The influence of materials characteristics and workmanship on rain penetration in historic fired clay brick masonry

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Moisture is a major source of damage in historic solid masonry. Therefore, control of moisture movement in masonry is instrumental to the durability of masonry buildings. From research and practical experience it is known that many factors may play a role regarding permeability problems in masonry. This paper is focused on materials aspects regarding water penetration in historic fired clay masonry walls, constructed with moderate-to-high absorption bricks and lime mortars; the occurrence and influence of parameters such as brick porosity, interface leakage and mortar joint resistance are discussed. Subsequently, quantitative tests results show the effects of these parameters on leakage of solid walls of different thicknesses. The results of the investigations lead to a number of recommendations to be used in case of repair of historic solid masonry. Finally, attention is paid to the influence of workmanship on the permeability behaviour of historic solid walls.

Key words: Rain penetration, historic masonry, brick, mortar

1 Introduction

Water leakage in historic solid masonry regularly occurs and is a major source of damage: in masonry, frost and salt damage; in timber, rot. Moreover, humidity may have negative effects on the living conditions in historic buildings. From the literature [Grimm 1982; Ramamurthy and Anand 2001] and practical experience a number of causes for moisture problems like leaking can be deduced:

- inadequate material properties of the applied fired clay brick and masonry mortar; incompatibility between brick and mortar properties
- cracks in masonry
- inadequate design (e.g. lack of protection measures)
- poor ventilation

- negative effects of a number of restoration interventions (like application of water repellents, application of dense plasters (prevention of drying) etc.)
- poor workmanship of the builders during construction and/or restoration

The amount of possible causes of moisture problems in historic masonry underlines the complexity of this phenomenon [Thomas 1996]. Additionally, this complexity is enlarged by the often difficult to predict effects of an inadequate construction. However, it is quite clear that the influence of workmanship on the occurrence or effective cure of moisture problems is underestimated. This paper is primarily focused on aspects dealing with an adequate choice of mortar and brick for water tight solid masonry.

2 Water permeance and porosity

Brick and mortar are porous media, which means that moisture absorption in these materials is governed by capillary action and drying by evaporation. For the separate materials moisture transport is easy to understand, for the composite material *masonry* this is more complicated. Under ideal conditions in masonry contact between brick and mortar is such that the two capillary systems are smoothly connected. Moisture transport from mortar to brick and vice versa are dependent on differences in pore dimensions and pore distributions of the two separate materials. Liquid moisture transport may take place as a result of pressure differences (e.g. wind pressure, drying, ventilation) if the moisture content in brick and mortar are higher than the critical moisture content (at the critical moisture content the capillaries are covered by a thin layer of water). Apart from capillary action "free" water transport through the wall may occur if interconnected cracks, fissures, hollows, cavities etc. of more than 100μm are present in the wall. This is a far more unfavourable condition for leakage. Injection using grouts may be a means to improve the water tightness of walls containing hollows, cavities. Applying injection, in fact, means that capillary moisture transport conditions are reinstated or created.

3 Rain penetration in thin walls: ½ and 1 brick length thick

*3.1 **Introduction***

Focusing on materials behaviour in masonry walls of ½ and 1 brick length thick (walls in which moisture may travel without restriction to the back of the wall) two main causes of leakage can be observed:,

(i) leakage through the brick

(ii) leakage through the brick-mortar interface

The first is a pure materials characteristic and the second mainly relates to the hygric compatibility between brick and mortar [Groot 1997]. These two types of leakage are shown in Figure 1.

