also temperature differences between mortar and brick. Consequently, the effects on water flow (and hydration) must be considered. Taking into account the possible temperature effects it is preferable to perform tests under controlled conditions.

The isothermal description of water flow in an unsaturated porous medium can be derived by eliminating the right hand member of equation (4.7):

\[
\frac{\partial \psi}{\partial t} = \nabla \cdot (D(\psi) \nabla \psi)
\]  

(4.8)

Equations (4.7) and (4.8) represent three dimensional descriptions of water flow. Brick suction from a free water surface and from fresh mortars can usually be considered as examples of one-dimensional water flow. In this case the isothermal flow equation (4.8) can be written as:

\[
\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left( D(\psi) \frac{\partial \psi}{\partial x} \right)
\]  

(4.9)

in which,

\( \psi \) : volumetric water content \((m^3/m^3)\)

\( t \) : time \((s)\)

\( x \) : place \((m)\)

\( D(\psi) \) : diffusivity due to a moisture gradient \((m^2/s)\)

Equation (4.9) may be transformed into an ordinary differential equation by applying the Boltzmann transformation:

\[
x(\psi,t) = \phi(\psi)t^{-1/2}
\]  

(4.10)

subject to the boundary conditions

\( \psi(0,t) = 1 \) (\( \psi \) saturated) = 1)

\( \psi(x,0) = 0 \)

Equation (4.9) then transforms into:

\[
2 \frac{d}{d\phi} \left( D \frac{d\psi}{d\phi} \right) + \phi \frac{d\psi}{d\phi} = 0
\]  

(4.11)
theoretical considerations

subject to $\psi(0)=1$ and $\psi(\infty)=0$

At this point the absorption problem is expressed entirely in terms of $\phi$ and $\psi$. Therefore, one may expect that the solution will be a unique function $\phi(\psi)$, which for each porous medium is determined by its particular $D(\psi)$ function and the boundary conditions.

When $\phi$ is known, the cumulative absorption $i$ is given by equation (4.12):

$$i(t) = t^{1/2} \int_0^1 \phi \, d\psi = S \cdot t^{1/2} \quad (4.12)$$

in which,

$i$ = volume of absorbed water per unit area (m)
$t$ = elapsed time (s)
$S$ = sorptivity (m/s)

Equation (4.12) is the hydrological equivalent of equation (4) (without intercept value). This means that the solution of the flow equation in the one-dimensional case is in accordance with the test results on water absorption from a free water surface by a porous medium like fired clay bricks.

N.B.
For the $\sqrt{t}$ water absorption law to hold, four conditions must be met:
- the capillary absorption flow must be normal to the inflow face, and not be converging or diverging,
- the material must be homogeneous in the flow direction,
- water must be freely available at the inflow surface (by direct contact with an unlimited reservoir),
- gravitational effects must be negligible in the absorption process.

**Diffusivity $D(\psi)$**
The diffusivity $D(\psi)$ is a characteristic material constant, depending on the type of material, the pore structure and pore volume, the moisture content of the material and the type of liquid absorbed (surface tension and viscosity). The relation between $D(\psi)$ and the water content of a porous medium can experimentally be determined and turns out to be a rather complicated function, see Fig. 4.1 curve 1. Simplified diffusivity functions are represented by the curves 2 and 3.
theoretical considerations

![Diagram of Moisture Content and Diffusivity](image)

1. moisture-diffusion: vapour transport 1a, liquid transport 1b (from experimental data)
2. domains with constant values of $D(\psi)$, (model)
3. exponential function of $D(\psi)$, (model)

Fig. 4.1 Diffusivity functions (van der Kooi, 1971)

Symbols used in Fig. 4.1:
- $D(\psi)$: diffusivity due to a moisture gradient (m$^2$/s)
- $\psi_c$: critical moisture content: transition from vapour transport to liquid transport (m$^3$/m$^3$)
- $\psi_s$: moisture content at saturation (m$^3$/m$^3$)

In order to solve the moisture transport equation (4.9) it may be useful to simplify the function of $D(\psi)$. At constant diffusivity $D(\psi)$, for example, it is possible to solve the equation analytically (Koo revaar et al., 1983). By means of modelling the diffusivity in two branches (Fig. 4.1), one with low constant $D(\psi)$ for $\psi$-values lower than the critical moisture content and the other with high constant $D(\psi)$ for values higher than the critical moisture content, such an analytical solution can be found.

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theoretical considerations

However, it is more realistic to assume the function $D(\psi)$ to be variable. In this case equation (4.12) cannot be solved analytically. Data for a number of building materials suggest that the diffusivity varies approximately according to an exponential function (Hall et al., 1983):

$$D(\psi) = D_0 \exp(B \psi)$$  \hspace{1cm} (4.13)

This is based on the determination of $D_0$ ($D(\psi)$ for $\psi=0$) and $B$ (a material constant) by means of gravimetrically determined absorption profiles (Kalimeris, 1984).

In this study $D(\psi)$ will be approximated for one of the brick types, using absorption profile data determined by means of a neutron radiography technique. A numerical method, developed by Augenbroe (1984), will be used for solving the moisture transport equation and estimating the diffusivity function (see Chapter 8).
experimental techniques

5 EXPERIMENTAL TECHNIQUES

5.1 Neutron transmission measurements

5.1.1 Introduction

From the literature (Neumann and Reppmann, 1988) it is known that for the study of water transport phenomena in ceramic materials neutron transmission may be applied as a research technique. 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 5.1. the cross sections pertinent to bricks and mortars are given:

Table 5.1. Scattering ($\sigma_s$) and absorption ($\sigma_a$) cross sections of elements normally present in brick or mortar (Sears, 1986)

<table>
<thead>
<tr>
<th>Element</th>
<th>$\sigma_s$ ($10^{-24}$ cm$^2$)</th>
<th>$\sigma_a$(0.1308nm)$^*$ ($10^{-24}$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>38</td>
<td>0.242</td>
</tr>
<tr>
<td>O</td>
<td>4.235</td>
<td>0.00014</td>
</tr>
<tr>
<td>Na</td>
<td>3.28</td>
<td>0.386</td>
</tr>
<tr>
<td>Mg</td>
<td>3.708</td>
<td>0.46</td>
</tr>
<tr>
<td>Al</td>
<td>1.504</td>
<td>0.168</td>
</tr>
<tr>
<td>Si</td>
<td>2.178</td>
<td>0.124</td>
</tr>
<tr>
<td>S</td>
<td>1.026</td>
<td>0.39</td>
</tr>
<tr>
<td>Ca</td>
<td>3.05</td>
<td>0.31</td>
</tr>
<tr>
<td>Fe</td>
<td>11.83</td>
<td>1.86</td>
</tr>
</tbody>
</table>

* 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.

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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.

5.1.2 Neutron transmission

The transmission of a neutron beam by a sample of thickness $\ell$ is given by:

$$I = I_o \exp \left\{ -\ell \sum \mu_i \right\}$$  \hspace{1cm} (5.1)

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

$$\mu_i = n_i (\sigma_s^i - \sigma_a^i)$$  \hspace{1cm} (5.2)

with $n_i$ the particle number density of element $i$, and $\sigma_s^i$ and $\sigma_a^i$ the cross sections for scattering and absorption, respectively rewritten:

$$\sum \mu_i = \mu_d + \psi \mu_w$$  \hspace{1cm} (5.3)

with $\mu_d$ the attenuation coefficient of dry brick or dry mortar, $\mu_w$ the attenuation coefficient of water and $\psi$ 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 (5.1) and (5.3) follows:

$$\psi = \frac{1}{\mu_w \ell} \ln \left( \frac{I_o}{I_w} \right) - \frac{\mu_d}{\mu_w}$$  \hspace{1cm} (5.4)

$(\varphi = 100 \psi$: water content in % by volume)$

with $I_w$ the intensity of neutrons transmitted by the wet brick or mortar.

For the precise determination of $\psi$ the influence of the dead time of the detector has to be considered, see Appendix 8.

Elaboration

The effects of attenuation of the beam intensity in a water containing brick is graphically illustrated in Fig. 5.1. Dry brick attenuation and water attenuation are separately presented. The relation between intensity ln$I$ and thickness $\ell$ is linear (see eq. (5.1)). The attenuation of dry brick and water were experimentally determined by means of transmission measurements
on samples of different thickness, see Fig. 5.6.

![Diagram of beam intensity and thickness](image)

**Fig. 5.1**  
*Attenuation of beam intensity for a water containing brick.*

The attenuation of dry brick material and water in the brick can, with reference to eq. (5.1), be expressed by:

$$I = I_0 \exp\left[-(l_y \mu_{d} + l_x \mu_{w})\right]$$  \hspace{1cm} (5.5)

The water content of the brick, as visualized in fig. 5.1, is given by:

$$\psi = \frac{l_y}{l_x}$$  \hspace{1cm} (5.6)

where, $\psi$: volume fraction of water

From eq. (5.5) and (5.6) follows:

$$I = I_0 \exp\left[-(l_y \mu_{d} + \psi l_x \mu_{w})\right]$$  \hspace{1cm} (5.7)

which leads to eq. (5.4).
5.1.3 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 5.2:

<table>
<thead>
<tr>
<th>Wave length [nm]</th>
<th>Neutron Flux [cm⁻²s⁻¹]</th>
<th>Intensity [s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1308</td>
<td>1.3 \times 10⁶</td>
<td>2.8 \times 10⁴</td>
</tr>
</tbody>
</table>

The neutron beam was monitored with a low efficiency monitor-detector (M) and the cross section restricted to 25x10 mm² 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 \(^3\)He 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 (section 5.1.3.1) and a monitoring technique (section 5.1.3.2). These techniques were used to study various aspects of water transport.

5.1.3.1 Scanning technique (lift facility)

In this test set-up (see Figs 5.2 and 5.3) 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. 5.2 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. 5.3 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).
experimental techniques

The specimen lift is operated through a computer program written for continuous data collection over longer periods of time. There are two ways of operation, either the transmitted neutron beam is measured while the lift remains in one position during a number of measurements - LEVEL mode - or the lift is raised or lowered a constant step between each measurement - SCAN mode -. Combined LEVEL and SCAN mode operation is possible.

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

5.1.3.2 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. 5.4  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 5.4 and 5.5) 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).

![Figures 5.5](image)

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)
5.1.4 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. To this end specimens of different thickness were prepared (see Fig. 5.6).

Fig. 5.6 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.

The measured data were corrected for background intensity. The attenuation coefficients of the bricks and water were calculated by means of linear regression analysis of the intensity (ln(I)) - thickness (ℓ) relationship (see Fig. 5.1). The results are presented in Table 5.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \mu ) (m(^{-1}\times 10^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extruded clay brick (dry)</td>
<td>(EB) 0.181(2)</td>
</tr>
<tr>
<td>Machine moulded clay brick (dry)</td>
<td>(MB) 0.143(1)</td>
</tr>
<tr>
<td>Calcium silicate brick (dry)</td>
<td>(LB) 0.254(2)</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
</tbody>
</table>
Containers of different thicknesses were used for the determination of the attenuation coefficients of the dry mortars. The dry mix was placed and compacted in these containers. The density of the dry mix during the transmission measurements differs from that of the dry components under real mix conditions, due to water and entrained air. Taking into account this difference, the attenuation coefficient of the dry components in the real mix is given by:

$$\mu(\text{in mix}) = \frac{\rho(\text{in mix})}{\rho(\text{meas.})} \mu(\text{meas.})$$  \hspace{1cm} (5.8)

in which,

- $\mu$ (in mix) : attenuation coefficient of $\Sigma$ dry components in mortar mix $(\text{m}^{-1})$
- $\rho$ (meas.) : density of measured dry mortar (in test containers) $(\text{kg/m}^3)$
- $\rho$ (in mix) : density of $\Sigma$ dry components in the mix, calculated from the mortar composition (see Table 5.4) under real mix conditions $(\text{kg/m}^3)$
- $\mu$ (meas.) : measured attenuation coefficient of dry mortar (in test containers) $(\text{m}^{-1})$

The calculated values of the mortar attenuation coefficients are accurate to $\pm 1 - 2 \%$.

### Table 5.4. Attenuation coefficients of dry mortar components.

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ meas $(\text{m}^{-1} \times 10^2)$</th>
<th>$\rho$ meas $(\text{kg/m}^3)$</th>
<th>$\rho$ in mix $(\text{kg/m}^3)$</th>
<th>$\mu$ in mix $(\text{m}^{-1} \times 10^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS1</td>
<td>0.208</td>
<td>1990</td>
<td>1690</td>
<td>0.177</td>
</tr>
<tr>
<td>PCS2</td>
<td>0.215</td>
<td>2020</td>
<td>1770</td>
<td>0.188</td>
</tr>
<tr>
<td>PCS3</td>
<td>0.219</td>
<td>2040</td>
<td>1730</td>
<td>0.186</td>
</tr>
<tr>
<td>PCS4</td>
<td>0.204</td>
<td>1970</td>
<td>1640</td>
<td>0.170</td>
</tr>
<tr>
<td>PCS5</td>
<td>0.228</td>
<td>2080</td>
<td>1780</td>
<td>0.195</td>
</tr>
<tr>
<td>LCS1</td>
<td>0.250</td>
<td>1890</td>
<td>1810</td>
<td>0.239</td>
</tr>
<tr>
<td>LCS2</td>
<td>0.252</td>
<td>1900</td>
<td>1870</td>
<td>0.248</td>
</tr>
<tr>
<td>LCS3</td>
<td>0.256</td>
<td>1920</td>
<td>1830</td>
<td>0.244</td>
</tr>
<tr>
<td>LCS4</td>
<td>0.247</td>
<td>1880</td>
<td>1780</td>
<td>0.234</td>
</tr>
<tr>
<td>LCS5</td>
<td>0.274</td>
<td>1980</td>
<td>1880</td>
<td>0.260</td>
</tr>
<tr>
<td>MCS1</td>
<td>0.204</td>
<td>1910</td>
<td>1780</td>
<td>0.190</td>
</tr>
<tr>
<td>MCS2</td>
<td>0.209</td>
<td>1940</td>
<td>1750</td>
<td>0.189</td>
</tr>
<tr>
<td>MCS3</td>
<td>0.213</td>
<td>1960</td>
<td>1750</td>
<td>0.191</td>
</tr>
<tr>
<td>MCS4</td>
<td>0.206</td>
<td>1920</td>
<td>1690</td>
<td>0.181</td>
</tr>
<tr>
<td>MCS5</td>
<td>0.223</td>
<td>2010</td>
<td>1790</td>
<td>0.198</td>
</tr>
</tbody>
</table>
5.2 Other techniques

- Tensile bond test (ASTM C 952)
  The cheap crossed brick couplet test is a useful method for assessing variations in tensile bond properties of masonry assemblies. The method provides good qualitative information on the mode of rupture. However, the variation of the test results is quite considerable (coefficient of variation > 10%).

- Flexural tensile bond test (ASTM D 1635, modified as proposed by Harris (1990)).
  Most of the flexural bond tests are quite labour-intensive. For a comparative test series a rapid and easily performed technique has been applied as proposed by H.A. Harris during the 5th North American Masonry Conference (Champaign, Illinois, 1990). The method is based on the point flexural test apparatus as described in ASTM 1635 (in the testing practice applied for soil-cement beams).

Figure 5.7  Testing device for flexural tensile bond test determination. On the left-hand side before, on the right-hand side after rupture of the test specimen.

- Mortar composition
  The following air content tests were carried out:
  . in fresh mortar before brick laying (ASTM C-185)
  . vacuum porosity of hardened mortars (NEN 2871)

Mortar consistency (DIN 1060 Teil 3)

- Brick composition
  The following air content tests were carried out:
experimental techniques

. Vacuum porosity (NEN 2871)
. Pore distribution measurement (mercury porosimetry).

- X-ray diffraction
  . See chapter 7.4.
6 TEST PROGRAMME

6.1 Selection criteria for sample constituents

The samples consisted of brick-mortar-brick combinations of which,
(i) water transport phenomena were studied by means of neutron radiography,
(ii) hydration products were analyzed in the mortars using X-ray diffraction,
(iii) bond strength properties were determined by means of mechanical testing.
The main selection criteria for the bricks and mortars, used in the test specimens, were the
variations in hygric properties and the relevance of a choice with regard to its use masonry
in practice.
Different water suction behaviour was the leading hygric criterion for brick selection.
Variation in suction expressed as the amount of water a unit can absorb, early and long-
term absorption rate and capillary pressure have been considered. With a view to the
important variation in behaviour between fired clay bricks and calcium silicate bricks, both
are covered in the test series.
The choice of the fired clay bricks was discussed in the Committee "Durability of
Masonry". After evaluation of a number of brick types, commonly used in masonry
practice, a low absorption wire cut brick and a high absorption machine moulded brick
were selected. Advised by the Research Institute of the Dutch Calcium Silicate Industry a
representative calcium silicate brick type was chosen for the test programme.

As to the composition of the mortars the following has been considered:
- for the study of the effects of water transport, significant variations in the initial
  water/air ratios and water/cement ratios are desirable. This consideration coincides with
  the research objective to investigate the differences in bond behaviour of traditional and
  modern mortars. In traditional mortars these ratios are usually high whereas in modern
  air-entrained mortars they are low.
- as a substantial influence of the sand grading on water transport behaviour and bond
  properties is to be expected, different sand mixtures were applied. To ensure constant
  composition of the mixtures, they are composed of fractions of defined grain sizes (test
  results on the consistency as a function of the water content showed excellent reproducibility).
Five different sand mixtures were included in the test series (see Table 6.2).
A finely (S4), a coarsely graded (S5) mixture and one graded in between (S3) are
composed in such a way that they fit the left hand curve, the right hand curve and an
intermediate curve of the recommended grading envelope of the Dutch Standard on
Masonry (NEN 3835). To study the effects of very fine inert material quartz flour was
added to two sand mixtures (see Table 6.2, the two mixtures (S1) and (S2) are derived
from (S4) and (S3) by replacing 10% and 5% of the grain sizes 0.125<d<0.250 by
quartz flour).

One series of traditional and two series of modern air-entrained mortars were prepared
with the 5 sand mixes. The aggregate/binding agent ratios represent typical combinations
as used in masonry practice. Lime-cement mortars (1:1:6 by volume) were applied in the

51
first series (lime without a.e.a.). The latter series comprised air-entrained cement mortars (1:4.5 by volume) and masonry cement mortars (1:3 by volume). The mortars, investigated in the test programme, were, for reproducibility reasons, composed of weight fractions. For further information on the mortars see Table 6.4.

6.2 Sample characteristics

The bricks

The three brick types with explicitly divergent absorption behaviour are:
- an extruded clay brick (EB), fine pores
- a machine moulded clay brick (MB), coarse pores
- a representative calcium silicate brick (LB)

Some brick characteristics are presented in Table 6.1.

Table 6.1 Brick characteristics

<table>
<thead>
<tr>
<th>Brick type</th>
<th>EB</th>
<th>MB</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1990</td>
<td>1630</td>
<td>1710</td>
</tr>
<tr>
<td>Pore volume (% by volume)</td>
<td>25</td>
<td>39</td>
<td>27</td>
</tr>
<tr>
<td>Initial Rate of Absorption (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in (kg/m²/min)</td>
<td>1.5</td>
<td>4.4</td>
<td>(2.5)’</td>
</tr>
<tr>
<td>in (g/dm²/min): Haller value</td>
<td>15</td>
<td>44</td>
<td>(25)”</td>
</tr>
</tbody>
</table>

’) the applicability of the IRA as a characterization of the absorption behaviour of calcium silicate bricks is rather contested.

Remarks

The Dutch machine moulded brick shows a remarkably high porosity and water absorption capacity. This "spongy" brick is widely used in masonry practice.

The pore size distribution of the bricks was determined by means of mercury porosimetry. The results are presented in Fig. 6.1):
Fig. 6.1. Pore size distribution of EB, MB and LB.
test programme

The mortars

Sand

The aggregate of the mortars consisted of Dutch river sand. This sand type has a rounded grain form, resulting in a relatively low water requirement for mortars of a defined consistency.

The grading characteristics of the 5 sand mixtures are shown in Table 6.2.

Table 6.2  Sand mixtures (grading: mass %)

<table>
<thead>
<tr>
<th>grain size [mm]</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP6 *)</td>
<td>10</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.125&lt;d&lt;0.250</td>
<td>20</td>
<td>15</td>
<td>20</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>0.250&lt;d&lt;0.500</td>
<td>30</td>
<td>25</td>
<td>25</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>0.500&lt;d&lt;1.00</td>
<td>30</td>
<td>35</td>
<td>35</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>1 &lt;d&lt; 2</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>2 &lt;d&lt; 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Totals</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

*)  SP6: quartz flour; grain size quantities:
    d < 63 µm: 94%; d > 40 µm: 54 %; specific surface 200 m²/kg (Blaine)

Binding agents

Cement, masonry cement and lime are used as binding agents. The properties of the cements are presented in Table 6.3.

