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QUALITATIVE MODELLING OF WATER LOSS OF FRESH MORTARS IMMEDIATELY AFTER BRICKLAYING

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ABSTRACT

The transport of water from mortar to brick, occurring immediately after bricklaying, may be approximated by modelling (i) the brick according to the Capillary Pressure Theory for Porous Solid Media and (ii) the mortar according to Pressure Theories for Particle Systems containing Liquids (Schubert, Luikov). Using these theories water absorption characteristics of the brick and the counter-acting water retention of the mortar may be evaluated.
In the paper the modelling of brick and mortar is described. Next, a qualitative comparison is made of the water loss occurring in different fresh mortars as a result of the brick suction of various brick types. Finally, the results are related to experimental data obtained from water flow measurements in a series of brick-mortar-brick combinations.
It may be concluded, that the interactive effects of capillary suction of mortar and brick on the final water distribution and the water flow can qualitatively be compared through this approach.

INTRODUCTION

Up to now mechanical behaviour of masonry is often predicted using an algorithm in which are introduced the mechanical properties of bricks and that of mortars hardened in steel moulds. Due to brick suction the hydration conditions of the mortar present in masonry, significantly differs from mortars hardened between bricks.

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It may be assumed that research in the field of mechanical performance prediction will more and more be focused on the evaluation of the real properties of the mortars. This may be aimed at by mechanical testing of mortars hardened between mortars. In this respect the evaluation of the hydration conditions of the mortar will be an interesting tool for the interpretation of the test results. Modelling of water transport from mortar to bricks may result in an estimation of the water losses of the mortar and subsequently contribute to the determination of the hydration conditions of the mortar.

BRICK MODELLING

Capillary pressure theory for porous solid media.
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 then 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 effects of friction and gravity, the capillary suction (under-pressure) is given by,

$$-p_c = \frac{2\sigma}{r} \qquad [1]$$

in which,
$-p_c$: capillary suction (N/m^2)
σ : surface tension (N/m)
r : pore radius (m)

The relationship between capillary suction and pore radius is presented in Fig. 2b.

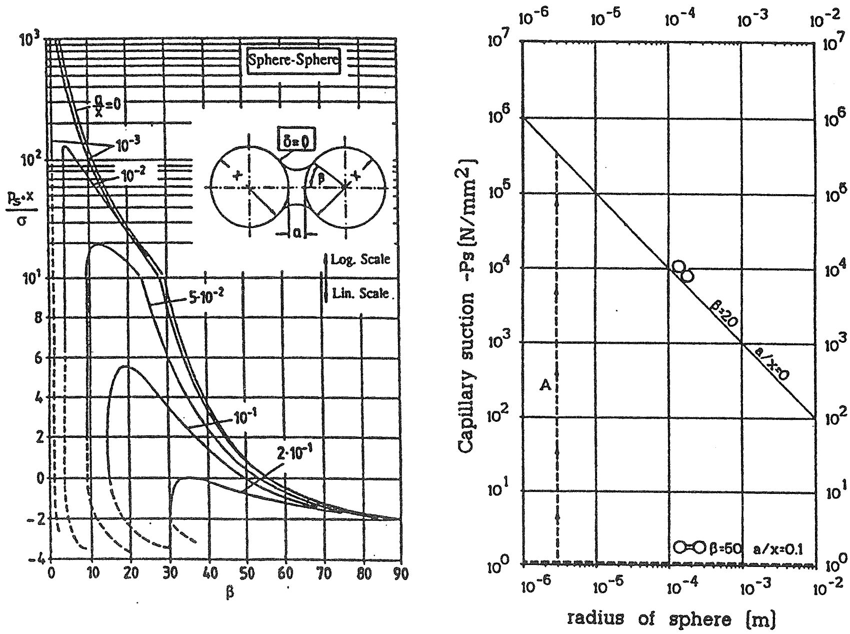
MORTAR MODELLING

Capillary pressure theory for particle systems containing a liquid
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 suction of the water in the mortar. The capillary pressure theory for porous (solid) media 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 suction of the water in the mortar. In this section these models will be used to optimize the description of the water suction of fresh mortars as a function of water content changes taking place in the mortar.