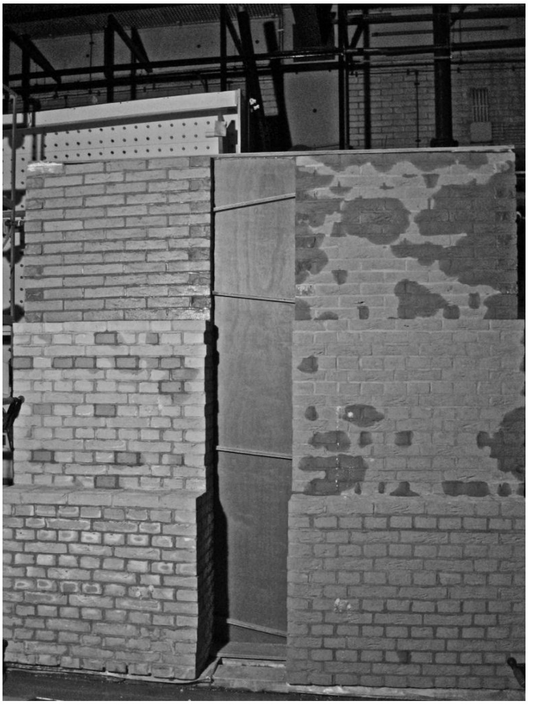
3.2 Brick porosity

Essential to moisture transport in materials such as bricks and mortars is the pore system. Moisture absorption is a function of the capillary action of the pores and drying is determined by the evaporation rate. Although capillary absorption is a much quicker process than drying through evaporation, both depend on the pore size (distribution) of the materials. Apart from clay type and the manufacturing process, the porosity of bricks is to a high degree determined by the firing process. The final stage of "sintering" (melting of the clay) has a significant effect on the porosity: with a higher degree of melting the total porosity decreases (causing shrinkage) and coarser isolated pores are formed; the permeability of this type of brick is low. With a lower degree of melting the total porosity is higher and pores form an interconnected network, enhancing the permeability of the brick (Fig. 2).

Figure 1. Leakage in test masonry walls

Left: Leakage through the brick caused by high porosity of the applied brick (IRA brick 5.5 kg/m²/min).

Right: Leakage through the mortar-brick interface (IRA brick 1.5 kg/m²/min).



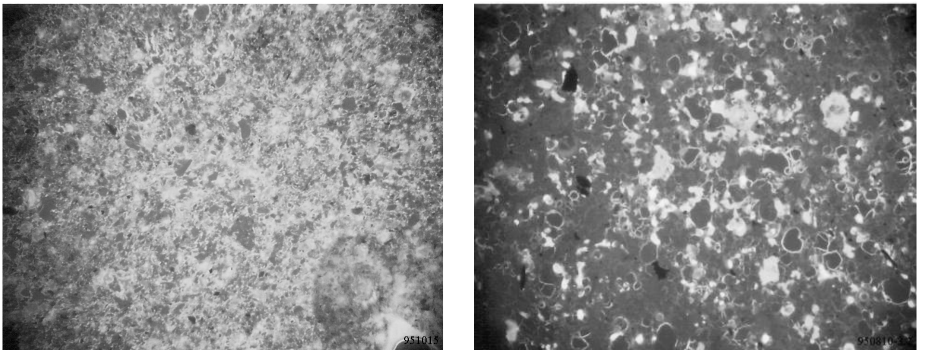


Figure 2. Two fluorescence-micro photos of fired clay bricks: Light gray indicates the porosity and dark is solid matter. Left: the strongly interconnected capillary network of a high absorption brick with a high absorption capacity. Right: a low absorption brick with isolated pores and a low absorption capacity (Photos Rockview, Amsterdam)

3.3 ***Brick characterization***

Basic aspects for moisture uptake in bricks are the "ease" of water absorption and the water storage capacity. The "ease" of water absorption maybe be characterized, for instance, by the Initial Rate of Absorption (IRA: water absorption per unit surface area in 1 minute) or, when measuring the water uptake over longer period of time, by the water absorption coefficient. The water storage capacity may be characterized by the total water

