Living concrete: Democratizing living walls

Benjamin Riley, François de Larrard, Valéry Malécot, Isabelle Dubois-Brugger, Hervé Lequay, Gilles Lecomte

Title:

Living Concrete:
Democratizing Living Walls

Author (Corresponding author):

Benjamin Riley

Affiliation:

UMR-3495 MAP-ARIA laboratory (Models and Simulations for Architecture, Urbanism and Landscape Applications and Research in Computer Science for Architecture) of the CNRS (research unit of the French National Center for Scientific Research) at the National Architecture School of Lyon (ENSAL)

Email address:

benj.r.riley@gmail.com

Postal address and telephone:

1 Bd de la Croix-Rousse, 69004 LYON

+33 6 95 01 74 12

Co-authors / Affiliation:

François de Larrard / Scientific Director, LCR - LafargeHolcim

Valéry Malécot / Associate-professor, IRHS, Agrocampus-Ouest, INRA, Université d'Angers, SFR 4207 QuaSaV, Beaucouzé, France

Isabelle Dubois-Brugger / R&D Director, LCR - LafargeHolcim

Hervé Lequay / Director, UMR-3495 MAP-ARIA laboratory, ÉNSA Lyon

Gilles Lecomte / Technician, LCR - LafargeHolcim

1. Introduction

1.1. Background

Cities facing population expansion and densification amid shifting climates require practicable solutions to meet biophilic, health, and safety needs of city dwellers. This can begin to be accomplished by bringing nature into dense urban environments on all feasible surfaces of a city's buildings and infrastructure [1] [2] [3] [4]. After greening all available horizontal surfaces, only vertical surfaces remain for leveraging, yet existing living wall systems lack affordability and/or longevity [5] [6]. Their high economic cost and environmental burden means living wall use is largely restricted to luxury applications and greenwashing [7] [8].

The goal of this work is to determine the possibility of having a living wall system which is durable, has the same longevity as its building, is unlimited by location and typology (especially high-rises), and is more affordable than currently available systems. The hypothesis asks if combining living-wall functions with the structural functions of a building's exterior will lower cost and increase longevity. The outcome sought is to push living walls beyond the economic threshold limiting their proliferation to extend nature's reach into the urban milieu.

This interdisciplinary study, of architecture, botany, and material science, shows how shifting the existing living wall paradigm from an additive to a systemic model creates the potential for affordable living walls. The material tested is concrete, because, after water [9], it is the most widely used building material in the world, and due to its widespread use [10], durability, cost, and flexibility, is currently a pragmatic choice to democratize living walls.

However, although recyclable [11] [12], concrete is not made from renewable materials. And because of its ubiquity (2014 cement production was 4,180,000,000 tons [13]), its environmental impact is enormous [14] [15], which this study aims to ameliorate by permitting concrete to spread nature.

1.2. About living walls

Green wall terminology is evolving. They have two categories: green façades and living walls [16] [17], although *extensive* and *intensive* have been borrowed from the green roof industry to describe them [18] [19] [20], these terms are best avoided to elude the confusion bred in that domain. Green walls are also called vertical greening systems [18], an allusion to their effect beyond surface treatment, i.e., they are complex systems with proportionate consequences. For example, a living wall may require a water storage system connected to a network of horizontal surfaces used to capture rainwater and a mechanical room to filter, irrigate, and fertilize. In other words, much more than just a wall.

Living walls and green façades have the same fundamental requirements, i.e., plants' indispensable needs: daylight, water, and nutrients [21]. Living walls share the same potential advantages of other green infrastructure: they can have biophilia-related health benefits [4] [22] [23], capture air pollutants [24] [25] [26], diminish noise pollution [27] [28], reduce the heat-island effect [29] [30], provide natural cooling [31] [32], add privacy, and promote biodiversity [33] [34].

Whereas green façades use climbing plants, living wall plants are distributed over the entire wall [35]. The two main types of living walls are hydroponic and soil-cell systems. Hydroponic systems often use a dense mat or felt-like material as a growing medium. Discovered by the French botanist Patrick Blanc –the father of modern green walls – these lightweight systems are wetted with nutrient-enriched water, and roots grow on and in-between layers of matted or felted substrate [36]. Soil-cell systems compartmentalize the growth of plants in individual cells of soil. Cells are grouped together in panels attached to a frame. However, some hydroponic systems use a modular, cell-based typology, replacing soil with horticultural growing media, e.g., rock wool or polyurethane foam. Cell-systems are essentially a collection of inter-connected potted plants subject to the same challenges facing potted house plants: soil compaction, drainage issues, climatic stress, and nutrient replenishment [37]. However, exterior soil-cell walls also face the problem of soil loss due to wind and water-driven erosion [38].

Green walls can humidify and oxygenate air, and, depending on the plants, improve air quality by trapping dust and absorbing pollutants like formaldehyde indoors and nitrogen dioxide outdoors [39] [40]. When mechanically forced, living wall systems can be designed to actively filter indoor air [41], though usually its the soil filtering.

Both systems can face plant stress, foremost because the growth-plane is vertical (although some canted cell-based systems have a more orthodox growing surface). Both hydroponic and modular-cell living walls require expert design and on-going maintenance, and both are prone to failure if their design and operation are not successfully synthesized [42]. Most hydroponic systems and cellular living wall systems have a life expectancy [43] [44], i.e., they require replacement, typically every 15–25 years [45], which adds to lifecycle costs.

1.3. Living wall costs

Costs include initial installation's labor and materials, ongoing maintenance, environmental burden, and total lifecycle cost. Collecting this data is challenging because of input variability. For example, initial costs of systems identically sourced and installed will differ because price is tailored by project; no two projects are identical. Geometrical or environmental differences between projects – orientation, microclimate, size, neighboring buildings – will affect solar access, wind patterns, and humidity, which affects plant species selection and growth, which in turn affects system efficacy and usefulness, but also initial and continued maintenance costs. How costs are defined also affect the data, e.g., some living walls necessitate replacing 30% of their plants in the first year [8], and depending on how the project is budgeted, this expense can be considered either installation or maintenance. Despite these challenges, predictable costs emerge.

Concerning initial and ongoing costs, living walls are the more expensive category of green walls [18]. Green façade installed system costs begin around €100/m^2, but go as high as €800/m^2; whereas living wall system initial costs begin about €400/m^2 and go as high as €1200/m^2 [5] [6] [46]. Ongoing maintenance costs can be as low as 2-5€/m^2 for yearly pruning of green screen climbing plants, and between 40-100€/m^2/year for living walls [46]. The marked contrast in cost between the two green wall categories are a result of differing complexities; living walls require a larger support network of: water supply, filtering, collection, storage, mechanical distribution (pumps), irrigation components, fertilizer, and maintenance for this equipment. Until cost and environmental burden are reduced, the potential biophilic richness of living walls will most likely remain stunted.

1.4. Objectives of the study

Principally, this study investigates a strategy to proliferate urban living walls. As cost is the major limiting factor, this study explores combining a living wall with the building structure as an approach to reduce costs and have a lifespan commensurate with its building. This study determines the validity of concrete growing plants for walls and green infrastructure. The initial objectives are to: create a concrete to host plants, determine its mechanical properties, verify its constructability, identify candidate native plant species, and study growing plants from seed. The intention of sowing seeds directly on the new concrete is to encourage the plants to create their own environment, eliminating the costs of raising and transplanting nursery plants and annual replacement. The final objectives are to: incorporate the new concrete into a conventional wall system, develop and test the new system's construction methodology, analyze how the new concrete's chemical composition will affect plants and irrigation, test the new system outdoors for germination and perenniality, and determine the new system's cost.

2. Methodology

The research methodology is in seven steps. Step 1 creates a new concrete to support plant life (see 2.1). Step 2 verifies constructability (see 2.2). Step 3 and its sub-steps validates plant growth on the new concrete (see 2.3). Step 4 verifies a new construction methodology (see 2.4). Step 5 analyzes the new concrete's chemical effect on plants and irrigation (see 2.5). Step 6 tests mechanical properties (see 2.6). Step 7 validates outdoor germination and perenniality (see 2.7). Step 8 analyzes costs (see 2.8).

