Materials Considerations Regarding Rain Penetration in Historic Fired Clay Brick Masonry

Considerações sobre materiais relativas à penetração de chuva em alvenarias históricas de tijolo de barro cozido

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Abstract

Moisture is a major source of damage in historic massive 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 a series of causes 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 are given on the effects of these parameters on the leakage of massive walls of different thicknesses. The results of the investigations lead to a number of recommendations to be used in case of repair of historic massive masonry. Finally, attention is paid to the influence of workmanship on the permeability behaviour of historic massive walls.

Keywords

Rain penetration; historic masonry; brick; mortar choice.

Resumo

A humidade é uma das principais causas de ocorrência de anomalias em alvenarias históricas. Deste modo, o controle dos movimentos da humidade em paredes maciças de alvenaria é um instrumento fundamental para a melhoria da durabilidade destas. A investigação e a experiência prática identificaram já várias das causas que podem influenciar os problemas de permeabilidade em alvenarias. O presente artigo é dedicado aos aspectos materiais relacionados com a penetração de água em paredes históricas em alvenaria de barro cozido, construídas com tijolos de absorção moderada a alta, assentes com argamassas de cal; discutem-se, nomeadamente, a ocorrência e influência de parâmetros como a porosidade dos tijolos, infiltrações nas interfaces e resistências das juntas de argamassa. Subsequentemente, são apresentados resultados quantitativos de testes que avaliam os efeitos destes parâmetros na ocorrência de infiltrações em paredes maciças de diferentes espessuras. Os resultados das investigações permitem apontar algumas recomendações às quais recorrer no caso de reparações em alvenarias históricas maciças. Finalmente, é ainda dedicada alguma atenção à influência da mão-de-obra na permeabilidade deste tipo de paredes.

Palavras-chave

Penetração da água da chuva; alvenaria histórica; tijolos; escolha de argamassas.

Introduction

Water leakage in historic massive 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 [1-2] 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.];
- inadequate craftsmanship 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 [3]. Additionally, this complexity is enlarged by the often difficult to predict effects of an inadequate execution. 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 massive masonry.

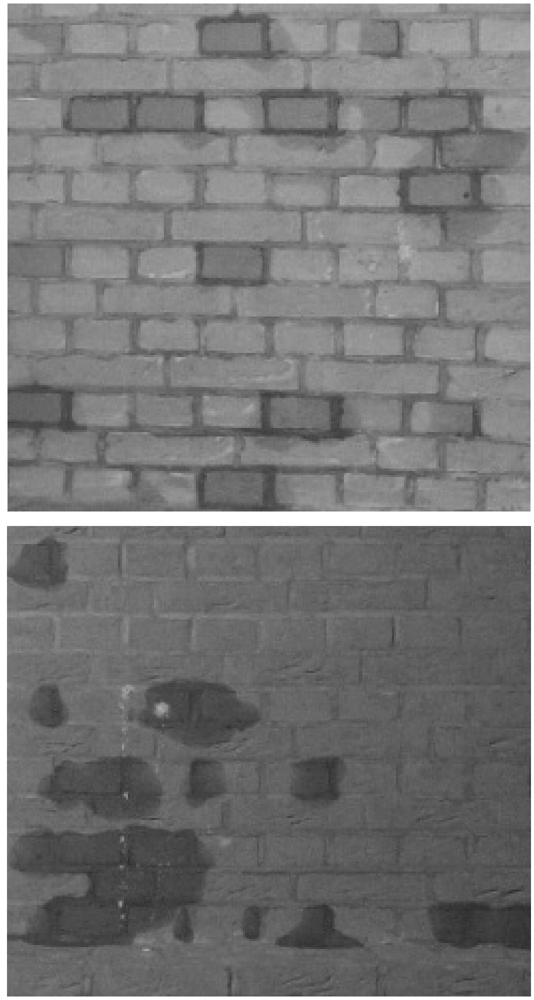


Fig. 1 Above: brick leakage in a 1 brick thick wall, caused by a high porosity of the applied brick (IRA brick 5.5 kg m^{-2} min^{-1}); Below: leakage in a 1 brick thick wall caused by mortar-brick interface leakage (IRA brick 1.5 kg m^{-2} min^{-1}) .

