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Title:

Living Concrete:

Democratizing Living Walls

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1 **1. Introduction**

2 *1.1. Background*

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

11
12 The goal of this work is to determine the possibility of having a living wall system which is
13 durable, has the same longevity as its building, is unlimited by location and typology
14 (especially high-rises), and is more affordable than currently available systems. The
15 hypothesis asks if combining living-wall functions with the structural functions of a
16 building's exterior will lower cost and increase longevity. The outcome sought is to push
17 living walls beyond the economic threshold limiting their proliferation to extend nature's
18 reach into the urban milieu.

19
20 This interdisciplinary study, of architecture, botany, and material science, shows how shifting
21 the existing living wall paradigm from an additive to a systemic model creates the potential
22 for affordable living walls. The material tested is concrete, because, after water [9], it is the
23 most widely used building material in the world, and due to its widespread use [10],
24 durability, cost, and flexibility, is currently a pragmatic choice to democratize living walls.

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

29

30 1.2. About living walls

31 Green wall terminology is evolving. They have two categories: green façades and living walls
32 [16] [17], although *extensive* and *intensive* have been borrowed from the green roof industry
33 to describe them [18] [19] [20], these terms are best avoided to elude the confusion bred in
34 that domain. Green walls are also called vertical greening systems [18], an allusion to their
35 effect beyond surface treatment, i.e., they are complex systems with proportionate
36 consequences. For example, a living wall may require a water storage system connected to a
37 network of horizontal surfaces used to capture rainwater and a mechanical room to filter,
38 irrigate, and fertilize. In other words, much more than just a wall.

39 Living walls and green façades have the same fundamental requirements, i.e., plants'
40 indispensable needs: daylight, water, and nutrients [21]. Living walls share the same potential
41 advantages of other green infrastructure: they can have biophilia-related health benefits [4]
42 [22] [23], capture air pollutants [24] [25] [26], diminish noise pollution [27] [28], reduce the
43 heat-island effect [29] [30], provide natural cooling [31] [32], add privacy, and promote
44 biodiversity [33] [34].

45 Whereas green façades use climbing plants, living wall plants are distributed over the entire
46 wall [35]. The two main types of living walls are hydroponic and soil-cell systems.

47 Hydroponic systems often use a dense mat or felt-like material as a growing medium.

48 Discovered by the French botanist Patrick Blanc –the father of modern green walls – these

49 lightweight systems are wetted with nutrient-enriched water, and roots grow on and in-
50 between layers of matted or felted substrate [36]. Soil-cell systems compartmentalize the
51 growth of plants in individual cells of soil. Cells are grouped together in panels attached to a
52 frame. However, some hydroponic systems use a modular, cell-based typology, replacing soil
53 with horticultural growing media, e.g., rock wool or polyurethane foam. Cell-systems are
54 essentially a collection of inter-connected potted plants subject to the same challenges facing
55 potted house plants: soil compaction, drainage issues, climatic stress, and nutrient
56 replenishment [37]. However, exterior soil-cell walls also face the problem of soil loss due to
57 wind and water-driven erosion [38].

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

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

68 1.3. *Living wall costs*

69 Costs include initial installation's labor and materials, ongoing maintenance, environmental
70 burden, and total lifecycle cost. Collecting this data is challenging because of input
71 variability. For example, initial costs of systems identically sourced and installed will differ
72 because price is tailored by project; no two projects are identical. Geometrical or

73 environmental differences between projects – orientation, microclimate, size, neighboring
74 buildings – will affect solar access, wind patterns, and humidity, which affects plant species
75 selection and growth, which in turn affects system efficacy and usefulness, but also initial and
76 continued maintenance costs. How costs are defined also affect the data, e.g., some living
77 walls necessitate replacing 30% of their plants in the first year [8], and depending on how the
78 project is budgeted, this expense can be considered either installation or maintenance. Despite
79 these challenges, predictable costs emerge.

80 Concerning initial and ongoing costs, living walls are the more expensive category of green
81 walls [18]. Green façade installed system costs begin around €100/m², but go as high as
82 €800/m²; whereas living wall system initial costs begin about €400/m² and go as high as
83 €1200/m² [5] [6] [46]. Ongoing maintenance costs can be as low as 2-5€/m² for yearly
84 pruning of green screen climbing plants, and between 40-100€/m²/year for living walls [46].
85 The marked contrast in cost between the two green wall categories are a result of differing
86 complexities; living walls require a larger support network of: water supply, filtering,
87 collection, storage, mechanical distribution (pumps), irrigation components, fertilizer, and
88 maintenance for this equipment. Until cost and environmental burden are reduced, the
89 potential biophilic richness of living walls will most likely remain stunted.