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

The lime characteristics meet the specifications of ASTM C 207 type S-Special hydrated lime. The lime (Supermekal, produced by NEKAMI) contains more than 90% of calcium hydroxide, has a density of 2250 kg/m³ and a bulk density of 400-425 kg/m³; 95% (m/m) of the material passes the sieve of 95 µm and the Emley plasticity P is >200. Specific surface 1500 m²/kg (Blaine). The lime does not contain any a.e.a.
Table 6.3  
**Cement properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Masonry Cement</th>
<th>Portland Cement A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific surface (m²/kg)</td>
<td>638</td>
<td>307</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>1070</td>
<td>1250</td>
</tr>
<tr>
<td>Density (kg/dm³)</td>
<td>2950</td>
<td>3150</td>
</tr>
<tr>
<td>Setting (Vicat):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>begin (min)</td>
<td>145</td>
<td>115</td>
</tr>
<tr>
<td>end (min)</td>
<td>220</td>
<td>175</td>
</tr>
<tr>
<td>Strength (28 days):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>compressive (N/mm²)</td>
<td>8</td>
<td>49</td>
</tr>
<tr>
<td>bending (N/mm²)</td>
<td>3</td>
<td>9</td>
</tr>
</tbody>
</table>

(specifications according to ENCI, Dutch Cement Industry)

*Water*

The water content of each mortar was determined as a function of a defined consistency (in accordance with DIN 1060 Teil 3, Flow Table Test). With the help of this test it is aimed at the water content to a workability, applicable under practical conditions. An automatic Hagermann flow table is used as testing machine.

*Air*

The air content of air-entrained mortars is known to be remarkably influenced by the applied mixing procedure. Therefore the mixing was carried out according to a standard procedure (DIN 1164, Teil 7, using a Hobart mixer type N-50). Tillman mortar stabilizer TM was used as a.e.a. for the portland cement mortars. For each mortar type the quantity to be applied was determined as a function of the desired air content (14-15%). The a.e.a. of the masonry cement has been added during production at the factory. So, variation in air-content of the mortars may be possible (see MCS1-mortars).

The air content of the mortars (after mixing) is established in conformity to ASTM C-185.

The data on the mortar properties are collected in Table 6.4.
Table 6.4  Mortar characteristics

<table>
<thead>
<tr>
<th>PC mortars</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>C:S (v/v)</td>
<td>1:4.5</td>
<td>1:4.5</td>
<td>1:4.5</td>
<td>1:4.5</td>
<td>1:4.5</td>
</tr>
<tr>
<td>C:S (m/m)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1919</td>
<td>1969</td>
<td>1952</td>
<td>1887</td>
<td>1974</td>
</tr>
<tr>
<td>C/S</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>W/C</td>
<td>0.81</td>
<td>0.74</td>
<td>0.79</td>
<td>0.91</td>
<td>0.67</td>
</tr>
<tr>
<td>Sand content (vol %)</td>
<td>53.1</td>
<td>55.1</td>
<td>54.2</td>
<td>51.5</td>
<td>55.8</td>
</tr>
<tr>
<td>Cement content (vol %)</td>
<td>9.0</td>
<td>9.3</td>
<td>9.2</td>
<td>8.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Water content (vol %)</td>
<td>22.9</td>
<td>21.6</td>
<td>22.6</td>
<td>24.8</td>
<td>19.7</td>
</tr>
<tr>
<td>Air content (vol %)</td>
<td>15.0</td>
<td>14.0</td>
<td>14.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Sand content (mass %)</td>
<td>73.3</td>
<td>74.1</td>
<td>73.6</td>
<td>72.3</td>
<td>74.9</td>
</tr>
<tr>
<td>Cement content (mass %)</td>
<td>14.8</td>
<td>14.9</td>
<td>14.8</td>
<td>14.5</td>
<td>14.1</td>
</tr>
<tr>
<td>Water content (mass %)</td>
<td>11.9</td>
<td>11.0</td>
<td>11.6</td>
<td>13.1</td>
<td>10.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LC mortars</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>L:C:S (m/m)</td>
<td>2:5:34</td>
<td>2:5:34</td>
<td>2:5:34</td>
<td>2:5:34</td>
<td>2:5:34</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2087</td>
<td>2129</td>
<td>2109</td>
<td>2067</td>
<td>2137</td>
</tr>
<tr>
<td>C/S</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>W/C</td>
<td>1.22</td>
<td>1.14</td>
<td>1.22</td>
<td>1.29</td>
<td>1.12</td>
</tr>
<tr>
<td>Sand content (vol %)</td>
<td>56.6</td>
<td>58.3</td>
<td>57.2</td>
<td>55.7</td>
<td>58.6</td>
</tr>
<tr>
<td>Cement content (vol %)</td>
<td>7.1</td>
<td>7.3</td>
<td>7.2</td>
<td>7.0</td>
<td>7.4</td>
</tr>
<tr>
<td>Lime content (vol %)</td>
<td>4.0</td>
<td>4.1</td>
<td>4.0</td>
<td>3.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Water content (vol %)</td>
<td>27.3</td>
<td>26.3</td>
<td>27.5</td>
<td>28.4</td>
<td>25.9</td>
</tr>
<tr>
<td>Air content (vol %)</td>
<td>5.0</td>
<td>4.0</td>
<td>4.0</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Sand content (mass %)</td>
<td>71.9</td>
<td>72.6</td>
<td>71.9</td>
<td>71.4</td>
<td>72.7</td>
</tr>
<tr>
<td>Cement content (mass %)</td>
<td>10.7</td>
<td>10.8</td>
<td>10.8</td>
<td>10.7</td>
<td>10.9</td>
</tr>
<tr>
<td>Lime content (mass %)</td>
<td>4.3</td>
<td>4.3</td>
<td>4.3</td>
<td>4.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Water content (mass %)</td>
<td>13.1</td>
<td>12.3</td>
<td>13.0</td>
<td>13.7</td>
<td>12.1</td>
</tr>
</tbody>
</table>
### MC mortars

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC:S (v/v)</td>
<td>1:3</td>
<td>1:3</td>
<td>1:3</td>
<td>1:3</td>
<td>1:3</td>
</tr>
<tr>
<td>MC:S (m/m)</td>
<td>1:375</td>
<td>1:375</td>
<td>1:375</td>
<td>1:375</td>
<td>1:375</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2012</td>
<td>1962</td>
<td>1962</td>
<td>1914</td>
<td>1989</td>
</tr>
<tr>
<td>C/S</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>W/C</td>
<td>1.14</td>
<td>1.06</td>
<td>1.06</td>
<td>1.16</td>
<td>0.96</td>
</tr>
<tr>
<td>Sand content (vol %)</td>
<td>52.9</td>
<td>52.0</td>
<td>52.0</td>
<td>50.2</td>
<td>53.3</td>
</tr>
<tr>
<td>Max.cem.content (vol %)</td>
<td>12.7</td>
<td>12.5</td>
<td>12.5</td>
<td>12.1</td>
<td>12.8</td>
</tr>
<tr>
<td>Water content (vol %)</td>
<td>23.4</td>
<td>21.5</td>
<td>21.5</td>
<td>22.7</td>
<td>19.9</td>
</tr>
<tr>
<td>Air content (vol %)</td>
<td>11.0</td>
<td>14.0</td>
<td>14.0</td>
<td>15.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Sand content (mass %)</td>
<td>69.7</td>
<td>70.2</td>
<td>70.2</td>
<td>69.5</td>
<td>71.0</td>
</tr>
<tr>
<td>Max. cem. cont. (mass %)</td>
<td>18.6</td>
<td>18.8</td>
<td>18.8</td>
<td>18.6</td>
<td>19.0</td>
</tr>
<tr>
<td>(portland A+limestone)</td>
<td>(10.2+8.4)</td>
<td>(10.3+8.5)</td>
<td>(10.3+8.5)</td>
<td>(10.2+8.4)</td>
<td>(10.5+8.5)</td>
</tr>
<tr>
<td>Water content (mass %)</td>
<td>11.6</td>
<td>11.0</td>
<td>11.0</td>
<td>11.9</td>
<td>10.0</td>
</tr>
</tbody>
</table>

**Remark**

The water-cement ratios of the masonry cement mortars are calculated from the cement content (55% by mass) of the masonry cement.

### 6.3 The programme

A number of test series were carried out in order to assess possible relationships between the effects of water transport from mortar to brick and bond strength properties:

**Neutron transmission measurements**

(i) water distribution profiles over the cross-section of a stretch of 50 mm brick-joint-brick combination. The specimen were scanned:
- from 15 min. up to 8 hours following their preparation (every hour).
- after drying at 378 °K, 28 days following their preparation.

The tests comprised the 45 combinations as described in chapter 6.2 (3 brick types, 3 binding agent types and 5 sand gradings). In this series the bricks were, if necessary, wetted according to the recommendations of the industry, to ensure satisfactory behaviour.

Some cases of water movement over a longer period (up to 20h) were studied.
To get an idea on the water distribution profiles of dry brick combinations (a case often encountered in practice) a number of tests on dry MB and LB combinations were carried out as well.
In order to compare site conditions with laboratory conditions (controlled humidity and temperature) some free evaporation tests were included in the programme. Finally some absorption tests from a free water surface were carried out in order to determine the diffusivity coefficients \( \text{D(\psi)} \) of MB, LB and MCS4. The results were used to relate some cases of experimentally determined velocity of water flow out of the mortars to the Unsaturated Flow Theory.

(ii) the velocity of water flow in the middle of the joint and at 2 mm from the upper surface in the lower brick (see chapter 5.1.3). As a result of the analysis of the water distribution profiles the sand gradings (S2) and (S3) have been discarded. However, dry as well as wetted bricks were used to evaluate the influence of the initial water content of the bricks on the absorption velocity. The aim of this test series is to obtain experimental data on the transport conditions of fine material, like cement, lime, ground lime stone, and air bubbles from the mortar to the interface. Combinations of three binding agent types, 3 sand gradings and 3 brick types (EB dry; MB and LB dry as well as wetted) were tested.

**Bond strength tests**

Tensile bond strength and flexural bond strength values were determined from cross couplet testing and 4 point bending testing, respectively (see chapter 5.2). The cross couplets were cured at 65% RH and 20°C; the bending test samples at 95% RH and 20°C. The tests are supposed to provide comparative information about the influence of the curing conditions on bond strength related to the water profile and water velocity data. The same combinations as for the water profile tests were covered in these series.

**X-ray diffraction**

X-ray diffraction was used in order to obtain a better understanding of the hydration conditions and the mortar composition of the mortar, in particular, at the interfacial zone. The attention was focused on differences between masonry cement and portland cement A mortars hardened between EB-, MB- and LB-bricks.

**Other tests**

The pore volumes of the mortars were measured through imbition of water (vacuum method NEN 2981). The data may provide information on the over-all shrinkage of the mortars and the relationship between the effective water-cement ratio and the porosity.
7 TEST RESULTS

7.1 Water distribution profiles by means of scanning technique (lift facility)

7.1.1 Introduction

By means of neutron radiography (scanning technique, as explained in Chapter 5) water distribution profiles were determined over the cross-sections of joints and relevant parts of vicinal bricks. The test results of a series of brick-mortar-brick combinations are evaluated by comparing the changes in water content in mortar and brick due to brick suction and retention characteristics of the mortar. Subsequently, attention is paid to the hardening conditions of the binding agent in the mortar.

The water distributions are visualized in graphs in which the vertical axis represents the scan position [mm] of the specimen and the horizontal axis the related water content [% by volume]. 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 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
S(1...5) : sand grading type

Example: MB15LC$S_4$, abbreviation used for a brick-mortar-brick specimen, consisting of prewetted (~ 15 mass %) machine moulded bricks and a lime-portland cement A mortar containing $S_4$ graded sand (for further details see Chapter 6).

The chemically bound water in the calcium silicate bricks is not presented in the water distribution profiles.

7.1.2 Reproducibility of test results

The reproducibility of the test results is influenced by the test accuracy and the differences in suction behaviour of the individual bricks. The analysis of the test accuracy showed that the imprecision in the test results depends mainly on the neutron beam intensity. The random error, originating from the scatter of the beam intensity, varies as a function of the neutron intensity used in a scan. The relatively long transmission periods, applied in the lift
test results

measurements, result in imprecisions smaller than 1 % in the determination of the water content values (calculation based on counting statistics, see Appendix 8).

By means of comparative testing it was found, that the variations in the test results due to differences in suction behaviour of individual bricks, by far exceed the variations caused by the applied technique.

The results of a series of comparative tests with similar brick-mortar-brick combinations and S1-graded sand are presented in Fig.7.1. Each * in the figure corresponds with a water/cement ratio of an individual test specimen in the middle of the joint, 8 hours after preparation of the test specimen. The w/c ratios are derived from the experimentally determined water content values and the initial w/c ratios of the mortars (marked o in the figure). For further details regarding the calculation procedure see next section.

<table>
<thead>
<tr>
<th>Water / Cement Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30</td>
</tr>
<tr>
<td>EB00</td>
</tr>
<tr>
<td>PCSI</td>
</tr>
<tr>
<td>LCSI</td>
</tr>
<tr>
<td>MCSI</td>
</tr>
<tr>
<td>MB15</td>
</tr>
<tr>
<td>PCSI</td>
</tr>
<tr>
<td>LCSI</td>
</tr>
<tr>
<td>MCSI</td>
</tr>
<tr>
<td>LB07</td>
</tr>
<tr>
<td>PCSI</td>
</tr>
<tr>
<td>LCSI</td>
</tr>
<tr>
<td>MCSI</td>
</tr>
</tbody>
</table>

Fig. 7.1 Water-cement ratios in the middle of the joint for various brick-mortar-brick combinations. S1 sand grading. Test conditions: RH 95%, 20 °C.
i: initial; A, C, C, D: 8 hours after preparation of the brick-mortar-brick assemblies.
test results

It is clear that the variations in water-cement ratio values in the mortar depend on the brick type as well as on the mortar type.
In order to facilitate the interpretation of the test results, the 95% confidence limits of the water-cement ratios have been determined:

Table 7.1 The 95% confidence limits of the water-cement ratios presented in Fig.7.1.

<table>
<thead>
<tr>
<th></th>
<th>Water-cement ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PCS1</td>
</tr>
<tr>
<td>EB00</td>
<td>0.40</td>
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<tr>
<td>MB15</td>
<td>0.49</td>
</tr>
<tr>
<td>LB07</td>
<td>0.13</td>
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</table>

The statistical figures in Table 7.1 show,
- significantly larger 95% confidence intervals for the LB07 water-cement ratios than for the comparable mortar bulk (in the middle of the joint) of EB00 and MB15,
- significant differences with respect to the w/c ratios in the bulk of the PCS1-, LCS1- and MCS1-mortars for the EB00- and MB15-combinations: no overlap of confidence intervals. This is not the case for the w/c ratios in the bulk of the LCS1- and MCS1-mortars in joints between LB07-bricks.

7.1.3 The influence of the brick type, the mortar type and the initial water content of the brick on the water loss of the mortars.

(i) Dry bricks

The form of the water distribution curves is in most cases more or less symmetrical. Deviations of symmetry may be attributed to differences in capillary suction behaviour of individual bricks. The influence of gravitation on the deviations of symmetry turns out to be negligible, since higher water contents are measured in the bricks below as well as above the joints.

The water content values in the cement mortars (PCS1) are nearly identical over the total width of the joint. Sharp moisture gradients are observed from mortar to brick over a stretch of about 2 mm. The effects of the higher water retention of the lime-cement mortars (LCS1) are not only evident from the higher final water contents of the mortar but also from the slightly higher water contents in the middle of the mortar joints of the fired clay brick combinations. The absence of these peak-values in the calcium silicate combinations (LB) is likely due to the considerably higher capillary suction of the very fine pores of this type of brick.
Fig. 7.2 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.
test results

Clear differences in transport behaviour are observed between the fired clay bricks (EB, MB) and the calcium silicate bricks (LB). The water, absorbed by EB and MB, quickly spreads into the bricks, while LB shows a long lasting concentration of water in the vicinity of the brick interface. This points to important variations in the porosity characteristics of the fired clay and calcium silicate bricks, see section 7.2.6.

The graphs, presented in Fig. 7.2, show substantial variations in water loss of the mortars. These losses can easily be calculated by comparing the initial water contents (as given in Chapter 6, Table 6.4) with the values measured after a definite period of mortar-brick contact.

**Water loss in middle of mortar joint**

The initial water contents of the cement mortar (PCS1) and the lime-cement mortar (LCS1), being 22.9 and 27.3 respectively, are marked in the graphs of Fig. 7.2, by dotted, vertical lines in joint areas. The measured water distributions represent the scanned situation after 8 hours mortar-brick contact (8 hours after brick laying).

Table 7.2 shows the effect of brick suction on the water loss of the mortar in the middle of the joints.

**Table 7.2  Water loss of cement mortars (PCS1) and lime-cement mortars (LCS1) due to brick suction (middle of joint) derived from Fig. 7.2. Test conditions: RH 95%, 20 °C.**

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<tr>
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<th>Water loss in middle of mortar joint</th>
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<tbody>
<tr>
<td></td>
<td>PCS1</td>
<td>LCS1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ϕ(init.) [vol %]</td>
<td>ϕ(8h) [vol %]</td>
<td>loss [%]</td>
</tr>
<tr>
<td>EB00</td>
<td>23</td>
<td>12</td>
<td>48</td>
</tr>
<tr>
<td>MB00</td>
<td>23</td>
<td>7.5</td>
<td>67</td>
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<tr>
<td>LB00</td>
<td>23</td>
<td>3</td>
<td>87</td>
</tr>
</tbody>
</table>

With the help of the test results it is possible to obtain indications on the hydration conditions of the cement in the mortars. To this end the initial water content and initial w/c ratio of the mortar, calculated from data on the initial mortar composition, are compared with water content and w/c ratio values derived from the scanned test data. The initial w/c ratios of the PCS1- and the LCS1-mortar are 0.81 and 1.22, respectively (see Table 6.4). These values are related to the following initial water contents (volume %) in the mortars: 22.9% and 27.3% (see Table 6.4 and Fig. 7.2). Subsequently, the w/c ratio in the mortar, at the moment of scanning, can be determined by means of the measured water content values.

Example: EB00PCS1 (Fig 7.2) shows, 8h after the start of the experiment, in the mortar core a water content of ~12% (by volume). Consequently, the corresponding w/c ratio is
test results

\[12/23 \times 0.81 = 0.42\] (The cement content in the middle of the mortar joint is assumed to be constant).

The water-cement ratio changes of the combinations, presented in Fig. 7.2, are collected in Table 7.3,

**Table 7.3** Initial and 8h water/cement ratios in the middle of the joints of Fig. 7.2. Test conditions: RH 95%, 20°C.

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<thead>
<tr>
<th></th>
<th>Water/cement ratio in middle of mortar joint</th>
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<tbody>
<tr>
<td></td>
<td>PCS1</td>
<td>LCS1</td>
</tr>
<tr>
<td>w/c(init.)</td>
<td>w/c(8h)</td>
<td>w/c(init.)</td>
</tr>
<tr>
<td>EB00</td>
<td>0.81</td>
<td>0.42</td>
</tr>
<tr>
<td>MB00</td>
<td>0.81</td>
<td>0.25</td>
</tr>
<tr>
<td>LB00</td>
<td>0.81</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The figures show, that it may be assumed that a high degree of hydration is achieved for the EB00PCS1-combination, while a lower and very low degree of hydration is obtained in the MB00- and LB00-combinations, respectively. The higher water retention of the lime-cement mortar appears to favour significantly the cement hydration of MB00LCS1 and LB00LCS1.

**Water loss at the mortar-brick interface of the joint**

The evaluation of the hydration conditions of the binder at the mortar-brick interface turns out to be far more complicated than that of the mortar cores. For such an evaluation the following data have to be known, (i) water content data over the last hundred of μm of the mortar nearby the brick and (ii) data about the composition of the mortar in the interfacial zone. A technical problem with respect to (i) is the spatial resolution of the neutron transmission measurements, namely 1 mm. Therefore it is not possible to detect deviations of the water content at micro-level. The occurrence of deviations is not hypothetical, as will be explained in Chapter 8.

Regarding (ii) it may be observed that, using for the interfacial zone the 'mean' water content, it is furthermore a problem how to determine the water/cement ratio. This is due to possible changes of the mortar composition in the interfacial zones, caused by transport effects in the mortar (resulting from the brick suction).

Hence, water-cement ratios derived from the water content measurements can only be used as a first indication for the evaluation of the hardening conditions at the interface. To this end the water-cement ratios in the mortar bulk and at the mortar interface of the combinations, shown in Fig. 7.2, are presented in Table 7.4.
test results

Table 7.4 The 8 hours water-cement ratios in the mortar bulk and at the mortar interface. Test conditions: RH 95 %, 20 °C.

<table>
<thead>
<tr>
<th></th>
<th>water/cement ratios in mortars</th>
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<tr>
<td></td>
<td>PCS1</td>
<td>LCS1</td>
</tr>
<tr>
<td></td>
<td>mortar-bulk</td>
<td>interface</td>
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<tr>
<td>EB00</td>
<td>0.42</td>
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<td>MB00</td>
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<td>0.18</td>
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<tr>
<td>LB00</td>
<td>0.11</td>
<td>0.42</td>
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(ii) Prewetted bricks

It is known from masonry practice that the use of dry bricks may result in low mortar-brick bond strength. This may, in particular, be the case with high suction rate fired clay bricks and calcium silicate bricks.

