Drainage of infiltrated rainwater in wall assemblies: test method, experimental quantification and recommendations

Stéphanie Van Linden*[1], Michael Lacasse[2], Nathan Van Den Bossche[1]

1. Ghent University, Faculty of Engineering and Architecture, Building Physics Research Group, Belgium

2. National Research Council of Canada, Construction Research Centre, Canada

Abstract

Drainage reduces the amount of water able to infiltrate towards the interior of wall assemblies. However, a portion of the infiltrated water remains in the assembly after drainage has occurred. The degree to which this retained portion of water affects the durability of the wall assembly can be evaluated by means of hygrothermal simulations. However, the number of studies reporting information on the retention percentage that can be applied as input for hygrothermal simulations and on the drainage performance of wall assemblies is, in general, quite limited. Therefore, an experimental study was developed, to assess governing test methods to evaluate drainage characteristics and to quantify retention of water in wall test specimens having various cavity widths and incorporating different drainage materials. It was concluded that apart from the absolute amount of retained water, the lateral spreading of water in the cavity and the overall wetted area, should also be considered, thereby resulting in reporting the retained amount relative to the wetted area. The latter values provide more detailed information on the behaviour of water in the cavity. Additionally, it was concluded that a clear cavity of 1 mm can drain water more efficiently than a cavity of 10 mm. As well, the surface texture of drainage materials affected the spreading and retention of water within the cavity and the use of a drainage mat in the cavity resulted in an increased relative retention but a reduced lateral spreading of the water.

Keywords: Drainage, retention, drainage cavity, drainage materials, rainwater infiltration, drainage efficiency

1. Introduction

Water penetration through the exterior cladding surface of wall assemblies, either through deficiencies at interface details or through the façade itself, is likely to occur over the lifespan of a building. It has therefore been recently acknowledged within the building industry that drainage of wall assemblies should be provided behind the exterior surface of the building envelope. This reduces the risk of damage to structural parts of wall assemblies caused by infiltrated rainwater (Morrison Hershfield, 1996). Although drainage enhances the water management of wall assemblies by reducing the amount of water able to penetrate towards structural parts of wall assemblies and

*Corresponding author
Email address: stephanie.vanlinden@ugent.be
Postal address: Sint Pietersnieuwstraat 41, B4, 9000 Gent, Belgium

insulating materials, a portion of the infiltrated rainwater remains in the assembly after the occurrence of a rain event and drainage has occurred. This retained portion of infiltrated rainwater may affect the moisture management of the wall assembly and in turn, risk degrading the durability of the assembly. The degree to which the retained portion of water may affect and potentially degrade the durability can be evaluated by means of hygrothermal simulations.

To perform hygrothermal simulations from which to ascertain the water management of the façade, a moisture load to the wall assembly should be defined. This requires detailed knowledge of the wind-driven rain load on the wall, the percentage of water infiltrating in the wall assembly, the percentage of water being retained in the assembly after drainage, and the location of the retained portion of rainwater. A considerable number of studies have reported data on the wind-driven rain load onto (Blocken and Carmeliet, 2004, 2006; Van Den Bossche et al., 2013), and the percentage of water infiltration into wall assemblies (Calle et al., 2020; Lacasse et al., 2003, 2019; Recatala et al., 2018; Recatalá et al., 2020). However, the number of studies reporting information on the percentage of water retention or on the drainage performance of wall assemblies is, in general, limited.

The ASHRAE standard 160 (ASHRAE 160-Criteria for Moisture-Control Design Analysis in Buildings, 2016) proposes a default penetration rate of 1% of the wind-driven rain load on the exterior surface of the cladding. The default deposition site for this load is the water-resistive-barrier (WRB). Moore and Lacasse (Moore and Lacasse, 2020) determined that 1% of the wind-driven rain load is a reasonable assumption for the infiltration percentage through a 3,2 mm hole drilled into the corner of a window frame in a vinyl-clad wall assembly. However, 1% is an overestimation when drainage of the infiltrated rainwater is taken into account.

There is a need for more detailed knowledge on drainage and retention characteristics of wall assemblies to provide more accurate information on moisture loads for hygrothermal simulations. Therefore, an experimental study was developed to: (i) assess governing test methods to evaluate drainage characteristics; (ii) evaluate the impact of the cavity width on drainage and retention, and; (iii) assess the impact of surface characteristics of drainage materials on the drainage performance.

In this paper, a literature review is first provided on laboratory studies concerning the drainage performance of wall assemblies. Subsequently, the test method and results of the performed drainage tests are reported. The results give insight into the impact of the test parameters on the drainage characteristics and provide information on how the properties of the drainage cavity affect the drainage results. Finally, recommendations are put forward on the drainage test method and test metrics, and the results obtained in this study are compared with results reported in literature.

2. Literature review

2.1 Test method

Many damage cases of Exterior Insulated Finishing Systems (EIFS) reported in the 1980's – 2000 (Morrison Hershfield, 1996; Parliamentary Library, 2002; Rousseau, 1999) and the understanding of the necessity of providing drainage of wall assemblies have led to the development of a test standard to evaluate the drainage efficiency of EIFS; this standard is ASTM E2273 (E06 Committee, 2018). The drainage efficiency is defined as a percentage value based on the amount of water that has drained through the test specimen over the course of the test divided by the total amount of water sprayed onto the weather barrier of the specimen (Figure 1). According to this standard, the test specimen should be at least 1220 mm by 2440 mm. A water spray system should be installed in front of a slot fault (51 mm by 610 mm) constructed in the insulation board, lamina and other components. A total of 8 litres of water should be sprayed over a period of 75 minutes and the weight of drained water should be recorded at 15-minute intervals.

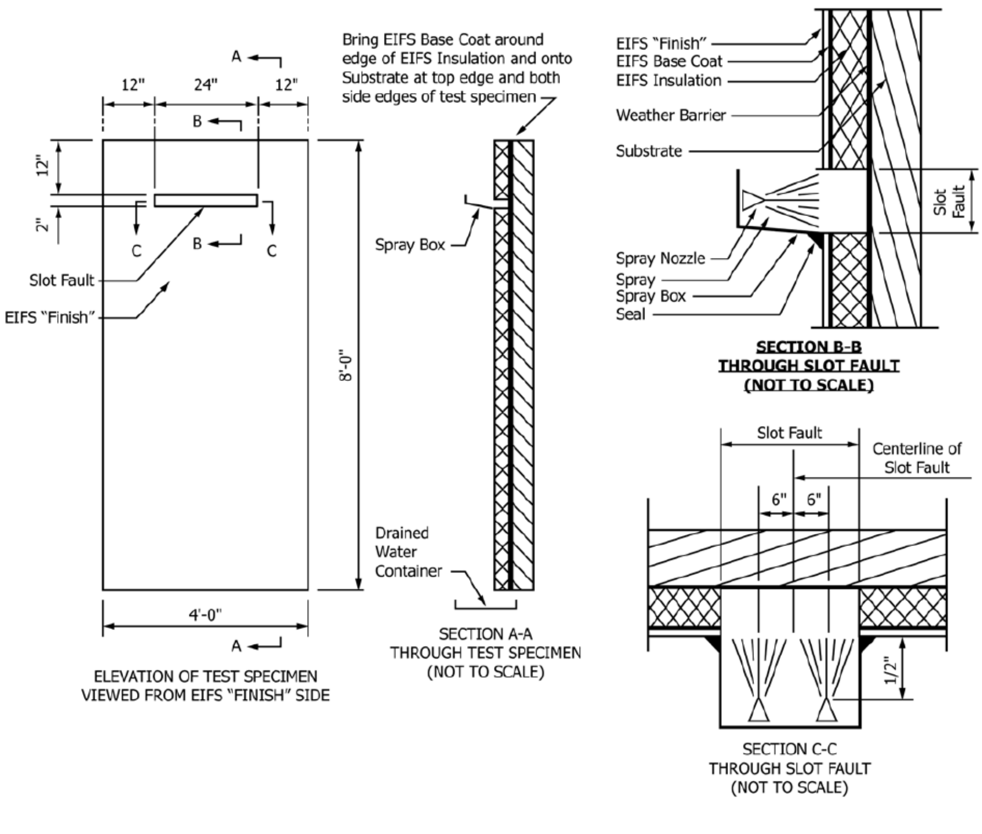


Figure 1: EIFS test specimen according to ASTM E2273 (E06 Committee, 2018)

However, drainage performance measurements reported in literature have adopted test methods that differ from the method described in the ASTM standard (see Table 1). These studies all have in common that a certain amount of water is injected into a wall assembly at a constant water flow rate, and that the drained water is collected over the course of the test. On the other hand, the studies differ in water delivery method, inlet width, total amount of delivered water, dosage rate, dosage time and test metrics.

The studies have either measured weight-related test metrics: (i) drainage efficiency and (ii) retained water, or time-related test metrics: (i) time before first water is drained, (ii) time to steady state of drainage, and (iii) drainage rate. Additionally, some studies have looked into leakage through the weather-resistive barrier (WRB) and drying time. Although the latter metrics provide valuable information on the durability of wall assemblies, these are out of the scope of the study reported in this paper.

Studies have shown that the same amount of retained water was reached for different amounts of water delivered to the test specimens (Straube and Smegal, 2007; Van Linden et al., 2018). This implies that a maximum amount of water can be retained by a wall system. Once this maximum is reached, the drainage efficiency will increase when more water is delivered to the system although the amount of retained water remains the same. It can easily be understood that a single system will have a drainage efficiency of 0% if the water ingress is smaller than the potential retention, but approaches 100% if the infiltration is orders of magnitude larger than the retention. It is therefore more relevant to measure the amount of retained water by weighing the test sample and measuring the change in weight over the course of the test.

Table 1: Overview of parameters of the applied drainage test methods in literature

	Specimen size [mm]	Water delivery method	Inlet width [mm]	Delivered water [l]	Dosage rate [l/h]	Dosage time [min]	Test metrics
ASTM E2273 (E06 Committee, 2018)	1220 x 2440	Two spray nozzles	610	7,95-8,745	6,36	75	Drainage efficiency
Williams - A (Williams, 2008)	1220 x 2440	Two spray nozzles	610	8,03	6,42	75	Drainage efficiency Time first water
Williams - B (Williams, 2008)	610 x 1220	Trickle dispensing	254	3,8	12,00	19	Time first water Leakage through WRB
Onysko (Onysko, 2007; Onysko and Thivierge, 2007b)	1220 x 2440	Trickle dispensing	610	8	8,00	60	Retained water Moisture mapping Drying time
Onysko and Thivierge (Onysko and	610 x 610	Trickle dispensing	Not reported	1,0 - 10	1,0 - 10	60	Retained water

Thivierge, 2007a)							
Moore and Nicholls (Moore and Nicholls, 2014)	1220 x 1830	Trickle dispensing	1220	3 - 8	3 - 8	60	Drainage/retention relation
Straube and Smegal (Straube and Smegal, 2007)	1220 x 2100 900 x 1800	Water pouring	1220 900	2 x 1,5 2 x 1,0	90,0	1	Retained water Drying time
Tonyan et al. (Tonyan et al., 1999)	305 x 1220	Static water head box	305	water head 102 +- 2 mm		9-975	Drainage rate Time first water Time to steady state
Leslie (Leslie, 2007)	850,9 x 1257,3	Static water head box	850,9	water head 13 mm		30	Drainage rate Leakage through WRB
Overton et al. (Overton, 2012; Overton et al., 2013)	1220 x 2440	Single dosing point	-	1,0	1,0	60	Retained water Moisture mapping Drying time

Time-related metrics provide insight into the extent to which injected water is able to flow freely and straight down towards the bottom of the test specimen or is obstructed by e.g. reduction in cavity width or material bridging the cavity, which may cause lateral movement of infiltrated water. Lateral movement may increase the wetted area within the cavity which may affect the durability of the assembly given that there is a risk of water reaching a deficiency in the drainage layer and can then permeate beyond the WRB. Overton (Overton, 2012) mapped the wetted area of test specimens by means of a capacitive moisture meter after drainage of injected water through a single dosing point. The moisture readings showed differences in lateral spreading for different materials in the drainage cavity. However, no specific area measurements were reported. Onysko and Thivierge (Onysko and Thivierge, 2007b) also detected moisture by means of a capacitance-based moisture meter and provided contours of the wetted area after a drying period of 48 hours. As expected, the regions with the highest moisture retention were located in the central part of the wall width. The authors suggest that to obtain more detailed information on the wetted area a closer spacing of measurement points could be used and the measurements could be conducted immediately after drainage has stopped and as well, once the weight of the specimen remains constant.

