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Measuring the water capacity and transfer properties of fresh mortar

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ABSTRACT

The water transport properties of fresh mortar are determined using three experimental techniques which are common in soil science but new in this field of application: permeameter tests, suction tests and pressure plate tests. A description of the phase relations of mortars during drainage (moisture-loss) leads to an expression of the water retention curve as a function of the water content using Van Genuchten's equation. The permeability curve is then derived from a single point measurement and a relation between permeability and water retention. Important differences between lime and cement mortars are expressed in terms of their residual water content and the slope of the water retention curve. These differences are found to be intrinsically related to the particle size distribution of the binder used.

1. Introduction

Mortar is widely used as a building material for bricklaying, plastering and rendering. In these applications the migration of water influences the workability of the fresh mortar [1] and the mortar–brick bond in the hardened state [2]. The amount of water flow and the rate of flow have an important influence on the nature of the interface [3]. The final water/binder ratio of the mortar is the most important factor which determines the hardened mechanical properties. Some combinations of high suction bricks with low water retention mortars may lead to ratios which are too low, causing partial hydration. At the free surface of a mortar joint the water transfer properties determine the rate of evaporation of the mortar, together with the convective vapour transfer in the air layer close to the surface. The existence of differential capillary pressures within the mortar during drying may cause cracking [4].

All these cases illustrate that a better understanding of the water transfer properties of fresh mortar is needed. As yet, no satisfactory measuring methods are available to measure these properties and due to this shortcoming existing transport models rely on simplistic assumptions [5]. This paper proposes a combination of methods which are adaptations of existing techniques in mortar technology and soil hydrology to determine parameters which may be used to compute both, the water retention and permeability of the mortar as a function of the water content. These parameters can be used as inputs in numerical models for assessing the water movement response of the mortar.

1.1. Phases in fresh mortar

Fresh mortars are three phase systems with coexisting solid, gaseous and liquid phases. The solid phase consists of sand and binder particles. The liquid phase is a solution containing ions and possibly organic admixtures. Groot [2] distinguishes three states from wet to dry through which a mortar evolves during dewatering. In the first state ("capillary" in the reference) the liquid phase is continuous: saturated or unsaturated liquid water transport is dominant. The water content of the mortar is higher than the critical value and the air content is below critical so that air cannot penetrate. In the second state ("funicular") air is dragged into the system, giving rise to higher capillary pressures. Both liquid and air (including vapour) transport are possible. The limiting state between the first and second states is the 'air entry value' or the 'bubble point' of the mortar which corresponds to the suction pressure which is needed for an external amount of air to break through the liquid–air interface and penetrate the porous system. Finally in the third state ("pendular") no liquid water transport is possible any more, and the remaining water, which exists in disconnected separate islands, can only be removed via vapour transport.

This description of water states can be linked to the hysteretic behaviour of cementitious materials which explains differences between drying and wetting phenomena. For the desorption (i.e. drying) of mortar, only the so-called 'drainage curve' is important, and the minimum is a residual water content larger than zero [6]. This residual level can be defined here as the lower limit which can be reached by applying suction at an ambient temperature. Lower water content can only be reached by slow vapour diffusion, which is not relevant for fresh mortar in practical situations. As long as there is a monotonous decrease of water content, a single drainage curve is

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sufficient to describe dewatering. In analogy to soil terminology we propose to call it the 'primary drainage curve' of the mortar.

The dewatering process is related to adhesion between the mortar and the substrate as per a theory proposed by Hall and Hoff [7]. Once the fresh mortar is applied, capillary suction (tension) pulls the slurry towards the substrate. The viscous drag forces of the liquid moving towards the substrate increase this tension. If the interface is not horizontal, it is this tension together with friction between the semi-solid slurry and the wall which keeps the mortar in static contact with the substrate. The increase of stiffness of the mortar is related to the increase of solid fraction with a power law. Compaction occurs as long as the capillary tensile forces are larger than the compressive yield stress of the slurry. From the moment the water content drops below a critical point and air penetrates into the pores (at a pressure higher than the air entry value) and the continuity of the liquid phase is broken, capillary forces can only act in discontinuous regions and adhesion is ensured by the stiffness of the compacted slurry which can originate from compaction of the mortar, gel-formation of the colloidal binder particles, hydration of hydraulic components, carbonation of air-hardening components or the action of admixtures such as polymer bridging.