Next, the effects in the mortar will be related to the brick suction .

Liquid cups

In Schuberts' study much attention is paid to the description of the capillary suction 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 suction. This case, presented in Fig. 1a, can easily be compared with the suction conditions in the interfacial zone, where many particles of similar dimensions are present.
Using the data of figure 1.a, the relation between the capillary suction of water cups and the radii of two identical spherical particles can be found, see Fig. 1b.



a

b

Fig. 1 *a) Relative capillary suction 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 suction as a function of the particle radius for two identical spheres.

The graphs clearly depict that,

- with decreasing distance between the spheres the capillary suction increases,
- as a result of water loss of the mortar the capillary suction 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 suction increases,
- theoretically, negative suction 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. 1b represents the increase of the capillary suction 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/x 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.

Schuberts' model demonstrates the enormous influence of compaction and water loss on the capillary suction in the mortar.

Moisture transport in particle systems

Three-dimensional moisture transport in particle systems can be explained by means of a theory developed by 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 suction is, according to Luikov, given by:

$$-p_s = 6.9\frac{\sigma}{r} \qquad [2]$$

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.

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

$$-p_s = 4.1 \frac{\sigma}{r} \qquad [3]$$

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 (pendular state). The maximum suction is given by:

$$-p_s = 12.9 \frac{\sigma}{r} \qquad [4]$$

The maximum pressure condition represents a state in which only vapour transport will occur.
The suction-sphere radius relationships of capillary, funicular and pendular state are presented in Fig. 2a.

Water transport from mortar to brick
During this initial stage of water transport from mortar to brick the process of liquid transport is fully active. This implies that water suction in the mortar is related to the capillary state (eq.2) and/or funicular state (eq.3).
Previous tests showed (Groot (1993)) that the water suction in the mortar may be about 10^5 Pa, almost immediately after bricklaying. Such a suction can be developed by spherical particles (of equal radius and under closest packing) with radii of ~ 5 µm (eq.2) and of 3 µm (eq.3), depending on the suction state of the mortar. (The value of the surface tension of water, used in the calculations is σ= 0.075 N/m)

It should be emphasized that the formation of a dense packing is essential for the development of the high mortar suction 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. Concentration of fines in the interfacial zone of the mortar may favour the increase of the water suction as well. These considerations support the assumption that the relatively high mortar suction, present almost immediately after brick laying is likely to be concentrated at the interfacial zones of the mortars.

As long as the mentioned transport modes hold and the brick suction is higher than the mortar suction, water will flow from mortar towards brick. As a result of this flow process the water suction in the bulk of the mortar will gradually increase.

With low brick suction it is possible that an equilibrium of brick and mortar suction 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 suction in the mortar, will occur if the mortar is exposed to high brick suction due to very fine pores (liquid transport followed by vapour transport).

EXPERIMENTS

Bricks

In the test programme are included a low absorption wire cut brick (EB), a high absorption machine moulded brick (MB) and a medium absorption calcium silicate brick (LB). Some characteristics of the dry bricks, EB00 etc., are listed in Table 1.

Table 1. Brick characteristics

Brick type		EB00	MB00	LB00
Density	(kg/m^3) (vol %)	1990 25	1630 39	1710 27
Initial rate of absorption	(kg/m^2.min)	1.50	4.40	

The influence of prewetting of the bricks on the water loss is studied for the high absorption brick (MB) and the calcium silicate brick (LB). Prewetting of the low absorption EB is omitted as an impairing effect on mortar properties is expected. The MB-brick is prewetted such that an initial rate of absorption of 1.5 kg/m^2.min is achieved. This is obtained by a prewetting of 15 mass %. The brick is indicated then as MB15. The prewetted LB-bricks contain 7 mass % water, as at this water content maximum bond strength performance may be expected (LB07).

The pore size distributions of the bricks are determined by means of mercury porimetry. The results are presented in Fig. 2b. Since the pores of the calcium silicate bricks are not cylindrical the results are indicatively presented.