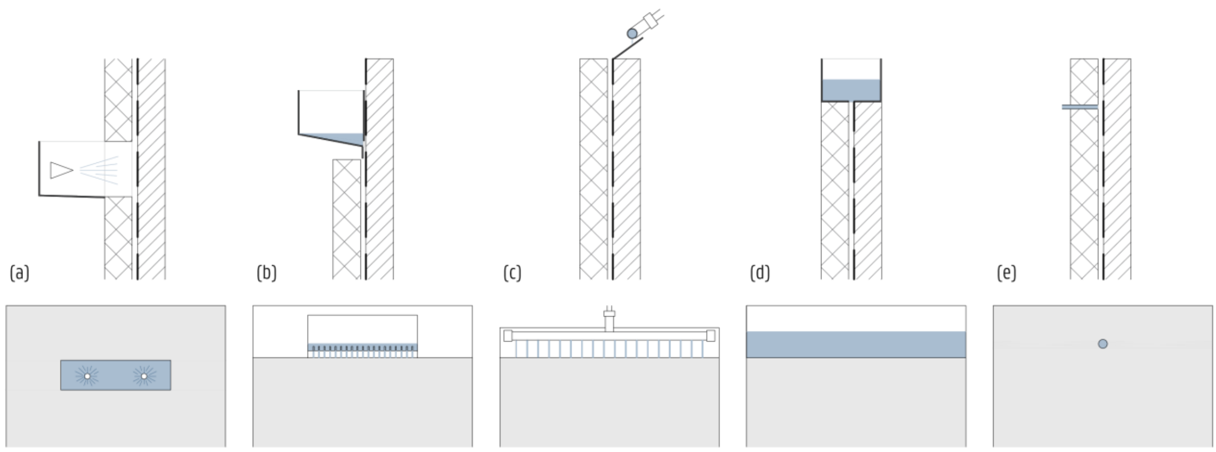


Figure 2: Schematic overview of inlet methods: (a) two spray nozzles (E06 Committee, 2018; Williams, 2008), (b) trickle dispensing trough (Onysko, 2007; Onysko and Thivierge, 2007a, 2007b), (c) trickle dispensing tube (Moore and Nicholls, 2014; Williams, 2008), (d) static water head box (Leslie, 2007; Tonyan et al., 1999), (e) single dosing point (Overton, 2012; Overton et al., 2013). Top: cross-section, Bottom; front view of top of test specimen

The reported studies also differ by the manner in which water is delivered to the test specimens. Delivering water to the test specimens was done by several means, including the use of two spray nozzles, a trickle dispensing method, pouring water in the cavity, a static water head box, or a single dosing point (Table 1 and Figure 2). In reality, rainwater most likely enters the drainage cavity through a local deficiency and therefore not over a relatively large horizontal length which is represented by spraying water onto the drainage layer, providing a hydrostatic head above the cavity or by pouring water in the cavity. Only when relatively large open joints (i.e. 8 mm) are present in the cladding, could wind-driven raindrops possibly be able to flow freely through the open joints and reach the drainage layer due to their kinetic energy, this scenario being representative of a sprayed water flow. This type of facade is however not the focus of the reported studies. These methods therefore provide information on the maximum retention and maximum drainage capacity of a system but do not provide information on the realistic behaviour of the flow of water in drainage cavities.

The trickle dispensing method on the other hand, and in particular a single dosing point, provide a more realistic scenario for water entering the drainage cavity, e.g. through local deficiencies at the sealed horizontal joint of a window-wall interface. By means of a trickle trough (Onysko, 2007; Onysko and Thivierge, 2007a) or a trickle tube (Moore and Nicholls, 2014; Williams, 2008) (Figure 2 (b) and (c)) water is provided through evenly spaced openings. When the inlet width is smaller than the width of the specimen, water is allowed to flow in the lateral direction and information can be obtained on the spreading of water in the cavity without the impact of the specimen edges.

Straube and Smegal (Straube and Smegal, 2007) found that the same maximum amount of retained water after drainage was reached for a dosage of 8 litres compared to a dosage of 4 litres or even smaller. Moore and Nicholls (Moore and Nicholls, 2014) on the other hand stated that for larger amounts of water deposited in the drainage cavity, a smaller proportion of that dosage was retained in the cavity. For most specimens however, the retained proportion remained within the same order of magnitude for a dosage of 1,2 litres compared to a dosage of 3,6 litres, suggesting that the maximum retention had been reached.

Moore and Nicholls (Moore and Nicholls, 2014) also found that the amount of retained water was not affected by the dosage rate of the delivered water to the specimens. The same conclusion was made by Onysko and Thivierge (Onysko and Thivierge, 2007a). They found that the order of magnitude of water retained at a dosage rate of 10 l/h and at a rate of 1 l/h was similar. Le Grand-Piteira (Le Grand-Piteira et al., 2006) on the other hand, reported different flow regimes for increasing flow rates for a liquid flowing down an inclined plane, i.e. individual drops, straight rivulets, meandering rivulets, dynamic rivulets and restable rivulets. Depending on the flow regime, a larger surface area will be wetted. Drops and straight rivulets flow straight down the plane, whereas meandering rivulets form small bends flowing over a wider surface area than the straight rivulet. Dynamic rivulets sweep from side to side over the plane, wetting an even larger area. Restable rivulets again flow straight down. This suggests that the amount of retained water in a specimen relative to the specimen area is dependent on the flow rate, when lateral spreading of the water in the cavity is not obstructed. As most studies report the measured retention quantities relative to the specimen area but not all studies applied an inlet width equal to the specimen width, lateral movements, or the lack thereof, may have affected the results.

2.2 Drainage test results

Studies concerning the drainage performance of wall assemblies either report weight-related data or time-related data. Weight-related data (Table A 1) is either the drainage efficiency, the absolute amount of water retained in the specimen, or the amount of retained water relative to the specimen area. In case only one of the metrics is reported but the inlet dosage and specimen area are known, the other metrics can be derived. However, due to differences in inlet dosage, inlet width and the lack of information on the wetted area, the results of one study cannot be directly compared to the results of another study.

Comparison of the drainage efficiencies reported in the different studies would be inaccurate due to the difference in total delivered amount of water to the specimen and the fact that it is unknown whether or not the maximum retention of the specimen was reached. For example, Onysko and Thivierge (Onysko and Thivierge, 2007a) reported an absolute retention of 12 g for a specimen consisting of EPS and a traditional housewrap after a total dosage of both 1 litre and 10 litres. This results in drainage efficiencies of 98,8% and 99,9% respectively.

Depending on the inlet width relative to the specimen width and the behaviour of the water in the cavity, the wetted area can be different from the total specimen area after drainage. This implies that the same amount of retained water per specimen area does not necessarily result in the same amount of retained water per wetted area. For example Onysko (Onysko, 2007) reported that the width of drained water at the bottom of an EPS with an EIFS specimen was similar as the inlet width, whereas dispersion of water over the entire width of a hardboard specimen was observed. Assuming that the wetted area of the EIFS specimen is 1,3 m^2 (projected area beneath inlet trough) and the wetted area of the hardboard specimen is 2,98 m^2 (entire specimen surface), the retained portion results in 56,9 g/m^2 and 41,5 g/m^2 respectively (considering the wetted area), whereas divided by the total specimen area this results in 24,9 g/m^2 and 41,5 g/m^2 respectively. Water spreading out over a larger surface area or being concentrated over a small area may have different consequences with regard to durability and the risk of reaching deficiencies in the drainage layer. This emphasizes the importance of knowledge of the behaviour of water in wall assembly cavities and the corresponding wetted area, and a normalisation procedure to report drainage test results.

Time-related data (Table A 2) is given as either the time before the first water is drained (TFW), the drainage rate, or the time it takes to obtain a steady state (TSS). Although the time to first water provides an indication of the drainage rate, the drainage rate over the course of the test or the time to steady state cannot be derived.

Although data from the different studies cannot be compared one on one, general observations can nonetheless be made. Williams (Williams, 2008) compared the performance of different drainage layer materials with and without plywood furring strips. Building paper (BP) and traditional housewraps (HW) provided little drainage without furring. Drainage-enhanced housewraps (DEHW) performed better and the highest drainage efficiency was measured for the drainage board (DB). Also with regard to the time before the first water is drained, the drainage-enhanced housewraps and drainage board performed better than the building papers and traditional housewrap. However, no specific information was provided on the characteristics of the drainage-enhanced housewraps and drainage board. Of all the tested specimens, the highest drainage efficiencies were found when plywood furring (PF) or a drainage mat (DM) was applied between the cladding and the drainage layer. Plywood furring with a thickness of 19 mm however, did not further increase the drainage efficiency compared to plywood furring with a thickness of 6,35 mm. This was also observed by Moore and Nicholls (Moore and Nicholls, 2014), who stated that a clear cavity of more than 10 mm did not necessarily improve the drainage capacity. They also stated that a clear cavity smaller than 10 mm may perform sufficiently depending on the materials that define the drainage cavity. The same conclusion was made by Straube and Smegal (Straube and Smegal, 2007) and Onysko and Thivierge (Onysko, 2007; Onysko and Thivierge, 2007a). Even small drainage cavities of less than 1 mm can drain significant amounts of water. Straube and Smegal performed initial tests on an idealized wall comprising a small gap of 1 mm between two stiff acrylic sheets. It was found that the 1 mm gap stored significantly less water than a single acrylic sheet, 24 g/m^2 and 65 g/m^2 respectively. This suggests that a very small gap may store less than a large gap. However, based on the results obtained no correlation was found between the cavity width and the amount of water retained in the cavity, as the retained amount was primarily affected by the materials defining the cavity.

Filling the cavity with a drainage mat, either a nylon mat or a dimpled mat, did not necessarily result in lower amounts of retained water compared to a clear cavity, either providing gravity or capillary drainage. For example Straube and Smegal (Straube and Smegal, 2007) measured a retained amount of water of 129,7 g/m^2 for a cavity defined by vinyl siding direct applied to a traditional housewrap, compared to a retained amount of 141,5 g/m^2 for a cavity filled with a dimpled drainage mat with an equivalent cavity of 3 mm and vinyl siding. Onysko (Onysko, 2007) found similar results. For a specimen with hardboard siding directly applied to a traditional housewrap the retained amount measured 123,5g compared to 231 g and 284 g for specimens with a channelled drainage mat with a thickness of 6,7 mm and a nylon mat with a thickness of 6,9 mm respectively. It was suggested that the drainage mats dispersed the water draining in the cavity, wetting a larger area of the specimen. Overton et al. (Overton, 2012; Overton et al., 2013) also performed drainage tests for specimens with and without nylon drainage mat. For both absorptive and non-absorptive cladding materials, the specimens with drainage mat retained more water compared to the specimen with a clear cavity, i.e. 55 g compared to 32 g for non-absorptive cladding and 494,5 g compared to 332,5g for absorptive cladding. The moisture mapping did not, however, show any difference in lateral spreading of the retained water for the specimen with and without drainage mat. Only the specimen with a textured drainage-enhanced housewrap showed a more extensive, wider spreading of the retained water. The moisture readings showed that the drained water spread out over a larger area for a textured housewrap compared to an open cavity, nylon mesh drainage mat, or a 6 mm channelled drainage mat. Bassett et al. (Bassett et al., 2015) also found that a larger percentage of water was retained in the insulation when a drainage mat with a thickness of 6 mm, consisting of polyester filaments, was applied in between a weatherboards cladding and insulation (approx. 8%) compared to direct-fixed weatherboards on a traditional housewrap (approx. 3%). When the drainage mat was fixed to a filter fabric on the other hand, no water was retained in the underlying insulation.