90 *1.4. Objectives of the study*

91 Principally, this study investigates a strategy to proliferate urban living walls. As cost is the
92 major limiting factor, this study explores combining a living wall with the building structure
93 as an approach to reduce costs and have a lifespan commensurate with its building. This study
94 determines the validity of concrete growing plants for walls and green infrastructure. The
95 initial objectives are to: create a concrete to host plants, determine its mechanical properties,
96 verify its constructability, identify candidate native plant species, and study growing plants

97 from seed. The intention of sowing seeds directly on the new concrete is to encourage the
98 plants to create their own environment, eliminating the costs of raising and transplanting
99 nursery plants and annual replacement. The final objectives are to: incorporate the new
100 concrete into a conventional wall system, develop and test the new system's construction
101 methodology, analyze how the new concrete's chemical composition will affect plants and
102 irrigation, test the new system outdoors for germination and perennality, and determine the
103 new system's cost.

104

105 **2. Methodology**

106 The research methodology is in seven steps. Step 1 creates a new concrete to support plant life
107 (see 2.1). Step 2 verifies constructability (see 2.2). Step 3 and its sub-steps validates plant
108 growth on the new concrete (see 2.3). Step 4 verifies a new construction methodology (see
109 2.4). Step 5 analyzes the new concrete's chemical effect on plants and irrigation (see 2.5).
110 Step 6 tests mechanical properties (see 2.6). Step 7 validates outdoor germination and
111 perennality (see 2.7). Step 8 analyzes costs (see 2.8).

112 *2.1. Testing new concrete formulas*

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

118

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

124

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

131

132 *2.2. Verify constructability*

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

141

142 *2.3. Validate the repeatability of germination indoors*

143

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

149 *2.3.1 1st and 2nd series: testing the concept and alternatives*

150

151 The first set of trials were installed in a greenhouse on June 25, 2015. Eight specimens were
152 tested with a seeded substrate, i.e., seeds were mixed into a growing medium before it was
153 applied to the concrete. The plant species chosen for their local presence, ability to survive in
154 alkaline environments, and small diameter roots, which would not damage the pervious
155 concrete, are shown in Table 1, along with additional selection criteria and characteristics [53]
156 [54] [55] [56]. Note: mosses arrive spontaneously.

157

Characteristics	<i>Ruta graveolus</i>	<i>Aurinia saxatilis</i>	<i>Cymbalaria muralis</i>	<i>Sedum acre</i>
<i>USDA Hardiness Zone</i>	6b to 11	4 to 10	3 to 7	4 - 9
<i>UK Hardiness Zone</i>		to zone 3	to zone 3	to zone 5
<i>Wall orientation preferred</i>	S, E, W	S, E, W	N, S, E, W	S, E, W
<i>Sun / habitat</i>	Prefers full sun	Cannot grow in the shade	Semi-shade	Cannot grow in shade
<i>Size (max. ht./dia.)</i>	60cm by 45cm	30cm by 30cm	10cm by 40cm	10cm by 30cm
<i>pH</i>	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
<i>Propagation</i>	Seed	Seed	Seed	Seed/cuttings
<i>Misc</i>	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

158 **Table 1.** Plant selection criteria and characteristics.

159

160 In the first set of trials, all substrates were a mix of topsoil and earth in equal amounts by
161 volume, except half of the test specimens' substrates were cementitious under the hypothesis
162 they would better withstand harsh weather events. For these, 5% cement by volume was
163 added to the substrate. The substrate compositions are 35% earth, 35% compost, and 30%
164 water and the seed mixture tested is (in g/m³) *Ruta graveolens* (198g), *Aurinia saxatilis* (85g),
165 *Cymbalaria muralis* (21g), and *Sedum acre* (4g).

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

170 2.3.2 3rd series: effects of temporality

171

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

177 *2.3.3 Greenhouse environmental conditions*

178

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

184 *2.4. Verification of construction methodology*

185 Test walls of pervious concrete with white cement/metakaolin/limestone filler supported by
186 C25 normal strength structural concrete were cast using standard formwork mirroring
187 presumed on-site construction methodology. Normal strength concrete, such as C25, is the
188 most common type of concrete, often used for footings and foundations [57]. C25, also known
189 as C25/30, represents its strength class as concrete is commonly classified by its compressive
190 strength; here signifying a test cylinder strength of 25 N/mm² [58] [59]). Each mini-wall
191 measured 50 cm x 88 cm x 24 cm (“A1”-sized mock-up of the wall system), had 16 cm thick
192 steel-reinforced C25 and 8 cm pervious concrete. Day one the pervious concrete was cast, day
193 two the forms were stripped, and day three the C25 was cast – the inside exposed face of the
194 pervious concrete being the C25 formwork’s inside face. Construction methodology
195 validation requires the “walls” to be: homogenous in appearance, permeable, and without

196 cavities and compacting flaws. Formula validation requires the multi-layers adhering well to
197 one another and the pervious layer's interconnected pores unobstructed by C25 for $\frac{3}{4}$ of its
198 width.