Mortars

Two mortar types are applied: a portland A cement mortar (PC) and a masonry cement mortar (MC). The masonry cement consists of portland A cement (55% by weight) and ground lime stone (45% by weight).
The aggregate of the mortars consists of river sand. The data on the mortar properties are collected in Table 2.

Table 2. Mortar characteristics

	Mortars*)			
	Portland cement		Masonry cement	
Property	PCS4		MCS4	
Cement/Sand ratio (v/v)	1:4.5		1:3	
Initial Water/Cement Ratio (m/m)	0.91		1.16	
Air content (vol %)	15.0		15.0	
Water content (mass %)	13.1		11.9	
Sand content (mass %)	72.3		69.5	
Cement content (mass %) (portland A + lime stone)	14.5		18.6 (10.2+8.4)	
Density (kg/m^3)	1887		1914	

*) Sand grading:
S4 represents a finely graded sand.
The grain size (d in mm) distribution (mass %) is,
for S4: 0125 < d < 0.250 : 30%; 0.250 < d < 0.500 : 30%; 0.500 < d < 1 : 30%; 1 < d < 2 : 10%.

The fineness of the portland A cement and the masonry cement in terms of specific surface, are 307 m^2/kg and 638 m^2/kg, respectively. This means that the mean grain size of the ground lime stone is considerably smaller than that of the portland A cement.

THEORY AND EXPERIMENT

Qualitative comparison
For the three states in which water may occur in the mortar, the water suctions (-p) are presented in Fig. 2a as a function of the particle radius (r). The dotted lines A and B indicate the suction-sphere radius relationships for the estimated mean particle radii of portland cement A and ground limestone.
The suction-pore radius relationships for the brick pores (cylindrical capillaries assumed) are presented in Fig. 2b.
The capillary suction 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 the capillary suction distributions are determined for the fired clay bricks, and tentatively indicated for the calcium silicate brick, see Fig. 2b.

Explanation: the intersection of a horizontal bar of a pore size distribution with the line in graph 2b indicates, on the horizontal axis the pore radius and on the vertical axis the related capillary suction. It is assumed that pores with radii smaller than 0.1 μm do not contribute to the moisture transport.

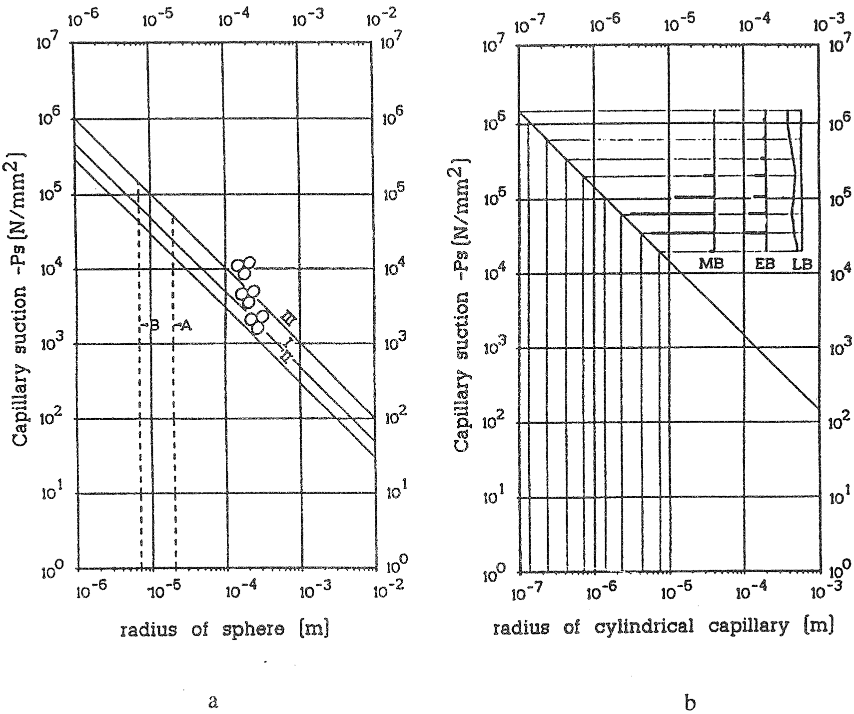


Fig. 2 *a) Capillary suction between identical particles with the densest packing: I) voids filled with water (capillary state), II) critical water content (funicular state), III) withdrawal of water (pendular state),*
b) Capillary suction in the bricks, as a function of the pore size distribution.