Rain penetration in walls of 1/2 and 1 brick length thick

Introduction

Focusing on materials behaviour in masonry walls of 1/2 and 1 brick length thick two main causes of leakage can be observed:

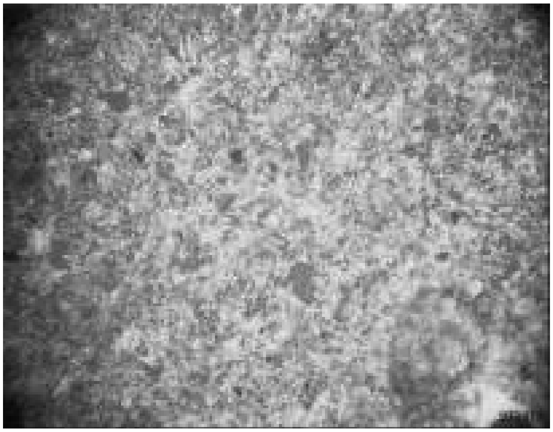
(i) leakage through the brick

(ii) leakage through the interface brick-mortar joint

the first cause being a pure materials characteristic and the latter mainly a hygric compatibility problem between brick and mortar [4]. These two types of leakage are shown in Fig. 1, being results of rain tests on two 1 brick length thick walls.

Brick Porosity

Essential to moisture transport in materials such as bricks and mortars is the pore system, as moisture absorption is a function of the capillary action of the



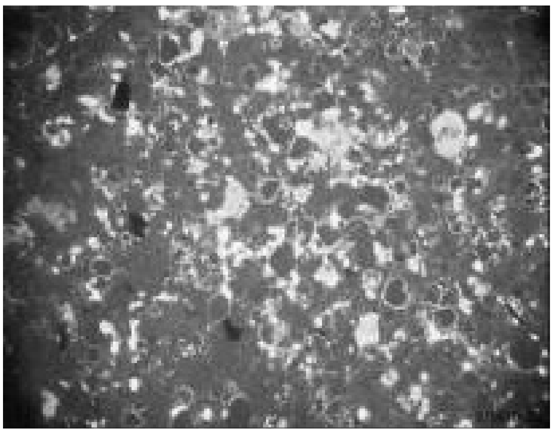


Fig. 2 Two fuorescence-microphotos of fired clay bricks: white indicating the porosity and dark is solid matter. Above: the strongly interconnected capillary network of a high absorption brick with a high absorption capacity. Below: a low absorption brick with isolated pores and a low absorption capacity (Photos Rockview, Amsterdam).

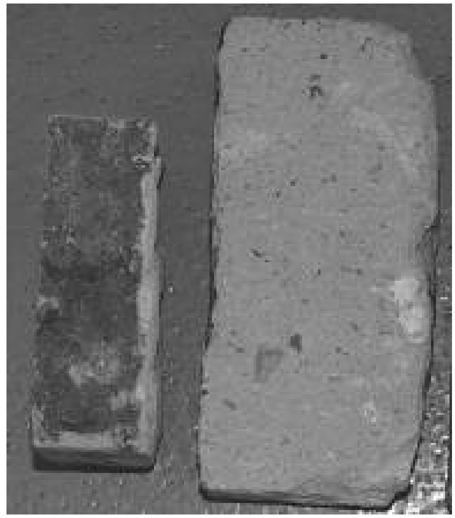


Fig. 3 Above, outside weathered side face of brick and inside (not weathered) original bed face of brick; below, outside weathered side of a wall.

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. In this 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 bricks 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 (see Fig. 2).

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), that is, the water absorption per surface unit in 1 minute, or, when measuring the water uptake over longer periods of time, by the absorption coefficient.

The water storage capacity may be characterized by the free or vacuum water absorption.

Often bricks with a strongly interconnected capillary network show a 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 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 with time as a function of the weathering conditions of the brick (see Fig. 3). In many buildings it can be observed that the IRA of the weathered side of the masonry significantly differs from that of the original material: the initial rate of absorption of the weathered outside is often less than half of the original material (the unchanged inside faces of the brick). The weathered side of brick is usually at the outer face of the masonry.

Consequently, with 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 with time as a result of weathering.

