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WATER ABSORPTION AND PENETRATION IN CLAY BRICK MASONRY EXPOSED TO UNIFORM WATER SPRAY

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ABSTRACT

This experimental study investigates the effect of brick absorption properties and mortar joint profiles on water absorption and penetration in clay brick masonry. A test setup is presented, making continuous measurements of absorbed and penetrating water possible. Further, damp patches on the backside of the specimens are tracked by utilizing a digital camera and image analysis. Twenty-four masonry specimens are prepared using three different brick types with two different types of mortar joint profile: flush and raked. The tests are performed with a water application rate of 6.3 $l/m^2/h \pm 5$ % and zero differential air pressure. Results indicate that water absorption and penetration are mostly dependent on brick absorption properties, and the main way for water to penetrate is through brick-mortar interfacial zone. Additionally, the effect of joint profile on water absorption and penetration in specimens is negligible. The first visible damp patches on the backside of specimens appeared close to the head joint, indicating the difficulty of workmanship in filling the head joints and the brick-mortar interface as the primary water penetration path.

KEYWORDS: *brick masonry, water absorption, water penetration, damp patches, mortar joint profile, wind-driven rain, sorptivity*

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INTRODUCTION

Clay brick masonry façades have been used frequently for centuries because of their high longevity and long-term durability. Nevertheless, deterioration of masonry façades exposed to climate agents such as wind-driven rain (WDR) is inevitable [1]. Since moisture is one of the main causes of the damage to the buildings' façades and WDR is the primary source of moisture, the resistance of masonry veneer walls against WDR penetration has been a design issue for several decades [2-4].

Several experimental studies are available in the literature investigating masonry's response to WDR [3, 5-12]. Water penetration through the masonry façade depends on brick and mortar absorption properties, the profile of mortar joints, mortar consistency, presence of cracks, the compatibility of units and mortar, thickness of mortar joint, and workmanship [9, 10, 12-17]. Accordingly, there are several test methods available in standards to assess the water penetration in masonry walls [18-20], where ASTM E514 is one of the most frequently used test methods [3, 11, 21]. In the ASTM E514 standard, the specimens should be tested at a water spray rate of 138 $l/m^2/h$ and 500 Pa pressure difference.

The test condition of ASTM E514 standard is, in most cases, more severe than natural exposures, as stated by Fishburn et al. [5], and can only occur at specific locations, with very low probabilities, as analyzed by Cornick and Lacasse [22]. Additionally, a comparative study reviewing existing water penetration test methods, conducted by Driscoll and Gates [23], identifies a need for a simple test method to complement existing ones. Furthermore, Ribar [8] suggests that current test standards need to be revised to incorporate a realistic exposure condition approach. Thus, Forghani et al. [11] adjusted the air pressure of 500 Pa in ASTM E514 [18] to 45 Pa, a reduction of 91 %. Further, performing tests with zero pressure was considered in studies conducted by Shahreza et al. [12], Slapø et al. [10], Anand et al. [21], and Lacasse et al. [24]. Besides, Gigla [4] developed a test setup to study the water absorption of veneer masonry walls without evaluating air pressure. Additionally, Shahreza et al. [12] developed a test setup to expose masonry specimens to a uniform water spray rate varying between 1.7 and 3.8 $l/m^2/h$, a reduction of 95 % with respect to the ASTM E514 [18] test condition. Yet, as no water penetration that could be collected from the backside of the specimens was observed, that study focused on the measurement of water absorption and the analysis of damp patches on the backside of specimens.

