Influence of brick and mortar properties on bioreceptivity of masonry
Results from experimental research

Lubelli, B.; Moerman, J.; Esposito, R.; Mulder, K.

DOI
10.1016/j.conbuildmat.2020.121036
Publication date
2021
Document Version
Final published version
Published in
Construction and Building Materials

Construction and Building Materials 266 (2021) 121036

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Influence of brick and mortar properties on bioreceptivity of masonry – Results from experimental research

B. Lubelli [a,*], J. Moerman [a], R. Esposito [b], K. Mulder [a]

[a] Delft University of Technology, Faculty of Architecture and the Built Environment, Julianalaan 134, 2628BL Delft, The Netherlands
[b] Delft University of Technology, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, Delft, The Netherlands

HIGHLIGHTS

- Moisture transport of brick-mortar combination is crucial for bioreceptivity.
- The composition of the mortar strongly affects its bioreceptivity.
- Lime-trass and, in lower extent, NHL binders show the best bioreceptivity.
- A compromise is needed between bioreceptivity and mechanical strength.

ARTICLE INFO

Article history:
Received 12 May 2020
Received in revised form 24 August 2020
Accepted 17 September 2020
Available online 5 October 2020

Keywords:
Bioreceptivity
Brick
Mortar
Binder
Porosity
Mechanical strength

ABSTRACT

The effect of mortar and brick properties on the growth of ivy-leaved toadflax (*Cymbalaria muralis*) and yellow corydalis (*Pseudofumaria lutea*) has been investigated in laboratory. Different mortar compositions were designed and tested in combination with two different bricks.

Highly porous bricks and mortars showed good bioreceptivity; mortars with lime-trass and, in lower extent, those with natural hydraulic lime binder, gave the best results in terms of bioreceptivity. The addition of vermiculite to the mortar was beneficial for plant growth.

The brick-mortar combinations most favourable for plant growth were those with estimated low compressive and flexural bond strength values. Proposals are advanced for obtaining a compromise between mechanical strength and bioreceptivity.

1. Introduction

Traditionally, biological growth on buildings and structures is an undesired event, as this can cause damage to building materials, due to pressure generated by the roots and/or to chemical reactions leading to dissolution of materials components (e.g. [1]). Besides, biological growth is often associated to feelings of untidiness and neglect. The terms "biodeterioration" and "biodegradation", used to address biological growth on building materials, reflect this negative connotation.

However, in the last years this attitude is slowly changing: urban ecology gained increasing attention and greening the city has become one of the aims of many municipalities. In particular, walls, and among these quay walls, have the potential to be ecologically engineered to encourage a greater diversity and range of species [2]. Research has therefore recently focused on the study of engineering solutions and materials to favour biological growth on walls.

The capacity of a wall to act as habitat for biological growth depends on several variables, including wall dimension, construction materials, inclination, microclimate, exposure, accessibility, wall age, sediment and humus and moisture [3,2]. The bioreceptivity of construction materials is one of the important variables. Bioreceptivity can be defined "the aptitude of a material to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration" or as "the totality of material properties that contribute to the establishment, anchorage and development of fauna and/or flora" [4]. Guillitte further differentiates between "primary bioreceptivity", which indicates the initial potential of colonization, and "secondary" and "tertiary" bioreceptivity which refers to the bioreceptivity of a material following changes in its properties due to biological growth or human action respectively. Another difference is made between "intrinsic bioreceptivity", which depends mainly on the properties of the

* Corresponding author.
E-mail address: b.lubelli@tudelft.nl (B. Lubelli).

https://doi.org/10.1016/j.conbuildmat.2020.121036
0950-0618/© 2020 The Author(s). Published by Elsevier Ltd.

material and "extrinsic" bioreceptivity, in which an exogenous deposit (such as soil, dust or organic particle) substantially modifies the material properties and makes biological growth possible.

Different variables contributes to the intrinsic bioreceptivity of a material: these include moisture transport behaviour (including water absorption, moisture retention, permeability and the related characteristics, such as porosity and pore size distribution), pH, roughness and presence of imperfections such as cracks, voids, fractures etc. [2]. As the presence of water is crucial for biological growth, materials allowing for high absorption and high water retention (i.e. material with sufficient open porosity and a bimodal pore size distribution with both coarse and fine pores) can theoretically provide favourable conditions. Studies confirm that the moisture transport properties of a material (e.g. open porosity, permeability, water absorption kinetics, etc.) can significantly affect biocolonization [5]. A study on growth of algae on clay bricks mentions surface roughness as another important factor [6].

An interesting review of the bioreceptivity of different building materials and of the variables affecting it, is given in [5]. Among building materials, masonry seems to have a better bioreceptivity and supports a larger range of species than monolithic concrete. The growth of plants is generally observed in relatively old masonry, more often in cases where the mortar has (partially) lost its original internal cohesion and its adhesion to the brick. This suggests that presence of (fine) cracks and voids, as well as the roughness of the surface of the masonry units and mortar have a positive influence on biological growth on walls. The pH value is another crucial factor affecting plant growth [5,7]. Plants cannot grow at very high pH, like the one present in fresh, not yet carbonated mortar or concrete. The pH can be up to a certain level adjusted by the mortar composition; a mortar with a high porosity and permeability will carbonate faster; the decrease of pH due to carbonation will positively affect plant growth. Based on the literature, lime-based mortars seem to be more prone for biological growth than cement-based ones [8]. This might be due to their faster carbonation, which is in turn related to their generally better permeability in comparison to natural hydraulic lime and cement-based mortars [9,10]. Moreover, the generally higher water absorption and retention of lime-based mortars in comparison to mortars based on hydraulic binders [10], may contribute as well to their better bioreceptivity, by favouring a sufficient and constant moisture content in the material. These considerations suggest that hydrated lime and, in case a hydraulic binder is necessary, hydraulic lime or a mixture of lime and a pozzolanic material, such as trass powder, could be better alternatives than cement. Besides, some cement types seem to show a higher bioreceptivity than others: for example, magnesium phosphate cement [11] or blast furnace slag cement are shown to have a better behaviour than Portland cement (Ottele, personal communication).

Despite the existence of some studies on bioreceptivity of building materials, literature on the engineering of material compositions is very scarce and mostly limited to concrete [12,13]. To the authors' best knowledge, no specific study on the effect of mortar composition on its bioreceptivity exists. As in masonry biological growth mainly occurs in mortar, elucidating the effects of the mortar composition on its intrinsic bioreceptivity is of crucial importance for favouring bioreceptivity of masonry walls.

The research presented in this paper, carried out in the framework of the European UIA project "Inclusive Quays", aims at improving the bioreceptivity of brick masonry with the final aim to build nature inclusive quay walls in the Dutch city of Breda. First of all, the effects of components (binder, aggregates, additives) on the physical and mechanical properties of the mortar are assessed; then the bioreceptivity of the mortars in masonry made with two different brick types is evaluated. As the requirements posed to masonry for bioreceptivity may be different, if not opposite, to those of sufficient strength and durability, both these aspects are considered. Based on both the bioreceptivity and estimated mechanical strength of the brick-mortar combination, a proposal for promising brick-mortar combinations to be tested in a following phase is made.

2. Materials and methods

2.1. Materials and specimen preparation

2.1.1. Brick

Two types of bricks (B2 and B8) have been selected to be tested in combination with different mortar types (Table 1, Fig. 1). These bricks have been chosen on the basis of some preliminary water absorption measurements carried out on several brick types, differing in clay type, production process and firing temperature. Bricks with different moisture transport properties have been selected in order to assess the effect of the brick properties on the bioreceptivity of the masonry. Bricks with perforations or a frog have been selected, as these cavities can be used for water or soil storage within the wall construction, probably favouring bioreceptivity. Only bricks declared by the producer as frost-resistant, i.e. within class F2 according to EN 771-1 [14], were chosen.

The selected bricks have been further characterized in terms of density, porosity, capillary water absorption, pore size distribution and mechanical strength.

