

# EXPERIMENTAL ANALYSIS OF WATER AND WATER VAPOR TRANSPORT IN COATING-SUBSTRATE SYSTEMS

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## **Abstract**

Experimental analysis of the protective function of five external coatings against water penetration and of their effect on water vapor transport under common service conditions is performed for ceramic brick substrates. The water absorption coefficient and the effective water vapor diffusion resistance factor are chosen as evaluation parameters for the assessment of water and water vapor transport properties of the systems.

**Key words:** water transport, water vapor transport, coating, ceramic brick substrate

## **1 Introduction**

The requirements to the barrier properties of coatings can sometimes be contradictory. The low water penetration rate through a coating is the most important condition for its proper function because it also prevents from the ionic ingress into the underlying structure (ionic diffusion is realized in the form of penetration of water solution of the particular aggressive substances). However, the coatings should be open for water vapor diffusion in the majority of applications. For example, external coatings have to make possible drying out of walls built of cast-in-situ concrete or aerated autoclaved concrete in the initial time period after completing the structure, they also should not prevent from water vapor transport through a structure in the winter period when the water vapor flux is in a direction from the interior to the exterior.

In this paper, an assessment of water and water vapor penetration properties of several exterior coatings on ceramic brick substrate is performed.

## **2 Materials and samples**

Ceramic brick produced in a Belgium factory was used as the substrate material. The samples of dimensions 47x68x20 mm were cut from the original blocks. One of 47x68 mm face sides of every sample was provided by one of the coatings which are characterized in Table 1. The same coating was used always on three ceramic brick specimens. The lateral 68x20 mm sides of all specimens were water and vapor proof insulated by epoxy resin so that one-dimensional water transport was ensured.

Table 1 Basic characteristics of studied coatings

Coating	Notation	Type of coating	Thickness [mm]
Primalex Plus	P	Polyvinylacetate dispersion	$0.50 \pm 0.05$
DÜFA Fassadenfarbe D7a	F	Resin dispersion with filler	$0.50 \pm 0.05$
DÜFA Silikat-fassadenfarbe S2-	S	One-component organic silicate stone paint	$0.40 \pm 0.05$
Karlocolor 30-001	K	Silicate modified paint	$0.65 \pm 0.05$
Gamadekor Flex 0101+ HC-4	HC	Flexible acrylate paint + ground coat	$0.75 \pm 0.05$

### 3 Experimental methods

#### 3.1 Water vapor transport properties

Standard cup methods in two basic configurations were employed in the measurements. In the dry cup method the sealed cup containing silica gel was placed in a controlled climate chamber with 30% relative humidity and weighed periodically. For wet cup method sealed cup containing potassium sulfate creating environment with 97% relative humidity was placed in an environment with the relative humidity of 30%. In both configurations the steady state values of mass gain or mass loss determined by linear regression for the last five readings were used for the determination of water vapor transport properties.

The water vapor diffusion coefficient  $D$  [ $\text{m}^2\text{s}^{-1}$ ] was calculated from the measured data according to the equation

$$D = \frac{\Delta m \cdot d \cdot R \cdot T}{S \cdot \tau \cdot M \cdot \Delta p_p}, \quad (1)$$

where  $\Delta m$  the amount of water vapor diffused through the sample [kg],  $d$  the sample thickness [m],  $S$  the specimen surface [ $\text{m}^2$ ],  $\tau$  the period of time corresponding to the transport of mass of water vapor  $\Delta m$  [s],  $\Delta p_p$  the difference between partial water vapor pressure in the air under and above specific specimen surface [Pa],  $R$  the universal gas constant,  $M$  the molar mass of water,  $T$  the absolute temperature [K].

On the basis of the diffusion coefficient  $D$ , the water vapor diffusion resistance factor  $\mu$  was determined:

$$\mu = \frac{D_a}{D}, \quad (2)$$

where  $D_a$  is the diffusion coefficient of water vapor in the air.

