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# Moisture Safety of Green Facades

**Abstract**

In Nordic climate, climbers covering facades are conventionally removed, although there is no evidence of the actual impact of the climbers on the moisture performance of facades. Such information is needed to support building design and nature-based solutions for climate change adaptation. This study aimed to find evidence on the performance of green facades from the physical and life-cycle engineering perspectives of buildings by testing double-skin green facades in laboratory and field conditions. First a mature thicket creeper was grown on a steel mesh over 100 days, and then it was exposed to rain and dry periods by accelerated weathering equipment in a laboratory until it withered. Then the leafless creeper was exposed to rain cycles on a rooftop-wall experiment in natural conditions. The results indicated the high protective capacities of the climber during the leaf season, but even during the winter season (without leaves) protective performance was measured in laboratory and natural conditions. In conclusion, double-skin green facades provide effective protection from wind-driven rain while the distance between the green structure and the load-bearing wall impacts the relative humidity levels, and the drying process of the load-bearing wall. Thus, moisture safety can be improved with a double-skin structure with ventilation and access for maintenance.

**Keywords:** green walls, integrated design, urban, nature, real estate, construction

## Introduction

Currently, the EU and cities globally are investing in green infrastructure and nature-based solutions (NBS), in order to adapt to the changing climate, and to produce healthy and liveable environments (European Commission 2015). Part of this development is building-integrated greening, such as the use of green facades. Green facades often refer to exterior walls greened by climbers (also called 'climber green walls'), in contrast to living walls (also called 'green walls') where plants are grown along the wall in specific structures such as

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pockets or modules (Jim 2015a; Manso & Castro-Gomes 2015; Medl, Stangl & Florineth 2017; Mårtensson *et al.* 2014). Here we use the term 'green facades' to describe exterior building walls covered by climbers that grow from ground-level plantings.

Green roofs and facades are NBS that mitigate building-related energy consumption and greenhouse gas emissions (Besir & Cuce 2018). Most of the hitherto scholarly work on green facades addressed the functionalities in milder climates. Vox *et al.* (2018) studied green facades (of evergreen plants *Pandorea jasminoides* variegated and *Rhyncospermum jasminoides*) to control (perforated brick) wall surface temperature, based on two years of experimental data in a Mediterranean climate. Taylor *et al.* (2016) found that shrubs and climbers on the mock-up walls improved the performance by 20-30% during the winter in Sheffield. Bolton *et al.* (2014) claimed 8% energy savings with English ivy (*Hedera helix*) covering a solid brick-walled building in Manchester, UK.

Despite the high global interest in NBS, the unexplored performance of green facades regarding the moisture balance of the building envelope has remained an unknown risk factor, particularly in varying weather conditions such as in the northern hemisphere. In the northern hemisphere, green facades encounter four seasons, exposing the facade to different weather conditions and impacting their performance. For example, during the past millennium in London, facades have been exposed on average five times per year to the freeze-thaw effect related to frost shattering according to a climate model by Brimblecombe and Grossi (2008) while in Finland the number of freeze-thaw cycles (crossings below and over 0°C) has been on average 37.8 in the south coastal areas and 30.4 inland in the present climate (Pakkala *et al.* 2014). Concrete is a porous material holding potentially varying amounts of water. There is a critical degree of water saturation above which porous and brittle material gets damaged while freezing. If the actual water saturation is below critical, no damage takes place during freezing (Fagerlund 1977). Reducing the moisture content can, thus, help mitigate the effect of freeze-thaw cycles on facades, which is the most common degradation mechanism in cold climates (Pakkala *et al.* 2014). The reduction in moisture content also hinders the effects of reinforcement corrosion (Köliö *et al.* 2016), mould or algae growth, leaching, pore filling, erosion, etc. (Neville 1995). Here we focus on the moisture performance of green facades that impact also the insulation capacity through protecting against the wind.

Climate change is expected to increase the exposure of facades to extreme weather conditions (for evidence regarding Finland, see Ruosteenoja *et al.* 2013; Pakkala *et al.* 2016). The increased wind-driven rain (WDR) together with fluctuating temperatures augment the frequency of freeze-thaw cycles, and the slow drying process of the facades during the cold season can impact the weathering and life-cycle performance of the buildings (Pakkala *et al.* 2014). In addition, both the relative humidity of outdoor air and cloudiness are increasing due to climate change. In particular, the freeze-thaw effect and corrosion are found to have a significant impact on the degradation of porous materials such as concrete (Köliö *et al.* 2014; Pakkala *et al.* 2014), brick (Kvande & Lisø 2009) or rendered facades (Annila *et al.* 2014). Together, the increase of WDR and the degrading drying conditions increase the moisture load on facades and thus also increase the range of conditions favourable for mould growth and moisture condensation (Vinha *et al.* 2013).

In this study, we present the results of laboratory experiments that simulated heavy wind-driven rain on a double-skin mock-up green facade, together with field measurements regarding the moisture balance of the facade. The rationale for this experiment was to find evidence on the performance of the green facades in varying weather conditions during different seasons for the practice of sustainable building design. The designs need to deliver solutions for real estate investments with a solid life-cycle performance and safety from the building physics point of view, for safeguarding the investments and global objectives for the resilience of cities. Two hypotheses were investigated: (1) climbers prevent the facades from getting wet during wind-driven rain events, and (2) climbers prevent the efficient drying of facades after rain events.

## Materials and Methods

### *Study Species and Site*

The study site was in Finland in the city of Tampere that belongs to the boreal vegetation zone, with a humid continental climate and a prevailing wind direction from the south-west.