2.1.2. Mortar

The composition of the mortars has been determined with the aim of investigating the effect of the following variables on bioreceptivity, moisture transport properties and mechanical strength:

- Binder/aggregate ratio: two binder/aggregate ratios have been selected: 1:2 and 1:4 in volume.
- Grain size distribution of the aggregate: well-graded quartz sand (CEN Standard Sand EN 196-1 [15]) and a gap-graded sand (obtained by sieving the 1 to 2 mm portion in the CEN standard sand) have been used.
- Type of aggregate: quartz aggregate has been used. In some of the mortars, the effect of an addition of expanded vermiculite (Voorzaaivermiculiet, Agra F2, Makkelijke Moestuin) has been investigated; part of the sand was replaced by vermiculite, to obtain a sand/vermiculite ratio 1:1 in volume. Vermiculite is a hydrous phyllosilicate mineral, which undergoes significant expansion when heated. The result is a very porous material, which is often used as a substrate for seed germination.
- Type of binder: different binders have been used, either alone or in combination. Hydrated lime (Supercalco 90) has been used in combination with trass in the proportion of 1:1 in volume (AT mortars). Natural hydraulic lime (Saint Astier NHL 3,5) has been used as only binder (H mortars) and in combination with blast furnace slag cement CEMIII-b (HC mortars), in the proportion of 1:1 by volume.

Next to self-mixed mortars, two ready-to-use mortars, representative of basic mortar types often used in the Netherlands in masonry walls, have been tested as comparison: Remix Masonry mortar without lime (MMzK) and Remix Masonry mortar with lime (MMmK). According to the information provided by the seller of the product, both mortars are based on Portland cement, with (MMmK) or without (MMzk) the addition of about 5% (as weight % of the dry mix) of hydrated lime; the aggregate is a quartz sand (with a well-graded grain size distribution (max grain size 4 mm) with the addition of a small percentage (4–6%) of limestone powder; an air-entraining agent is used as additive.

Table 1
Bricks selected for the tests.

Brick code	Product name	Nominal size	Production process	Cavities
B2	Wienenrberger Terca Beerse – Basia Spaans rood	210x100x50mm	soft mud moulded brick	frog
B8	Wienerberger Terca Heteren - Avenue Rood Naturel Onbezand strengpers WF	210x100x50mm	Extruded	6 vertical perforations

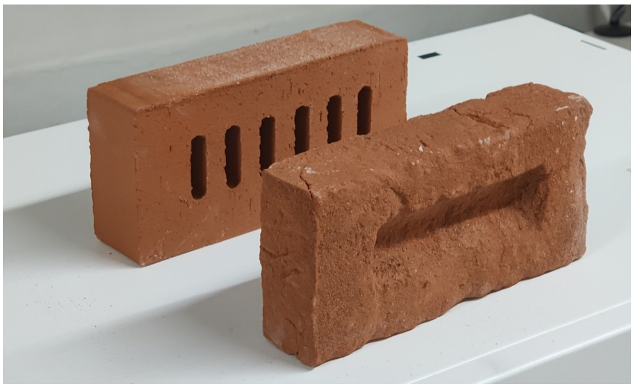

Fig. 1. Bricks B2 with frog and B8 with perforations.

In order to speed up the growth of plants, seeds of ivy-leaved toadflax (*Cymbalaria muralis*) and yellow corydalis (*Pseudofumaria lutea*) were added to some of the mortars. For each mortar type, specimens with and without seeds were prepared. Table 2 summarizes the composition of the mortars used in this research.

The water content of the fresh mortar was determined as that sufficient to obtain a spreading of 160 ± 5 mm, measured using a flow table, according to the standard NEN EN 1015-3 [16].

The water content of the fresh mortars is reported in Fig. 2. As the water content for mortars of the same composition, with and without seeds, is identical, a single value is reported. It is clear that the presence of vermiculite increases the water demand considerably.

For each mortar type, two different series of specimens were prepared, to be used for different tests:

- Slabs with a size of about 210 × 100 × 20 mm: For each mortar type, 2 slabs were prepared. These slabs were prepared on bricks of type 2 (B2) and detached from the brick after 7 days of curing. In order to facilitate the detachment of the mortar slab without affecting the moisture transport between brick and fresh mortar, a plastic net was used between the mortar and the brick. These specimens were used for the measurement of the water absorption.
- Mortar prisms of the size of 160 × 40 × 40 mm: these specimens were prepared in polystyrene moulds. For each mortar type, 3 prisms were prepared. These specimens were used to measure the compressive strength of the mortars and the carbonation depth.

The mortar specimens, both slabs and prisms, were cured according to the standard NEN-EN 1015-11 [17] They were stored for a period of 7 days (of which the first 2 days inside the mould) under plastic; afterwards, they were stored in a room with a RH of 65 ± 5%, until the moment the characterisation tests were carried out.

2.1.3. Brick-mortar combinations

While microorganisms such as algae and mosses can grow on brick and natural stones, plant growth (which is the object of this work) generally occurs in mortar joints. Therefore, assessing the bioreceptivity on mortar specimens could have been an option. However, as moisture content in the substrate is one of the most relevant variables affecting plant growth, and this is affected by the moisture transport properties of the brick/mortar combination [18], the use of brick/mortar specimens has been preferred.

All prepared brick–mortar combinations are reported in Table 3. For each combination, both specimens without and with seeds mixed in the mortar were prepared. One brick–mortar specimen was prepared for each combination. The code of the brick–mortar combination is given as follow: mortar type - brick type - without (ref) or with seeds (seeds), e.g. "Hst2-B2-seeds" is built by mortar with NHL binder, 1:2 binder-aggregate ratio and well-graded sand with the addition of seeds; the mortar is combined with a brick type B2.

Each specimen consisted of 2 bricks and two mortar joints. Mortars were prepared as described in section 2.1.2; bricks were prewetted prior to the application of the mortar. The surface of the mortar joint was not smoothed, but raked rough, in order to favour bioreceptivity. Once prepared, brick–mortar specimens were stored under plastic for 7 days and then placed outside (autumn 2019). A polystyrene structure was designed to position all stacks with a slope of 20 degrees, lifted from the ground (Fig. 3). In order to provide all specimens similar exposure conditions, they were protected from rain (which could reach the stacks in different amounts depending on their location) but sprayed with water at regular time intervals.

2.2. Methods

2.2.1. Characterization tests on brick

The water absorption by capillarity of the bricks was measured according to EN 772-11 [19]. Measurements were carried out in threefold. The average water absorption coefficient (WAC) and the initial rate of absorption (IRA) of the bricks have been calculated. The WAC is the slope of the initial, linear part of the absorption curve; the IRA is the amount of water absorbed per unit of area in the first minute of the test. After saturation by capillarity at atmospheric pressure, the density and porosity of the bricks was assessed according to the following procedure [20]: the bricks were immersed in water for one week; then the saturated weight in water and in air was measured and their density (D, kg/dm^3) and porosity (P, vol%) calculated as follows:

$$D = 1000 * \frac{m_d}{(m_a - m_w)} \tag{1}$$

$$P = 100 * \left(1 - \frac{D}{2650}\right) \tag{2}$$

where:
m_d = mass of the dry brick
m_a = mass of the saturated brick in air
m_w = mass of the saturated brick in water
and where 2650 kg m^{-3} is the density of a stone-like material with no porosity [20].

The compressive strength of the bricks, having length l_u, height h_u and thickness t_u, was determined in agreement with EN 772-1. [14] The test was carried out through a displacement-controlled apparatus including a hydraulic jack with 300-ton capacity. The

Table 2
Composition of mortars.