2.1. Testing new concrete formulas

The first step required finding a mix design for living concrete. Pervious concrete was chosen for its interconnected pores accommodating water percolation and plant roots. Three pervious concrete mix designs were tested: pure cement, pure cement with metakaolin and limestone filler, and the same but with white cement. The designs were measured for slump, density, and porosity [47] [48] [49].

The merits of using pure cement are economy and efficiency, while metakaolin was proposed for its ability to lower pH and suppress lime content in hardened concrete [50]. With metakaolin natural carbonation reaction is accelerated, eventually lowering pH to ~9, whereas with pure cement the initial pH is ~12-13. The choice of limestone filler is to complete the original volume of pure cement [51]. The white cement option was for aesthetic reasons [52].

The rheology of the mix designs were adjusted to obtain sufficient coating around each aggregate (stone aggregates are not used in the laboratory when studying cement rheology) and a lubricating effect. Once found, this rheological state facilitates an optimized configuration of stone aggregates and contact between aggregates, which in turn facilitates obtaining the desired mechanical resistance and porosity. Cement rheology targets were met when measured values of viscosity and spread fell within acceptable ranges of workability.

2.2. Verify constructability

Once met, an A1-sized wall was vertically cast using standard formwork. The merit of vertically cast-in-place pervious concrete – as opposed to pre-fabricated – is it forgoes specialized labor or equipment, expanding market potential beyond prefabrication. The formula was considered validated if the cast pervious concrete "wall" was homogenous in appearance, permeable (laid flat, tested with running water), without cavities, and without compacting flaws. Once the construction methodology had been validated the mix designs' mechanical characteristics were tested to determine the concrete's strength by measuring compression, density, permeability and porosity.

2.3. Validate the repeatability of germination indoors

Once the concrete mix designs were chosen, test specimens measuring 25 cm x 25 cm x 10 cm were cast to test germination. The germination tests were piloted at a greenhouse linked to INRA in Angers, France. To lower cost and ensure the plants would create their own environment, the choice was made to grow plants from seed in situ. The Angers trials were conducted in three waves.

2.3.1 1st and 2nd series: testing the concept and alternatives

The first set of trials were installed in a greenhouse on June 25, 2015. Eight specimens were tested with a seeded substrate, i.e., seeds were mixed into a growing medium before it was applied to the concrete. The plant species chosen for their local presence, ability to survive in alkaline environments, and small diameter roots, which would not damage the pervious concrete, are shown in Table 1, along with additional selection criteria and characteristics [53] [54] [55] [56]. Note: mosses arrive spontaneously.

Characteristics	*Ruta graveolus*	*Aurinia saxatilis*	*Cymbalaria muralis*	*Sedum acre*
USDA Hardiness Zone	6b to 11	4 to 10	3 to 7	4 - 9
UK Hardiness Zone		to zone 3	to zone 3	to zone 5
Wall orientation preferred	S, E, W	S, E, W	N, S, E, W	S, E, W
Sun / habitat	Prefers full sun	Cannot grow in the shade	Semi-shade	Cannot grow in shade
Size (max. ht./dia.)	60cm by 45cm	30cm by 30cm	10cm by 40cm	10cm by 30cm
pH	Prefers soils pH 6.6 to 8.5	Suitable pH: acid, neutral and basic (alkaline) soils and can grow in very alkaline soils.	Suitable pH: acid, neutral and basic (alkaline) soils	Suitable pH: acid, neutral and basic (alkaline) soils
Propagation	Seed	Seed	Seed	Seed/cuttings
Misc	Flowers are yellow; blossoms in mid-summer; drought-tolerant and can grow outdoors year-round depending on the climate	Flowers are yellow; plants can be grown on dry-stone walls and also old brick walls; attracts butterflies and bees	Flowers are purple; blossoms in spring; plant is self-fertile; meaning that it can self-pollinate, although this means it does not receive the benefit of genes from other plants	Flowers are yellow; blossoms in spring; is self-fertile; Often found on limestone hills, it avoids acid soils; can tolerate maritime exposure; aggressive and invasive; grows well on walls; roots form from even the tiniest stem

Table 1. Plant selection criteria and characteristics.

In the first set of trials, all substrates were a mix of topsoil and earth in equal amounts by volume, except half of the test specimens' substrates were cementitious under the hypothesis they would better withstand harsh weather events. For these, 5% cement by volume was added to the substrate. The substrate compositions are 35% earth, 35% compost, and 30% water and the seed mixture tested is (in g/m^3) *Ruta graveolens* (198g), *Aurinia saxatilis* (85g), *Cymbalaria muralis* (21g), and *Sedum acre* (4g).

The second series was sent to Angers on December 15, 2015, approximately six months after the success of the first trials. Twelve specimens were tested with alternative seeds and substrates. The alternative plant species tested were perennial grasses, *Lolium perenne* and *Festuca rubra*.

2.3.2 3rd series: effects of temporality

The third set of trials were sent to Angers on June 14, 2016. Ten specimens were tested to study the effects of concrete pH on plants through changes to the time between concrete casting and seeded substrate installation. These temporal trials were a physical way to empirically compare the effects of carbonatation. Ten blocks were seeded on the same day, but the blocks were cast in pairs one, seven, 14, 21, and 28 days before seeding.

2.3.3 Greenhouse environmental conditions

Both faces on each block were identically treated, observed for development, and oriented north and south. The greenhouse, except during extreme events such as heat waves, has a temperature of 20°C – 22°C during the day and 18°C – 20°C during the night, and has a humidity of 60%. Potable municipal water without fertilizer was used for irrigation, and the protocol evolved over time (see section 3.3.3 for details).

2.4. Verification of construction methodology

Test walls of pervious concrete with white cement/metakaolin/limestone filler supported by C25 normal strength structural concrete were cast using standard formwork mirroring presumed on-site construction methodology. Normal strength concrete, such as C25, is the most common type of concrete, often used for footings and foundations [57]. C25, also known as C25/30, represents its strength class as concrete is commonly classified by its compressive strength; here signifying a test cylinder strength of 25 N/mm^2 [58] [59]). Each mini-wall measured 50 cm x 88 cm x 24 cm ("A1"-sized mock-up of the wall system), had 16 cm thick steel-reinforced C25 and 8 cm pervious concrete. Day one the pervious concrete was cast, day two the forms were stripped, and day three the C25 was cast – the inside exposed face of the pervious concrete being the C25 formwork's inside face. Construction methodology validation requires the "walls" to be: homogenous in appearance, permeable, and without cavities and compacting flaws. Formula validation requires the multi-layers adhering well to one another and the pervious layer's interconnected pores unobstructed by C25 for ¾ of its width.

After validation, the integration of the living concrete into the building envelope was studied. A probe into generic wall types highlighted global characteristics: the use of water/air/moisture barriers; building insulation; customary interior finishes; integration of primary structure; distribution of mechanical, electrical and plumbing; and potential to resist lateral and shear forces (if the wall is non-structural, i.e., infill, curtain, or cladding, it is required to resist lateral loads from wind; unless used as a shear diaphragm). The propositions are based on norms adopted by France's Scientific and Technical Center for Building (CSTB) in their Unified Technical Document on cast-in-place concrete [60] and in their Register of Unified Documents of general conditions for the use of exterior thermal insulation systems [61]. Additionally, one proposition complies with the Passive House Institute's standards for energy efficiency, comfort, and affordability [62]; and a thermal insulation requirement of R-40, chosen for Paris, France.

2.5. Chemical analysis

Irrigation water was tested to define: cement's effect on plant life, when it would be chemically safe to seed, the fewest days carbonatation will affect the plants. Three (3) test walls measured the chemical composition of the irrigation water passing through to pinpoint the earliest date for seeding. Each A-1 mini-wall had 16 cm thick C25, and 8 cm thick pervious concrete stopping 15 cm from the base. The walls were installed inside a laboratory with equal irrigation, drainage, and light exposure. They were watered regularly and uniformly with a flow-rate approximating the Angers's greenhouse. Water samples were taken from each specimen to measure pH, cations, and anions (SiO2, Al2O3, Fe2O3, CaO, MgO, K2O, Na2O, SO3, P, Cl et NO3) every two hours for the first day, three times/day for the first week, and once/day thereafter, for four weeks. The water passing through the pervious layer of the wall was compared to the potable tapwater. Additionally, for test specimen “C”, continuous measurements were taken to measure pH and conductivity.