One of the traditional and frequent ornamental species in Scandinavia, thicket creeper (*P. inserta*), was selected for this study. It is commonly growing on the walls of the residential buildings in the Nordic countries, so it has great potential for use as a component of green facades. However, the question of its potential harmfulness to the underlying wall structure has been debated in the practice of building design and maintenance, but no scientific evidence for or against it has been presented from the moisture performance point of view. Thicket creeper is a deciduous, perennial woody climber belonging to Vitaceae (the grape family of flowering plants), having palmate leaves with five leaflets, and leaf-opposed branched, twining tendrils (e.g. Brizicky 1965; Gerrath & Posluszny 1989). The growth pattern and morphology of thicket creeper is similar to other species of *Parthenocissus* and *Vitis* (e.g. Gerrath & Posluszny 1989). Thicket creeper requires rod, mesh or other supporting structures to climb on walls. Generally, mesh-climbers may have faster establishment and growth rates than self-clinging climbers (i.e. climbers that can attach to bare wall surface) (Jim 2015b). In addition, *Parthenocissus* species may have high stem and foliage density that creates a dense cover on walls (e.g. Jim 2015b).

### *Growing and Harvesting of the Thicket Creeper Outdoors*

The first study part involved growing and harvesting the thicket creeper to provide material for the study. The creeper grew on the brick wall of the old Hiedanranta Mansion (Fig. 1). Three 1000 x 2000 mm² steel reinforcement meshes, each with a grid of 150 x 150 mm² were installed behind the thicket creeper on 2017-05-24 allowing the plant to grow and attach to each mesh for 100 days until harvested on 2017-09-01. The diameter of the branches of the creeper varied between 2-25 mm. After the growing period, the leaves covered the mesh 100% without any visual access through the mesh, thus fully covering the facade.

The creeper was harvested and transported to the laboratory for the experiments (see section 2.3.1. below). The time gap between harvesting and start of the experiment was 6 hours. At the beginning of the experiment, the creeper branches were considered morphologically equivalent to a live plant.

### *Experimental Design*

The aim of these experiments was to test the performance of green facades in varying weather conditions during different seasons (i.e. creeper with and without leaves). The experiments consisted of two parts explained in detail below: (1) testing the material in laboratory in a rain simulation experiment using accelerated weathering laboratory equipment (AWLE) in summer (with green, firm leaves) and winter conditions (without leaves), and (2) testing the performance outdoors on a vertical rooftop-wall to simulate winter conditions (without leaves).


Figure 1. Locations of the mesh frames (1,000 x 2,000 mm2) on the brick wall of the Hiedanranta Mansion for collecting the thicket creeper for the laboratory experiment.

### *The Laboratory Experiment*

The first part of the study consisted of experiments with the AWLE over 14 days, with two different installations of double-skin green facades. The plant on the mesh together with the concrete wall formed the double-skin facade of the laboratory experiment. The creeper on the mesh was installed with threaded rods in the same position to the background wall in the AWLE, as it had grown against the south-east facing facade at the harvesting site. The mesh contained two distances, 150 mm and 300 mm (hereinafter called 150- and 300-mm green facades), between the mesh and the concrete wall for equally-sized wall areas. A reference wall area without the double-skin was also constructed of equal size to the double-skin facades (three times 1,000 x 2,000 mm²; Fig. 2). The rationale was to measure the potential differences of the two distances as regards the ability to protect the concrete wall from wind-driven rain. The background wall was a 100-mm thick solid concrete wall element (dimensions 3,000 x 2,000 mm²).

This laboratory work was divided into three different stages for the analysis according to the vitality and condition of the creeper at each stage: (1) starting from a fresh and flourishing condition (heyday phase simulating summer conditions) from the 2017-09-01 at 12:30 Central European Time (CET)+2 until the 2017-09-03 at 12:30 CET+2, (2) leaves still green and firmly attached but wilting and losing the ability to resist the force of the rain drops (wilt phase simulating autumn conditions) from the 2017-09-03 at 12:30 CET+2 onwards until the 2017-09-07 at 12:30, (3) cold season simulation first with very wilted leaves and finally with the bare structure of the creeper without leaves (winter phase) from the 2017-09-11 at 12:30 CET+2 onwards until the 2017-09-14 at 12:30. The analysis of the results follows these stages.

The initial humidity of the background wall was RH 94% of front sensors (drilled 30 mm into concrete) representing typical field conditions and no attempt was made to lower the starting RH level. Typically, the RH levels are beyond RH 90% in real-life Nordic climate conditions (Ilomets 2017). The starting level of the rear RH sensor in the concrete wall (drilled 50 mm into concrete) was 1 RH% higher than the one at the front RH sensor. This was because the front sensor was only 30 mm below the facade surface, and the rear sensor was 50 mm below, in the centre of the concrete wall where the encapsulated RH level was higher than closer to the surface. This feature is known from the drying behaviour of concrete surfaces exposed to periodical wetting and drying cycles (Gjørv 2009).

**Simulated Weather Conditions.** The double-skin mock-up facade was exposed to different simulated weather conditions involving rain and dry periods in two temperatures (heyday and wilt phase 23 °C, winter phase 10 °C) for 14 days. The weather conditions represent real-life weather conditions that may occur. The test began with two periods of 5-min rain and 3-h drying, followed by a series of 1-min rain events with 3 h of drying in between, and after the first 24 h an event of 15-min rain. During the wilt phase rain events of 15 min followed by 1-min rain events were used with 3-h drying periods. The winter simulation started with two events of 15-min rain and continued with 1-min rain and 3-h drying periods. There were two longer drying periods from the 2017-09-02 at 12:30 CET+2 until the 2017-09-04 at 12:30 CET+2, and from the 2017-09-06 at 12:30 CET+2 until the 2017-09-11 at 12:30 CET+2.

