Pressure-equalised façade systems: Evaluation of current watertightness test standards used to assess the performance of enclosure components

Maria Arce Recatalá1, Soledad García Morales1 and Nathan Van den Bossche2

Abstract
Watertightness test standards are used to evaluate enclosure components in terms of water penetration resistance. Currently, there is a wide variety of watertightness tests in use for façades elements and wall systems; however, none of them specifically addresses and evaluates the drainage capacity in pressure-equalised façade systems. In addition, recent research has revealed many inconsistencies in the possibility of these test standards to represent all possible conditions that can occur under different operating conditions, varying building configurations and at different locations. As such, the three main variables for water penetration testing (water spray rate, pressure differential and duration of the pressure application) have been called into question. Nonetheless, these studies do not bring up the protocols and other technical specifications incorporated in the test standard procedures. Furthermore, neither are concerns raised about the influence that these other parameters might have on the outcomes of the watertightness test, which is the aim of this research. To this end, the article provides a critical review of current watertightness tests standards from around the world in the first section. Thereafter, a thorough comparison of the information incorporated

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in the protocols of the test standards has been carried out. The evaluation and discussion of the test parameters and technical specifications incorporated in the tests standards is undertaken based on the state of the art and laboratory experiments of three mock-ups with pressure-equalised façade systems, where the water management capacity of the system is assessed. As a result of this research work, a guideline was prepared for the establishment of test procedures when developing new watertightness standards for pressure-equalised façade systems.

Keywords
Wind-driven rain, watertightness test standards, weathertightness performance, water penetration resistance, water infiltration, water leakage

Introduction

Standards, codes and guidelines are developed on the basis of a broad scientific consensus that has arisen from a mutual understanding of the subject and agreement on issues that may substantially affect outcomes, being these, for example, standard test methods and test parameters, loads as defined in codes or approaches offered in guidelines (Van den Bossche, 2013). Currently, there is a wide variety of watertightness tests for façade components and wall systems (e.g. AAMA 501, 2017; AAMA 502, 2012; AAMA 503, 2014; AAMA 509, 2014; AAMA 511, 2008; AAMA/WDMA/CSA 101/L.S.2/A440-08, 2008; AS 4420.1, 2016; AS/NZS 4284, 2008; ASTM C1601, 2014; ASTM C1715/C1715M, 2015; ASTM E1105, 2015; ASTM E1105, 2015; ASTM E2273, 2011; ASTM E331, 2016; ASTM E514, 2014; ASTM E547, 2009; CWCT TN 41, 2004; CWCT Standard, 2006; EN 1027, 2000; EN 12865, 2001; ENV 13050, 2000; EN 13051, 2001; FprEN 15601, 2009; ISO 15821, 2007; NT BUILD 116, 1980; NT BUILD 421, 1993; NT BUILD 488, 1998; NZS 4211, 2008; SS 381, 1996). These tests all adopt the same basic principle. Namely, that the outer surface of a full-scale façade test specimen (in the case of laboratory tests) or a section of the façade (in the case of field tests) is subjected to exposure conditions that attempt to simulate wind-driven rain and driving rain wind pressures by means of the application of a constant water supply and pressure differentials between the exterior and interior surfaces of the test specimen, respectively (Pérez-Bella et al., 2013a). Over the course of the test, the inner surface of the test specimen or façade section, which should have no internal finishes, is examined for any water leakage. Typically, water leakage is considered as ‘the water that is uncontrolled, exceeds the resistance, retention or discharge capacity of the system, or causes subsequent damage or premature deterioration’ (e.g. ASTM E2128 (2012)). In terms of discharge capacity of the system, some American standards (e.g. ASTM C1715/C1715M (2015) and AAMA 501 (2017), among others) determine that the collection of up to 15 mL of water in a 15-min test period on top of an interior stop or stool shall not be considered water leakage. The maximum pressure difference that the design withstands without allowing
water to pass to the interior face of the test specimen characterises its watertightness performance.

Several research studies have been conducted to characterise the water flow rate and pressure difference across the wall in relation to actual in-service exposure conditions (Cornick and Lacasse, 2005, 2009; Giarma and Aravantinos, 2011; Pérez-Bella et al., 2013a, 2013b, 2014a, 2015; Sahal and Lacasse, 2008; Van den Bossche et al., 2013a, 2013b). Some of these studies have demonstrated that the standardised parameters (wind-driven rain and driving rain wind pressures) set by the tests do not represent all possible conditions that can occur under different operating conditions, varying building configurations and at different locations (Henriques, 1992; Pérez-Bella et al., 2013a, 2015; Sahal and Lacasse, 2008; Van den Bossche et al., 2013a). As on one hand, the studies have shown that watertightness test standards do not properly reproduce the relationship between precipitation and simultaneous wind speed as in actual exposure (Deress and Zimmer, 2009; Pérez-Bella et al., 2014b). These studies conclude that current watertightness test standards subject the façade elements and wall systems to extreme rain events, which might not occur in many locations around the globe as each location has a unique driving rain index. Indeed, this index may vary when considering the annual driving rain or another measure of driving rain (i.e. the most disfavourable driving rain index in a return period of 50 years).

On the other hand, the studies have exposed that although the water-penetration testing attempts to simulate wind-driven rain, there are some significant limitations in replicating that which occurs during actual in-service wetting conditions (Deress and Zimmer, 2009; Pérez-Bella et al., 2013a). Therefore, it is not feasible to set standardised test parameters that reproduce actual exposure conditions for every single location around the world since standards, codes and guidelines are typically developed as a tool to provide a common framework to evaluate the performance of façade components and wall systems that can be used anywhere around the globe.

As previously commented, the existing research has focused on the study of the predominant boundary conditions for establishing test parameters for watertightness tests, such as occurrence of peak wind loads, rainfall intensity, wind-driven rain loads and associated assumptions in respect to raindrop size. However, as yet, little is known about the impact of the test parameters on the outcome of the watertightness tests. Therefore, the purpose of this article is to describe a critical evaluation of the adequacy of all parameters prescribed in watertightness test standards used to assess the performance of enclosure components to resist water entry in an effort to determine if the test standards could be considered deficient in the specification of such parameters that might detrimentally alter the outcome of the test. This assessment is based on a review of the state of the art of the currently available watertightness test standards spread worldwide and 49 laboratory experiments over three mock-ups. The review of the standards enables the identification of the recurring parameters while the experiments, the quantification of their influence on the watertightness performance results. Finally, a guideline is made for the
establishment of such procedures for developing new watertightness standards including those standards focused on window-wall interfaces.