In this experimental study, water absorption and penetration in brick masonry are studied using a newly developed test setup. Instead of the other test methods where a water film is maintained on the specimen surface [3, 6, 7], the present test applies a uniform and adjustable water spray to the surface. In addition to continuous water absorption and penetration measurements, the area and location of damp patches on the backside of specimens during the entire test period are monitored. The experimental campaign includes three Series of clay brick masonry specimens, prepared with three different types of bricks and two different mortar joint profiles, namely flush and raked. Since the overall objective of the present study is to investigate the WDR-related effects of mortar joint erosion on increased water uptake and penetration in clay brick masonry, raked specimens were chosen to be studied as a representative of eroded mortar joints. The comparison between water absorption and penetration of flush and raked specimens can facilitate understanding of how WDR-related water absorption and penetration might be affected in eroded mortar joints. The tests were conducted at zero differential air pressure, at a water spray rate of 6.3 $l/m^2/h \pm 5$ %, approximately 90% lower than the water application rate in current standards and studies [3, 11, 18, 21].

MATERIALS AND METHODS

Test setup

A test setup was designed to expose masonry specimens to a uniform water spray. The specimen was mounted on a scale to allow for continuous monitoring of weight. Any water penetrating through the backside of the specimen was led to a collector mounted on a second scale. A nozzle with a conical spray pattern was mounted in a fixed position at a horizontal distance of 50 cm from the specimen's exposed surface. In order to minimize variation and monitor the water flow, two water pressure regulators and a water flow meter were mounted between the water supply and the nozzle. A digital camera was mounted behind the specimen to record any visible dampness. The resulting time-lapse image sequence was analyzed through image analysis to obtain the location of the first visible dampness and the relative damp area over time. A more detailed description of the test setup is presented in Reference [12]. A schematic illustration of the test setup is shown in Figure 1.

Each specimen was tested over a period of 23 hours, including six consecutive cycles; each cycle consisted of 210 min of water spraying and 20 min of drying. Tests were done with zero pressure, whereas the water application rate was maintained at 6.3 $l/m^2/h \pm 5$ %.

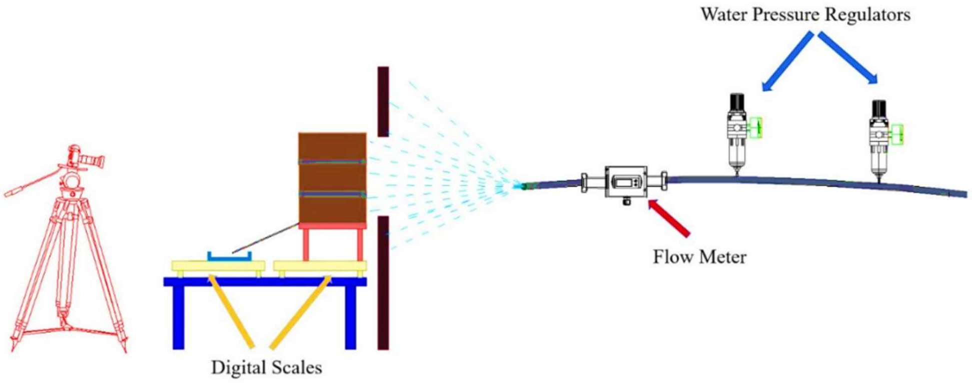

Figure 1: Schematic of the test setup

Bricks and mortar

In this study, three types of bricks, type I, II, and III with different absorption properties, were tested. Twenty bricks from each type were studied to characterize their initial rate of absorption (IRA) and 24-h water absorption properties. Ten bricks of each type were tested to characterize the sorptivity of the bricks. Table 1 summarizes the results of IRA, 24-hour cold water absorption, and sorptivity tests. Brick types I and II are both classified as medium suction bricks, whereas type III is categorized as low suction. Note that the absorption capacity of type I and II differ by a factor of 2.

Mortar M 2.5, widely used in Northern Europe for masonry façades, was used in this study. Twelve 100 mm-side cubes were cast to characterize the mortar. Table 1 summarizes the average results of the IRA and sorptivity properties of mortar. It should be noted that all tests to characterize brick and mortar properties were conducted according to ASTM C67 [25] and ASTM C1403 – 15 [26] standards.