The simulated rain cycles were created with blower fans with a measured wind speed of 2-3 m/s and sprinkler arrays, perpendicular to the mock-up facade, exposing the wall to water spray. The combination of wind and sprayed water caused the wind-driven rain collectors on the reference wall area to capture 265 ml, being comparable to 6.6 mm/m² of rain on a vertical surface, which equates to approximately 1/10 of the 2017 overall precipitation amount of 697,4 mm (Finnish Meteorological Institute, 2018) in the Tampere Region. The amount of precipitation corresponds to a realistic weather event that may potentially occur in real-life, however, the objective of the study was not to mimic a specific location with distinct weather data while this would call for accounting the microclimate factors also, such as the impact of neighbouring buildings to wind-driven rain events. During the drying periods, the blower fans were left on.

**Description of AWLE conditions and equipment.** The mock-up wall placed inside the AWLE was equipped with four Rotronic Hygrolog HL-NT3 dataloggers, each equipped with three hygroclip 2 A sensors for measuring temperature and humidity. The RH sequence behaved logically throughout the experiment indicating a solid performance of the hardware. The research configuration of the wall is described in Fig. 2 indicating the positions of the sensors, the locations of the 150- and 300-mm green facades each 1,000 x 2,000 mm², and the bare reference concrete wall 1,000 x 2,000 mm². Sensors were placed inside the concrete drilled 50 mm from the back surface (mid wall), inside the concrete drilled 30 mm from the front side, on the surface of the concrete, and under the canopy attached to a mesh, 150 mm or 300 mm away from the concrete, depending on the void of the double skin facade. The sensors at the surface and canopy were equipped with protective caps preventing them from direct rain events. Seven wind-driven rain water collectors with an opening of 200 x 200 mm² and a tank for water collection were mounted on the concrete wall, measuring the amount of water hitting the wall surface (l/m²/h).

The order of the panels was fixed (see Fig. 2.) with an assumption of no impact on the experiment since, in the laboratory conditions, the wind impact was perpendicular to the wall, thus representing a stable weather condition. The variation of the conditions was not feasible as it would have required changing the background concrete wall for each experiment for testing variable weather conditions such as the impact of wind direction. Furthermore, the RH levels and structure of each concrete wall should have been the same at the beginning of the experiment for comparable results, which would have required a