### 3.2 Water transport properties

Standard experimental setup for water sorptivity measurements was used. The specimen was water and vapor-proof insulated on four lateral sides and the face side was immersed 1-2 mm in the water, constant water level in tank was achieved by a Mariott bottle with two capillary tubes. One of them, inside diameter 2 mm, was ducked under the water level, second one, inside diameter 5 mm, was above water level. The automatic balance allowed recording the increase of mass. The water absorption coefficient  $A$  [ $\text{kgm}^{-2}\text{s}^{-1/2}$ ] was then calculated using the formula

$$i = A \cdot \sqrt{t}, \quad (3)$$

where  $i$  is the cumulative water absorption [ $\text{kg/m}^2$ ],  $t$  is the time from the beginning of the suction experiment. The water absorption coefficient was then employed for the calculation of the apparent moisture diffusivity in the form [1]

$$\kappa_{app} \approx \left( \frac{A}{w_c - w_0} \right)^2, \quad (4)$$

where  $w_c$  is the saturated moisture content [ $\text{kgm}^{-3}$ ] and  $w_0$  the initial moisture content [ $\text{kgm}^{-3}$ ].

## 4 Experimental results and discussion

Table 2 shows effective water vapor diffusion resistance factors of the analyzed coating-ceramic brick systems. Table 3 presents water vapor diffusion resistance factors of particular coatings calculated on the basis of their thickness and the known water vapor diffusion resistance factors of both ceramic brick and the particular two-layer system given in Table 2. It should be noted, however, that the data in Table 3 have more or less just orientation value. The error range of the calculated water vapor diffusion resistance factors is quite high taking into account the large difference between the thicknesses of the coating and the substrate and the uncertainty in the determination of the exact coating thickness. Also, it is necessary to consider that the calculated values are not exactly the water vapor diffusion resistance factors of “pure” coatings but rather of two-layer systems including both the coating layer itself and the mushy zone on the coating/substrate interface where the coating penetrated into the porous system of the brick substrate.

Table 2 Effective water vapor diffusion resistance factors of coating-ceramic brick systems

System	Dry cup method	Wet cup method
Ceramic brick	$11.4 \pm 10\%$	$4.5 \pm 10\%$
Ceramic brick - P	$10.6 \pm 10\%$	$4.8 \pm 10\%$
Ceramic brick - F	$16.8 \pm 10\%$	$6.7 \pm 10\%$
Ceramic brick - S	$14.2 \pm 10\%$	$6.3 \pm 10\%$
Ceramic brick - K	$12.1 \pm 10\%$	$6.1 \pm 10\%$
Ceramic brick - HC	$29.3 \pm 10\%$	$7.1 \pm 10\%$

Table 3 Water vapor diffusion resistance factors of particular coatings calculated on the basis of their thickness and the known water vapor diffusion resistance factor of ceramic brick

Coating	Dry cup method	Wet cup method
P	1 ± 20	20 ± 20
F	230 ± 70	90 ± 30
S	150 ± 80	100 ± 40
K	30 ± 40	50 ± 20
HC	500 ± 70	80 ± 20

Table 4 Water vapor diffusion resistance factors of particular coatings determined in common cup method arrangement

Coating	Dry cup method	Wet cup method
P	40 ± 10	32 ± 8
F	27 ± 6	11 ± 3
S	11 ± 3	4 ± 1
K	16 ± 4	8 ± 2
HC	4000 ± 1000	45 ± 11

Table 4 shows water vapor diffusion resistance factors of particular coatings determined in common cup method arrangement where a coating formed just one layer. A comparison of data in Tables 3 and 4 reveals that in most cases (except for P and dry cup measurements of HC) the values of water vapor diffusion resistance factors of coatings themselves were lower than in the system with ceramic brick. This gives a clear evidence of the significance of the mushy zone on the coating/substrate interface for the diffusion process of water vapor through a coating-substrate system.