1.2. Existing measuring methods

Various European and American standards propose methods to quantify 'water retention' of a mortar by desorbing an amount of water through contact with absorbing filter paper sheets or plates, or by applying a vacuum under a portion of mortar in a perforated dish [8–10]. These are all single point measurements which can only give an indication for a combination of mortar with one specific type of masonry unit. An indirect method based upon the estimation of the mean pore radius in the mortar was proposed by Groot [2]. This requires however data of specific surface area and relies on several assumptions.

The direct measurement of the desorptivity of mortar has been the subject of some publications during the last decades, notably making use of a filter press commonly used for dewatering slurry or sludge e.g. in mining applications. First published by Green et al. [11], the method consists of placing a portion of mortar on a perforated support and applying high air pressure at the top, while keeping the bottom in contact with atmospheric pressure so that water flows out. The result of this test gives a value for desorptivity, which is characteristic for the applied pressure level. It is in fact the slope of the mass-square root of time curve and is analogous to the sorptivity of absorbing materials. The same method was applied by Carter et al. who also proposed a capillary suction time apparatus with a filter paper for comparable purposes [12]. Both methods give information about a transfer quantity (permeability of the filter cake), but not about the moisture capacity of the mortar. Collier et al., based on a theory of Hall and Hoff, demonstrated the validity of the theory for the rather academic case of semi-infinite volumes of mortar and brick [7,13]. The water capacity and transfer properties of hardened cement mortars have been measured previously [14,15]. However they differ strongly from the fresh material.

1.3. Objectives

The novelties proposed in this article are: an expression for permeability over the whole range of water content instead of only the most compacted state, and an expression for the water retention (suction or total potential) of the mortar as a function of water content. Both expressions are related to and rely on well-established theories of soil science. A simple hypothesis is used to describe the evolution of phase-relationships in mortar during drainage.

2. Materials

Two types of mortar were tested: a lime hydrate mortar and a cement mortar. Their composition and some relevant properties of the binders are listed in Table 1. The first is known to have relatively high water retention in standard tests as opposed to the second, which has low water retention. Particle size distributions obtained with a Coulter LS 230 laser diffractometer are plotted in Fig. 1. The lime is a dry-slaked hydrate type Tradical 98 (CL 90 S, EN 459-1) by Lhoist and the cement an ordinary Portland cement (CEM I 42.5R, EN 169-1) by Schwenck. The sand is a rather fine and fairly rounded siliceous sand of grading 0/0.5(0/1) according to EN 13139 (sieving procedure EN 933-1). The background of the chosen binder/sand ratios and water/binder ratios, as well as extensive testing results of these mortars is published elsewhere [1]. The water/binder ratios are averages of the measured amounts chosen by a panel of 6 experienced masons. The specific surface area and median particle size of the binder can be expected to have an important influence on both the water retaining capacity and permeability of the mortar.

Both mortars contain no air entraining agent or other admixtures. The presence of a large amount of entrained air bubbles is common in practice and alters the pore system. Some admixtures influence the interface characteristics (surface tension, contact angle) or the viscosity of the liquid. Such cases are not covered in this paper and require further study.

3. Experimental techniques

Four test methods were used to construct the water retention and permeability curves of the mortars: a permeability test using an adapted soil permeameter, a suction test for desorptivity, a pressure plate test for drainage characteristics and a filter press test. All tests were started between 1 and 3 min after a fixed mixing procedure. For each test new mixtures were prepared. During the whole time span of the tests, and especially the first few minutes, important micro-structural changes may occur in the mortar. An approximately linear increase of the shear yield stress with time was measured previously and suggests that also water transport properties may evolve due to e.g. flocculation of colloidal particles [16]. Keeping in mind that the manipulations of the mortar in the test procedures (mixing; scooping in a recipient; leaving at rest while liquid migrates) are similar to practical situations, the time-dependent behaviour can be considered as being incorporated in the approach.

3.1. Permeameter

The cylindrical sample holders of a commercial soil permeameter with constant pressure head were used in an adapted setup and procedure (Fig. 2). For soil testing the lower ring is usually a core drilled in situ from an existing soil layer and cut off at top and bottom face. These samples are first slowly saturated in the lab before the test is started. Pressure heads of 20 to 25 mm are normal and the test proceeds slowly.