Weathering of high absorption bricks of an exterior face of a wall results in a slower absorption of rain water; however, and this is an advantage, water storage capacity of the wall remains equally high.

Cleaning of weathered walls may result in an increase of the water absorption rate of the masonry, making it prone to leakage (especially sand blasting).

Brick – mortar interface

An important parameter for leakage is the quality of the interface layer between mortar and brick. With quality it is meant the porosity / density of the interface. The porosity of the interface is largely influenced by moisture transport from mortar to brick, directly upon 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 [5]. 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.

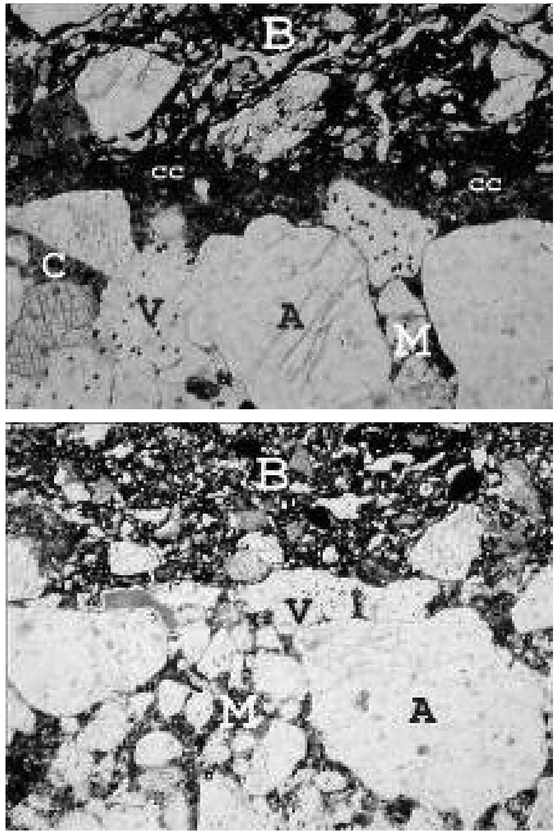


Fig. 4 Two examples of Brick-Mortar interfaces. Above: High void content at the interface; B: brick (IRA=0.29); M: mortar; A: aggregate; V: void; C: hydrated cement. Below; Layer of cement (cc) at the interface; B: brick (IRA=3.34); M: mortar; A: aggregate; V: void; cc: partially hydrated cement layer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

In figure 4, examples of an open and of a dense interface are shown [6]. Two types of bricks were used, with free water absorption values of 2.5 % and 19.5 % respectively, and an IRA of 0.29 kg m^{-2} min^{-1} and 3.34 kg m^{-2} min^{-1} respectively; and one type of mortar: a cement mortar (cement/sand ratio 1:4.5 (v/v) and water/cement ratio 1.03) was applied.

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 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 moisture content of the mortar is 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).

Rain penetration in walls > 1.5 brick length thick

Rain water that penetrates in walls with thicknesses > 1.5 brick length has to travel through a brick as well as crossing a mortar layer. So, water transport through a wall may be influenced by a moisture transport resistance exerted by (a) mortar layer(s).

Tests

A test program was set-up to study the effect of the mortar layer on the moisture transport in masonry test specimens. Starting point for the mortars was the lime mortar, as lime was generally used as binder in historic masonry with leakage problems. Test specimens were designed such that they can be considered as part of a wall, see figure 5. The test specimen consists of 3 courses of brick, 1½ bricks long and 1½ bricks thick (3 layers) put together using a bedding mortar.

During testing the uncovered face of the test specimen was immersed in a few centimetres of water. After a period of water absorption (24 h) 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 test for 2/3 of the cross section water has to travel through the brick *as well as* crossing a mortar layer.

For the tests two types of bricks were used: a red brick with a moderate IRA of 2.3 kg m^{-2} min^{-1} and a yellow brick with a high IRA of 3.5 kg m^{-2} min^{-1}. The bedding mortars applied were: two lime mortars: A and C; a weakly natural hydraulic lime mortar: B; and a strongly hydraulic mortar: X. The binder-to-sand proportions were always 2:1. No special allowance was made for the difference in brick IRA during specimen construction. Curing procedure: 1 week protected then in open air at 20 °C and 50-60 % RH.