199 After validation, the integration of the living concrete into the building envelope was studied.
200 A probe into generic wall types highlighted global characteristics: the use of
201 water/air/moisture barriers; building insulation; customary interior finishes; integration of
202 primary structure; distribution of mechanical, electrical and plumbing; and potential to resist
203 lateral and shear forces (if the wall is non-structural, i.e., infill, curtain, or cladding, it is
204 required to resist lateral loads from wind; unless used as a shear diaphragm). The propositions
205 are based on norms adopted by France's Scientific and Technical Center for Building (CSTB)
206 in their Unified Technical Document on cast-in-place concrete [60] and in their Register of
207 Unified Documents of general conditions for the use of exterior thermal insulation systems
208 [61]. Additionally, one proposition complies with the Passive House Institute's standards for
209 energy efficiency, comfort, and affordability [62]; and a thermal insulation requirement of R-
210 40, chosen for Paris, France.

211 *2.5. Chemical analysis*

212 Irrigation water was tested to define: cement's effect on plant life, when it would be
213 chemically safe to seed, the fewest days carbonatation will affect the plants. Three (3) test
214 walls measured the chemical composition of the irrigation water passing through to pinpoint
215 the earliest date for seeding. Each A-1 mini-wall had 16 cm thick C25, and 8 cm thick
216 pervious concrete stopping 15 cm from the base. The walls were installed inside a laboratory
217 with equal irrigation, drainage, and light exposure. They were watered regularly and
218 uniformly with a flow-rate approximating the Angers's greenhouse. Water samples were
219 taken from each specimen to measure pH, cations, and anions (SiO₂, Al₂O₃, Fe₂O₃, CaO,

220 MgO, K₂O, Na₂O, SO₃, P, Cl et NO₃) every two hours for the first day, three times/day for
221 the first week, and once/day thereafter, for four weeks. The water passing through the
222 pervious layer of the wall was compared to the potable tapwater. Additionally, for test
223 specimen “C”, continuous measurements were taken to measure pH and conductivity.

224 *2.6. Determination of mechanical properties*

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

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

241 *2.7. Validate germination and perenniality outdoors*

242 To validate the new system, the living wall vegetation must survive their first winter, so four
243 cardinally oriented (facing: due south, due north, due east, and due west) exterior concrete

244 living walls were cast at full-size (2.7m high x 2.0m wide). The four exterior walls were built
245 in LafargeHolcim's outdoor construction testing laboratory near Lyon, France.

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

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

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

266 *2.8. Cost analysis*

267 A financial cost analysis was performed based on a hypothetical project in Paris, France. The
268 five-stories-high living wall with 150m² of uninterrupted surface, had: 8 cm of pervious
269 concrete and 16 cm of C25, three rows of irrigation; four rows of water collection trays, one
270 overflow gutter, and seeded substrate without cement. Accessories include irrigation piping
271 and emitters, rainwater piping, repartition trays, collection gutter, control panel and timer,
272 regulators for water pressure and quantity, electric valves, pump, and a backup pump.
273 Estimated costs of water storage containers were not included in the study. Regarding life
274 cycle costs, the concrete living wall is also the building's structure, so it matches its building's
275 lifespan. At end of life its concrete is recycled [11] [66].

