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PHENOMENOLOGIC ANALYSIS ON THE MOISTURE FLUX THROUGH CRACKS IN MASONRY CONSTRUCTIONS

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Abstract

Historic masonries contain a lot of cracks in different sizes and shapes because of structure movements over time, frost thaw cycles, poor workmanship and so many other reasons. But are these cracks worth mentioning in light of rain penetration and hygrothermal behavior? On the one hand most historic masonries are rather thick, so it can be assumed that the driving force for rain penetration, the pressure difference over the first brick layer, will be rather small if the interior finish is plastered relatively airtight. But on the other hand historic masonries have highly unreliable material properties and even air gapes in the construction cannot be excluded, which might lead to a vulnerable situation. To be able to discuss this subject for porous building materials the physical processes behind water penetration through cracks without pressure difference has to be discovered more precisely. Therefore preliminary rain penetration tests through slits in PMMA plates will be discussed depending on their width and direction. The pressure difference over the construction will be kept at 0 Pa most of the time to imitate the first brick layer of a thick historic wall construction with an air cavity behind it.

1. Introduction

Since a decade the pressure on historic buildings is on. With the goals of 2020 in sight, even these buildings undergo a low energy-retrofit more and more. But because of that, a lot of hygrothermal risks are introduced to esthetical valuable masonry constructions. Interior insulation often increases the number of freeze-thaw cycles due to a reduced heat flux through the wall. Next to that, it also leads to a higher moisture content again inducing a higher risk of frost damage. In general, statistics on building pathology show that high moisture contents are the cause of 50% of the defects in buildings of which 54% are associated with rain water penetration [1]. Next to the risk of frost damage, a high moisture content may lead to a decreased comfort experience of the building users, a decrease in strength of the structure, a degradation of the aesthetic value and a promotion of fungus in poorly ventilated areas. On top of this, the impact on the operating cost associated with heating and air conditioning of the building should not be underestimated [2].

Therefore, many researchers have focused on quantifying moisture contents in building by developing powerful HAM (Heat Air Moisture) models like Wufi and Delphin based on the research of Künzel [3] and Grunewald [4] on the heat, air and moisture transport in building materials. But these HAM models have a few shortcomings in modeling the actual physical behavior of WDR(wind driven rain): e.g. no raindrop impacts are modeled nor is the effect on absorption and evaporation of a runoff water film [5]. CFD (Computational Fluid Dynamics) models can simulate wind driven rain [6] and can be coupled with HAM models but even these CFD models take only impingement and absorption into account. The so called secondary effects, splashing and bouncing of raindrops and the runoff, are simplified. Finally, Van Den Brande *et al.* [5] made the first attempt to implement runoff in a coupled runoff-HAM model. Hereby is assumed that runoff only occurs when the brick surface is fully saturated. They claim that a runoff can have a great influence on the absorption coefficient of materials with a low absorption coefficient. Vandersteen [7] researched the capillary absorption in fractured porous media, but the calculation time of her model is very high, and because the flow of fluids is not taken into account water penetration and ingress are not modeled.

On top of the frost cracks, historic brick constructions are full of other cracks, from small crimp (often between mortar and brick) and thermal expansion cracks to big structural movement cracks. Often the footing of the building is instable or the lintels and beams are too flexible, causing overstressing in the masonry which again leads to cracks [2]. These fractures have a big influence on the moisture conductivity of the brickwork, as proved by Tammes and Vos [8], but these effects are hard to simulate in coupled runoff-HAM simulations. Therefore there is need for a principal phenomenological approach on how water penetrates through a cracked brick. For rain to penetrate through a building façade there are three necessities: a supply of water (rain), a route for the water to go through (crack) and a driving force to push the water along the route [2]. Until now, most studies assume that the driving forces are wind and rain impinging on the wall. As described by Baker *et al.* in some full scale model tests, the pressure difference between a cavity and the exterior (and so the crack leakage) can be defined for a wide range of crack dimensions by an equation that incorporates discharge coefficients [9]. Fazio and Kontopidis on the other hand, researched the pressure equalization principle of the cavity, which explains the reduction of rain penetration through exterior walls found by Killip and Cheetman [1]. Sevarajah S. *et al.* [2] assumed air pressure differences over a single brick masonry between 343 and 1176 Pa while realistic pressure differences lay in the range of 0 to 40 Pa [8]. Therefore, and because this research is done in the perspective of calibrating rain penetration through the first brick layer of a thick historic masonry, the pressure difference between the outside and a cavity in the wall is assumed to be negligible in this study. This means that there is no clear driving force for the rain penetration. However, given that rain penetration is found in some preliminary tests, the driving force is most likely the runoff water film running from the exterior façade.