code	b/a ratio	binder type	Aggregate type	grain size sand (mm)	Seeds
MMzK	Unknown	Portland cement	sand + limestone powder	Well-graded (max 4 mm)	no
MMzK-S	Unknown	Portland cement	sand + limestone powder	Well-graded (max 4 mm)	yes
MMmK	Unknown	Portland cement + hydrated lime	sand + limestone powder	Well-graded (max 4 mm)	no
MMmK-S	Unknown	Portland cement + hydrated lime	sand + limestone powder	Well-graded (max 4 mm)	yes
HCst2	1:2	NHL 3.5/CEMIII-b	sand	0.08–2	no
HCst2-S	1:2	NHL 3.5/CEMIII-b	sand	0.08–2	yes
Hst2	1:2	NHL 3.5	sand	0.08–2	no
Hst2-S	1:2	NHL 3.5	sand	0.08–2	yes
ATst2	1:2	hydrated lime + trass	sand	0.08–2	no
ATst2-S	1:2	hydrated lime + trass	sand	0.08–2	yes
HCsf2	1:2	NHL 3.5/CEMIII-b	sand	1–2	no
HCsf2-S	1:2	NHL 3.5/CEMIII-b	sand	1–2	yes
Hsf2	1:2	NHL 3.5	sand	1–2	no
Hsf2-S	1:2	NHL 3.5	sand	1–2	yes
ATsf2	1:2	hydrated lime + trass	sand	1–2	no
ATsf2-S	1:2	hydrated lime + trass	sand	1–2	yes
HCvt2	1:2	NHL 3.5/CEMIII-b	sand + vermiculite	1–2	no
HCvt2-S	1:2	NHL 3.5/CEMIII-b	sand + vermiculite	1–2	yes
Hvt2	1:2	NHL 3.5	sand + vermiculite	1–2	no
Hvt2-S	1:2	NHL 3.5	sand + vermiculite	1–2	yes
ATvt2	1:2	hydrated lime + trass	sand + vermiculite	1–2	no
ATvt2-S	1:2	hydrated lime + trass	sand + vermiculite	1–2	yes
HCst4	1:4	NHL 3.5/CEMIII-b	sand	0.08–2	no
HCst4-S	1:4	NHL 3.5/CEMIII-b	sand	0.08–2	yes
Hst4	1:4	NHL 3.5	sand	0.08–2	no
Hst4-S	1:4	NHL 3.5	sand	0.08–2	yes
ATst4	1:4	hydrated lime + trass	sand	0.08–2	no
ATst4-S	1:4	hydrated lime + trass	sand	0.08–2	yes
HCsf4	1:4	NHL 3.5/CEMIII-b	sand	1–2	no
HCsf4-S	1:4	NHL 3.5/CEMIII-b	sand	1–2	yes
Hsf4	1:4	NHL 3.5	sand	1–2	no
Hsf4-S	1:4	NHL 3.5	sand	1–2	yes
ATsf4	1:4	hydrated lime + trass	sand	1–2	no
ATsf4-S	1:4	hydrated lime + trass	sand	1–2	yes
HCvt4	1:4	NHL 3.5/CEMIII-b	sand + vermiculite	1–2	no
HCvt4-S	1:4	NHL 3.5/CEMIII-b	sand + vermiculite	1–2	yes
Hvt4	1:4	NHL 3.5	sand + vermiculite	1–2	no
Hvt4-S	1:4	NHL 3.5	sand + vermiculite	1–2	yes
ATvt4	1:4	hydrated lime + trass	sand + vermiculite	1–2	no
ATvt4-S	1:4	hydrated lime + trass	sand + vermiculite	1–2	yes

MMzK: Masonry mortar without lime.
MMmk: Masonry mortar with lime.
H: natural hydraulic lime 3,5 (NHL 3,5).
AT: hydrated lime + trass.
HC: natural hydraulic lime + cement.
st: 0.08 to 2 mm sand.
sf: 1 to 2 mm sand.
vt: 1 to 2 mm sand + vermiculite.

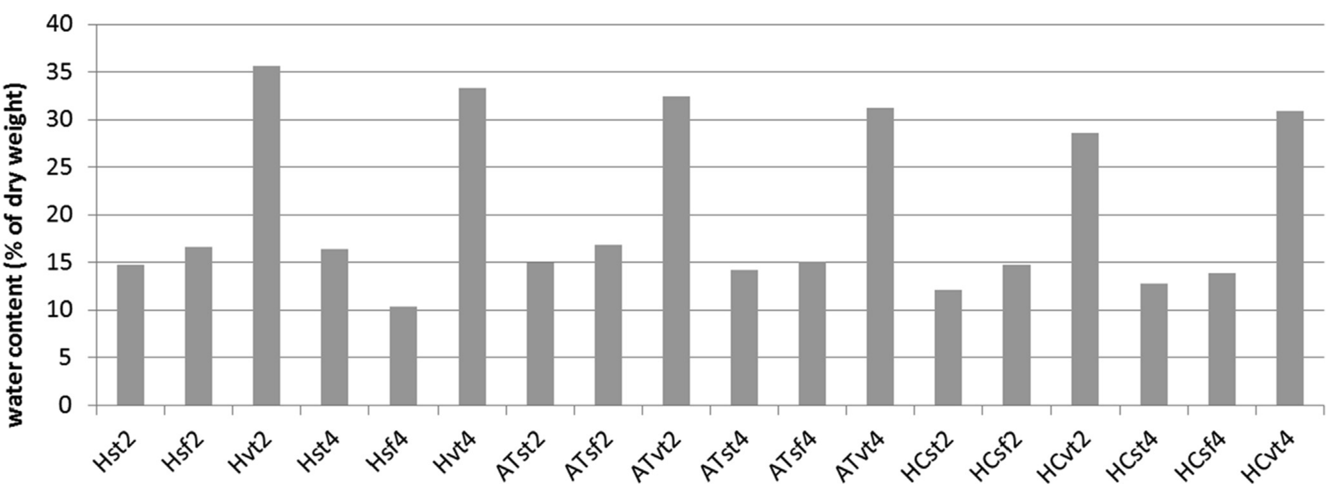

Fig. 2. Water content (100* weight water/weight dry components) of the fresh mortars.

Table 3
Brick-mortar combinations.

	MMzK	MMmK	HCst2	Hst2	ATst2	HCsf2	Hsf2	ATsf2	HCvt2	Hvt2	ATvt2	HCst4	Hst4	ATst4	HCsf4	Hsf4	HCvt4	Hvt4
B2	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
B8	x	x	x	x	x	x	x	x				x	x	x	x	x		

Fig. 3. Brick-mortar specimens in outdoor conditions.

hydraulic jack lifts a steel plate, the active side, and there is a passive load plate at the top. A hinge between the load cell and the top steel plate reduces possible eccentricities during loading. A load cell that measures the applied force is attached to the top steel plate. The loading direction was perpendicular to the brick bed face. For both types of bricks tested, the rate of the jack displacement was set to 0.01 mm/s in order to reach the maximum force in not less than 2 min. Tests have been carried out on 6 specimens for each type of brick.

The compressive strength of the masonry unit $f_b{}^*$ is determined as follows:

$$f_b^* = \frac{F_{max}}{l_u t_u} \tag{3}$$

where F_{max} is the maximum force, l_u and t_u are the length and thickness of the masonry unit, respectively.

Following the Annex A of standard EN 772-1 [14], the normalised compressive strength of the masonry unit f_b is determined as:

$$f_b = \delta \cdot f_b^* \tag{4}$$

where δ is the shape factor determined in agreement with Table A.1 of the standard EN 772-1 [14], that for the studied bricks is equal to 0.755 ± 0.005.

2.2.2. Characterization tests on mortar

The water absorption by capillarity of the mortar was measured according to the same procedure used for the brick. In this case, specimens of the size 50 × 50 × 20 mm were cut from the mortar slab and the water absorption was measured through the 50 × 50 mm surface, originally in contact with the brick. When the mortar specimens reached a constant weight, they were immersed in water, and their porosity and density were determined, according to the same procedure as used for the brick (see section 2.2.10 [20]). For each mortar composition, only mortars without the additions of seeds were measured. All measurements were carried out in threefold.

The compressive strength of the mortar prisms (with and without seeds) was measured according to the procedure described in the standard NEN EN 1015-11 [17]. The rate of loading was selected in such a way to fulfil the requirements established in the standard. For each mortar at least 6 specimens were tested.

The mortar pH is crucial for plant growth. The pH of a mortar is largely determined by the occurrence of carbonation. The pH of a fresh mortar is about 13, too high for plant growth. After carbonation, the mortar pH becomes lower (about 9) and some microorganism and plant species may grow. In order to assess whether the pH of the mortar was low enough to allow for plant growth, a solution of phenolphthalein in ethanol was sprayed on the two halves of freshly broken 4x4x16 cm specimens before the execution of the compressive test. Phenolphthalein is a pH indicator: when the colour of the mortar turns to pink, it means that the pH is higher than 9 and thus that the mortar is not carbonated yet; if the mortar is carbonated, its colour will not change.

2.2.3. Monitoring of plant growth

The plant growth in the brick–mortar specimens was visually and photographically monitored at different time intervals. Specimens were removed from the outdoor exposure to be photographed. A special set-up was developed in order to always ensure the same light conditions. In order to facilitate monitoring and comparison between walls, a qualitative scale was created to evaluate the plant growth.

3. Results

3.1. Brick properties

3.1.1. Moisture transport properties

The water absorption curves of brick 2 and 8 are reported in Fig. 4. Density, porosity, WAC and IRA values are summarized in Table 4.