2.6. Determination of mechanical properties

The pervious concrete’s strength and porosity were tested using ten test cylinders for each of the mix design. One test cylinder was used for porosity and nine were kept in normalized conditions (of ~100% humidity) to test for their compressive strength after 7, 28 and 90 days. The density of each of two mix designs was also measured. The above protocol was repeated for the tests in interior lighted conditions with regular watering, to approximate greenhouse conditions, and for each full-size exterior-casting (with adjacently-stored cylinders).

The cohesion between the pervious concrete and its supporting layer of normal concrete was also determined. Two A1 wall mock-ups with 8 cm pervious concrete layer and 16 cm of C25 were fabricated. Three transversal core samples were taken from the wall’s upper, middle, and lower regions, and one longitudinal core from the middle region. The physical and mechanical characteristics of the cohesion between the two layers were examined by measuring the indirect traction (using a tensile splitting test of the longitudinal core – the longitudinal core was cut in half transversally to accommodate two separate tests), the direct traction of two transversally-cut cores taken from the upper and lower regions of the wall, and (visually) the infiltration of the C25 concrete into the pervious concrete (longitudinally splitting the middle region’s transversally-cut core).

2.7. Validate germination and perenniality outdoors

To validate the new system, the living wall vegetation must survive their first winter, so four cardinally oriented (facing: due south, due north, due east, and due west) exterior concrete living walls were cast at full-size (2.7m high x 2.0m wide). The four exterior walls were built in LafargeHolcim's outdoor construction testing laboratory near Lyon, France.

Lyon's climate became a major factor in plant selection. Lyon's climate is temperate, mild, has no dry season and warm summers, and is classified as a maritime temperate or oceanic climate by the Köppen-Geiger classification system [63] [64]. July is the warmest month with an average high/low temperature of 27.0°C/15°C [64]. January is the coldest month with an average high/low temperature of 5.8°C/-0.5°C [64]. Lyon's average rainfall is 763 mm; autumn is the rainiest season; May and June are also very rainy [64]. Despite its considerable rain, Lyon is also very sunny, averaging 2018 hours of sunshine/year, indicative of its changeable/unpredictable weather [63]. Geographically affected by being in the Rhône valley (cold winds from the Alps and warm Mediterranean winds from the south), Lyon's chilly winds making winter days feel colder than recorded temperatures suggest [65].

The walls were cast with the methodology described in section 2.4. An irrigation system was installed, balanced, and functioned in an open cycle (using potable water). The seeded substrates were installed in two bands: the largest band for the five-seed mix and the middle band with the grass mix (later, a third band was seeded on each wall – see section 3.7.2).

Plant monitoring used time-lapse photography for data collection taken hourly by four cameras suspended from each wall (see Fig. 7E). The walls were observed and analyzed for germination, plant development, substrate evolution, irrigation functioning and water consumption. Moisture content was monitored using internal and surface moisture sensors. The chemical analysis of irrigation water was analyzed before and after watering Monday, Wednesday and Friday during the first three months, and biweekly thereafter.

2.8. Cost analysis

A financial cost analysis was performed based on a hypothetical project in Paris, France. The five-stories-high living wall with 150m^2 of uninterrupted surface, had: 8 cm of pervious concrete and 16 cm of C25, three rows of irrigation; four rows of water collection trays, one overflow gutter, and seeded substrate without cement. Accessories include irrigation piping and emitters, rainwater piping, repartition trays, collection gutter, control panel and timer, regulators for water pressure and quantity, electric valves, pump, and a backup pump. Estimated costs of water storage containers were not included in the study. Regarding life cycle costs, the concrete living wall is also the building's structure, so it matches its building's lifespan. At end of life its concrete is recycled [11] [66].

3. Results

3.1. Pervious concrete formulas

The mix designs, now patented [67] [68] [69] [70] [71], were tested for slump, density and porosity. Measuring pervious concrete slump was found to be inutile: the mix is either too stiff (zero slump) or too liquid (maximum slump), relative to aggregate size.

Vibrating pervious concrete, or otherwise manipulating its compaction, was found to be unrealistic; picking is workable only for small castings. Concrete immersion (needle) vibrators only have local effect due to the absence of cement paste saturation in the granular mix. Ostensibly, the pervious concrete's voids impede vibrator wave transmission, only affecting material around the needle. Vibrating formwork could lead to over-vibration and risk: a damming effect via slurry pooling, heterogeneous vibration – consequently non-uniform porosity, and the premium cost of uncommon construction practices [72].

Sand was omitted from the mix to lessen stiffness (improving workability), rendering the material conducive to vertical casting, and aided the cement paste's lubricating effect [73]. The observable representation of this is the appearance of "strings" between adjacent aggregates. The stringy appearance of a cementitious binder is a function of the cement paste's composition and viscosity and an indicator of pervious concrete rheological success. The final mix designs are shown in Table 2.

Component	F1 (weight in kg/m^3)	F2 (weight in kg/m^3)
Cement	333.6	179.5
Aggregates 6 - 10 mm	1570.8	1570.9
Metakaolin		82.5
Limestone filler		41.2
Superplastifier	3.3	3.9
Viscosity modifying agent	0.011	
Water	90.0	91.0

Table 2. Pervious formulas of the new concrete. F1 = cement formula. F2 = formula with cement, metakaolin and limestone filler.

3.2. Constructability verification

The living concrete's constructability was verified after vertically casting of a mini-wall using the pure cement formula and standard concrete formwork and techniques [see Fig. 1A]. Moreover, validation followed the wall's homogenous appearance, permeability, self-compactability, and absence of compacting flaws/cavities.

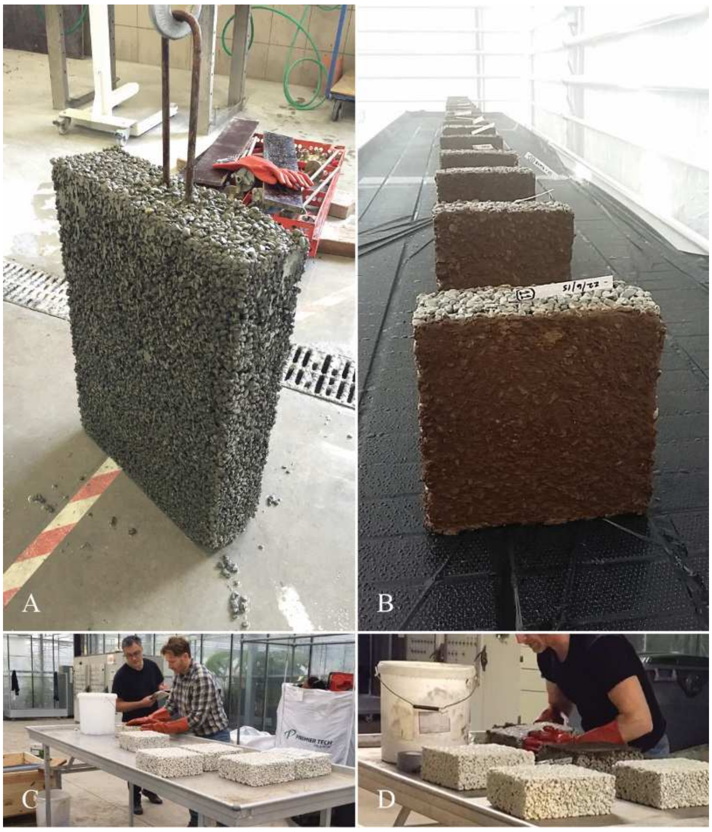

Fig. 1. A: Vertically cast-in-place pervious concrete mini-wall validated construction methodology and mix formula. B: Test bodies installed in the greenhouse in Angers, France. C&D: Seeded substrate installation in the greenhouse laboratory. Photos by Benjamin Riley.

3.3. Validating the repeatability of germination

3.3.1 1st and 2nd series results

The installation of the first and second series of seeded-substrates is shown in Fig. 1B-D. All first series plant species installed themselves (*Cymbalaria muralis, Aurinia saxatilis, Ruta graveolens, and Sedum acre*). However, *Ruta graveolens* appeared one year after seeding. Mosses and other bryophytes installed themselves spontaneously. The first series success opened the door to more rigorous, larger-scale testing.