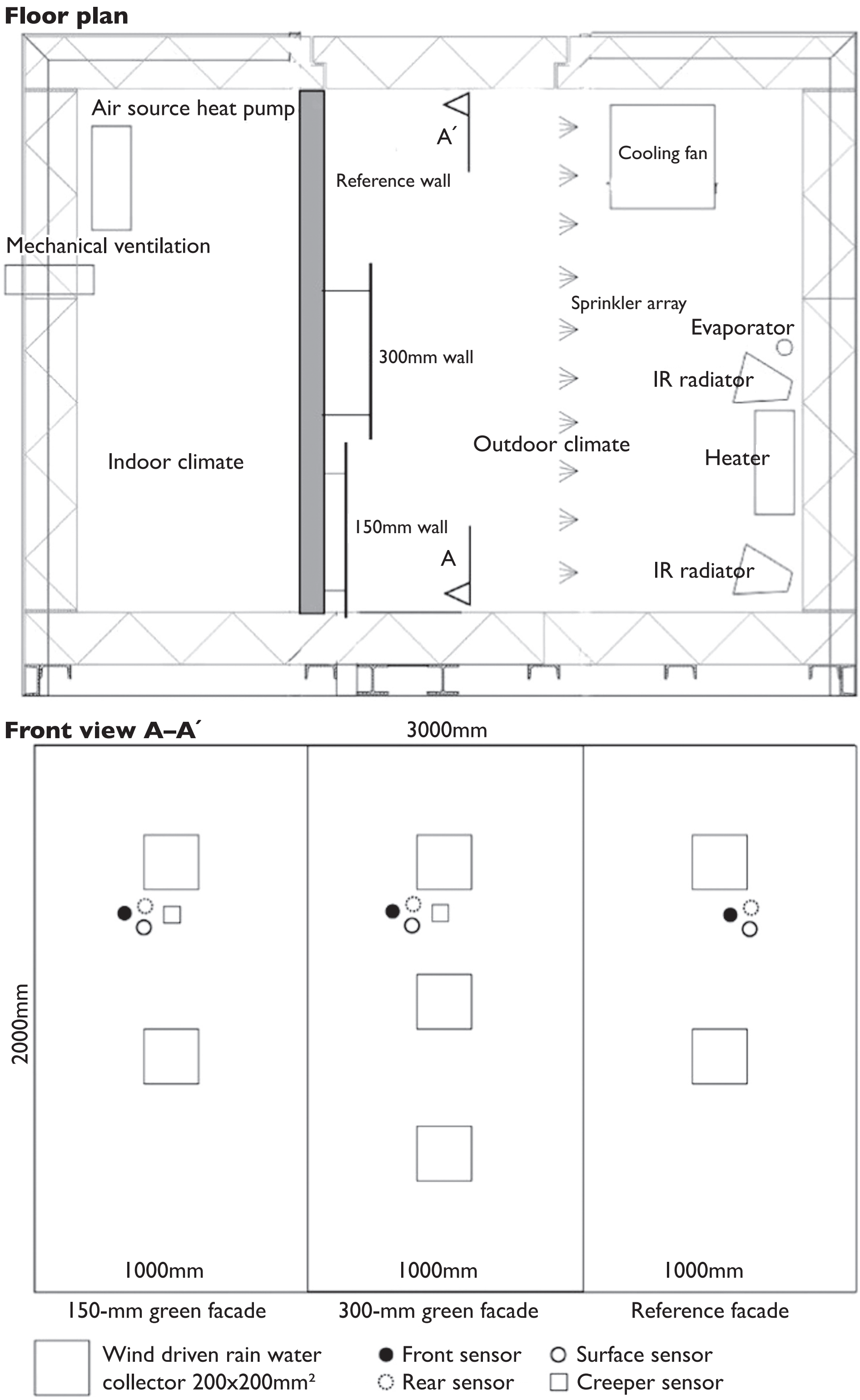


Figure 2 a and b. a Floor plan of accelerated weathering laboratory equipment (AWLE) and b front view of the mock-up facade with the locations of the sensors: front i.e sensor located inside the concrete wall, 30 mm below the facade surface; surface i.e. sensor located at the surface of the wall; rear i.e. sensor located in the centre of the concrete wall, 50 mm below the surface); and creeper sensors i.e. sensors located on the surface of the thicket creeper on 150- and 300-mm green facades.

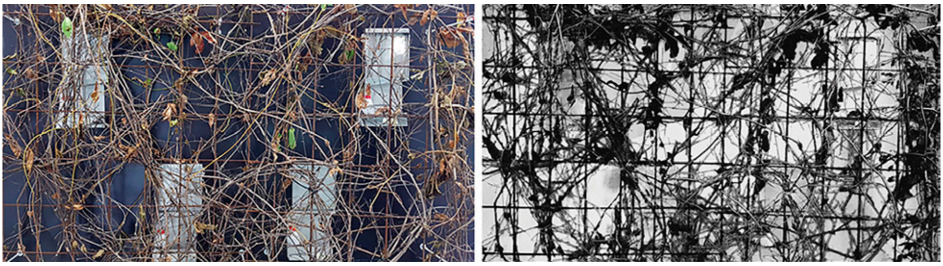

Figure 3 a and b. Image processing for the leafless thicket creeper density. Left panel (3 a) shows RGB image of the mock-up wall. The right panel (3 b) shows the same image in black-and-white with high contrast showing the hard wall surface clearly for enabling the pixel count.

very large stock of concrete elements stored in stable conditions and with the same origin of manufacturing. Each of the sensors can be considered as independent measurement points, because the capillary and hygroscopic moisture transfer in concrete is slow and does not cross the 1 m distance between the sensors. The slow movement is also apparent in the delay of rising RH in sensors installed in different depths in this study.

**Density analysis of the leafless creeper.** The density of the creeper covering the wall must be known in order to analyse its protective qualities impacting the moisture performance of the double-skin wall. The density of the leafless thicket creeper together with the mesh was measured with the pixel ratios of the protective components (creeper and double-skin structures) and the background surface, that is, the area of the wall. A projection image was taken of the wall structure. The veneer surface of the background wall was separated from the mesh and the thicket creeper through image processing (Fig. 3.), then the number of pixels covering the creeper and the mesh were counted and compared to the total number of pixels using Adobe Photoshop software. The total area of the mock-up wall image was 6,684,804 px (3,444 x 1,941 px). The area covered by the leafless creeper with the mesh was 2,899,097 px, so 43% of the total surface offered the functionalities for testing our hypothesis. The information on density was first used to analyse the impact of the creeper autumn (100% cover), winter (43%) and spring (100%) conditions on moisture protection in the AWLE experiment.

### *Field Experiment on a Rooftop-wall*

The second part of the experiment took the mock-up wall with the leafless creeper back outdoors. The rationale was to collect data on the performance during the cold seasons with a leafless creeper, which is essential for the performance of the wall. The data collected outdoors complemented the wind-driven rain data collected with the leafless creeper in AWLE. The creeper was tested on the vertical test wall on a university campus rooftop of the 8th floor with full exposure to wind and rain. As *P. inserta* can grow up to 10-20 m high and can cover vertical structures on vegetated roofs. The roof top conditions can reflect the reality of extreme weather conditions around tall buildings.

The mesh with the creeper element that was used in the AWLE was installed on a background wall of 15-mm plywood simulating a hard facade surface. Three vertical mock-up walls were made: one reference wall and two walls with the creepers (150-mm and 300-mm cavities in the double-skin facade). All walls had two wind-driven rain collectors at two different heights. The mock-up walls were installed next to each other on the rooftop and mounted against the south-west facing wall of a heating, ventilation and cooling (HVAC) room of the campus building. The mock-up walls were in place from

2017-09-13 until 2018-06-18, and the measurements were conducted during three week-long measurement periods to capture representative rain events: 2017-12-08 until 2017-12-15, 2018-04-26 until 2018-05-03, and 2018-05-03 until 2018-05-11.

## Results

## Laboratory experiment

### *Heyday Phase simulating Summer Conditions*

The phase covers the time period of the first two days at the AWLE. During this period, the leaves were in a condition that resembles the normal growth period with wet and dry weather. Fig. 4 (see online supplement[1]) illustrates the RH performance of the 150- and 300-mm green facades during the first 48 hours. When the first heavy rain cycle began, the reference surface with no plants and mesh responded immediately. The RH levels of the front sensors (blue) of the double-skin facades increased after a delay, but no visible rainwater reached the double-skin facades during the heyday phase neither on the surface of the facade or in the rain water collectors, which indicated a full blockage of visible rain with 100% leaf cover in the double-skin. The RH of surface sensors (red) rose immediately after the first rain cycle in the 300-mm green (long dashed) facade while the wetting of the 150-mm green facade (short dashed) was slower. After the last rain cycle, the surface of the 300-mm green facade (red long dashed) dried fastest.