The results show that brick 8 has a much slower water absorption rate and a lower capillary absorption and open porosity than brick 2. The slow water absorption suggests that brick B8 has smaller pores than brick B2. The differences in moisture transport properties are in agreement with what was expected based on the production process of the bricks. Soft mud moulded bricks, such

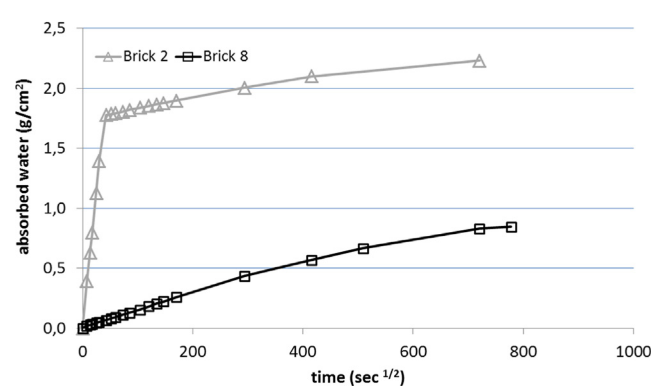

Fig. 4. Capillary water absorption curves of brick 2 and 8 (each curve is the average of measurements on 3 bricks).

Table 4
Physical and mechanical properties of bricks B2 and B8.

Brick n.	WAC (g/m^2 sec$^{1/2}$)	IRA (Kg/m^2 min)	P (vol%)	Density (kg/dm^3)	f_b* (MPa)	f_b (MPa)
2	418.7	3.91	31.66	1811	14.43 ± 1.78)	10.88 ± 1.38
8	14.8	0.20	15.73	2233	95.97 ± 10.69)	71.69 ± 8.34

as brick B2, are generally made with lean clay mixtures (i.e. low clay content) with generally high water content, in order to facilitate the shaping process; this results in a quite high porosity of the bricks. In the case of extruded bricks, such as brick B8, generally fatter clay mixtures are used, often in combination with a vacuum pump in the extruder; this leads to brick with a lower porosity.

3.1.2. Compressive strength

Table 4 reports the compressive strength f_b* and normalised compressive strength f_b for B2 and B8 (average of 6 specimens for each type). The compressive strength of brick B8 is much higher than that of brick B2, as expected based on the physical properties and the production process.

3.2. Mortar properties

3.2.1. Density, porosity and water absorption

The density and porosity of the mortars are reported in Table 5. Based on the total porosity, it can be concluded that:

- The binder/aggregate ratio and the grain size distribution of the aggregate have a major influence on the total porosity. The use of a lower binder/aggregate ratio and of sieved sand leads to a higher porosity in the mortar.
- The binder type has a minor influence on the total porosity of the mortar.
- The mortars with an addition of vermiculite show the highest porosity, because of the high porosity of this material.
- The ready-to-use mortars have very high porosity, comparable to that of mortars with vermiculite. The high values are most probably due to the presence of an air entraining agents.

The capillary water absorption curves of the mortar specimens are reported in Fig. 5. Based on the water absorption curves of the mortars, the following conclusions can be drawn:

- The binder has a strong influence on the water absorption rate: among the self-mixed mortars, the lime-trass mortars show the fastest capillary absorption, the cement-based mortars the

Table 5
Density, porosity, carbonation depth (maximum value) and compressive strength of mortars.

Mortar	Density (kg/m^3)	Porosity (%)	Max. carbonation depth at 28d (mm)	Compressive strength (MPa)
MMzK	1531	42.2	11	2.1
MMzK-S			11	2.0
MMmK	1422	46.3	14	2.7
MMmK-S			12	2.3
HCst2	2138	19.3	0.5	19.5
HCst2-S			1	24.5
Hst2	2080	21.5	2.5	3.2
Hst2-S			2	3.5
ATst2	2013	24.0	9	3.5
ATst2-S			6	2.3
HCsf2	1786	32.6	2	23.9
HCsf2-S			1	18.7
Hsf2	1834	30.8	0	3.5
Hsf2-S			0	3.3
ATsf2	1840	30.6	15	3.2
ATsf2-S			6	2.3
HCvt2	1578	40.5	1.5	10.8
HCvt2-S			1.5	6.3
Hvt2	1519	42.7	2	1.7
Hvt2-S			0	1.4
ATvt2	1390	47.5	5	1.4
ATvt2-S			5	1.1
HCst4	1908	28.0	2	11.5
HCst4-S			2	8.1
Hst4	1911	27.9	0	1.4
Hst4-S			1	1.2
ATst4	1945	26.6	8	0.8
ATst4-S			12	0.4
HCsf4	1611	39.2	3.5	6.3
HCsf4-S			3	4.8
Hsf4	1728	39.2	3.5	1.2
Hsf4-S			3	0.5
ATsf4	1678	26.6	8	*
ATsf4-S			12	0.2
HCvt4	1419	46.5	3	4.1
HCvt4-S			2	3.4
Hvt4	1308	50.6	0.5	0.6
Hvt4-S			0.5	0.5
ATvt4	1217	54.1	*	0.6
ATvt4-S			*	0.2

*The mortar crumbled, making the measurements not possible.

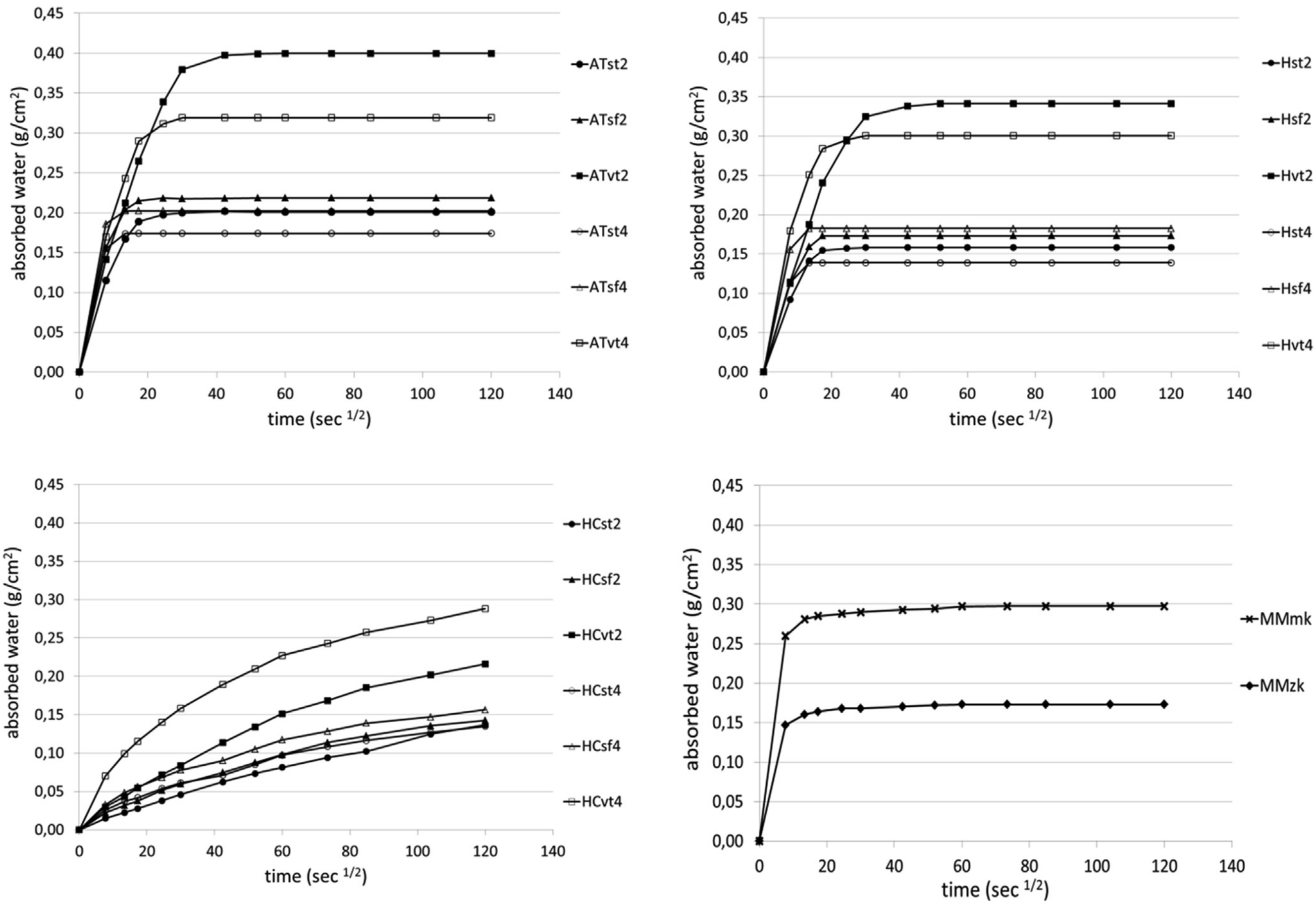

Fig. 5. Water absorption curves of different mortars (each curve is the average of measurements on three specimens).

slowest. These results are consistent through all the mortar specimens, independently from binder to aggregate ratio and grain size distribution of the aggregate.