In the first half of this paper we will summarize the earlier studies on moisture penetration and discus the physical processes in a saturated brick crack. In the second half we will discuss two preliminary experiments which are both of a different level of abstraction of a real cracked brick. First the water ingress through slits in a PC (polycarbonate) plate in different

directions and widths will be discussed. Secondly, different slits in a PMMA (Polymethyl methacrylate) plate in different directions and widths are extended to the backside with a small box to mimic the depth of a brick.
With this study we hope to induce a better understanding of the mechanisms inducing water ingress through cracks without a pressure difference and to be a guideline for developing new watertightness tests. As mentioned by Van Den Bossche [12], different test protocols are necessary to assess building components that may comprise different types of failure mechanisms.

2. Literature review

Van Den Bossche *et al.* [12] discuss in “Water infiltration through openings in a vertical plane under static boundary conditions” the water ingress through circular holes in a polycarbonate plate (contact angle=66°) of 1, 4 and 8 mm diameter for different pressures and two spray rates. In these circular holes comparable effects take place as in slits. Van Den Bossche precisely describes the balance between capillary pressure, surface tension and hydrostatic pressure in the hole. We can conclude from his study that only for a high sprayrate and a big diameter (8mm) water breached through the hole without any (wind) pressure difference.

Tammes and Vos researched the hydrostatic pressure developed by runoff over a brick surface and found hydrostatic pressures up to 20 mm high, which means an average over the height of 100 Pa. Tammes and Vos claimed the hydrostatic pressure is linear with the water supply in the slit.

$$\phi_s = \frac{w^2 \rho h \Delta p}{8\eta d} . 2\, wh \qquad (1)$$

This equation of Tammes and Vos [12] shows the moisture penetrating rate (ϕ_s) in function of the dimensions of a crack (w/h/d), the mass density of water (ρ), the viscosity (η) and the pressure difference over the crack (Δp). The equation might give the impression that without any pressure difference applied by wind water ingress is impossible. But this is not the case because a runoff film can apply an exterior pressure difference as well as described below.

3. Physical mechanism in the abstraction of a crack in a brick

$$p_e + p_c + p_h = p_m \qquad (2)$$

This formula describes that the water surface tension of the meniscus on the inside (p_m), has to be overcome by the capillary pressure (p_c), the external pressure (p_e) and the hydrostatic pressure (p_h) to let water breach through. Capillary pressure can be calculated for circular holes by the Young-Laplace equation where γ is the surface tension of water (74.42mN/m at 10°C), ϑ the contact angle of water and substrate (PMMA: 70°, PC: 66°) and r the radius.

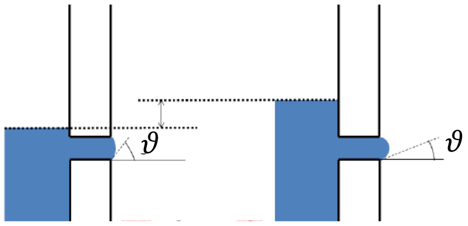


Fig. 2. Schematic representation on how the change in hydrostatic pressure causes a changes in the contact angle (ϑ) [11]

$$p_c = \frac{2\gamma cos\vartheta}{r} \qquad (3)$$

But for capillary pressure between two surfaces at a distance w from each other this equation becomes:

$$p_c = \frac{2\gamma cos\vartheta}{w} \qquad (4)$$

This makes it possible to calculate the raising height (h):

$$h = \frac{2\gamma cos\vartheta}{w\rho g} \qquad (5)$$

The hydrostatic pressure has no orientation and is therefore equal in vertical and horizontal direction. In a deep slit the vertical capillarity will be balanced with the hydrostatic pressure which will cause a specific water level in the slit. This means that the hydraulic pressure can then be assumed equal to the vertical capillary pressure in a slit. Van Den Bossche explained the principle of hydrostatic pressure by a basic setup (Fig. 2.). When the water level is raised the hydrostatic pressure increases and this will reduce the contact angle till the surface tension is overcome and the water breaks through.

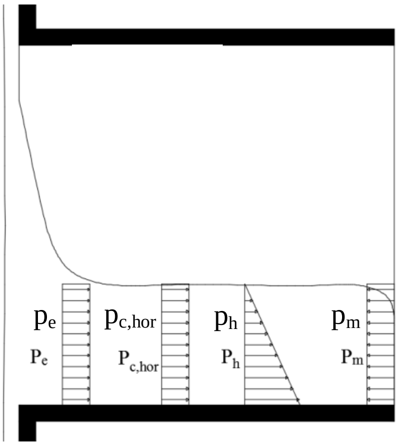


Fig. 3. Working pressures in the slit to prevent/obtain water penetration

The hydrostatic pressure, with g the gravitational acceleration (9,81 N/kg) is:

$$p_h = \rho g h \qquad (6)$$

As mentioned above the hydrostatic pressure and the capillary pressure in a 2D capillary (between two surfaces) keep each other in balance.

$$p_{c,vertical} = p_h \qquad (7)$$

The maximum necessary pressure to breach through the surface tension of a rectangular slit can perhaps be estimated as follows:

$$p_m = \gamma.2.(w+h)/(w.h) \qquad (8)$$

This means that only the external pressure applied by the flow of the runoff film is unknown in this equation. Note that this is only a first approximation using the perimeter of the deficiency, which will probably overestimate the pressure, as one can easily see that an infinitely long slit would require an infinitely high pressure difference. In practice, secondary effects such as variations in surface roughness will also affect the required pressure to breach the surface tension.

4. Pressure or suction induced by the runoff film

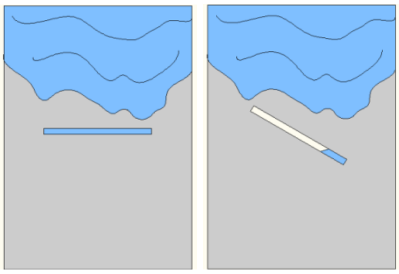
It is currently unclear to what extent a water runoff film on a surface reaching a deficiency induces a pressure difference: is it a positive pressure or a suction effect? If one considers the

Bernoulli law, it is clear that any obstruction located in the streamline may induce a positive pressure, whereas an opening located at the edge of the flow lines in the surface may be susceptible to the venture effect and thus induce negative pressures. Furthermore, fluid dynamics may also affect the flow inside the deficiencies. Flow disturbances may cause vortexes in front of and inside the deficiency, generating additional pressure fluctuations that may breach the surface tension of the meniscus on the interior side of the deficiency.

5. Preliminary experiments

5.1 Horizontal and tilted slits in a polycarbonate plate

In a preliminary experiment a 2 mm wide 30° tilted slit and a horizontal slit were made in a PC plate (contact angle PC =66°). Different air pressures were applied on the surface during runoff and plotted in Figure 3. As can be seen in the graph for horizontal slit there is no water ingress found for low pressure differences. In contract, for tilted slits water ingress already occurred at a pressure difference of 0 Pa. This can be an indication than the water ingress will depend highly on a balance between the runoff water captured in the slit and the hydrostatic pressure provoked by the total height of the slit.