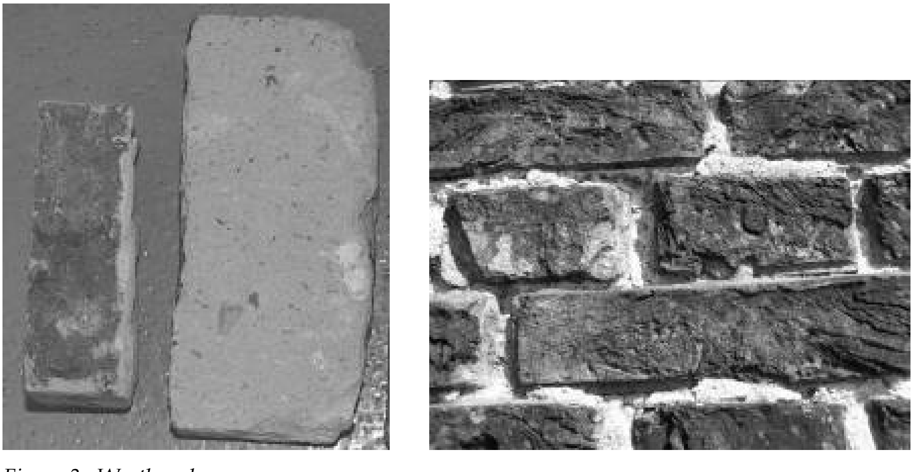


Figure 3. Weathered masonry
Left: The outside weathered face of a brick and inside (non-weathered) original bed face of a brick,
Right: The outside weathered face of a wall

absorption (free or vacuum water absorption). Generally, bricks with a strongly interconnected capillary network show high (initial) water absorption combined with a high water storage capacity. However, from tests on various brick types it was concluded that for a comparable water storage capacity the IRA may significantly vary. This means in case of equal water storage capacity that a brick type with a higher IRA will be saturated in a shorter time than a brick type with a lower IRA. Another aspect is that the IRA may vary in time as a function of the weathering conditions of the brick (Fig. 3). In many buildings it can be observed that the IRA of the weathered exterior face of the masonry significantly differs from that of the original material: the IRA of the weathered face is often less than half of the original value (compared to the non-weathered interior faces of the brick). Consequently, in time the moisture uptake (rain absorption) of a wall will diminish; it is even conceivable (and observed in reality) that a leaking wall will stop leaking in time as a result of weathering. However, it is a considerable advantage that weathering of the exterior face of high absorption bricks does not influence the high water storage capacity. Cleaning of weathered walls may result in an increase of the water absorption rate of the masonry, making it prone to leakage (especially cleaning by sand blasting).

3.4 ***Brick–mortar interface***

An important parameter for leakage is the quality of the interface layer between mortar and brick. With quality is meant the porosity/density of the interface. The porosity of the interface is largely influenced by moisture transport from mortar to brick during brick laying. A dense interface may be formed if the brick exerts enough suction so that fine particles like cement or lime are transported to the interface and compaction at the interface occurs (Détriche, 1981). An open porous interface is created if the moisture of the mortar is not absorbed by the brick; this may easily occur using very low absorption bricks. In Figure 4 examples of an open and a dense interface are shown (Groot & Larbi† 1999). Two types of bricks were used with free water absorption value of 2.5% and 19.5% respectively, and an initial rate of absorption (IRA) of 0.29 and 3.34 kg/m²/min respectively. One type of mortar was applied: a cement mortar (cement/sand ratio 1:4.5 (v/v) and water/cement ratio 1.03).