Since there was no visible water on the concrete surfaces of the double-skin facades during this phase, the process of RH increase needs to be elaborated on. The moisture levels at the front sensors (blue) increased despite the dry periods measured by the surface (red) RH sensor (Fig. 4). Further, the moisture is transferred to the concrete by its capillary and hygroscopic behaviour through rain particles not visible to the eye and through air humidity, so the continuous accumulation of moisture inside the concrete wall was caused by water droplets in the gap of the double-skin green facade.

During the drying period from the 2017-09-02 at 12:30 CET+2 until the 2017-09-03 at 12:30 CET+2, the reference surface humidity decreased by 50 RH%. The pace of drying during the above period appeared faster in the 300-mm green facade than in the 150-mm one, likely due to the wider distance between the wet leaves and the better ventilation of the void in the wider gap (Fig. 4).

The drying cycle starting after the last raining period ends and the surface appears dry once the surface has reached the starting RH levels of the laboratory air. However, the rear sensors (black) also showed accumulation of RH during the dry period due to moisture encapsulated in the concrete, so the inner parts of the wall did not show cycles of drying during the experiment (Fig. 5.; see online supplement). It should also be noted that the fluctuation in RH levels is not only about wetting and drying, but also caused by minor temperature fluctuations in the AWLE as seen by comparing RH rear 150 (black short dashed) and T rear 150 (black dotted) in the drying period 2017-9-3 after 00:30 (Fig. 5.).

The 150-mm green facade resisted the moisture accumulation better but also dried more slowly with the narrower cavity of the double-skin facade (and likely less ventilation), and wet leaves in the proximity of the wall (Fig. 4). Further, it should be noted that the cavity of the double-skin facades may have allowed better penetration of humidity behind the 300-mm green facade, especially following the longer rain periods at 17:18 on 2017-09-01 and at 12:30 on 2017-09-02.

The RH levels in both creepers (green) of the 150- and 300-mm green facades behaved in a similar fashion (Fig. 5), which indicates an even exposure to the wind-driven rain during the experiment. A closer look at the 150-mm green facade indicates that the front

[1]Figures 4-7 are published as supplementary online material, and can be found in https://doi.org/10.30663/ay.83370

(blue) and rear (black) sensors respond to each rain cycle, and the RH levels were gradually rising. The temperatures (dotted) impacting the RH levels have a cyclic pattern. The rapid increase in the RH levels in the creepers appeared to contribute to the absorption of moisture by the concrete as the RH in the front and rear sensor tend to rise after every peak in the creeper RH (Fig. 5). The cyclic appearance of the RH levels in the rear sensor is caused by temperature fluctuation, but both the front and rear sensors showed an accumulation of moisture without significant drying of the concrete wall.

### *Wilt Phase simulating Autumn Conditions*

During this period, a maximum of 17% of simulated wind-driven rain penetrated the 300-mm green facade, and only 2% the 150-mm green facade (Fig.7; see online supplement). A greater distance of the creeper from the concrete wall allowed a larger catchment area for the penetration of water through the double-skin facade. In the case of 100% leaf coverage and rain blockage, this condition does not apply, but once the rainwater starts to penetrate, the distance impacts the amount of water ending up in the wind-driven rain water collectors, that is, the surface of the wall. Consequently, the distance of the skins impacts the performance of the green wall during the wilt phase and also at the beginning of the growing season in spring, when the leaves are emerging.

Protective capacity against the wind-driven rain was impacted by the degree of perforation of the double-skin (i.e. the combination of the creeper and the mesh structure). The uneven vegetation-mesh cover affects the vorticity of wind, which in turn affects our results.

The moisture performance of the green facades during the wilt phase is shown in Fig. 6 (see online supplement) showing RH sensors of 150 mm facade and front sensors. Despite the withered leaves, the wind-driven rain influenced the green facade only a little, as moisture behaviour of 150 mm green facade does not differ much comparing to Figure 5. The RH levels rose during the first two days of this period as rain events occurred steadily until 2017-09-06 at 10:30 CET+2. By the end of the wilt phase, the RH levels at the front sensors (blue) of both the 150- and 300-mm green facades had returned close to the same level as at the beginning of the wilt phase. The reference wall (solid), in turn, had continued steadily to accumulate moisture with the front sensor reading over 99 RH% indicating a fully saturated pore network of the concrete mock-up facade at the end of the wilt phase. In summary, the double-skin facade allowed very little rain to reach the concrete wall as the wilted leaves with reduced vigour still provided protection from the rain.

The RH levels of the front sensors (blue) recorded on 2017-9-6 at 12:30 CET+2 after intensive rain periods were lower in the 150-m green facade and higher in the 300-mm green facade (Fig. 6) and decreased to 95 and 96%, respectively, in 48 hours. Although the readings are not fully reliable after the long test period in very moist conditions, the levels of RH show the protective qualities of the 150-mm green facade and the almost equal drying capacity in comparison to the 300-mm green facade. The result implies only a small impact of distance on the moisture functionality of the facades.

### *Winter Simulation in the AWLE*

The laboratory studies indicated that in the beginning of the winter simulation the double-skin with wilted leaves allowed 20% (150-mm distance) to 54% (300-mm distance) of the rainwater to reach the wall (Fig. 7). Even when the creeper was completely without leaves only 54% (150-mm distance) to 68% (300-mm distance) of the rainwater reached the wall. The wind-driven rain penetrating the double-skin facade is shown in Fig. 7 for all the seasons to allow cross-season comparison.

The analysis of the winter phase is complicated due to differences in the coverage of the double-skin structure. Thicket creepers provide rarely 100% coverage in winter conditions – usually they are quite uneven, so the potential benefits depend much also on capacity of the support structure to alter the microclimate in such a way that wind-driven rain does not reach the wall as effectively as without the double-skin structure.