Fig. 2. Interior trials 1&2: A: 2^{nd} series results and the prodigious *Sedum acre* (*Cymbalaria muralis showing*) on a white cement/Metakaolin/limestone filler test block with Rockwool seeded-substrate (2016). B: wider view of 1^{st} and 2^{nd} series trials in the Angers greenhouse (2016). C: Mid-term results (2017) showing a test block of the cement formula with soil substrate and *Cymbalaria muralis* taking over. D: 1^{st} series test block of the cement formula with soil substrate and cement added to soil and *Aurinia saxatilis* dominating. Photos by Benjamin Riley.

The second series studied alternative substrates and plant species. Fiber reinforcement and cement reinforcement were added to substrates for better resistance to weather. The substrates tested included earth/compost with cement (1%, 2%, 3%, or 4% by mass), coconut-fiber/humus/compost, glass-fibers/earth/compost, Polyethylene-fibers/earth/compost, and Rockwool mineral fiber [see Fig. 2A]. In addition, *Centranthus ruber, Lolium perenne, and Festuca rubra* were tested. The plant and spontaneous bryophyte evolution was positive, matching the first series. There is no noticeable preference for any single concrete formula. The success of the second series of trials inspired a third series [see 3.3.2. and Fig. 3 bottom row].

Fig. 3. **Interior trials 1, 2&3:** Top row: Long-term results of 1st and 2nd series in 2018. A: 2nd series block showing *Lolium perenne, and Festuca rubra* (2018). B: 2nd series test block showing *Centranthus ruber* and *Cymbalaria muralis* taking over but *Ruta graveolens* peeking through (2018). C: 1st series test block (Metakaolin formula with soil substrate) after three years (2018) with *Ruta graveolens* taken over (note: the *Ruta Graveolens* appeared one year after seeding). Bottom row: Mid-term results of 3rd series of temporal trials (2017). D: Seeded one week after casting. E: Seeded two weeks after casting. F: Seeded three weeks after casting. Photos by Fabienne Mathis and Vegepolys.

3.3.2 3rd series results

The third series of trials analyzed the temporal relationship between plant germination and the delay between casting and seeded substrate installation. Long-term results showed substrates installed one day after casting will lead to the same results as waiting 28 days. Short-term results after 2½ months show little plant development differences between 7&14-day and 21&28-day pairs. However, between the 1-day and the 7&14-day pairs there was a noticeable difference. Likewise, differences were seen between the 7&14-day pairs and the 21&28-day

pairs. After one year there are little to no differences in the aesthetic aspect of any of the blocks [see Fig. 3].

3.3.3 Greenhouse irrigation

Irrigation was with potable municipal water without fertilizers. 1st series blocks were watered by aspersion for six minutes, five times/day (three minutes of aspersion corresponds to 1 l/m²). On December 15, 2015 three minutes of aspersion/hour was delivered between 08:00 and 18:00 each day. Then on June 14, 2016, drip irrigation was delivered to two points on each block for five minutes five times/day between 07:00 and 19:00. Dripline flow is 20 ml/minute. Watering by aspersion was stopped between October 18, 2016 and May 18, 2017, provoking a slow degradation of mosses and some plants on the 1st and 2nd series of blocks.

Irrigation flow remains to be optimized because the test blocks consume a large quantity of water. However, evapotranspiration is <20%. The remaining water percolates through and is lost to greenhouse drains. If recycled, water consumption would plummet.

3.4. Living wall construction methodology

Several A1-size mini-walls were cast in a manner replicating typical construction practices [see Fig. 5B and Fig. 5C], except for the reversed pouring order: the pervious concrete was cast before its reinforced concrete (C25) support, and the pervious concrete's inside face becomes the outer formwork for the C25 layer. Thereafter, normal construction sequencing resumes.

The cast pervious concrete "walls" were found to be homogenous in appearance, permeable, without cavities, without compacting flaws, both layers adhering well to one another, and the porosity of the pervious concrete was unimpeded by the C25 for ¾ of its width. This validated the white cement/metakaolin/limestone filler formula.

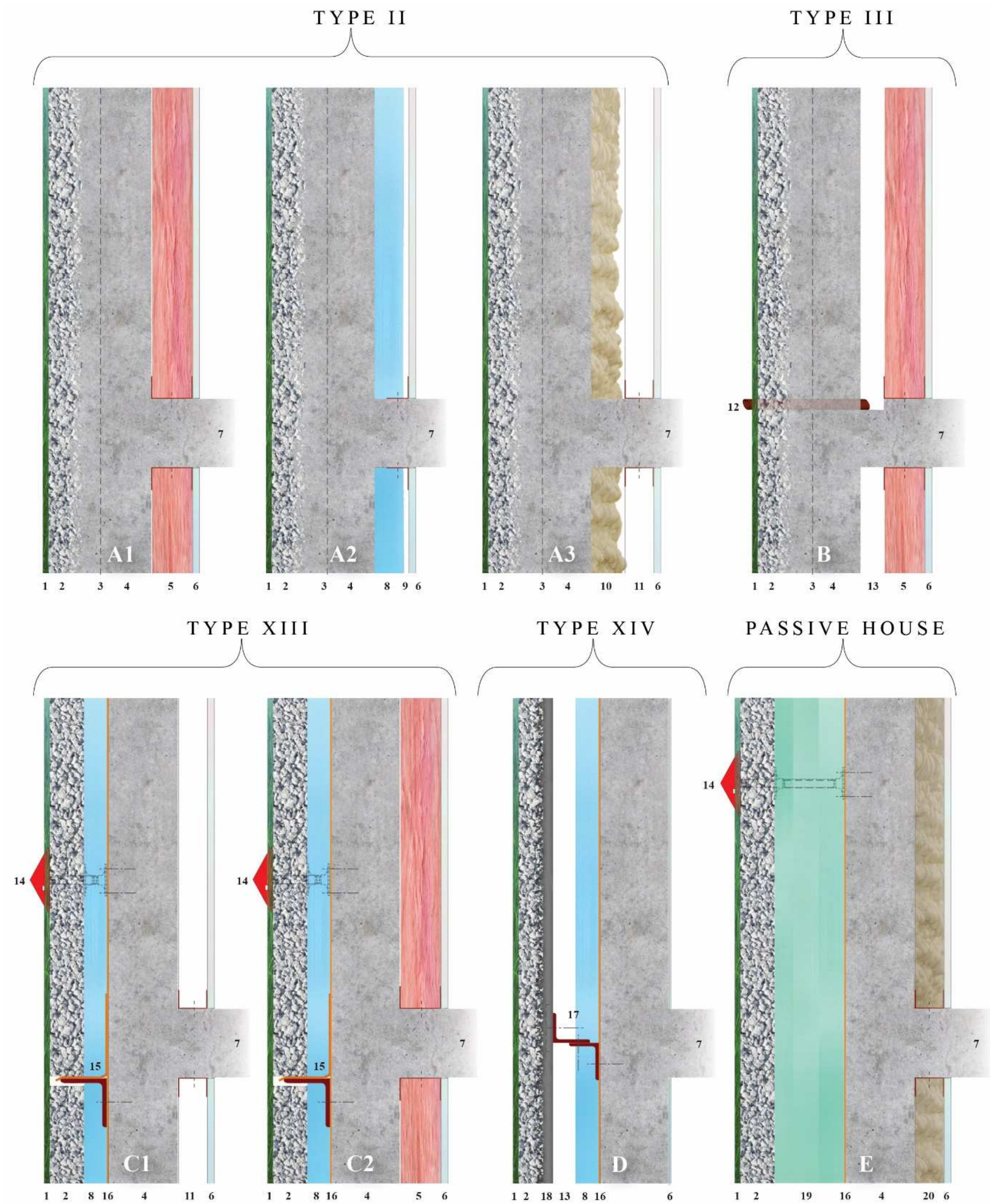

Fig. 4. Generic wall type study: vertical wall section propositions. 1. Vegetation layer/drainage plane, 2. Pervious concrete/auxiliary drainage plane, 3. Welded wire fabric, 4. Normal strength or insulating concrete, 5. Thermal insulation – unfaced batts, spray-applied cellulose, or low-density spray-applied foam of an air-permeable water sensitive cavity insulation (can dry inwards/through interior finish); because air-permeable this wall assembly is not for cold, very-cold, subarctic, and arctic hygro-thermal regions, 6. Gypsum wall board (or