There is a considerable amount of evidence in the research literature that prewetting resulted in increased bond strength (see e.g. Goodwin & West, 1980). In order to study the influence of prewetting on the bond performance of masonry, prewetted bricks have also been included in the test programme. The prewetting conditions are as follows,

- the high-absorptive machine moulded bricks (MB) are prewetted such that an initial rate of absorption (IRA) of 1.5 kg/m²/min is achieved. This value, recommended by the Dutch brick industry, stems, in fact, from Hallers' (1958) conclusion that the IRA of high-quality bricks should not exceed values of 1.5 to 2.0 kg/m²/min.

- the dry wire cut bricks, used in the test series, have an IRA of about 1.4 kg/m²/min. For this reason prewetting of this brick type has not been applied.

- the calcium silicate bricks are prewetted to a water content of ~7% (mass %); recommendation of the industry: 5-8% (mass %).

In Fig. 7.3 the water distribution profiles are presented for the wetted MB- and LB-bricks, combined with portland cement, lime-cement and masonry cement mortars. Comparing the Figs 7.2 and 7.3 it is clear that the water contents (volume %!) in the portland cement mortars of the MB-combinations are affected by the initial water content of the bricks. The water/cement ratio in the mortar bulk is in this case \( \frac{15}{22.9} \times 0.81 = 0.53 \) (compared to \( \sim 0.25 \) for MB00PCS1). The lime-cement mortar and the masonry cement mortar also show reduced water losses combined with prewetted MB-bricks. The water/cement ratios in the bulk of these mortars turn out to be very high. Consequently, it may be assumed that the hardened mortars will show high porosities. The hydration conditions in the interfacial zone may be substantially influenced by the high water content of the machine moulded bricks as well.
Fig. 7.3  Absorption behaviour of prewetted MB- and LB-bricks in contact with various mortar types. The profiles are scanned 8 hours after preparation of the test specimens. Test conditions: RH 95%, 20 °C.
Prewetting of the calcium silicate bricks hardly favours the w/c ratio of the cement mortar, as can be concluded from the comparison of graph LB07PCS1 of Fig. 7.3 with LB00PCS1 of Fig. 7.2. The suction of the prewetted bricks apparently remains high enough to absorb nearly the same volume of water out of the cement mortar as in case of the dry bricks. The effect of the higher water retention of the lime-cement mortar and the masonry cement mortar on the final water distribution is found to be relatively large. For instance, the water-cement ratio in the mortar core of the prewetted combination LB07LCS1 is ~0.56 compared to ~0.31 for the dry combination LB00LCS1.

7.1.4 Effects of evaporation on the water distribution

It should be emphasized that the interpretation of the test results, in the previous section, has been based on water distribution profiles, recorded under controlled laboratory conditions, RH 95% and 20 °C. The high RH was obtained by placing the specimens in an aluminium container during the transmission measurements. The moisture evaporation is negligible under these conditions. Under site conditions moisture may evaporate out of the bricks and joints. The degree of evaporation depends on the environmental conditions. To get insight into the effects of evaporation on the water distribution in the test specimens, various combinations have been tested under RH ~50% and 20 °C.

Fig. 7.4 shows examples regarding the influence of the evaporation on both an EB- and a MB-combination. Water distribution profiles are compared, which have been scanned 1 hour and 8 hours after preparation of the test specimens.

In the EB-combination a decrease of water content, from ~12 to ~7.5 vol. % can be observed in the mortar core. Other measurements with similar EB-combinations, but tested at RH 95 % and 20 °C, show after 8h a water content of 12-13%, see Fig 7.2. The water content at the interface mortar-brick turns out to be 3-4% lower under the 50% RH, 20 °C conditions.

For the MB-combination the decrease in water content in the mortar bulk is negligible during the testing period of 7 hours as presented in the graphs. A significant drop in the water contents, ~5 vol.%, of the bricks can be observed.

It may be assumed that in case of free evaporation, the water distribution over the width of the specimen is not uniform, as drying starts from the outer faces of the test specimen. Consequently, the measured water contents represent mean values. The evaporation may cause lower degrees of hydration and even shrinkage cracking in the outer portion of the joint. The decrease of the water content in the inner part of the brickwork will be less significant. The effect of this on the mortar-brick bond in the inner region of the brickwork depends, among others, on the initial water contents of brick and mortar. The influence of evaporation on the bond strength development is difficult to predict; sometimes trends can be indicated, see Chapter 7.3.
test results

Fig. 7.4 Effect of free evaporation on the water distribution profiles of the combinations EB00PCS1 and MB15PCS1. 1 hour and 8 hours after preparation of the test specimens. Test conditions: RH ~50%, 20 °C.

7.1.5 Influence of the sand grading on the water distribution

As a result of differences in sand grading the initial water contents of the mortars vary for equal consistency (flow table test). In Table 6.4 of Chapter 6 it is shown that for the mortars with sand gradings S3, S4 and S5, the water requirement of the finest sand grading (S4) is always the highest and that of of coarsely graded S5 always the lowest, as is to be expected. The artificial gradings S1 and S2 are derived from S4 and S3, by replacing 10% and 5% of the grain sizes 0.125<d<0.250 by very fine quartz flour (SP6). This results in lower water requirements of the PC and LC mortars than of the coarser gradings S4 and S3. The quartz
the grain sizes 0.125<d<0.250 by very fine quartz flour (SP6). This results in lower water requirements of the PC and LC mortars than of the coarser gradings S4 and S3. The quartz flour particles turn out, in fact, to diminish the friction between the grains. In the MC-mortars there is little or no difference between the water requirements of S4 and S1 and between S3 and S2. Probably, the effect of friction decrease is less apparent in the MC-mortars due to the relatively high content of ground lime stone. For the interpretation of the test results it is important to know whether the brick-suction may result in significant differences in the hydration conditions of the mortars as a function of the sand grading. In order to arrive at reliable conclusions, it is then desirable to dispose of a number of test results for each of the 45 combinations tested in the series. For practical reasons it was not possible to perform so many tests.

Therefore, it was decided to use the 95% confidence intervals of the water-cement ratios of the S1-combinations for an estimation of the differences in w/c ratios of the other sand combinations. Hence, it is assumed that an S1-interval for a defined brick/binder combination holds for the other sand gradings as well. The initial and 8h water-cement ratios in the mortar core and the 95% confidence intervals of the w/c ratios of the S1-combinations are collected in Fig. 7.5. The water distribution profiles from which the w/c ratios have been derived, are presented in Appendix 1.

A first observation to be made is that the most significant decrease of the water-cement ratio occurs in the S4-mortars. The lowest drops are, generally measured in the S1- and S5-mortars. Secondly, lower degrees of hydration are to be expected in the PC-mortars combined with LB07.

Comparing the 95% confidence intervals of the w/c ratios of the S1-mortars in each mortar group, PC, LC and MC, per brick type, with the supposed similar intervals of the mortars containing S2...S5 graded sand, it may be estimated that,

- in none of the mortar groups, combined with LB07, significant differences occur between the 8h water-cement ratios of all 5 sand gradings: there is overlap of intervals.
- in none of the mortar groups, combined with EB00 and MB15 significant differences occur between the 8h water-cement ratios of the sand gradings S3, S4 and S5.
- in the PC- and LC-mortars, combined with EB00 and MB15 significant differences are observed between the water-cement ratios of sand gradings S1 and S5 (and sometimes between S1 and S2 or S3): there is no overlap of intervals. Taking into account the relatively high water-cement ratios in the LC-mortars of the fired clay combinations, it may be concluded that only with respect to the PC-combinations a variation in the degree of hydration may be expected, see further section 7.1.6.

From the estimation in Table 7.5 it is to be concluded that the influence of the sand grading on the hydration conditions in the mortar bulk of the considered combinations is negligible or small.
test results

### Water / Cement Ratio

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**Fig. 7.5**  Initial and 8h water-cement ratios in the mortar core of 45 combinations; 95% confidence intervals of the w/c ratios of the S1-mortars. Test conditions: RH 95%, 20 °C.
7.1.6 Hydration water in the mortars

In the test results, shown in the previous sections, the water content profiles, represent the total volume of, (partially) physically/chemically bound water and free, capillary, water in the mortar. An indication on the degree of hydration in the mortar can be obtained determining the chemically bound water content. This may be achieved by drying the specimen at 105 °C after hardening; physically bound water and capillary water will evaporate at this temperature, while the chemically bound water will remain in the mortar. Characteristic differences between water distribution profiles scanned 8h after mortar-brick contact and profiles determined after 28 days of hardening and subsequently dried at 105 °C, are shown in Fig 7.6 (different specimens were used for both scans).

From the hydration water volume profiles, collected in Fig.7.6 and Appendix 1 it may be concluded, that in most of the mortar cores the hydration water contents are more or less constant over a relatively large stretch over the cross-section of the joint, ~8 mm.

The graphs show substantial variations of physically bound and capillary water, depending on the type of mortar and brick applied. Some insight into the degree of hydration can be acquired by comparing the theoretically determined volumes of hydration water of the mortars, at complete hydration, with the experimentally obtained values.

Taking into account shrinkage due to chemical reactions, the volume of hydration water, at complete hydration of the cement, is given by,

\[
V_{hw} = 0.75 \times 0.25 \times \frac{(\rho_c)}{(\rho_w)} \times V_c
\]  

(7.1)

in which,
\[
\begin{align*}
V_{hw} & : \text{volume of hydration water (m}^3) \\
\rho_c & : \text{density of cement (kg/m}^3) \\
\rho_w & : \text{density of water (kg/m}^3) \\
V_c & : \text{volume of cement (m}^3) \\
0.75 & : \text{factor due to chemical shrinkage} \\
0.25 & : \text{factor indicating the amount (25 mass %) of chemically bound water as a function of the cement content.}
\end{align*}
\]

The cement contents of the PC, LC and MC mortars are 8.7-9.5 %, 7.0-7.4 % and 6.0-6.4 % by volume, respectively (see Table 6.4 of Chapter 6). Consequently, the related volumes of hydration water, at complete hydration, are 5.1-5.6 %, 4.1-4.4 % and 3.5-3.8 %.
Comparison of 8h water distribution profiles with chemically bound water profiles (left hand curves in the graphs). Test conditions of 8h profile specimens: RH 95%, 20 °C. The chemically bound (hydration) water profiles were scanned after 28 days of hardening at RH 95%, 20 °C, and subsequent drying at 105 °C.
test results

The EB00PCS1-combination of Fig.7.6 and the other Portland cement mortar combinations with EB00 and MB15 (see Appendix 1) show volumes of hydration water in the mortar bulk of about 5 to 6%. Hence, a high degree of hydration may be assumed. Comparing the measured degrees of hydration in the mortar bulk of the EB- and prewetted MB-combinations with the estimations made in section 7.1.5, it can be concluded that no significant differences regarding the occurrence of hydration products in the various combinations are observed.

A slightly lower degree of hydration is attained in the PC-mortars combined with the prewetted calcium silicate bricks (values 4-5%). This result is in agreement with the estimation made in the previous section.

The hydration water volumes in the lime-cement mortars include about 2% of hydration water of the calcium hydroxide as well. Consequently, the measured values of the EB00, MB15 and LB07, being 5 to 6%, represent 3-4% of hydration water of the Portland cement. Also regarding the lime-cement mortars it can be concluded that a high degree of hydration is reached.

The MC-mortars show sometimes unexpectedly high hydration water volumes, 3.5-5.5%. This phenomenon might point to non-uniform mixing of cement and ground limestone during the grinding process.

Free evaporation
For various specimens, hardened at RH 50% and 20 °C during 28 days, the hydration water profiles have been recorded as well.

The hydration water profile of LB07PCS1 shows in this case a hydration water volume, of only 3% in the mortar bulk. It may be assumed that the hydration is less complete due to evaporation losses. In fact, the Portland cement mortar combined with LB07 does not contain any 'excess' water to cope with evaporation losses, see graph LB07PCS1 of Fig 7.6.

The final hydrated water volume at the mortar core of LB07LCS1, hardened at ~50% RH and 20 °C, does not essentially differ from the comparable combination hardened at 95% RH and 20 °C. This result emphasizes the relevance of higher water retention values of mortars applied with this calcium silicate brick type and/or measures for improving the curing conditions of young masonry.

From the evaluation of Fig. 7.5 it may be concluded that for various fired clay brick combinations, particularly with PC-mortars, evaporation losses will result in an undesired decrease of the degree of hydration as well.
Gradients
It was supposed that the gradients of the hydration water profiles in the interfacial zones might provide indications of the bond potentiality of a specific brick-mortar-brick combination. In general, it is observed that the gradients in the PC-mortars are steeper than those in the LC- and MC-mortars. This may imply that higher concentrations of C-S-H are closer to the brick surface in the PC-mortars than in the other ones. However, the variation in the gradients in each mortar type is rather substantial, see Appendix 1. Moreover, it is doubtful whether the occurrence of hydration products in the outer zone of the mortar interface can be determined at a desirable micro-level (spatial resolution of the applied measuring technique, 1 mm, insufficient for a reliable interpretation). Consequently, there is no conclusive evidence for the significance of the steepness of the gradient for the development of mortar-brick bond strength.

7.1.7 Mortar porosity

It is assumed that the decrease of the water-cement ratio of the mortar often has a favourable effect on the mechanical properties, in particular the compressive strength, of the mortar. This is attributed to lower pore contents of the mortar when hydrated at lower w/c ratios. However, this assumption may only be true if simultaneously with the water decrease of the mortar, compaction occurs.

The influence of the compaction on the decrease of the porosity of the mortars has been studied, comparing the potential pore volumes of the fresh mortars with the vacuum porosities of the hardened mortars. The potential pore volume is defined as the sum of the initial air and water content of the fresh mortar.

The vacuum porosity measurements were performed on two series of mortar joints, left from mechanical testing, see Chapter 7.3. The first series was hardened at RH 65% and 20 °C, the second series at RH 95% and 20 °C; the hardening period of both series was 28 days. The measured pore contents represent mean values over the total width of the joint.

The potential porosities of the mortars vary for the PC-mortars from 35 to 40 vol.%, for the LC-mortars from 30 to 33 vol.% and for the MC-mortars from 34 to 38 vol.%. Whereas the vacuum porosities of the PC-mortars ranged from 28 to 33 vol.%, of the LC-mortars from 23 to 27 vol.% and of the MC-mortars from 27 to 32 vol.%.

The decrease in porosity of the mortars ranged from 6 to 8 vol.%. The porosity decrease was slightly higher for mortars of the MB-combinations than for mortars of the EB- and LB-combinations. The MC-mortars showed a slightly lower porosity decrease than the PC-and LC-mortars. The porosity decrease turned out to be independent of the water loss of the mortars.
From Appendix 2 it can be derived that the water losses, in the PC-mortars, are always higher than the observed compaction of 6-8 vol.%. The same holds for the LC- and MC-mortars when these are combined with the calcium silicate bricks. The compaction follows the water loss in the LC- and MC-mortars when they are used with fired clay bricks. However, in these combinations the hydration takes place at high w/c ratio.

It may, however, be assumed that due to the absorption process the compressive strength of the mortar in the joint is usually higher than that of the initial composition (with exception of the mortars which harden under unfavourable hydration conditions, see Appendix 2).

### 7.1.8 Reversal of water flow

When the water flow over a longer period of time is studied a reversal of the flow may be observed. Immediately after mortar brick contact water starts flowing from the mortar towards the bricks. This process continues until an equilibrium is reached between the capillary suction of the bricks and the physical and, later on, chemical forces retaining the water in the mortar. After some hours of hydration the water begins to move in the opposite direction: from brick to mortar (see Fig.7.7). Apparently, pores finer than those present in the brick are formed in the mortar during the hydration process causing the reversed movement.

The water reversal was studied for a number of combinations and the results turned out to be a clear illustration of the interactive effects of mortar and brick on water flow as a function of their different porosities. This is explained by means of the following observations:
- the quantity of water flowing in reverse was higher for the fired clay brick combinations (EB and MB) than for calcium silicate combinations (LB); finer pores in LB than in EB and MB.
- the lime-cement mortars show a higher reversed water flow than the portland cement and masonry cement mortars: lower air content and/or finer pores in the LC-mortars than in the PC- and MC-mortars.

The reversal of water flow may favour the mortar-brick bond strength development, since the reverse water may contribute to the hydration of cement in the interfacial zones. However, a negative effect on bond strength is also possible; for instance, in the case of already high water-cement ratio conditions at the interface.
Comparison of water distributions showing the phenomenon of water flow reversal (EB and LB combinations). The test specimens were scanned 15 min. (graphs 1), 2 hours (graphs 2) and 20 hours (graphs 3) after brick laying. Graphs 2 represent the lowest water content values of the mortar. Test conditions: RH 95 %, 20 °C.
7.2 Water flow velocity measurements by means of the monitoring technique (brick laying device)

7.2.1 Introduction

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.

As explained in Chapter 5, a masonrying device was constructed enabling the continuous monitoring of water content changes in the specimens at two positions. Test data have been collected in the middle of the joint and at two mm from the upper surface of the lower brick. From the evaluation of the test results of the lift measurements it has been decided to continue the tests with S1, S4 and S5 mortars. In order to study the differences of the flow rates as a function of the initial water content of the bricks, the following brick/moisture combination have been included in the test series: EB00, MB15 and MB00, LB07 and LB00.

The scanning regime and the test period were adapted to the absorption behaviour of the brick. For the MB-combinations the scan step period ranged from 2.5 seconds just after the first moment of mortar-brick contact to 20 seconds after some time of water suction. The tests with the EB- and LB-combinations started with scan step periods of 5 seconds and finished with periods of 20 and 60 seconds, respectively. The accuracy of the measured water content values based on counting statistics, see Appendix 8, varied from 1.00% for the 2.5 second scans to 0.26% for the 60 second scans.

The test periods have been as follows: about 0.5 h for the MB-combinations, ~1 h for the EB-specimens and ~4 h for the LB-combinations.

The test results are presented in graphs in which the following relationships are shown:
- water content changes in mortar and brick as a function of time (q,v/t),
- mass of absorbed water by the adjacent bricks as a function of time (m'2,v/t),
- flow rate per unit area as a function of time (v,v/t).

7.2.2 Reproducibility of the test results

In order to gain insight into the reproducibility of the tests carried out with the masonrying device, a comparison has been made between mortar core water/cement ratios, determined by means of this technique and those derived from the lift measurements.

To this end w/c ratio data presented in the Figs 7.1 and 7.5, the Table 7.1, and w/c ratios derived from Appendix 2 are collected in Table 7.5.
Table 7.5  Comparison of water/cement ratios in the middle of the mortar joint, determined by means of monitoring (brick laying device) and scanning (lift facility).

<table>
<thead>
<tr>
<th>Brick</th>
<th>Mortar</th>
<th>Monitoring (Mas.Dev.)</th>
<th>Scanning (lift)</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB00</td>
<td>PCS1</td>
<td>0.44</td>
<td>0.42-0.46</td>
<td>0.40-0.47</td>
</tr>
<tr>
<td></td>
<td>LCS1</td>
<td>0.94</td>
<td>1.03-1.07</td>
<td>1.00-1.09</td>
</tr>
<tr>
<td></td>
<td>MCS1</td>
<td>0.83</td>
<td>0.85-0.93</td>
<td>0.85-0.96</td>
</tr>
<tr>
<td>EB00</td>
<td>PCS4</td>
<td>0.37</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCS4</td>
<td>0.82</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCS4</td>
<td>0.80</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>EB00</td>
<td>PCS5</td>
<td>0.34</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCS5</td>
<td>0.94</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCS5</td>
<td>0.65</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>MB15</td>
<td>PCS1</td>
<td>0.42</td>
<td>0.50-0.55</td>
<td>0.49-0.56</td>
</tr>
<tr>
<td></td>
<td>LCS1</td>
<td>0.94</td>
<td>0.96-1.03</td>
<td>0.94-1.04</td>
</tr>
<tr>
<td></td>
<td>MCS1</td>
<td>0.80</td>
<td>0.85-0.93</td>
<td>0.84-0.93</td>
</tr>
<tr>
<td>MB15</td>
<td>PCS4</td>
<td>0.37</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCS4</td>
<td>0.82</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCS4</td>
<td>0.74</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>MB15</td>
<td>PCS5</td>
<td>0.34</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCS5</td>
<td>0.76</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCS5</td>
<td>0.70</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>LB07</td>
<td>PCS1</td>
<td>0.25</td>
<td>0.18-0.25</td>
<td>0.13-0.25</td>
</tr>
<tr>
<td></td>
<td>LCS1</td>
<td>0.60</td>
<td>0.54-0.76</td>
<td>0.42-0.76</td>
</tr>
<tr>
<td></td>
<td>MCS1</td>
<td>0.44</td>
<td>0.54-0.68</td>
<td>0.48-0.72</td>
</tr>
<tr>
<td>LB07</td>
<td>PCS4</td>
<td>0.18</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCS4</td>
<td>0.52</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCS4</td>
<td>0.51</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>LB07</td>
<td>PCS5</td>
<td>0.17</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCS5</td>
<td>0.43</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MCS5</td>
<td>0.43</td>
<td>0.60</td>
<td></td>
</tr>
</tbody>
</table>

With regard to the fired clay brick combinations it is clear that the water/cement ratios measured by means of the monitoring technique (brick laying device) are often slightly to moderately lower than those determined using the scanning technique (lift facility). Probably this may be attributed to the preparation procedure of the test specimens with the brick laying device. Before placing the mortar on the lower brick, it is put in a container.
test results

positioned out of reach of the neutron beam (see Fig. 5.5). The container is subsequently covered by a lid. By closing of the container some water may be squeezed out of the mortar. Hence, the initial water content of the mortar may be slightly lower than assumed. This may then result in a lower final water content and water/cement ratio values in the mortar core. The possible influence of the applied technique can not be observed in the LB-combinations due to higher variation in the test results of this type of specimens: see the 95% confidence intervals of the LB07S1-combinations in Table 7.5.