276

277 **3. Results**

278 *3.1. Pervious concrete formulas*

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

282

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

290

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

297

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

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

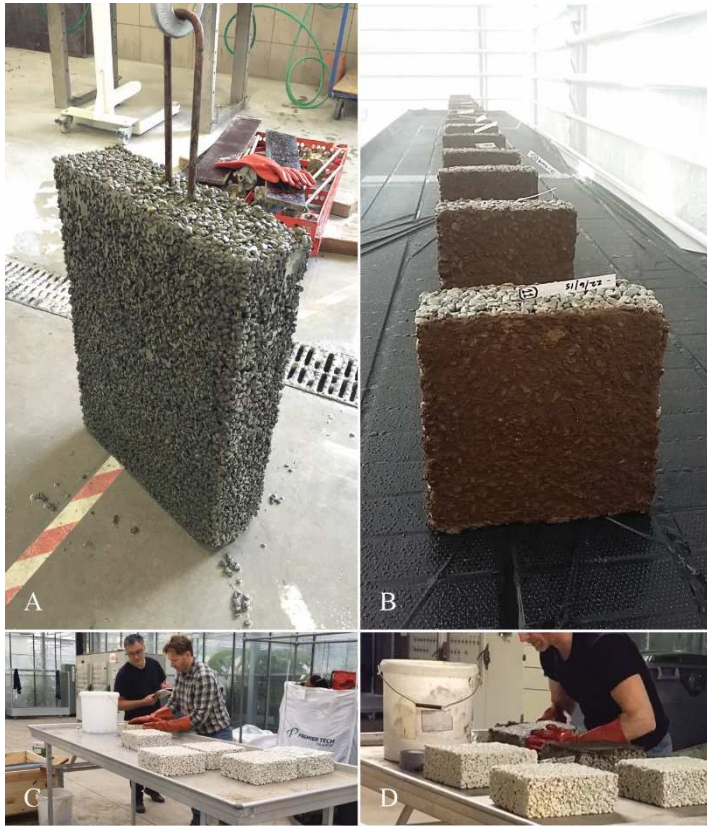
300

301 3.2. Constructability verification

302

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

307



308

309

310

311

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.

312

3.3. Validating the repeatability of germination

313

314

3.3.1 1st and 2nd series results

315

The installation of the first and second series of seeded-substrates is shown in Fig. 1B-D. All

316

first series plant species installed themselves (*Cymbalaria muralis*, *Aurinia saxatilis*, *Ruta*

317

graveolens, and *Sedum acre*). However, *Ruta graveolens* appeared one year after seeding.

318

Mosses and other bryophytes installed themselves spontaneously. The first series success

319

opened the door to more rigorous, larger-scale testing.



320

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

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



336

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

344 3.3.2 3rd series results

345 The third series of trials analyzed the temporal relationship between plant germination and the
 346 delay between casting and seeded substrate installation. Long-term results showed substrates
 347 installed one day after casting will lead to the same results as waiting 28 days. Short-term
 348 results after 2½ months show little plant development differences between 7&14-day and
 349 21&28-day pairs. However, between the 1-day and the 7&14-day pairs there was a noticeable
 350 difference. Likewise, differences were seen between the 7&14-day pairs and the 21&28-day

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

353

354 *3.3.3 Greenhouse irrigation*

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

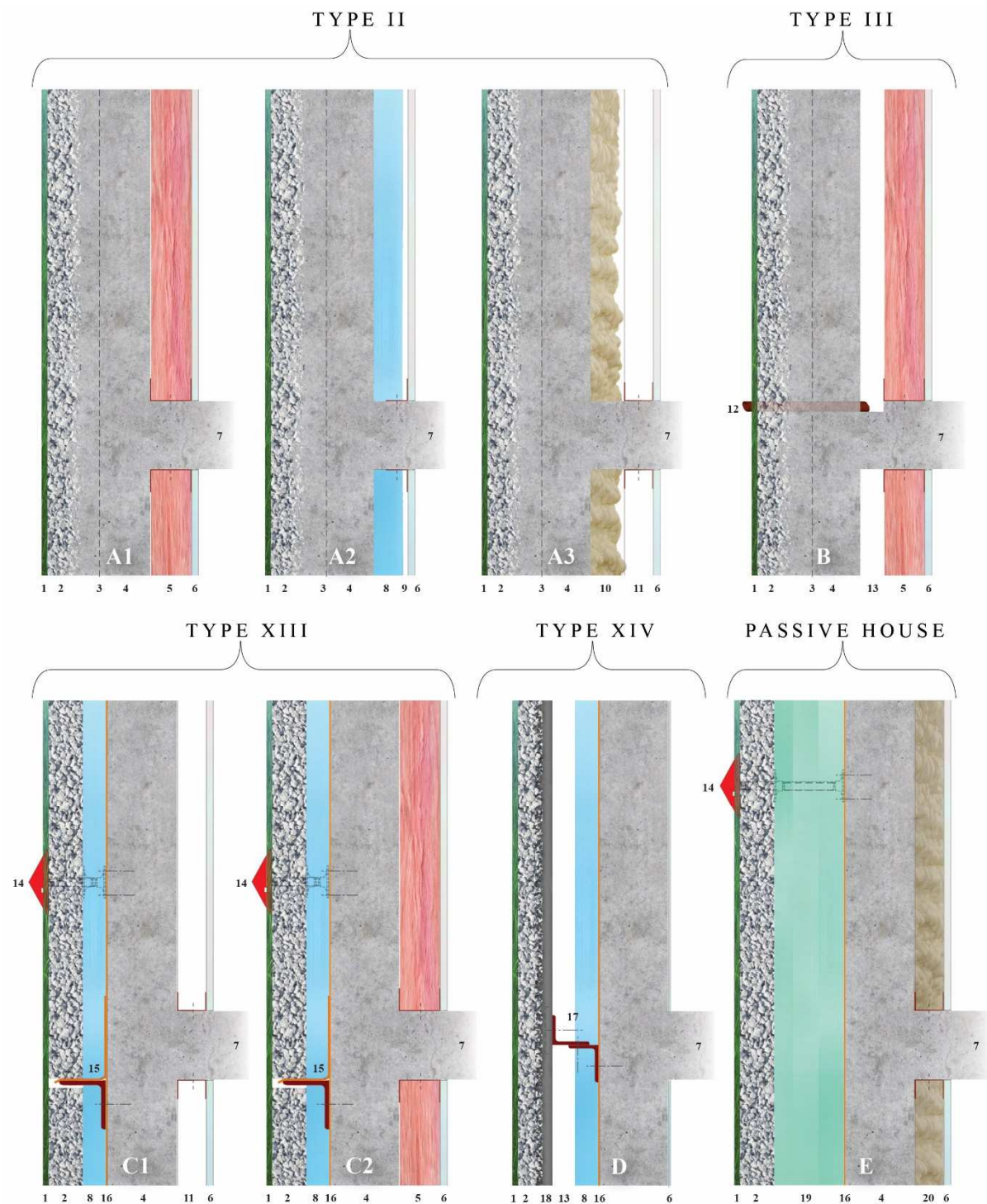
362 Irrigation flow remains to be optimized because the test blocks consume a large quantity of
363 water. However, evapotranspiration is <20%. The remaining water percolates through and is
364 lost to greenhouse drains. If recycled, water consumption would plummet.