In order to obtain a good water tightness of the interface, the mortar composition should be compatible to the absorption properties of the brick. Fig. 4 (left) shows an incompatible combination: low IRA brick (IRA 0.29) combined with a mortar with a relatively high water/cement ratio (w/c ratio 1.03). This results in concentration of water at the interface, which cannot be absorbed by the brick (resulting in porosity after drying). So, adaptation

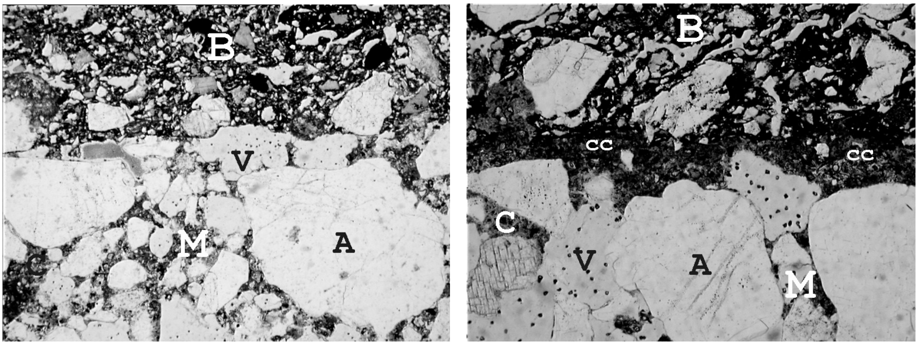


Figure 4. Two examples of brick-mortar interfaces
Left: High void content at the interface; B: brick (IRA 0.29) ; M: mortar; A: aggregate; V: void; C: hydrated cement
Right: Layer of cement (cc) at the interface; B: brick (IRA 3.34); M: mortar; A: aggregate; V: void; cc: partially hydrated cement layer
(Photos Joe Larbi †, TNO-Built Environment and Geosciences, the Netherlands).

of the mortar composition to the brick properties is needed to assure a good interface. Basically, this means that the mortar composition, and in particular the coarseness of the sand and the moisture content of the mortar are adjusted to the absorption properties of the brick. Experience and trial-and-error are often the tools to find compatible brick-mortar combinations, as hygric characterization of the separate materials (mortar and brick) may not sufficiently predict the hygric behaviour of the mortar-brick combination. In building practice some simple site tests can be applied to test the brick-mortar bond on site (the one-minute test and the 10 minutes test).

4 **Rain penetration in thick walls: >1.5 brick length thick** [Groot & Gunneweg 2007]

Rain water that penetrates in walls with thicknesses larger than 1.5 brick length has to travel through a mortar layer as well as the brick. The moisture transport resistance exerted by the mortar may therefore influence the water transport through the wall.

*4.1 **Tests***

A test program was set-up to study the effect of the mortar on moisture transport through masonry test specimens. Starting point for the mortars was lime mortar, as lime was generally used as binder in historic masonry with leakage problems. The masonry specimens were designed such that they can be considered as part of a wall (Fig. 5). They consist of 3 courses of brick, 1½ bricks long and 1½ bricks thick (3 layers). During testing the uncovered face of the test specimen was immersed in a few centimetres of water. After a period of water absorption (24h) the test specimen was removed and placed face up to let it dry (36 days). Looking at the test specimens it is clear that during the absorption phase, water has to cross a mortar layer before reaching the back face (mortar 'collar' joints cover two-thirds of the cross-section). For the tests two types of bricks were used: a red brick with a moderate IRA of 2.3 kg/m²/min and a yellow brick with a high IRA of 3.5 kg/m²/min. The bedding mortars applied where two lime mortars A and C (C lime with some trass), a weakly natural hydraulic lime mortar B and a strongly hydraulic masonry cement mortar X. The binder to sand proportion was 1:2. No special allowance was made for the difference in brick IRA during specimen construction. The curing procedure consisted of 1 week protected then in open air at 20 °C and 50-60% RH. In order to indicate the effects of the different mortars on the moisture transport in the specimens some of the water absorption test results are presented in Figure 6.