After analysis of the above mentioned influence of the testing technique on the results of the final water content in the mortar, the question arose to what extent the other parameters, such as the total mass of absorbed water and the flow rates, are affected by the procedure as well. In order to study this problem a number of comparative tests were carried out, in which the total water loss of the mortar was measured in similar combinations, however, with different initial water content conditions of the mortar. From the tests it is concluded that, for the fired clay combinations, the total quantity of absorbed water and the flow rates, are more or less independent of the initial water content of the mortar (see Fig 7.8).

Fig. 7.8  Comparison of the water absorption of similar mortar-brick combinations with different initial water content of the mortars. Curve marking: 1, water content in the middle of the joint; 2, water content at 2mm from the upper surface of the lower brick.
7.2.3 Water content changes as a function of time

Some characteristic graphs concerning water content changes as a function of time are collected in Fig 7.9. The curves indicating the water content in the middle of the joint are marked 1, the water content at 2 mm from the upper surface of the lower brick marked 2.

Fig. 7.9 Graphical presentation of water content changes at two positions of brick-mortar-brick combinations determined by means of neutron radiography, brick laying device.
The graphs show clearly the significant influence of the brick type on the absorption process. Constant water content values in the mortar core are reached in the MB-combinations after 6-7 minutes. For the EB- and LB-combinations this is the case after about 1 hour and 4 hours, respectively. Obviously, the water retentivity of the mortars, of MC substantially higher than PC, does not essentially affect the course of the suction process. Higher water retentivity, however, does result in higher final water contents in the mortar. The same phenomenon is observed when prewetted MB- and dry MB-combinations and prewetted, LB- and dry LB-combinations (see Appendix 3.) are compared one with another. Also, in these cases the course of the suction processes is hardly influenced by the wetting, but the final water content values in the mortar cores are lower in the dry combinations.

It can be noticed that the prewetting of the MB-bricks up to about the same initial rate of absorption (~1.5 kg/m²/min) as that of the EB-bricks, results in more or less similar final water contents in the joint core of identical mortars. The monitoring of the water content changes at 2 mm from the upper surface of the lower brick shows maximum values quite soon after brick laying. These values rapidly decrease in the MB-bricks as a result of an easy water transport further into the brick. The transport process, apparently, takes more time in the LB bricks, as can be deduced from the graphs.

### 7.2.4 Mass of absorbed water by the bricks as a function of time

The water uptake in the bricks, adjacent to the joint, can be derived from the decreasing water contents measured in the middle of the joint. Assuming a front-like decrease of water content over the cross-section of the joint, which is more or less the case, and assuming an equal water uptake by the upper and lower brick, the water absorption of each brick can be determined as follows:

\[
m' = \frac{(\varphi(i) - \varphi(t))}{100} \times \frac{t}{2} \times \rho \tag{7.2}
\]

in which,

- \(m'\) : mass of absorbed water per unit area (kg/m²)
- \(\varphi(i)\) : initial water content of the mortar (% by volume)
- \(\varphi(t)\) : measured water content of the mortar after period of time \(t\) (% by volume)
- \(t\) : thickness of the joint (m)
- \(\rho\) : density of water (kg/m³)

A series of representative examples of brick absorption of water out of mortars as a function of time, brick type, initial water content of the brick and mortar type are presented in Fig. 7.10. The complete graphical presentation of the test results is given in Appendix 4.
**Fig. 7.10**  
Brick absorption of water out of mortars as a function of time, brick type, initial water content of the brick and mortar type.
The left hand graphs of Fig. 7.10 show the water absorption as a function of time as calculated from measured data for the fired clay bricks (EB and MB) with similar IRA and the prewetted LB bricks. The right hand graphs present the suction behaviour of the dry MB and LB bricks. In each graph the water suction from the two mortar types PCS1 and LCS1 are plotted.

The following is noted, analysing the graphs:

a) the initial absorption rates of the dry and prewetted MBPC-combinations are almost identical,

b) the mass of absorbed water from the LC-mortars is substantially lower than those from the PC-mortars for the fired clay combinations. This is not the case for the dry calcium silicate combinations. The effect of the higher water retention of the LC-mortars is, however, clear in the case of the prewetted LB-combinations.

Comparing the water absorption by the fired clay bricks and calcium silicate bricks it may be observed that the influence of the hydration process is substantial in the LB-combinations, negligible in the MB-combinations and small in the EB-combinations. For this reason it may be interesting to consider the use of a quicker setting cement in the mortars of the calcium silicate combinations. Some preliminary tests have been carried out to study the effect of the cement type on the water absorption. As is to be concluded from Fig. 7.11, the water loss of the mortar can significantly be influenced by the cement choice.

**Fig. 7.11** Comparison of water absorption from two lime-cement mortars containing different cement-types: portland cement A (pcA) and portland cement B (pcB).
7.2.5 Flow rates

The flow rates were derived from the test data, using a spline function. Often spline functions are used for the purpose of interpolation. Strict interpolation, however, is unsuitable for the curve fitting of experimental data, as they represent approximate values. For this reason a spline function, as proposed by Reinsch (1967), was used, enabling the determination of a smoothed curve fit, taking into account the standard deviations of the measured data points. The spline fits were calculated by means of the computer program MIRROR developed by H. Fredrikze, IRI, TU-Delft.

From the test results it is concluded that, generally, almost immediately after mortar-brick contact maximum flow rates are achieved. The water content values show, however, during the first 10-20 seconds irregular patterns. This is an indication of initial adjustment effects of the suction process. The variation in the measurement of the initial period of time is reflected in the curve form of the spline fit. In order to gain a regular curve form the degree of smoothing in the calculation has to be adapted to the initial variations of the water content values. This results in differences in the curve form occurring especially in the initial period of the suction process. Analysis of this phenomenon shows that the differences in the spline fit fade out after a definite period of time (see Fig. 7.12).

![Effect of Smoothing on Fit](image)

**Fig. 7.12** The effect of the degree of smoothing on the spline fit: the highest initial flow rates correspond with the lowest degree of smoothing.
test results

The analysis shows that the flow rates given in the graphs represent reliable values after about 25 seconds of testing.

The flow rate graphs are related to the absorption graphs, since the flow rate at a defined time \( t \) is the first derivative of the absorption function at time \( t \). The flow rate may be expressed in m/s when it is derived from absorption functions in which the absorbed water is expressed in volume per unit surface (m\(^3\)/m\(^2\)). The volume absorption is of course directly proportional to the, up to now, used mass absorption (kg/m\(^2\)). Hence, dimensional compatibility between absorption graphs and flow rate graphs may easily be achieved.

Since the flow rates are calculated as a function of the total surface area it is clear that the real flow rates in the mortars are substantially higher: after all, the water volume is only a part of the total volume of the mortars. The really average flow rates in the mortars can be calculated using Table 6.4 of Chapter 6. The initial water contents of the mortars range in the PC-mortars from ~20 to ~25 %, in the LC-mortars from ~26 to ~28 % and in the MC-mortars from ~20 to ~23 %. Consequently, the average flow rates in the mortars are ~5 to 3.5 times higher than the flow rates per total surface area.

A number of flow rate curves are presented in Fig. 7.13. The mortars contain the finely graded S4. The flow rates are related to the total unit surface. The right hand graphs show examples of flow rates caused by dry bricks. In the left hand graphs the prewetted machine moulded and calcium silicate bricks are presented.

Fig. 7.13 depicts that, during the first minute of mortar-brick contact, the flow rates in the MB-combinations are substantially higher than in the EB- and LB-combinations. This is not only the case for the PC-mortars but also for the mortars with higher water retentivities, LC and MC.

The variation of the flow rates is relatively modest for all mortars combined with the wire cut and the calcium silicate bricks.

The influence of wetting on the flow rates is markedly small, as can be noted by comparing the left hand and right hand graphs. This means that possible transport of fine particles from the mortar bulk towards the interfacial zones is hardly affected by the initial water content of the bricks.
Fig. 7.13  Flow rates from mortar to brick for EB-, MB- and LB-combinations with mortars containing S4-graded sand.
Flow rate and sand grading

The flow rates may be influenced by the sand gradings used in the mortars. In particular, differences in fineness and variations in initial water content may play a role in this respect. 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 which are presented in Appendix 5. In order to facilitate the analysis, the flow rates after 25 seconds of mortar-brick contact are presented in graphical form, see Fig. 7.14,

![Graph showing flow rates](image)

*Fig. 7.14  Flow rates after 25 seconds of mortar-brick contact.*

The most important conclusion to be drawn from Fig. 7.14 turns out to be that the brick type has a far greater effect on the flow rate at t=25 sec. than the sand grading applied in the mortars.

Focusing on the differences between the flow rates with regard to the sand grading it is to be noted, that the number of tests is not sufficient to allow judgments about the statistical significance of the differences between the flow rates as a function of the sand grading per mortar group.

The effects of differences in fineness on the pore structure of the mortars and the variations
test results

of the initial water contents can be evaluated as follows (see Appendix 5):

- the flow rate at \( t=25 \) sec of the S5-combination of a mortar group is often higher or as high as those of S1- and S4- combinations.
- the flow rate gradients in the high-suction-rate MB-combinations are often steeper in the S5-mortars.

Hence, it may be assumed that, initially, the water transport in the S5-mortars is favoured as a result of the relatively coarse pore structure of this mortar type. The combination of high initial flow rate and low initial water content, however, will limit the suction period.

7.2.6 Interpretations

The porosity characteristics of the bricks, as collected in Table 7.6, may, in any case partly, provide the explanation for the different effects of brick suction on water loss of the mortar.

Table 7.6 Porosity characteristics of the bricks used in the test programme

<table>
<thead>
<tr>
<th>(i)</th>
<th>Pore volumes of the test bricks, in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB</td>
</tr>
<tr>
<td>Vacuum pore volume (%)</td>
<td>-25</td>
</tr>
<tr>
<td>Free water absorption pore volume (%)</td>
<td>12-13</td>
</tr>
<tr>
<td>Mercury - total pore volume - &gt;0.1μm (%)</td>
<td>8-12</td>
</tr>
<tr>
<td>Maximum water vol. in brick ~ 2 mm from interface mortar/brick *) (%)</td>
<td>8-9</td>
</tr>
</tbody>
</table>

*) see Appendix 3

Table 7.6 (continued)

<table>
<thead>
<tr>
<th>(ii) Pore volume distributions as a function of the pore radius (in % of the total mercury pore volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pore radius in μm</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>( r&lt;10^{-2} )</td>
</tr>
<tr>
<td>( 10^{-2}&lt; r &lt; 10^{-1} ) *)</td>
</tr>
<tr>
<td>( 10^{-1}&lt; r &lt; 10^{0} )</td>
</tr>
<tr>
<td>( 10^{0}&lt; r &lt; 10^{1} )</td>
</tr>
</tbody>
</table>

*) pores with radii smaller than 0.1 μm are supposed not to contribute to the capillary water transport.
When the data of Table 7.6 are combined with the test results, presented in the appendices 3 and 4, and the pore size distributions of EB, MB and LB, presented in Figure 6.1, the following can be noted:

**EB00-combinations**
The volume data show a considerable discrepancy between the vacuum pore volume and the free water absorption volume. This test result might indicate, in combination with the low mercury pore volume, the occurrence of a significant amount of 'isolated' coarse pores connected with the pore system through very fine pores. The practical relevance of the test data is that up to 12-13 volume percent of the brick may contribute to the water absorption from the mortar. The maximum water contents, measured in the bricks nearby the interface mortar/brick are 8 to 9 vol%. This means that 70-80 % of all the pores available for water absorption, pore radii > 0.1 µm, contribute to the suction process. For an explanation of the inactivity of 20-30 % of the pores see next section.

**MB00-combinations**
From the pore volume data of Table 7.6 it follows that the free water absorption volume is about 80% of the vacuum pore volume. Taking into account the variation in mercury porosimetry results it may be assumed that the free water absorption and the mercury pore volumes are similar. Further analysis of the mercury porosimetry data reveal the occurrence of a substantial amount of very coarse pores. These pores combine a low capillary potential with a high suction rate.

When the mercury pore volume of pores > 0.1 µm is compared with the maximum water content in the brick, it may be concluded that about 50 % of the pores, available for water absorption, are active. This is in remarkable contrast with the water content values found in free water absorption tests. However, an essential difference between the water absorption from a free water surface and that from a mortar is, that the water in the mortar shows a considerable capillary potential. Hence, the inactivity of a large amount of MB-pores, as measured through neutron transmission, may be due to a higher capillary potential of the mortar than that of the coarsest brick pores.

For the EB-bricks a comparable reasoning holds. The porosity data show clearly pore radii in the order of the coarsest pores of the MB-bricks. The amount of this type of pores is, however, significantly lower in the EB-bricks. A lower percentage of inactive pores, as observed previously, may then expected to be present.

**EB00- versus MB00-combinations**
Appendix 3 depicts different courses of absorption for both brick types: an absorption period of 6-7 minutes for the MB-combinations and one of ~1hour for the EB-combinations. An indication for the logic regarding the different absorption behaviour of the bricks can be
found through application of the capillary absorption theory as treated in Chapter 4. The absorption behaviour of the bricks is, according to this theory, mainly governed by the following suction characteristics of the capillary pores,
- the mass of absorbed water is proportional to $r^{2.5}$ and $\sqrt{t}$, with $r$: pore radius and $t$: time,
- the capillary potential is inversely proportional to $r$.

Comparing the pore distributions of MB and EB, it can be understood that the initial flow rates in the MB-combinations are higher than in the EB-combinations, since the positive effect of the higher absorption capacity surpasses the negative effect of the lower capillary potential of the brick.
Due to the fast water uptake by the MB-bricks, the brick potential will decrease fast as well. Furthermore, the water potential, in particular, in the mortar bulk (see Chapter 8) will increase faster in the MB-combinations.
This may explain the differences between the duration of the absorption processes of the MB and the EB-combinations.

**MB15-combinations**
In section 7.2.5 it was found that the influence of prewetting on the absorption rates in combinations of the same brick and mortar type are markedly small.
The graphs of Appendix 3 show a very small increase of the water content in the bricks during the absorption process. An explanation for this absorption behaviour can be found, through analysis of the diffusivity characteristics of the brick and the driving force during the water transport. The diffusivity is known to be a function of the initial water content. Test results, presented in Chapter 8, show the enormous increase of the diffusivity with increasing initial water content of the MB-brick. The driving force, for instance expressed in the water content gradient, will diminish with higher water content; the capillary suction of the mortar will counteract the driving force as well. The combined effect of diffusivity and driving force may result in similar flow rates in the wetted and the dry bricks.
Contrary to the portland cement and lime-cement specimens of MB, the prewetted MC-combinations show higher initial flow rates than the dry MC-combinations, in particular with S1-graded sand and, to a lesser degree, with the S4-graded one. It may be suggested, that this is due to compaction effects immediately after mortar-brick contact. The masonry cement mortars contain relatively high quantities of fine material, cement and ground lime stone. The S1-graded and S4-graded sands are fine as well. It is assumed, that higher flow rates in the dry masonry cement combinations than in the wetted combinations at the very beginning of the absorption process, will cause a denser compaction in the mortars of the first. Subsequently, the flow rate in the dry combinations will be lower than in the prewetted specimens. The flow rates in the EB- and LB-combinations are supposed to be so low that this difference in initial compaction does not occur.

**LB00- and LB07-combinations**
The calcium silicate bricks show a substantial difference between vacuum pore volume and mercury pore volume. The measured water contents (neutron transmission) in the brick nearby
the interface are higher than the pore volumes available for absorption (according to the mercury porosimetry data). The higher water contents at ~2 mm from the interface cannot be attributed to higher porosities in the interfacial zones of the calcium silicate bricks, as free water absorption measurements, using neutron transmission, showed a uniform water content distribution from the water surface to the top of the specimens.

An explanation for the different response of the fired clay and the calcium silicate products to mercury porosimetry may be found in differences with respect to:

- pore structure: tubular in the fired clay products and spherical packing in the calcium silicate material,
- pore wall morphology, a rather smooth internal surface in the sintered products and a rough one in the calcium silicate brick, due to the growth of hydration products on the sand grains.

As a result of differences in cohesion it may be expected that the water pore volume will be larger than the mercury pore volume: the mercury will not fully fill the capillary space.

Hence, the application of mercury porosimetry will, in the case of calcium silicate bricks, result in the determination of a too low pore volume of the capillaries.

With respect to the flow rates the following should be considered. Calcium silicate usually contains a large amount of very fine pores. These pores, only filled with vapour, will develop high capillary pressures. Since the fine pores are connected with the coarser pores the capillary pressure in the latter will increase. This will result in higher flow rates in the coarser pores.

The test results show initial flow rates in the LB-combinations comparable with or higher than those of the EB-combinations and, mostly substantially lower than in the MB-combinations. The flow rates in the wetted LB-combinations are usually lower than those in the dry specimens. This means that the effect of an increased diffusivity in the wetted bricks is surpassed by the effect of a decreased driving force.

Long term absorption behaviour of the LB-combinations

The effect of the high amount of fine pores on the long term behaviour of the calcium silicate combinations turns out to be very substantial.

Appendix 3 reveals, that only the combined use of wetted LB- bricks and mortars of high water retentivity provide satisfying final water contents in the mortar cores. Obviously, the prewetting of the calcium silicate bricks is an effective means to render inactive the capillary suction of a considerable number of the finest pores. As a result of this the effectiveness of a higher water retentivity significantly increases.
7.3 Mechanical Testing

7.3.1 Tensile bond strength

The tensile bond strengths of the 45 combinations (10 specimens per combination) have been determined by means of cross-couple testing (according to ASTM C 952). The scatter in the test results is known to be considerable. This is partly due to the test set-up, partly a result of the scatter in material characteristics of the bricks. The test results are discussed as to brick types, mortar composition, water distribution profiles and rupture modes. The results of the tensile bond strength tests are presented in Table 7.8:

Table 7.8  Tensile Bond Strength Results (ASTM C952, cross-couplets)

<table>
<thead>
<tr>
<th></th>
<th>EB00</th>
<th></th>
<th>MB15</th>
<th></th>
<th>LB07</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ_{TB}</td>
<td>s</td>
<td>R</td>
<td>σ_{TB}</td>
<td>s</td>
</tr>
<tr>
<td>PCS1</td>
<td>0.35</td>
<td>0.05</td>
<td>1</td>
<td>0.31</td>
<td>0.07</td>
</tr>
<tr>
<td>LCS1</td>
<td>0.27</td>
<td>0.02</td>
<td>1</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>MCS1</td>
<td>0.17</td>
<td>0.04</td>
<td>1</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>PCS2</td>
<td>0.45</td>
<td>0.04</td>
<td>1.2</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>LCS2</td>
<td>0.41</td>
<td>0.05</td>
<td>1.2</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>MCS2</td>
<td>0.20</td>
<td>0.04</td>
<td>1</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>PCS3</td>
<td>0.46</td>
<td>0.04</td>
<td>1.23</td>
<td>0.41</td>
<td>0.08</td>
</tr>
<tr>
<td>LCS3</td>
<td>0.48</td>
<td>0.05</td>
<td>1.2</td>
<td>0.34</td>
<td>0.08</td>
</tr>
<tr>
<td>MCS3</td>
<td>0.28</td>
<td>0.04</td>
<td>1</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td>PCS4</td>
<td>0.47</td>
<td>0.05</td>
<td>2.3</td>
<td>0.42</td>
<td>0.06</td>
</tr>
<tr>
<td>LCS4</td>
<td>0.41</td>
<td>0.07</td>
<td>1.2</td>
<td>0.34</td>
<td>0.07</td>
</tr>
<tr>
<td>MCS4</td>
<td>0.25</td>
<td>0.03</td>
<td>1</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>PCS5</td>
<td>0.50</td>
<td>0.04</td>
<td>2.3</td>
<td>0.40</td>
<td>0.07</td>
</tr>
<tr>
<td>LCS5</td>
<td>0.43</td>
<td>0.05</td>
<td>2</td>
<td>0.30</td>
<td>0.07</td>
</tr>
<tr>
<td>MCS5</td>
<td>0.30</td>
<td>0.04</td>
<td>1</td>
<td>0.21</td>
<td>0.06</td>
</tr>
</tbody>
</table>

σ_{TB}  : mean tensile bond strength (MPa) of 10 specimens  
s       : standard deviation (MPa) of the mean tensile bond strength  
R       : mode of rupture;  
1: interface rupture  
2: mortar rupture, some mm from interface  
3: mortar rupture over cross section  
4: brick rupture, some mm from interface  
5: brick rupture (flexion)
Curing conditions: RH 65%, 20°C, 28 days.