- A smaller binder/aggregate ratio lead to a higher porosity and slightly faster water absorption rate; this is most probably due to the presence of more intergranular pores, not fully filled by the binder, in mortars with a lower binder content.
- The mortars made with gap-graded sand have higher porosity and faster water absorption than those made with well-graded sand. These results are in agreement with the expectations, as the use of gap-graded sand leads to coarser pores (for an equal binder/aggregate ratio).
- The ready-to-use mortars, despite the cement binder, have a very fast rate of absorption; the type containing hydrated lime (MMmk) has the highest rate of absorption of all mortars. Based on the information on the composition of the mortars provided by the producer, a lower rate of absorption would be expected than actually measured. While the high porosity of these mortars can be related to the presence of an air entraining additive, which leads to round, coarse pores in the hardened mortar, the fast rate of capillary absorption can hardly be explained. The high absorption rate measured suggests that a well-connected network of coarse pores is present. However, pores created by air entraining additives are generally only connected through the fine porosity present in the binder (e.g. [21]) and have therefore no positive effect on the capillary absorption rate. Microscopy observations on thin sections could provide more information on the pore network of these mortars and clarify this issue.

3.2.2. Carbonation depth

The pH of the mortar, and thus indirectly their carbonation depth, has been indicatively assessed by means of phenolphthalein. The carbonation depth measured on mortar prisms after 28 days curing (Table 5) varies significantly. There are large and not always consistent differences between mortars with and without seeds, which are hard to explain. In general, the mortars made with air-hardening lime and trass (ATsf2, ATst2, ATst4) show the largest carbonation depth among the self-made mortars; also the ready-to-use mortars show deep carbonation. These results are most probably related to the high porosity and capillary absorption rate (thus, likely a high permeability) of these ready-to-use mortars (see section 3.2.1).

3.2.3. Compressive strength

The average compressive strength of the mortars after 28 days curing are reported in Table 5. Based on these results it can be concluded that the binder type has a strong influence on the mechanical strength of the mortar, for similar values of total porosity (Fig. 6). Self-mixed mortars prepared with hydrated lime and cement (HC mortars) have the highest compressive strength; pure NHL mortar and air-hardening lime-trass mortar have similar compressive strength values. Ready-to-use mortars (MMmk and MMzk) have low compressive strength, despite the presence of a cement binder: these low values can be attributed to the very high porosity of these mortars.

The binder/sand ratio is another parameter to have a substantial effect on the mechanical strength of the mortar (Fig. 7). This result

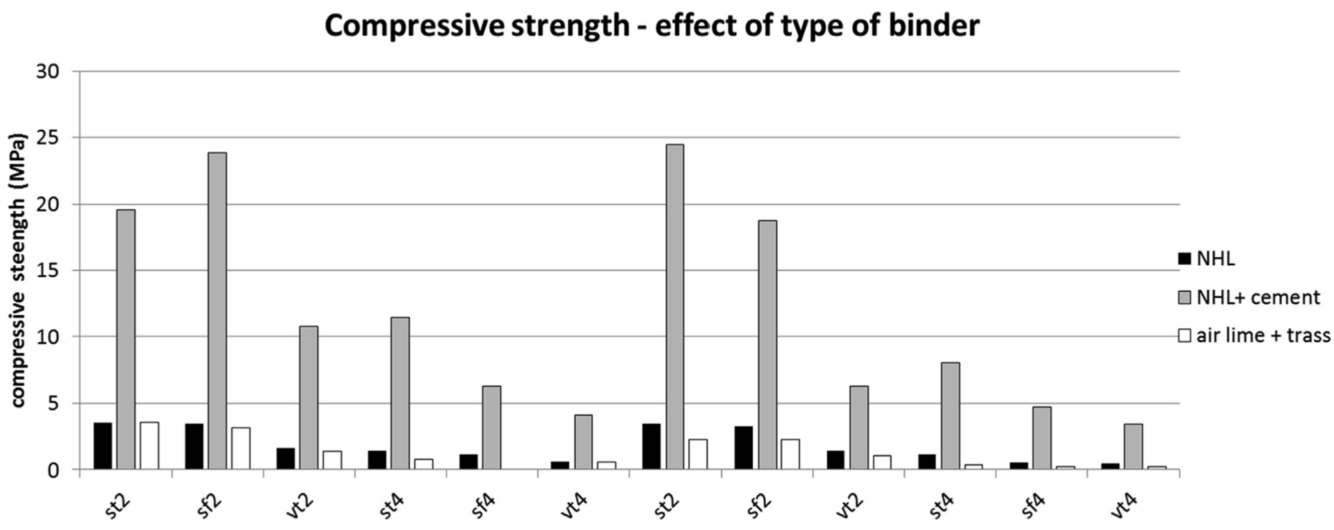

Fig. 6. Compressive strength of mortars – effect of binder type (each bar is the average of at least 6 measurements).

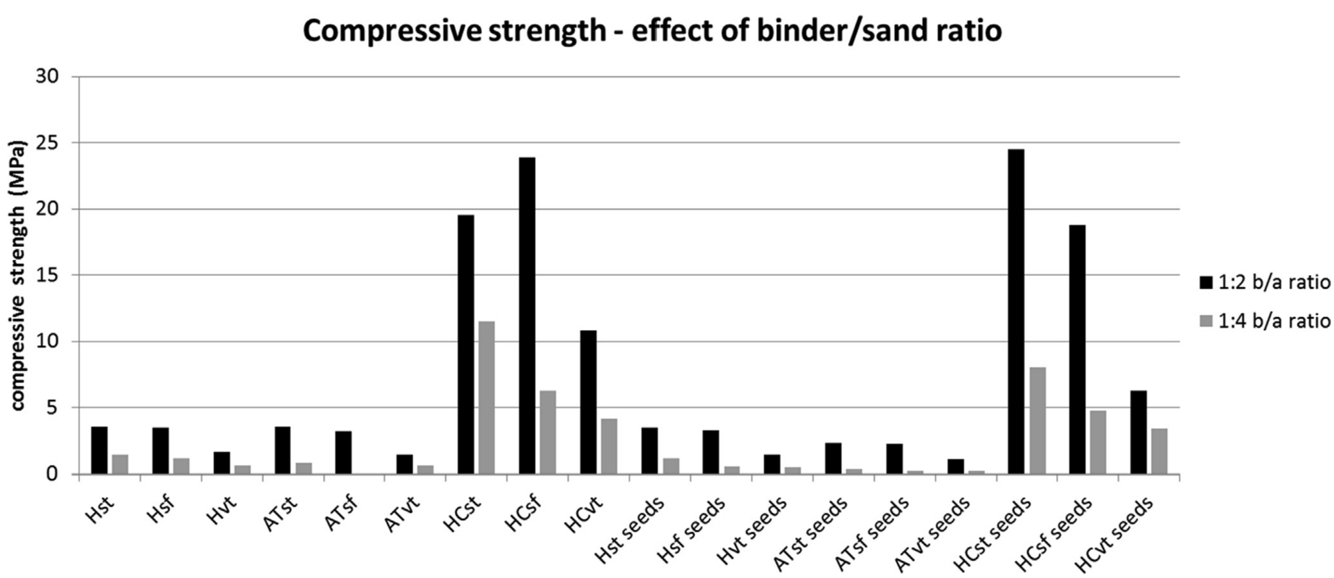

Fig. 7. Compressive strength of mortars – effect of binder/sand ratio (each bar is the average of at least 6 measurements).

could be expected as a low binder/sand ratio corresponds to the high porosity of the mortar and thus to a lower strength.

The effect of the grain size distribution of the sand on the mechanical strength is less important: in mortar with 1:4 binder/sand ratio, a gap graded sand (between 1 and 2 mm) leads to a lower strength than a well-graded sand (Fig. 8); however, in the case of mortars with a 1:2 binder/sand ratio, the strength is not significantly affected by the grain size distribution of the sand.