Looking on the measured results from a purely practical point of view, it is possible to state that HC affected the water vapor diffusion properties of ceramic brick in a very significant way. The remarkable increase of water vapor diffusion resistance factor due to the application of this coating was for external surfaces quite undesirable. Relatively high values of water vapor diffusion resistance factors showed also F and S. However, their effect on the water vapor diffusion properties of brick was lower, possibly also taking into account their lower thickness. On the other hand, P and K increased the diffusion resistance of the coating-substrate systems only relatively little so that their application did not have negative effects on the permeability of the structure for water vapor.

Fig. 1 presents the history of water penetration into ceramic brick without any coating. The initial part of the water suction process was characterized by a fast increase of the mass of water in the sample with a constant slope of the  $m(t^{1/2})$  curve which indicates a good capillary activity of the material. After achieving the limit of about 10 g water in the specimen, the water front apparently penetrated near to the upper surface of the sample (assuming the vacuum water saturation moisture content of the brick 230 kg/m<sup>3</sup>, the maximum water content which can be achieved in ideal conditions in the analyzed

brick samples is 14 g). Since that time, water transport in the specimen was affected by water evaporation from the upper surface which gradually converged to equilibrium with the amount of water penetrating into the specimen.

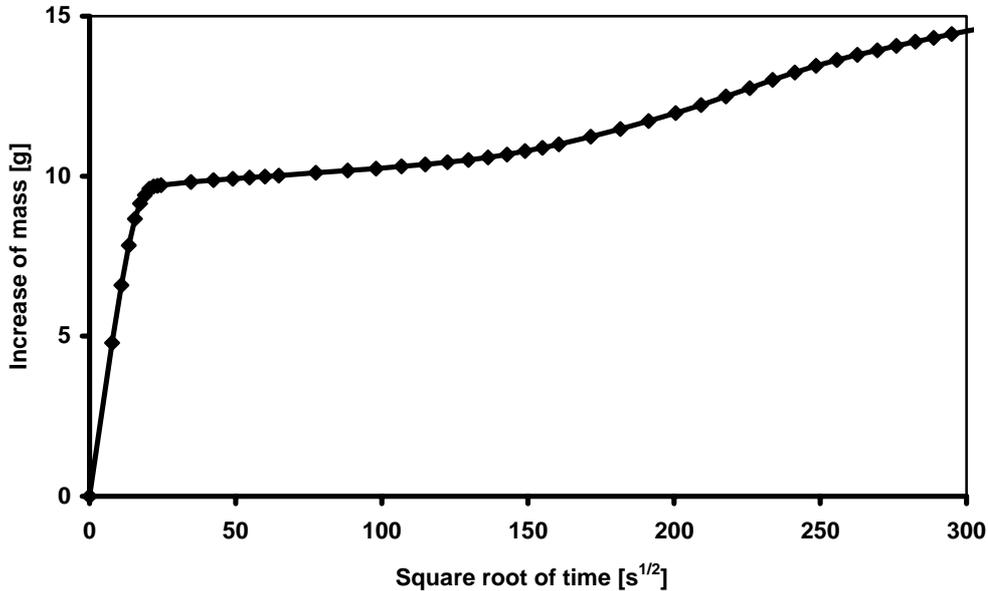


Fig. 1 Sorptivity of ceramic brick

The analysis of coating-substrate systems revealed that S exhibited the highest resistance against water penetration among the studied coatings. Fig. 2 shows that after a small initial increase of the mass of water in the system, further water penetration was fully suppressed. The maximum water content in the coating layer itself (assuming fully water saturated state) can be estimated as about 0.2-0.3 g. Therefore, the maximum mass of water achieved in the specimen of 0.65 g indicates formation of a water impenetrable barrier on the coating/substrate interface which prevented further water transport into the substrate material.