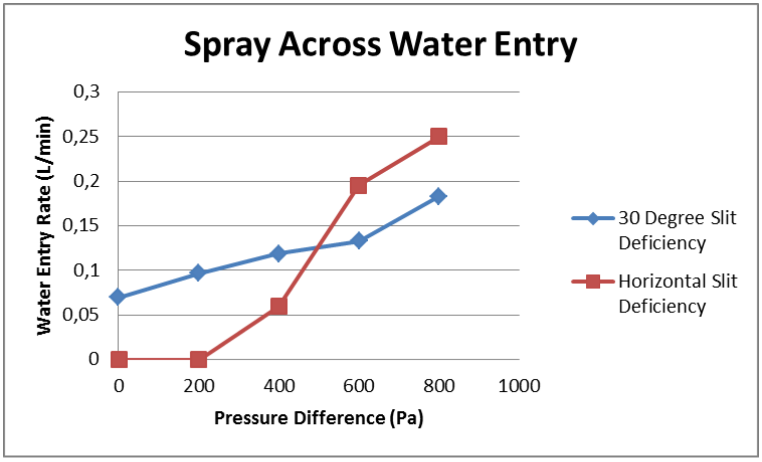


Fig 3. Left: Vertical PC plate with a 2 mm wide 30° tilled slit and a horizontal slit
Right: Water entry rate dependent on the pressure difference over the slit

Table 1: Expectations.

	Flat meniscus [Pa]	**Capillary pressure [Pa]**	**Hydrostatic pressure [Pa]**	**Req. Ext. pressure [Pa]**
Horizontal slit	77.40	30.27	19.62	27.51
30° angled slit	98.54	30.27	30.27	38.00

From these expectations and results we can learn that the difference in moisture penetration between these two orientations is mainly defined by the external pressure of the runoff film because the required external pressure to let water penetrate through the surface tension (Eq. 2) is almost equal for both orientations while the infiltration rate is quite different.

5.2 Vertical and angled slits in a PMMA plate with an extension at the backside

A) Experimental Setup

To generate a runoff film as uniform and constant in thickness as possible over the slits, different options were taken into account: a full cone nozzle, a flat fan axial spray nozzle. But finally a PMMA construction was built so that a thin film of water can escape from a water reservoir at the top of the plate. This method ensures that the thickness of the water film running down the surface is not influenced by the impact of raindrops flying around. The flow to fill the reservoir is controlled by a flow sensor and a water pump so the flow can be controlled precisely. Because of the transparent PMMA all water flows can be easily visualized. On the backside of the slits PMMA boxes (without front and backside) are glued with an interior dimension of 65 mm high, 65 mm in depth and a width equal to the slit. This makes the slit a lot deeper than in the previous test which will influence the penetration rate. The PMMA plate is cut with a laser cutter. This gives a smoother cut than other cutting devices but the roughness of the surface is still increased, which can lead to a lowered contact angle and thereby a lowered surface tension as mentioned by Van Den Bossche [12].

