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Factors favouring vegetation in quay masonry walls: A pilot field study

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ABSTRACT

Walls overgrown with plants can have a positive impact on urban comfort and contribute to biodiversity in the city. In particular, quay walls, thanks to their close contact with water, have the potential to be ecologically engineered to encourage the growth of herbaceous plants. Different factors can affect growth of vegetation on walls. This research aims at experimentally investigating the effect of several variables, including quay wall design, building materials and environmental conditions, on receptivity of brick masonry quay walls for herbaceous plants. To this scope, ten quay walls (size 2 m × 2 m x 0.43 m), have been built and placed in a canal in the city of Breda (the Netherlands). The survival and growth of vegetation and the moisture content in the wall were monitored during a period of about 2 years. The results show that the presence of a layer of soil substrate with high capillary suction, positioned in between the masonry cladding and the concrete structure of the wall, has the most relevant positive effect on vegetation growth on the masonry. Mortar composition and irregularities of the wall surface influence bio-receptivity too, but to a less extent; orientation had only a limited effect. Moreover, the strategy of using a mechanically strong bedding mortar in combination with a weaker but more bio-receptive pointing mortar has proven successful at favouring growth of herbaceous plants, while providing sufficient strength to the masonry.

1. Introduction

A growing number of cities struggles with unsustainable urbanisation, degradation of urban ecosystems and lack of resilience to climate changes [1,2]. Integration of nature-based solutions in the urban landscape can contribute to more sustainable urbanization [3,4]. In particular, green walls can provide several benefits, including improvement of air quality, enhancement of biodiversity, better acoustic [5,6] and thermal comfort [5–11], and contribute thereby to the overall physical and psychological health of citizens [12].

In the last years, urban ecology has gained increasing attention in the Netherlands. Interventions such as the uncovering of buried portions of urban rivers and streams (e.g. river Mark in the city of Breda) and the conversion of old harbour areas into residential districts (e.g. Houthaven in Amsterdam) offer the occasion to renature urban areas, by taking into account the settlement of wall plants when constructing new walls.

In particular, quay walls, thanks to their close contact with water, have a great potential to be ecologically engineered to encourage the growth of herbaceous plants, which can also benefit other species (such as insects). Contemporary quay walls are much less prone than traditional ones to be colonized by plants. Traditional brick quay walls are solid, earth retaining walls, generally made of brick/stone and (lime-based) mortar, which are in direct contact with moist soil. Being in contact with soil, traditional quay masonry walls can remain moist for long time, fact which provides a favourable environment for the growth of plants [13,14]. Historic quay walls form indeed an important habitat for some endangered species in the Netherlands, such as the Wallflower (*Erysimum cheiri*) and the Amplexicaul Hawkweed (*Hieracium sect. Amplexicaulia*), as well as for less rare plants, Ivy-leaved Toadflax (*Cymbalaria muralis*) and Pellitory-of-the-wall (*Parietaria Judaica*). Differently, in contemporary quay walls, the actual earth retaining structure is usually a steel sheet piling, drilled deep into the ground. In Dutch cities, generally, a Z-shaped concrete apron is hung over the steel sheet piling, and covered with masonry made with brick (or, more rarely, basalt stone blocks) and (cement) mortar [15]. In this construction, the masonry is only a cladding, with mainly an aesthetical role. The masonry cladding is therefore no longer in contact with the moist ground behind and its surface can become very hot and dry during warm periods. These conditions do not offer an ideal habitat for wall plants.

In recent years, in the Netherlands, different attempts have been

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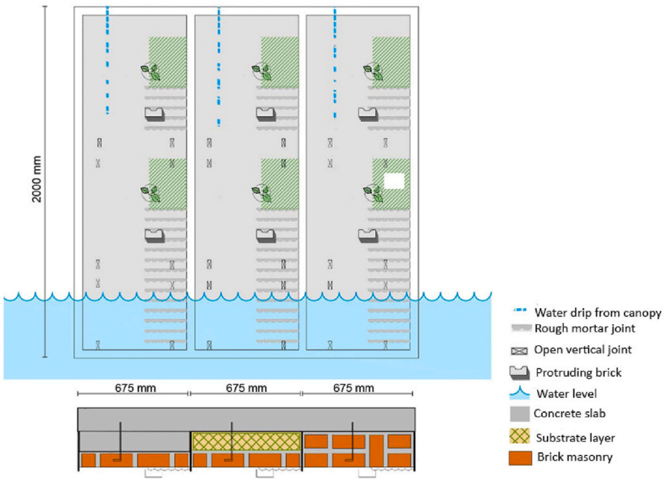


Fig. 1. Schematic front view and horizontal section of a wall, with 3 vertical panels.

made to favour the growth of vegetation on quay walls (e.g. Ref. [16]). However, developments are still limited and further scientific research is hardly needed. In the Green Quay project [17], in the framework of which the research presented in this paper has been developed, the effort is made to improve the bio receptivity of the masonry itself, with the aim of favouring (spontaneous) germination and growth of herbaceous plants in the wall. To this scope a preliminary laboratory study was carried out by the authors, in order to select brick and mortar combinations able to favour bio-receptivity, while still providing sufficient strength to the masonry. The results of this first study are reported in [18] and have been used as input for the research presented in this paper.

The present research aims to assess, on small scale models in the field, the influence of different materials and environmental variables on the receptivity of brick masonry quay walls for herbaceous plants. The ultimate scope is to develop masonry quay walls with improved bio-receptivity.

Based on literature [13,18–22] and outcomes of on-site applications [16,23], several variables have been identified as possibly influencing the growth of vegetation in quay walls. These include: composition (binder type and availability of nutrients) and moisture transport behaviour of brick/mortar combinations, presence of a moisture-supplying substrate layer behind the masonry wall, thickness of the masonry, orientation and irregularity of the masonry surface. The effect of these variables on favouring vegetation has been assessed by measuring the moisture content in the walls, crucial factor for bio-receptivity, and by monitoring the growth of plants during a period of about 2 years.