A comparative evaluation of the water loss of the fresh mortars can be made with the help of the figures 2.a and 2.b:

Fired clay brick combinations (EB, MB)
Comparing the dry wire cut brick (EB) and the machine moulded brick (MB) combinations it is to be concluded that the water absorption by EB will be lower than that

of MB both for the portland cement A and the masonry cement mortars.
Since the ground lime stone particles are finer than the cement particles higher capillary suction will occur in the masonry mortars than in the cement mortars: this can be verified by comparing, in figure 2.a, the mortar suction of both mortars as a function of the mean sphere radii of ground lime particles and cement particles. Relating the mortar suction to the brick suction (fig. 2.b), it may be assumed that significant differences in water loss are to be expected with regard to the two mortar types. After all, the amount of brick pores showing higher capillary suction than the mortar decreases drastically with decreasing particle diameter of material present in the mortar.
During to the process of water absorption the finer pores are gradually filled with water. This will result in a decrease of the brick suction. The water transport from mortar to brick will stop when an equilibrium between brick and mortar suction is reached.
It can be noted that the process of water absorption will last longer in the MB-combinations than in the EB-combinations, as the EB bricks contain relatively more fine pores.
It may be clear that lower water losses will occur in fresh mortars in the wetted MB-combinations. This is due to the lower capillary brick suction caused by the inactivity of the finest brick pores (filled with water).

Calcium silicate combinations (LB)
The calcium silicate bricks contain a substantial amount of pores showing high capillary suction. Comparing Figs. 2a and 2b, it can be understood that the capillary brick suction in the dry LB-combinations may remain higher than the mortar suction: the quantity of fine pores is so high that a decrease of brick suction (due to the filling of the finest pores) will be limited. This means, in fact, that the process of water transport from mortar to brick will last till hydration of the cement will cause a denser structure of the mortar.
Hence, it may be concluded that the water loss in the mortars of the dry LB-combinations will be very substantial.
The situation is a different one for the wetted LB-combinations, due to the inactivity of the finest pores (filled with water). From the data in the figures 2.a and 2.b it is not sure whether prewetting of the calcium silicate bricks is a very effective means to diminish the water loss of portland cement mortars: the amount of finer pores available for capillary suction of water from the mortar can not be deduced the data. Anyhow, it can be concluded that the water loss of the masonry cement mortars will be lower than that of the portland cement mortars.

Experimental results
By means of a special experimental technique (Groot(1993)) the water content changes in the middle of the joint were monitored during the process of water transport from mortar to brick.
From mortar data and water content measurement data water-cement ratios were calculated (i) the initial water-cement ratio of the mortars and (ii) the water-cement ratio in the middle of the mortar after water loss (the moment of equilibrium (no water content changes in the mortar) were experimentally determined).
The initial w/c ratio of the mortars and the w/c ratios in the middle of the mortars after water loss are collected in Table 3.

Table 3 Water-cement ratios

	initial w/c ratio mortar	w/c ratio in the middle of the joint after water loss				
		EB00 dry	MB00 dry	MB15 prewetted	LB00 dry	LB07 prewetted
Portland cement A mortar	0.91	0.37	0.26	0.37	0.11	0.18
Masonry cement mortar	1.16	0.72	0.61	0.72	0.18	0.51

Comparison of the test results with the theoretical considerations shows the validity of the modelling approach. However, no absolute values can be derived for the water losses occurring in the mortars.

CONCLUSIONS

The experimentally determined interactive effects of capillary suction 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.

It was demonstrated that a satisfactory explanation can be given for the significant differences in absorption behaviour of fired clay bricks and calcium silicate bricks. Moreover, a better understanding can be obtained regarding the influence of fines (cement, ground lime stone, lime) on the counteracting capillary forces in the mortar.

It can be concluded that insight into the hygric effects of the capillary properties of bricks and mortars may contribute to the design of compatible mortar-brick combinations.

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.

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