Straube and Smegal (Straube and Smegal, 2007) performed tests on smooth non-absorptive materials to determine the impact of the hydrophobicity of the materials on the amount of retained water on the surface. They applied a fine spray of water on a vertical sheet of polyethylene and an acrylic sheet. Three tests were performed and the results were averaged. The polyethylene sheet retained 35 g/m^2 whereas the acrylic sheet retained 65 g/m^2. Although both materials were smooth and hydrophobic (i.e. a contact angle (CA) larger than 90°), it was hypothesized that the larger hydrophobicity of the polyethylene sheet resulted in a smaller retained amount. Blocken and Carmeliet (Blocken and Carmeliet, 2006) also conducted a study to evaluate the impact of the hydrophobicity on the amount of water adhered to a vertical surface after being wetted. Materials with a contact angle ranging from 14,5° to 106,6° were evaluated. No clear correlation was found between the contact angle and the amount of water retained to the surface. However, in contrast with Straube and Smegal (Straube and Smegal, 2007), more water was retained on hydrophobic surfaces (CA > 90°) compared to hydrophilic surfaces (CA < 90°).

3. Test methodology

Based on the reviewed studies a drainage test setup was developed to evaluate the impact of, on the one hand, different test parameters with regard to the drainage test method, and on the other, the impact of the characteristics of the test specimens. The following test parameters were varied: total dosage, dosage rate and water delivery method, and the impact on the amount of retained water, wetted area and spreading of the water was evaluated. The assessed characteristics of the specimen were the: cavity width, contact angle or hydrophobicity, and the texture of the drainage layer and drainage mats.

3.1 Test setup

Test specimens of either 600 x 600 mm or 600 x 450 mm were suspended from two weighing scales to measure the weight of the wetted specimen over the course of the test. An inlet tray was attached to the back of each sample. Water was delivered to the specimen from a water supply tank with a constant water head. The water supply tank was connected by means of a flexible tube either to a copper tube with multiple openings or a single tube with different outlet diameters. The copper tube included 10-12 evenly spaced (20 mm on centre) openings with a diameter of 2 mm. The single tubes had diameters of 1,8; 2,5 and 6 mm. A valve was installed between the supply tank and the copper tube or single tube to start and stop water delivery. The drained water was collected at the bottom of the specimen and weighed over time by means of a third weighing scale. The weighing scales had an accuracy of 0,1 g.

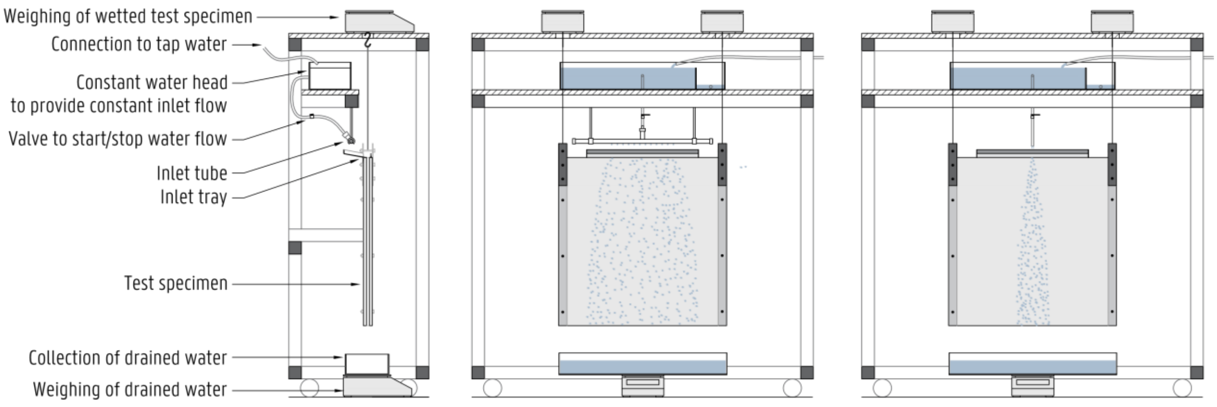


Figure 3: From left to right: Cross-section of test setup; Front view of test setup with wetted test specimen by means of copper tube; Front view of test setup with wetted test specimen by means of single tube

3.2 Test program and procedure

To provide insight into the impact of different test parameters, first the total dosage, dosage rate and inlet method were varied. The test specimen consisted of two polycarbonate panels with a cavity width of 10 mm. The total dosage ranged from 1 to 4 litres. One litre was chosen as a minimum based on the dosage amounts applied in literature. The dosage was delivered through multiple openings by means of the copper tube described in section 3.1. Afterwards, the inlet method was varied, i.e. multiple entry points by means of the copper tube, a stationary single entry point and a single entry point moving along the same width as the width of the multiple entry points. The dosage rate was varied by changing the height of the constant water head in the water supply tank and the diameter of the inlet tube. Based on the results obtained, the test parameters of the subsequent tests were established.

Table 2: Summary of test matrix

Test variable	Materials	Cavity width (mm)	Inlet method	Dosage rate (l/min)	Total dosage (l)
Total dosage	Polycarbonate	10	Multiple	0,455 ± 0,003	1; 2; 4
Dosage rate - inlet method	Polycarbonate	10	Multiple - single - moving single	0,032 - 0,577 per entry point	2
Cavity width	Polycarbonate	1; 2; 3; 5; 10	Multiple	0,693 ± 0,006	2
Contact angle	Formwork plywood, PMMA, traditional housewrap, PE-foil, PMMA with hydrophobic coating (CA: 45°-124°)	Single panel	Multiple	0,693 ± 0,006	2
Texture - drainage medium	Traditional housewrap, drainage-enhanced housewrap, nylon drainage mat, polycarbonate	1; 2; 5; 10	Single	0,090 ± 0,001	1

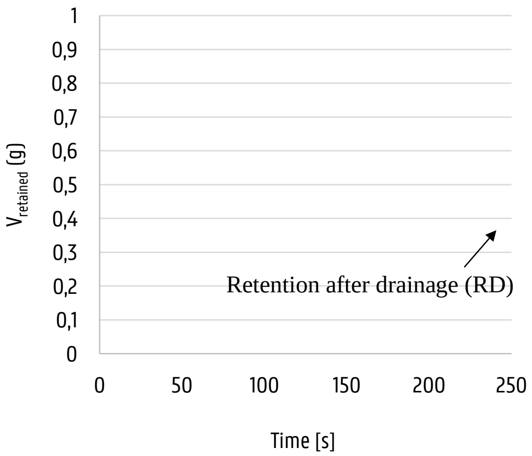
The following test procedure was applied:

1. The test specimen was suspended from two weighing scales and verticality was assured.
2. The water supply tank was filled with tap water. Filling continued over the course of the test.
3. The weighing scales to weigh the retained and drained amount of water were turned on.
4. The valve was opened when a constant water head in the supply tank was reached.
5. Immediately after opening the water flow valve, water started to flow in the specimen cavity or ran off a single panel at the required flow rate.
6. When the required total dosage was reached, the valve was closed.
7. Weighing measurements stopped when drainage was finished and the weight of the retained and drained water remained constant.
8. Pictures were taken of the wetted specimen to determine the wetted area (A Nikon D5000 camera was used for this purpose).
9. Each test was repeated at least three times.

The metrics used to characterize the drainage performance of the specimens were:

- the change in weight of the specimen over the course of the test ($V_{retained}$ [g])
- the Retention of water after Drainage (RD [g]),
- the Wetted Area of specimen (WA [m^2]),
- the Retention of water after Drainage relative to the Wetted Area (RDWA [g/m^2]),
- the maximum lateral spreading of water (L_{spread} [mm/mm]), which was always measured at the bottom of the test specimen.

The wetted area of the specimen (WA) was determined by drawing the largest perimeter enveloping the retained drops on the specimen using Autodesk Autocad. The largest perimeter was always situated at the back panel of the specimen, which is not surprising as water is supplied to the cavity along this panel. The wetted area of the front panel relative to the wetted area of the specimen varied for different tests. The absolute retained amount (RD) measured by weighing the difference in weight of the specimen after drainage was then divided by the wetted area (WA) to obtain the amount of retained water relative to the wetted area (RDWA). The spreading of the water was defined as the lateral movement of the water relative to the inlet width over the height of the specimen and was obtained by subtracting the inlet width from the spreading at the bottom of the specimen and dividing the difference by the height of the specimen (Figure 4).



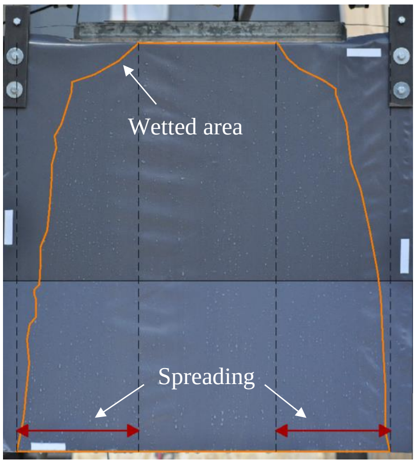


Figure 4: Left: Typical curve of amount of water on specimen during the test and after drainage resulting in the retained amount of water; Right: Picture of PE-foil specimen showing perimeter of wetted area and lateral spreading of water

4. Test results

4.1 Evaluation of test method

The literature review showed that the total dosage, the applied dosage rate and the water delivery method differed from study to study. Therefore, the impact of varying these test parameters on the retention characteristics was evaluated.

Figure 5 shows the change in weight of three individual tests on a polycarbonate specimen with a cavity width of 10 mm and a total dosage of 2 litres. After each test, the specimen was removed from the setup, cleaned and dried by means of tap water and a paper towel. The figure shows that the test procedure provides repeatable results. Small peaks are visible due to lateral movement of the rivulets flowing over the specimen surface leaving behind drops of water and the associated increase in wetted area and movement of the suspended specimen.