In this paper, after a description of the design and materials selected for the small scale models, and of the methodology for monitoring (section 2), the results of the monitoring of the small scale models are presented (section 3). The effects of the different material and environmental variables are discussed in section 4. The main conclusions of the research are summarized in section 5, where an outlook on future developments is given as well.

2. Materials and methods

2.1. Small scale model design

Ten small scale models walls were built to be tested on site. Each wall is 2,0 m long, 2,0 m high and 0.43 m thick. The walls are constituted by a concrete slab to which the brick masonry wall is connected. Each masonry wall is subdivided in three vertical panels (Fig. 1):

- The left panel is constituted by a half-brick thick masonry layer (thickness 100 mm), in contact with the concrete slab;
- The middle panel is made of a half-brick thick masonry wall, with a layer of soil substrate (thickness 120 mm) between the brick masonry and the concrete slab; the aim of the substrate is to absorb water by capillarity and to transfer it the masonry;
- The right panel is made of a one-brick thick masonry wall (thickness 210 mm), directly in contact with the concrete slab.

In each panel, some areas were treated in a different way than the rest, in order to assess the influence of different variables on bio-receptivity of the masonry wall (see Fig. 1):

- protruding bricks are added
- some vertical joints are left open (i.e. not filled with mortar)
- the surface of the mortar joint is left protruding and rough (i.e. not tooled)

One type of brick and different mortars were used to build the panels, for a total of 5 brick/mortar combinations. In total 10 walls were built: 5 walls were exposed to SSW (panels 1S, 2S, 3S, 4S and 5S) and 5 to NNE (1 N, 2 N, 3 N, 4 N and 5 N). This way, the possible influence of solar radiation, rain and wind on the growth of plants, mosses and algae on the surface of the masonry can be assessed.

2.2. Brick

The brick was chosen based on previous research [18]. The selected brick is a soft-mud moulded brick with frog (Wienerberger Terca Beerse –Spaans rood), with size 210 × 100 × 50 mm. This brick has a fast and high water absorption (Water Absorption Coefficient: 418 g/m^2 $sec^{1/2}$, Initial Rate of Absorption 3.91 kg/m^2 min) and a density of 1811 kg/m^3 [18]. Its average compressive strength and normalized compressive strength, measured according to EN 772–1 [24], were determined to be 14,43 MPa and 10,88 MPa respectively.

Table 1
Brick and mortar types used in the small-scale models.

Panel	Orientation masonry surface	Brick	Bedding mortar	Pointing mortar	Seeds of plants	Expected bioreceptivity of mortar surface
1-N	North	B2	MMmK	No	Added on surface	–
1-S	South	B2	MMmK	No	Added on surface	–
2-N	North	B2	Hst2	No	Added on surface	+
2-S	South	B2	Hst2	No	Added on surface	+
3-N	North	B2	HT2	No	Added on surface	++
3-S	South	B2	HT2	No	Added on surface	++
4-N	North	B2	HCst2	ATst2	Mixed in pointing	+++
4-S	South	B2	HCst2	ATst2	Mixed in pointing	+++
5-N	North	B2	HCst2	CHstVB	Mixed in pointing	++++
5-S	South	B2	HCst2	CHstVB	Mixed in pointing	++++

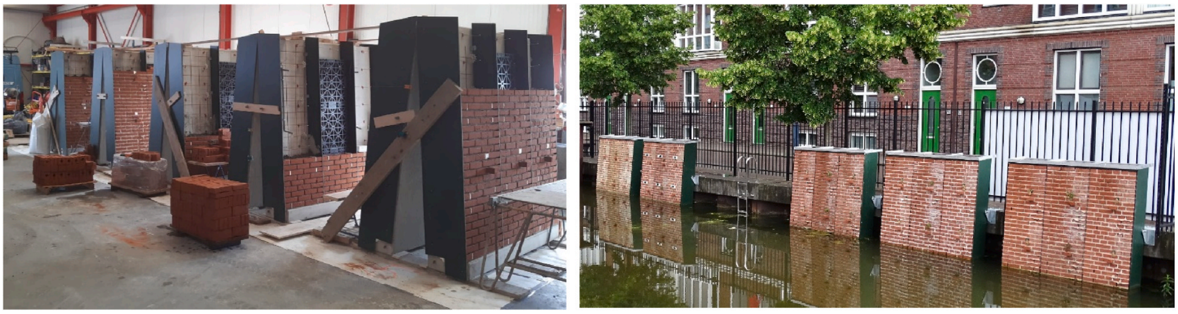


Fig. 2. left: Building of the walls; in the middle panel space between the masonry and the concrete slab is left for pouring of the substrate (the plastic containers had only a safety function); right: South facing walls placed at test location.

2.3. Mortar

Several mortar compositions were used: in some walls (1 N&S, 2 N&S and 3 N&S) only a bedding mortar was used, whereas in others (4 N&S and 5 N&S) a combination of a bedding mortar and a pointing mortar was applied. This last solution has been chosen to guarantee sufficient mechanical strength to the wall, while keeping a good bio-receptivity of the joint [18]. Table 1 reports the bedding and mortar used in the different walls:

- In walls 1 N&S a commercial bedding mortar (*Sakrete Remix Metselmortel met kalk*) is used: this is a highly porous ready-to-use mortar with a Portland cement binder and the addition of 1.5% hydrated lime (MMmk). Based on previous laboratory tests [18] and, the known low bio-receptivity of Portland cement binder [21,25], this mortar is not expected to favour the growth of plants and is used as reference.
- In walls 2 N&S a mortar consisting of natural hydraulic lime (NHL 3.5) binder and quartz sand in a ratio 1:2 in volume is used (HSt2). This mortar showed a sufficient bio-receptivity in laboratory tests, while still providing a satisfactory mechanical strength [18].
- In walls 3 N&S a mortar with natural hydraulic lime (NHL 5.0) and trass, in proportion 1:1 vol is used (HT2); the aggregate is a mix of quartz sand and vermiculite (9:1 in volume). This mortar recipe is based on the positive effect of trass-lime binders and vermiculite on bio-receptivity, observed in previous laboratory tests [18]. Differently from previous tests, in this case NHL was used instead of air-hardening lime, in the attempt to confer higher strength to the mortar.
- In walls 4 N&S, bedding and pointing mortars are used: the bedding mortar is constituted by natural hydraulic lime (NHL 3.5) and cement (CEMIII-b) in 1:1 proportion in volume, mixed with quartz sand, with a binder: aggregate ratio 1:2 in volume. This mortar was shown to confer sufficient mechanical strength to the masonry, when combined with the selected brick [18]. The pointing mortar is based on air-hardening lime and trass (proportion 1:1 in volume) and quartz sand aggregate, with 1:2 binder:aggregate ratio in volume. This mortar showed a very good bio-receptive behaviour in previous laboratory tests [18].
- Also in walls 5 N&S, a combination of bedding and a pointing mortar is used. The bedding mortar is the same as in 4 N&S. The pointing mortar is a mixture of clay and natural hydraulic lime (NHL 3,5), with ratio 3:1 in volume, and with aggregate composed by quartz sand and vermiculite (1:1 in volume). Vermiculite is a light weight aggregate with a high porosity and ion-exchange capacity and thus expected to favour bio-receptivity [26]. The binder/aggregate ratio is 1:1 in volume. Barley straw is added to the mortar to reduce shrinkage cracks, while improving its bio-receptivity [27].

2.4. Capillary substrate

In the middle panel of each wall, a substrate layer is used between the masonry and the concrete structure, with the aim of absorbing water from the canal by capillarity and provide it to the masonry, favouring thereby the growth of plants. The capillary substrate mixture used in this experiment is made of soil (ACCAP 7120 by BVB substrates), with the addition of a biological binder, (Groenemorgen! 12 ZR by Groenemorgen), in proportion 9:1 in volume. The initial water content of the substrate mixture was enough to make the substrate sufficiently fluid for pouring it into the cavity.

2.5. Seeds and potted plants

Seeds of Wallflower (*Erysimum cheiri*) and Ivy-leaved Toadflax (*Cymbalaria muralis*) were either applied with corn-starch glue on the surface of the mortar joint (walls 1 N&S, 2 N&S and 3 N&S) or mixed in the pointing mortar (walls 4 N&S and 5 N&S). Ivy-leaved Toadflax has been selected as an example of a wall plant that often appears quay walls in the first weathering stage. Differently, Wallflower is a climax species that only appears when the wall is severely weathered. Both these wall plants can survive dry periods and live in an environment with a pH similar to that found in a masonry wall. Moreover, these plants have relatively thin and weak roots, factor which limit the risk of mechanical damage to the mortar.

Next to seeds, potted plants Trailing Bellflower (*Campanula poscharskyana)* and Ivy-leaved Toadflax were inserted at some locations in the walls. Plants were added at two different heights (at the top and bottom) in each of the three panels (Fig. 1). In the case of the middle panel, the potted plants can root into the substrate layer.

2.6. Construction of the walls

The walls were constructed at a building location and then moved to the site (Fig. 2 left). The substrate was poured in the cavity, 10 days after completion of the wall, when the masonry had acquired enough strength. The pointing mortar was applied after removing the outer part of the bedding mortar (up to 2 cm depth), directly after application. Some vertical joints were left without mortar, to favour water flowing and nesting of insects. On two spots at the right-end side of each panel, the mortar joints were not smoothed at the surface, but left protruding and rough. This way the influence of the surface roughness on bio-receptivity could be assessed.

In each panel, two bricks were positioned perpendicularly to the masonry, so that they would protrude about 5 cm from the surface. They were positioned to have the frog on the top surface, to easily collect rain water and organic material and favour plant growth.

When ready, the walls were transported to Breda and placed in the canal (Fig. 2 right). The lower part of the walls, up to 40 cm, is immersed in water. At this point the plants were potted; later, the sensors for monitoring of the climate and surface temperature of the panels were

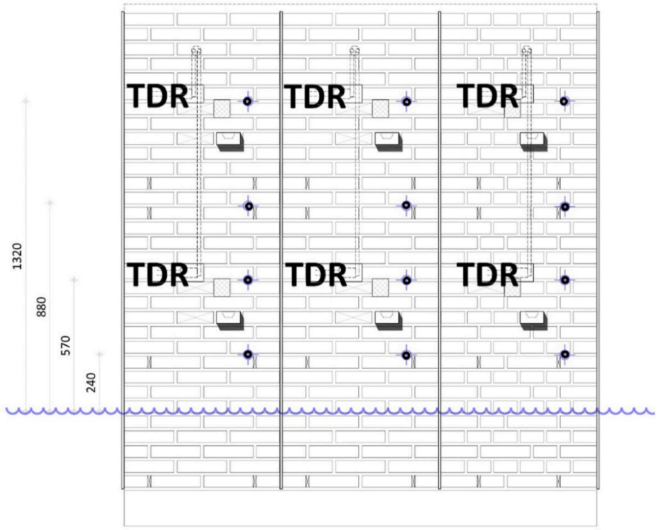


Fig. 3. Location of the TDR sensors in panel 4S; the dots indicate the sampling locations.

positioned.

2.7. *Monitoring of the walls*

The walls were monitored during a period of 24 months. The main aim of monitoring was to assess the influence of different variables (both building materials and orientation) on the vegetation growing on the masonry walls.

Visual and photographic monitoring of the germination of the seeds and the survival of seedlings and potted plants was carried out each three months, in the spring to autumn period. The occurrence of damage to the masonry was assessed at the end of the experiment, in June 2022, using the terminology reported in the MDCS damage atlas [28].

The moisture content in the walls, crucial for the growth of vegetation, was monitored by means of different methods and techniques. Infrared camera (FLIR T420) images were collected in different seasons. IR images provide information on the surface temperature: as evaporation at the surface of the wall leads to a decrease in temperature, wetter (colder) and drier (warmer) areas at the surface of the masonry can be spotted (e.g. Refs. [29,30]). It should be however considered that IR technique cannot provide precise information about the moisture content in the wall.