Table 1
Composition of mortars and geometric properties of the binder particles.

	Lime mortar	Cement mortar
Composition		
Binder to sand mass ratio (kg/kg)	0.112	0.218
Water to binder mass ratio (kg/kg)	2.016	0.907
Geometrical properties of binder particles		
BET specific surface area (m^2/g)	12.0	1.3
Median particle size (μm)	6.03	12.5

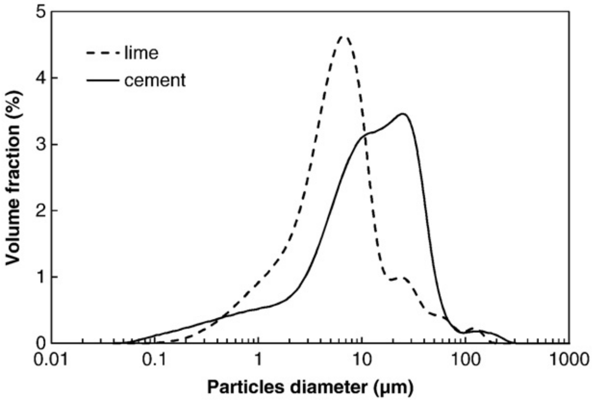

Fig. 1. Particle size distribution of the binders.

For the case of fresh mortar the material was scooped into the ring immediately after mixing and a larger pressure head of h = 60 mm was created to reduce testing time. Water flows from bottom to top and is sucked from the surface with a pipette and weighed at regular intervals. Evaporation between the moments of measuring was prevented by covering the setup with a wet cloth. The flow through the saturated sample is described using Darcy's law:

$$q = K_{sat}\frac{Ah}{l} \qquad (1)$$

where q is the volume flux (m^3/s), A (m^2) and l (m) the dimensions of the sample, h the pressure head (m) and K_{sat} is the saturated permeability (m/s).

3.2. Suction test

This test uses an adapted version of the water retention setup in ASTM C110-04:10. A vacuum pump is connected to the bottom of a perforated dish, in which the mortar sample is placed over a wet filter paper sheet (Fig. 3). In the standardised test the applied vacuum is constant and it is maintained during 15 min. No mass loss is measured. The height of the dish wall was increased up to 60 mm, the mass loss was measured at fixed steps of the square root of time, until air breakthrough prevented maintaining the vacuum, which was usually after 1 to 3 h of testing. The test can be done at various pressures; the theoretical maximum is 1 bar, but the practically achievable maximum appeared to be about 0.5 bar.

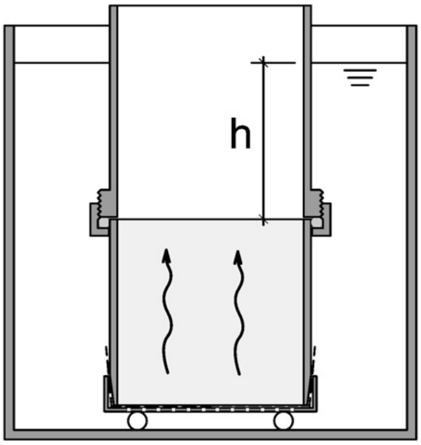

Fig. 2. Vertical section of a cylindrical permeameter sample holder with mortar. The assembly is placed in a water bath, which creates a pressure head h over the mortar sample.

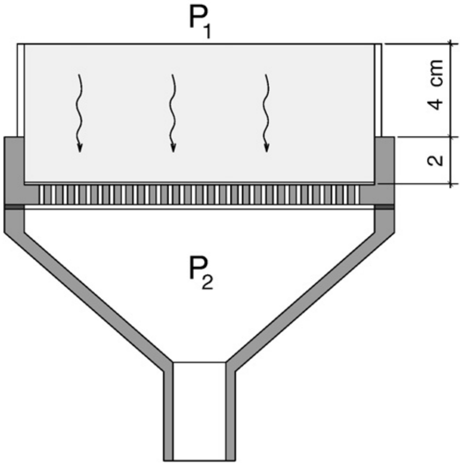

Fig. 3. Vertical section through the suction apparatus: a dish with perforated bottom is placed on a funnel, which is in contact with a vacuum pump.