365 *3.4. Living wall construction methodology*

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

371 The cast pervious concrete "walls" were found to be homogenous in appearance, permeable,
372 without cavities, without compacting flaws, both layers adhering well to one another, and the

373 porosity of the pervious concrete was unimpeded by the C25 for $\frac{3}{4}$ of its width. This validated
 374 the white cement/metakaolin/limestone filler formula.



375

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

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

402 Type II, III and XIII wall assemblies [see Fig. 4] comply with load-bearing exterior wall
403 requirements in all hygro-thermal climate zones if insulation recommendations are followed
404 (noted in legend). These wall assemblies are suitable for unsheltered buildings of all heights,
405 except in coastal areas where the maximum height recommended is 50 m regardless if it is in
406 a seaside district or at water's edge [76]. Type XIII, XIV [61], and Passive House wall
407 assemblies advantage over Type II and III wall assemblies is their exterior insulation reduces
408 thermal bridging at floors. Beyond thermal bridging elimination, the principal advantage of
409 the Types XIII, XIV, and Passive House propositions is their walls dry both inwards and
410 outwards owing to an impermeable vapor barrier (resulting from placing the rigid insulation
411 on the exterior of the vapor barrier). This permits the vapor barrier to be both drainage plane
412 and air barrier. The major difference between Type XIII and the Passive House wall is the
413 added rigid insulation thicknesses. Note: if the prefabricated concrete living wall panels (Fig.
414 4D) function as a rainscreen rather than a semi-permeable barrier, the wall rating will lower
415 from Type XVI to Type XIII [76].