When considering the effect of the additions, vermiculite (half of the volume of the aggregate) leads generally to a decrease of the compressive strength; this is more evident in the case of the mortars with a binder/sand ratio 1:2 than in those with 1:4 ratio (Fig. 9).

The addition of seeds (about 450 seeds, equivalent to 1,7 g) did not cause a significant change in the mortar strength; in most cases, a slightly lower mechanical strength was measured in the presence of the seeds.

3.3. Estimation of mechanical strength of brick–mortar combinations

To select brick–mortar combinations suited for the construction of the masonry quay wall, the compressive and flexural bond strength of masonry is estimated and compared with a dataset of mean mechanical properties for Dutch masonry reported in NPR 9998:2018 [22].

Based on the compressive strength of an individual materials (brick and mortar), an indication of the compressive strength of the masonry was obtained making use of the procedure reported in Eurocode 6 [23] and EN 1052-1 [24]. For the type of masonry units and mortar thickness considered, the following formulas have been applied to obtain an estimation of the compressive strength of the masonry f'_m:

$$f'_m = 1.2f_k = 1.2Kf_b^{\alpha}f_m^{\beta} \tag{5}$$

where: f_k, f_b and f_m are, respectively, the characteristic compressive strength of masonry, the mean normalised compressive strength of bricks and the mean compressive strength of mortar expressed in $N/mm^{2.}$; K, and, = constants, equal to 0.55, 0.7 and 0.3 for clay masonry units Group 1 with general purpose mortar.

The flexural bond strength of masonry f_w was estimated by adopting the formulation proposed by [25]:

$$f_w = 0.031f'_m \tag{6}$$

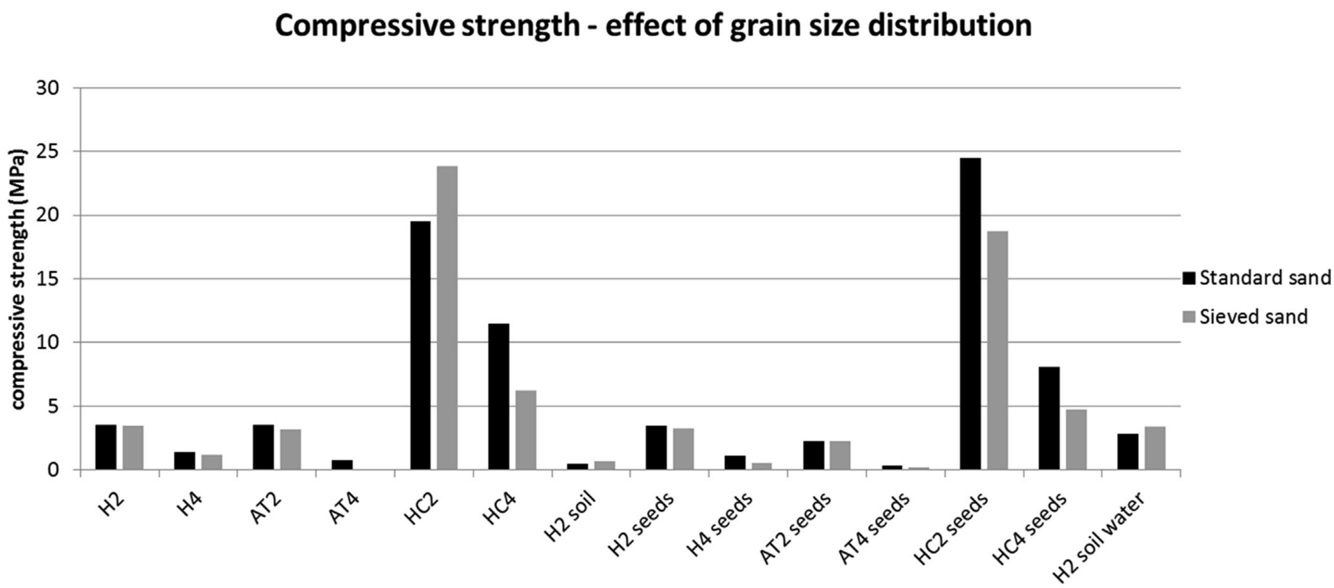

Fig. 8. Compressive strength of mortars – effect of the grain size distribution of the sand (each bar is the average of at least 6 measurements).

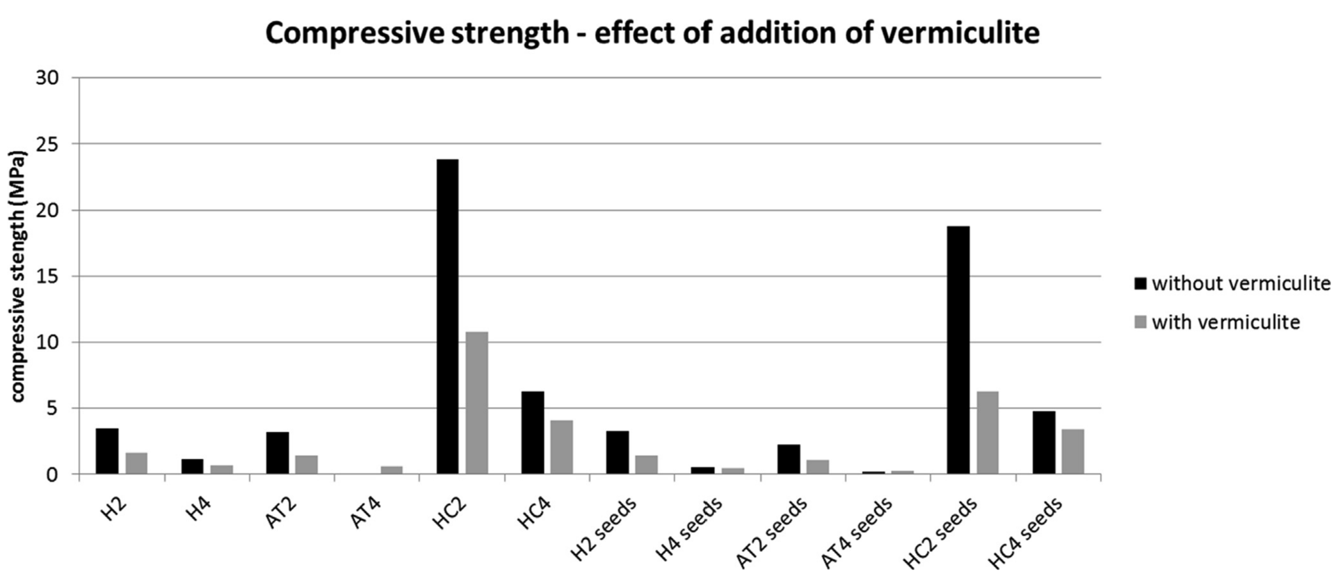

Fig. 9. Compressive strength of mortars – effect of the addition of vermiculite (each bar is the average of at least 6 measurements).

A minimum and a preferred lower limit were defined for the strength of masonry on the basis of, respectively, the properties of Dutch masonry built before and after 1945, as reported in NEN-NPR 9998:2018 [22]. The values reported in the standard were obtained based on an extensive experimental campaign for the characterisation of existing residential masonry buildings [26,27] and on literature data for the Dutch masonry (e.g. [28,29])

Fig. 10 shows the relation between the estimated compressive and the flexural bond strength of masonry, together with the two lower limits, for each mortar-binder combination. For both brick types, the estimated strength value approaches or overcomes the lower limits only in the case of mortar with a binder made of natural hydraulic lime and cement (HC mortars). All the other brick–mortar combinations, including the ones built with the ready-to-use mortar, show very low estimated strength values. In case of the brick–mortar combinations built with brick B2, the estimated masonry properties are below the limit for both the compressive and the flexural bond strength. On the contrary for masonry with brick B8, a sufficient masonry compressive strength is expected independently of the type of mortar.

3.4. Bioreceptivity of brick–mortar combinations

After 3 months exposure, plant sprouts are observed to grow mostly in mortars in which seeds where added during mixing. These are all plant sprouts of ivy-leaved toadflax (*Cymbalaria muralis*) and yellow corydalis (*Pseudofumaria lutea),* of which the seeds were added during mortar preparation. In a few cases the growth of plant sprouts has been observed in mortars in which no seeds were added (Hvt4-B2, Hvt4-B8 and HCvt4-B2). In these cases, it is supposed that seeds have been transported by wind. It is interesting to notice that all these mortars have a vermiculite addition.