Two results were derived from each measurement: the slope of the initial mass-square root of time curve and the equilibrium water content, which is calculated by extrapolating a fitted exponential curve [17]. The first value corresponds to the desorptivity or coefficient of desorption of the mortar at the specific pressure level. The necessity and nature of the extrapolation remain a weak point of this method.

3.3. Pressure plate test

In the pressure plate apparatus a porous ceramic plate is initially saturated and hydraulically connected to the atmosphere via a small metal outlet connected to a burette (Fig. 4). This plate is placed within a sealed container in which the air pressure is increased. Initially wet samples are placed in hydraulic contact with the plate, by pouring them in plastic rings (d = 54 mm, h = 30 mm) resting on it. When the air pressure increases, water is expelled until the difference between air pressure and liquid pressure (equal to atmospheric pressure) is in equilibrium with the suction exerted by the solid matrix. This differential pressure corresponds to the capillary suction of the material.

Preliminary tests were done to achieve optimal hydraulic contact between the plate and the sample. Three arrangements were tested: the mortar directly on the plate, on a wetted nylon textile, and on a thin layer of kaolin–water paste covered with wetted nylon textile. It appeared from these tests that the largest amount of water was expelled through the nylon and kaolin layer, and this method was adopted for all further tests. Use of kaolin paste is often mentioned in the literature both for testing soils and solid porous materials.

The duration of the test is a critical factor: it should be long enough to reach equilibrium, but not too long so that the binder doesn't start to hydrate. Adding setting retarders may influence the hygric

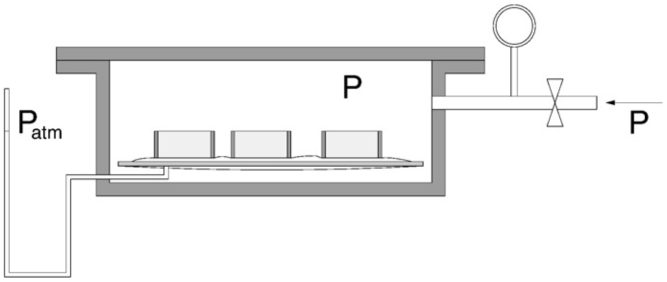

Fig. 4. Vertical section through the pressure plate apparatus. Mortar samples are placed in rings on a bed of kaolin paste on top of the wet porous plate.

properties of the mortar, e.g. by changing the contact angle, so it is preferred to do the tests within the so-called dormant period of hydration, i.e. approximately the first 3 h after water addition. The time for reaching equilibrium depends mostly on the permeability of the plate and can be determined by observing the water level in the burette. Different plates were used depending on the maximum allowable pressure: 1, 3 or 15 bar. The 15 bar plate has finer pores and lower permeability. Tests were done at 0.5, 1, 3, 8 and 14 bar. In this set of points the measurement at 8 bar using a 15 bar plate is the slowest combination. An empty run (with kaolin layer but without mortar) revealed a time to reach equilibrium of 8 h, which means that an error due to reactions in the mortar or non-equilibrium state cannot be avoided. In most other cases however 2 to 3 h was sufficient to reach equilibrium and no problems of the hydration reaction occurred.

Determination of the water content of the samples after equilibrium was mainly done by oven drying at 105 °C during 4 h and comparing the wet and dry weight. This method is not straightforward because the high temperature favours both the hydration and carbonation reactions: the first consumes water, and the second causes an increase in mass when CO_2 from the air in the oven is taken up by the moist lime hydrate. Hence comparative measurements were done using a freeze-dryer, which is recommended in literature to remove free water and capillary water effectively from early-age cement and lime pastes [18]. The material was vacuum-dried at −63 °C and at a very low pressure during 4 h. With reference to the vacuum-dried results, the oven drying leads to errors of not more than 5% which is still acceptable considering the average scatter in the results due to other factors. In each test 6 specimens were measured: 3 with lime hydrate mortar and 3 with cement mortar.

3.4. Pressure filtration

Pressure filtration theoretically provides the same possibilities as the pressure plate apparatus: an overpressure is created on the top of a sample and drainage is allowed at the bottom, which is at atmospheric pressure (Fig. 5). Two types of filtration cells are commonly used: with a pressurised chamber in direct contact with the sludge or with a piston, as shown in the figure.