**Overview of existing watertightness test standards**

The stages over a product’s lifetime during which watertightness testing principally occurs are as follows: (1) product design and development, (2) recently installed products and (3) during the useful service-life of the product (Deress and Zimmer, 2009). In the early-life stages of the product, testing is completed to determine performance limits, to establish certification levels and to help ensure quality control. Hence, a mock-up of the façade or wall system is built and thereafter tested in laboratory conditions. Alternatively, testing occurs on-site over the product’s mid- and later-life stages. Mid-life stages are considered those occurring prior to the issuance of the building occupancy permit and no later than 6 months after the installation of the component (Deress and Zimmer, 2009). Watertightness testing in mid-life stages is for quality assurance of the workmanship, whereas the testing is intended to reproduce actual leakage that has been observed during in-service conditions of the installed product in later-life stages.

**Field test standards**

Chew (2001) presented a review of the currently available on-site watertightness tests standards for masonry walls. Arce Recatala et al. (2018) extended this review to every type of façade component and wall system in their study, also relating the test procedure to the product lifetime stage.

When studying the correlation between field watertightness tests and the mechanisms that contribute to water penetration, Chew (2001) assessed that kinetic energy and pressure differential are a function of water application, pressure differential being one of the most important parameters to test the watertightness of building components (Chew, 2001; Cornick and Lacasse, 2009; Lacasse et al., 2003, 2009b; Mayo, 1998a, 1998b, 1998c; Sahal and Lacasse, 2008; Van den Bossche et al., 2008, 2009a, 2009b, 2012b). Water can also penetrate a wall by being transported along a stream of moving air (considered as local air currents) percolating through cracks and openings within the envelope (ASTM E2128, 2012). The air movement across a test specimen is a function of wind pressure, material properties and geometry of the opening. The other mechanisms contributing to water leakage (capillary forces, gravity action, surface tension and hydrostatic pressure) are a function of material properties and geometry of the opening (Chew, 2001).

Wind-driven rain and driving rain wind pressures produce leaks as a consequence of the kinetic energy of the raindrops caused by wind velocities and the differential pressure caused by the wind, respectively (ASTM E2128, 2012). In this regard, on-site watertightness test standards use three distinct approaches in which
Hose testing generates a strong jet of water with a penetrating power far in excess of normal wind-driven rain exposure conditions (CWCT TN 41, 2004). Although hose testing does not reproduce the effect of wind pressure, it is assumed that the effect of kinetic energy can be simulated by the calibrated nozzle operating at a prescribed pressure at a specific distance from the test surface and moved at a specified sweep rate (ASTM E2128, 2012).

A spray bar is a long pipe fitted with holes or nozzles at regular intervals along its length. The spray bar will spray water at a set working pressure range, ensuring a constant film of water is sprayed onto the face of the façade test specimen although the pressure is not sufficient to force water into the joints, as in the case of hose testing. Spray bar nozzles can be directed at specific joints but it is usually recommended directing the nozzles at points above the joint, as it is a test for resistance against water penetration from water runoff.

Spray bar testing and hose testing may not simulate all of the effects of differential pressure and the ability of air moving through cracks or openings to transport water by percolation (ASTM E2128, 2012). By contrast, site cabinet testing is supposed to better reproduce the extreme weather conditions and the action of both wind-driven rain and driving rain wind pressures, as is typically the purpose of watertightness test standards. In site cabinet testing, an air chamber is either mounted on the external or internal face of the façade test specimen and incorporates a means of pressurising or de-pressurising the cabinet, respectively. The basis of cabinet testing is to create a pressure difference on the façade test specimen, while spraying water onto the external face (CWCT TN 41, 2004).

Actual watertightness tests subject façade components and wall systems to extreme climatic exposures for water penetration, which might not occur in every location and do not always reflect real exposure conditions. These extreme climatic exposures are reproduced by standard test conditions whose test method and apparatus vary among watertightness test standards. The main test conditions defined in on-site watertightness test standards are air pressure, flow rate of water through the nozzle and test duration. Consequently, the capability of the test for simulating kinetic energy of water droplets, pressure differences and local air currents relies upon how these conditions are applied. For this purpose EN, UNE and CWCT on-site watertightness tests standards define the flow pattern of the water over the surface, the pressure of water entering the nozzle, the spraying angle of the nozzle, the distance to the outermost surface of the specimen, the nozzle/spray bar position, the nozzles spacing and the spray direction. Table 1 provides a summary of the set values for these parameters in currently available EN, UNE, CWCT, AAMA and ASTM watertightness test standards used in the field.

In contrast with EN, UNE and CWCT test standards, AAMA and ASTM test standards do not consider when undertaking tests how the most relevant climatic exposure conditions are reproduced. Conditions that according to Pérez-Bella et al. (2013b) are more appropriate for recreating high levels of climate exposure.
Table 1. Summary of parameters specified in the currently available EN, UNE, CWCT, AAMA and ASTM field watertightness test standards.