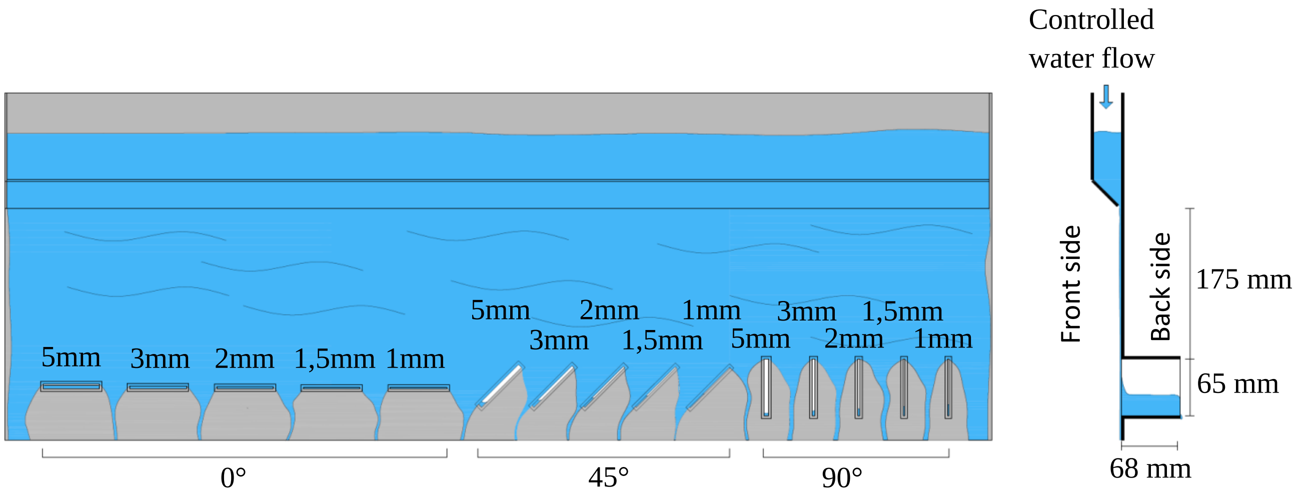


Fig 4. Test setup to generate an equal runoff film, Left: Back side view, Right: Section

With the theoretical background of the first part of the paper it is possible to make a prognosis through which type of slits water penetration is (im)possible. For the horizontal and vertical slits with a 1 or 1.5 mm width no water penetration is expected if there is no big external pressure. In those cases the meniscus pressure is theoretically big enough to prevent infiltration. In diagonal slits on the other hand, even penetration for small slits is expected because of the high hydrostatic pressure in them.

Table 2: Expectations.

	Flat meniscus [Pa]	**Capillary pressure [Pa]**	**Hydrostatic pressure [Pa]**	**Req. Ext. pressure [Pa]**
Horizontal slit (5 mm)	32.06	10.18	49.05	-27.17
Horizontal slit (3 mm)	51.90	16.97	29.43	5.50

Horizontal slit (2 mm)	76.71	25.45	19.62	31.64
Horizontal slit (1.5 mm)	101.52	33.94	14.72	52.86
Horizontal slit (1 mm)	151.13	50.91	9.81	90.41
Diagonal slit (5 mm)	37.68	11.97	78.48	-52.76
Diagonal slit (3 mm)	55.95	19.94	98.10	-62.10
Diagonal slit (2 mm)	79.70	29.91	117.72	-67.94
Diagonal slit (1.5 mm)	102.95	39.88	166.77	-103.70
Diagonal slit (1 mm)	150.65	59.83	343.35	-252.53
Vertical slit (5 mm)	54.57	10.18	58.86	-14.47
Vertical slit (3 mm)	74.42	16.97	58.86	-1.41
Vertical slit (2 mm)	93.03	25.45	78.48	-10.91
Vertical slit (1.5 mm)	248.07	33.94	9.81	204.32
Vertical slit (1 mm)	241.87	50.91	15.70	175.26

The flat meniscus and the hydrostatic pressure are calculated by the real height of the water level measured during the experiment because the calculated raising height due to the capillary forces working between the two surfaces is a lot lower between 1.04 and 5.19mm. The dynamic equilibrium (with runoff) of the water level in the slit is higher than the static equilibrium (no runoff). Therefore the water level is clearly influenced by the runoff film.

B) Visual findings

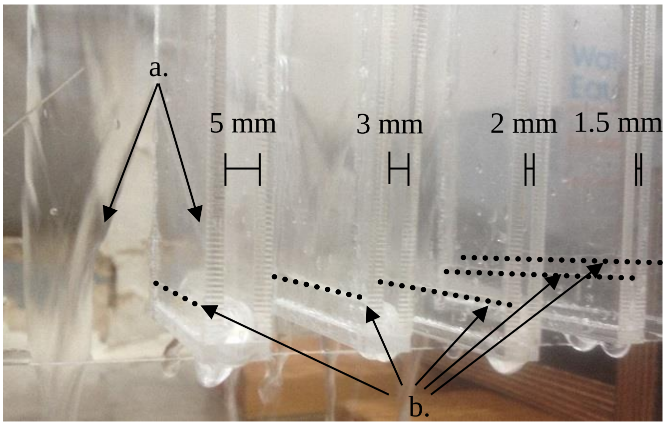


Fig. 5. a) Formation of rivulets / b) Different water hights in the cracks for the different widths

-At the top of each slit in the PMMA plate the runoff film does not run over the slit but it splits in two rivulets (Fig. 5 a), as already described by Van Den Bossche [11] [12] and Kondic and Diez [16].