interior plaster&lath) and interior finish (latex paint or a vapor semi-impermeable textured finish); avoid impermeable finishes such as vinyl wall coverings – very cold, subarctic, and arctic regions permit impermeable interior finishes **[74]**. 7. Concrete floor slab, 8. Interior rigid insulation - in lieu of air-permeable insulation - allows Type II wall assembly in all hygro-thermal regions; in cold hygro-thermal regions use vapor semi-permeable rigid insulation so wall dries inwards; ensure foam sheathing is unfaced/unskinned with aluminum foil, polypropylene, or other impermeable surfacing preventing wall drying inwards; recommended rigid insulation types for vapor semi-permeability are typically unfaced extruded polystyrene, unfaced expanded polystyrene or fiber-faced isocyanurate; in very cold, subarctic, and arctic regions avoid vapor permeable foam sheathings and interior finishes can be vapor impermeable, e.g., vinyl wall coverings **[74]**, 9. Metal channel/wood furring, 10. Interior non-moisture sensitive low-density spray-applied foam which is vapor semi-permeable, except in very cold, subarctic, and arctic regions where a high-density spray-applied foam insulation should be used which is vapor impermeable, 11. Uninsulated steel/wood stud cavity, 12. Evacuation pipe, 13. Air cavity&weep system, 14. Wall-tie fasteners (prevent separation/resist lateral loads), w/penetrations flashed and sealed to restore integrity of impermeable vapor barrier (hollow center filled w/high-density spray-applied foam insulation reduces thermal bridging), 15. Shelf angle (supports dead load of pervious concrete w/counter-flashing), 16. Impermeable vapor barrier, 17. Structural steel shelf angle and clip angle supports concrete living wall panels, 18. HPC/HPFC backup, 19. Passive House minimum rigid foam insulation R-factor of 5.5/inch for polyisocynaurate high-density non-permeable insulation sheathing aged 15 years (thickness determined by local climate) **[75]**, 20. Steel/wood stud wall w/interior non-moisture sensitive low-density vapor semi-permeable spray-applied foam, in very cold, subarctic, and arctic regions use a high-density spray-applied foam vapor impermeable insulation. Drawings by Benjamin Riley.

Type II, III and XIII wall assemblies [see Fig. 4] comply with load-bearing exterior wall requirements in all hygro-thermal climate zones if insulation recommendations are followed (noted in legend). These wall assemblies are suitable for unsheltered buildings of all heights, except in coastal areas where the maximum height recommended is 50 m regardless if it is in a seaside district or at water's edge [76]. Type XIII, XIV [61], and Passive House wall assemblies advantage over Type II and III wall assemblies is their exterior insulation reduces thermal bridging at floors. Beyond thermal bridging elimination, the principal advantage of the Types XIII, XIV, and Passive House propositions is their walls dry both inwards and outwards owing to an impermeable vapor barrier (resulting from placing the rigid insulation on the exterior of the vapor barrier). This permits the vapor barrier to be both drainage plane and air barrier. The major difference between Type XIII and the Passive House wall is the added rigid insulation thicknesses. Note: if the prefabricated concrete living wall panels (Fig. 4D) function as a rainscreen rather than a semi-permeable barrier, the wall rating will lower from Type XVI to Type XIII [76].

3.5. Interior water analysis

Three A1-sized test specimens were created, two 14 days in advance. Yet, all three wall tests began on the same day, one day the final wall was cast. This permitted a comparison of concrete's carbonatation effects on water passing immediately through fresh and two-week old pervious concrete. Chemical analysis shows no significant difference between municipal water and the levels of chlorine, nitrate, and sulfate in recuperated irrigation water.

Unexpectedly, there is an uptake of calcium ions by the material. There is a slight pH increase, which could increase if water is recycled [77]. The principal lesson is the recommended minimum delay between fabrication and seeding is 10 days, although the temporal trials showed delayed-seeding has little effect on longterm plant development [see section 3.3.2]. Note: soil and water contact must also be considered because substrate loss and eluviation of minerals is an important aspect of substrate hydrology [78].

3.6. Living wall mechanical properties

The strength characteristics of the living wall are encouraging. The 28-day compressive strength result of ~10 MPa show the new pervious material is self-supporting, yet not sufficient to be used as a load bearing wall without a support layer. It has a porosity is 32% and a density of 1.7.Even more promising were the positive results of the splitting test showing the interface between the pervious concrete and the C25 is not a zone of weakness [see Fig. 5A]. The splitting test adhesion analysis averaged 1.9 MPa, therefore the pair act monolithically [see Fig. 5D].

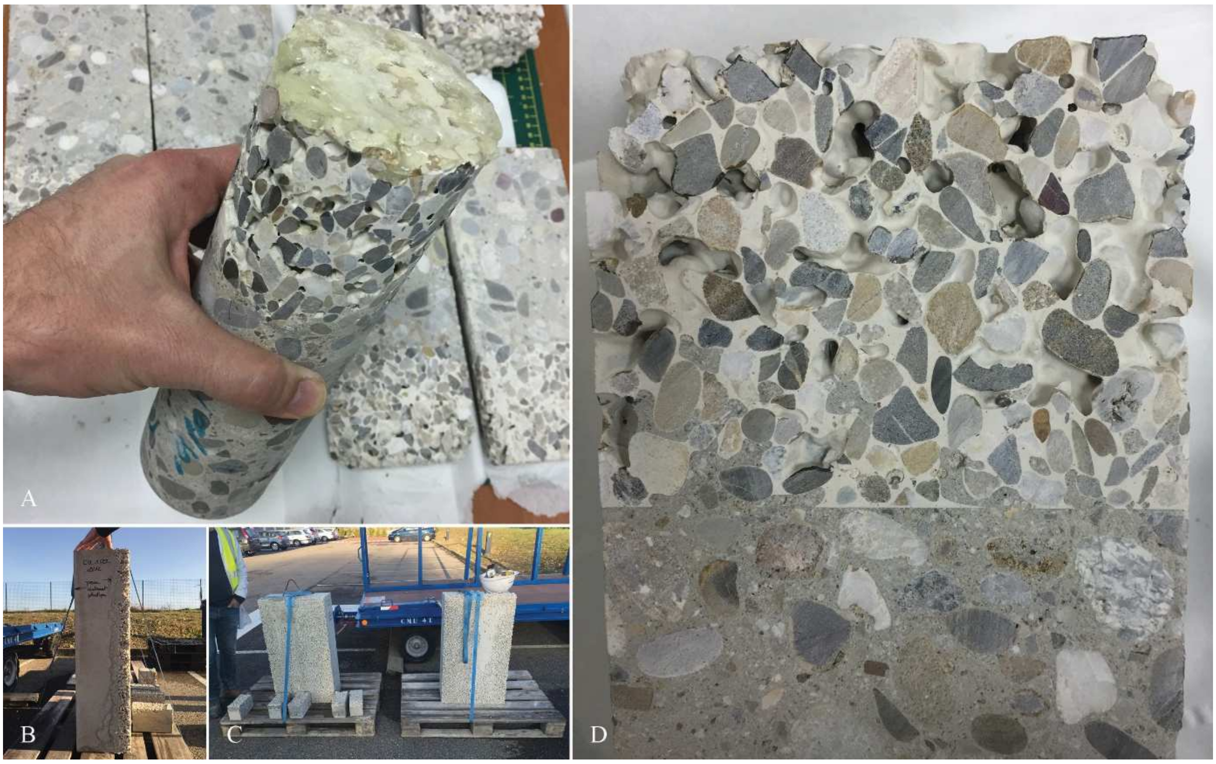

Fig. 5. Testing the cohesion between the pervious concrete and the supporting layer of normal concrete (C25) using core samples cut from the A1-sized mini-walls (images B and C). A: Epoxy failure before splitting the interface between pervious concrete and C25. D: Living concrete wall: a new monolithic material. Photos by Benjamin Riley.