<table>
<thead>
<tr>
<th>Standards</th>
<th>Type of test</th>
<th>Water flow rate</th>
<th>Water pressure</th>
<th>Wetting point spacing</th>
<th>Wetting position (height)</th>
<th>Wetting direction</th>
<th>Distance to the sample</th>
<th>Nozzle spraying angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>European</td>
<td>Spray bar</td>
<td>5 L/min per m</td>
<td>200–300 kPa</td>
<td>400 mm</td>
<td>Head of the area tested</td>
<td>0°</td>
<td>250 mm</td>
<td>–</td>
</tr>
<tr>
<td>(EN 13051, 2001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spanish</td>
<td>Spray bar</td>
<td>2 L/min per m</td>
<td>200–300 kPa</td>
<td>400 mm</td>
<td>150 mm below top interface</td>
<td>24°</td>
<td>250 mm</td>
<td>120°</td>
</tr>
<tr>
<td>(UNE 85247, 2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>British</td>
<td>Hose</td>
<td>22 ± 2 L/min</td>
<td>220 kPa</td>
<td>NA</td>
<td>Moved</td>
<td>0°</td>
<td>300 mm</td>
<td>30°</td>
</tr>
<tr>
<td>(CWCT Standard, 2006)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CWCT-S9:2006</td>
<td>Spray bar</td>
<td>5 L/min per m</td>
<td>200–300 kPa</td>
<td>400 mm</td>
<td>Head of the area tested</td>
<td>0°</td>
<td>250 mm</td>
<td>–</td>
</tr>
<tr>
<td>(CWCT Standard, 2006)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American</td>
<td>Interior cabinet-Matrix of nozzles</td>
<td>3.4 L/min per m²</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(ASTM E1105, 2015)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM C1601-14 (ASTM C1601, 2014)</td>
<td>Exterior cabinet-Spray bar</td>
<td>2.3 L/min per m²</td>
<td>–</td>
<td>25 mm</td>
<td>≤40 mm below the interior top of the cabinet</td>
<td>0°</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ASTM C1715-15 (ASTM C1715/C1715M, 2015)</td>
<td>Hose</td>
<td>Calculated Low</td>
<td>≤840 mm</td>
<td></td>
<td>&gt;entry point spacing or 400 mm (greater)</td>
<td>30 ± 5°</td>
<td>0 mm</td>
<td>NA</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Standards</th>
<th>Type of test</th>
<th>Water flow rate</th>
<th>Water pressure</th>
<th>Wetting point spacing</th>
<th>Wetting position (height)</th>
<th>Wetting direction</th>
<th>Distance to the sample</th>
<th>Nozzle spraying angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAMA 501.1-17 (AAMA 501, 2017)</td>
<td>Cabinet-Matrix of nozzles</td>
<td>3.4 L/min per m²</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AAMA 501.2-15 (AAMA 501, 2017)</td>
<td>Hose</td>
<td>–</td>
<td>200–240 kPa</td>
<td>NA</td>
<td>Moved</td>
<td>0°</td>
<td>305 mm</td>
<td>80°</td>
</tr>
<tr>
<td>AAMA 502-12 (AAMA 502, 2012)</td>
<td>Interior cabinet-Matrix of nozzles</td>
<td>3.4 L/min per m²</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AAMA 503-14 (AAMA 503, 2014)</td>
<td>Cabinet-Matrix of nozzles</td>
<td>3.4 L/min per m²</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AAMA 511-08 (AAMA 511, 2008)</td>
<td>Cabinet-Matrix of nozzles</td>
<td>Weather data</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Note that laboratory watertightness tests may not require to be undertaken under real exposure conditions as compliance may indicate the wall system has been proofed for a wide variety of locations and a broad range of wind-driven rain loads to which the wall is to demonstrate resistance to water penetration. However, knowledge of real exposure conditions when completing field tests might be an essential requirement, especially in test standards used for forensic in-service performance assessments. Forensic in-service performance tests can provide information for drainage testing (Smegal, 2006), such as ASTM C1715/C1715M (2015) or can simply be used to evaluate water penetration (Smegal, 2006), like AAMA 511 (2008), ASTM E2128 (2012) and ASTM C1601 (2014).

**Laboratory test standards**

While field tests are useful to ascertain the performance of on-site workmanship, laboratory tests are useful to evaluate the design of the component (i.e. blocked drainage pathways and wrong detailing of joints). Laboratory tests are applied in the early stage of the product life to rate it with a performance class or performance level. While the performance class is generally prescribed as a direct function of peak wind pressure on the building, the performance level is obtained with respect to the ultimate limit state for resistance to wind loads of the product. Although both are affected by parameters such as geographical location, surroundings, local shielding and height of the building, there is no consensus on how the performance should be defined as a function of the climate conditions to which these components might be subjected during their lifetime (Van den Bossche, 2013). Typically, laboratory test standards show an increase in required performance level as a function of wind load, but there are major differences with respect to required watertightness levels, as shown in Figure 1.

![Figure 1. Watertightness requirements based on design peak pressure loads (Van den Bossche, 2013).](image-url)
Sahal and Lacasse (2008) presented an overview of current laboratory water penetration test standards, which are classified according to the type of test procedure, applied test pressures, water spray rates and duration of tests. A more recent and expanded overview of the ASTM, AAMA, CWCT, EN, NZS, SS, NT BUILD, ISO and AS laboratory test standards is given in Arce Recatalá et al. (2017).

Laboratory test conditions tend to eliminate all influencing parameters but three main variables for water-penetration testing: water application (i.e. water spray rate), air pressure difference between the interior and exterior surfaces of the test specimen (Deress and Zimmer, 2009) and duration of the pressure application. These variables are enforced and have a great impact on the water penetration performance of the test specimen as they directly affect some of the forces acting to induce water infiltration of the test specimen (kinetic energy, pressure differential and local air currents). In addition, these variables may have very different influences on the penetration of water within the test specimen as relates to the size of the opening or the porosity of the test specimen’s cladding material (Lacasse et al., 2003; Pérez-Bella et al., 2013a). It appears to be broadly accepted that capillary suction, kinetic energy and surface tension are the least common mechanisms for water penetration (i.e. AS/NZS 4284, 2008). However, recent research on pressure-equalised rainscreens has demonstrated that kinetic energy and splashed back water can have a significant impact on water penetration onto the back wall (Arce Recatalá et al., 2018). In addition, surface tension and capillary suction can be trigger factors for water infiltration through narrow openings and cladding materials with open pore structures.

Laboratory water penetration test standards also define other related test parameters, whose typical range of values is suggested as well. These other variables, which are not always enforced, are the conditioning of the laboratory (temperature of the water, surface tension of the water, relative humidity of the laboratory and temperature of the laboratory), the conditioning of the test specimen (amount of time a test specimen should be stored in the laboratory prior testing), the test equipment used to project water over the outermost surface of the test specimen (water spraying system, model of nozzle, method for applying the water load to the surface of the test specimen, working pressure range of the nozzle, spraying angle of the nozzle, distance to the outermost surface of the specimen, spray bar position, nozzles spacing and spray direction), the type of test procedure (static, cyclic, dynamic and wind tunnel testing) and the duration of inspection for water leakage.

A comparison of the most typical range of values is provided in Table 2 for the main and related test parameters defined in ASTM, AAMA, EN, CWCT, SS, AS and NZS laboratory water penetration test standards. Note that not all of the test parameters considered in the table are defined in the standards that were reviewed (AAMA 501, 2017; AS 4420.1, 2016; AS/NZS 4284, 2008; ASTM E2268, 2016; ASTM E2273, 2011; ASTM E331, 2016; ASTM E514, 2014; ASTM E547, 2009; CWCT, 2006; EN 1027, 2000; EN 12155, 2000; EN 12865, 2001; ENV 13050, 2000; FprEN 15601, 2009; ISO 15821, 2007; NT BUILD 116, 1980; NT BUILD 421,
Table 2. Overview of the most typical range of values provided for the test parameters defined in ASTM, AAMA, EN, CWCT, SS, AS and NZS laboratory test standards used to assess the watertightness of facades and façade elements.