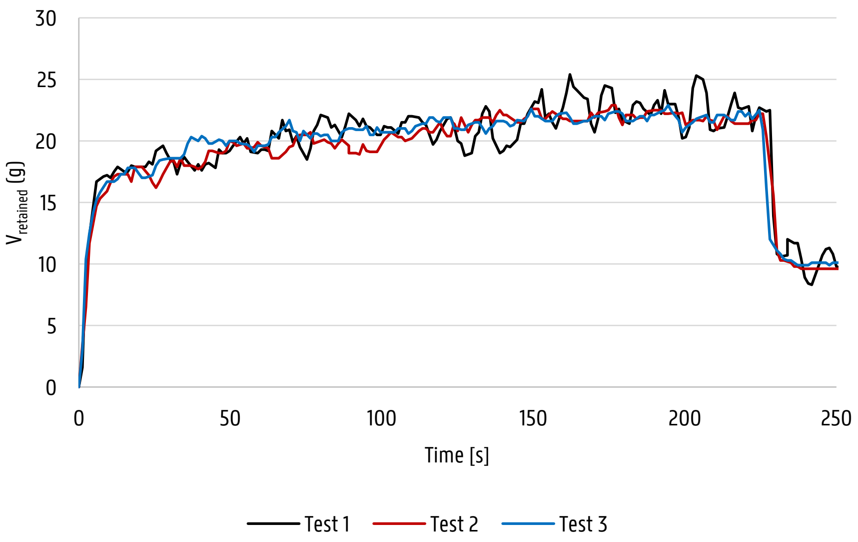


Figure 5: Change in weight of three tests on a polycarbonate specimen with a total dosage of 2l

Inlet dosages of 1, 2 and 4 litres were applied at a flow rate of 0,4552 ± 0,0034 l/min by means of the copper tube with 10 openings to a specimen consisting of two polycarbonate panels and a cavity of 10 mm. Figure 6 shows that independent of the total amount of delivered water to the specimen, the change in weight of the test specimen reaches the same maximum value over the course of the test. As the flow rate is constant and identical for each test, the amount of water adhered to the panel during the test also reaches the same maximum value independent of the total dosage. Based on Figure 6 one can conclude that the retained amount of water after drainage (RD) is higher for a dosage of 4 litres compared to a dosage of 1 litre. In contrast, when evaluated relative to the wetted area (Figure 7), the retained amount (RDWA) decreases for an increase in dosage. Over time, a larger area is wetted by lateral movement of the rivulets flowing over the surface which compensates the larger value of the RD. The difference in RDWA after a dosage of 1 litre or 4 litres is however, not significant (p>0,05). This implies that the same maximum RDWA of the polycarbonate specimen with a cavity of 10 mm was reached after dosages of 1, 2 and 4 litres. The maximum retained amount was reached in a relatively short time as only non-absorptive materials were evaluated. In case of absorptive materials, the time before maximum retention is obtained might be longer and hence the total required dosage should be larger.

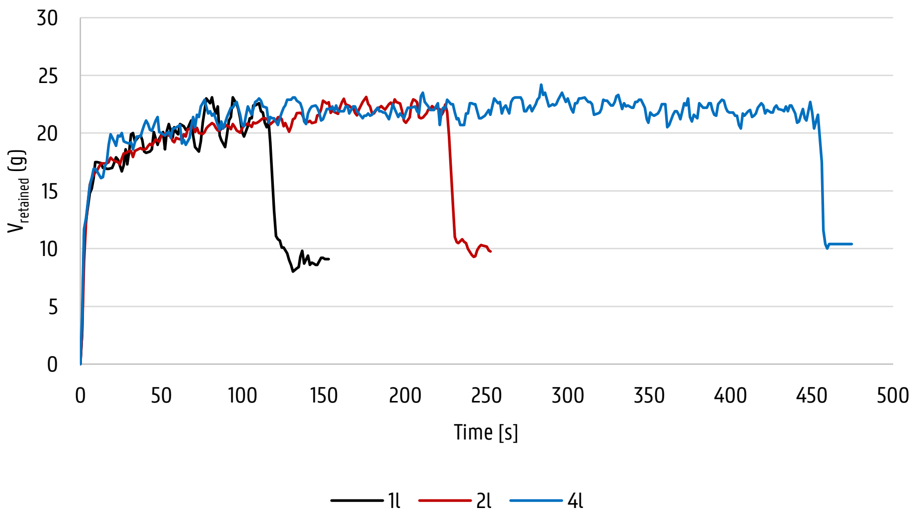


Figure 6: Change in weight of a polycarbonate specimen with a 10 mm cavity for inlet dosages of 1, 2, and 4 litres

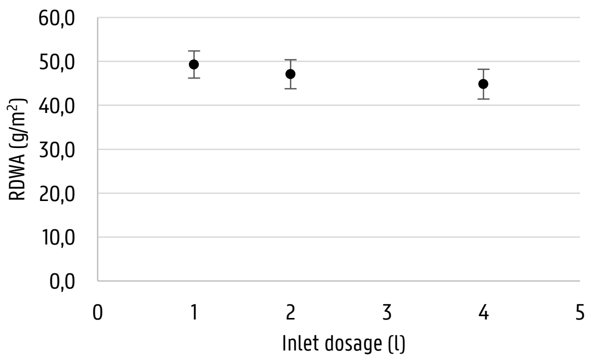


Figure 7: Amount of retained water relative to the wetted area of a polycarbonate specimen with a 10 mm cavity for inlet dosages of 1, 2, and 4 litres

In the following test series, the total dosage was fixed to 2 litres but the flow rate and inlet method were varied. The flow rate was varied between 0,038 ± 0,001 l/min and 0,577 ± 0,001 l/min per entry point. A single entry point at a fixed position, multiple entry points by means of openings in the copper tube over a length of 240 mm, and a single entry point moving over a width of 240 mm were applied. All tested flow rates and inlet methods resulted in rivulets flowing over the polycarbonate surface of the specimen with a cavity width of 10 mm leaving behind a trail of drops.

Le Grand-Piteira et al. (Le Grand-Piteira et al., 2006) defined different rivulet flow regimes dependent on the flow rate. The onset for meandering was determined at a flow rate of 0,028 l/min for a vertical PMMA panel (advancing θa and receding θr contact angle of 70° and 35° respectively) and the onset for the dynamic regime was determined at a flow rate of 0,080 l/min. Preliminary tests conducted by the authors of this study showed that the onset for meandering on a vertical polycarbonate panel (θa = 83,3° ± 1,5° and θr = 48,7°± 1,5°) was 0,030 l/min and the onset for the dynamic regime was 0,087 l/min. This implies that the rivulets generated by means of multiple entry points were of the meandering type and the rivulets generated by means of the single tube were dynamic.

The rivulets flowing from the copper tube with multiple entry points were relatively stable meanders at the top of the specimen. However, as the distance between the entry points was shorter than the lateral spreading of the meanders, the stable form of rivulets was disturbed and unstable meanders flowed over the main part of the specimen surface (Figure 8 (a)). The dynamic rivulets from the single entry points can be further subdivided into an unstable regime with a garden hose-like stream sweeping over the surface observed at a flow rate of 0,090 ± 0,001 l/min (Figure 8 (b)), small braid at the top of the stream and an unstable but sinus locus with an almost constant width observed at a flow rate of 0,292 ± 0,004 l/min (Figure 8 (ac) and a wider braid over a longer length reaching an almost restable regime observed at a flow rate of 0,577 ± 0,001 l/min (Figure 8 (d)) (Le Grand-Piteira et al., 2006; Nakagawa, 1992).

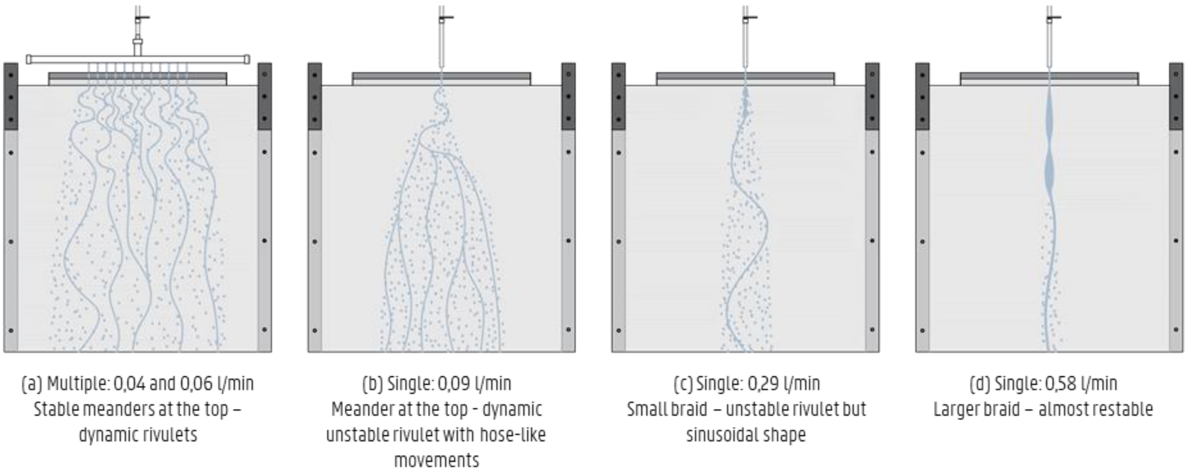


Figure 8: Observed rivulet flow regimes for increasing flow rate

The different flow rates and respective regimes resulted in differences in RD and differences in lateral spreading of the rivulets. For an increase in flow rate, a decrease of the RD and a decrease in the lateral spreading of the retained drops was observed. Only for the moving entry point, the spreading remained constant for increasing flow rates. It is hypothesized that movement of the inlet point caused disturbances in the sinusoidal shape of the rivulets resulting in rivulets flowing straight down. It should be noted that the specimen inlet tray with the moving tube was installed in the cavity instead of at the back of the specimen. This resulted in a larger retained amount on the front panel relative to the other specimens and thus a larger RDWA (Figure 9).

The decrease in RD and decrease in wetted area for a fixed single entry point and multiple entry points resulted in a constant RDWA. For the moving entry point a decrease of the wetted area for increasing flow rate was apparent (Figure 9).

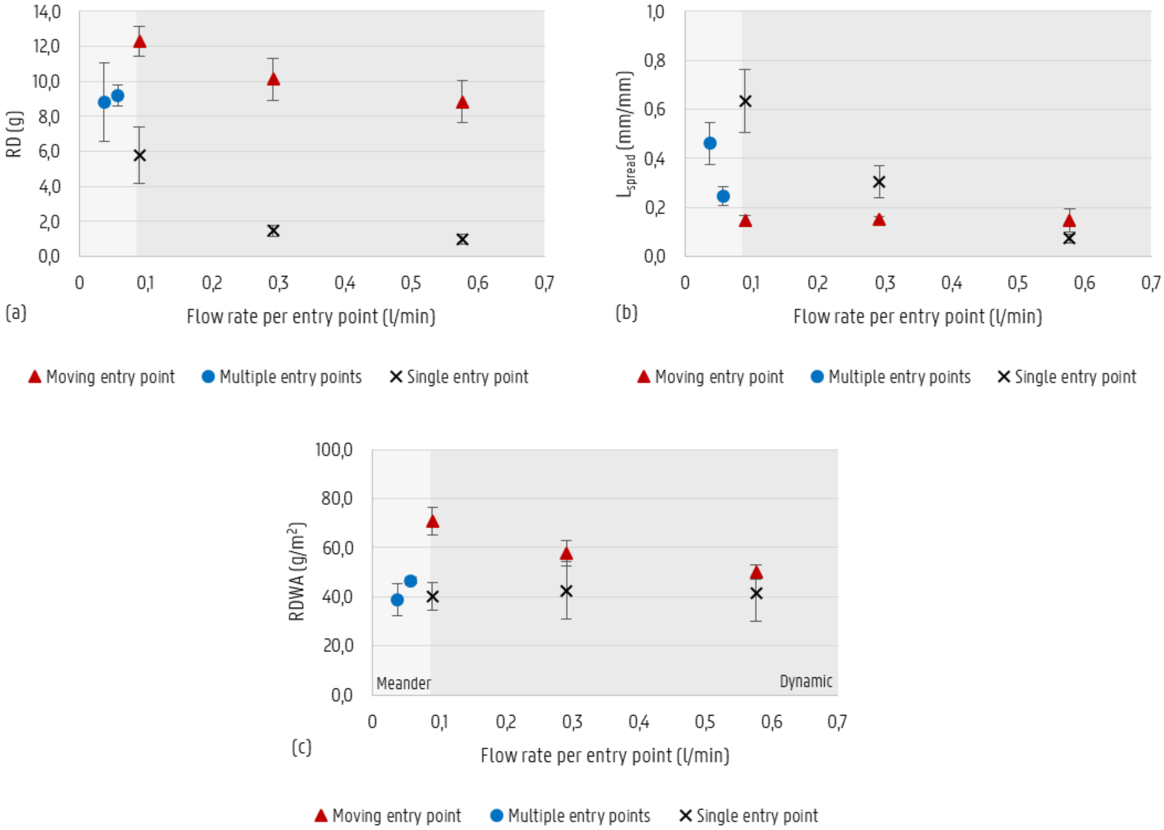


Figure 9: (a) Retained amount after drainage (RD), (b) Lateral spreading of the retained drops over the height of the specimen, (c) Retention after drainage relative to wetted area (RDWA) in a polycarbonate specimen with a cavity width of 10 mm for varying inlet method and flow rate

Based on the results obtained as discussed above, and infiltration rates obtained from laboratory studies (Lacasse et al., 2019), the subsequent tests were conducted at a flow rate of 0,057 ± 0,001 l/min for multiple entry points (a total flow rate of 0,693 ± 0,006 l/min), or a single entry point with a flow rate of 0,090 ± 0,001 l/min. When the RDWA was the primary test metric of interest, multiple entry points were applied. A larger wetted area is generated by multiple entry points, reducing the relative impact of irregularities in the spreading of the rivulets and therefore reducing the error on the results. When the spreading of the retained drops was the primary metric of interest, a single entry point was applied. The single entry point allows the rivulet to flow in the cavity without any disturbances from adjacent rivulet flows. This represents the realistic behaviour of infiltrated water in a cavity through a deficiency in the cladding (L Olsson, 2016).