3.7. Validating outdoors germination repeatability

3.7.1. *Full-size construction*

Following validation of the new material’s mechanical properties, the A1-sized construction methodology was repeated at full-size [see Fig. 6].

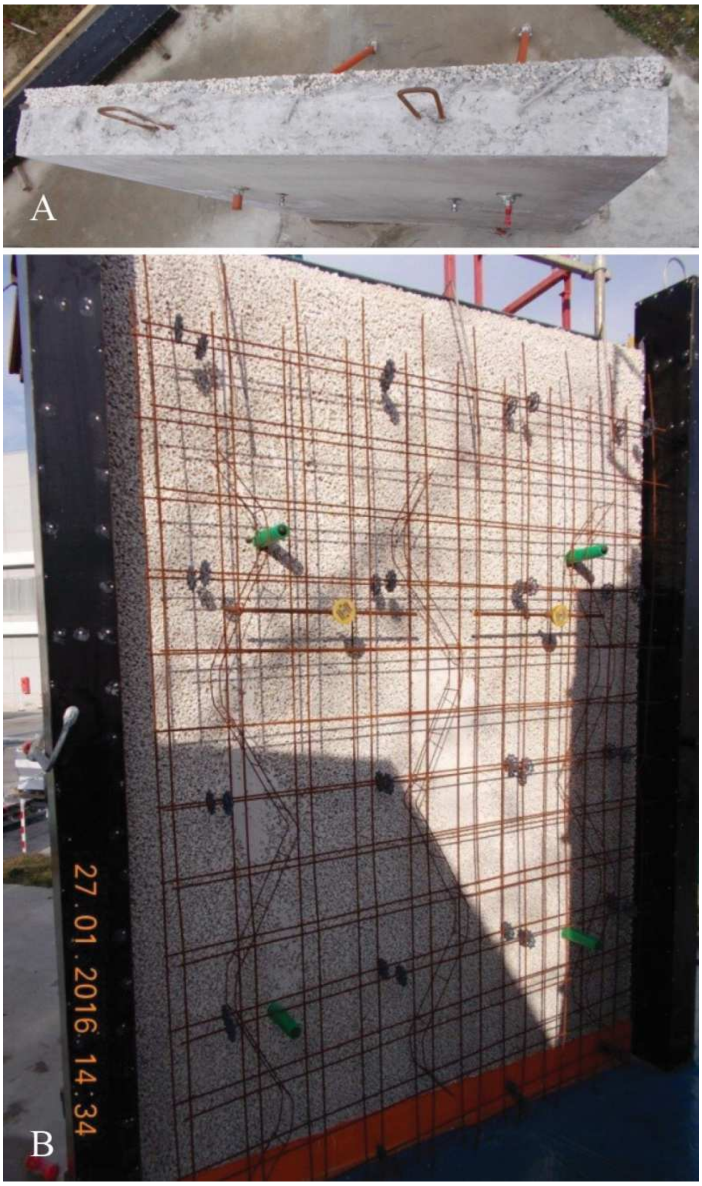

Fig. 6. A: View of concrete living wall from above. The pervious layer is toward the top of the image. B: Steel reinforcement in place for the normal concrete (the structural layer) and ready for the formwork to be closed. The steel reinforcement is installed AFTER the pervious concrete is poured, along with escutcheon embeds for the bracing, and wall tie sleeves (seen in green). The inner wall form is repositioned as the inner face of structural wall, the pervious wall acts as its outer formwork face.

Full-size construction led to altering the concrete formula. After the third wall was poured the cement paste was reduced by 10%/m^3 (the quantity of aggregates remained the same). To reduce built-up cement paste the sleeve/chute was moved constantly and the number of lifts minimized.

3.7.2. Seeded substrate installation

All walls were identically seeded with a substrate of earth and compost. Each wall face was divided into three vertical full-height bands: Band-1 with a 5-seed-mix substrate (112 cm wide); Band-2 with a grass-seeded substrate (44 cm wide); and Band-3 (44 cm wide) for climbing plants [see Fig. 7C]. In spring 2017, a wildflower seeded substrate replaced the climbing plants using a pre-purchased mixture (*Vilmorin 5860943 Pack de Graines Fleur Vivace pour Rocaille)* of >14 species, including ground cover varieties and one sedum.

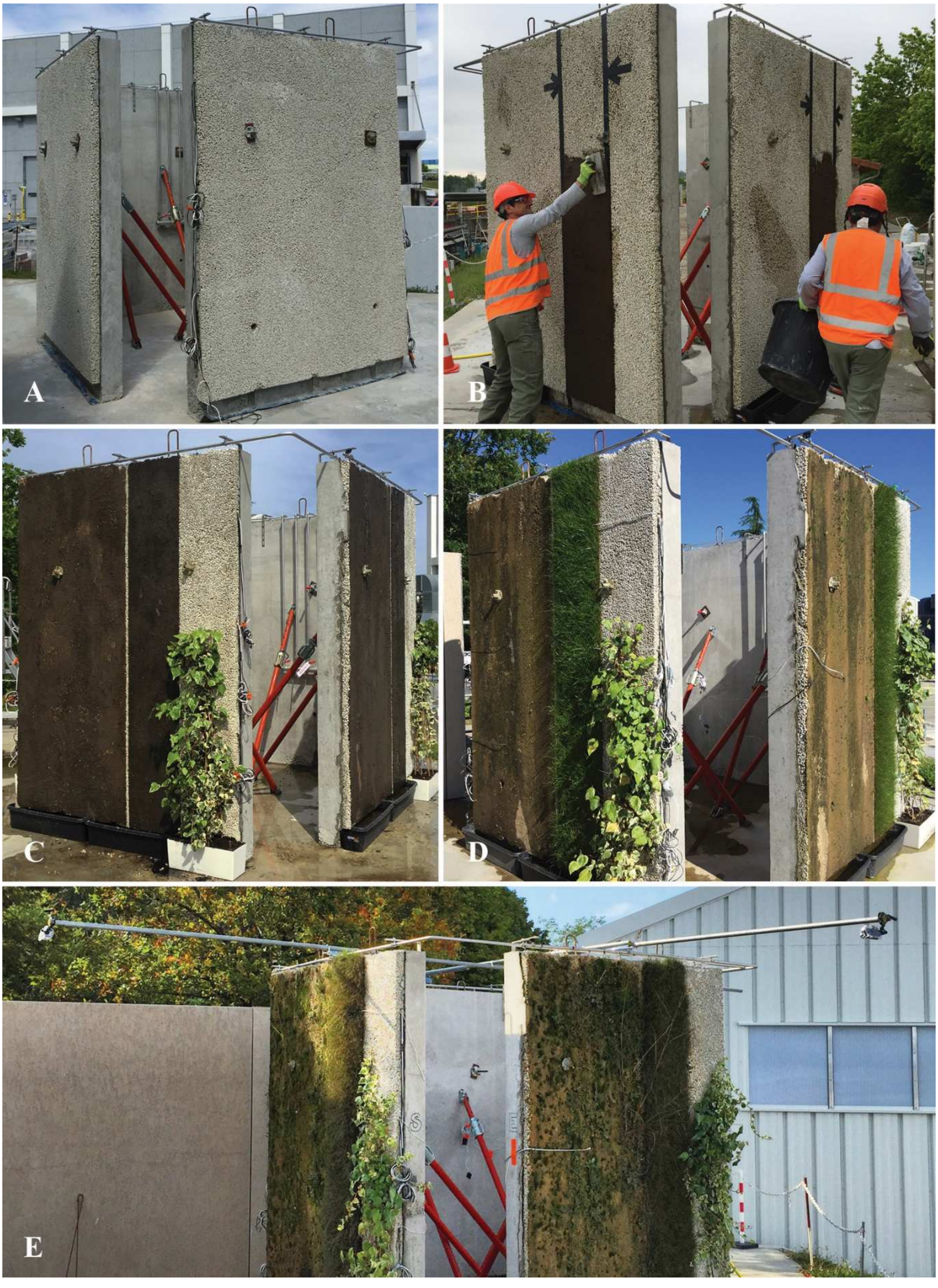

Fig. 7. Seeded substrate installation and plant development on the exterior trials. A: View of walls after irrigation installation, April 29, 2016. B: Troweling-on seeded substrate, May 2, 2016. C: Completed seeded-substrate installation, May 3, 2016. D: June 23, 2016. E: View of living concrete walls and time-lapse cameras, September 23, 2016. Photos by Benjamin Riley.