The moisture content (MC) at different depths in the walls was assessed in August 2020 and September 2021. The MC was measured gravimetrically, on powder samples collected at different heights and depths in the masonry wall and substrate behind (Fig. 3).

Samples were collected in the horizontal mortar joints and in the soil substrate behind the middle panel, in each N-walls and in wall 4S; additionally, samples were collected in bricks in panel 4 N.

The samples were then dried in an oven at 40 °C until they reached the constant weight and their moisture content calculated as follows:

MC [%] = 100 * (initial weight sample – dry weight sample) / dry weight sample

Time Domain Reflectometry (TDR) sensors (ACCLIMA 310-H) were used to monitor the moisture content in the mortar in time [31–34]. In June 2020, TDR sensors for moisture content were embedded in the mortar joints, at two different heights for each section of panel 4S, for a total of 6 TDR sensors (Fig. 3). The TDR sensors were connected to a datalogger. Data were recorded every 30 min for a period of about 4 months.

3. Results of monitoring

3.1. *Moisture measurements*

Moisture is crucial for the germination of the seeds and the survival of the potted plants. The presence of moisture in the wall has been monitored by different non-destructive and little destructive methods.

IR images of the panels recorded in June 2020, after a dry period, are reported in Fig. 4.

These images show that the middle panel has generally a lower temperature than the right and left panels, suggesting it is wetter at the surface. Colder areas are visible in the upper part of the walls; these areas are more clearly distinguishable in the middle panel, suggesting the substrate layer behind the wall keeps the wall wet. The lowest part of the N-walls and of 4S and 5S walls are clearly colder: most probably these brick layers are wet, due to water from the canal, rising into the wall by capillarity.

The moisture content distribution in the wall was assessed by collecting samples. The moisture content (MC) of samples collected in the first campaign of August 2020 resulted to be strongly affected by some short rain fall which occurred during the sampling period. Therefore, only the results of the second sampling campaign are considered here. Fig. 5 shows the MC in the mortar of the different panels of all N-walls. It is possible to observe that the MC is consistently higher in the middle panel, whereas the lowest MC values are generally recorded in the left panel. In the middle panels, the MC is higher in the lower part of the wall and decreases with height (apart for the substrate layer in which an irregular moisture distribution is observed, probably due to the presence of voids in the not homogeneously compacted soil substrate). The MC in the masonry of the middle panels is generally higher in depth than at the surface (with the exception of panel 5 N). The moisture distribution in

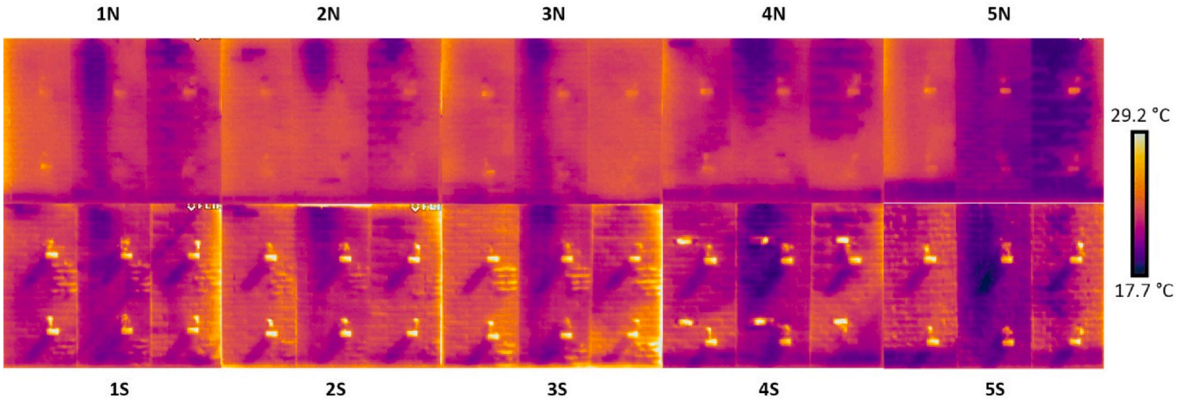
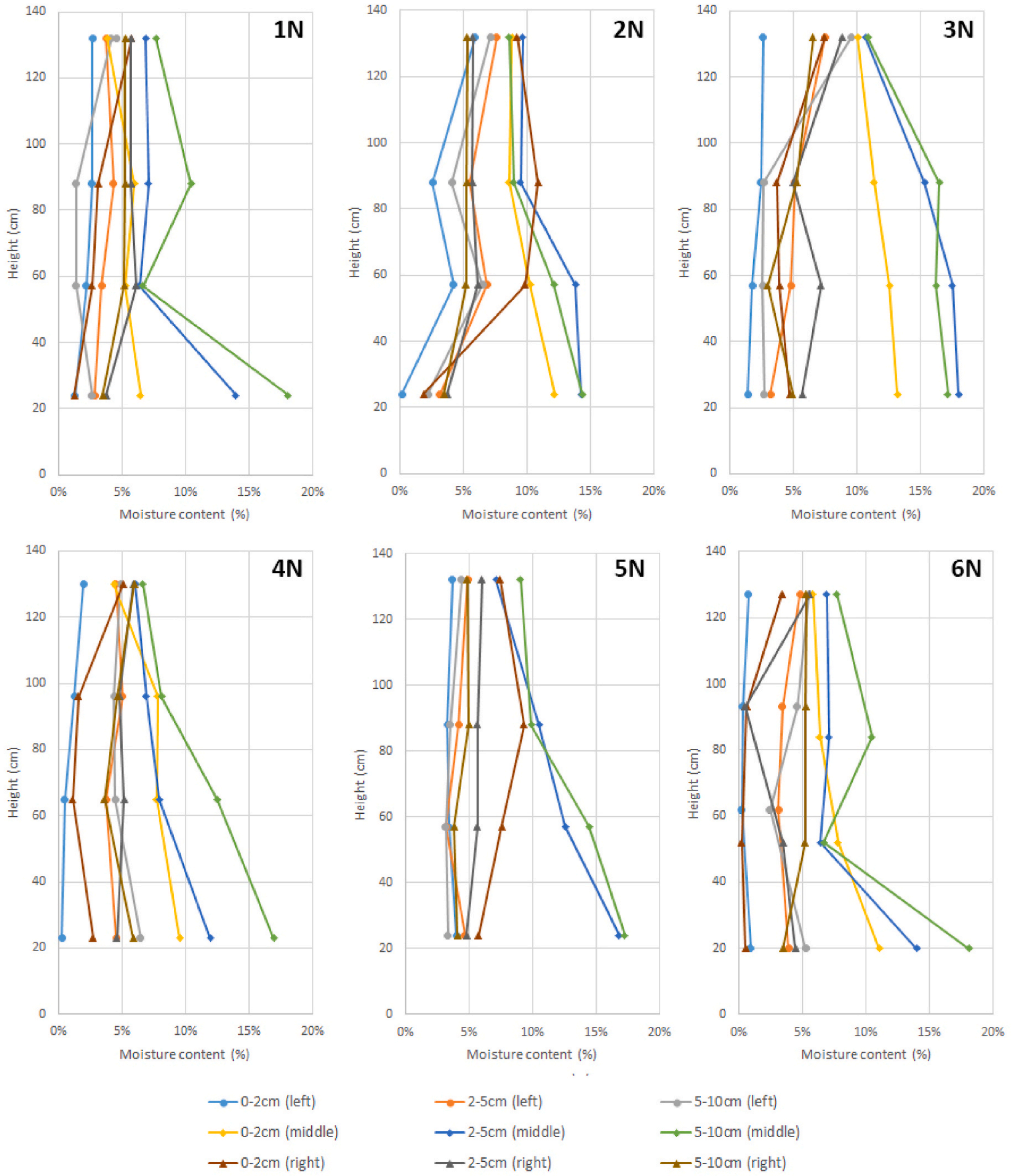