4.2 Barrier effect

The moisture absorption of the masonry specimens with high-absorption brick (left in Fig. 6) is significantly higher with lime mortar than with weakly natural hydraulic lime mortar

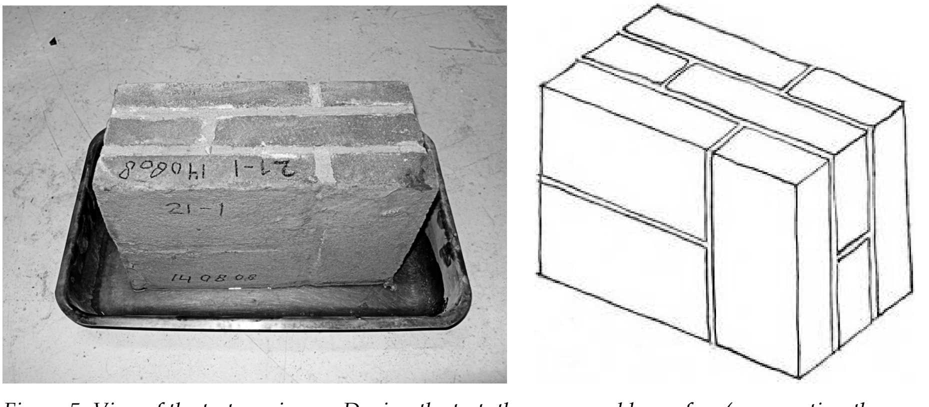


Figure 5. View of the test specimens. During the test, the uncovered lower face (representing the outer face of the wall) absorbs water from a free water surface ("wetting by rain") or (after moisture absorption) to is drying through evaporation; the four vertical faces are covered by a paint layer to allow only wetting/drying from the uncovered face (unidirectional wetting/drying as in a wall). The tests were performed by TNO-Built Environment and Geosciences, the Netherlands.

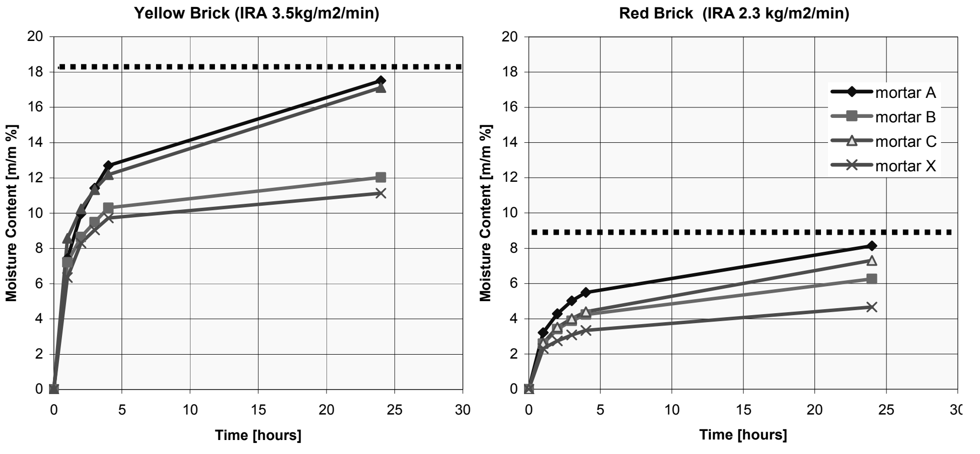


Figure 6. Water absorption tests on brick-mortar combinations. A and C are lime mortars, B and X are hydraulic mortars. The horizontal dotted lines indicate the values of the free water absorption by weight of the bricks (by capillary absorption from one face, over a 24 hour period); 18.4% for the yellow bricks; 9% for the red bricks.

and strongly hydraulic masonry cement mortar. After 24 hours of water absorption, the specimens with the lime mortars are almost saturated (close to their free water absorption capacity of 18.4%: horizontal dotted line). This is not the case for the test specimens containing the two hydraulic mortars (B and X); here, the water absorption is about two-thirds of the free water absorption capacity (11-12%). Apparently in the latter case the mortar acts as a barrier, restricting the movement of water to the back of the test specimen. The difference in water uptake in the masonry specimens with the lower-absorption brick made with lime and hydraulic mortars is much less (right in Fig. 6). However, the relative magnitude in the water uptake is the same for the four different mortars.