Table 1: Average water absorption properties, including initial rate of absorption, 24-hour absorption, and sorptivity of bricks and mortars

Materials	Dimensions (mm×mm×mm)	Density ρ (kg/m^3)	Average IRA (kg/m^2/min.)	Average IRA (g/30in^2/min.)	CoV (%)	Average 24-h water absorption (%)	CoV (%)	Average sorptivity mm/min^{½}	CoV (%)
Bricks type I	250×120×62	1800	1.95	37.7	2.3	16.0	1.6	1.495	0.6
Bricks type II	250×120×62	1990	1.81	35.0	5.1	8.6	14.5	1.028	18.4
Bricks type III	240×115×62	2235	0.71	13.7	23.0	4.0	38.6	0.268	22.8
Mortar M 2.5	100×100×100	1869	0.3	5.8	19.7	-	-	0.159	8.7

Masonry specimens

This study aimed to study water absorption and penetration in clay brick masonry exposed to a uniform water spraying. Three different types of bricks and two different joint profiles were considered. In total, 24 triplet specimens were built consisting of three courses of brick, with the length of one brick and the thickness of half-brick length.

Specimens herein presented are divided into three Series according to the brick absorption properties. Each Series is divided into two groups according to the joint profile (Table 2). Group G1 includes twelve specimens pointed with mortar M 2.5 with a tooled flush joint profile, whereas Group G2 consists of twelve specimens pointed with mortar M 2.5 with a raked joint profile. To eliminate uncertainties regarding workmanship, a single craftsman built all specimens. Extra effort went into ensuring that the same amount of water was added to each batch of mortar mix, i.e., eliminating the effect of mortar flow on water penetration.

Specimens of group G1, with mortar M 2.5, were tooled with a wooden stick to have a flush profile. For specimens with the raked joint profile, group G2, the specimens were pointed with mortar M 2.5, and then a 5 mm screw was used to remove extra mortar to reach the depth of 5 mm (Figure 2). The workmanship technique used for bricklaying in this study was the so called pushing of the head joints. Figure 3 shows the backside of the representative specimens.

The specimens are named according to the notation A-B-C, where A, B, and C correspond to the brick type (I = medium suction [I], II = medium suction [II], III = low suction), mortar joint profile (F = flush and R = raked), and specimen number, respectively. For example, specimen I-R-2 belongs to Series I, was built with medium suction bricks, with a raked joint, and it is the second specimen of group G2.

Table 2: Specimen designation and configurations

Series	Group	Brick	Mortar	Joint profile finishes	No. of specimens
Series I (250 mm × 215 mm × 120 mm)	G1	Medium Suction I	M 2.5	Flush	4
	G2			Raked	4
Series I (250 mm × 215 mm × 120 mm)	G1	Medium Suction II	M 2.5	Flush	4
	G2			Raked	4
Series III (240 mm × 215 mm × 120 mm)	G1	Low Suction	M 2.5	Flush	4
	G2			Raked	4

After bricklaying, the specimens were cured for 28 days under plastic sheets. Subsequently, all sides of the specimens except the exposed surface and backside were sealed using a two-component sealant producing a flexible waterproof coating. Prior to testing, all specimens were kept in a climate room under controlled conditions (temperature of 20 °C and relative humidity of 60 %). Figure 2 shows a representative sealed specimen of each group within each Series.