Fig. 4. IR images recorded on 23-06-2020 at 10:30 a.m., after a dry period of 3 days °



* MC at 0-2 depth in the middle panel is out of scale, varying between 35 and 46 wt%

Fig. 5. Moisture content distribution in the mortar at different heights and depths.

the masonry of the middle panels, increasing with depth and decreasing with height, suggests that water is transported by capillarity from the canal into the soil substrate layer and, from here, to the masonry.

Differently, in the left and right panels the MC remains generally constant along the height. This suggests no significant capillary rise occurs in the masonry in the absence of a soil substrate layer behind it.

Gravimetric measurements of the MC provide quantitative data, but they are affected by the moment of the sampling and do not give information on the evolution of the MC during time. To get insight into moisture content in the mortar during time, TDR sensors were placed in wall 4S. Fig. 6 reports the permittivity values collected in the period between June and October 2021. A high permittivity indicates a high moisture content; the observed daily changes in permittivity values are due to temperature changes.

The results show that in the middle panel, the permittivity is higher in the lower part of the wall (430 mm) than in the higher part (1200 mm); the opposite occurs in the left and right panels. This suggest that, whereas capillary transport of water from the canal into the substrate and to the masonry occurs in the middle panel, water from the canal does not rise high enough in the masonry of the left and right panel. These results are in agreement with those of the MC measurements.

3.2. *Visual and photographic monitoring of damage and vegetation*

Fig. 7 reports the state of the walls at the start (May 2020) and after 2 years of exposure (May 2022). There are different moist spots visible on

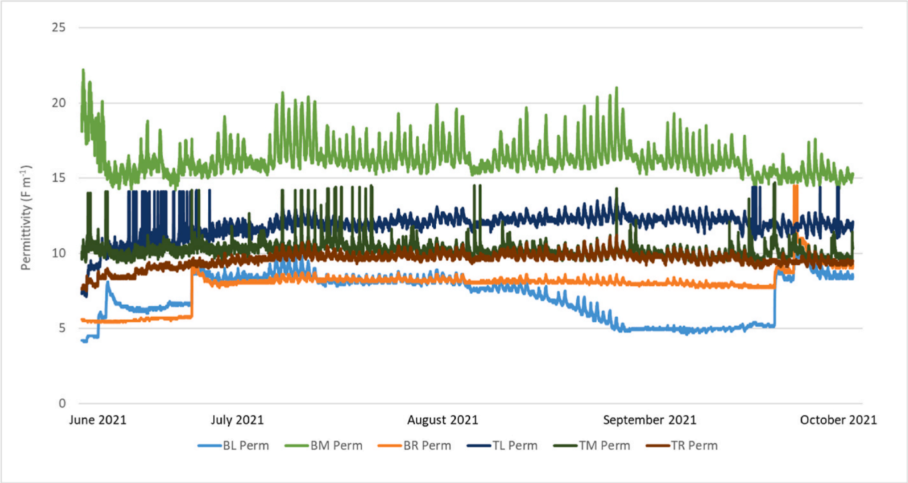


Fig. 6. Permittivity measured in the period 17 June 2021–15 October 2021 by TDR sensors positioned in wall 4S (BL = bottom left, BM = bottom middle, BR = bottom right, TL = top left, TM = top middle, TR = top right).