Notes
By interface rupture mode is meant a failure pattern showing minor traces of mortar at the bed face of the brick, and/or minor traces of brick at the mortar layer.

For the interpretation of the bond strengths no attention has been paid to the influence of stresses originating from restrained deformation of young mortars (see Bijen et al., 1993).

A second test series has been carried out in order to study the influence of the curing conditions on the development of tensile bond strength. The results are presented in Appendix 7.

7.3.2 Preliminary observations

**Sand grading**
The mortars composed with S1 and S2 represent, in fact, artificial mixtures. This is due to the partial replacement of finest sand fraction by much finer quartz flour. The S1 and S2 mortars contain 10% and 5% quartz flour, respectively. The reason for including these sand gradings in the test programme was the need for data regarding the effect of fines on the hydration of the binder (see next section). Common practice mortars are made with the S3, S4 and S5 sand gradings (for details regarding the grading characteristics, see Table 6.2).

**Cement content and bond efficiency** (BE)
The comparison of the performance of the mortars, as presented in Table 7.8, is hindered by the differences in cement contents. This problem may be solved by relating the bond strength values to equal cement contents of the mortars. Subsequently, the bond performance of a combination may be evaluated comparing its bond strength with that of a reference combination. The test results of Table 7.8 show a maximum tensile bond performance of the combination EB00PCS5,SC. Taking this performance as a standard efficiency of 100%, the tensile bond efficiency (BE) of another combination (C) of the test series may be determined as follows:

\[
BE_{(C)} = \frac{\sigma_{TBC}}{\sigma_{TBS5}} \times 100 \quad \% \tag{7.3}
\]

in which,

\[
BE_{(C)} : \text{Bond Efficiency of combination (C)} \quad (\%)
\]
\[ \sigma_{\text{TBC}}^{*} = \frac{\text{cement content standard mortar (SC)}}{\text{cement content mortar (C)}} \times \sigma_{\text{TBC}} \] (MPa)

(Cement contents by mass)

\[ \sigma_{\text{TBC}} : \text{Tensile Bond Strength of combination (C) (MPa)} \]
\[ \sigma_{\text{TBC(SC)}} : \text{Tensile Bond Strength of standard combination (SC) (MPa)} \]

The calculation of the bond efficiencies is based on the cement content data of the mortars, presented in Table 6.4. The portland A cement content of the masonry cement mortars is 55% of the total masonry cement content. The comparison of the bond efficiencies of the mortar-brick combinations is presented in Fig. 7.15. The bond efficiency values are related to the cement content and the tensile bond strength of EB00PCS5, and based on the comparison of mean bond strength values, see Table 7.8. For further details see Appendix 6.

**Tensile Bond Efficiency [%]**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB00 PC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
</tr>
<tr>
<td>LC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S4</td>
<td>S5</td>
</tr>
<tr>
<td>MC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S5</td>
</tr>
<tr>
<td>MB15 PC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
</tr>
<tr>
<td>LC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
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<td>S5</td>
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<tr>
<td>MC</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S5</td>
</tr>
<tr>
<td>LB07 PC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
</tr>
<tr>
<td>LC</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S5</td>
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<tr>
<td>MC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S5</td>
</tr>
</tbody>
</table>

**Fig. 7.15**  
Tensile bond efficiency (BE) of the mortar-brick combinations compared to that of EB00PCS5 (100%); cross-couplet testing, curing conditions RH 65%, 20 °C, 28 days.
test results

Portland A cement content with respect to the fines
The cement content of the mortar may provide indications on the mechanical bond strength development. A better measure for that is often the portland cement content with respect to the so-called ‘fines’, i.e. all material in the matrix, inclusive of cement, of about the same as or smaller grain size than that of the cement (see, for instance, Taylor (1990) on filler effects).

The following can be noted:
- the masonry cement contains two types of fine particles: portland A cement and ground limestone,
- the S1- and S2-mortars contain quartz flour, which is characterized by grain sizes in the same order as that of the portland cement. Consequently, the quartz flour may functionally be considered as an (inert) part of the binder (like ground limestone in the masonry cement). This will result, for the S1 and S2 mortars, in lower portland A cement content values of the fines than in case of the S3, S4 and S5 mortars.

According to Högbred (1967) the fines of the matrix should contain between 50 and 75 % of portland cement in order to obtain satisfactory bond strength between brick and non-air-entrained mortar.

The calculated portland A cement content values of the fines in the matrix are shown in Table 7.9.

Table 7.9  Portland A cement content of the fines in the matrix

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3, S4, S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC-mortar</td>
<td>66</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>LC-mortar</td>
<td>48</td>
<td>58</td>
<td>71</td>
</tr>
<tr>
<td>MC-mortar</td>
<td>40</td>
<td>46</td>
<td>55</td>
</tr>
</tbody>
</table>

Air content
Differences in air content between LC-mortars (non air-entrained) and PC/MC mortars have to be considered analysing bond behaviour (see Table 6.4 and Chapter 7.1.7).

7.3.3 Observations regarding the bond strength development

The PC-mortar/brick combinations
The portland cement specimens show, with the exception of the PCS1-combinations, a very reasonable bond strength performance. In comparison with the EB-specimens the MB-
test results

combinations show bond efficiencies of 80 to 90% and the LB-combinations of 70 to 80%. With regard to the S3-, S4- and S5-mortars it can be noted that the brick type turns out to have a greater effect on the bond efficiency than the sand grading. The bond efficiencies of EB00PCS1 and LB07PCS1 are relatively low.

An explanation for this phenomenon cannot be found through analysis of the water profiles (w/c ratio), as they show more or less similar forms in each sand grading group (see Appendix 1). In the PCS1-combinations merely modes of interface rupture are detected, while in all other PC-combinations a variety of rupture modes are found (from interface rupture to brick rupture).

The LC-mortar/brick combinations
The main differences between the lime-cement mortars and the cement mortars are, (i) the lime-cement mortars contain less cement than the portland cement mortars (see Table 6.4), (ii) the cement content with respect to the fines is less favourable (see Table 7.9), (iii) the air content of the lime-cement mortars (~5% by volume) is substantially lower than that of the PC-mortars (~15% by volume).

Comparing bond behaviour of the lime-cement combinations with that of the portland cement combinations it is noted, with regard to the S3-, S4- and S5-gradings, that
- the bond efficiency is largely influenced by the brick type,
- the bond efficiencies of the LC-mortars combined with EB are even higher than those of comparable PC-combinations,
- the bond efficiencies of the LC- and the PC-mortars combined with MB are more or less similar; this is also the case, although with slightly lower efficiencies, for the LC-and PC-mortars combined with LB.

Hence, the bond efficiencies of the lime-cement mortars are relatively high. This is remarkable, as the content of cement of the mortar as well as that of the fines in the LC-mortars is lower than that of the PC-mortars. Probably, the negative effect of the unfavourable cement content conditions is neutralized or even surpassed by the positive effect of the lower air content.

The bond efficiency values, per brick type, of the combinations with LCS1- and LCS2-mortars are substantially lower than those of the mortars containing S3, S4 and S5.
As was observed for the PCS1-combinations, these low efficiencies cannot be explained with the help of the water distribution profiles.

The majority of the LC-rupture modes are cases of combined interface rupture and mortar failure some mm from the interface. No ruptures over the cross-section of the joint, as in the PC- combinations, have been observed. The S1- and S2-combinations, with the exception of EB00LCS2, show interface rupture.
The MC-mortar/brick combinations
Specific MC-mortar characteristics compared with that of the LC- and PC-mortars are, (i) the cement content of the masonry cement mortars is comparable with that of the LC-mortars, see Table 6.4, (ii) the cement content with respect to the fines is even lower than that of the LC-mortars, due to the high content of ground lime stone of the masonry cement, see Table 7.9), (iii) the air content of the MC-mortars is as high as that of the PC-mortars (~15%).

The bond strength values of the fired clay brick/MC-mortar combinations are always substantially lower than those of the comparable LC-combinations. Bond strengths zero or very low bond strengths develop in two of the five MB-specimens, MB15MCS1 and MB15MCS2. The other three MBMC combinations perform better, but the tensile bond strength values of S3 and S4 remain lower than 0.2 N/mm², a minimum tensile bonds strength assumed to be present in normal masonry, see McNeil et al.(1991). The higher cement content with respect to the fines in the S3-, S4- and S5-mortars may be of decisive influence on the development of the bond strength.

For all the masonry cement combinations rupture occurs at the interface.

7.3.4 Question marks and further research

Comparing the tensile bond efficiencies of the EB-combinations with those of the MB- and LB-combinations, there are no satisfactory explanations at hand for:
- the poor and very poor bond performance of the S1 and S2 graded lime-cement and masonry cement mortars, combined with the machine moulded bricks,
- the poor bond performance of the S1 graded portland cement mortars combined with the calcium silicate bricks,
- the relatively poor performance of the S1 and S2 graded lime-cement and masonry cement mortars combined with LB07.

Comparative analysis of the mortar compositions and the water distributions do not contribute to the solution of the problems.

The test results, however, indicate that solutions may be found by a closer study of the composition of the mortar-brick interface of the problem combinations.
7.4 X-ray diffraction testing

7.4.1 Micro techniques

An attempt has been made to obtain a better understanding of the hydration conditions and the mortar composition of the mortar in critical zones of the joint with the help of micro test techniques.

Micro-hardness testing has been applied in order to obtain information about possible variation in the mechanical properties over the cross-section of the mortar joint. An important quality of this technique is the supposed direct relationship between hardness and mechanical strength. Specimens were prepared of a number of brick-mortar-brick combinations. Although the specimens were polished using glycol as a lubricant the matrix of several mortars is rinsed away. As a consequence, it is not possible to acquire comparative quantitative information about the micro-hardness of the combinations. Only, some qualitative comparison with respect to the degree of hydration could optically be achieved.

Also some SEM-analyses were carried out. Significant differences between the hydration products could be observed. A decisive interpretation problem regarding this technique is to assess relationships between image and mechanical characteristics.

More encouraging was the study of the micro-structure using X-ray diffraction techniques.

7.4.2 Potentiality of the X-ray diffraction technique

By means of the X-ray diffraction technique the phase composition of materials can be studied. This technique is applicable to crystalline phases of materials.

According to Diamond (1976), the properly crystalline compounds likely to be present in hydrated cement pastes include calcium hydroxide (CH), ettringite (AFt) and calcium aluninate monosulfate hydrate (perhaps C₄AH₁₅) and residual clinker phases such as alite (C₃S), belite (β-C₂S) and tetra calcium aluminoferrite (C₄AF). For further details see Section Symbols and Abbreviations.

The phases of lesser crystallinity involve primarily calcium silicate gel, but also include small amounts of residual glassy material from the clinker, amorphous calcium hydroxide, organic complexes formed by organic additives with C₃A hydration products, etc.

Diamond concluded from the evaluation of the weak diffraction pattern of C-S-H gel that either the gel is almost amorphous, or it consists of completely amorphous material with a small portion of particles of better crystallinity.

With the lower concentration of cement in mortars, it is to be expected that the number of phases observed in the diffraction patterns will be less than in the case of cement pastes.
It may be assumed from the above mentioned X-ray diffraction results that this technique can be used to improve the knowledge about the mortar composition over the cross-section of the joint.

7.4.3 Experimental

Measurements
The measurements were performed on a Siemens D500 diffractometer equipped with a position sensitive detector and an incident-beam monochromater (CoKα1-radiation) as well as on a Siemens D500 diffractometer with a diffracted-beam monochromator (CuKα-radiation). In both cases the effective penetration depth was about 30 μm. Specimen rotation was applied to minimize the effect of coarse grains. A 2 theta step of 0.1 degree was used.

Interpretation
The most reliable way to evaluate the measurements is to compare peaks of relevant phases in the separate diffraction patterns. Since all the diffractograms were recorded under the same conditions, ratios of peak areas are proportional to ratios of phase quantities. An increase of the degree of hydration is indicated by (i) an increase of area of peaks of calcium hydroxide and (ii) a simultaneous decrease of the area of peaks of residual clinker material. Important components of the clinker are alite and belite. These are very difficult to recognize separately by X-ray diffraction of mortars, because of overlap of peaks and low intensities of isolated ones.

Specimens
Three types of specimens were used, see Fig. 7.16:

(i) Surface specimens were obtained through separation of the mortar joint from the brick. Since the surface shows irregularities with a large variation in appearance, 4 different samples of each mortar-brick combination were measured to obtain a representative result.

(ii) Bulk specimens were obtained by removal of about 1 mm from both sides of the surface specimens and grinding the remaining joint material. The resulting powder was pressed in a specimen holder with a diameter of 20 mm and a depth of 2 mm (a backfilling technique was used to avoid the introduction of preference orientation). For each mortar-brick combination 2 specimens were measured.

(iii) Depth profile specimens were obtained by grating small layers of mortar material from the surface of the joint after which the newly formed surfaces were measured.
Fig. 7.16  Types of X-ray diffraction (XRD) specimens

Tests
The test series comprised the study of,
- the phase composition of bulk specimens and surface specimens of masonry cement (MCS1) mortars hardened between EB00-, MB15-, MB00-, LB07- and LB00-bricks,
- the phase composition of surface specimens of masonry cement and portland cement mortars of the following combinations: EB00MCS1, EB00PCS1, MB15MCS1, MB15PCS1, MB15MCS5 and MB15PCS5.
- the phase composition variation in the outer 2 mm (closest to the brick) of masonry mortars (MCS1), hardened between EB00-, MB00-, LB07-, and LB00-bricks.

7.4.4 Test results and interpretation

Bulk of masonry cement mortar joints
The joints were allowed to harden between the bricks for 28 days at RH 65% and 20 °C. The X-ray diffraction test specimens, prepared from material in the middle of brick-mortar-brick combinations, were stored in a dessicator containing soda lime in order to prevent carbonation.

The diffraction patterns of the bulk specimens are presented in Fig. 7.17,
Fig 7.17 X-ray diffraction patterns (CoKα1-radiation) of bulk material of MCS1-mortar joints. 28 days hardening. Q=quartz CH=calcium hydroxide Cc=calcite R=alite+belite ?=unidentified reflection.

It can be concluded from the calcium hydroxide (CH) and residual clinker (R) peaks in the diffraction patterns that the degree of hydration of the MCS1-mortar hardened between EB00- and MB15- bricks is significantly higher than of that hardened between LB00- bricks. It can be noted as well, that the MCS1-bulk hydration of the MB00- and LB07-combinations takes an intermediate position; however, clearly closer to EB00/MB15 than to LB00.

This result may be compared with interpretations of the hydration of the MC-mortars based on the findings of the neutron transmission measurements. Appendix 2 and Table 7.5 show the following final water/cement ratios in the middle of the joint: for the EB00 and MB15 mortars 0.85-0.90, for the MB00 and LB07 mortars 0.50-0.70 and for the LB00 ones 0.15-0.20.

The real hydration conditions of the test specimens were less favourable than during the transmission tests, since the specimens were cured at RH 65% and 20 °C.
It may be concluded that the X-ray diffraction results are, comparatively, in agreement what
was to be expected from the neutron transmission measurements. Traces of residual clinker material found in the bulk of the MC-mortars of EB00, MB15, MB00 and LB07 may point to an important evaporation effect on the hydration.

Surface of masonry cement mortar joints
Diffraction patterns obtained from the surfaces of mortar joints, hardened and stored as described in the previous section, are presented in Fig. 7.18,

![Diffraction Patterns](image)

**Fig. 7.18** X-ray diffraction patterns (CoKα1-radiation) of surface material of MCS1 mortar joints. 28 days of hardening. Q=quartz Cc=calcite R = alite + belite ?=unidentified reflection.

From a comparison of the Figs 7.17 and 7.18 it is clear that the phase compositions of bulk and interface of the joints are different.

First of all, the amount of calcite is larger at the surface than in the bulk of the MCS1-mortars, compare the peaks at 56-57 degrees. The surface diffraction patterns show a complete absence of calcium hydroxide peaks and, at the same time, the (very) weak peaks of residual alite and belite.
test results

This result may point to a relatively low content of (hydrated) clinker material in the interfacial zone. However, it is not clear whether the Cc-peaks contain carbonated CH: although carbonation between preparation of the test specimen and X-ray testing has been prevented, carbonation during the period of hardening may have occurred.

In order to gain a better insight into the mortar composition it has been considered useful,
- to relate the diffraction patterns of the masonry cement mortar joint surfaces to that of portland A cement mortars,
- to study the composition of the outer 2 mm of the MCS1-joints more extensively.

Surface compositions of masonry cement and portland cement mortar joints
In Fig 7.19 diffractograms are presented, that were recorded from surfaces of mortar joints left from mechanical testing (as far as the rupture occurred at the mortar-brick interface). They were hardened for about a year, exposed to carbon dioxide of the air. Hence, carbonation is to expected.

An important difference between the diffraction patterns of the MC- mortars and the PC-mortars is the occurrence of vaterite in the latter. Vaterite, a modification of calcium carbonate, may be formed in concretes and mortars due to carbonation of CSH-gel as was demonstrated by Schröder (1962). Subsequent formation of calcite (Cc) may occur as a consequence of the meta-stable character of the vaterite phase. Hence, vaterite and calcite must be taken together analysing diffraction patterns of the portland cement mortars. The different bond strengths with the PC- and MC-mortars (see Table 7.8) are likely to be due the occurrence of hydrated clinker phases at the surfaces of the PC-mortar-joints and their absence (or very low quantity) at the surfaces of the MC-mortar joints. Differences between the PC-combinations are observed as well: more hydration products are formed at the surface of MB15PCS5 joints than at the surfaces of MB15PCS1 and EB00PCS1 joints (between the latter two joints no further distinction can be made as part of the vaterite may have transformed into calcite). The bond strength of the PC-mortar with S5 is higher than that of the PC-mortar with sand S1. The variation in interfacial hydration products of the combinations is in agreement with the variation in bond strengths. It is noted that the surfaces of the S1-joints are somewhat enriched with fine-grained quartz particles (SP6), see the lower three diffractograms of Fig 7.19. The lower bond strengths of the S1-combinations are an indication of an impairing filler effect of the silica dust SP6 in sand S1.

The same effect may play a role with regard to the bond strengths of the MCS1- and MCS5-mortars. The calcite peaks from the MCS1-mortars in Figs 7.18 and 7.19 are very much alike, indicating that no significant amounts of hydration products have been formed at the surface of MCS1-mortars during 1 year of hardening.
Fig. 7.19 X-ray diffraction patterns (CoKα1-radiation) of surface material of MC- and PC-joints. CoKα1 radiation: 1 year hardening. Q=quartz  Cc=calcite  V=vaterite  ?=unidentified reflection.

Composition gradients near the surfaces of MCS1-mortar joints

Microscopic study of the interfacial zones revealed the occurrence of a layer of fine material in the MCS1-mortars. The thickness of this layer is different in each combination: ∼120 μm in EB00MCS1, ∼250 μm in MB15MCS1, ∼180 μm in MB00MCS1, ∼120 μm in LB07MCS1 and ∼90μm in LB00MCS1. Roughly, the thickness of the surface layer is twice as high in the MB-combinations as in the EB- and LB- combinations. Measurements, using neutron transmission (brick laying device), showed higher flow rates in the mortars of the MB-combinations than in those of the EB- and LB-combinations. It may be assumed that the layer thickness increases with increasing flow rate. Moreover, a decrease of the cement/ground limestone ratio is likely to occur with increasing flow rate, as more finely ground limestone particles than coarser cement grains are transported to the interface.

The composition as a function of the distance to the original mortar surface of the joint was further investigated by means of X-ray diffraction of a series of surfaces, obtained through
grating of the test specimens starting from the mortar surface. It should be noted that the grating of the mortar, removed from LB00, resulted in a rather rough surface; this may have influenced the results of this specimen.

In the evaluation of the diffractograms peak heights are assumed to be proportional to the amount of the corresponding phases. The results are shown in Fig. 7.20 (for trivial technical reasons CuKα was used in stead of CoKα1, as for Figs 7.17, 7.18 and 7.19).

**General**

The data presented in Fig. 7.20 provide clear indications for the occurrence of composition gradients near the surfaces of the MCS1- joints. From Fig 7.20c it is evident that the amount of calcite is substantially higher at the surface than in the bulk of the joint. It may be assumed that the higher calcite contents in the interfacial zones of the MCS1-mortars, for the most part, are caused by transport of ground lime stone to the interface as a result of water flow from mortar towards brick. The increase of calcite (and probably fine grained quartz, SP6) corresponds, as a matter of fact, with a decrease of portland A cement at the surface. The presence of clinker, Fig 7.20b, and the absence if calcium hydroxide, Fig 7.20a, point to (very) low degree of hydration. However, it is not excluded that the CH values at the interface are influenced by carbonation.