<table>
<thead>
<tr>
<th>Standards</th>
<th>ASTM and AAMA</th>
<th>NZS and AS</th>
<th>EN and CWCT</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water flow rate</td>
<td>3.4 L/min</td>
<td>3 L/min</td>
<td>2 L/min</td>
<td>4 L/min</td>
</tr>
<tr>
<td>Main pressure</td>
<td>137 Pa(^b)</td>
<td>300 Pa</td>
<td>50–100–150–200–300–450–600 Pa</td>
<td>3 steps to 30% of d.w.p.</td>
</tr>
<tr>
<td>Pressure application per stage</td>
<td>10/15 min(^b)</td>
<td>15 min</td>
<td>5/10 min</td>
<td>5 min</td>
</tr>
<tr>
<td>Laboratory conditioning</td>
<td>Water temperature</td>
<td>–</td>
<td>–</td>
<td>4°C–30°C</td>
</tr>
<tr>
<td></td>
<td>Water surface tension</td>
<td>–</td>
<td>–</td>
<td>60 × 10(^{-3}) N/m</td>
</tr>
<tr>
<td></td>
<td>Relative humidity</td>
<td>(_b)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>(_b)</td>
<td>–</td>
<td>23°C ± 5°C</td>
</tr>
<tr>
<td>Specimen conditioning</td>
<td>device</td>
<td>Matrix of nozzles</td>
<td>Matrix of nozzles</td>
<td>Matrix of nozzles/spray bar</td>
</tr>
<tr>
<td>Spraying system</td>
<td>Position (height)</td>
<td>NA</td>
<td>Within 100 mm from the top of specimen</td>
<td>Within 75 mm from the top of chamber</td>
</tr>
<tr>
<td></td>
<td>Distance to the exterior surface of specimen (d)</td>
<td>Uniform</td>
<td>90 cm</td>
<td>25 cm</td>
</tr>
<tr>
<td></td>
<td>Spacing between nozzles</td>
<td>Uniform</td>
<td>180 cm max.</td>
<td>If d = 25, 40 cm</td>
</tr>
</tbody>
</table>

(continued)
### Table 2. Continued

<table>
<thead>
<tr>
<th>Standards</th>
<th>ASTM and AAMA</th>
<th>NZS and AS</th>
<th>EN and CWCT</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direction of the nozzle spray</td>
<td>0°</td>
<td>–</td>
<td>0/24(+2)°</td>
<td>0°</td>
</tr>
<tr>
<td>Wetting pattern</td>
<td>–</td>
<td>Solid cone</td>
<td>Full cone</td>
<td></td>
</tr>
<tr>
<td>Spraying angle</td>
<td>–</td>
<td>Wide angle</td>
<td>Wide angle</td>
<td>–</td>
</tr>
<tr>
<td>Working pressure</td>
<td>–</td>
<td>–</td>
<td>200–300 kPa</td>
<td>–</td>
</tr>
</tbody>
</table>

*The British CWCT Standard Test Method for Building Envelopes (Centre for Window and Cladding Technology (CWCT), 2006) and the International Standard ISO 15821 (2007) prescribe a flow rate of 3.4 L/min per m² instead of the usual water spray rate of 2 L/min per m² set in EN standards. CWCT Standard (CWCT, 2006) considers that the specimens tested at a flow rate of 3.4 L/min per m² meet the requirements of a test with a spray rate of 2 L/min per m².*

*ASTM E514 (ASTM E514, 2014), which provides a procedure for determining the resistance to water penetration and leakage through masonry walls, recommends a main pressure of 500 Pa, a laboratory temperature of 24°C ± 8°C, a laboratory relative humidity of 55% ± 25% and a test specimen conditioning of 14 days. There is no European and Australian laboratory test standard specifically addressed to evaluate the drainage capacity and/or the weathertightness of masonry walls.*
Furthermore, the range of values provided for the test parameters can vary significantly between standards developed for the same regions. In addition, the duration of the pressure application can also vary within the same standard from static, cyclic and dynamic pressure application procedures (i.e. AS/NZS 4284, 2008). All these inconsistencies suggest that there is not a common criterion on the way of simulating the exposure conditions in the test procedures used to determine the resistance to water penetration of facades and façade elements.

Experimental method

Recent research (Cornick and Lacasse, 2005, 2009; Giarma and Aravantinos, 2011; Henriques, 1992; Pérez-Bella, et al., 2013b, 2014a, 2014b, 2015; Sahal and Lacasse, 2008; Van den Bossche, 2013; Van den Bossche et al., 2012a, 2013a, 2013b) has primarily studied the relationship between the three main variables for water-penetration testing (water application, air pressure difference and duration of the pressure application) and the real exposure conditions of facades in the built environment. Nonetheless, it is still uncertain how the performance class or performance level is affected by the range of values provided for the related test parameters typically defined in water penetration test standards. For this purpose, an experimental approach was adopted to study the effect of varying watertightness test parameters on the results of water penetration. The analysed test parameters are the following:

- Method for applying the water load to the surface of the test specimen: wind-driven rain or surface water flow.
- Distance of the spraying system to the outermost surface of the test specimen: 25 or 40 cm.
- Direction of the nozzle spray: 0° or 25° below the horizontal line.
- Working pressure of the nozzle, which is determined by the type of nozzle utilised and the applied water flow rate: QPHA-2.8W or QPHA-5.6W or QPHA-8W are the tested nozzle types.
- Intensity of water spray rate.
- Type of test procedure: static or cyclic.

In total, 49 watertightness laboratory experiments were conducted on three wall system full-scale mock-ups. Different wall configurations were designed for the test equipment used to project water to the outermost surface of the test specimens. The façade test specimens were built with varying open joint cladding arrangements for wall systems employing the pressure-equalisation principle; refer to Figure 2 for further details of the mock-ups. The facade specimens were fitted into an externally mounted pressure box of approximately 196 × 228 cm².
The façade specimens were evaluated on their ability to drain infiltrated water from the system. The entry of water within the façade system was collected in a gutter system located beneath the test specimens. This gutter system consisted of two trays, one to collect the water infiltrating inside the air cavity and another to collect the water reaching the back wall, refer to Figure 3. The water that collected in the trays during a test sequence was poured into buckets through plastic tubes. These

**Figure 2.** Façade test specimens with the different open joint cladding arrangements: (a) Mock-up 01 had one open vertical joint and five open horizontal joints (surface measured marked-up in red); (b) Mock-up 02 comprised one baffled horizontal joint and five open vertical joints and (c) Mock-up 03 had two open vertical joints and five open horizontal joints.