Successful results with the first type are reported in the literature [11,12], but proved difficult to reproduce with the selected mortars. Three problems emerged in the tests: premature air breakthrough, clogging at the membrane and development of effective pressure in the solid skeleton. When an apparatus with direct air-sample contact is used, air breakthrough occurs at higher water contents than expected, probably because preferential air channels are gradually formed and prevent an equal distribution of the pressure. Due to this problem it is difficult to reach an equilibrium value. Clogging at the bottom was most observed with lime mortar: a quantity of binder particles is dragged along by the flowing liquid and causes blockage of the flow at the membrane. This gives rise to inhomogeneities in the material and leads to decreased drainage. Besides experimental difficulties, this is also an indication of what may happen in real situations of mortar desorption. The third problem of effective stress occurs only in piston filters. As long as the mortar is oversaturated the applied stress is transferred to the liquid, but below saturation water content the solid particles take up part of the stress. By lack of direct measurement of the pore liquid pressure, meaningful results cannot be formulated.

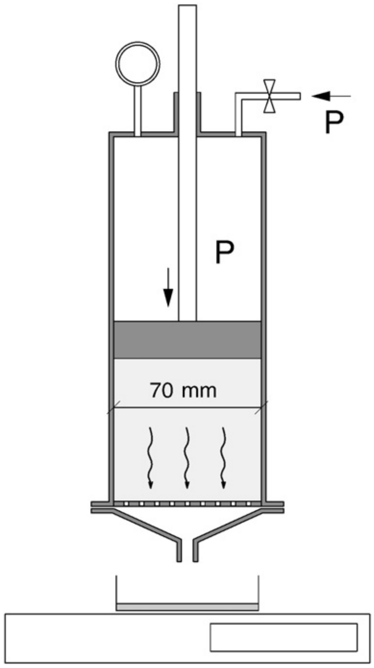

Fig. 5. Vertical section through a filter press. The pressure is in this case transferred by a sliding piston. The expelled liquid is caught in a dish on a monitored balance.

4. Results and discussion

4.1. Fitting of the primary drainage curve

Data from the suction test and the pressure plate test were used to construct primary drainage (water retention) curves of the mortars. The calculation of water content in mass per unit of volume out of the experimental results (in mass/mass) relies on an assumption about the evolution of the phase relations which is represented in Fig. 6. The initial mortar with water content w_{sat} reduces its volume upon dewatering. In the first linear part of the curve the loss of water equals the total volume loss. This proceeds until a minimum (critical) void ratio is reached, corresponding to critical water content w_{cr}. This assumption of gradual compaction by dewatering is justified by measurements of mechanical compaction according to the ASTM D698-91 test. The obtained values for maximal solid fraction ϕ_{Max} were 0.698 for lime mortar and 0.700 for cement mortar, whereas the initial solid fractions of the fresh mix are 0.632 for lime mortar and 0.628 for cement mortar (see [1] for more details). This indicates that the initial mortars contain an amount of excess water with respect to the available void space in their compacted state. The initial values of ϕ were calculated from

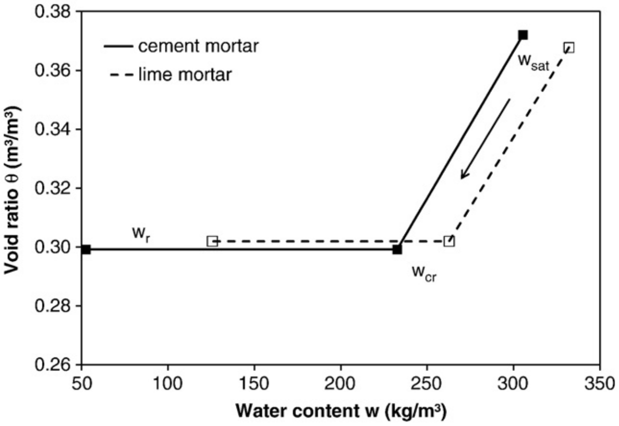

Fig. 6. Void ratio versus mass water content of lime mortar and cement mortar. The squares indicate the initial, critical and residual water content. The direction of the arrow indicates the evolution of the fresh mortar. Below the critical value w_{cr} no further compaction occurs.