The bond strength results indicate that a possible accelerating effect of ground lime stone (Taylor, 1990) on the hydration is surpassed by an impairing filler effect, due to the high limestone content (and the SP6).

**Mutual comparison**

The bond strength of the EB00MCS1-combination is significantly higher than that of the MB15MCS1-combination. Indications for an explanation are:
- at the surface of the joints the calcite content is lower for the EB00- than for the MB15-bricks, see Fig. 7.20c.
- the occurrence of residual clinker material at the interface of EB00 turns out to be higher than that of MB15, compare the calcium hydroxide and residual clinker intensities of Figs 7.20a and 7.20b. The interpretation regarding the variation in residual cement content may be hampered by differences in the degree of hydration. Fluorescence microscopic analysis of the MB15 and EB00 interfaces showed, however, a comparable degree of hydration of the cement grains in the interfacial zones.

From the graphs 7.20a and 7.20b it can be concluded that the hydration conditions at the surface of the joints hardened between MB00-bricks are inferior to that hardened between MB15-bricks. Tensile bond strengths measured for MB00MCS1-combinations were zero, as for the MB15-combinations. (Extended tensile bond strength tests, using MB-bricks with initial water contents 3, 6, 9 and 12 % (mass %), showed zero tensile bond strengths as well).
Fig. 7.20  X-ray diffraction intensities of calcium hydroxide, residual clinker (alite+belite) and calcite (reflections used are ca. 21°, 38° and 34°, respectively) in MCS1-mortar joints as a function of the distance from the joint surface. 28 days hardening. The splines through the data points serve as guidelines.
test results

Hence, it may be concluded that the poor tensile bond strength performance of the MB-combinations is, primarily, likely to be due to unfavourable mortar compositions in the interfacial zone.
The possible influence of differences in porosity in the interfacial zones of the wetted and dry MB-combinations are believed to be of secondary importance: curing at 95% RH and 20 °C, 28 days resulted in higher bond strength for MB15MCS1 than curing at 65% RH and 20 °C, 28 days.

The initial flow rates in the mortars of LB07 and EB00 are almost similar. Therefore, it may be assumed that the compositions of the mortar in the interface are more or less similar as well. When the differences in occurrence of residual clinker material for EB00 and LB07 are evaluated, see Fig. 7.20.b, it seems probable that the degree of hydration of the cement grains in the LB07 interfacial zone is low. This observation seems to be in contradiction with the relatively favourable water content conditions in the brick nearby the mortar interface in the LB07-combination (see Appendix 1). However, as will be explained in Chapter 8.1.2., the water content in the interfacial mortar zone is likely to be low as a result of the high capillary pressures of the calcium silicate brick (vapour transport conditions). This may explain the lower degree of hydration found in the interfacial mortar zone of the LB07MCS1-combination.

Water profile data show that the water loss caused in the MCS1- mortar by the dry calcium silicate bricks (LB00), is so high that hardly any hydration can be expected. This is confirmed by the X-ray diffraction results, see Fig. 7.20.a/b. Considering the very low degree of hydration and the low cement content of the fines in the interfacial zone, a lack of bond strength is not surprising for the LB00MCS1-combinations.
8 DISCUSSION

The discussion in this chapter primarily includes the comparison of experimental test results regarding water flow to capillary pressure theories and unsaturated flow theory. Other findings of this study, especially those related to the effects of water on mortar-brick bond, have been discussed in chapter 7, see sections 7.3.3 and 7.4.4.

8.1 Porosity and water transport

Three ways of modelling are compared with experimental results from neutron transmission measurements.

The first approximation is based on a proposition made by Détriche (1985) to model mortar and brick by means of the mean hydraulic diameter model (see section 8.1.1). The validation of this approximation shows a very poor correlation between theoretical and experimental results.

In section 8.1.2 an attempt is made to improve the modelling through application of particle pressure theories to the mortar. It is shown that the experimentally determined water distributions and flow rates can comparatively be explained with the help of this approximation.

Results of preliminary investigations regarding the application of the Unsaturated Flow Theory on the water flow in brick-fresh mortar combinations are presented in section 8.1.3.

8.1.1 Mean Hydraulic Diameter Model

When bricks and mortar are modelled according to the Carman-Kozeny theory, see Chapter 4, the mean pore diameter of the materials can be calculated with equation (8.1):

\[ D(H) = \frac{4 \times V}{S} \]  

(8.1)

in which,

- \( D(H) \) : mean pore diameter
- \( V \) : void volume of material
- \( S \) : internal surface area of material

Using the data on void volumes and internal surface areas obtained by means of mercury porosimetry, the mean pore radii of the bricks can be calculated, since \( D(H) = 2r_{\text{mean}} \). The results for the test bricks, excluding LB for reasons indicated in section 7.2.6, are shown in Table 8.1:

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Table 8.1 Mean pore radii of bricks

| Type of brick | r_{(mean)} (m*10^{-6}) | pore volume @
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EB &quot;*&quot;</td>
<td>0.71</td>
<td>9</td>
</tr>
<tr>
<td>MB</td>
<td>1.72</td>
<td>30</td>
</tr>
</tbody>
</table>

* pore radii smaller than 0.1 μm are neglected, since it is assumed that no capillary water transport will occur.

@ see Table 7.6

Initial Rate of Absorption (IRA) of the fired clay bricks

Theoretically, the Initial Rate of Absorption of the dry bricks can be calculated, using an extended version of equation (4.2) of Chapter 4:

\[ m' = n \times \pi (r_{(mean)})^2 \times \sqrt{\frac{\sigma r_{(mean)}}{2\eta}} \times \sqrt{t} \times \rho \]  

(8.2)

in which,

- \( m' \): mass of absorbed water per unit area (kg/m²)
- \( n \): number of pores per unit area (1/m²)
- \( r_{(mean)} \): mean pore radius (m)
- \( \sigma \): surface tension of water (N/m)
- \( \eta \): dynamic viscosity of water (Ns/m²)
- \( t \): time (s)
- \( \rho \): density of water (kg/m³)

Assuming 'absorption active' pore volumes of 9% for EB and 30% for MB the Initial Rates of Absorption, calculated with equation (8.2) are

\[ \text{IRA}_{(theor)} \text{ for EB} = 0.404 \text{ kg/m}^2/\sqrt{s} \]
\[ \text{IRA}_{(theor)} \text{ for MB} = 2.085 \text{ kg/m}^2/\sqrt{s} \]

Free water absorption measurements produce IRA values of 1.5 and 4.4 kg/m²/min, see Table 6.1, which correspond with,

\[ \text{IRA}_{(exp.)} \text{ for EB} = 0.194 \text{ kg/m}^2/\sqrt{s} \]
\[ \text{IRA}_{(exp.)} \text{ for MB} = 0.404 \text{ kg/m}^2/\sqrt{s} \]
The results show a significant discrepancy between theory and experiment. In fact, this is not surprising. After all, the mean pore diameter model is based on the assumption, that the pores may be considered as a system of independent parallel capillaries. The reality is different: coarse and fine pores are (inter)connected, which implies, that the fine pores are a determining factor regarding the flow rates in the capillaries. Moreover, the occurrence of closed pores will influence the absorption behaviour. Theory and experiment may be related to each other by introduction of the effective mean pore radius, \( r_{(m,e)} \). This parameter can be derived from the experimental IRA-values, using equation (8.2). This means, that it is assumed that the number of 'absorption active' pores for MB and EB are the same as in the previous calculations.

Substituting in equation (8.2) for \( m^* \) the experimentally determined IRA and for \( n \) the number of pores per unit area derived from the mercury porosimetry data, the effective mean pore radii are,

\[
\begin{align*}
  r_{(m,e)} \text{ for EB} & : 0.536 \ \mu m \\
  r_{(m,e)} \text{ for MB} & : 1.022 \ \mu m
\end{align*}
\]

**Water absorption from the mortar**

The water absorption by the brick is influenced by the capillary suction of the mortar. Considering the mortar as a system of cylindrical capillaries, the capillary pressure may be determined through the mean pore diameter of the mortar. To this end void volume and internal specific surface of the mortar must be known.

The void volume of each mortar can be obtained by subtracting the volumes represented by the aggregate, the binder(s) and that part of the air content consisting of air bubbles from the apparent volume of the mix (see Table 6.4). It is assumed that 5 vol % of the mortars consist of open air pores.

The internal surface areas of the mixes can be calculated using,

- the weight fractions of the solid mortar components as derived from Table 6.4,
- the Blaine values of the different sand gradings and the binders.

The influence of entrained air bubbles on the specific surface of the mixes are neglected. This is justified by the relatively high pore radii of these air bubbles (100-500 \( \mu m \)).

The initial mean pore radii of the fresh mortars are presented in Table 8.2.

**Table 8.2** *Initial mean pore radii of fresh mortars*

<table>
<thead>
<tr>
<th>Mortar type</th>
<th>( r_{(mean)} ) (m*10(^{-6}))</th>
<th>Mortar type</th>
<th>( r_{(mean)} ) (m*10(^{-6}))</th>
<th>Mortar type</th>
<th>( r_{(mean)} ) (m*10(^{-6}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS1</td>
<td>4.31</td>
<td>LCS1</td>
<td>2.20</td>
<td>MCS1</td>
<td>2.03</td>
</tr>
<tr>
<td>PCS4</td>
<td>5.34</td>
<td>LCS4</td>
<td>2.49</td>
<td>MCS4</td>
<td>2.17</td>
</tr>
<tr>
<td>PCS5</td>
<td>4.37</td>
<td>LCS5</td>
<td>2.23</td>
<td>MCS5</td>
<td>1.91</td>
</tr>
</tbody>
</table>
Discussion

Comment
The low mean pore radii of the MC-mortars are due to the relatively high specific surface values of this mortar type in these compositions. The high specific surface values of the MC-mortars are not caused by the occurrence of the finest material in this type of mortars, but by the high quantity of ground limestone: the specific surface of the lime, applied in the lime-cement mortars, is higher than that of ground limestone.

Consequently, mean capillary pressures in the mortars derived from Table 8.2, using \( p = 2\sigma/r \), range from,

2.7\times10^4 \text{ Pa} \text{ for the PCS4-mortar,}

to

7.6\times10^4 \text{ Pa} \text{ for the MCS5-mortar.}

Brick and mortar
A first evaluation regarding the influence of the mortar pressure on the water absorption by the dry bricks may be found through the assumption that a uniform mortar suction counteracts the capillary suction of the brick capillaries (compaction neglected). Hence, the initial absorption rates of water moving from mortar towards brick, may be calculated, as follows:

\[
m = n \times \pi(r_{\text{mean}})^2 \times \left( \frac{2r^2}{8\eta} \left\{ \frac{2\sigma}{r_{\text{(m.e.)}}} - p_{\text{(initial)}} \right\} \right) \times \sqrt{l} \times p
\]  \hspace{1cm} (8.3)

in which,

\( r_{\text{(m.e.)}} \): effective mean pore radius of the brick (m)

\( p_{\text{(initial)}} \): initial mean capillary pressure of the mortar (N/m²)

other symbols: see equation (8.2)

By means of equation 8.3 the theoretical values of the initial absorption rates are determined for EB00- and MB00-bricks combined with PCS4- and MCS5-mortars, see Table 8.3. These theoretical initial absorption rates can be compared with the experimentally determined absorption rates presented in Appendix 4, see Table 8.3.
Table 8.3  Theoretical and experimental initial absorption rates

<table>
<thead>
<tr>
<th>Brick/Mortar Combinations</th>
<th>Flow rates (kg/m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
</tr>
<tr>
<td>EB00PCS4</td>
<td>0.185</td>
</tr>
<tr>
<td>EB00MCS5</td>
<td>0.165</td>
</tr>
<tr>
<td>MB00PCS4</td>
<td>0.274</td>
</tr>
<tr>
<td>MB00MCS5</td>
<td>0.369</td>
</tr>
</tbody>
</table>

Comment
Table 8.3 shows significant discrepancies between the theoretical and experimental values of the absorption rates.

With the help of the experimental data and using equation 8.3, the effective mortar pressure for each combination presented in Table 8.3, can be calculated. The effective capillary pressures in the mortars then turn out to range from $1.2 \times 10^5$ Pa to $2.6 \times 10^5$ Pa. The values of $2.7 \times 10^4$ Pa to $7.6 \times 10^4$ Pa, as calculated for the mean capillary pressures, in the previous section, are substantially lower.

It can be concluded that the result of the approximation of the absorption rates by means of the mean hydraulic diameter model is rather unsatisfactory.

8.1.2 Capillary pressure in particle systems containing a liquid

Introduction
Important effects of brick suction on the fresh mortars are the decrease of the water content and the compaction of particles. Both effects may considerably influence the capillary pressure of the water in the mortar. The mean hydraulic diameter model is inadequate to explain these effects.
Luikov (1966) and Schubert (1982) developed models for the determination of 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 these models will be used to optimize the description of the water pressure of the fresh mortars as a function of water content changes taking place in the mortar. The effects in the mortar will be related to the brick pressure. The brick pressure will be obtained through the Mean Hydraulic Diameter Model.
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. This case, presented in figure 8.1.a, can easily be compared with the pressure conditions in the interfacial zone, where many particles of similar dimensions are present, see Chapter 7.4.

Using the data of figure 8.1.a, the relation between the capillary pressure of water cups and the radii of two identical spherical particles can be found, see figure 8.1.b.

Fig 8.1  
a) Relative capillary pressure of a liquid cup between two identical spheres as a function of the cup angle (β), contact angle (δ) and distance (a/x ratio) (Schubert, 1982).  
b) Capillary water pressure as a function of the particle radius for two identical spheres.
The graphs clearly depict that,
- with decreasing distance between the spheres the capillary pressure increases,
- as a result of water loss of the mortar the capillary pressure increases (lower β):
  . in case of surface contact (a=0) continuously,
  . in case of a=0 up to a certain value and subsequently decreases to zero due to the
    collapse of the cup,
- with decreasing sphere diameter the capillary pressure increases,
- theoretically, negative pressures may develop in the case of liquid bridges between spheres.
Practically, this is unlikely to happen; it may explain the occurrence of initial air contents
in non air-entrained mortars.

Line A in fig 8.1.b 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 reduces from 50
to 20 degrees and the a/r ratio diminishes from 0.1 to 0.

Further analysis of the capillary pressure between spherical particles 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.

Moisture transport in the mortar
The data derived from Schuberts’ model can be used for the interpretation of water transport
phenomena from mortar towards brick taking into account some observations of Luikov
(1966). For water transport in the mortar to occur it is essential that the water cups between
the particles are in contact with each other. This contact depends on the degree of water
filling and the packing of the particles.

Assuming the densest packing of particles, equal spherical dimensions and the voids between
the particles being completely filled with liquid (the so-called capillary state), the capillary
pressure is, according to Luikov, given by:

\[ p_s = 6.9 \frac{\sigma}{r} \]  

(8.4)

Liquid flow is not only possible with completely filled voids. The space between the particles
may also be filled partly with trapped air and partly with liquid. Liquid flow under minimum
liquid content conditions: the critical liquid content, may occur when the liquid cups
surrounding the trapped air are just in contact with each other. Then the critical liquid content
depends on the packing of the particles: 5.9 % for the densest packing and 8.5 % for cubic
packing. The critical liquid content will increase when the particles are not in contact with
each other.

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The capillary pressure under critical liquid content conditions and the densest packing (the funicular state) is given by:

\[ p_s = 4.1 \frac{\sigma}{r} \quad (8.5) \]

In the course of the transport process, air, present in the mortar, will be dragged into the interfacial zone. Under these conditions, the capillary pressure in the mortar will increase and reach a maximum value. The maximum pressure is given by:

\[ p_s = 12.9 \frac{\sigma}{r} \quad (8.6) \]

Since equation (8.6) is related to Schuberts’ theory on liquid cups, it can be concluded that the maximum pressure corresponds with the water pressure of a liquid cup with a cup angle of 20 degrees. Hence, it may be assumed that during the absorption process trapped water (the pendular state) will remain in the material from which the water is removed. The maximum pressure condition represents a state in which only vapour transport will occur.

*Experimental implications*

From the experimental results it can be deduced, see section 8.1.1, that the water pressures in the mortars may be about $1.2 \times 10^5$ N/m$^2$ almost immediately after brick laying. During this initial stage the process of liquid transport is fully active. This implies that water pressures in the mortar are related to the capillary state (eq. 8.4) and/or funicular state (eq. 8.5). Hence, assuming the closest packing of particles, mortar pressures of $\sim 1.2 \times 10^5$ N/m$^2$ can be developed by particles with radii of $\sim 4 \, \mu m$ (eq. 8.4) and of $2.5 \, \mu m$ (eq. 8.5).

It should be emphasized that the formation of a dense packing is essential for the development of the high mortar pressures as observed in the experiments. The conditions for the formation of a dense packing are, during the initial period of water flow, only met at the interface, as an immediate significant decrease of the water content in this zone is possible. The observed concentration of fines in the interfacial zone of the mortar, see Chapter 7.4, may favour the density of the packing as well. These considerations support the assumption that the relatively high mortar pressures, present almost immediately after brick laying are likely to be concentrated at the interfacial zones of the mortars.

As long as the mentioned transport modes hold and the brick pressure is higher than the mortar pressure, water will flow from mortar towards brick. As a result of this flow process the water pressure in the bulk of the mortar will gradually increase.
With low brick pressures it is possible that an equilibrium of brick and mortar pressure is reached at which the water in the mortar shows a capillary or funicular state (only liquid transport). The transition from the funicular to the pendular state, causing maximum pressure in the mortar, will occur if the mortar is exposed to high brick pressures (liquid transport followed by vapour transport).

**Mortar and brick**
For the three states in which water may occur in the mortar, the water pressures ($p$) are presented in figure 8.2.a, as a function of the particle radius ($r$). The dotted lines A, B and C indicate the $r$-$p$ relationships for the estimated mean particle radii of portland cement A, ground limestone and hydrated lime, respectively.

The $r$-$p$ relationships for the brick pores (cylindrical capillaries) are presented in Fig. 8.2.b.

---

**Fig. 8.2**

*a) Capillary pressures between identical particles with the densest packing: I) voids filled with water (capillary state), II) critical water content (funicular state), III) withdrawal of water (pendular state),
b) Capillary pressures in the bricks.*
The capillary pressures in the cylindrical capillaries are calculated, using $p = 2\sigma/r$. The suction exerted by the various brick types depends on the pore distribution. Using the mercury porosimetry data of Fig. 6.1, the capillary pressure distributions are determined for the fired clay bricks, and tentatively indicated for the calcium silicate brick, see figure 8.2.b. It is assumed that pores with radii smaller than 0.1 $\mu$m do not contribute to the moisture transport.

A comparative evaluation of the water flow from mortar towards brick can be made using the figures 8.2.a and 8.2.b:

- Equilibrium between the relatively low brick pressures of MB and the mortar pressure may easily be established after compaction of the interfacial zones. The different water losses of portland cement mortars, masonry cement mortars and lime cement mortars may be attributed to differences in amounts and fineness of very fine particles: 1-5 $\mu$m, available for the interfacial zone. The lower water losses of the mortars in the wetted combinations are likely to be due to the lower capillary brick pressure caused by the inactivity of the finest brick pores (filled with water).

- The pressure distribution of EB shows an important percentage of pressures comparable with that of MB and a low percentage of higher pressures. The test results of Appendix 3 show the significant influence of, in particular, the low pore volume of the EB-bricks. At first sight it may be expected that the total water absorption of the dry EB-combinations is higher than that of the dry MB-combinations, as more fine pores are available in the EB-bricks. This is apparently not the case. The explanation for this phenomenon may be found in the assumption that during the absorption process the small number of fine pores will rather soon be filled. This will cause a drop in the brick pressure and eventually stop the water flow.

- The calcium silicate bricks contain a substantial amount of pores showing high capillary suction. Comparing Figs. 8.2.a and 8.2.b, it can be understood that the capillary brick suction in the dry LB-combinations remains during the first 2-3 hours of hydration always higher than the mortar suction: the capillary pressures in the finest pores is higher than the water pressures that can be developed in the mortars. Moreover, so many fine pores are available that a decrease of the brick pressure due to water absorption will be limited. The situation is a different one for the wetted LB-combinations, due to the inactivity of the finest pores (filled with water). In this case the capillary pressure in the coarser brick pores will not surpass the water pressures, developed between finest particles. The influence of the amount and the fineness of very fine particles on the total water loss of the mortars is also observed in the LB-combinations.

Conclusions
The experimentally determined interactive effects of capillary pressures in mortar and brick on the final water distribution and the water flow can, for the greater part, be comparatively explained by means of a combined application of the mean hydraulic diameter model (to the bricks) and the particle capillary pressure theory (to the mortar).
Analysing the experimental data and the findings from the particle pressure theory, one can demonstrate that relatively high capillary pressures in the mortar, almost immediately after brick laying, are likely to be concentrated in the interfacial zones of the mortar.