4.2 Evaluation of drainage cavity characteristics

4.2.1 Cavity width

Straube and Smegal (Straube and Smegal, 2007) suggested that a large cavity may retain more water than a small cavity. The impact of the cavity width on the retention after drainage (RD and RDWA), the spreading of water in horizontal direction, as well as bridging the cavity was therefore further investigated. Water was drained in a polycarbonate specimen with cavity widths of 1, 2, 3, 5 and 10 mm. Spacers were applied at the right and left edge of the specimen as well as small spacers along the centre line to ensure a uniform cavity width.

Similar trends were observed for the RD, the RDWA and the lateral spreading of the retained drops. The retained amount, both RD, RDWA and the lateral spreading increased for an increase in cavity width up to a width of 3 mm and decreased for cavity widths of 5 and 10 mm. The smallest retained amount and spreading was observed for a cavity width of 1 mm (Figure 10 (a), (b), (c)).

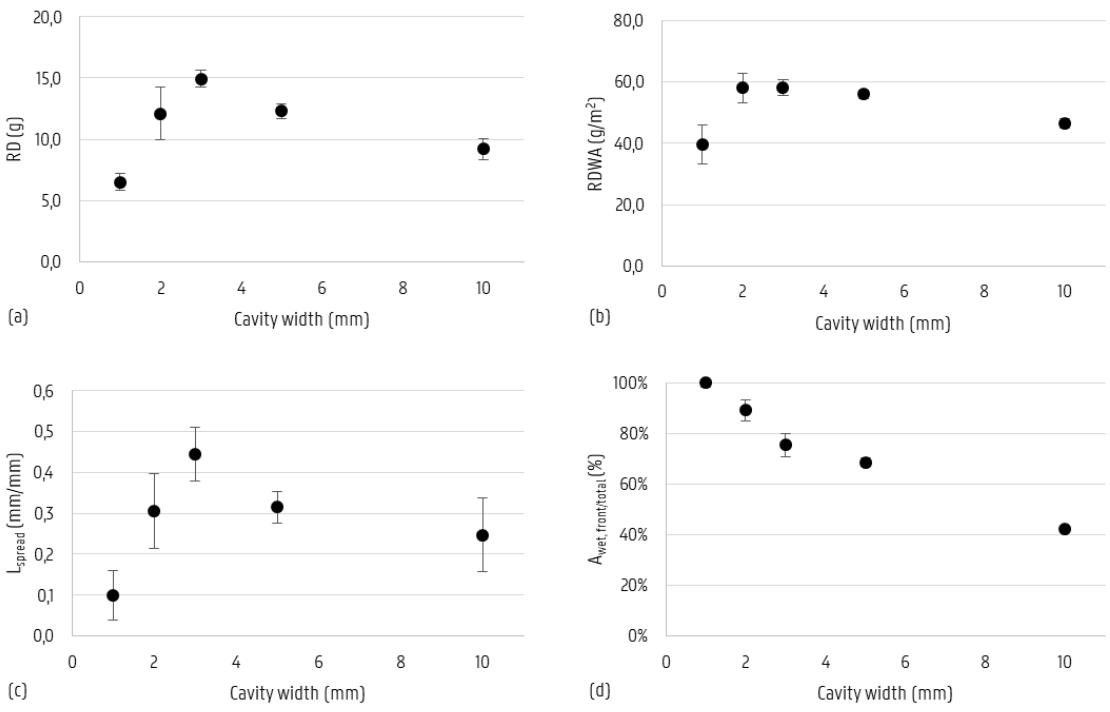


Figure 10: (a) Retained amount after drainage (RD), (b) Retention after drainage relative to the wetted area (RDWA), (c) Lateral spreading of retained drops relative to specimen height and (d) Wetted area of front panel relative to the wetted area of the specimen (WA) for a polycarbonate specimen with varying cavity width

Rivulets flowing along one side of the 10 mm cavity only bridged the cavity when splashed open on the centre line spacers. It is assumed that when no spacers were positioned in the centre line, the ratio of wetted area of the front panel (the panel opposite to the inlet) to the wetted area of the test specimen (which is equal to the wetted area of the back panel) would be close to zero. The wetted area of the front panel relative to the wetted area increased for decreasing cavity width and became 100% for a cavity width of 1 mm, meaning that the wetted area of the front panel was the same as the wetted area of the back panel (Figure 10 (d), Figure 11).

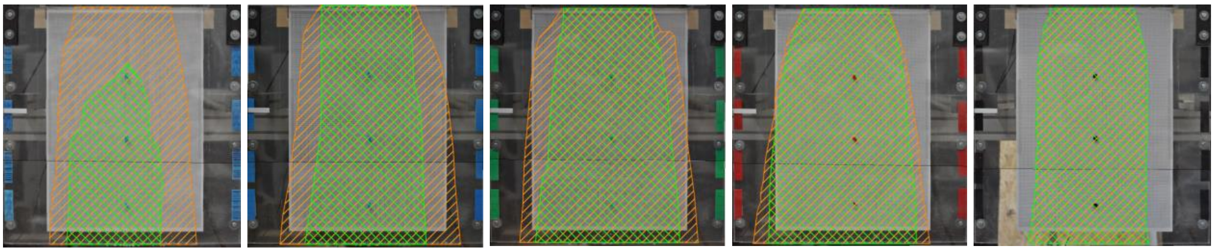


Figure 1: Wetted area of front panel (green) and total wetted area (orange) for cavity widths of 10, 5, 3, 2, 1 mm (from left to right)

Rivulets flowed simultaneously along both the front and back panel for a cavity width of 1 and 2 mm. For cavities of 3, 5 and 10 mm, rivulets flowed either along the front or the back panel. The width of the rivulet in the 2 mm cavity was relatively small (< 1 mm) whereas the width of the rivulet in the 1 mm cavity was significantly larger (> 3 mm). The rivulet spreads in the 1 mm cavity to accommodate the imposed flow resulting in a larger width relative to the 2 mm cavity and a reduced velocity (McCreery et al., 2007). As the size of droplets caused by the tail of the rivulets reduces with the velocity (Le Grand et al., 2005), the retained amount for a cavity of 1 mm is smaller than the retained amount for a cavity of 2 mm and larger. Most retained drops after drainage adhered either to the front or the back panel. Only a limited number of drops were held between both panels with a 1 mm cavity by capillarity.

4.2.2 Contact angle

The impact of the hydrophobicity of drainage materials on the retained amount of water and the lateral spreading of the retained drops was evaluated by means of the following materials with these respective static contact angles:

- Formwork plywood 45,1 ± 3,2°
- PMMA with hydrophilic coating 57,2 ± 1,0°s
- PMMA 74,6 ± 0,9°
- Traditional housewrap 89,5 ± 3,0°

- PE-foil 101,9 ± 1,7°
- PMMA with hydrophobic coating 123,8 ± 1,4°

Contact angle measurements were performed using a goniometer (Krüss Drop Shape Analyzer DSA25S) and the sessile drop method. The goniometer dispensed droplets of demineralised water with a volume of 2 µl onto the contact surface. The contact angles were determined by means of the Drop Shape Analysis (DSA4) software set to measure the contact angles using the Young-Laplace fitting method.

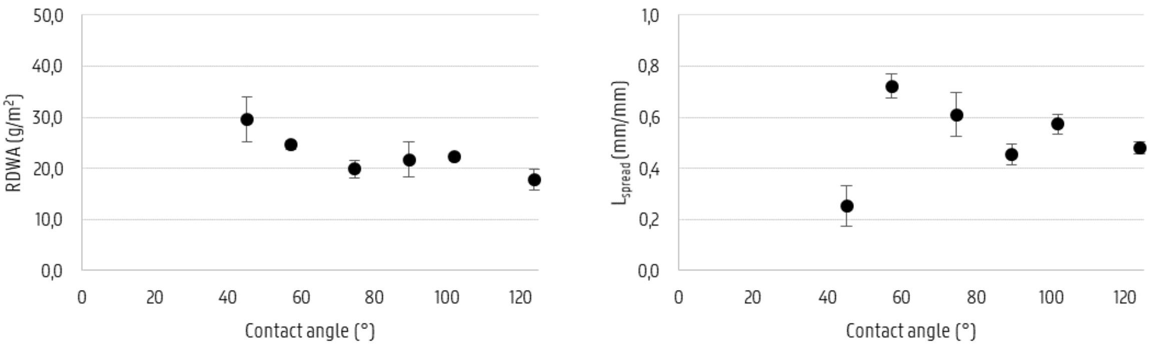


Figure 12: Retention after drainage relative to the wetted area (RDWA) (left) and spreading of the retained droplets over the height of the specimen (right) for materials with varying contact angle

The introduced rivulets onto the hydrohilic plywood specimen flowed almost straight down due to the increased pinning forces preventing meandering, whereas the rivulets flowing on the PE-foil or the PMMA-surface with hydrophobic coating were considerably more dynamic and swept over the surface, resulting in a larger spreading of the retained drops (Figure 12, right). The specimen with the lowest measured contact angle, i.e. formwork plywood (θ=45,1°), resulted in the highest measured RDWA and the specimen with the highest measured contact angle, i.e. PMMA with hydrophobic coating (θ=123,8°), resulted in the lowest RDWA (Figure 12 left). For the specimens with intermediate contact angles, no significant differences were measured for the RDWA.

Additional tests were performed on a housewrap with a contact angle of 115,6 ± 4,4° and a textured surface. A cross-section and picture of the textured surface is shown in Figure 13. The total thickness of the housewrap (0,60 mm) is locally lowered up to a thickness of 0,24 mm. The recessed parts have an ellipse shape with an area of 0,5 mm^2. Rivulets flowing over the surface enter the recessed parts, increasing the adhesion of the rivulet to the surface (Feng et al., 2008). This resulted in a lateral spreading of close to zero and an RDWA of 83,25 ± 13,19 g/m^2, which is significantly larger than that for the PE-foil or PMMA with hydrophobic coating (PMMA had a static contact angle in the range of the contact angle for the dry textured housewrap). This implies that the surface texture of WRBs may have a significant effect on their drainage characteristics. The increase in retained amount can be primarily attributed to the filled ellipse shaped recessions after drainage. The reduction in lateral spreading is assumed to be caused by the surface texture which results in an increased adhesion of water to the surface. However, further research is necessary to verify this hypothesis.