Figure 2: Representative specimens from each group and Series after sealing

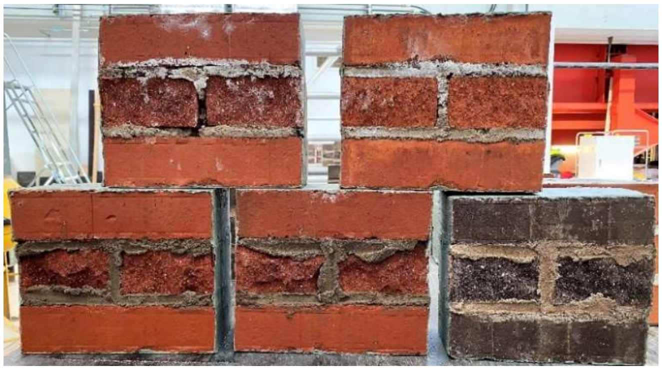

Figure 3: Backside of the representative specimens

RESULTS AND DISCUSSION

Water absorption

As the test setup was capable of measuring the amount of absorbed water, i.e., mass gain continuously, it provides the opportunity to study each specimen's absorption behavior during testing. The absorption herein is defined as the ratio between the mass gain, i.e., the difference between measured weight and initial weight, and the initial weight. Figure 4 shows the average absorption of each group within each Series during 23-h of the test. The linear branch of the absorption curve indicates that surface saturation was not yet attained, as most sprayed water is absorbed. The point when surface saturation occurs can be seen from the deviation from a linear slope of the absorption curve. Surface saturation is attained during the 1st cycle for all groups of each Series. The obtained results suggest that there is a strong correlation between brick's sorptivity and the time to attain surface saturation. Accordingly, a high sorptivity allows rapid moisture transport and postpones surface saturation, as shown by Van Den Bossche et al. [27] and Shahreza et al. [12]. As can be seen in Figure 1, surface saturation takes a shorter time to occur for Series III than Series I and II. Thus, the higher the brick's sorptivity is, the shorter time it takes to attain surface saturation.

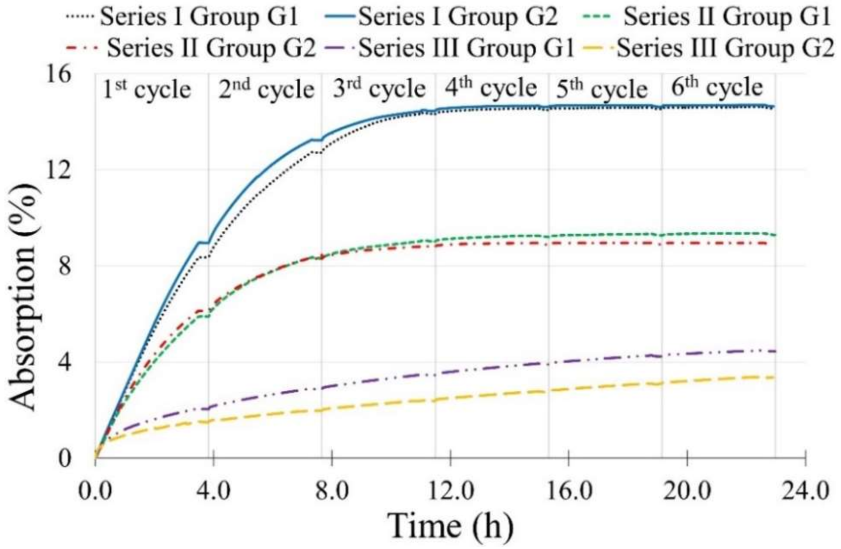

Figure 4: Average water absorption vs. time response for each group within each Series

As the test progressed beyond surface saturation, the slope of the absorption curve decreases. For Series I and II, specimens prepared with medium suction bricks type I and II, the absorption ends during the 4th cycle, whereas for Series III, specimens built by low suction bricks, the absorption continues until the end of the test. The results indicate that the rate of absorption in masonry specimens during 23-h of the test is highly dependent on the sorptivity of the bricks, whereas the amount of absorbed water at the end of the test is mostly correlated to the absorption capacity of the masonry.

Further, in Series I and II, in spite of the relatively high absorption capacity of bricks, full saturation of specimens occurred during the 4th cycle because of the relatively high sorptivity properties of bricks (the sorptivity of medium suction bricks type I and II was roughly 5.5 and 3.8 times more those of low suction bricks). In contrast, for Series III, specimens prepared with relatively low water absorption capacity, the low sorptivity of bricks resulted in continuous absorption during the test, indicating that the specimens did not attain full saturation.