The water contents at micro-level, in the outer zone of the mortar interface, depend largely on the capillary pressures in the brick. These are in the calcium silicate bricks (LB) significantly higher than in the fired clay bricks (EB and MB), as a result of the finer pores of the calcium silicate bricks. This points to possibly lower water content values in the interfacial zones of the LB- than in those of the EB- and MB-combinations: the pendular state of water, corresponding with very low water contents, is more likely to occur in the LB-mortars. The very low flow rates measured in the mortars of the LB-combinations in the later phase of the absorption process are an indication for vapour transport conditions. This is in agreement with the assumed occurrence of the pendular water state.

However, it can be observed as well, that the comparison of theory and experiment is more of a qualitative and comparative than of a quantitative nature. This is not astonishing, as a number of assumptions are to be made with regard to:
- the degree and the mode of compaction of the mortar, in particular in the interfacial zone: type and way of grain packing,
- the development of the brick pressure as a function of the increasing water content caused by the brick suction.
Moreover, in case of long-term water transport (e.g. calcium silicate combinations) the effect of hydration on the mortar porosity is difficult to quantify.

It may be assumed that the quantitative modelling of water transport from fresh mortar towards brick is extremely complex.

8.1.3 Unsaturated Flow Theory (UFT)

**Determination of the diffusivity D(ψ)**

Theoretically, the most promising method in evaluating moisture transport in porous media, like bricks, is the unsaturated flow theory (UFT), see Chapter 4. The problems related to the modelling of water transport, using pore size distribution and pore structure characteristics are avoided, since the UFT describes the transport problem at a macroscopic level. This theory also includes the evaluation of water transport for different initial water content conditions of the porous medium.

However, a critical problem of the applicability of the UFT, is the determination of the diffusivity D(ψ), see equation 4.9, Chapter 4. In order to determine D(ψ) of a porous material, data are needed about the water distribution changes during the flow process. Practically, these may be obtained by studying water content changes in consecutive layers of the porous material subjected to an upward flow from a fixed water table.
Up to now the diffusivity $D(\psi)$ of a porous material is mostly determined by graphimmetrical methods. Such methods imply the sectioning of the specimens in thin layers after a defined water flow period, whereupon the water content of each layer must be measured. This process has to be repeated several times. The gravimetical methods are very time consuming and usually not very accurate.

Using the neutron scanning technique, see Chapter 5, changes in water content can be determined in different cross sections of brick specimens non-destructively. Upward water flow was obtained by placing one face of the brick specimen about 5 mm in water; the water table was fixed through a combined water supply / water outlet system. Water content values, as a function of time, were obtained in consecutive cross sections by moving the test specimen stepwise with respect to the fixed restricted neutron beam (see fig. 5.2 of Chapter 5). The distances between the cross sections were 5 mm; the specimens were monitored up to saturation of the specimens.

The moisture dependent diffusivity $D(\psi)$ can be determined using a parameter estimation technique developed by Augenbroe (1984). This technique is based on minimizing the differences in measured and calculated moisture contents and uses a random search technique and finite element method calculations to find the optimal parameters of the functions in which $D(\psi)$ is modelled.

**Diffusivity of the MB-bricks**
It may be assumed that the diffusivity of porous materials, like bricks, resembles the curve presented in Fig. 8.3.

![Diffusivity curve](image-url)
discussion

The curve shows, basically, two branches with (i) high diffusivities, but a relatively moderate increase of $D(\psi)$ for increasing moisture contents (the region of liquid transport) and (ii) low diffusivities, but a strong increase of $D(\psi)$ for increasing moisture content (the region of vapour transport).
The two branches meet at the so-called critical water point, marking the transition from liquid to vapour transport.

As indicated in Chapter 4, the diffusivity is often approximated by an exponential function in the form $D(\psi) = D_{(0)} \exp(B\psi)$.

From Fig. 8.3 and from the considerations about the influence of the type of moisture transport on the diffusivity, it may be concluded that $D(\psi)$ will not correctly be modelled by means of one exponential function applied to the whole moisture range.

In order to obtain a better approximation of the diffusivity $D(\psi)$ the function may be modelled, using different functions in different regions of the moisture range (Tumbuan & Augenbroe, 1993). Four diffusivity functions were composed in this way for the modelling of $D(\psi)$ of the machine moulded bricks (MB),

function A: the moisture range was divided in regions of different widths depending on the expected increase of $D(\psi)$ with increasing water content; in every region $D(\psi)$ was introduced as an exponential function.

function B: the moisture range was divided in 4 regions.
region 1: 5th degree polynomial
region 2: exponential function
region 3: 5th degree polynomial
region 4: exponential function

The polynomials were included in order to cover the possible occurrence of two maxima in the curve.

function C: the moisture range was divided in 2 regions.
region 1: constant value
region 2: one exponential function

function D: moisture range divided in regions of $d\psi=2\%$ with constant value in each region.

A first attempt to relate the modelled functions to the experimental data failed as a result of a too low number of measurements in the zone of vapour transport; in this zone a steep increase within a small moisture range can be observed.
In order to cope with this problem the test set-up was modified in such a way, that a higher testing speed was achieved. This resulted in a more satisfying number of test data below and around the critical moisture point.

The results of the 4 approximations of the diffusivity for the MB-bricks are presented in Fig. 8.4.

![Graph of Diffusivity log (D) vs Moisture content (ψ)]

**Fig. 8.4** *Diffusivity of MB-bricks (Tumbuan & Augenbroe, 1993)*

The curves show a good resemblance for all four approximations in the region of liquid transport, the high water contents.

The curves A and B show a reasonable similarity around the critical moisture point. The best approximation of the test results is achieved with function A, assuming in the low moisture region an initial diffusivity of 3.10^-9. This conclusion is supported by the correlation between the measured moisture contents and calculated moisture contents of the four approximations. Function A, presented in Fig. 8.5, showed the best correlation between measured and calculated moisture contents.
Fig. 8.5  Measured and calculated moisture contents of diffusivity function A of the MB-bricks (Tambuan & Augenbroe, 1993).

The correlation confirms that with the help of the applied measuring and calculation techniques, the liquid diffusivity of the MB-brick can be satisfactorily obtained. The results in the low moisture content region are less convincing. The latter results emphasize the need for even more measurement data in the vapour zone, see also Pel et al. (1993).

Diffusivity and driving force
In Chapter 7.2 it was observed that the flow rates in each mortar type do not significantly deviate for different initial water contents of the brick. In fact, the type of brick is far more determining for the flow rate than the initial water content.

This phenomenon can be understood by application of the UFT. The flow rate is governed by the diffusivity and a driving force. The diffusion of water in a prewetted brick occurs with higher flow rates than in a dry brick, see this Chapter. The driving force may, for instance, be expressed in moisture content gradients or in potential (pressure) gradients in the brick. The decrease of the driving force with increasing water content of the brick can be derived experimentally as well as theoretically: (i) the test results, presented in Appendix 3 show
lower water content gradients in the prewetted than in the dry bricks, (ii) lower potentials (pressures) can be deduced from the diffusivity function and the pore distribution.

The combined effect of increasing diffusivity and decreasing moisture/potential (pressure) gradient with increasing moisture content of the porous medium explains the relatively low influence of moisture conditions of a brick on the flow rates in each mortar type.

Water flow from mortar to brick
The modelling of water flow from the joint towards the brick is hindered by the lack of knowledge about the pressure development in the mortar as a function of brick suction and time.
In section 8.1.2 it was demonstrated that, in particular, the packing of particles in the interfacial zone of the mortar is an important factor regarding increase of the water pressure. The type and the density of packing depend, among others, on the compaction, the particle grading and the occurrence of fine particles. Due to the unpredictability of the packing characteristics of the mortar the modelling of the water flow turned out to be unsuccessful up to now.

An attempt was made to find a potential function of the mortar starting from test results on the water content changes in mortar and brick of the combination MB15PCS4, see Appendix 3. To this end the brick potential was modelled by means of the diffusivity function A, see previous section, and the mercury porosity data on the pore distribution of the MB-brick. The same calculation technique was applied to the approximation of the potential function of the mortar as was used for the diffusivity function. The results of this first attempt showed the feasibility of the applied method. Hence, a possible improved modelling of the water flow in the fresh mortars may be found by further analysis of the test data on flow measurements. From the analysis a number of potential functions of mortars may be derived. Evaluation of these potential functions may result in generalisations of the compaction behaviour of the mortars as a function of the mortar composition and the brick potential.
9 CONCLUSIONS

9.1 Introduction

From the literature study 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 and quantitative information on water content changes in fresh masonry mortars.

9.2 Novel measuring techniques

In order to quantify, non-destructively, water distributions and flow rates in fresh mortars and relevant parts of the vicinal bricks two testing techniques were developed, using thermal neutrons.

Scanning technique
- By means of this technique water distribution profiles are determined over the cross-section of brick-joint-brick combinations (possible interpretation of hydration conditions). The spatial resolution of this technique is 1 mm, i.e. 50 measurements for a testing range of 5 cm.

Monitoring technique
- This technique was developed in order to measure flow rates in the mortars (possible interpretation of transport effects). In this set-up simultaneous and continuous monitoring of water content changes at two positions of the specimens is achieved. Spatial resolution in this test set-up is also 1 mm.

The test accuracy of the techniques is such that water contents can be determined with an imprecision of less than 1% (based on counting statistics).
9.3 Experimental results of water content measurements in mortar and brick

*Water distribution measurements*
The technique allows the quantitative determination of the influence of brick type, mortar type, the initial water content of the brick and the environmental humidity conditions on the water distribution in mortar and brick.

*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,
- a negligible or very small variation in the occurrence of hydration products as a function of the sand grading.

*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.

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

*Flow rate measurements*
From the transmission measurements it was 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 sec, 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.

In assemblies of high absorption fired clay bricks it was observed, that the initial flow rates in a mortar type do not vary significantly for different initial water contents. From this it may be concluded that possible transport effects are not prevented by prewetting.
The absorption process in the calcium silicate combinations lasts significantly longer than in the fired clay brick combinations.

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9.4 Theory and experiment regarding water transport from mortar to brick

Capillary pressure theories
The experimentally determined interactive effects of capillary pressures in mortar and brick on the final water distribution and the water flow can, for the greater part, be comparatively explained by means of a combined application of the mean hydraulic diameter model (to the bricks) and particle capillary pressure theory (to the mortar).

Analysing the experimental data and the findings from the particle pressure theory, one can demonstrate that relatively high capillary pressures in the mortar, almost immediately after brick laying, are likely to be concentrated in the interfacial zones of the mortar.

The water contents at micro-level, in the outer zone of the mortar interface, depend largely on the capillary pressures in the brick. These are in the calcium silicate bricks (LB) significantly higher than in the fired clay bricks (EB and MB), as a result of the finer pores of the calcium silicate bricks. This points to possibly lower water content values in the interfacial zones of the LB- than in those of the EB- and MB-combinations: the pendular state of water, corresponding with very low water contents, is more likely to occur in the LB-mortars. The very low flow rates measured in the mortars of the LB-combinations in the later phase of the absorption process are an indication for vapour transport conditions. This is in agreement with the assumed occurrence of the pendular water state.

Unsaturated Flow Theory (UFT)

Absorption from a free water surface
By means of data obtained from neutron transmission measurements and the application of a parameter estimation technique an approximation of the moisture dependent diffusivity function $D(\psi)$ of the machine moulded brick (MB) was made. The obtained result was satisfactory in the liquid region but less satisfactory in the low moisture content region of the system. Further improvements of the applied measuring technique are needed in order to bring the approximation to more perfection. When this has been carried out, water absorption of the MB-brick, under different initial water content conditions, can be predicted.

Water flow from fresh mortar to brick
The modelling of water transport from fresh mortar to brick turned out to be unsuccessful up to now. Further studies on the pressure development in the mortar, especially in the interfacial zones, are needed to further the modelling. Therefore, one should aim at providing insight into the generation of the type and the density of particle packing as a function of capillary brick pressure and time.
9.5 Mortar-brick bond strength and effects of water

Tensile bond strength testing showed very poor bond between mortars, containing relatively high quantities of fine inert materials and high absorption, fired clay bricks and calcium silicate bricks.

In order to find explanations for unexpected 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 results it was concluded that,
- the phase compositions in the bulk and in the surface region of mortar joints are different,
- more hydration products are formed in the surface region of the joints of PC-mortars than in that of MC-mortars.

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,MCS2) 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).
- 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).
10 RECOMMENDATIONS

Characterization of mortar and brick
The comparative analysis of results of masonry bond tests, presented in papers and reports, is often hindered by an incomplete characterization of mortar and brick. The discussion should be started to establish a minimum list of properties to be determined before mounting a research programme in this field. As a contribution to the discussion the following set of characterizations is proposed:

for the brick
- type of brick
- early rate and long-term rate of absorption
- free water absorption volume
- vacuum pore volume
- pore distribution (mercury porimetry)

for the fresh mortar
- sand grading
- cement type
- cement / sand ratio
- cement / total fines ratio (fines: material of about the same or finer grain size than that of portland cement)
- type, dimensions and content of the fines in the mix
- water / cement ratio
- water content
- air content
- additives (type, function, grading)

Prediction of bond behaviour
Further research in the field of water flow modelling (Unsaturated Flow Theory) may, in particular, be interesting with regard to the prediction of the hydration conditions in the mortar. It should, however, be noted that with the adequate description of water flow the prediction of mechanical performance is still not achieved. The reason is that changes in mortar composition like compaction and local particle enrichment are difficult to determine by means of flow calculations. These changes may have an important influence on the bond development. Variations in mortar composition can be studied by a number of microtechniques, e.g. X-ray diffraction.
Hence, it is to be concluded that the application of a combination of techniques is needed for estimating the bond development in a mortar-brick combination.

It is not to be excluded that, in the future, prediction of bond performance only using UFT-calculations will be feasible. This is, however, only possible if one can dispose of a data bank with results of former tests, by which flow rates and the effects of flow rates on the composition of the mortar on bond behaviour were determined.
Improvement of bond

It was concluded that the bond problems in fired clay masonry (high absorption fired clay with modern mortars) are primarily caused by an unfavourable cement/fine inert material ratio in the interfacial zone, while bond problems in calcium silicate brick masonry are primarily caused by unfavourable hydration conditions in the interfacial zone.

Improvement of bond performance of modern mortars applied in combination with high absorption fired clay bricks may be obtained by one or a combination of the following measures:
- increase of the cementitious material/all fines ratio (in order to ensure the occurrence of sufficient cementitious material in the interfacial zone),
- increase of the water retention of the mortar (in order to diminish the initial flow rates and consequently the transport of inert fines to the interface),
- decrease of the air-content (in order to increase the contact area between mortar and brick and to increase the initial water content of the mortar).

Poor mechanical performance of calcium silicate masonry in which modern mortars are applied will most likely result from the presence of too many fine pores in the bricks. In such cases it is advised to consider the following measures:
- increase of the water retention of the mortar (in order to increase the counteracting pressures in the mortar),
- prewetting of the brick (in order to render the suction of the finest brick pores inactive); this measure is only effective if a uniform prewetting can be ensured,
- changing of the sand grading (in order to obtain a coarser porosity); the feasibility of measures meant to change the brick properties is considered more favourable for calcium silicate than for fired clay bricks.

A complicating factor regarding the application of the proposed measures is the effect on the workability of the mortar. The complimentary use of additives seems to be inevitable to ensure a good workability of the mortars.

The measures imply as well an increase in the cost price of the masonry mortars. A better definition of the bond requirements in specific masonry applications may be a first step to promote research activities focused on an improved mortar/brick bond performance.
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references


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references


# List of Symbols and Abbreviations

## Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>a</td>
<td>gravitational acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>m</td>
<td>mass</td>
<td>kg</td>
</tr>
<tr>
<td>m'</td>
<td>mass per unit area</td>
<td>kg/m³</td>
</tr>
<tr>
<td>ℓ</td>
<td>transmission thickness of sample</td>
<td>m</td>
</tr>
<tr>
<td>i</td>
<td>volume per unit area</td>
<td>m</td>
</tr>
<tr>
<td>P_i(0,m)</td>
<td>initial mean capillary pressure of the mortar</td>
<td>N/m²</td>
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<tr>
<td>r</td>
<td>radius</td>
<td>m</td>
</tr>
<tr>
<td>r_{mean}</td>
<td>mean pore radius</td>
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<tr>
<td>r_{m.e.}</td>
<td>effective mean pore radius</td>
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<td>t</td>
<td>time</td>
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<th>Symbol</th>
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<tr>
<td>A</td>
<td>water absorption coefficient</td>
<td>kg/m²/s</td>
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<tr>
<td>C</td>
<td>intercept value absorbed water</td>
<td>kg/m³</td>
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<td>D(H)</td>
<td>hydraulic diameter</td>
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</tr>
<tr>
<td>D</td>
<td>diffusivity</td>
<td>m²/s</td>
</tr>
<tr>
<td>D(ψ)</td>
<td>diffusivity due to a moisture gradient</td>
<td>m²/s</td>
</tr>
<tr>
<td>D(T)</td>
<td>diffusivity due to a temperature gradient</td>
<td>m²/s</td>
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<tr>
<td>H</td>
<td>meniscus elevation of liquid in capillary</td>
<td>m</td>
</tr>
<tr>
<td>H_o</td>
<td>maximum meniscus elevation of liquid in capillary</td>
<td>m</td>
</tr>
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<td>I_o</td>
<td>number of neutrons counted per unit of time, empty beam</td>
<td>1/s</td>
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<tr>
<td>I</td>
<td>number of neutrons counted per unit of time, sample in the beam</td>
<td>1/s</td>
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<tr>
<td>IRA</td>
<td>Initial Rate of Absorption</td>
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<td>sorptivity</td>
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<td>T</td>
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<tr>
<td>η</td>
<td>viscosity</td>
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<td>ρ</td>
<td>density</td>
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<td>σ</td>
<td>surface tension</td>
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<td>σ_i</td>
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<tr>
<td>σ_a</td>
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<td>ψ</td>
<td>volumetric moisture content</td>
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<tr>
<td>ψ_c</td>
<td>volumetric critical moisture content</td>
<td>m³/m³</td>
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<td>φ</td>
<td>percentual volumetric moisture content</td>
<td>%</td>
</tr>
<tr>
<td>μ</td>
<td>linear attenuation coefficient</td>
<td>1/m</td>
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</table>
list of symbols and abbreviations

ABBRREVIATIONS

AFt  Ettringite: 3CaO.Al₂O₃.3CaSO₄.32H₂O
Alite see C₃S
binder cementitious material (e.g. portland cement) or a combination of cementitious material and 'filler' (e.g. hydrated lime, ground lime stone)
Belite 8-C₃S, see C₃S
Blaine specific surface measured with Blaine apparatus
C₄AF Tetracalcium aluminoferrite: 4CaO.Al₂O₃.Fe₂O₃
Cc Calcium carbonate: CaCO₃
CH Calcium hydroxide: Ca(OH)₂
C-S-H Calcium-silica-hydrate
C-S-H type I Calcium-silica-hydrate, classification according to Diamond (1976)
C₃S Dicalcium silicate: 2CaO.SiO₂
C₃S Tricalcium silicate: 3CaO.SiO₂
RH Relative humidity (%)
Q Quartz
R Alite + Belite
R Mode of rupture
BE Bond efficiency
SEM Scanning electron microscopy
UFT Unsaturated Flow Theory
V Vaterite
w/c ratio water-cement ratio
XRD X-ray diffractometry

Test specimens

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
S(1...5) : type of sand grading

For further specifications of the test specimen constituents see Chapter 6.
APPENDIX 1

In this appendix water distribution profiles are presented over the cross-sections of 45 brick-joint-brick combinations.

The water distributions are visualized in graphs in which the vertical axis presents the scan position [mm] of the specimen and the horizontal axis the related water content [% by volume]. The interfaces mortar-brick are indicated by means of a horizontal, dotted lines. The initial water content in the the mortar is marked by a vertical, dotted line.

In each graph are shown,
- a profile, scanned 8 hours after preparation of the test specimen. Test conditions: RH 95%, 20 °C.
- a profile of a similar specimen, dried at 105 °C after 28 days of hardening (presenting the chemically bound water in the mortar). Curing conditions: RH 95%, 20 °C.

The notations used in the graphs are:

<table>
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<th>Code</th>
<th>Description</th>
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Ditto after drying at 378 K

EB00PCS2 8H
Ditto after drying at 378 K

MB15PCS1 8H
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MB15PCS2 8H
Ditto after drying at 378 K

LB07PCS1 8H
Ditto after drying at 378 K

LB07PCS2 8H
Ditto after drying at 378 K
appendix 1

EB00PCS5 8H
Ditto after drying at 378 K

MB15PCS5 8H
Ditto after drying at 378 K

LB07PCS5 8H
Ditto after drying at 378 K
appendix I

EB00LCS3 8H
Ditto after drying at 378 K

EB00LCS4 8H
Ditto after drying at 378 K

MB15LCS3 8H
Ditto after drying at 378 K

MB15LCS4 8H
Ditto after drying at 378 K

LB07LCS3 8H
Ditto after drying at 378 K

LB07LCS4 8H
Idem after drying at 378 K
APPENDIX 2

In order to evaluate the hydration conditions of the mortars it may be useful to determine the water/cement ratio at relevant positions in the joint.