5 Rain penetration tests

Rain penetration through fired clay masonry walls has been studied in walls with thicknesses of half, one and two brick length. The test walls consisted of high IRA bricks (5.5 kg/m²/min) and moderate IRA bricks (1.5 kg/m²/min). They were built with a weakly-hydraulic lime mortar. A rain penetration test of 90 hours was performed according to NEN 2778. After that water spray was applied to the inner face of the wall at the rate of 2 liter/m²/min (= 120 liter/m²/hour) and the air pressure difference across the

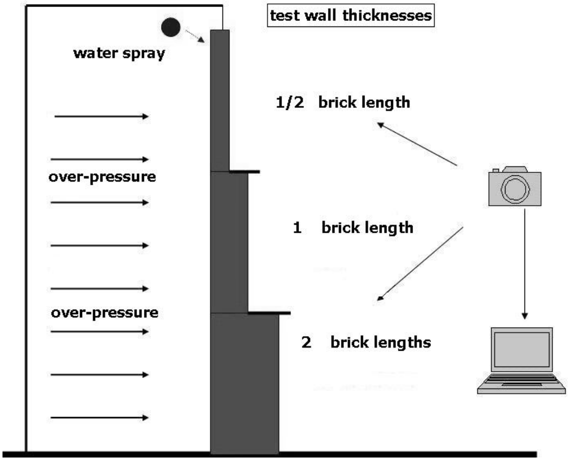


Figure 7. Test set-up

Left: Cross-section showing the three masonry thicknesses tested

Right: Yellow high-absorption bricks (5.5 kg/m²/min) and grey moderate-absorption bricks (1.5 kg/m²/min)

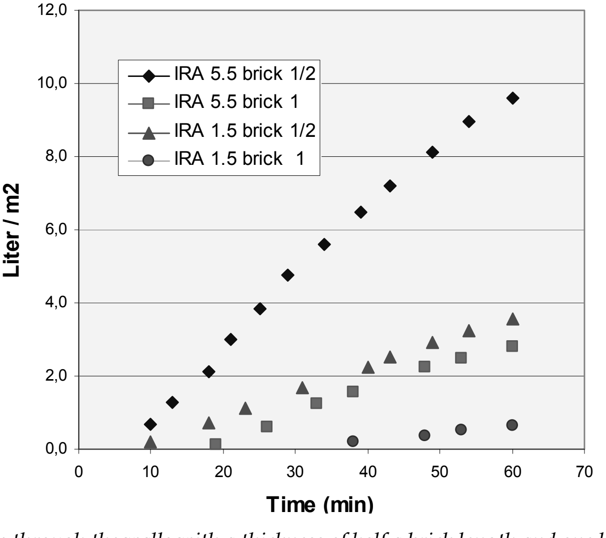


Figure 8. Leakage through the walls with a thickness of half a brick length and one brick length Two types of brick were used: a high absorption brick (IRA: 5.5 kg/m²/min) and a moderate absorption brick (IRA: 1.5 kg/m²/min); the walls were put together with a weakly hydraulic natural lime mortar.

wall was 400 Pa (these are extreme conditions). Water leaking through the walls was collected (through the gutters, see Figure 7 right) and weighed. The leakage of the ½ brick thick wall with high absorption bricks (IRA 5.5) is significant: after 1 hour ~10 Liter/m² (Fig. 8). The water in this case mainly travels through the interconnected pores from one side of the brick to the other side (see as well Figure 1, left wall). The leakage of the one brick thick wall (IRA 5.5) is more than 50% lower, which mainly can be attributed to the barrier effect of the mortar collar joints in 50% of the masonry (see brick bond in Figure 1, left). The leakage of the moderate absorption (IRA 1.5) brick walls appears to be mainly caused by open brick-mortar interfaces and apparently is substantially less than for the high absorption walls. However, the leakage of the moderate absorption brick walls could have been further diminished if the bedding mortar composition would have been more compatible to the applied bricks (so that the occurrence of open brick-mortar interfaces had not taken place). With the two different brick types, walls with thicknesses of 2 brick lengths were also constructed. The same weakly hydraulic natural lime mortar was used. During the rain penetration test no leakage occurred in the either wall. Apparently, the barrier effect of mortar layers was sufficient to prevent leakage in the walls with both high and moderate absorption bricks.