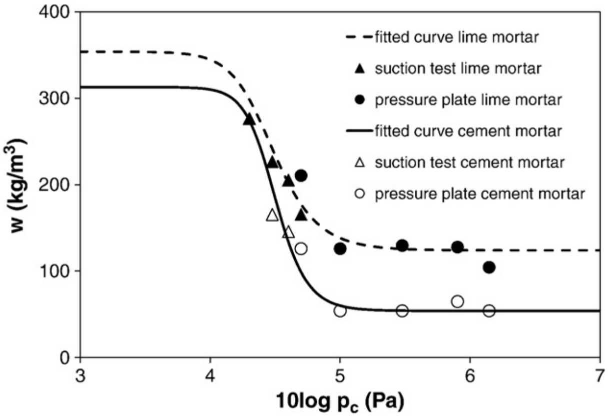

Fig. 7. Data points and fitted primary drainage curve of lime mortar and cement mortar.

the mix ratios, the measured particle densities (pyknometry) and measured air content (by gravity and compression method). The critical void ratio is simply $1-\phi_{\max}$. The corresponding critical water content w_{cr} is derived by assuming that no air penetrates the system before w_{cr} is reached. The lower limit of water content reached by suction is the residual water content w_r, the left most point of the second linear part.

The zones of constant void ratio and linear increase in Fig. 6 are observed in all swelling soils; the transition between both is of course smooth in the real case [6]. It can be noted that any chemical shrinkage, which leads to further compaction in later stages, is not considered here.

The selected form for the drainage curve is based on Van Genuchten's equation [19]:

$$w = w_{sat}\left[\frac{1}{1+(ap_c)^n}\right]^{1-1/n} \tag{2}$$

where w stands for the mass/volume water content (kg/m³), w_{sat} the initial or saturation water content, p_c capillary suction (Pa) and a and n dimensionless parameters. The data and fitted curves are plotted in Fig. 7. The parameter w_{sat} is taken equal to the initial water content. It can be noted that this level of w_{sat} is somewhat arbitrary (not a real material parameter) and that a mortar with more initial water would lead to a higher starting point of the curve. But in fact the water potential in this range is very low and except for the shift in the left upper branch, the range of interest of the curve would remain quasi unchanged by a shift of w_{sat}. The most important difference between the two mortars is the level of the residual water content: larger than 100 kg/m³ for lime mortar and about 50 kg/m³ for cement mortar. If we identify the ordinate of the onset of a strong decrease of water content as the air entry value, we can say that this value is in the same order of magnitude for both mortars: $2 \cdot 10^4$ Pa. But the slope of the decrease of water content with increasing capillary pressure is clearly smaller for lime mortar than for cement mortar.

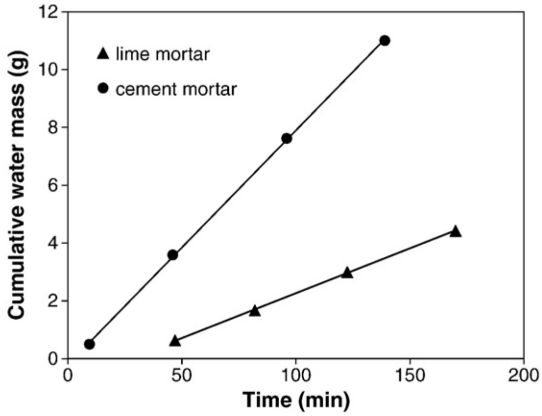

Fig. 8. Data from permeameter, averaged over two tests: cumulative mass of transferred water versus time and linear regression lines.

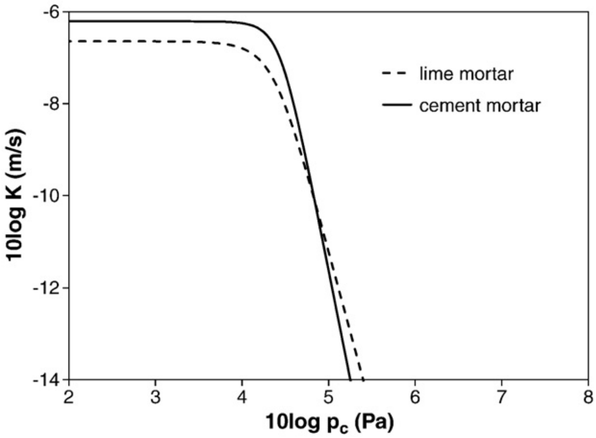

Fig. 9. Van Genuchten-Mualem curves for permeability of both mortar types, based on measured saturated permeability and the water retention curve.