-As can be seen on Fig. 5 b, the height of the water level in a crack depends on the width of the crack. This is a combined effect of the vertical capillary pressure (Eq. 4) together with an external pressure.

-Most of the time a stratified flow is seen in the crack: an air flow at the top and a water flow at the lowest part of the crack. Tracers in the water and visual observation pointed out that the runoff film of water intrudes into the crack at the front side and drains again to the front side or to the backside as presented in Figure 6 a. Sometimes the water flow can be strong enough to burst through the surface tension at the back side of the crack. Then water penetration occurs. And this brings us to the next visual finding.

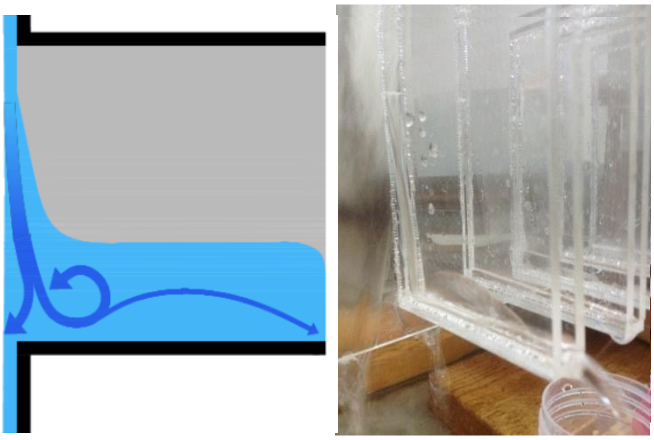


Fig. 6. Moisture flows in the crack / A rivulet entering a wide crack

-On the top of the slit rivulets are formed, but when these rivulets diagonally collide with a neighboring crack, a big water flow can intrude the crack and burst through at the back as can be seen on fig 6 b. Wide cracks are the most vulnerable to this effect. Hence, the formation and occurrence of rivulets at the exterior surface will mainly influence the moisture penetration. This brings us to the visual assumption that diagonal and probably horizontal cracks will have a higher penetration rate.

-The moisture profile in the crack is influenced by many aspects. The water level is very high at the outside of the crack (Fig 6 b.). This effect is most distinct in cracks with a small width. Although there has to be a suction pulling the water into the crack there. Central in the crack the water level is smoothened. On the inside the water level increases slightly and then curves down because of the surface tension at the backside.