416 3.5. Interior water analysis

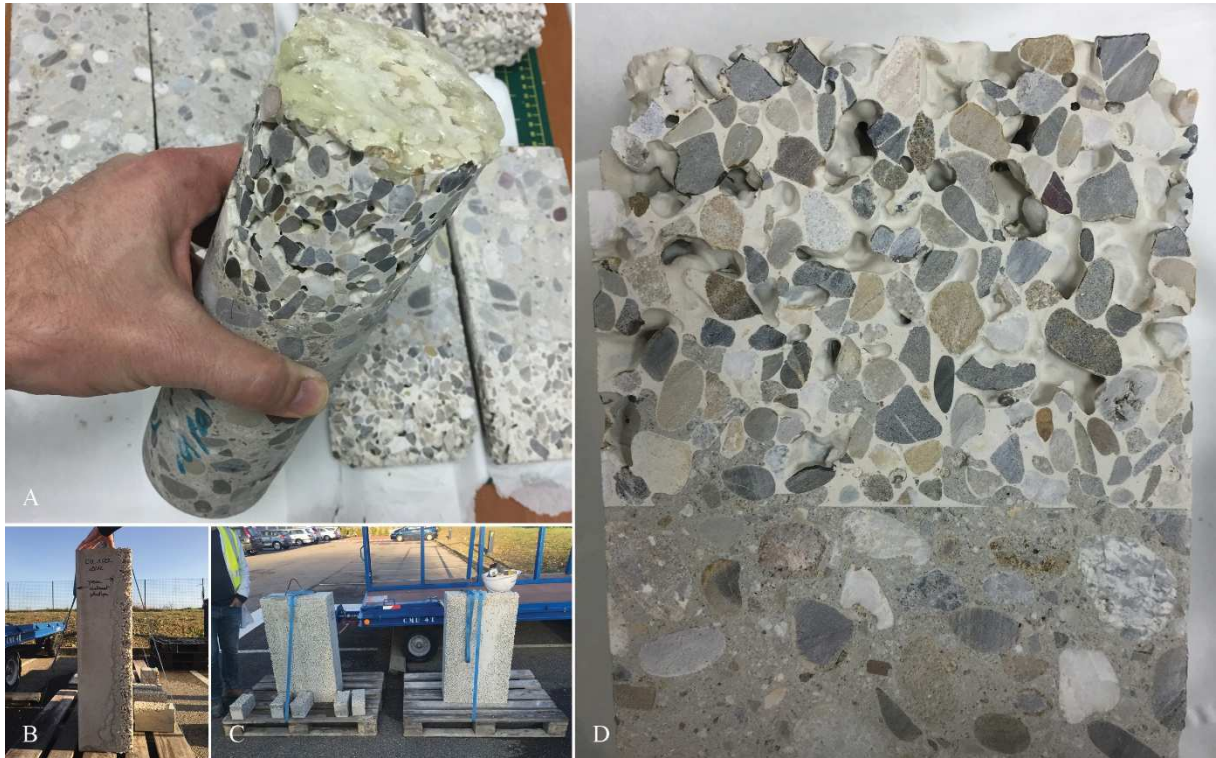
417 Three A1-sized test specimens were created, two 14 days in advance. Yet, all three wall tests
418 began on the same day, one day the final wall was cast. This permitted a comparison of
419 concrete's carbonatation effects on water passing immediately through fresh and two-week
420 old pervious concrete.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

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

428 3.6. *Living wall mechanical properties*

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

436



437

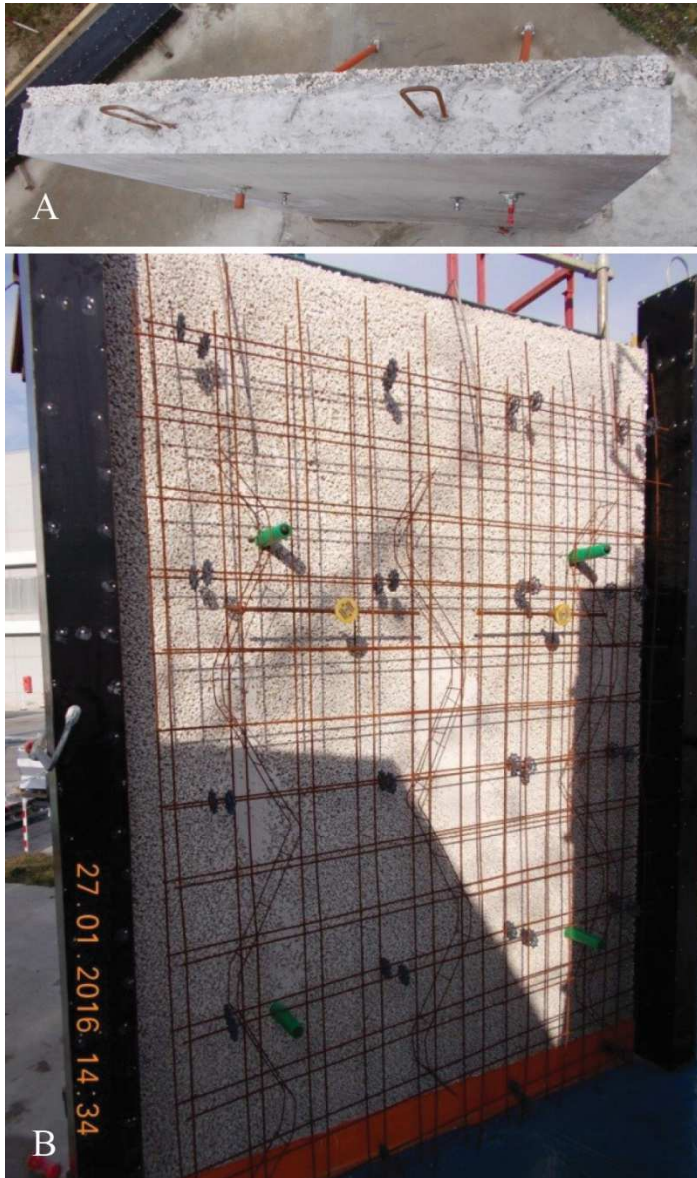
438 **Fig. 5.** Testing the cohesion between the pervious concrete and the supporting layer of normal concrete (C25)
439 using core samples cut from the A1-sized mini-walls (images B and C). A: Epoxy failure before splitting the
440 interface between pervious concrete and C25. D: Living concrete wall: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