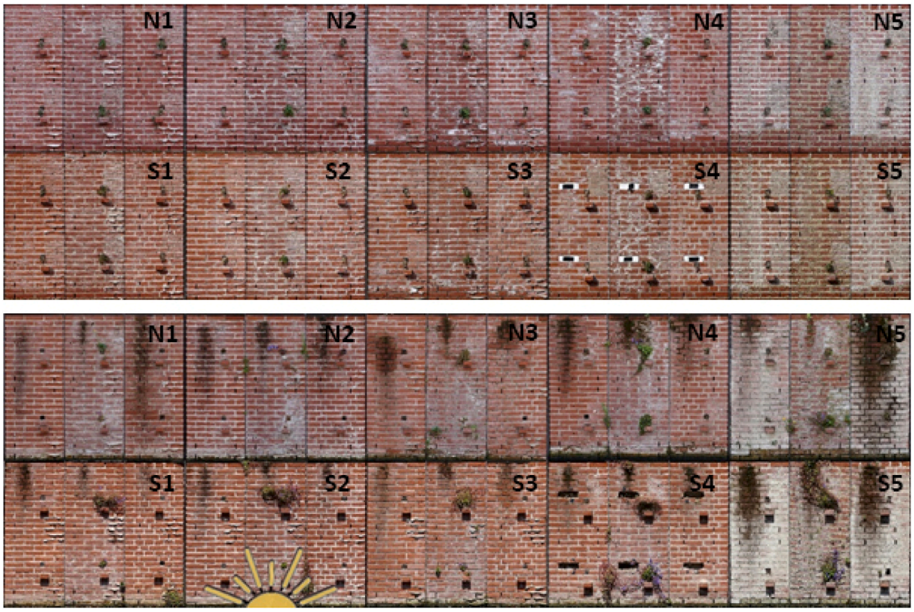
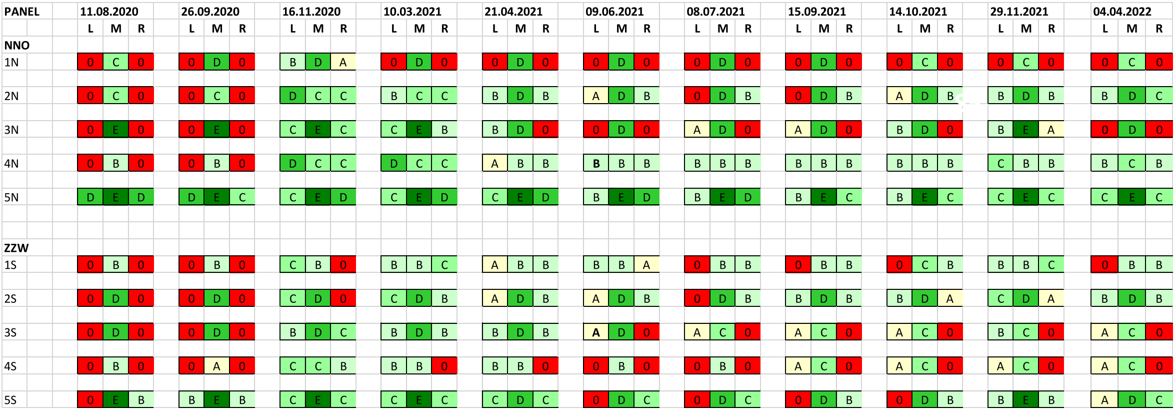


Fig. 7. Pictures of the walls taken in May 2020 (above) and May 2022, after 2 years of exposure (below).



PANEL	11.08.2020			26.09.2020			16.11.2020			10.03.2021			21.04.2021			09.06.2021			08.07.2021			15.09.2021			14.10.2021			29.11.2021			04.04.2022		
	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R	L	M	R
NNO																																	
1N	0	C	0	0	D	0	B	D	A	0	D	0	0	D	0	0	D	0	0	D	0	0	D	0	0	C	0	0	C	0	0	C	0
2N	0	C	0	0	C	0	D	C	C	B	C	C	B	D	B	A	D	B	0	D	B	0	D	B	A	D	B	B	D	B	B	D	C
3N	0	E	0	0	E	0	C	E	C	C	E	B	B	D	0	0	D	0	A	D	0	A	D	0	B	D	0	B	E	A	0	D	0
4N	0	B	0	0	B	0	D	C	C	D	C	C	A	B	B	**B**	B	B	B	B	B	B	B	B	B	B	B	C	B	B	B	C	B
5N	D	E	D	D	E	C	C	E	D	C	E	D	C	E	D	B	E	D	B	E	D	B	E	C	B	E	C	C	E	C	C	E	C
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2S	0	D	0	0	D	0	C	D	0	C	D	B	A	D	B	A	D	B	0	D	B	B	D	B	B	D	A	C	D	A	B	D	B
3S	0	D	0	0	D	0	B	D	C	B	D	B	B	D	B	**A**	D	0	A	C	0	A	C	0	A	C	0	B	C	0	A	C	0
4S	0	B	0	0	A	0	C	C	B	B	B	0	B	B	0	0	B	0	0	B	0	A	C	0	A	C	0	A	C	0	A	C	0
5S	0	E	B	B	E	B	C	E	C	C	E	C	C	D	C	0	D	C	0	D	C	0	D	B	0	D	B	B	E	B	A	D	C

Fig. 8. Germination of seeds (combined data Wallflower and Ivy-leaved Toadflax) in the panels in the period August 2020–April 2022. The different colours and letters give the amount of observed seedlings: O = no sprouts; A = 1 seedling; B: 2–5 seedlings; C = 6–25 seedlings; D = 26–50 seedlings; E = 51–500 seedlings. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