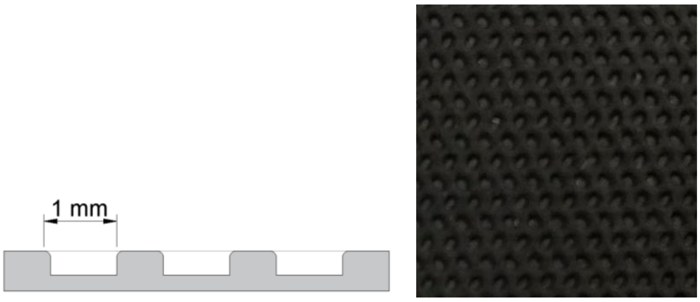


Figure 13: Cross-section and picture of ellipse-shaped recesses of textured housewrap

4.2.3 Surface texture and drainage mat

The retained amount of water and lateral spreading was compared for the following drainage materials having different surface textures (Figure 14):

- a traditional housewrap (spunbonded polyolefin),
- a deficient housewrap: the housewrap was not installed perfectly flat, resulting in a waved surface with changes in thickness of approximately 0,4 mm,
- a drainage-enhanced housewrap incorporating vertical grooves with a depth of 0,68 mm and
- the combination of a housewrap with a nylon drainage mat (thickness of 10 mm).

These materials were all applied as drainage layer and the front panel consisted of a polycarbonate panel. Cavity widths of 1, 2, 5 and 10 mm were evaluated.

Figure 14: From left to right: Traditional housewrap, drainage-enhanced housewrap and housewrap with drainage mat

The retained amount of water after drainage (RD) was larger for a deficient housewrap compared to a flat housewrap for a cavity width of 1 mm and 2 mm (Figure 15 (a)). However, due to a larger spreading of the water caused by the waved surface of the deficient housewrap, the retention relative to the wetted surface (RDWA) of the deficient housewrap was within the same range as the RDWA of the flat housewrap (Figure 15 (b)). For a cavity width of 5 mm or larger, the effect of the waved surface of the deficient housewrap on the retention may be considered negligible.

At a cavity width of 10 mm, the RD of water on the specimen with a drainage mat was not significantly more or less than the RD on the traditional housewrap. The RD on the drainage-enhanced housewrap, however, was less than the RD on the traditional housewrap. In contrast, the RDWA on the drainage-enhanced housewrap was within the same range as the traditional housewrap, whereas the RDWA on the specimen with drainage mat was significantly larger. This emphasizes the importance of not only considering the absolute retention (RD) but also the retention relative to the wetted area (RDWA).

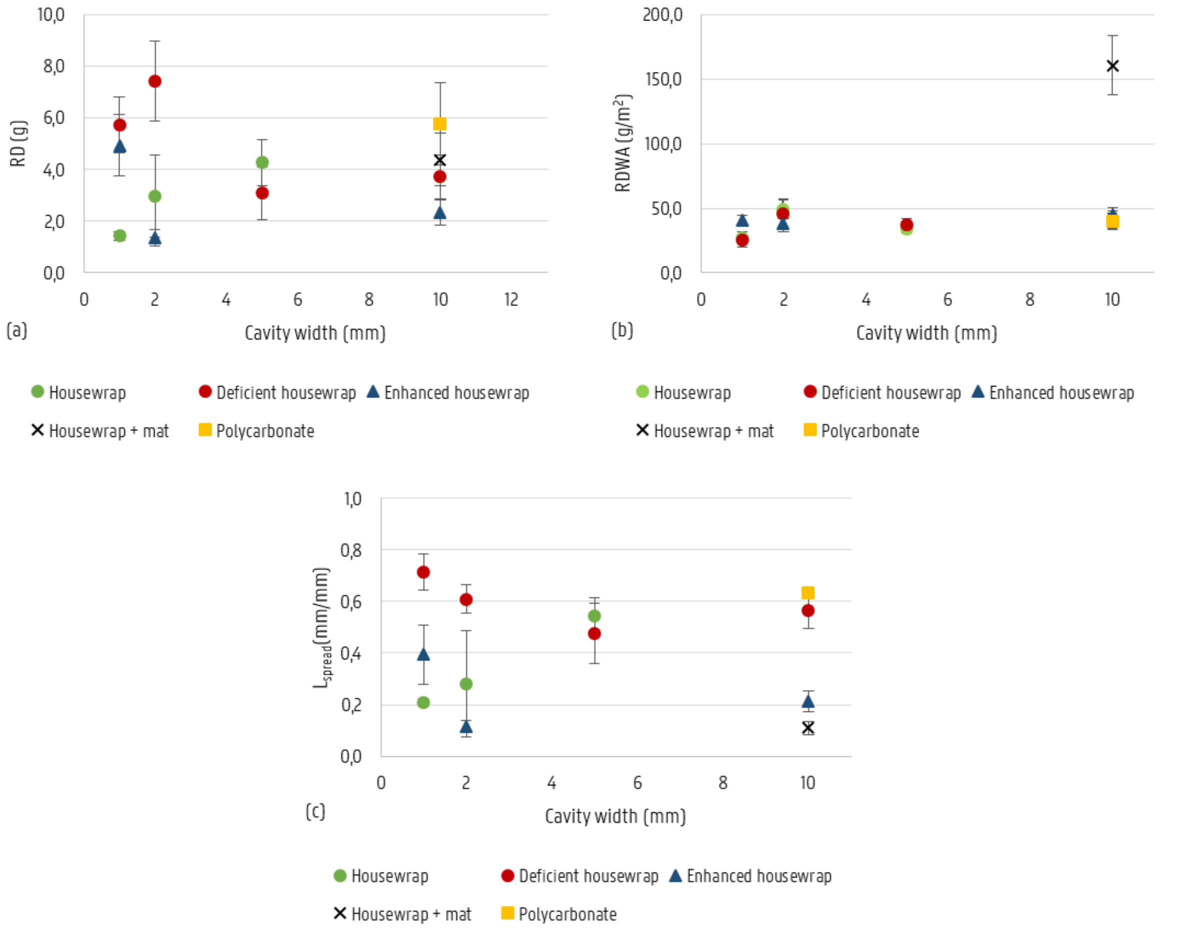


Figure 15: (a) Retained amount after drainage (RD), (b) Retention after drainage relative to the wetted area (RDWA), (c) Spreading of the retained drops over the height of the specimen for drainage layer materials with varying texture and nylon drainage mat

The rivulets on both the specimen with drainage-enhanced housewrap and specimen with drainage mat flowed, to a greater extent, straight down compared to the specimen with traditional housewrap and polycarbonate at a cavity width of 10 mm. Both the nylon mesh and the grooved surface of the enhanced housewrap disturbed the anticipated sinusoidal shape of the rivulets on a smooth surfaces, which results in a smaller spreading of the retained drops.

The smallest RDWA values were measured for the specimens with traditional housewrap either with a flat surface or a waved surface, at a cavity width of 1 mm. Similar to that which was achieved with the polycarbonate specimens, as was discussed in section 4.2.1, the specimens with traditional housewrap and a cavity of 1 mm retained less water than the specimens having a cavity of 2 mm. For the specimen with drainage-enhanced housewrap there was, however, no difference between the RDWA for a 1 mm cavity compared to a 2 mm cavity. The reduced cavity width at the top of the grooves of the drainage-enhanced housewrap resulted in capillary held water. Water was not able to spread out as much as in the specimen with deficient housewrap. The grooves caused locally larger reduced cavity widths than the deficient housewrap resulting in a larger retained amount.

5. Discussion

5.1 Test method

As was mentioned in the literature review, different test methods have been applied measuring either weight-related or time-related metrics. The present study focused on weight-related metrics as these can be applied as input for hygrothermal simulation.

Previous studies in which the drainage performance of wall assemblies was evaluated have reported the drainage efficiency or the amount of retained water either in absolute values or relative to the specimen area. The results of this study confirm the finding of Straube and Smegal (Straube and Smegal, 2007) that a maximum amount of water can be retained by a wall system, independent of the total amount of delivered water. This implies that once the maximum retention is reached, the drainage efficiency will increase when more water is added to the specimen. Comparing this result with the efficiency of a specimen that has not reached maximum retention would be incorrect. It is thus, more relevant to measure the retained amount of water by weighing the change in weight of the specimen over the course of the test. In this study the maximum retention was already reached after a dosage of 1 litre as the retained amount was the same for a dosage of 1 litre, 2 and 4 litres. It should be noted that only non-absorptive materials were used and the specimens were relatively small (600 x 600 mm). It is recommended to monitor the change in weight of the specimen during the test and to only stop the test when the weight remains constant for a significant period of time (e.g. > 1 minute). The total required dosage for subsequent tests should then be chosen based on the results obtained from the tests.

The absolute retained amount of water measured after drainage (RD) represents the combined effect of the retained amount in the specimen and the lateral spreading of the retained water. The results of this study showed the importance of measuring both the retained amount of water relative to the wetted area (RDWA) and the lateral spreading of the water (L_{spread}) separately to characterise the drainage performance of a wall assembly. The wetted area (WA) was determined by the perimeter enveloping the retained drops on the specimen after drainage. For every test, the front panel representing the cladding, consisted of a transparent polycarbonate panel, which allowed measuring the wetted area from pictures taken after each test. In the event it is preferred evaluating a test specimen in which the actual cladding is included, evidently the wetted area cannot be derived in this manner. The wetted area can then be approximated by drawing a trapezoidal or rectangular shape between the inlet width and the spread of water drained at the bottom of the specimen. For the specimens evaluated in this study, the maximum degree of spreading was always situated at the bottom of the specimen. Based on the results obtained for various flow rates, inlet methods and cavity widths, the use of a trapezoidal shape to estimate the wetted area resulted in an average underestimation of 6,5% of the wetted area which in turn resulted in an overestimation of the RDWA of 9,4%. It can thus be concluded that the use of a trapezoidal shape to estimate the wetted area based on the inlet width and width of drained water at the bottom generates a conservative approach to estimate the RDWA.

It is assumed that for specimens smaller or larger than the specimens evaluated in this study, the maximum spreading will also be situated at the bottom of the specimen when the maximum retention is reached and the weight of the specimen remains constant. Further research should be undertaken to confirm this hypothesis.

The results in this study confirm the findings of Moore and Nicholls (Moore and Nicholls, 2014) and Onysko and Thivierge (Onysko and Thivierge, 2007a) with regard to the dosage rate not affecting the RDWA for a single or multiple entry points at a fixed location. In these studies, the inlet width was the same as the specimen width. It is therefore assumed that the wetted area was the same as the specimen area and lateral spreading of the water was impossible. However, is was shown in the present study that the dosage rate affected the flow regimes of the rivulets that drained in the cavity and therefore this affected the lateral spreading of the water retained in the cavity. It is therefore of importance to choose dosage rates based on expected infiltration rates that can be obtained by laboratory studies on watertightness testing or from field studies for which water entry in wall assemblies has been monitored. In this study flow rates of 0,057 ± 0,001 l/min for multiple entry points or a total flow rate of 0,693 ± 0,006 l/min (= 2,888 ± 0,025 l/min.m over a length of 240 mm or 1,925 ± 0,017 l/min.m^2 for a specimen area of 0,36 m^2) and 0,090 ± 0,001 l/min for a single entry point as maximum values based on infiltration rates obtained in laboratory studies on different wall assemblies (Lacasse et al., 2003, 2009, 2019; Lars Olsson, 2016; L Olsson, 2016).