**Figure 3.** Scheme showing the two trays of the gutter system designed for water collection: (i) water infiltrating into the cavity and (ii) water reaching the back wall.
buckets stood on weighting scales, which recorded the weight over time and thus the rate of water ingress measured. The measurements of the weighting scales had an accuracy of 0.1 g. This means that measuring 10 g involved 1% of uncertainty.

The water infiltration rates obtained for the different configurations of the spraying system and test procedure enabled a comparison between the use of different test parameters when conducting tests and from this, permitted discussing the influence of the respective test parameters on the results of water penetration.

**Results and discussion**

**Method for applying the water load to the surface of the test specimen**

ASTM, AAMA, AS and NZS laboratory watertightness test standards typically suggest a matrix of nozzles to project water over the test specimen surface (Table 2). However, some European test standards (e.g. EN 12865, 2001; FprEN 15601, 2009; NT BUILD 116, 1980; NT BUILD 421; 1993) make a distinction in the method for applying the water to the outermost surface of the test specimen, these being the following:

1. **Surface water flow**, in which water flows down the vertical face of the test specimen by gravity. In this case, a horizontal row of nozzles spraying evenly above the top of the test specimen is proposed (e.g. EN 1027, 2000).

2. **Wind-driven rain**, in which it is intended to deliver water droplets over the outermost surface of the test specimen with a certain kinetic energy load that is determined by the working pressure of the nozzle and the distance to the outermost surface of the test specimen. Accordingly, a matrix of uniformly spaced spray nozzles is suggested (e.g. EN 12865, 2001).

Lacasse et al. (2009a) acknowledged these methods as (1) the cascade mode and (2) the full-spray configuration, respectively. The full-spray configuration results in a water load increase in proportion to the wall height due to migration downwards of water along the face of the test specimen. Alternatively, water applied in a cascade mode prevents that non-absorptive test specimens are exposed to cumulative water loads at the lower portion of the test specimen. Furthermore, the water load on non-absorptive test specimens is independent of vertical location of the spray bar in the cascade mode (Lacasse et al., 2009a).

Nine watertightness tests were conducted over two full-scale mock-ups with non-absorptive claddings to study the impact of each method on the water penetration within the pressure-equalised façade systems. The first mock-up (mock-up 01) had one open vertical joint and five open horizontal joints. Alternatively, the second mock-up (mock-up 02) comprised one baffled horizontal joint and five open vertical joints. A joint profile blocked the opening of the only horizontal joint in mock-up 02 (refer to Figure 2). A row of evenly spaced water spray nozzles was used to deposit water at a rate of 2 L/min per m² over the outermost surface of the
test specimens. The surface water flow and the wind-driven rain effect were simulated by means of the placement of the row of nozzles in relation to the open horizontal joint. The distance of the spraying system to the outermost surface of the test specimen (25 cm for mock-up 1 and 40 cm for mock-up 2), the direction of the nozzle spray (25° for mock-up 1 and 0° for mock-up 2), the working pressure of the nozzle and the test procedure (static pressure conditions) remained unchanged throughout the whole range of tests. During the tests, the water that infiltrated into the cavity was measured as was the water reaching the back wall of the façade specimens.

The results obtained from the watertightness tests are summarised in Table 3. Note that the percentages presented hereafter in the article have always been determined from the total amount of water sprayed onto the surface of the test specimen.

A small amount of water reached the back wall in mock-up 02 regardless of the method used for applying the water load. Therefore, it became difficult to discern between the actual measurements and the uncertainty of the weighting scales. Note that the façade system evaluated was pressure-equalised, but a profile blocked the opening of the open horizontal joint.

Very similar percentages of water infiltration into the cavity were obtained in mock-up 01 regardless of the method used for applying the water load. Regarding the amount of water reaching the back wall of mock-up 01, an increase of 0.20% in the water entry rates was observed when the test specimen was sprayed with wind-driven rain. Alternatively, a decrease of 0.37% in the amount of water that infiltrated into the cavity was recorded in mock-up 02 when the façade specimen was sprayed with wind-driven rain. This reduction in the water infiltration rate might be due to the effect of blocking the opening of the horizontal joint. The wind-driven rain approach provides water droplets with more kinetic energy load. Consequently, a greater amount of water droplets can splash away from the profile at the horizontal joint not entering into the cavity. These results suggest that blocked horizontal joints are more sensitive to runoff water than to wind-driven rain. On the other hand, wind-driven rain causes higher water entry rates onto the back wall in both open vertical and horizontal joints.

Table 3. Water infiltration percentages, averaged over nine tests, obtained for each façade mock-up in relation to the method for applying the water load to the surface of the test specimen.

<table>
<thead>
<tr>
<th>Surface water flow</th>
<th>Wind-driven rain</th>
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<tbody>
<tr>
<td>Water infiltrated into the cavity (%)</td>
<td>Water reaching back wall (%)</td>
</tr>
<tr>
<td>Mock-up 01</td>
<td>22.05 ± 0.42</td>
</tr>
<tr>
<td>Mock-up 02</td>
<td>1.84 ± 0.10</td>
</tr>
</tbody>
</table>
Distance of the spraying system to the outermost surface of the test specimen

EN, CWCT and NT BUILD watertightness test standards typically suggest a distance of the spraying system to the exterior surface of the test specimen of either 25 or 40 cm (refer to Table 2). Research by Hoigard and Kudder (1998) has shown that as the nozzle distance from the test surface decreases, the water pressure impinging on the test surface increases. By consequence, the water droplets acquire more kinetic energy and are able to reach further along the infiltration path in open joints. To evaluate to what extent the infiltration rates are affected by the distance of the spraying system to the outermost surface of the test specimen, four watertightness tests were conducted on mock-up 02 (a pressure-equalised façade specimen with one baffled horizontal joint and five open vertical joints). Note that a joint profile blocked the opening of the horizontal joint. The façade specimen was subjected to surface water flow at a spray rate of 2 L/min per m². This surface water flow was generated by a bar of nozzles evenly spaced and placed above the horizontal joint. The distance of the nozzles to the exterior surface of the test specimen was varied from 25 to 40 cm in every other test. Other test parameters related to the spraying system and nozzles were kept constant the direction of the nozzle spray (0°), the working pressure of the nozzle and the test procedure (static pressure conditions). The amount of water that infiltrated into the cavity through vertical and horizontal joints was separately measured.