6 Material choices

The rain penetration investigations in solid fired clay masonry were triggered by leakage problems in historic windmills in the west of the Netherlands. These age-old mills were usually built with high absorption bricks and lime mortars. Leakage was not exceptional. The test results show that an important reason may be the poor barrier effect of lime mortars (poor workmanship could be another major factor). The situation may have improved as the bricks weathered with time. In the case of windmills the effect of the heavy dynamic oscillations of the sails on the masonry requires a high deformation capacity of the mortar. This is provided by a lime mortar. In the case of repair, it is recommended to use bricks with similar hygric properties to the weathered old bricks (in practice 1.5< IRA< 3.0); for the mortars a weakly hydraulic mortar (with a hydraulicity index of 0.3-0.5, acc to Boynton 1966) may be used in order to maintain as much as possible the deformation capacity of the masonry and to prevent compatibility problems with the old mortar.

If, in historic solid masonry, pozzolanic binders (for instance trass) was used the permeability problems are usually less severe: a better barrier action. These mortars also show a satisfactory deformation capacity, important in masonry with few or no expansion joints. When choosing a repair mortar this deformation capacity should be maintained. In cases where little deformation capacity is required, water tightness could be achieved more easily since the introduction of modern binders at the nineteenth century. Many churches, towers and factories, built from the 1880's onwards, show very good water tightness. This was achieved by using moderate to low absorption bricks (IRA 10-20 kg/m²/min) and hydraulic (shell) lime-cement mortars (for instance in a binder-rich composition of 10 shell lime, 3 cement and 10 sand).

7 Workmanship

From the study of a number of problem cases in practice, the influence of workmanship on leakage problems in solid masonry is unmistakable. This aspect should not be underestimated. A basic requirement for water tightness is that during execution no voids are left; to avoid this every brick should be fully surrounded by mortar. This is only possible if the brick laying is carefully done brick-by-brick. Skilful laying of bricks is a

Figure 9. Construction of the windmill "de Kameel" (the Camel) in Schiedam in solid masonry (2009). For the choice of brick and bedding mortar the determining factors were good water tightness and good deformability (low E-modulus) of the wall masonry.

relatively slow process. In practice economic considerations often prevail and quicker brick laying methods may be applied with negative effects on the water resistance (voids introduced as a result of the applied brick laying technique). Poor bond at the brick/mortar interface also increases risk of water leakage (See the discussion at the beginning of paper). In practice it is observed that voids, apart from being water reservoirs in the wall, may also promote leaching of soluble material (such as calcium hydroxide). The filling up of voids by (mineral) grouts, using injection techniques, may significantly improve the water tightness of solid masonry.

8 Conclusions

From field and laboratory testing could be concluded that for historic solid masonry, constructed with moderate-to-high absorption bricks and lime mortars, the barrier effect of the mortar is limited, causing high moisture contents in this type of masonry and an enhanced chance of leakage problems. The situation may improve if the bricks have weathered with time, as the moisture uptake is slowed down. The barrier effect of mortars significantly improves if the mortar contains hydraulic components; it was observed that even with weakly hydraulic mortars (a hydraulicity index of 0.3-0.5, acc to Boynton 1966) leakage problems in solid masonry with a thickness of more than 1.5 brick length can be avoided. Inspection of a number of problem cases in practice has shown that a skilful execution of the masonry (no voids and a good mortar/brick bond) is essential to prevent leakage problems.

Acknowledgements

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