The specimens made with air lime-trass mortar (with 1:4 binder/sand ratio) in combination with brick B2 shows the most developed plant growth: several plant sprouts have grown on the mortar and they are still alive after more than 3 months (Fig. 11).

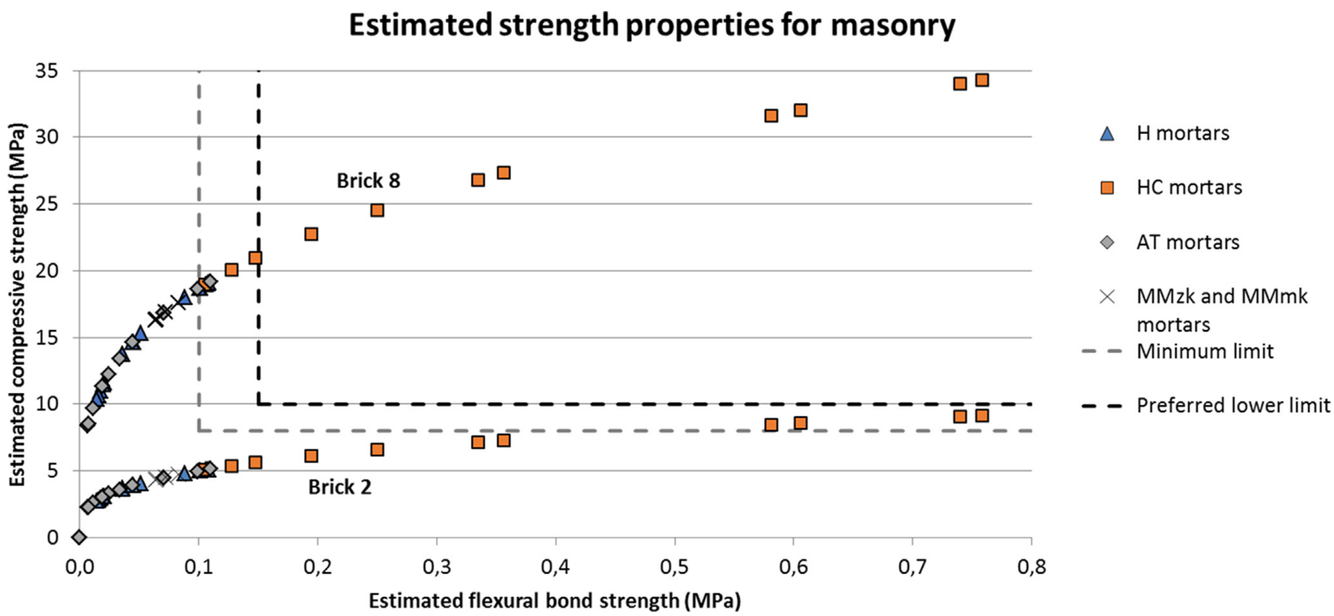

Fig. 10. Estimated compressive and flexural bond strength of brick–mortar combinations; the black and grey lines indicate the minimum limit and the preferred lower limit based on property of clay brick masonry built before and after 1945 as per NPR9998 [22].

The results of the plant growth from seeds after several weeks of exposure are summarized in Table 6. Based on these results, the following conclusions can be drawn:

- The moisture transport properties of the brick/mortar combination have an important influence on the growth of the plants in the mortar: in all cases but one, plants have grown in mortar joints of masonry made with brick type B2. This brick has a higher open porosity and faster absorption than brick B8 (suggesting the presence of coarser pores): the brick works therefore as a kind of water reservoir for the mortar, which, thanks to its finer pores can extract water by capillarity from the brick and retain it long enough for the plants to grow.
- The binder has a strong influence on plant growth. Air-lime/trass-based mortars are the best-performing ones; the NHL/cement-based mortar shows the lowest performance (no growth is observed).
- No growth is observed in ready-to-use mortars, despite their high porosity and favourable pH. A possible reasons of this behaviour might be the composition of these mortars, e.g. the presence of additives and/or the hydration products of the cement binder. Another possible explanation might be related to the low water retention of these mortars. Despite this property was not measured in this research, hypotheses can be made based on the water absorption curves. The water absorption curves of these mortars have two clear branches, (an initial fast, linear absorption followed by a flat line) suggesting a pore size distribution with mostly coarse pores. Based on these observations, a fast drying and a low water retention can be expected for these mortars. The fast drain of water would have a negative effect on plant growth.
- The aggregate/binder ratio and the grain size of the aggregate seem to have limited influence on plant growth
- The addition of vermiculite has a strong positive effect on plant growth.

It should be mentioned that, at this stage, it is likely that the plant sprouts are relying on the seeds for the nutrients. Only in a later stage it will be possible to assess whether sufficient nutrients are provided to the plant by the soil and/or the mortar.

Fig. 11. Plant growth after 3 months outdoor exposure on ATst4-S-B2 specimen.

Table 6
Plant growth on walls during outdoor exposure (only brick-mort combination on which some plant growth is observed are reported).

Brick-mortar combination	Plant growth after			
	2 weeks	8 weeks	12 weeks	18 weeks
Hst2-S-B2	+ (1p)	died	–	–
ATst2-S-B2	+ (1p)	+ (1p)	+ (2p)	died
Hvt2-S-B2	+ (1p)	+ (2p)	++ (3p)	+ (2p)
ATvt2-S-B2	++ (3p)	++ (3p)	+ (1p)	+ (1p)
HCst4-S-B2	–	–	+ (1p?)	died
HCst4-S-B8	–	–	+ (1p)	+ (2p)
ATst4-S-B2	++ (3p)	++ (3p)	++ (3p)	++ (3p)
ATst4-S-B8	+ (1p)	?	+ (1p)	+ (1p?)
Hsf4-S-B2	–	–	+ (1p)	+ (1p)
HCvt4-S-B2	–	–	+ (1p)	?
HCvt4-S-B2	–	–	+ (1p)	+ (1p)
Hvt4-B2	+ (1p)	died		
Hvt4-S-B2	+ (1p)	died	+ (1p?)	+ (1p)
Hvt4-B8	–	+ (1p)	+ (1p)	+ (1p)

- = none, +: present, scale from + (low, 1 or 2 plants), to +++ (high, >5 plant sprout).

4. Discussion and conclusions

The research has highlighted that the growth of the selected plant species is possible in relatively fresh mortars, provided the conditions are favourable enough for this. Some plant sprouts were observed to grow on the mortar with mixed-in seeds in the 3 months after preparation.

The effect of brick and mortar properties on bioreceptivity of masonry walls has been elucidated. The moisture transport properties of the brick–mortar combination and the composition of the mortar (mainly binder type and additions) were proven to be the most relevant factors influencing and plant growth.

Despite plant sprouts grow mainly in the mortar joint, the brick properties were shown to be crucial to determine bioreceptivity of the mortar. Brick B2 was proven as most favourable for plant growth. This brick has a higher open porosity and faster absorption than brick B8 (suggesting the presence of coarser pores): the brick works therefore as a kind of water reservoir for the mortar, which, thanks to its finer pores, can extract water by capillarity from the brick and retain it long enough for the plants to grow.

Similarly, mortars with a higher rate of capillary absorption and higher porosity were shown to have better bioreceptivity. Only exception were the ready to-use mortars which, despite their high porosity and rate of capillary absorption, were not prone to biological growth. This might be related to their composition (cement binder and/or additives) and/or to their supposed low water retention. Further investigation of their pore system (e.g. by microscope observations on thin sections) and drying behaviour could clarify this point.

The binder type has an important role in favouring plant growth: mortars with lime-trass and, in lower extent, those with a natural hydraulic lime binder, perform the best in terms of bioreceptivity. The addition of vermiculite, a light-weight aggregate, to the mortar has been shown to be very beneficial for plant growth. This is most probably due to its high porosity, which can work as water reservoir and to its high ion exchange capacity, which provides a buffer for the supply of nutrients to the plants [7].

When considering the mechanical strength, unfortunately, the brick–mortar combinations most favourable for plant growth are those with estimated low compressive and flexural bond strength values. Therefore, in the next phases of the research and for the final practical application, a compromise needs to be found: the masonry should be sufficiently strong to withstand the applied loads, but still able to favour plant growth on its surface.