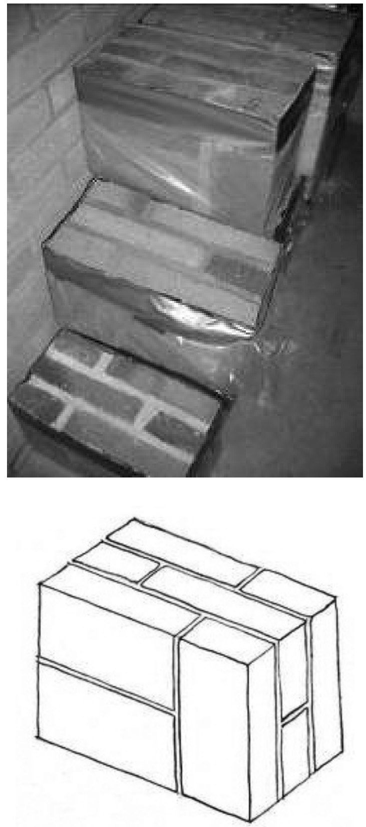
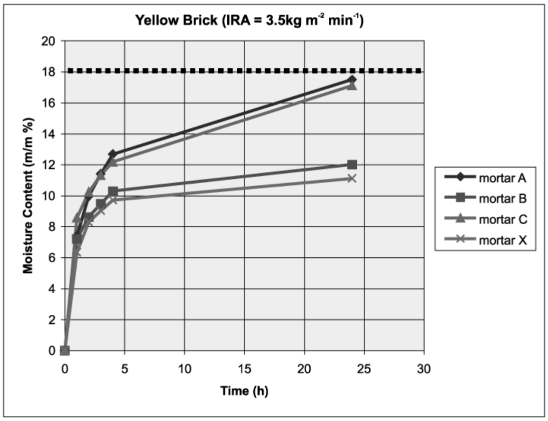


Fig. 5 View of test specimens. During the test, the uncovered face (the outer side of the wall) is exposed to absorption of water ("rain") or drying ; the other 5 sides are protected by plastic to allow drying from the uncovered face only (unidirectional drying as in a wall). Tests were performed by TNO-Built Environment and Geosciences, the Netherlands.

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.



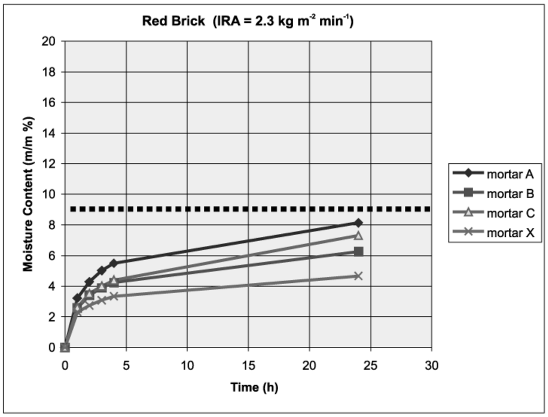


Fig. 6 Water absorption tests on various brick-mortar combinations tested; mortar A and C are lime mortars, mortar B and X are hydraulic mortars; the horizontal dotted lines in the figures indicate the values of the free water absorption by weight of the bricks (by capillary absorption from one face, over a 24 hour period) for the yellow bricks ~18 (m/m %); for the red bricks 9 (m/m %).

Barrier effect

The moisture absorption of the high-absorption brick specimens (left in Fig. 6), with the lime mortars (A) and (C), is significantly higher than that of the specimens with the weakly natural hydraulic lime mortar (B) and the strongly hydraulic masonry cement mortar (X).

After 24 hours of water absorption, test specimens A and C are almost saturated (up to their free water absorption capacity: 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 2/3 of the free water absorption capacity (11-12 m/m %). Apparently in the latter case the mortar acts as a barrier, restricting the rise of water to the top of the test specimen.

The distinction in water uptake of test specimens made with lime and hydraulic mortars, and low-absorption bricks is much less (right in Fig. 6). However, the order in the quantity of water uptake of the test specimens is the same for the four different mortars.

Rain leakage tests

Rain leakage of fired clay masonry walls was studied in walls with thicknesses of half, one and two brick length. The test walls consisted of high IRA bricks (5.5 kg m^{-2} min^{-1}) and moderate IRA bricks (1.5 kg m^{-2} min^{-1}). They were built with a weakly-hydraulic lime mortar.