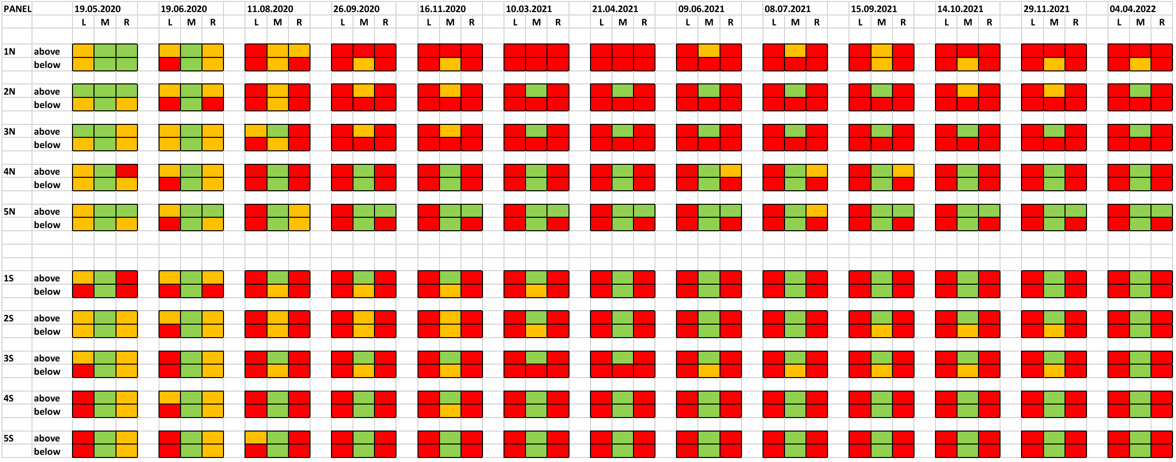

Fig. 9. Survival of the potted plants in the panels in the period May 2020–April 2022. The different colours indicate the health of the plants: green = alive and healthy; orange: suffering, but with green parts; red = dead. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the brick masonry: the most evident is present directly under the rain water collector, where leakage occurred. At these locations algae and mosses are present too. Algae and mosses are most evident in walls 5 N and 5S: here significant leaching of mortar components (lime and clay) has occurred as well, resulting in soiling of the surface.

A whitish/greyish deposit developed mainly in the middle panel of all the walls. The whitish/greyish deposit is probably due to leaching of lime components present in the mortar, in combination with soluble salts and soiling, probably favoured by the high moisture content in the middle part of the wall (see section 3.1). The deposit is most evident in walls 5 N&S, where it covers the entire surface of the wall.

Apart for the above described damage, which is mainly aesthetic, only limited damage to the materials is observed. In few cases, some bricks nearby the water level show delamination, possibly caused by frost (these bricks are probably saturated with water and in the winter of 2021 the temperature dropped below 0 °C [35]). The pointing mortar in panels 5 N and 5S shows craquele and erosion; this last is most severe nearby the water level and in the middle panels.

The germination of the seeds during time has been recorded by counting the amount of seedlings in each panel. Fig. 8 reports a summary of the evolution of the germination in the period May 2020–April 2022. Based on this overview, it is evident that panel 5 N, and somewhat less, panels 5S and 4 N, show the best results in terms of vegetation. Germination of Wallflower occurred only directly after the start of the experiment; differently, the germination of Ivy-leaved Toadflax seeds occurred in the autumn of 2020 and 2021. The first flowers of Wallflower were observed after two years, in the spring 2022, in the middle panels of N-walls; this confirms the preference of this plant for light shadow areas. Differently, the seedlings of Ivy-leaved Toadflax flowered within the first year, independently from the orientation.

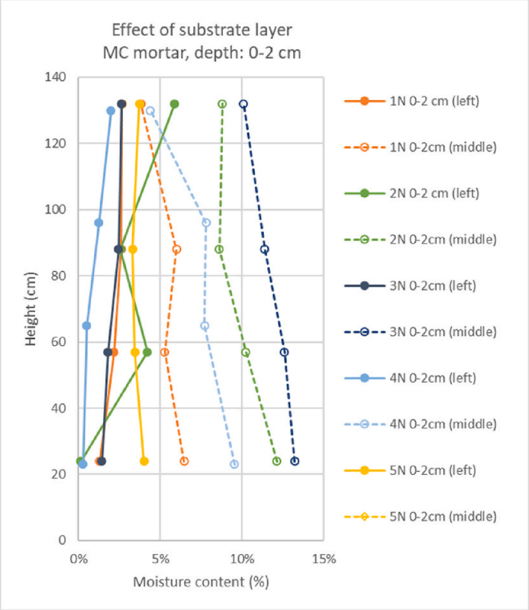

Fig. 10. Moisture content in mortar in the left and middle panel of N-walls.

The survival of the potted plants was monitored by recording their conditions at regular time intervals. Fig. 9 shows that, with the exception of the right panel of wall 5 N, plants did not survive in the absence of capillary substrate layer behind the masonry. In the presence of substrate behind the masonry (middle panels), plants could manage to survive in most of the walls. In general, plants potted at higher level in the wall survived better that those potted at lower level. The best results are obtained in walls 4 N and 5 N. The worse results are reported for panel 1 N: in this case also plants in the middle panel died within few months.

4. Discussion – effects of material and environmental variables on vegetation

4.1. Effect of mortar type

Clear differences in vegetation between walls with different mortars are observed. Pointing mortar CHstVB (walls 5 N&S) performs the best in terms of bio-receptivity: for this mortar, germination occurs in all panels, independently from the MC in the outer layer of the mortar (Fig. 8). Mortar CHstVB is the most favourable for vegetation, followed by pointing mortar ATst2; mortar MMmk gave the worse results; mortars Hst2 and HT2 showed a comparable behaviour, only slightly better than MMmK mortar.

These results confirm results of previous laboratory research by the authors [18] and are in agreement with the expectations, based on literature (see section 2.3).

The approach of using different bedding and pointing mortars resulted successful for favouring bio-receptivity of the mortar joints, while providing sufficient strength to the masonry.

Fig. 11. Wallflower growing in the cracks present in a rough mortar joint.

4.2. *Effect of capillary substrate*

The results of the monitoring unanimously confirm that the presence of a layer of capillary substrate behind the masonry wall is of crucial importance in providing moisture to the mortar and thus to favour germination of seeds and survival of both seedlings and potted plants. The water of the canal is absorbed by the substrate by capillary suction, stored and provided to the mortar joints. The height reached by water transported in a material by capillary suction depends on several variables. Among these variables, pore size is a crucial one: the smaller the radius of the capillary pores, the higher the level which can be reached by water (e.g. [36]). These results confirm that this soil substrate has, (next to other favourable properties such as hydrophilic behaviour and good pore connectivity) pores small enough to ensure capillary transport higher up to at least ~0.9 m. Moreover, the presence of high moisture content in the mortar joint means that the mortar could absorb water from the substrate and retain it during dry periods; this suggests that the mortars used have a sufficient amount of small pores. Additional investigation on porosity, pore size and moisture transport behaviour of these materials can clarify these points and help to further improve bio-receptivity.