Fig. 3 shows that HC presented further relatively successful water protection layer. This coating was almost impenetrable for water until about 6 hours from the beginning of water action – only about 1 g of water penetrated into the system during that time. The  $m(t^{1/2})$  function was linear with a small slope during that period. However, after 6 hours a substantial increase of the amount of water was observed in the system, which was probably a consequence of achievement of water saturated state in the coating layer accompanied by an acceleration of water transport through the coating. In this phase the coating was losing gradually its water protective function, and the ability of the substrate to absorb water was a decisive factor for water transport in the system. This can be supported by the finding (see Fig. 3) that after another hour from the beginning of the sudden increase of the amount of water, the water transport in the system was stabilized again and the  $m(t^{1/2})$  function became linear with a much higher slope than in the first phase. From the point of view of practical application on building site, the water

protection performance of this coating can be considered as sufficient because in the conditions of Middle Europe, there are very few rains lasting more than 6 hours.

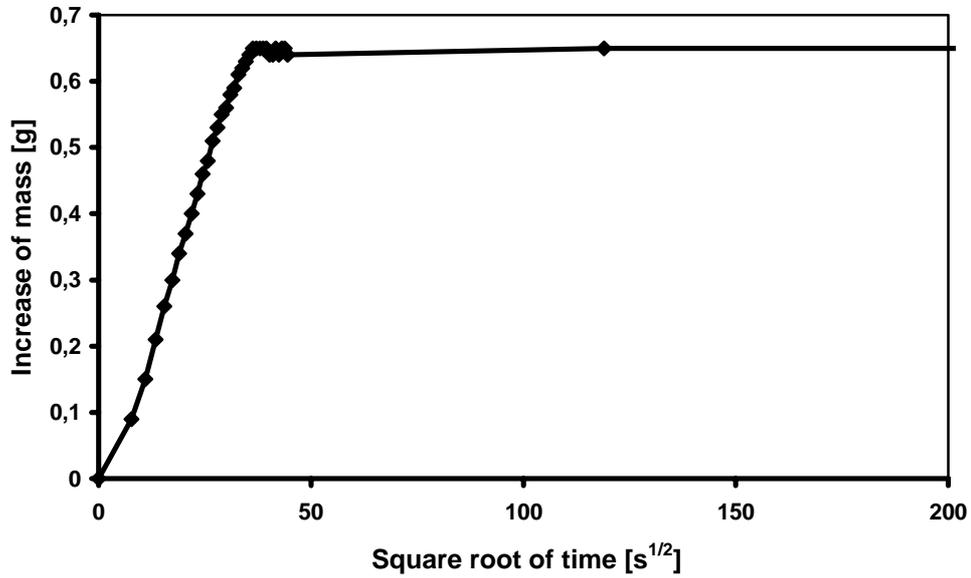


Fig. 2 Sorptivity of the S-ceramic brick system

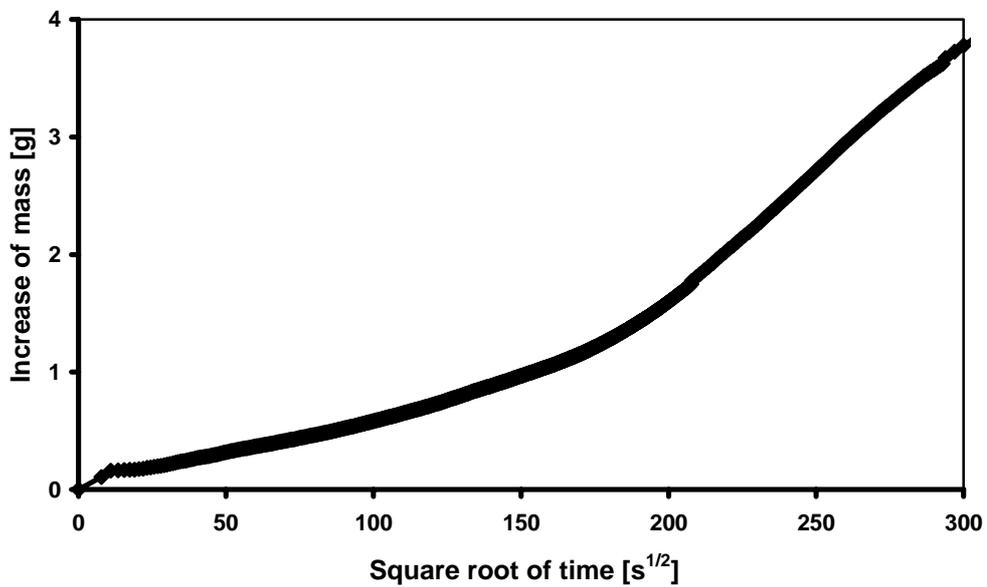


Fig. 3 Sorptivity of the HC-ceramic brick system

A similar course of the water suction curve as HC exhibited also P which after 6 hours allowed just about 0.5 g of water to penetrate into the system. So, it can be considered as a relatively successful water protection layer. The F and K coatings had a similar shape of the  $m(t^{1/2})$  function as HC and P but the increase of the amount of water in the system was much faster, 4-5 g after 6 hours. Therefore, they did not show a suitable water protection function.

On the basis of the measured  $m(t^{1/2})$  functions, water absorption coefficients of the studied coating-substrate systems were calculated in both characteristic water suction phases identified before. The values of water absorption coefficient and saturated water content then made it possible to calculate apparent moisture diffusivity. The results summarized in Table 5 justify partially the above hypothesis on the mechanism of water penetration into ceramic brick substrate through coatings. The apparent moisture diffusivity of the coating-ceramic brick systems in the second phase of water suction process were for F and K very similar to the value for ceramic brick without any coating. This indicates that the coating lost its water protection function and the water transport into the system was driven by the capillary properties of the brick itself. On the other hand, P and HC coatings achieved in the second phase of water suction apparent moisture diffusivity values almost two orders of magnitude lower than for ceramic brick without coating. Therefore, these two coatings presented even in the second phase certain water protection although a lower effective one than in the first phase.