3.7.3. Plant development

Bands-1 germinated successfully, except in substrate dry-zones. All species germinated, but few survived the seedling stage. Plant loss was partly caused by the irrigation network's imprecise water flow (it was not built to specifications). By the time acceptable control was established, most seedlings had disappeared, either wilted in zones under-watered or drowned by overwatering.

Despite these challenges, many plants survived, including mosses. 70% - 95% vegetative coverage was achieved on the bands.The spontaneous mosses proliferated regardless of orientation. Orientation impacted plant growth. The west wall exhibiting better coverage. This may be due to its partial sheltering by two of the test site's later unrelated constructions [see Fig. 7D before and Fig. 7E after construction of a large hangar].

Only the *Sedum acres*, one specimen of *Cymbalaria muralis*, two specimens of spontaneous vascular species, and the moss survived the first winter. Hindering factors include the four-month irrigation shutoff during the test-site's winterization (November 2016 – March 2017) and three-week irrigation stoppage (April-May 2017, see section 3.7.5).

No pruning or maintenance was performed during the study, only visual inspection, apart from the removal of two spontaneous self-installed ligneous seedlings and in the spring of the second year when the top half of each grass band was trimmed to 5 cm, to study if growth would be affected (it was not) [see Fig. 8].

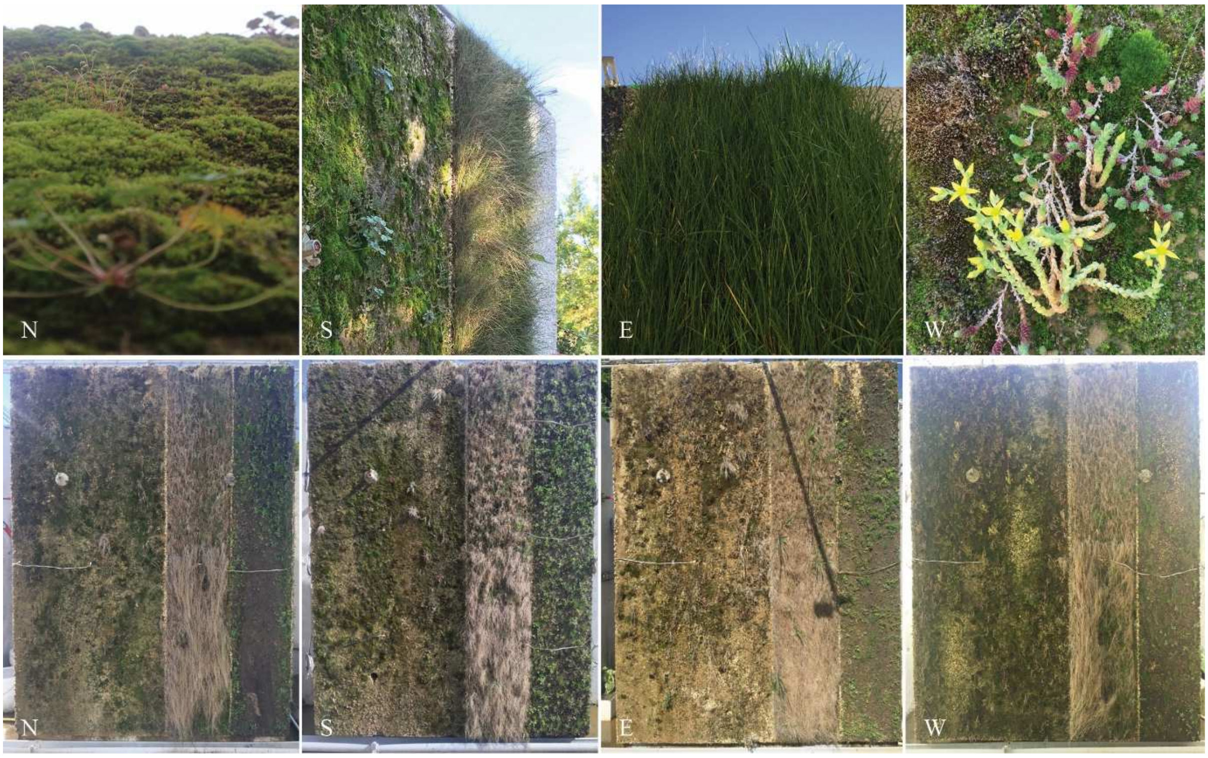

Fig. 8. Exterior wall plant development. Top row: details of vegetation on wall surfaces oriented north (N), south (S), east (E), and west (W) (end of first growing season November 23, 2016). Bottom row: survived the first winter: elevations of exterior walls after spring (June 27, 2017). Photos by Benjamin Riley.

Grass bands germinated with complete coverage; no dry zones were visible. The grass survived the first winter, but did not regenerate 100%. Reasons are unknown, but probably linked to the aforementioned irrigation stoppages.

Climbing plant results were inconclusive; the vines only attached to surface zones receiving moisture. The wildflower plants (that replaced the vines) germinated quickly, but – unlike the grasses – telegraphed the heterogeneous irrigation pattern.

Miscellaneous lessons learned: As at the west wall, partial sheltering may aid growth. If installed early, mosses create a better, future, microenvironment. A 100% humid environment aids plant germination. Reducing the system's moisture will limit moss development; mosses only grow in wet zones. There is no risk of mosses dominating vascular plants outside of excessively moist areas.

Plant selection also afforded several lessons learned, e.g., seeding is less expensive than planting, obtaining local seed varieties can be challenging, and some seeds take more than a year to germinate. Spontaneous plant installation provided negligible coverage. Unexpectedly, after two growing seasons, local species did not auto-populate the wall.

3.7.4. Substrate development

A major 50-year storm (June 8, 2016) eroded the north wall's band-1 superficial substrate and ~50% of the embedded substrate. Remarkably, the grass band's substrate remained intact; presumably, the grass roots created a continuous mat locking the soil substrate to the pervious concrete.

3.7.5. Irrigation summary

The flow rate rose significantly during the first week of irrigation, in response to the concerns over heterogeneous irrigation patterns. Obtaining homogeneous irrigation was a challenge, and several strategies were tested, primarily temporal.

A month after substrate installation, irrigation flow was optimized and the flow-rate greatly reduced from 6 liters/m^2/day to 1 liter/m^2/day. This approximates the water consumption of the more efficient living walls currently used in temperate regions. The water reduction did not impede plant development.

Irrigation was unexpectedly cut-off for four-months for the testing site's winterization. In the interim the walls received half-a-dozen waterings by hand using a spray bottle. Nevertheless, the plants regrew after winter and irrigation resumption. A technical problem in April led to three-week irrigation stoppage, apparently killing the plants. In the hope of their regenerating, the irrigation was repaired and the flow increased to 2 liters/m^2/day for one month. Fortunately, despite the interruption, the plants regrew – except the majority of grass plants;

presumably because the stoppage coincided with a heat-wave. After the month-long flow increase, the flow returned to 1 liter/m².

3.7.6. Exterior water analysis

To protect plants, metakaolin was chosen to lower pH of and the chemical analyses show this is unnecessary (natural carbonatation quickly decreases surface pH even with the pure cement mix). The exterior water analysis showed calcium oxide levels stabilize within 10 days, the pH rapidly stabilizes within a week and then averages 8.3 (municipal water averages ~7.9). For all elements monitored, rainwater is much less charged than municipal water. The pH, CaO, and ultimately SO3 are the most pertinent values, e.g., SO3, sulfur trioxide values –acid rain's primary agent – remain slightly higher than municipal water supply control values.

3.7.7. Perenniality validation

Fig. 8's bottom-row show the four walls at study's end in June 2017. Despite irrigation difficulties – over/under-watering, failures, and stoppages – the concrete living walls survived their first winter. Not all plants survived, whether due to poor selection or maintenance is unknown. Hence, species selection data is inconclusive, apart from the sedums and moss. Nevertheless, the vegetation continued to grow after the winter validating concrete living wall perenniality.