The absorption in each specimen after the 1st cycle and the 6th cycle is summarized in Table 3. It can be seen that the difference in the average total absorption between each group within Series I and II is negligible. In contrast, after performing the 1st cycle, for both Series I and II, the average absorption of group G1, specimens with flush joint profile, is roughly 7.0 % smaller than that of group G2, specimens with raked joint profile. However, it can be observed that after the 6th cycle, the total absorption is consistent with the absorption capacity of the corresponding brick type and the effect of joint profile is negligible, e.g., the absorption is equal to roughly 14.5 % for both groups G1 and G2 of Series I, whereas for groups G1 and G2 of Series II, the absorption is equal to 9.3 % and 8.9 %, respectively. The difference between the total absorption of group G1 and G2 of Series III is related to the large variability in bricks' absorption properties (CoV = 38.6 %).

Table 3: Water absorption of specimens after the 1st and the 6th cycle

	Specimens	Initial weight (g)	1st cycle Absorp (%)	Ave (%)	Total Absorp (%)	Ave (%)	CoV (%)
Series I Group G1	I-F-1	11746	8.1	8.4	14.4	14.5	1.9
	I-F-2	11766	8.6		14.3		
	I-F-3	11558	8.4		14.9		
	I-F-4	11731	8.4		14.4		
Series I Group G2	I-R-1	11668	8.8	9.0	14.5	14.6	0.9
	I-R-2	11718	9.3		14.4		
	I-R-3	11628	9.1		14.6		
	I-R-4	11585	8.8		14.8		
Series II Group G1	II-F-1	12664	5.5	5.9	9.1	9.3	10.1
	II-F-2	12623	4.3		7.9		
	II-F-3	12591	7.5		9.7		
	II-F-4	12637	6.3		10.4		
Series II Group G2	II-R-1	12762	7.3	6.1	10.1	8.9	10.2
	II-R-2	12575	5.3		8.6		
	II-R-3	12628	6.1		9.3		
	II-R-4	12720	5.7		7.6		
Series III Group G1	III-F-1	12405	1.3	2.1	3.1	4.4	20.2
	III-F-2	12356	2.4		4.3		
	III-F-3	12469	2.4		5.5		
	III-F-4	12219	2.1		4.9		
Series III Group G2	III-R-1	12184	1.7	1.5	3.9	3.3	11.0
	III-R-2	12134	1.5		3.4		
	III-R-3	12010	1.5		2.9		
	III-R-4	12320	1.4		3.2		

Based on the available results, water absorption in brick masonry depends on the brick absorption properties, particularly sorptivity, whereas the impact of joint profile is negligible, particularly after a long exposure to driving rain, as already noted by Shahreza et al [12].

Damp patches

Figure 5 shows the location of the 1st damp patch on the backside of the specimens. With some exceptions, the first patch appeared in close proximity to the head joint. Exceptions include specimens III-F-4, III-R-2, and III-R-4. Due to the difficulty of workmanship in filling and compacting the head joint, the vertical joints can be the primary path for water penetration and leakage.