After a rain test of 90 hours, performed according to NEN 2778, leakage of the walls was tested using a water supply of 2 L m^{-2} min^{-1} and an overpressure of 400 Pa (these are extreme conditions). Water leaking through the walls was collected and weighed.

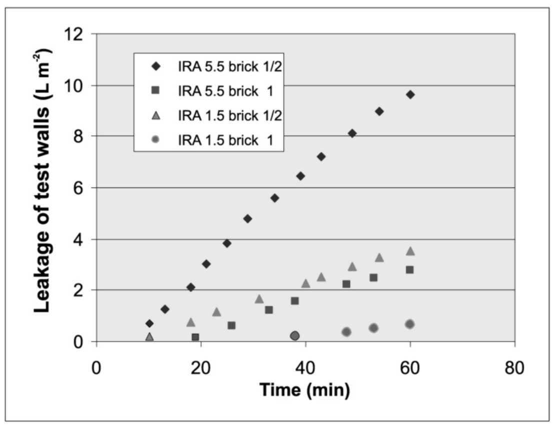


Fig. 7 Leakage of walls with thicknesses of half and one brick lengths. Two types of bricks have been used: a high absorption brick (IRA=5.5 kg m^{-2} min^{-1}) and a moderate absorption brick (IRA=1.5 kg m^{-2} min^{-1}); the walls were put together with a weakly hydraulic natural lime mortar.

As from Fig. 7 can be deduced, the leakage of the ½ brick thick wall with high absorption bricks (IRA=5.5) is significant: after 1 h is about 10 L m^{-2}. The water in this case mainly travels through the interconnected pores from one side of the brick to the other side (see as well Fig. 1, left). 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 joints in 50 % of the masonry (see Fig. 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 still have been diminished if the bedding mortar composition would have been more compatible to the applied bricks.

With the two different brick types also walls with thicknesses of 2 brick lengths have been constructed. The same weakly hydraulic natural lime mortar was used. Applying the same "rain intensity" (120 L m^{-2} h^{-1}) and overpressure (400 Pa) no leakage occurred, neither in the high absorption masonry (brick IRA=5.5), nor in the moderate absorption masonry (brick IRA=1.5).

Apparently, the barrier effect of mortar layers is sufficient to prevent leakage in both mortar-brick combinations.

Materials choices

The investigations regarding rain penetration in massive fired clay masonry was 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. Unsatisfactory permeability resulting in leakage was not exceptional. The test results show that this is mainly caused by a poor barrier effect of lime mortars. The situation may be improved by weathering of the bricks.

In the case of windmills, the use of lime mortars is not only a disadvantage as the heavy dynamic solicitations of the sails on the masonry require a high deformation capacity of the mortar; and this is provided by a lime mortar.

In the case of repair, it is recommended to use bricks with similar hygric properties as 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, according to [7]) 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 massive masonry pozzolanic binders (for instance trass) were used the permeability problems are usually less severe, as a better barrier action is secured. Also these mortars show a satisfactory deformation capacity, important in masonry with few or lacking dilation joints. Choosing a repair mortar this deformation capacity should be maintained.

In cases where little deformation capacity is required, water tightness can relatively easy be achieved since the introduction of modern binders at the nineteenth century. Many churches, towers and factories, built from the 1880's on, show a very good water tightness. This was achieved by using moderate to low absorption bricks (IRA=1-2 kg m^{-2} min^{-1}) and hydraulic (shell lime, that is, lime obtained from burned sea shells, which may be non--hydraulic to feebly hydraulic) lime-cement mortars (for instance in a binder-rich composition of 10 shell lime, 3 cement and 10 sand).

Workmanship

Studying a number of problem cases in practice the influence of workmanship on permeability problems in massive masonry is unmistakable. This aspect is often 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 done brick-by-brick.

Skilful laying of bricks is a relatively slow process. As in practice economic considerations may prevail and quicker brick laying methods may be applied with negative effects on the water tightness (whereas voids are introduced as a result of the applied brick laying technique)

In practice it is observed that voids, apart from being water reservoirs in the wall, as well may 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 massive masonry.

Acknowledgments

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