In this appendix the water/cement ratios are collected in the mortar core and in the interfacial zone of mortar and brick. The values are determined from
(i) the experimental results of neutron transmission scanning of 45 brick-mortar-brick combinations as presented in the graphs of Appendix 1,
(ii) the experimental results of neutron transmission monitoring of 45 brick-mortar-brick combinations as presented in the graphs of Appendix 3.

The initial water content values (\(\Phi(\text{init.})\)) and the initial water/cement ratios (w/c(\text{init.})) of the mortars are derived from Table 6.4: Mortar Characteristics of Chapter 6.

The water/cement ratios in the interfacial zones may be influenced by changes in mortar composition, caused, for instance, by transport effects resulting from the brick suction. As a consequence these values must be considered as preliminary estimations.

The notations 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
S(1...5) : sand grading type
Results determined from Neutron Transmission Scanning (Lift Facility)

Extruded fired clay brick combinations (EB)

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152
Calcium silicate brick combinations (LB)

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# Results determined from Neutron Transmission Monitoring
(Brick Laying Device)

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<td>5.0</td>
<td>0.91</td>
<td>0.18</td>
<td>20.2</td>
</tr>
<tr>
<td>LB07PCS5</td>
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<td>5.0</td>
<td>0.67</td>
<td>0.17</td>
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</tr>
<tr>
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<td>13.5</td>
<td>1.22</td>
<td>0.60</td>
<td>23.6</td>
</tr>
<tr>
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<td>1.14</td>
<td>0.44</td>
<td>20.9</td>
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<tr>
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<td>10.0</td>
<td>1.16</td>
<td>0.51</td>
<td>22.0</td>
</tr>
<tr>
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<td>19.9</td>
<td>9.0</td>
<td>0.96</td>
<td>0.43</td>
<td>19.3</td>
</tr>
</tbody>
</table>
Calcium silicate brick combinations (LB)

<table>
<thead>
<tr>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>φ (init.)</td>
<td>φ (4h)</td>
<td>w/c (init.)</td>
<td>w/c (4h)</td>
<td>φ (init.meas.)</td>
</tr>
<tr>
<td>LB00PCS1</td>
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<td>3.0</td>
<td>0.81</td>
<td>0.11</td>
<td>18.8</td>
</tr>
<tr>
<td>LB00PCS4</td>
<td>24.8</td>
<td>3.0</td>
<td>0.91</td>
<td>0.11</td>
<td>21.3</td>
</tr>
<tr>
<td>LB00PCS5</td>
<td>19.7</td>
<td>3.0</td>
<td>0.67</td>
<td>0.10</td>
<td>17.8</td>
</tr>
<tr>
<td>LB00LCS1</td>
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<td>8.0</td>
<td>1.22</td>
<td>0.36</td>
<td>24.6</td>
</tr>
<tr>
<td>LB00LCS4</td>
<td>28.4</td>
<td>6.0</td>
<td>1.29</td>
<td>0.27</td>
<td>22.4</td>
</tr>
<tr>
<td>LB00LCS5</td>
<td>25.9</td>
<td>5.0</td>
<td>1.12</td>
<td>0.22</td>
<td>20.6</td>
</tr>
<tr>
<td>LB00MCS1</td>
<td>23.4</td>
<td>3.5</td>
<td>1.14</td>
<td>0.17</td>
<td>20.8</td>
</tr>
<tr>
<td>LB00MCS4</td>
<td>22.7</td>
<td>3.5</td>
<td>1.16</td>
<td>0.18</td>
<td>20.9</td>
</tr>
<tr>
<td>LB00MCS5</td>
<td>19.9</td>
<td>4.5</td>
<td>0.96</td>
<td>0.22</td>
<td>18.2</td>
</tr>
</tbody>
</table>
APPENDIX 3

Water content as a function of time, measured
- in the middle of the joint (marked in the graphs by 1),
- at 2 mm from the upper surface of the lower brick (marked in the graphs by 2).

The notations 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
S(1...5) : sand grading type
APPENDIX 4

Mass of absorbed water by the bricks as a function of time.

The water uptake in the bricks, adjacent to the joint can be derived from the decreasing water contents measured in the middle of the joint, see Appendix 3. Assuming a uniform decrease in water content over the cross-section of the joint, which is more or less the case, and assuming an equal water uptake by the upper and lower brick the water absorption of each brick can be determined, using equation 7.2 of Chapter 7.2,

\[ m' = \frac{(\varphi(i) - \varphi(t))}{100} \times \frac{\ell}{2} \times \rho \]

in which,

- \( m' \): mass of absorbed water per unit area \( (\text{kg/m}^2) \)
- \( \varphi(i) \): initial water content of the mortar \( \text{(vol.%)} \)
- \( \varphi(t) \): measured water content of the mortar after period of time \( t \) \( \text{(vol.%)} \)
- \( \ell \): thickness of the joint \( \text{(m)} \)
- \( \rho \): density of water \( \text{(kg/m}^3\) \)

In each graph three water absorption profiles are plotted. The numbers used in the graphs correspond with the sand gradings of the mortars.

The notations 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
- S(1...5): sand grading type
appendix 4

EB00PC S1 S4 S5

MB15PC S1 S4 S5

MB00PC S1 S4 S5

LB07PC S1 S4 S5

LB00PC S1 S4 S5
In this appendix the flow rates in the mortars are presented, originating from the brick suction.

The flow rate graphs are related to the absorption graphs (Appendix 4), as the flow rate at a defined time $t$ is the first derivative of the absorption function at time $t$.

The flow rate is determined as a function of the total surface area. Hence, the effective water flow in the mortars is higher, see Chapter 7.2.5.

The notations 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
- S(1...5) : sand grading type
appendix 5
Determination of the bond strength efficiencies (BE) of the tensile bond strength test results presented in Table 7.8 of Chapter 7.3.1.

The notations used in the Table A6.1 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
S(1...5) : sand grading type
Cement content and bond efficiency (BE)

The comparison of the performance of the mortars as presented in Table 7.8 is hindered by the differences in cement contents. This problem may be solved by relating the bond strength values to equal cement contents of the mortars. Subsequently, the bond performance of a combination may be evaluated comparing its bond strength with that of a reference combination.

The test results of Table 7.8 show a maximum tensile bond performance of the combination EB00PCS5, (SC). Taking this performance as a standard efficiency of 100%, the tensile bond efficiency (BE) of another combination (C) of the test series may be determined as follows:

$$BE_{(C)} = \frac{\sigma_{TB(C)}}{\sigma_{TB(SC)}} \times 100 \text{ (%)}$$

(7.3)

in which,

- $BE_{(C)}$: bond efficiency of combination (C) (%)
- $\sigma_{TB(C)}$: tensile Bond Strength of combination (C) (MPa)
- $\sigma_{TB(SC)}$: tensile Bond Strength of standard combination (SC) (MPa)

For the results from the BE-calculation, see Table A6.1
Table A6.1  Tensile Bond Efficiencies (BE) of the mortar-brick combinations related to EB00PCS5 (Cross-couplet test results of Table 7.8)

<table>
<thead>
<tr>
<th></th>
<th>EB00</th>
<th>MB15</th>
<th>LB07</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$ MPa</td>
<td>$\sigma'$ MPa</td>
<td>BE %</td>
</tr>
<tr>
<td>PCS1</td>
<td>0.35</td>
<td>0.36</td>
<td>72</td>
</tr>
<tr>
<td>LCS1</td>
<td>0.27</td>
<td>0.38</td>
<td>76</td>
</tr>
<tr>
<td>MCS1</td>
<td>0.17</td>
<td>0.25</td>
<td>50</td>
</tr>
<tr>
<td>PCS2</td>
<td>0.45</td>
<td>0.46</td>
<td>92</td>
</tr>
<tr>
<td>LCS2</td>
<td>0.41</td>
<td>0.57</td>
<td>114</td>
</tr>
<tr>
<td>MCS2</td>
<td>0.20</td>
<td>0.29</td>
<td>58</td>
</tr>
<tr>
<td>PCS3</td>
<td>0.46</td>
<td>0.47</td>
<td>94</td>
</tr>
<tr>
<td>LCS3</td>
<td>0.48</td>
<td>0.67</td>
<td>134</td>
</tr>
<tr>
<td>MCS3</td>
<td>0.28</td>
<td>0.41</td>
<td>82</td>
</tr>
<tr>
<td>PCS4</td>
<td>0.47</td>
<td>0.49</td>
<td>98</td>
</tr>
<tr>
<td>LCS4</td>
<td>0.41</td>
<td>0.58</td>
<td>116</td>
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<tr>
<td>MCS4</td>
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<td>0.37</td>
<td>74</td>
</tr>
<tr>
<td>PCS5</td>
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<td>0.50</td>
<td>100</td>
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<tr>
<td>LCS5</td>
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<td>120</td>
</tr>
<tr>
<td>MCS5</td>
<td>0.30</td>
<td>0.43</td>
<td>86</td>
</tr>
</tbody>
</table>
Influence of the curing conditions on the bond efficiencies

The notations used in the Tables 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
S(1...5) : sand grading type
Tensile strength from flexural testing

A second test series was carried out to study the bond behaviour of the combinations. The aim of these tests was to evaluate the possible influence of the curing conditions on the bond strength development. A secondary objective was to test a flexural bond strength procedure, as proposed by Harris (1990).

In order to relate the test results of the flexural bending tests to those of the tensile tests, the calculation of the flexural tensile stresses was based on a bending theory adapted to the elastic behaviour of masonry in bending. Experiments carried out by Fried (1991) showed, for masonry under bending, neutral axis positions significantly nearer the compression side than those predicted by classical bending theory. \( \sigma = M/W \). This is caused by different moduli of elasticity to the areas of joint in tension and compression. For different materials the position of the neutral axis could be expressed as the ratio of the distance from the neutral axis to the compression face to the thickness of the unit. He found for brickwork materials a ratio of \( \sim 0.21 \). Assuming a linear stress decrease from the compression and tension face towards the neutral axis, simple calculation shows that the acting tensile stresses in the case of flexural bending are about 63% of the values calculated by means of the classical bending theory.

The tensile bond strength values, derived from the flexural testing by means of the modified bending theory, are presented in Table A7.1:

<table>
<thead>
<tr>
<th></th>
<th>EB00</th>
<th></th>
<th>MB15</th>
<th></th>
<th>LB07</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS1</td>
<td>0.47</td>
<td>0.12</td>
<td>1</td>
<td>0.11</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>LCS1</td>
<td>0.37</td>
<td>0.08</td>
<td>1</td>
<td>0.09</td>
<td>0.04</td>
<td>1</td>
</tr>
<tr>
<td>MCS1</td>
<td>0.23</td>
<td>0.09</td>
<td>1</td>
<td>0.09</td>
<td>0.04</td>
<td>1</td>
</tr>
<tr>
<td>PCS2</td>
<td>0.50</td>
<td>0.14</td>
<td>1.2</td>
<td>0.06</td>
<td>0.04</td>
<td>1</td>
</tr>
<tr>
<td>LCS2</td>
<td>0.33</td>
<td>0.11</td>
<td>1</td>
<td>0.04</td>
<td>0.03</td>
<td>1</td>
</tr>
<tr>
<td>MCS2</td>
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<td>0.09</td>
<td>1</td>
<td>0.04</td>
<td>0.04</td>
<td>1</td>
</tr>
</tbody>
</table>

Table A7.1  Tensile Bond Strength Results from Flexural Testing
(ASTM D1635, modified according to Harris (1990))
### Summary of Tensile Bond Strength and Mode of Rupture

<table>
<thead>
<tr>
<th>Material</th>
<th>σ&lt;sub&gt;TB&lt;/sub&gt; (MPa)</th>
<th>σ' (MPa)</th>
<th>σ&lt;sub&gt;BE&lt;/sub&gt; (%)</th>
<th>σ&lt;sub&gt;BE&lt;/sub&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS3</td>
<td>0.48</td>
<td>0.21</td>
<td>0.17</td>
<td>0.05</td>
</tr>
<tr>
<td>LCS3</td>
<td>0.49</td>
<td>0.12</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>MCS3</td>
<td>0.31</td>
<td>0.08</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>PCS4</td>
<td>0.64</td>
<td>0.12</td>
<td>0.37</td>
<td>0.09</td>
</tr>
<tr>
<td>LCS4</td>
<td>0.45</td>
<td>0.13</td>
<td>0.17</td>
<td>0.05</td>
</tr>
<tr>
<td>MCS4</td>
<td>0.22</td>
<td>0.05</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>PCS5</td>
<td>0.55</td>
<td>0.14</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>LCS5</td>
<td>0.62</td>
<td>0.11</td>
<td>0.14</td>
<td>0.03</td>
</tr>
<tr>
<td>MCS5</td>
<td>0.37</td>
<td>0.10</td>
<td>0.16</td>
<td>0.07</td>
</tr>
</tbody>
</table>

- **σ<sub>TB</sub>**: mean tensile bond strength (MPa) of 10 specimens
- **σ'**: standard deviation (MPa) of the 10 specimens
- **R**: mode of rupture:
  - 1: interface rupture
  - 2: mortar rupture, some mm from interface
  - 3: mortar rupture over cross section
  - 4: brick rupture, some mm from interface
  - 5: brick rupture (flexion)

Curing conditions: RH 95%, 20 °C; 28 days.

The tensile bond efficiencies, derived from the flexural bond testing and related to the standard efficiency of EB00PCS5 (cross-couplet testing) are collected in Table A7.2.

---

### Table A7.2 Tensile bond efficiencies determined from the flexural bond test results (curing conditions RH 95%, 20 °C; 28 days)

<table>
<thead>
<tr>
<th></th>
<th>EB00</th>
<th>MB15</th>
<th>LB07</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ MPa</td>
<td>σ' MPa</td>
<td>σ BE</td>
</tr>
<tr>
<td>PCS1</td>
<td>0.47</td>
<td>0.48</td>
<td>0.11</td>
</tr>
<tr>
<td>LCS1</td>
<td>0.37</td>
<td>0.52</td>
<td>0.09</td>
</tr>
<tr>
<td>MCS1</td>
<td>0.23</td>
<td>0.34</td>
<td>0.09</td>
</tr>
<tr>
<td>PCS2</td>
<td>0.50</td>
<td>0.51</td>
<td>0.06</td>
</tr>
<tr>
<td>LCS2</td>
<td>0.33</td>
<td>0.46</td>
<td>0.04</td>
</tr>
<tr>
<td>MCS2</td>
<td>0.37</td>
<td>0.54</td>
<td>0.04</td>
</tr>
</tbody>
</table>

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180
<table>
<thead>
<tr>
<th></th>
<th>EB00</th>
<th>MB15</th>
<th>LB07</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS3</td>
<td>0.48</td>
<td>0.49</td>
<td>0.17</td>
</tr>
<tr>
<td>LCS3</td>
<td>0.49</td>
<td>0.69</td>
<td>0.16</td>
</tr>
<tr>
<td>MCS3</td>
<td>0.31</td>
<td>0.45</td>
<td>0.10</td>
</tr>
<tr>
<td>PCS4</td>
<td>0.64</td>
<td>0.67</td>
<td>0.37</td>
</tr>
<tr>
<td>LCS4</td>
<td>0.45</td>
<td>0.64</td>
<td>0.17</td>
</tr>
<tr>
<td>MCS4</td>
<td>0.22</td>
<td>0.32</td>
<td>0.13</td>
</tr>
<tr>
<td>PCS5</td>
<td>0.55</td>
<td>0.55</td>
<td>0.14</td>
</tr>
<tr>
<td>LCS5</td>
<td>0.62</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>MCS5</td>
<td>0.37</td>
<td>0.10</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The tensile bond efficiencies of both test series, cross-couplet bond testing and flexural bond testing are listed in Table A7.3.

**Table A7.3** Comparison of the tensile bond efficiencies of the cross-couplet bond testing (RH 65%, 20 °C; 28 days) and the flexural bond testing (RH 95%, 20 °C; 28 days)

<table>
<thead>
<tr>
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<th>LB07</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS1</td>
<td>72</td>
<td>96</td>
<td>64</td>
</tr>
<tr>
<td>LCS1</td>
<td>72</td>
<td>104</td>
<td>32</td>
</tr>
<tr>
<td>MCS1</td>
<td>50</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td>PCS2</td>
<td>92</td>
<td>102</td>
<td>72</td>
</tr>
<tr>
<td>LCS2</td>
<td>114</td>
<td>92</td>
<td>40</td>
</tr>
<tr>
<td>MCS2</td>
<td>58</td>
<td>108</td>
<td>8</td>
</tr>
<tr>
<td>PCS3</td>
<td>94</td>
<td>98</td>
<td>84</td>
</tr>
<tr>
<td>LCS3</td>
<td>134</td>
<td>138</td>
<td>96</td>
</tr>
<tr>
<td>MCS3</td>
<td>82</td>
<td>90</td>
<td>38</td>
</tr>
<tr>
<td>PCS4</td>
<td>98</td>
<td>134</td>
<td>88</td>
</tr>
<tr>
<td>LCS4</td>
<td>116</td>
<td>128</td>
<td>96</td>
</tr>
<tr>
<td>MCS4</td>
<td>74</td>
<td>64</td>
<td>36</td>
</tr>
<tr>
<td>PCS5</td>
<td>100</td>
<td>110</td>
<td>80</td>
</tr>
<tr>
<td>LCS5</td>
<td>120</td>
<td>172</td>
<td>84</td>
</tr>
<tr>
<td>MCS5</td>
<td>86</td>
<td>106</td>
<td>60</td>
</tr>
</tbody>
</table>

*) CT: Cross-couplet Bond Testing (RH 65%, 20 °C; 28 days)

@) FT: Flexural Bond Testing (RH 95%, 20 °C; 28 days)
Observations

Comparison of the tensile bond efficiencies show,
- higher or comparable efficiencies of the EB00-combinations, cured at 95 % RH and 20 ºC; slightly positive effect of higher water content in mortar and brick on bond strength: favourable water/cement ratios at the interface.
- lower or comparable efficiencies for the portland cement and lime cement combinations of MB15 and LB07, cured at 95 % RH and 20 ºC, during 28 days. (exception LB07PCS4); impairing effect of the relatively high water content in mortar and brick on the bond strength: high porosity at this hydration conditions.
- comparable efficiencies of the masonry cement combinations of MB15 and LB07, cured at 95% and 20 ºC (exception MB15MCS1). Probably, higher porosity is balanced by better hydration of the cement.
- the test series performed by Harris (1990) showed significantly lower variations in the test results than was found in the series presented in this appendix. Generally, the variation in the cross-couplet test results were lower than those in the three point bending test.
APPENDIX 8

Determination of the standard deviation of the volumetric water contents, originating from the applied neutron transmission measuring technique.

The volume fraction $\psi$ of water in brick or mortar can be determined using equation (5.4), presented in chapter 5,

$$\psi = \frac{1}{\mu_w \ell} \ln \left( \frac{I_o}{I_w} \right) - \frac{\mu_d}{\mu_w}$$ \hspace{1cm} (A8.1)

in which,

$I_o$: number of neutrons counted per unit of time with empty beam \hspace{1cm} (1/s)
$I_w$: number of neutrons counted per unit of time with sample in the beam \hspace{1cm} (1/s)
$\ell$: transmission length \hspace{1cm} (m)
$\mu_w$: attenuation coefficient of water \hspace{1cm} (1/m)
$\mu_d$: attenuation coefficient of dry material (dry brick, dry mortar) \hspace{1cm} (1/m)

Correcting for the dead time $\tau$ of the neutron detector and expressing the water content in volume % ($\varphi$), equation (5.4) transforms into,

$$\varphi = \frac{100}{\mu_w \ell} \left[ \ln \left( \frac{I_o}{I_w} \right) + \ln \frac{1-\epsilon I_w}{1-\epsilon I_o} \right] - \frac{\mu_d}{\mu_w}$$ \hspace{1cm} (A8.2)

The standard deviation ($S_\varphi$) is given by,

$$S_\varphi = |\frac{\partial \varphi}{\partial I_w}| * \sqrt{I_w}$$ \hspace{1cm} (A8.3)

Determination of $|\frac{\partial \varphi}{\partial I_w}|$:

Since $I_o$ and $\frac{\mu_d}{\mu_w}$ are constants equation (A8.2) can be written as follows,
\[ \varphi = \frac{100}{\mu_w \ell} \left( -\ln I_w + C_1 + \ln (1-\tau I_w) + C_2 \right) - C_3 \]

Consequently,

\[ \left| \frac{\partial \varphi}{\partial I_w} \right| = \frac{100}{\mu_w \ell} \left| \frac{1}{I_w} - \frac{\tau}{1-\tau I_w} \right| \]

\[ = \frac{100}{\mu_w \ell} \left| \frac{1-\tau I_w + \tau I_w}{I_w(1-\tau I_w)} \right| \]

\[ = \frac{100}{\mu_w \ell} \left| \frac{1}{I_w(1-\tau I_w)} \right| \]

Hence, the standard deviation of the volumetric water content \( \varphi \) is given by,

\[ S_\varphi = \frac{100}{\mu_w \ell} \left| \frac{1}{I_w(1-\tau I_w)} \right| \times \sqrt{I_w} \]

\[ = \frac{100}{\mu_w \ell} \left| \frac{1}{\sqrt{I_w(1-\tau I_w)}} \right| \]
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