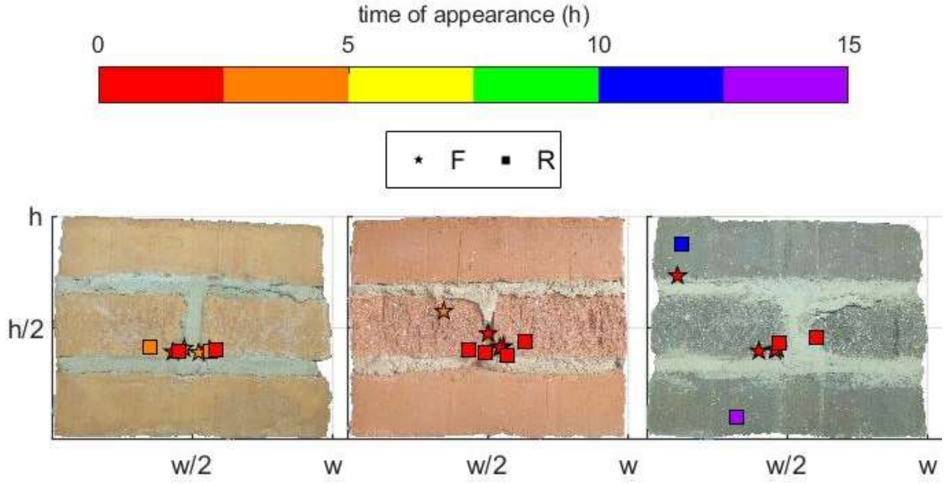

Figure 5: Location of the first visible damp patch on the backside of specimens

The first visible damp patch appeared after 2.5, 2.6, 2.0, and 1.5 hours for groups G1 and G2 of Series I and II, respectively (Table 4). Whereas, for group G1 and G2 of Series III, the dampness appeared after 1.0 and 6.9 hours (Table 4). In Series III, the first dampness appeared after 0.1 h for specimen III-R-1, whereas it took 14 h for specimen III-R-2. This large variability is attributed to the relatively large variability of the bricks' properties and the effects of workmanship.

Additionally, the time when the backside of the specimens reached a relative dampness of 15 % and 50 % are summarized in Table 4. As can be seen, the backside of the specimens in Series I and II reached 15 % dampness roughly 2 hours after the apparition of the 1st visible dampness. The corresponding time in Series III varied between 5 – 10 hours, indicating the importance of the sorptivity on water transport in masonry. A similar trend is discernible when it comes to reach 50 % dampness as it takes roughly 5 hours more in the case of Series I and II and 14 hours in the case of Series III. It should be further observed that for Series III Group G2, 50 % dampness was not reached during the 21 hours of water spray exposure.

Moreover, it can be observed that the adequate filling of the head joint might affect the location and the time to the appearance of the first visible damp patch, as demonstrated for Series III (Figure 5).

Table 4: Time to the first damp patch, 15 % dampness, and 50 % dampness on the backside of specimens, and total water penetration of tested specimens

	Specimen	time to the 1st patch (h)	Ave (h)	time to reach 15 % dampness (h)	Ave (h)	time to reach 50 % dampness (h)	Ave (h)	Water penetration (g)	Ave (g)
Series I Group G1	I-F-1	2.0	2.5	4.4	5.0	8.0	7.6	60	108
	I-F-2	3.3		5.2		7.5		120	
	I-F-3	1.7		5.5		7.2		150	
	I-F-4	3.0		4.8		7.5		102	
Series I Group G2	I-R-1	2.0	2.6	4.7	4.7	6.8	6.7	190	182
	I-R-2	2.8		4.3		5.7		156	
	I-R-3	3.2		5.0		6.8		344	
	I-R-4	2.3		4.8		7.3		32	
Series II Group G1	II-F-1	1.6	2.0	4.0	4.0	7.2	7.7	198	206
	II-F-2	3.2		4.7		11.7		30	
	II-F-3	1.3		3.3		4.8		250	
	II-F-4	1.8		3.8		7.0		346	
Series II Group G2	II-R-1	2.3	1.5	3.3	3.4	5.8	6.3	216	146
	II-R-2	1.2		3.3		6.2		154	
	II-R-3	1.3		4.0		6.7		16	
	II-R-4	1.2		2.8		6.5		196	
Series III Group G1	III-F-1	0.6	1.0	3.3	5.7	11.8	14.9	50	14
	III-F-2	0.7		5.0		15.7		0	
	III-F-3	0.3		6.8		15.4		2	
	III-F-4	2.3		7.5		16.5		2	
Series III Group G2	III-R-1	0.1	6.9	13.3	17.5	-	-	0	1
	III-R-2	14.0		21.0		-		2	
	III-R-3	2.5		14.0		-		0	
	III-R-4	10.8		21.7		-		2	

Water penetration

The amount of water penetration that could be collected from the backside of specimens after 21 hours of exposure to water spraying is summarized in Table 4. As can be seen, the average amount of penetrated water of group G1 and G2 of Series I and II is equal to 108 g, 182 g, 206 g, and 146 g, respectively. In contrast, there is no considerable water penetration for specimens of Series III except specimen III-F-1. The results suggest that water penetration is highly dependent on the water absorption properties of bricks.