An average rate of 7.69% ± 0.82% of the sprayed water was found to infiltrate the cavity through vertical joints for a distance of 25 cm of the spraying system to the exterior surface of the test specimen. This percentage increased to an average rate of 9.09% ± 1.08% for a distance of 40 cm. Regarding the infiltration rates through horizontal joints, it was found that 1.88% ± 0.09% of the sprayed water infiltrated the air cavity through horizontal joints at a distance of 25 cm. Alternatively, an average rate of 1.83% ± 0.27% was obtained for a distance of 40 cm.

Very similar infiltration rates of water entry through horizontal joints were obtained for distances of 25 and 40 cm. These results suggest that the distance of the spraying system to the exterior surface of the test specimen does not have an impact on the water entry rates through baffled horizontal joints, when the surface of the specimen is wetted via surface water flow. In contrast, increasing the distance of the spraying system to the exterior surface of the test specimen yielded higher infiltration rates through open vertical joints. It appears that open joints are sensitive to the splash and bounce effect created when the distance of the spraying system to the surface of the test specimen is reduced and water pressure impinging on the test surface is increased.

Direction of the nozzle spray

High impact velocities of water drops yield splashing and repeating rebounds, whereas the spreading of water is obtained at low-speed impacts (Rein, 1993; Seo and Yoda, 1972). In this sense, angling the nozzle with respect to the test surface to
focus on a glazing seal, as may occur at a protruding mullion, for example, will increase the pressure at the plane of the intersection of the two test surfaces (Hoigard and Kudder, 1998). How this increase in pressure affects the watertightness response of a test specimen is uncertain, as it depends on many other factors. However, if the direction of the nozzle spray is instead focused on an open joint, the degree of infiltration will be more severe. This is because water droplets might have more velocity, greater flow and a shorter trajectory. EN, CWCT and NT BUILD laboratory watertightness test standards are not clear in this aspect as they can recommend that the nozzle axis either lies on a line 24( + 2)° below the horizontal line or coincides with the horizontal line (0°) (Table 2).

Six watertightness tests were conducted on mock-up 01 (a pressure-equalised façade specimen with one open vertical joint and five open horizontal joints) to quantify the impact of the direction of the spray nozzle (i.e. direction either 0° and 25°) on the water penetration within the façade system. The amount of water that infiltrated into the cavity was measured as was the amount of water reaching the back wall. The set-up of the spraying system included a bar of nozzles evenly spaced spraying water at a rate of 2 L/min per m². The method for applying the water load to the test specimen surface (wind-driven rain), the distance of the spraying system to the outermost surface of the test specimen (25 cm), the working pressure of the nozzle and the test procedure (static pressure conditions) remained unchanged throughout the whole range of tests. Figure 4 displays the water infiltration percentage in relation to the applied pressure differential and direction of the nozzle spray.

![Figure 4. Average water infiltration percentages into cavity in relation to applied pressure differential and direction of the nozzle spray.](image-url)
penetration percentages into the cavity in relation to the applied pressure differential and the direction of the nozzle spray.

Higher water entry percentages into the cavity were measured when the nozzle axis coincided with the horizontal line ($0^\circ$). The water ingress into the cavity decreased close to a 20.5% when the direction of the nozzle spray was angled to $25^\circ$. This reduction was similar in the case of the water ingress onto the back wall. An average percentage of 0.37% of the sprayed water reached the back wall of the façade specimen when the nozzle axis coincided with the horizontal line ($0^\circ$). Alternatively, an average percentage of 0.29% was reported when the nozzle axis was angled to $25^\circ$. Angling the nozzle axis lengthens the trajectory of water drops, and consequently badly impairs the kinetic energy load and velocity with which they impinge on the surface of the test specimen. Longer distances yield to lower velocities and kinetic energy loads of water drops when reaching the surface of the test specimen and therefore to lower infiltration rates.

These results suggest that a drop of approximately 25% in the water infiltration percentages within the test specimens can be expected when the nozzle axis is angled to $25^\circ$ and the surface of the test specimen is sprayed with wind-driven rain. It could also be anticipated that this percentage will grow with increasing angles for the nozzle axis since for increasing angles, water drops have to travel longer trajectories to reach the surface of the test specimen.

**Working pressure of the nozzle**

Many laboratory test standards suggest full cone nozzles (e.g. ASTM E331, 2016; ASTM E547, 2009; CWCT Standard, 2006; EN 1027, 2000; EN 12155, 2000; ENV 13050, 2000; NT BUILD 488, 1998; NZS 4211, 2008; SS 381, 1996). This type of nozzle is the one supplying water drops with the largest diameters. Drop diameter will affect drop velocity. Small drops may have a higher initial velocity, but velocity will diminish quickly. Alternatively, larger drops might retain velocity longer and travel further. In addition, in accordance with the industry (e.g. Spraying Systems Co., www.spray.com), the higher the working pressure of the nozzle, the greater the spray impact force on the outermost surface of the test specimen and the smaller the drop diameter. Note that the working pressure is dependent on the applied volumetric flow rate for a type of nozzle.

Therefore, smaller drop sizes and greater impact forces will yield water droplets having a greater level of kinetic energy, but what would define the worst-case scenario for the same range of drop sizes: (1) to spray water at a higher velocity (high working pressure) with a lower volumetric flow rate? or (2) to spray water at a lower velocity (low working pressure) with a higher volumetric flow rate?

It is rather difficult to control the velocity of water drops although it can be determined what type of nozzle should be used for a given water flow rate. As such, the nozzle will have a working pressure in accordance with the applied volumetric water flow rate. This working pressure will provide water droplets with a certain kinetic energy load. The higher the working pressure, the greater the kinetic energy
load. To analyse how the nozzle working pressure influences water penetration, an experiment consisting of 12 watertightness tests was performed. These watertightness tests were conducted over a pressure-equalised façade specimen, which had two open vertical joints and five open horizontal joints (mock-up 03). A bar of nozzles evenly spaced subjected the surface of the test specimen to water at varying spray rates using three types of full cone nozzles from Spraying Systems Co. whose product reference is QPHA-2.8W, QPHA-5.6W and QPHA-8W, respectively. The performance of these nozzles was evaluated in terms of volumetric water flow rate and working pressure. The method for applying the water load to the test specimen surface (wind-driven rain), the distance of the spraying system to the outermost surface of the test specimen (40 cm), the direction of the nozzle spray (25°) and the test procedure (static pressure conditions) remained unchanged throughout the whole range of tests.