Depending on the primary test metric of interest, i.e. maximum retention or lateral spreading, and the expected infiltration mode, i.e. multiple infiltration locations in close proximity, e.g. through an open joint or long crack, or a single infiltration location, e.g. a deficiency at a window-wall interface, one can opt to deliver water by means of a tube with multiple openings or a single entry point respectively. In case both metrics are of interest or the expected infiltration mode is unknown, it is suggested to apply multiple entry points. The maximum retention can be measured more accurately compared to a single entry point as a larger surface area is wetted. Differences in spreading can also be observed although the behaviour of the rivulets will be affected by collision against one another.

5.2 Drainage cavity characteristics

In the literature review, general conclusions were made with regard to the drainage performance of wall assemblies and the impact of the drainage cavity characteristics, based on prior studies. To obtain more detailed insights, drainage test were conducted to study the impact of the cavity width, the hydrophobicity and texture of drainage layer materials, and the application of a drainage mat. Both the RD, RDWA and the lateral spreading of the retained water over the height of the specimen were determined.

Straube and Smegal (Straube and Smegal, 2007) showed that a 1 mm cavity was able to drain significant amounts of water and suggested that cavities with a small width may retain less water than cavities with a large width. The results of the present study are in line with those of Straube and Smegal and confirm that a cavity of 1 mm retains less water than a cavity of 10 mm and also results in a reduced lateral spreading of the water. This implies that cavities of 1 mm are more efficient in draining water than larger cavities. It should however be noted that for these tests the cavity was defined by non-absorptive polycarbonate panels which can be considered as ideal surfaces. In contrast, when the cavity was defined by a deficient housewrap with a waved surface or a drainage-enhanced housewrap with a grooved surface, the RD in the 1 mm cavity was larger compared to the RD in the 10 mm cavity. On the other hand, as the water was able to spread out in the 1 mm cavity with the deficient housewrap, the resulting RDWA was lower for the 1 mm cavity than for the 10 mm cavity. Whereas, the RDWA in the 1 mm cavity with the drainage-enhanced housewrap was within the same range as the 10 mm cavity due to a smaller lateral spreading. This implies that only when a clear cavity with a width of 1 mm is present an improved drainage performance can be obtained compared to larger cavity widths. Future research may look into the performance of cavities with a width smaller than 1 mm.

Straube and Smegal (Straube and Smegal, 2007) and Onysko (Onysko, 2007) found that the use of a nylon drainage mat in the cavity did not necessarily result in lower amounts of retained water compared to a clear cavity. The results of this study are in agreement with this finding. However, in contrast with what was suggested by Onysko (Onysko, 2007), the drainage mat did not disperse the water over a larger area of the specimen but results in a significantly smaller lateral spreading of the water compared to a clear cavity. Larger amounts of water were held in capillarity within the nylon mesh of the mat and a larger amount of water was retained on the front panel compared to a clear cavity. Water was able to bridge the cavity along the nylon threads of the mat resulting in a higher retention.

One should consider what is more critical in respect to water retention in the cavity: a concentrated amount of water over a small area, or an amount of water spread out over a larger surface area. It is suggested that for materials with high absorptivity a concentrated flow of water may reduce the absorption by the materials that, in turn, affects the moisture management of the wall by reducing the risk to moisture uptake and possible damage. Next to that, when these materials store the retained amount, the risk of water reaching a deficiency where it can infiltrate is reduced. Whereas for non-absorptive materials the risk of damage is reduced if water is spread out. As well, for non-absorptive materials, once a deficiency is reached water may directly infiltrate towards the interior without being absorbed. It is therefore preferred to limit the amount of water reaching a deficiency and thus have the retained water spread out. However, further research should be undertaken to support this hypothesis.

Measurements of the retained amount and lateral spreading were conducted for drainage layer materials with contact angles ranging from 45,1 to 123,8°. The results showed that the greater the contact angle, the smaller the RDWA, which is in agreement with what was stated by Straube and Smegal (Straube and Smegal, 2007) but in contrast with what was found by Blocken and Carmeliet (Blocken and Carmeliet, 2006). Future studies should look into the impact of dynamic contact angle and in particular the hysteresis effect. Research on rivulet flow and drops in motion have shown that the boundary conditions for rivulet flow regimes are dependent on dynamic contact angle (Le Grand-Piteira et al., 2006) and that drops or rivulets in motion leave behind a trail of smaller droplets of which the size is dependent on the velocity of the drops which, in turn, relates to the dynamic contact angle (Le Grand et al., 2005).

6. Conclusions

In this paper literature on drainage test methods and drainage test results was reviewed, the impact of the test parameters was evaluated and a test method based on the findings obtained was described. The experimental study was set up to evaluate, in detail, the impact of drainage cavity characteristics on the extent of water retention in wall cavities; this included drainage cavity characteristics such as: cavity width, hydrophobicity and texture of the drainage materials, and the use of a drainage mat, which were considered as relevant in prior studies.

In general, it was observed that it is more relevant to compare the maximum retained amount of water after drainage than to compare the drainage efficiency. It was also demonstrated that next to the absolute retained amount of water after drainage (RD), also the lateral spreading of the retained water (L_{spread}) and the wetted area (WA), resulting in the relative retained amount (RDWA) should be evaluated. The latter values provide more detailed information on the behaviour of the water in the cavity and may result in different conclusion than when only the absolute retained amount is considered.

Based on the results obtained, the following should be taken into account when designing a drained wall assembly with a drainage cavity of 10 mm or smaller:

- A 1 mm cavity can drain significant amounts of water and can drain the water more efficiently, i.e. lower RDWA and smaller lateral spreading, than a 10 mm cavity. This is however, only valid for clear cavities.
- The lower the contact angle or hydrophobicity of the materials defining the drainage cavity, the higher the amount of relative retained water.
- The surface texture of the drainage layer materials may be more determinative to the amount of retained water than the contact angle. A textured drainage material with ellipse shaped recessed parts retained significantly more water than a smooth drainage material with a similar contact angle.
- The vertical grooves (0,68 mm) of a drainage-enhanced housewrap reduce the lateral spreading of the retained water in a cavity of 10 mm without affecting the RDWA compared to a traditional housewrap.
- The waved surface of a deficient housewrap increased the lateral spreading of the retained water for cavity widths up to 5 mm. This emphasizes the fact that it is of importance to test materials in the same conditions as they will be applied on-site and not applied in the most perfect way. The latter may result in an underestimation of the actual wetted area when applied in reality. For small cavity widths and large irregularities in the placement of the housewrap, this may also result in an underestimation of the RDWA.
- A nylon drainage mat increases the RDWA in the cavity but reduces the lateral spreading.

Future research should also consider absorptive materials and replace the polycarbonate panel by a material representing the cladding. The results obtained in this study may be used as input parameters for hygrothermal simulations. The retained amount can be defined as a percentage of the infiltration percentage with a maximum set to the maximum retained amount relative to the wetted area or the characteristics of the materials defining the drainage cavity may be changed to ensure that the materials can hold water up to the same amount as the maximum relative retained amount. Future research should point out what the best approach is to evaluate the impact of the retained amount of water in the cavity after drainage on the durability of the wall assembly.

Declaration of conflicting interests

The author(s) declare(s) that there is no conflict of interest.

Appendix

Table A 1: Overview of weight-related data of drainage tests in literature (BP: building paper; HW: traditional housewrap; DEHW: drainage-enhanced housewrap; DB: drainage board; LAB: liquid applied barrier; PF: plywood furring; DM: drainage mat; FC: fiber cement; NR: not reported; DE: drainage efficiency; EPS': EPS specimen including a reversed T-joint between the panels; A: absorptive; NA: non-absorptive) Numbers in italic are derived by the authors. The retained amount $V_{ret.}$ is given in absolute values (g) and relative to the specimen area (g/m^2)

Ref.	Sheathing	Drainage plane	Cavity	Width (mm)	Cladding	DE [%]	$V_{ret.}$ [g]	$V_{ret.}$ [g/m^2]	$V_{ret., sec.}$ [g/m^2]
(Williams, 2008)	OSB	#30 BP	-	-	XPS	0,0%	*8030,0*	*2697,5*	
	OSB	#15 BP - DEHW	-	-	XPS	1,7%	*7893,5*	*2651,7*	
	OSB	#15 BP	PF	6,35	XPS	97,0%	*240,9*	*80,9*	
	OSB	#15 BP	FF	6,35	XPS	75,4%	*1975,4*	*663,6*	
	OSB	#15 BP	PF	19	XPS	90,9%	*730,7*	*245,5*	
	OSB	HW	-	-	XPS	9,0%	*7304,6*	*2453,9*	
	OSB	HW	PF	6,35	XPS	94,5%	*441,7*	*148,4*	
	OSB	HW	FF	6,35	XPS	77,5%	*1806,8*	*606,9*	
	OSB	HW	DM	NR	XPS	94,1%	*473,8*	*159,2*	
	OSB	DEHW	-	-	XPS	71,0%	*2330,3*	*782,8*	
	OSB	DEHW	PF	6,35	XPS	89,3%	*861,9*	*289,5*	
	OSB	DEHW	FF	6,35	XPS	88,3%	*936,8*	*314,7*	
	OSB	DB	-	NR	XPS	97,3%	*216,8*	*72,8*	
(Straube and Smegal, 2007)	-	PE sheet	-	-		*94,0%*	*89,6*	35,0	-
	-	Acrylic sheet	clear cavity	1	PMMA	*96,2%*	*57,6*	22,5	24,0
	-	Acrylic sheet	-	-		*88,9%*	*166,4*	65,0	-
	Gypsum	Gypsum	adhesive	> 1	EPS	*85,0%*	*225,3*	88,0	77,0
	Gypsum	Trowel	adhesive	1,5	EPS	*76,8%*	*348,2*	136,0	163,0
	Gypsum	Trowel	grooves	6,35	EPS	*67,6%*	*486,4*	190,0	204,0
	Gypsum	Trowel	adhesive	3	EPS	*81,7%*	*275,2*	107,5	129,5
	Gypsum	Trowel	adhesive	2	EPS	*92,2%*	*117,1*	45,8	73,0
	Plywood	HW	grooves	NR	EPS	*87,7%*	*184,3*	72,0	131,3
	Gypsum	#15 BP (2 layers)	-	-	Stucco	*59,6%*	*606,7*	237,0	338,5
	Gypsum	#15 BP (2 layers)	PF	19	Stucco	*63,2%*	*551,7*	215,5	308,5
	OSB	dimpled DM	dimpled DM	3	Vinyl	*75,9%*	*362,2*	141,5	170,0
	OSB	#15 BP	-	-	Vinyl	*73,2%*	*401,9*	157,0	192,5
	NR	HW	-	-	Vinyl	*77,9%*	*331,9*	129,7	159,7
	NR	#15 BP	-	-	Vinyl	*74,2%*	*386,6*	151,0	181,0
	NR	HW	wrinkled HW	NR	FC sheet	*62,5%*	*562,9*	219,9	373,3
	NR	HW	-	-	FC	*84,0%*	*239,8*	93,7	130,0
	NR	#15 BP	-	-	FC	*83,9%*	*241,9*	94,5	140,0
	NR	HW	-	-	Cedar	*66,3%*	*505,6*	197,5	331,5
	NR	HW	-	-	Cedar	*85,4%*	*218,9*	85,5	116,5
(Onysko, 2007)	OSB	LAB	adhesive ribbons	2-3	EPS	*99,1%*	74,0	*24,9*	
	OSB	HW	-	-	Vinyl	*97,1%*	230,0	*77,3*	
	OSB	#15 BP	-	-	Vinyl	*95,5%*	364,0	*122,3*	
	OSB	HW	-	-	Hardboard	*98,5%*	123,5	*41,5*	
	OSB	HW	channelled nylon DM	6,7	Hardboard	*97,1%*	231,0	*77,6*	
	OSB	HW	nylon DM	6,9	Hardboard	*96,5%*	284,0	*95,4*	
	OSB	HW	-	-	Wood	*94,7%*	426,0	*143,1*	
	OSB	HW	dimpled DM	6,3	Wood	*96,8%*	260,0	*87,3*	
	OSB	HW	PF	19	Wood	*94,2%*	467,0	*156,9*	
	OSB	HW	-	-	FC	*95,8%*	340,0	*114,2*	
	OSB	#15 BP	-	-	FC	*97,5%*	197,0	*66,2*	
(Onysko and Thivierge, 2007a)	OSB	HW	-	-	EPS	*98,8%*	12,0	*32,2*	*32,2*
	OSB	HW	-	-	EPS'	*97,2%*	28,0	*75,2*	*126,3*
	OSB	HW	DM	NR	EPS	*98,8%*	12,0	*32,2*	*29,6*