## The Rooftop-wall Field Experiment

The AWLE winter phase results were supported by the findings of the field test on the rooftop-wall in real-life conditions. The results of the field experiment indicated a similar performance as in the AWLE experiment: on average 49% (150-mm distance) and 70% (300-mm distance) of the wind-driven rain penetrated the facade into the rainwater collectors. Again, similar amounts of rain water were blocked by the double-skins at two distances, indicating that a wider cavity in the double-skin facade had almost equal sheltering performance to the narrower one. However, it must be noted that the varying wind conditions with gusty winds and the microclimate created by the building impact the directions of wind. Consequently, the speed and direction of the rain vary and impact the penetration of the rain.

## Discussion

The results of this study showed that double-skin structures can reduce the moisture load on a solid facade that often also functions as a thermal insulation wall, so the pros and cons of the wall structure can be looked at from moisture and thermal points of view. In both cases, moisture can affect the life-cycle performance and durability of the wall.

Reducing the moisture content can help mitigate the effect of freeze-thaw cycles on facades, which is the most common degradation mechanism in cold climates (Pakkala *et al.* 2014). The reduction in moisture content also hinders the effects of reinforcement corrosion (Köliö *et al.* 2016), mould or algae growth, leaching, pore filling, erosion, etc. (Neville 1995). In particular, our experiment showed that high moisture content on the concrete wall and direct exposure to rain were avoided, and the moisture levels on the surface of the wall rapidly returned close to the base level. The measurements also show that the concrete surfaces sheltered with the green facades avoided the formation of liquid film of water during wind-driven rain. The liquid water is responsible of localised moisture excess and damage in discontinuity points of the facade such as joints, seams, angles and window openings. In addition to the degradation of the facade structure, its thermal properties may change due to wind and moisture. The thermal conductivity of mineral wool increases very quickly with increasing moisture content, resulting in poor insulation capacity (Jerman & Černý 2012).

The design of a green facade can mitigate the moisture risks through a double-skin structure, while the distance of the leaves and the ventilation of the void space contribute to the drying process of the load-bearing wall. For the analysis of moisture performance, the structure and material of the wall need to be considered, in particular, what kind of conditions exist for the growth of mould. We recommend a wider distance of 300 mm between the load bearing wall and the double-skin, since it has a slightly better drying capacity and offers design options for maintenance solutions. A distance of approximately 700 mm remained unexplored due to dimensional limitations in the laboratory equipment. This wider distance has relevance for the building design, in order to arrange an easy, safe and cost-effective building maintenance for facades via of a service platform.

Finally, the impact of the green facade on the building will depend on the plant species used for greening, as different species have different leaf, branch, stem and root morphology, and different physiological characters (cf. Cameron *et al.*. 2014 who found that different green facade species had different cooling capacities; and Hunter *et al.* 2014 who discussed the importance of plant parameters for the functionality of green facades). Even though research has hitherto focused on the thermal performance of green facades, hypothetically important parameters regarding rain include, for example, those describing foliage and stem cover and morphology, depth and rigidity. For example, Gotsch *et al.* (2018) found that the branch angle of urban trees affected stem flow (water running down the stems), and Holder and Gibbes (2017) found four-fold differences in how much water is captured by the canopy surface of 13 different perennial and shrub species. This suggests the hypothesis that, on green facades, the configuration of the support structure and the choice of the plant species may together have a significant impact on how much water reaches the ground and how storm water is managed as part of the ecosystem of ground infrastructure and facades.

Furthermore, different plants species transpire at different rates (Gotsch *et al.*, 2018), recycling rainwater into the ambient air. Hypothetically, this may have an impact on the microclimate in the gap between the hard wall and the green part of the facade. For example, Zhang *et al.* (2013) and Gillner *et al.* (2015) showed that small plant communities increase the relative humidity under and inside the canopies, respectively. Zhang *et al.* (2013) used 500-600-m² parks, comparable to the size of a large building wall while Gillner *et al.* (2015) used street trees. While our research provides implications on the capacity of a double-skin green facade to function in a protective way, it nevertheless ignores this very basic function, transpiration, as our experimental plants were branches removed from the main stem and root system. Furthermore, we used a mesh-climber in our experiment (i.e. a climber that attaches e.g. with tendrils or hooks to mesh or other training system; see Jim 2015b). Compared to self-clinging climbers (i.e. climbers that can attach to bare wall surface e.g. with adhesive pads), mesh-climbers may cause less direct damage on a facade e.g. via chemical effects. Further research that compares the impacts of different fully-grown climber species in field conditions are needed in order to understand the full morpho-physiological impact of different species on the hard surfaces of building walls.

The green facade should form a significant coverage of leaves, nearly 100%, to secure the direct protective functionality of the structure against wind-driven rain. Further, the green facade should cover the entire facade, or specific parts that need to be protected. Small fragmented green elements are less likely to provide protective qualities from the viewpoint of moisture, but they may offer shading qualities or could be used in locations that are expected to be exposed to harsh weather conditions, such as facades facing prevailing wind directions in the proximity of sea.

We tested a high-density branch structure of the creeper mimicking an approximate coverage of at least 43% of the facade when not in leaf. This coverage appeared to have protective qualities outside the growing season. This has significance in colder climates when the creepers have no leaves, and when weather conditions are harsh for the facade in terms of moisture loads.

The experiment with the AWLE showed piling of leaves at the end in the chamber and its structures. In double-skin facades, support structures attached to the load-bearing wall are inevitable, so there are likely to be locations collecting leaves. Particular attention should therefore be paid to the design of the double-skin facade to support regular cost-effective maintenance. Old leaves piling against the facade must be removed in order to avoid a constant moisture load on it. Second, the growth of plants should be monitored in order to avoid branches penetrating behind window sills or other structural elements.