Table 4 presents the average water infiltration percentages obtained as a function of nozzle type, applied spray rate and working pressure of the nozzle at this spray rate. The percentages are given for the water infiltrated into the cavity and the amount of water reaching the back wall of the façade specimen. The working pressures for the applied water flow rates were calculated from the technical references provided by the nozzle manufacturer.

From Table 4, it can be seen that the tested working pressures fell outside the range of working pressures suggested by EN laboratory test standards (refer to Table 2). This raises concerns about which type of nozzle might reach the range of values given in the standards for the prescribed 2 L/min per m² water spray rate. In addition, the standards appear to show a lack of precision in the specification of this parameter. In this regard, it appears to be a reasonable approach for laboratory watertightness test standards to suggest the type of nozzle for watertightness testing instead of defining the working pressure range of the nozzles. Note that some AAMA and ASTM standards specify the type of nozzle for on-site watertightness testing.

As expected, higher working pressures led to higher water entry rates onto the back wall as water drops have more kinetic energy load to reach longer distances.
Moreover, the results suggest that the amount of water reaching the back wall is extremely sensitive to the changes in the working pressure of the nozzles. For instance, an increase of 5 kPa in the working pressure of the nozzle brought about an increase of 0.09% (close to a 20% of the total) in the infiltration rates onto the back wall. This was not that observed for water ingress into the cavity. Higher working pressures yielded lower water entry rates into the cavity, as the splash and bounce effect of water droplets was higher due to the kinetic energy of the droplets. Furthermore, the water infiltration into the cavity appeared to be rather sensitive to the nozzle working pressure. This suggests that a dramatic change in the working pressure of the nozzles is required to have a minor variation in the infiltration rates into the cavity.

These results appear to indicate that the working pressure of the nozzle could have a greater influence on the infiltration rates within the wall system than the volumetric flow rate. This evidence suggests that the worst-case scenario for testing the weather performance of open joints would be to spray the surface of the facade specimen via nozzles that use higher velocity (high working pressure) for a defined volumetric flow rate.

**Intensity of water spray rate**

Concerning the water flow rate, all EN standards prescribe a uniform static water spray rate of 2 L/min-m² for watertightness tests. Note that CWCT Standard recommends a water spray rate of 3.4 L/min-m². By contrast, NZS and AS standards stipulate a constant spray rate of 3 L/min-m² and ASTM and AAMA standards determine a spray rate of 3.4 L/min-m². These values likely represent the most severe wind-driven rain intensity conditions over a return period of 30 years (Mayo, 1998a, 1998b). In addition, spraying water at a constant rate to form and maintain a continuous flow of water over the outermost surface of the test specimen does not attempt to mimic the kinetic energy of wind-driven rain. In rain events, heightened wind speeds are translated into increased wind-driven rain and driving rain wind pressure values at a constant precipitation (Pérez-Bella et al., 2013a).

The effect of the intensity of the water spray rate on the results of watertightness testing of building components is an ambiguous situation (Van den Bossche et al., 2012a). This is because the supply of water required to undertake the watertightness test depends on the porosity, roughness and saturation state of the material, joints arrangement and irregularities (Pérez-Bella et al., 2014b). Some research has been conducted to study the influence of the water spray rate on the infiltration rates within diverse types of wall systems. For example, Mayo (1998a, 1998b) studied this phenomenon in curtain walls; Sahal and Lacasse (2005) completed this work for hardboard sidings; Selvarajah and Johnston (1995) for masonry brick walls and Arce Recatalá et al. (2018) in pressure-equalised rainscreens. According to Sacré (1984), the spray rate will not be a determining factor as to whether or not a component is watertight, but it will indeed affect the quantity of water that enters into
the construction once the infiltration is established. Thus, the amount of water deposited onto the test specimen can have a significant effect in constructions where the drainage capacity determines the performance (Van den Bossche et al., 2012a) as in pressure-equalised façade systems. In agreement with this statement, Arce Recatalá et al. (2018) assessed that the higher the water spray load, the higher the infiltration rates through pressure-equalised rainscreens.

As was found by Seo and Yoda (1972), Lacasse et al. (2003) and Sahal and Lacasse (2005), there is a straight correlation between the water spray rate and water infiltration rate parameters. However, Arce Recatalá et al. (2018) found that the correlation between the spray rate and water entry was better fitted to a parabolic function (refer to Figure 5). This outcome suggests that water ingress rates within pressure-equalised façade systems could indeed remain constant for a given intensity of spray rate on the test system onwards.

**Type of test procedure**

The resistance of wall elements to water penetration can be determined with four types of watertightness test methods: static, cyclic, dynamic and wind tunnel testing. In static test methods, the pressure differences are constantly applied and step-wise increased to assess the performance level of a component (e.g. AS 4420.1, 2016; ASTM E2273, 2011; ASTM E331, 2016; ASTM E514, 2014; CWCT Standard Section 6 (CWCT Standard, 2006); EN 1027, 2000; EN 12155, 2000; Nordtest Method, 1998; NZS 4211, 2008; SNZ AS 4284 Method A (AS/NZS 2008).
Cyclic test methods are similar to static test methods, but instead of applying a constant pressure difference, rapid pressure pulses are applied (e.g. AAMA/WDMA/CSA 101/L.S.2/A440-08, 2008; ASTM E547, 2009; EN 12865, 2001; NT BUILD 116, 1980; NT BUILD 421, 1993; SNZ AS 4284 Method B (AS/NZS 4284, 2008); UNE 85-229, 1985). In dynamic test methods, an axial flow wind generator is installed in sufficient proximity to the test specimen to generate a turbulent flow field, while water droplets with kinetic energy are sprayed over the surface of the test specimen (e.g. AAMA 501.1 (AAMA 501, 2017); CWCT Standard Section 7 (CWCT Standard, 2006); CWCT Standard Section 8 (CWCT Standard, 2006); ENV 13050, 2000; ISO 15821, 2007).