4.2. Construction of the permeability curve

Unsaturated permeability can be derived from the water retention curve if the saturated permeability is known. This approach relies on the experimental determination of one single point with the permeameter and the validity of an equation, e.g. the following equation by Mualem [19]:

$$K_r(h) = \sqrt{\Theta}\left[\int_0^{\Theta}\frac{1}{h(x)}dx \Big/ \int_0^{1}\frac{1}{h(x)}dx\right]^2 \tag{3}$$

with h the pressure head, which relates to capillary pressure as: $h = p_c/\rho g$. This equation stems from the simplification of the pore network shape to a bundle of cylindrical tubes (see e.g. [20] for a review). The quantity Θ is the dimensionless water ratio. Water ratio θ is the volume of water divided by the volume of solids in a portion of a porous material.

$$\Theta = \frac{\theta-\theta_r}{\theta_{sat}-\theta_r} \tag{4}$$

where subscripts r and sat stand for residual and saturated. Eq. (3) remains valid when replacing water ratios Θ (−) and θ (m³/m³) by

Table 2
A summary of experimental methods used to measure the water transport properties of fresh mortars.

	+	−
Permeameter	Easy to perform,	Large scatter in low permeability range,
Suction	Good repeatability	Labour-intensive, difficult to perform, small pressure range
Pressure plate	Good repeatability, large pressure range	Expelled water mass unknown, long testing time for some combinations of plate and pressure
Pressure filter	Large pressure range, easy pressure control	Air breakthrough, clogging of membrane, effective stress

water contents W (−) and w (kg/m³), and pressure head h by capillary pressure p_c:

$$K_r(p_c) = \sqrt{W}\left[\int_0^W \frac{1}{p_c(x)}dx \Big/ \int_0^1 \frac{1}{p_c(x)}dx\right]^2. \tag{5}$$

If a monomodal Van Genuchten equation with fitting parameters a, n and m (Eq. (2)) is substituted for the relation w(p_c), Eq. (5) can be reformulated as [19]:

$$K_r(p_c) = \frac{\left[1-(ap_c)^{n-1}\left(1+(ap_c)^n\right)^{-m}\right]^2}{\left(1+(ap_c)^n\right)^{m/2}}. \tag{6}$$

Fig. 8 shows the averaged stationary saturated water flow obtained in the permeameter. The slope of the fitted lines gives a saturated permeability of $K_{sat} = 2.27 \cdot 10^{-7}$ m/s for lime mortar and $6.17 \cdot 10^{-7}$ m/s for cement mortar. The resulting permeability curves $K(p_c) = K_{sat} \cdot K_r$ are plotted in Fig. 9 for both mortar types.

5. Summary and conclusions

A methodology is proposed for the experimental determination of the water transfer properties of fresh mortar. The approach was developed in three steps: (1) initial assumptions about the evolution of phases in a drained mortar, (2) the development of original experimental methods and (3) the selection of suitable equations for the analysis. All of the setups exist in a standardised form, but had to be adapted for use with fresh mortars. Some advantages and disadvantages of the methods are summarised in Table 2.

The results of suction test and pressure plate test were demonstrated to be in good agreement and they result in a good fit to a monomodal Van Genuchten curve for water retention. This outcome supports the choice of the simple bilinear assumption for the mortars' water loss/volume relation and of the equation for the curve. Results of pressure filtration tests were not used because of some experimental difficulties (Table 2). The findings of preliminary experiments are shown as these provide potentially useful practical information.

The lime mortar appears to have a significantly higher residual water content, a lower slope of the water retention curve, and comparable air entry value with respect to the cement mortar. This can be related to the different particle properties: the lime has smaller particles with a higher specific surface. This leads to a finer pore system, resulting in higher suction and lower permeability. It can be concluded that the two obtained curves express in an unambiguous and precise way the general existing notion that lime mortars ‘have higher water retention’ than cement mortars.

The mortars' permeability is more difficult to measure in a direct way. A value of saturated permeability was used together with the water retention curve to derive permeability using Mualem's equation. This completes the full determination of isothermal liquid transfer properties of the mortars. However it should be kept in mind that many realistic phenomena cannot be fully explained with these data alone, because they may be influenced by inhomogeneities in the mortar. Future research should be directed to determine how the bulk transport properties, as measured and discussed in this article, change near interfaces in real systems.

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