442 3.7. Validating outdoors germination repeatability

443 3.7.1. Full-size construction

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

446



447

448 **Fig. 6.** A: View of concrete living wall from above. The pervious layer is toward the top of the image. B: Steel

449 reinforcement in place for the normal concrete (the structural layer) and ready for the formwork to be closed.

450 The steel reinforcement is installed AFTER the pervious concrete is poured, along with escutcheon embeds for

451 the bracing, and wall tie sleeves (seen in green). The inner wall form is repositioned as the inner face of

452 structural wall, the pervious wall acts as its outer formwork face.

453 Full-size construction led to altering the concrete formula. After the third wall was poured the

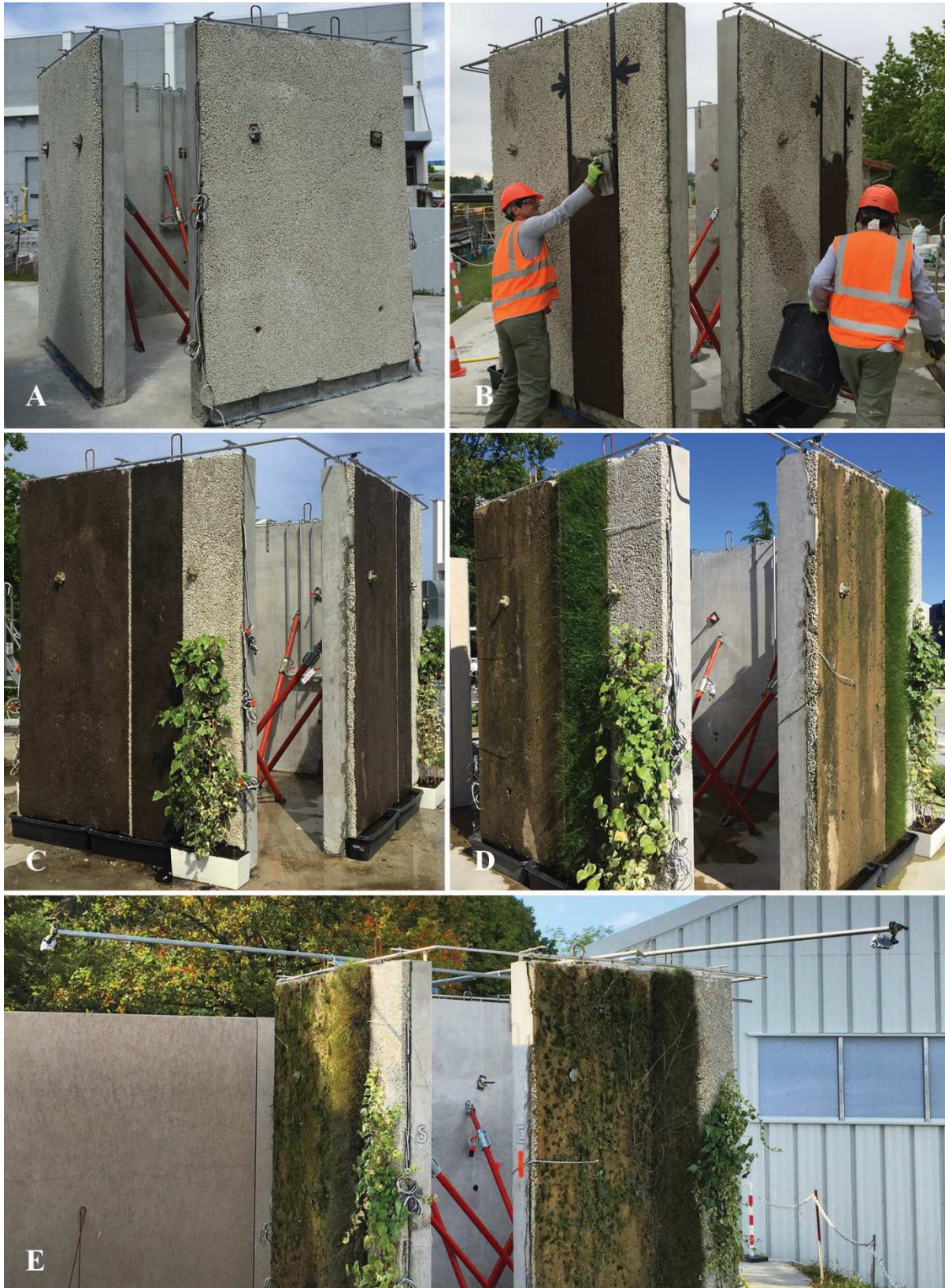
454 cement paste was reduced by 10%/m³ (the quantity of aggregates remained the same). To