The importance of brick-mortar interface on masonry's resistance to WDR is also noticeable, as most of the collected water from the backside of the specimens, penetrated through the interfacial zone. For instance, in seven out of eight specimens in Series III, the amount of water penetration was limited to between 0 – 2 g. The sharp contrast compared to Series I and II is attributed to continuous contact in the brick-mortar interface and absence of known defects. Yet, in specimen

III-F-1, a water penetration of 50 g was registered, indicating that the quality of the workmanship might not have been as high as in the case of the previously mentioned specimens. It should be further observed that the amount of penetrated water varied within a considerable range also in Series I and II – between 32 – 344 g and 16 – 346 g respectively.

In addition, comparing water penetration of Series I and II with Series III highlights the impact of brick water absorption properties, particularly sorptivity, on the leakage through specimens, as already noted by Ritchie and Plewes [14]. Moreover, comparing water penetration of groups G1 and G2 within each Series indicates the negligible effect of mortar joint profile on water penetration.

Based on the available results, several factors might influence water penetration in brick masonry. Firstly, the primary path for water to penetrate masonry walls is through the brick-mortar interface for low to medium suction bricks, as already noted by Groot and Gunneweg [9] and Slapø et al. [10]. Secondly, although specimens were prepared without any known defects and voids, the difficulty of filling head joints can lead to leakage through masonry specimens. Nevertheless, Jonell and Moller [15] believe on the difficulty of complete filling of the head joint with the pushing technique, as the head joint of specimens in this study were prepared with this technique.

CONCLUSIONS

The presented experimental study was aimed to study water absorption and penetration in clay brick masonry exposed to a uniform water spray by employing a modified test setup. A digital camera was employed to monitor damp patches on the backside (the protected side) of the specimens, and continuous water absorption and penetration measurements were carried out using two digital scales. Parameters investigated were: three different types of bricks and two different mortar joint profiles: flush and raked. The tests were performed with zero differential air pressure between the specimens' exposed side (the front side) and protected side (the backside) with a water application rate of 6.3 $l/m^2/h$ ± 5 %.

Based on the obtained results, the effect of mortar joint profiles on water absorption is negligible, whereas the water absorption in masonry specimens is highly dependent on the water spray rate and sorptivity of bricks prior to the surface saturation. Once the surface saturation was attained, the behavior was dependent on both sorptivity and water absorption capacity of the bricks. Moreover, the first visible damp patch appeared close to the brick-mortar interface, indicating low resistance of the head joint to WDR attributed to low compaction and difficulty in filling the vertical joints.

Furthermore, the main way for water to penetrate a brick masonry was the brick-mortar interface and the water penetration in masonry specimens was influenced by the bricks' absorption properties, whereas the mortar joint profiles did not affect water penetration considerably. The average penetrated water of group G1 and G2 of Series I and II is equal to 108 g, 182 g, 206 g, and 146 g, respectively. However, the water penetration in Series III specimens was roughly zero except for specimen III-F-1, indicating the high resistance of masonry specimens built with low sorptivity and low absorption capacity bricks to WDR.

Nevertheless, the effect of workmanship to achieve non-open brick-mortar interface on the water penetration in all three Series is noteworthy; a) the difference between the water penetration of individual specimens in Series I and II is substantial, with a minimum of 16 g and a maximum of 346 g; and b) water penetration in specimen III-F-1 was around 50 g despite near zero penetration for the rest of the specimens in Series III.

Eventually, the newly developed test setup might facilitate the verification of moisture simulations as it enables continuous water absorption and penetration measurements combined with tracing of damp areas on the backside of masonry specimens.

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