	OSB	HW	DM	NR	EPS'	*96,4%*	36,0	*96,7*	*75,2*
	OSB	BP	DM	NR	EPS	*99,0%*	10,0	*26,9*	*18,8*
	OSB	BP	DM	NR	EPS'	*95,8%*	42,0	*112,9*	*107,5*
	OSB	BP (2 layers)	-	-	EPS	*98,8%*	12,0	*32,2*	*32,2*
	OSB	BP (2 layers)	-	-	EPS'	*95,6%*	44,0	*118,2*	*172,0*
	Gypsum	LAB	notch adhesives	9,5	EPS	*98,7%*	13,0	*34,9*	*56,4*
	Gypsum	LAB	notch adhesives	9,5	EPS'	*99,0%*	10,0	*26,9*	*107,5*
(Overton, 2012)	-	HW	nylon DM	NR	FC (A)	*50,6%*	494,5	*166,1*	
	-	HW	nylon DM	NR	FC (NA)	94,5%	55,0	*18,5*	
	-	HW	nylon DM with filter fabric	NR	FC (A)	46,0%	540,0	*181,4*	
	-	HW	NR	20	EIFS	96,8%	32,0	*10,7*	
	-	HW	-	-	FC (A)	27,2%	728,5	*244,7*	
	-	HW	NR	20	FC (A)	66,8%	332,5	*111,7*	
	-	HW	channelled DM	11	FC (A)	54,8%	452,0	*151,8*	
	-	HW	channelled DM	11	FC (NA)	94,2%	58,0	*19,5*	
	-	HW	channelled DM	6	FC (A)	38,8%	612,5	*205,8*	
	-	DEHW	-	-	FC (A)	40,7%	593,5	*199,4*	

Table A 2: Overview of time-related data of drainage tests in literature (BP: building paper; HW: traditional housewrap; DEHW: drainage-enhanced housewrap; DB: drainage board; PF: plywood furring; F: furring (material not defined); DM: drainage mat; NR: not reported; TFW: Time first water; Rate: drainage rate; TSS: time to steady state)

Ref.	Sheathing	Drainage plane	Cavity	Width [mm]	Cladding	TFW [s]	Rate [l/h.m]	TSS [s]
(Williams, 2008)	OSB	#30 BP	-	-	XPS	No drainage		
	OSB	#15 BP - DEHW	-	-	XPS	No drainage		
	OSB	#15 BP	PF	6,35	XPS	23,0		
	OSB	#15 BP	PF	19	XPS	13,0		
	OSB	HW	-	-	XPS	1646,7		
	OSB	HW	PF	6,35	XPS	13,7		
	OSB	HW	DM	NR	XPS	22		
	OSB	DEHW	-	-	XPS	184,8		
	OSB	DEHW	PF	6,35	XPS	10		
	OSB	DB	-	NR	XPS	16		
(Williams, 2008)	OSB	HW	-	-	XPS	120 s		
	OSB	DEHW	-	-	XPS	5 s		
	OSB	HW	F	NR	XPS	Immediate		
	OSB	DEHW	F	NR	XPS	Immediate		
(Tonyan et al., 1999)	OSB	#15 BP	-	-	PIR	120	8,69	600
	OSB	#15 BP	-	-	EPS	75	19,87	3600
	OSB	#15 BP	F	0,8	EPS	5	309,24	300
	OSB	#15 BP	-	-	Cement board	10	531,55	180
	OSB	#15 BP	DM	3,2	Cement board - EPS	7	1235,72	300
	OSB	#15 BP	Grooves	NR	EPS	5	2568,32	180
(Leslie, 2007)	OSB	BP (2 layers)	-	-	stucco		26,72	
	OSB	BP - higher perm HW	-	-	stucco		40,08	
	OSB	BP - DEHW	-	-	stucco		40,08	
	open frame	BP	-	-	stucco		53,44	
	OSB	BP (2 layers)	-	-	one-coat stucco		53,44	
	OSB	BP (2 layers)	Channels	NR	stucco		80,16	
	OSB	BP (2 layers)	-	-	cracked stucco		347,37	
	OSB	BP (2 layers)	DM	NR	EIFS		347,37	

7. References

ASHRAE 160-Criteria for Moisture-Control Design Analysis in Buildings (2016) ASHRAE.

Bassett MR, Overton G and McNeil S (2015) Water management in walls with direct-fixed claddings. *Journal of Building Physics* 38(6): 560–576. DOI: 10.1177/1744259114527808.

Blocken B and Carmeliet J (2004) A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Aerodynamics* 92(13): 1079–1130. DOI: 10.1016/j.jweia.2004.06.003.

Blocken B and Carmeliet J (2006) On the accuracy of wind-driven rain measurements on buildings. *Building and Environment* 41(12): 1798–1810. DOI: 10.1016/j.buildenv.2005.07.022.

Calle K, Coupillie C, Janssens A, et al. (2020) Implementation of rainwater infiltration measurements in hygrothermal modelling of non-insulated brick cavity walls. *Journal of Building Physics* 43(6): 477–502. DOI: 10.1177/1744259119883909.

E06 Committee (2018) Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies. ASTM International. DOI: 10.1520/E2273-03R11.

Feng L, Zhang Y, Xi J, et al. (2008) Petal Effect: A Superhydrophobic State with High Adhesive Force. *Langmuir* 24(8). American Chemical Society: 4114–4119. DOI: 10.1021/la703821h.

Lacasse MA, O'Connor TJ, Nunes S, et al. (2003) *Report from Task 6 of MEWS Project - Experimental Assessment of Water Penetration and Entry into Wood-Frame Wall Specimens - Final Report*. Canada: National Research Council of Canada.

Lacasse MA, Armstrong M, Ganapathy G, et al. (2009) Assessing the Effectiveness of Wall-Window Interface Details to Manage Rainwater—Selected Results from Window Installation to a Wall Sheathed in Extruded Polystyrene. *Journal of ASTM International* 6(9): 101270. DOI: 10.1520/JAI101270.

Lacasse MA, Van Den Bossche N, Van Linden S, et al. (2019) A brief compendium of water entry results derived from laboratory tests of various types of wall assemblies. *MATEC Web of Conferences* Černý R, Kočí J, and Kočí V (eds) 282: 02050. DOI: 10.1051/matecconf/201928202050.

Le Grand N, Daerr A and Limat L (2005) Shape and motion of drops sliding down an inclined plane. *Journal of Fluid Mechanics* 541(1): 293. DOI: 10.1017/S0022112005006105.

Le Grand-Piteira N, Daerr A and Limat L (2006) Meandering Rivulets on a Plane: A Simple Balance between Inertia and Capillarity. *Physical Review Letters* 96(25): 254503. DOI: 10.1103/PhysRevLett.96.254503.

Leslie NP (2007) Evaluation of Water-Resistive Barrier Performance in Stucco Walls. In: *ASHRAE Buildings X*, 2007, p. 13.

McCreery GE, Meakin P and McEligot DM (2007) Measurements of rivulet flow between parallel vertical plates. *International Journal of Multiphase Flow* 33(4): 432–447. DOI: 10.1016/j.ijmultiphaseflow.2006.10.003.

Moore T and Nicholls M (2014) *Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads - Task 5: Characterization of Water Entry, Retention and Drainage of Components*. National Research Council of Canada.

Moore TV and Lacasse MA (2020) Approach to Incorporating Water Entry and Water Loads to Wall Assemblies When Completing Hygrothermal Modelling. In: Lemieux DJ and Keegan J (eds) *Building Science and the Physics of Building Enclosure Performance*. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International, pp. 157–176. DOI: 10.1520/STP161720180088.

Morrison Hershfield (1996) *Survey of building envelope failures in the coastal climate of British Columbia*. Canada: Canada Mortgage and Housing Corporation.

Nakagawa T (1992) Rivulet meanders on a smooth hydrophobic surface. *International Journal of Multiphase Flow* 18(3): 455–463. DOI: 10.1016/0301-9322(92)90028-F.

Olsson L (2016) Laboratory study of driving rain resistance of four façade systems with window fittings - Experimental results of leakage flows. In: *Central Europe towards Sustainable Building*, 2016, p. 9.

Olsson Lars (2016) Laboratory Study of Rates of Inward Leakage in 7 Gaps in a Façade Exposed to Driving rain or Water splash. In: *Thermal Performance of the Exterior Envelope and Whole Buildings XIII International Conference*, 2016, p. 12. ASHRAE.

Onysko D (2007) *Drainage and retention of water by cladding systems - Part 8: Summary report*. Canada Mortgage and Housing.

Onysko D and Thivierge C (2007a) *Drainage and retention of water by cladding systems - Part 2: Testing and Measurement Methodologies*. Canada Mortgage and Housing.

Onysko D and Thivierge C (2007b) *Drainage and retention of water by cladding systems - Part 3: Drainage testing of EIFS wall systems*.

Overton G (2012) *Study Report - Drainage Planes and their Applicability in New Zealand*. SR 268. BRANZ Building Research Levy.

Overton G, Bassett MR and McNeil S (2013) *The performance of wall drainage media in New Zealand*. New Zealand: BRANZ Building Research Levy.

Parliamentary Library (2002) Leaky buildings.

Recatala MA, Morales SG and Van Den Bossche N (2018) Experimental assessment of rainwater management of a ventilated façade. *Journal of Building Physics* 42(1): 38–67. DOI: 10.1177/1744259117719077.

Recatalá MA, Morales SG and Van den Bossche N (2020) Pressure-equalised façade systems: Evaluation of current watertightness test standards used to assess the performance of enclosure components. *Journal of Building Physics* 43(5): 369–397. DOI: 10.1177/1744259119880284.

Rousseau J (1999) *Survey of building envelope failures in the Coastal Climate of British Columbia*. 98–102, Technical Series. CMHC.

Straube J and Smegal J (2007) The Role of Small Gaps Behind Wall Claddings on Drainage and Drying.: 16.

Tonyan TD, Moyer KW and Brown WC (1999) Water management and moisture transport in direct-applied and EIFS wall assemblies. *Journal of Testing and Evaluation* 27(3): 14.

Van Den Bossche N, Lacasse MA and Janssens A (2013) A uniform methodology to establish test parameters for watertightness testing - Part I: A critical review. *Building and Environment* 63: 145–156. DOI: 10.1016/j.buildenv.2012.12.003.

Van Linden S, Lacasse M and Van Den Bossche N (2018) Drainage and retention of water in small drainage cavities: Experimental assessment. In: *Healthy, Intelligent and Resilient Buildings and Urban Environments*, 2018, pp. 91–96. International Association of Building Physics (IABP). DOI: 10.14305/ibpc.2018.be-2.04.

Williams (2008) Evaluating Drainage Characteristics of Water Resistive Barriers as Part of an Overall Durable Wall Approach for the Building Enclosure. *Journal of ASTM International* 5(7): 12.