## Conclusions

Based on testing the protective capacities of thicket creeper (*Parthenocissus inserta*) for a double-skin green facade in an accelerated weathering equipment laboratory, the following conclusions can be made. First, the load-bearing wall of the double-skin facade did not receive any visible rain or any water in the wind-driven rain collectors when the creeper was in full leaf. Second, both researched distances of 150 mm and 300 mm of the green double-skin facade protected the background wall. Third, the 150-mm green facade accumulated moisture more slowly than the 300-mm one, but also dried more slowly. Fourth, despite absorbing more moisture, the 300-mm green facade with a higher RH level dried faster than the 150-mm one. Fifth, after a long rain period, the surface moisture levels decreased rapidly and at the same pace on all hard wall surfaces, independent of distance to, or lack of the green double-skin.

Lastly, our research showed that climbers can also protect facades from moisture during the winter season without any leaves, yet, to generalise this result, the protective effect should be tested with a range of branch-stem densities. We measured protective capacities ranging between 32-46% in laboratory conditions when branches, stems and the support structures covered 43% of the wall surface.

We suggest that living double-skin facades based on climbers are promising multifunctional nature-based solutions. The researched distances between the load-bearing wall and protective green double skin imply equal functionality with varying distances. Thus, there may be a wider cavity inside the wall allowing flexibility in the architectural design for the benefit of balconies or maintenance platforms of the facade. From the building physics point of view, only larger consistent green walls are functional and may introduce the benefits found in this research. Obviously, the size and frequency of green facades both at the building and city scale will determine the overall city-wide impacts of such elements (cf. e.g. Nurmi *et al.* 2016 for scenic benefits). The visual appearance of a large green wall may be considered both as an asset or a restriction for the architecture and urban design depending on the viewpoint and the desired style of city design. If all facades of a building are not covered with vegetation and the objective of the design is to use green facades for moisture protection, the facades facing the prevailing winds carrying wind-driven rain should be designed with extensive cover of vegetation. Single green elements in the facades, such as vegetation on the balconies, do not offer the benefits from the building physics point of view although they may have other benefits related, for example, to biodiversity (e.g. by providing food, shelter and nesting sites) or urban health.

Future research should test the systems of double-skin facades in pilot projects and evaluate both the technical and cost performance from the life-cycle point of view in order to contribute to the adoption of nature-based solutions in cities. Additionally, the impact of choice of plant species in different climates needs further research.

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## References

Annila, P. J., Pakkala, T. A., & Suonketo, J. (2014) Examining of weather resistance of ETICS with stresses which correspond to weather conditions in Finland. In van Breugel, K. & Koenders, E.A.B. (eds.) *Proceedings of the International Conference on Ageing of Materials & Structures*, 73–80. Delft University of Technology, Delft, the Netherlands.

Besir, A. B., & Cuce, E. (2018) Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews* 82 915–939. https://doi.org/10.1016/j.rser.2017.09.106.

Bolton, C., Rahman, M.A., Armson, D., & Ennos, A.R. (2014) Effectiveness of an ivy covering at insulating a building against the cold in Manchester, U.K: A preliminary investigation. *Building and Environment* 80 32–35. https://doi.org/10.1016/j.buildenv.2014.05.020.

Brimblecombe, P., & Grossi, C.M. (2008) Millennium-long recession of limestone facades in London. *Environmental Geology* 56 463–471. https://doi.org/10.1007/s00254-008-1465-z.

Brizicky, G. K. (1965) The genera of Vitaceae in the Southeastern United States. *Journal of the Arnold Arboretum* 46 48–67. https://www.jstor.org/stable/43781526.

Cameron, R.W.F, Taylor, J.E., & Emmett, M.R. (2014) What´s ´cool´ in the world of green facades? How plant choice influences the cooling properties of green walls. *Building and Environment* 73 198–207. https://doi.org/10.1016/j.buildenv.2013.12.005.

European Commission (2015) *Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities, Final report of the Horizon 2020 expert group on 'Nature-based solutions and re-naturing cities'*. Directorate-General for Research & Innovation. https://publications.europa.eu/en/publication-detail/-/publication/fb117980-d5aa-46df-8edc-af367cddc202/language-en

Fagerlund, G. (1977) The critical degree of saturation method of assessing the freeze/thaw resistance of concrete. Tentative RILEM recommendation. Prepared on behalf of RILEM Committee 4 CDC. Materiaux et Constructions 1977 no 58, 217–229.

Fagerlund, G. (2004) *A service life model for internal frost damage in concrete* (Report TVBM Vol. 3119). Lund, Sweden: Division of Building Materials, LTH, Lund University.

Finnish Meteorological Institute (2018). Annual precipitation statistics in Härmälä Tampere in 2017. <https://ilmatieteenlaitos.fi/havaintojen-lataus#!/>. 16.10.2018

Gerrath, J.M., & Posluszny, U. (1989) Morphological and anatomical development in the Vitaceae. III. Vegetative development in *Parthenocissus inserta*. *Canadian Journal of Botany* 67 803–816. https://doi.org/10.1139/b89-108.

Gillner, S., Vogt, J., Tharang, A., Dettmann, S., & Roloff, A. (2015) Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landscape and Urban Planning* 143 33–42. https://doi.org/10.1016/j.landurbplan.2015.06.005.

Gjørv, O. E. (2009) *Durability Design of Concrete Structures in Severe Environments*. Taylor & Francis, Oxon.

Gotsch, S.G., Draguljić, D., & Williams, C.J. (2018) Evaluating the effectiveness of urban trees to mitigate storm water runoff via transpiration and stemflow. *Urban Ecosystems* 21 183–195. https://doi.org/10.1007/s11252-017-0693-y.