Table 5 Water transport parameters in the ceramic brick-coating systems

System	Saturated water content [kg/m <sup>3</sup> ]	Water absorption coefficient in the first phase [kg/m <sup>2</sup> s <sup>1/2</sup> ]	Water absorption coefficient in the second phase [kg/m <sup>2</sup> s <sup>1/2</sup> ]	Apparent moisture diffusivity in the first phase [m <sup>2</sup> /s]	Apparent moisture diffusivity in the second phase [m <sup>2</sup> /s]
Ceramic brick	230	1.65E-1	-	5.1E-7	-
Ceramic brick - P	230	1.03E-3	7.38E-3	2.0E-11	1.2E-9
Ceramic brick - F	230	7.89E-3	1.48E-2	1.2E-9	1.4E-8
Ceramic brick - S	230	5.14E-3	-	5.0E-10	-
Ceramic brick - K	230	6.93E-3	3.58E-2	9.1E-10	1.9E-7
Ceramic brick - HC	230	1.53E-3	6.66E-3	4.4E-11	1.1E-9

Looking on the water vapor transport and water transport properties of the studied coatings together, it is possible to conclude that the most successful solution among the analyzed coatings was S. Its water protective function was very good and it remained still

relatively open for water vapor diffusion at the same time. The P coating was another successful solution because it exhibited reasonable water protection behavior and was very open for water vapor diffusion. The other coatings were not found to be suitable for application on ceramic brick in the exterior. HC was too vapor tight and only moderately protected the substrate against water penetration. F and K did not exhibit a suitable water protection function.

## **5 Conclusions**

The experimental analysis of water penetration into coating-ceramic brick substrate systems in this paper revealed two basic mechanisms of water transport. In the first case the coating completely sealed the surface of the porous substrate so that water penetration was stopped. This was probably due to the chemical reaction of the coating with the material of the substrate which resulted in sealing the mushy zone between the coating and the substrate. In the second case the coating slowed down water transport into the substrate for certain time only. Then it was saturated by water and its protective function was either worsened or even vanished completely. It was also observed that achievement of a good water protection function and retaining openness to water vapor transport at the same time, which is a principle requirement for external coatings, is not a common feature for many coatings being considered for an application in the exterior. This should be taken into account in practical applications on building site.

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## **References**

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