C) Results

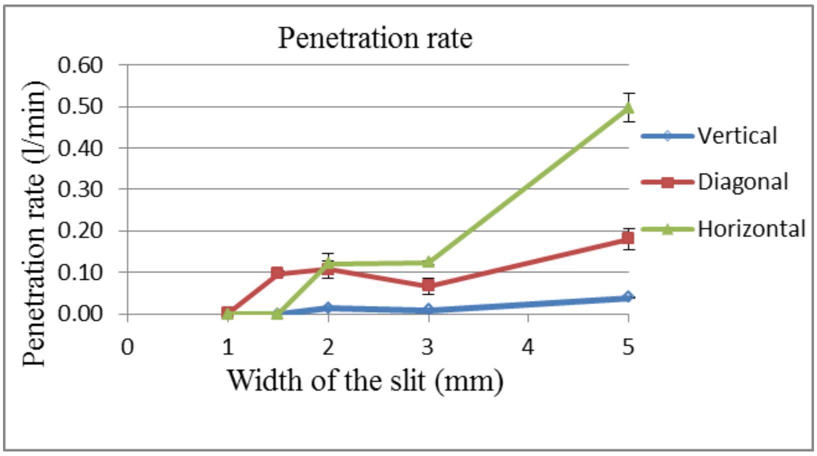


Fig. 7. Result of the first preliminary test

The gravimetrical measurements for the three directions (vertical, diagonal (45°) and horizontal) are reported in table 3-5. The small variations in penetration rates are most likely induced by irregularities in the water flow. The results show - as expected, please refer to table 2 - that vertical slits have the lowest penetration rates, and for small slits the penetration rate is minimal. This can be explained by a smaller capture area compared to the other orientations, and this conclusion is similar to what Severajah S. et al. found [2]. Through the 1.5 mm slit the water did not penetrate but it did through the 1 mm slit. This is an unexpected result and it is probably caused by small deviations in the setup. The moisture penetration in wide horizontal slits is very high compared to the expectations. Please note that these cracks are not often found in reality. Small widths (1.5 - 1 mm) on the other hand, seem no problem in this case. In diagonal slits the penetration rate is quite high for all the widths, except for a 1 mm slit where almost no rain penetration occurs.

Table 3: Water penetration in vertical slits (ml/min)

	5mm	**3mm**	**2mm**	**1.5mm**		**1mm**	
Test 1			42.90	10.10	14.20	0.00	3.20
Test 2			38.80	8.90	13.40	0.00	3.00
Test 3			39.70	9.50	13.30	0.00	3.20
Test 4			37.60	10.10	12.50	0.00	2.60
Test 5			39.30	9.10	12.70	0.00	2.40
Average			39.66	9.54	13.22	0.00	2.88
Stan. Dev.			1.98	0.55	0.67	0.00	0.36
Coeff. of var.			0.05	0.06	0.05	/	0.13

Table 4: Water penetration in diagonal slits (ml/min)

	5mm	**3mm**	**2mm**	**1.5mm**	**1mm**
Test 1	137.00	93.10	132.90	100.80	1.30
Test 2	177.60	76.70	86.10	92.60	1.50
Test 3	189.80	67.70	125.30	104.40	1.50
Test 4	199.90	46.70	95.80	97.60	1.30
Test 5	197.30	49.70	92.50	90.20	1.30
Average	180.32	66.78	106.52	97.12	1.38
Stan. Dev.	25.72	19.28	21.08	5.81	0.11
Coeff. of var.	0.14	0.29	0.2	0,06	0.08

Table 5: Water penetration in horizontal slits (ml/min)

	5mm	**3mm**	**2mm**	**1.5mm**	**1mm**
Test 1	532.30	128.00	77.70	0.00	0.00
Test 2	506.00	124.90	135.10	0.00	0.00
Test 3	518.40	124.90	136.60	0.00	0.00
Test 4	483.10	124.10	130.80	0.00	0.00
Test 5	445.80	117.10	121.20	0.00	0.00
Average	497.12	123.80	120.48	0.00	0.00
Stan. Dev.	33.91	4.03	24.56	0.00	0.00
Coeff. of var.	0.07	0.03	0.20	/	/

6. Conclusion

To understand water infiltration through cracks in brickwork we must know the physical mechanisms behind it. This will make it easier to link HAM models to wind driven rain. Today this knowledge lacks and therefore a test setup is built to gain more insight in water penetration through cracks. These preliminary tests show relevant effects that allow us to better understand infiltration. No external pressures are subjected to see the pure effect of a water film running down an exterior facade. The film is clearly pulled to the inside of the slit (as found by visualizing the moisture flows in the slit). In general the infiltration rate is proportional to the width of the slit (small slits have lower infiltration rates). This can have two reasons: a smaller external pressure by the runoff film or a bigger required external pressure to breach through the meniscus on the inside. As the calculated required external pressure is not always directly proportional to the width and orientation of the crack (table 2), a smaller external pressure must be the cause. The orientation of the crack does seem important in calculating the pressure exerted by the runoff film.

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