Based on these considerations, the following choices have been made for the next phases of the research:

- In addition to masonry with tooled bedding mortar joint, masonry with joints including bedding and pointing mortars will be tested: the bedding mortar confers the necessary strength to the masonry, while the pointing mortar provides an optimal bioreceptivity. HCst2 and Hst2 are selected as bedding mortars for their higher strength; ATst2 mortar as pointing mortar being favourable for plant growth.
- Brick B8 was shown to not be suitable for plant growth and thus not considered in further research. Next to brick B2, a different type of brick, with a higher compressive strength than B2, but still a high porosity and water absorption rate will be considered.

At the moment both above mentioned solutions are tested in the laboratory and on site.

Another point which would need to be considered in the next step of the research is the durability of the mortar with mixed-in plant seeds. When seeds germinate and roots develop, these might damage the mortar, with possible negative effect on the strength of the masonry. To tackle this issue the following solutions can be considered:

- as mentioned above, the bio-receptive mortars can be used only as pointing mortars; therefore, damage would have very limited effect on the strength of the masonry. Moreover, the roots of the selected plants are relatively weak and hardly able to generate pressures high enough to affect sound, relatively strong mortars, such as the HCst2 cement-lime bedding mortar.
- a dry-stack masonry system can be used, in which bricks are assembled using plastic connection elements, leaving space free in between the bricks for mortar or compost [30]. This way, the mechanical strength of the masonry does not relay on the mortar joint and its interaction with the brick, and the roots growing in the joint would not constitute a problem.

CRediT authorship contribution statement

B. Lubelli: Conceptualization, Methodology, Writing - review & editing, Supervision, Visualization. **J. Moerman:** Investigation, Data curation. **R. Esposito:** Methodology, Visualization. **K. Mulder:** Funding acquisition, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors thank researcher Maria Belen Gaggero and technician Ton Blom of the Faculty of Civil Engineering and Geoscience of the Delft University of Technology for carrying out the mechanical test on bricks and mortars. The authors wish to thank the anonymous reviewers for help in improving the paper. The research was carried out as a preliminary study in preparation to the UIA project Green Quays, grant number UIA04-139 (see also www.greenquays.nl), and financed by the municipality of Breda (the Netherlands).

References

[1] M. Ford Cochran, R.A. Berner, Promotion of chemical weathering by higher plants: field observations on Hawaiian basalts, Chem. Geol. 132 (1-4) (1996) 71–77, https://doi.org/10.1016/s0009-2541(96)00042-3.
[2] R.A. Francis, Wall ecology: A frontier for urban biodiversity and ecological engineering, Prog. Phys. Geogr. 35 (1) (2011) 43–63, https://doi.org/10.1177/0309133310385166.
[3] R.A. Francis, S.P.G. Hoggart, Waste not, want not: The need to utilize existing artificial structures for habitat improvement along urban rivers, Restor. Ecol. 16 (2008) 373–381. https://doi.org/10.1111/j.1526-100X.2008.00434.x.
[4] O. Guillitte, Bioreceptivity: a new concept for building ecology studies, Sci. Total Environ. 167 (1-3) (1995) 215–220, https://doi.org/10.1016/0048-9697(95)04582-L.
[5] A.Z. Miller, P. Sanmartín, L. Pereira-Pardo, A. Dionísio, C. Saiz-Jimenez, M.F. Macedo, B. Prieto, Bioreceptivity of building stones: A review, Sci. Total Environ. 426 (2012) 1–12, https://doi.org/10.1016/j.scitotenv.2012.03.026.
[6] M. D'Orazio, G. Cursio, L. Graziani, L. Aquilanti, A. Osimani, F. Clementi, C. Yépremian, V. Lariccia, S. Amoroso, Effects of water absorption and surface roughness on the bioreceptivity of ETICS compared to clay bricks, Build. Environ. 77 (2014) 20–28, https://doi.org/10.1016/j.buildenv.2014.03.018.
[7] A.C. Bunt, Modern potting composts, George Allen & Unwin Ltd, London, 1976.
[8] K. van Balen, B. van Bommel, R.P.J. van Hees, M. van Hunen, J. van Rhijn, M. van Rooden, Kalkboek. Het gebruik van kalk als bindmiddel voor metsel- en voegmortels in verleden en heden: LK - https://tudelft.on.worldcat.org/oclc/1078580470, (2003).
[9] J.J. et al Hughes, The role of mortar in masonry: an introduction to requirements for the design of repair mortars., in: 2nd Hist. Mortars Conf. HMC 2010, RILEM TC 203-RHM Final Work., 2010.
[10] A. Isebaert, L. Van Parys, V. Cnudde, Composition and compatibility requirements of mineral repair mortars for stone – A review, Constr. Build. Mater. 59 (2014) 39–50, https://doi.org/10.1016/j.conbuildmat.2014.02.020.
[11] S. Manso, W. De Muynck, I. Segura, A. Aguado, K. Steppe, N. Boon, N. De Belie, Bioreceptivity evaluation of cementitious materials designed to stimulate biological growth, Sci. Total Environ. 481 (2014) 232–241, https://doi.org/10.1016/j.scitotenv.2014.02.059.
[12] H.H. Kim, C.S. Kim, J.H. Jeon, C.G. Park, Effects on the physical and mechanical properties of porous concrete for plant growth of blast furnace slag, natural jute fiber, and styrene butadiene latex using a dry mixing manufacturing process, Materials (Basel). 9 (2016) 1–11, https://doi.org/10.3390/ma9020084.
[13] K.-H. Lee, K.-H. Yang, Development of a neutral cementitious material to promote vegetation concrete, Constr. Build. Mater. 127 (2016) 442–449, https://doi.org/10.1016/j.conbuildmat.2016.10.032.
[14] CEN, EN 772-1 - Methods of test for masonry units - Part 1: Determination of compressive strength, 1 (2015).
[15] CEN, NEN-EN 196-1 Methods of testing cement - Part 1: determination of strength, (2016).
[16] CEN, EN1015-3:1999 -Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table), (1999).
[17] CEN, EN 1015-11 - Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar, (1999).
[18] J. Petkovic, Moisture and ion transport in layered porous building materials: a nuclear magnetic resonance study, 2005. http://www.tue.nl/fileadmin/content/faculteiten/tn/TPM/Thesis/PhD-Petkovic-2005.pdf.
[19] CEN, EN 772-11 - Methods of test for masonry units - Part 11: Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water abs, (2000).
[20] L.J.A.R. van der Klugt J.A.G. Koek De kwaliteit van voegen in metselwerk SBR 1994
[21] B. Lubelli, M.R. de Rooij, NaCl crystallization in restoration plasters, Constr. Build. Mater. 23 (5) (2009) 1736–1742, https://doi.org/10.1016/j.conbuildmat.2008.09.010.
[22] NEN, NPR 9998 - Assessment of structural safety of buildings in case of erection, reconstruction and disapproval - Induced earthquakes - Basis of design, actions and resistances., (2018).
[23] CEN, EN 1996-1-1 + A1 - Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures, (2013).
[24] CEN, EN 1052-1 - Methods of test for masonry - Part 1 : Determination of compressive strength, (1998).
[25] R. Lumantarna, D.T. Biggs, J.M. Ingham, Compressive, Flexural Bond, and Shear Bond Strengths of In Situ New Zealand Unreinforced Clay Brick Masonry Constructed Using Lime Mortar between the 1880s and 1940s, J. Mater. Civ. Eng. 26 (4) (2014) 559–566. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000685.
[26] S. Jafari, J.G. Rots, R. Esposito, F. Messali, Characterizing the Material Properties of Dutch Unreinforced Masonry, Procedia Eng. 193 (2017) 250–257, https://doi.org/10.1016/j.proeng.2017.06.211.
[27] S. Jafari, J.G. Rots, R. Esposito, Core testing method to assess nonlinear behavior of brick masonry under compression: A comparative experimental study, Constr. Build. Mater. 218 (2019) 193–205, https://doi.org/10.1016/j.conbuildmat.2019.04.188.
[28] J.G. Rots, B. Picavet, Structural masonry : an experimental/numerical basis or practical design rules LK - https://tudelft.on.worldcat.org/oclc/905477614, Balkema, Rotterdam SE - XIII, 152 p. : ill. ; 26 cm, 1997.
[29] R. van der Pluijm, Out-of-plane bending of masonry behaviour and strength LK - https://tudelft.on.worldcat.org/oclc/6899858693, Technische Universiteit Eindhoven SE -, 1999
[30] https://drystack.nl/, (n.d.).