The method for applying the pressure differences in watertightness tests influences the severity of the exposure (Pérez-Bella et al., 2013a). However, it is yet unclear which test method renders the most realistic or the most severe test conditions (Van den Bossche et al., 2015). On one hand, there are studies suggesting that cyclic and dynamic variation in the applied pressure creates more severe test conditions (Mayo, 1998a, 1998b). On the other hand, Van den Bossche (2013) remarks that different failure mechanisms require different test protocols. This author underscores that static test conditions are more suitable to evaluate the drainage capacity of a façade system, whereas cyclic test conditions are more suitable to assess the watertightness of face-sealed façade systems. Brown et al. (1997) subjected Exterior Insulation and Finish Systems (EIFS) with cavity to laboratory watertightness tests, measuring higher drainage rates under dynamic pressure conditions. In this sense, Sasaki (1971) stated that an important requirement for a good rain penetration test is the simulation of the lateral deflection of runoff water across the façade and its accumulation in vertical joints. Whereas static test methods cannot simulate these features, dynamic test methods can reproduce pressure variations and lateral runoff flows. Very interesting and promising research on new dynamic test methods has been published in the past 10 years (Bitsuamlak et al., 2009; Kopp et al., 2010; Salzano et al., 2010). However, these methods have typically focused on hurricane risk mitigation. Furthermore, it remains to be determined whether these test methodologies are too complex to be viable for routine testing of façades and façade components (Van den Bossche et al., 2012a).

In this context, 18 watertightness tests (12 static and 6 cyclic) were completed out to study the impact of the test method in applying pressure differences across façade test specimens on the drainage capacity of the specimen. The tests were conducted on the three previously described mock-ups (mock-up 01, mock-up 02 and mock-up 03), which were sprayed with water at a rate of 2 L/min per m² by means of an evenly spaced bar of nozzles. The method for applying the water load to the test specimen surface (wind-driven rain), the distance of the spraying system to the outermost surface of the test specimen (25 cm for mock-up 1, 40 cm for mock-up 2 and 40 cm for mock-up 3), the direction of the nozzle spray (25° for mock-up 1, 0° for mock-up 2 and 25° for mock-up 3) and the working pressure of the nozzle remained unchanged throughout the whole range of tests.
The average percentages obtained for infiltration rates into the cavity for the static and cyclic variations in applied pressures are given in Table 5. As these percentages were very similar for each façade specimen tested, a multifactor statistical analysis of variance (ANOVA) was completed. The ANOVA offered the same results for the three mock-ups that were tested. No statistically significant differences in the rates of water collection into the cavity were found with respect to the ‘Test method’. Therefore, static or cyclic variation in the applied pressures did not have an influence on the drainage capacity of the pressure-equalised façade specimens tested in this study. This was an expected result as in a pressure-equalised façade specimen the air pressure differential across the outer wall is negligible and therefore the method used for applying pressure differences would not have an impact on the water penetration caused by wind-induced differential pressure. However, note that this is a typical result for pressure-equalised rainscreens that might not be applicable to other type of façade systems where the wind-induced differential pressure is meaningful (i.e. face-sealed façade systems or moisture buffering façade systems).

Table 5. Average water infiltration percentages into the cavity as function of test method used for applying pressure differences.

<table>
<thead>
<tr>
<th></th>
<th>Static test method</th>
<th>Cyclic test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mock-up 01</td>
<td>26.98 ± 1.24</td>
<td>26.40 ± 0.77</td>
</tr>
<tr>
<td>Mock-up 02</td>
<td>21.29 ± 1.09</td>
<td>20.00 ± 0.57</td>
</tr>
<tr>
<td>Mock-up 03</td>
<td>24.83 ± 0.80</td>
<td>25.78 ± 0.90</td>
</tr>
</tbody>
</table>

The conclusion is that the comparison of different watertightness test standards and the subsequent critical evaluation of the related test parameters has called into question many of the technical specifications incorporated in these standards.

The first concern being observed is the variance in the range of values provided for the test parameters and technical specifications. These inconsistencies suggest that there is not a common criterion on the way of simulating the exposure conditions in the test procedures used to determine the resistance to water penetration of facades and façade elements. Furthermore, it has been shown that the technical specifications incorporated in the standards are sometimes too vague and the lack of precision in providing test specifications can greatly affect the water penetration results. The study of test parameters and technical specifications incorporated in watertightness test standards in the water management capacity of some pressure-equalised façade systems has given an indication on the importance of precisely defining these parameters in watertightness test standards. Therefore, it is
understood that a lack of precision in defining test parameters for watertightness test standards may impair the outcome of the test and this is an issue that requires further research on other types of façade systems and façade elements, to assist in the determination of the impact of such parameters on the performance class or performance level of the tested specimens.

The experimental work undertaken on pressure-equalised façade specimens has shown that the method for applying the water load to the surface of the test specimen, the direction of the nozzle spray and the working pressure of the nozzle are prone to detrimentally affect the water penetration outcomes within the façade system. Alternatively, it was demonstrated that the type of test procedure does not impair the water ingress in pressure-equalised façade systems. Furthermore, the distance of the spraying system to the exterior surface of the test specimens only slightly influences the water penetration outcomes in façade specimens subjected to surface water flow.

When developing a new watertightness test procedure, it is important to take into account not only the needs of the industry but also the reliability and repeatability of the results. Proposals for new test procedures should be practical, simple and must be able to be completed in a reasonable amount of time. In addition, as per the results obtained from the present research conducted on pressure-equalised façade systems, the method for applying the water load and the incorporated technical specifications for the spraying system and the nozzles should be carefully considered in establishing test procedures. In this regard, the following concerns are especially raised when evaluating the water management characteristics of pressure-equalised façade systems:

- Blocked horizontal joints are more sensitive to runoff water, whereas wind-driven rain causes higher water entry rates onto the back wall in open vertical and horizontal joints.
- The distance of the spraying system to the exterior surface of the test specimen does not affect the water penetration rates through closed horizontal and vertical joints.
- Angling the nozzle axis causes a dramatic drop in the water penetration rates because it decreases the impact force of the water drops impinging the surface of the test specimen.
- The working pressure has a greater influence on the infiltration rates within the wall system than the volumetric water flow. This means that the worst-case scenario for testing the weather performance of open joints would be to spray the surface of the façade specimen via nozzles that use higher velocity (high working pressure) for a defined volumetric flow rate.
- The water spray rate is not a determining factor as to whether or not a component is watertight. However, it affects the quantity of water that enters into the construction once the infiltration is established. Hence, it is of importance when testing pressure-equalised systems; however, there will be a point in which the water entry will remain constant onwards.
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References

AAMA 502 (2012) Voluntary specification for field testing of newly installed fenestration products.
AAMA 503 (2014) Voluntary specification for field testing of newly installed storefronts, curtain walls and sloped glazing systems.
AAMA 509-14 (2014) Voluntary test and classification method for drained and back ventilated rain screen wall cladding systems.


Henriques FMA (1992) Quantification of wind-driven rain – an experimental approach. *A general review on driven rain and details of an experiment in Portugal to supplement
existing research results in Norway, the UK and elsewhere. *Building Research and Information* 20(5): 295–297.