Holder, C.D., & Gibbes, C. (2017) Influence of leaf and canopy characteristics on rainfall interception and urban hydrology. *Hydrological Sciences Journal* 62 182–190. https://doi.org/10.1080/02626667.2016.1217414.

Hunter, A. M., Williams, N. S.G., Rayner, J. P., Aye, L., Hes, D., & Livesley, S. J. (2014) Quantifying the thermal performance of green facades: A critical review. *Ecological Engineering* 63 102–113. https://doi.org/10.1016/j.ecoleng.2013.12.021.

Ilomets, S. (2017) *Renovation need and performance of envelopes of concrete apartment buildings in Estonia* (Doctoral dissertation). https://digi.lib.ttu.ee/i/?7670&

Jerman, M., & Černý, R. (2012) Effect of moisture content on heat and moisture transport and storage properties of thermal insulation materials. *Energy and Buildings* 53 39–46. https://doi.org/10.1016/j.enbuild.2012.07.002.

Jim, C.Y. (2015a) Greenwall classification and critical design-management assessments. *Ecological Engineering* 77 348–362. https://doi.org/10.1016/j.ecoleng.2015.01.021.

Jim, C.Y. (2015b) Assessing growth performance and deficiency of climber species on tropical greenwalls. *Landscape and Urban Planning* 137 107–121. https://doi.org/10.1016/j.landurbplan.2015.01.001.

Kvande, T., & Lisø, K.R. (2009) Climate adapted design of masonry structures. *Building and Environment* 44 2442–2450. https://doi.org/10.1016/j.buildenv.2009.04.007.

Köliö, A., Pakkala, T.A., Lahdensivu, J., & Kiviste, M. (2014) Durability demands related to carbonation induced corrosion for Finnish concrete buildings in changing climate. *Engineering Structures* 62-63 42–52. https://doi.org/10.1016/j.engstruct.2014.01.032.

Köliö, A., Pakkala, T. A., Hohti, H., Laukkarinen, A., Lahdensivu, J., Mattila, J. & Pentti, M. (2016) The corrosion rate in reinforced concrete facades exposed to outdoor environment. *Materials and Structures* 50 1–16. http://dx.doi.org/10.1617/s11527-016-0920-7

Lahdensivu, J. (2012) *Durability properties and actual deterioration of Finnish concrete facades and balconies* (Doctoral dissertation). http://urn.fi/URN:ISBN:978-952-15-2823-1

Manso, M., & Castro-Gomes, J. (2015) Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews* 41 863–871. https://doi.org/10.1016/j.rser.2014.07.203.

Mårtensson, L-M., Wuolo, A., Fransson, A-M. & Emilsson. T. (2014) Plant performance in living wall systems in the Scandinavian climate. *Ecological Engineering* 71 610–614. http://dx.doi.org/10.1016/j.ecoleng.2014.07.027.

Medl, A., Stangl, R. & Florineth F. (2017) Vertical greening systems - A review on recent technologies and research advancement. *Building and Environment* 125 227–239. https://doi.org/10.1016/j.buildenv.2017.08.054.

Neville, A. M. (1995). *Properties of concrete* (4th ed.). Longman Group, Essex.

Nurmi, V., Perrels, A., Votsis, A., Lehvävirta, S. (2016) Green Roof Cost Benefit Analysis: Special Emphasis on Scenic Benefits. Journal of Benefit-Cost Analysis 7(3) 488–522.

Pakkala, T.A., Köliö, A., Lahdensivu, J. & Kiviste, M. (2014) Durability demands related to frost attack for Finnish concrete buildings in changing climate. *Building and Environment* 82 27–41. https://doi.org/10.1016/j.buildenv.2014.07.028.

Pakkala, T. A., Lemberg, A-M., Lahdensivu, J. & Pentti, M. (2016). Climate change effect on wind-driven rain on facades. *Nordic Concrete Research* 54 31–49.

Ruosteenoja, K., Jylhä, K., Mäkelä, H., Hyvönen, R., Pirinen, P. & Lehtonen, I. (2013) *Weather data for building physics test reference years in the observed and projected future climate - results from the REFI-B project* (Reports 2013:1). Finnish Meteorological Institute, Helsinki, Finland.

Taylor, J.E., Cameron, R.W.F. & Emmett, M.R. (2016) The role of shrubs and climbers on improving thermal performance of brick walls during winter. *Acta Horticulturae* 1108 353–359. https://doi.org/10.17660/ActaHortic.2016.1108.47.

Vinha, J., Laukkarinen, A., Mäkitalo, M., Nurmi, S., Huttunen, P., Pakkanen, T., Kero, P., Manelius, E., Lahdensivu, J., Köliö, A., Lähdesmäki, K., Piironen, J., Kuhno, V., Pirinen, M., Aaltonen, A., Suonketo, J., Jokisalo, J., Teriö, O., Koskenvesa, A. & Palolahti, T. (2013) Effects of climate change and increasing of thermal insulation on moisture performance of envelope assemblies and energy consumption of buildings. *Research report 159*. Tampere University of Technology, Department of Civil Engineering, Tampere, Finland.

Vox, G., Blanco, I. & Schettini, E. (2018) Green facades to control wall surface temperature in buildings. *Building and Environment* 129 154–166. https://doi.org/10.1016/j.buildenv.2017.12.002.

Zhang, Z., Lv, Y. & Pana, H. (2013) Cooling and humidifying effect of plant communities in subtropical urban parks. *Urban Forestry & Urban Greening* 12 323–329. https://doi.org/10.1016/j.ufug.2013.03.010