3.7.8. Cost analysis

A labor and material cost analysis was calculated for the project discussed in section 2.8 for spring 2017 [see Table 3]. The irrigation system includes the capture and recirculation of irrigation water and its accessories detailed in section 2.8.

		Labor				Material			
Description	Unit	Labor (h/m^2)	Total labor (€/m^2)	Material	Unit	Quantity	Cost (€/m^2)	Total Material (€/m^2)	Total (€/m^2)
Pervious Concrete 8 cm	m^2	1,80	54,00	Concrete	m^3	0,08	75,00	6,00	66,78
				Formwork	m^2	2,00	3,39	6,78	
							Total material	12,78	
C25 Concrete 16 cm	m^2	1,60	48,00	Concrete	m^3	0,16	100,00	16,00	74,30
				Formwork	m^2	2,00	3,39	6,78	
				Reinforcement	kg	3,09	1,14	3,52	
							Total material	26,30	
Seeded substrate 1 cm	m^2	0,18	5,40	Earth	m^3	0,01	0,38	0,01	7,42
				Compost	m^3	0,01	1,19	0,01	
				Seeds	g	1,00	2,00	2,00	
							Total material	2,02	
Irrgn. Sys.	m²	0,52	15,60					28,60	44,20
								Total Cost (€/m^2)	192,70

Table 3. Labor and material cost analysis of living concrete wall system. Subtract the C25 for cost comparisons with other systems. The addition of overhead and profit is discussed in this section (section 3.7.8).

The total cost of the system is 193€/m², but this includes the building's load-bearing exterior wall. The living wall's supplemental cost is 67€/m² + 8€/m² + 45€/m² = 120€/m². Much lower than contemporary systems costing 400€–€1200/m^2 (see section 1.3) [5] [6] [46], and equals the installed cost of the least expensive green façade systems.

An additional margin of 50% (60€/m^2) can be added for unforeseen costs (overhead expenses) the total would be 180€/m^2. Adding 10% profit (18€/m^2) to this and the living concrete cost swells to 198€/m2, still half the cost of living walls on the low end price of the spectrum.

4. Conclusions

Rethinking living walls as indivisible from their building's exterior wall can lead to affordable and accessible solutions. Potentially, this approach can stimulate greening the walls of urban canyons, the city zones with the least available horizontal surfaces for planting, and resulted in a cast-in-place living concrete wall system.

Several advances were made. New pervious concrete formulas were invented, tested and their mechanical characteristics defined. The new pervious concrete can be cast vertically – poured-in-place into a self-supporting wall – without compaction or vibration. Local plants were selected for their: tolerance to alkaline soils, seed growth, small root diameter, solar orientations, and adaptability to vertical environments. New substrates and installation methodologies were created permitting seeded-substrate application. Blocks with seeded substrates were tested in the controlled greenhouse environment and their fertile development was presented.

A new construction methodology was invented and vetted: the pervious concrete layer is cast before the structural backup layer and becomes its wall form, locking the two concretes together. A chemical analysis of water irrigated through concrete was presented. The study shows fertilizer is not necessary for living walls to survive. The exterior tests proved that the germination and perenniality achieved in the indoor trials is possible outdoors. However, lush vegetation indoors was not achieved outdoors. The outdoor tests showed water consumption can be 1 l/m^2/day if runoff is recycled.

A conservative analysis shows living concrete costs ~200€/m^2 – half the cost of the least expensive contemporary systems, validating the approach of rethinking the additive living wall paradigm to encourage their proliferation.

5. Discussion

The study resulted in the development of a new living material for interior and exterior architectural and green infrastructural applications. And the first cast-in-place living wall: the innovation of vertically-cast pervious concrete. The trials also validate growing living wall plants from seed in-situ. The interior and exterior trials validated the repeatability of germination, formulas, and construction methodologies of a concrete living wall. Still flourishing after three years, the interior trials show the perenniality of living concrete given the right conditions.

The interior trials demonstrate living wall plants survive without fertilizer – and soil, since plants grow in Rockwool, which lacks the minerals in the soil-substrate. Likewise, no fertilizer was used on the exterior trials; further tests are needed to confirm sustainability.

The exterior trials establish the likelihood of large-scale applications, but require further study to produce the lush aesthetic of interior trials. Perenniality was ascertained, but prior to commercialization long-term testing is necessary to master plant development and maintenance protocols. For example, increasing the pervious layer's width - partially filled by C25 concrete – or aggregate diameter (to resemble the porosity available to roots in the unencumbered interior test-blocks) could improve plant development.

Cardinal orientation notwithstanding, all four exterior walls hosted plant growth, implying any orientation can support a concrete living wall, given the right environmental conditions. Only grass was unaffected by location. Biodiversity may hold the key to ensure plant perenniality irrespective of orientation. A minimum number should be set for species in a substrate without grasses; 30 is recommended. This number will ensure plants will install themselves in all wall zones regardless of orientation or micro-environment, e.g., wind turbulence-driven moisture variances.

Several watering lessons were learned. A concrete living wall consumption can average 1 liter/m^2/day. More water is needed for initial germination and spring regeneration. Furthermore, homogenous plant coverage requires running irrigation until moistening the entire substrate, thus defining the event's duration. If internal irrigation moistens completely, supplemental watering is unnecessary for germination. Evidently, the height between the irrigation pipe and collection point will dictate the event's duration. Future tests are recommended to validate usage data in closed-circuit irrigation (recycled water).

Concrete living wall durability and structural potential foretell its use for green infrastructure, but also portent its weight disadvantage compared to contemporary additive living walls, such as Patrick Blanc's lightweight felt system or heavier-weight modular-cell systems. For example with retrofitting. The proposed system is for new construction only, limiting its use. However, alternative solutions for retrofitting are detailed in the dissertation on this subject [79]. In these cases, weight may become an adverse factor: a 5 cm layer of living concrete weighs nearly 88 kg/m^2.

Conversely, concrete living walls would share benefits of green walls and have advantages over existing living wall systems. The primary advantage is the likelihood to be half the cost. Reasons for lower cost include: concrete's durability that gives it a life cycle equal to its building; growing plants from seeds in-situ bears considerable savings over growing plants in a nursery; and its integration into the building's exterior load-bearing wall. This means subtracting the some of the building's exterior structure from the concrete living wall's initial costs. No fertigation also predicts a cost – and environmental – advantage, foreshadowing a living wall that allows local plants to create their own environment. This prospective to adapt to its surroundings could prove valuable to cities confronting shifting climates.

Consideration was given to the system's potential to host pests such as mosquitos, which in turn could harbor Vector borne diseases, e.g., the Zika virus in Europe [80]. The interconnected pores of the living concrete are unconnected to outside air by the seeded-substrate. Thus, exposure is limited to water distribution and collection points. Here, covers, insect screens, and adequately pitched collection trays are necessary to allay access to irrigation or standing water.

The ongoing financial cost of yearly maintenance was not calculated. No regular maintenance was executed during the study, only daily observations, except for the incidents discussed in section 3.7.3. Growing plants from seed in situ is meant to eliminate the need to replace plants and allow the wall to evolve naturally with relatively little maintenance, the benefit of having plants create their own environment. However, the presence of self-installing tree seedlings show regular inspection and weeding is necessary to prevent damage to the pervious concrete structure. Furthermore, the irrigation system will require the regular maintenance obligatory to all living walls – minus fertigation expenses. Yearly ongoing operation and maintenance costs are anticipated to be between the ranges of green screens and living walls noted in section 1.3.

If green walls are to play a positive role in confronting the three most pressing challenges facing contemporary cities – population densification, shifting climates, and access to nature – they are obliged to satisfy the requirements of a sustainable city. They must contribute to satisfying the social, environmental, and economic needs of their urban environments, including durability and affordability. The impact of green walls on a city can be multi-faceted and multi-scalar [81], but only if system innovation leans toward their democratization. Further tests on the concept's perenniality are required before commercialization, but the initial results show rethinking living wall design holds potential to have broad contextual impact on the urban hardscape.

Patents note: the system presented above is patented in France, China, the United States, Europe, and by the World Intellectual Property Organization [67-71].

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