Fig. 10 shows the difference between the MC in the middle panel, with substrate behind, and the left panel, with the same thickness but no substrate layer behind. The thickness of the substrate layer is enough to support germination of the seeds and to provide water for the survival of the plants during the dry periods. However, a too high moisture content in the wall can have a negative effect on wall-plants, as shown by the fact that, generally, plants in the lower part of the middle panel survive less than those at higher level in the wall (see Fig. 6).

4.3. *Effect of thickness of masonry*

The thickness of the wall has a limited effect on the moisture content and bio-receptivity of the masonry. The MC in left and right panels is generally not enough for allowing germination of the seeds and survival of the potted plants.

4.4. *Effect of other variables*

Irregularities, such as protruding rough mortar joints, empty vertical joints and dilation joints, were shown to favour germination of seeds and subsequent plant growth. This is particularly evident in the left and right panels and it is probably related to the fact that these irregularities offer grip for plants (Fig. 11). This confirms the positive effect of surface roughness on bio-receptivity reported in the literature [13,37]. Germination of Wallflower is observed also in the frog of the protruding bricks, where rain water accumulates; however, seedlings did not develop into plants, due to insufficient supply of organic material.

The effect of the orientation on the moisture content is assessed by comparing the MC measured in walls 4 N and 4S (Fig. 12). No significant and consistent effect of the orientation on the moisture content is observed. Orientation seems to have only a slight effect on vegetation. In the case of germination of the seeds, a slightly better behaviour is observed in N-walls. Similarly, the survival of potted plants is generally better in N-walls than in S-walls (apart for 1 N&S). A possible reason might be the reduced evaporation in N-walls, exposed to North.

5. Conclusions

The research has experimentally assessed the effect of different variables on the moisture content and bio-receptivity of quay walls for herbaceous plants. Ten quay walls, each of size 2 m × 2 m x 0.43 m (l x b x d) and subdivided in three vertical panels, were built and placed in a

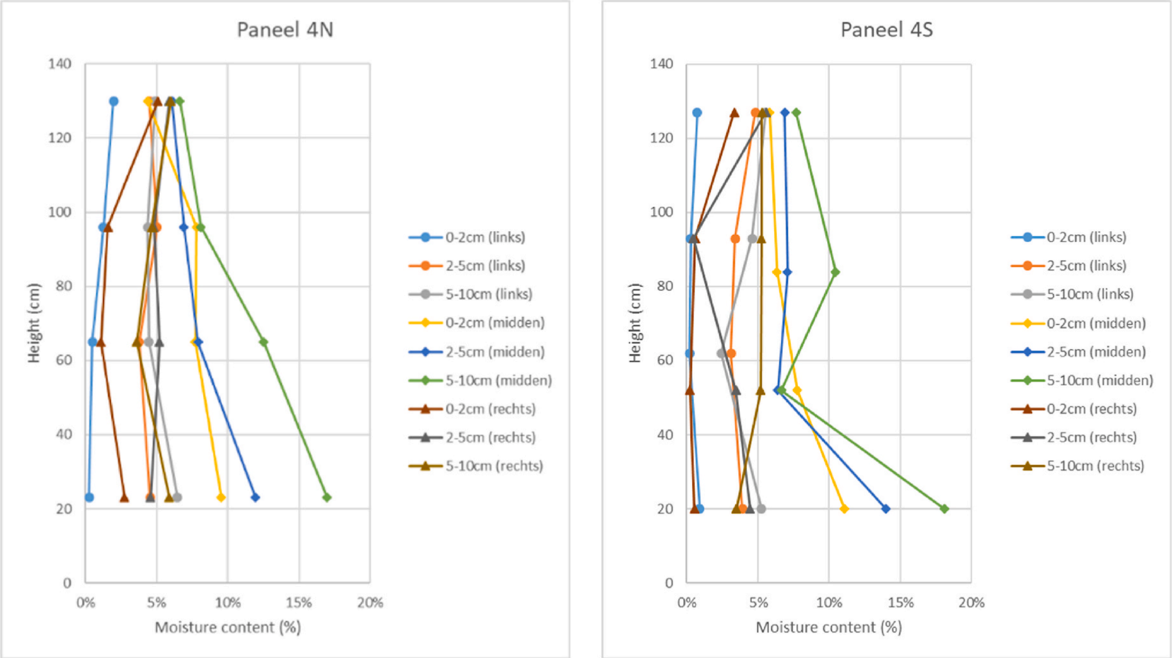

Fig. 12. Moisture content in walls 4 N and 4S

canal in Breda and monitored for a period of about 2 years.

The results indicate that the presence of a soil substrate layer with high capillary absorption and positioned between the masonry wall and the concrete structure, has a clear positive impact on vegetation in the wall, by providing a high and constant water supply to the masonry. In the absence of the capillary active substrate, the masonry is not able to absorb an retain enough (rain)water to allow for significant germination and plant growth; this is valid both for half-brick and one-brick thick panels.

Next to the presence of substrate providing sufficient moisture to the masonry, the growth of vegetation is also strongly affected by the mortar type. Cement-based mortars show the less satisfactory results; mortar based on NHL and air-hardening lime, with the addition of vermiculite and organic material, such as clay and barley straw, show in general a good bio-receptivity. The strategy of using a mechanically strong bedding mortar in combination with a weaker but more bio-receptive pointing mortar proven successful at favouring bio-receptivity, while providing sufficient strength to the masonry.

Irregularities, such as protruding mortar joints with a rough surface, the presence empty vertical joints and dilation joints, were shown to have a positive effect on the growth of plants from seeds.

The results of this research will inform the decisions related to the construction of the new quay wall in the city of the Breda and can provide direction for further developing green quay walls. Some questions are left which require additional research: these are related, next to further characterization of the moisture transport of the soil substrate, to the optimal thickness of the substrate layer and to the optimization of the durability the most bio-receptive pointing mortar, in order to limit leaching and erosion.

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CRediT authorship contribution statement

Koen Mulder: Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Barbara Lubelli:** Writing – original draft, Methodology, Investigation, Conceptualization. **Edwin Dijkhuis:** Writing – review & editing, Resources, Investigation.

Data availability

Data will be made available on request.

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