455 reduce built-up cement paste the sleeve/chute was moved constantly and the number of lifts

456 minimized.

457 3.7.2. Seeded substrate installation

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



464

465
466
467
468

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.

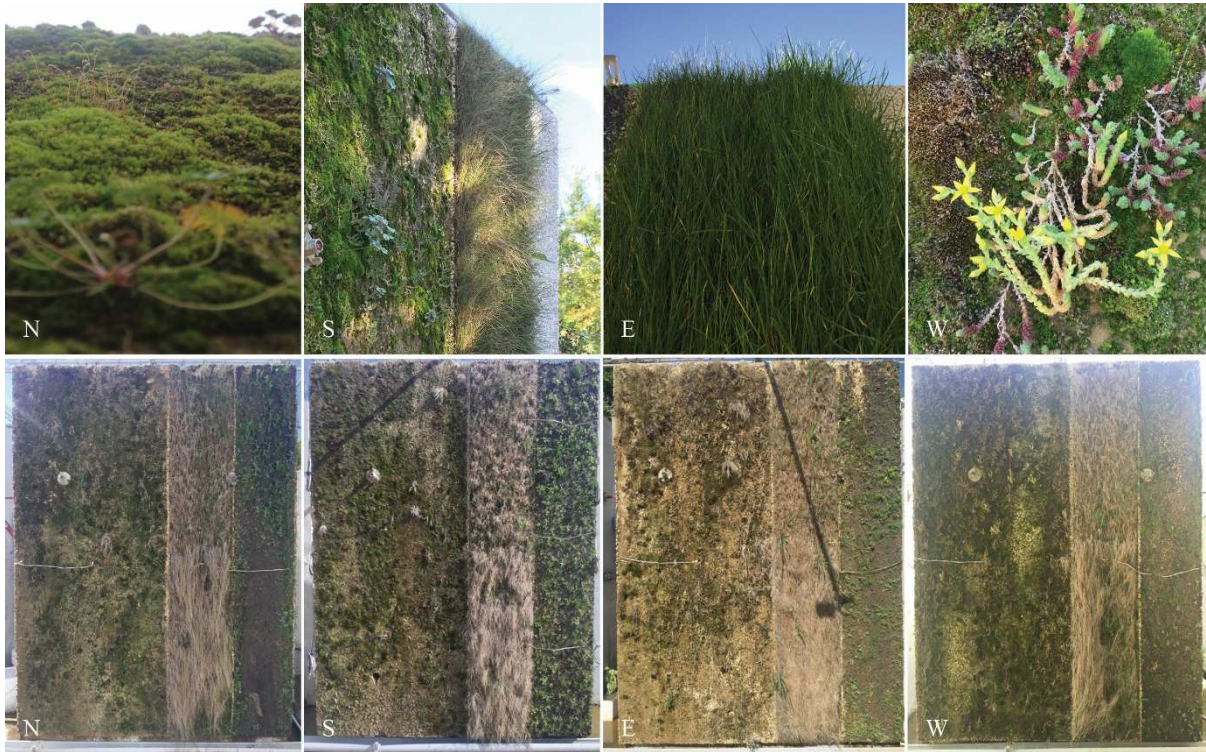
469 3.7.3. Plant development

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

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

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

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



488

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

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

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

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

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

507 3.7.4. Substrate development

508 A major 50-year storm (June 8, 2016) eroded the north wall's band-1 superficial substrate and
509 ~50% of the embedded substrate. Remarkably, the grass band's substrate remained intact;
510 presumably, the grass roots created a continuous mat locking the soil substrate to the pervious
511 concrete.

512 3.7.5. Irrigation summary

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

516 A month after substrate installation, irrigation flow was optimized and the flow-rate greatly
517 reduced from 6 liters/m²/day to 1 liter/m²/day. This approximates the water consumption of
518 the more efficient living walls currently used in temperate regions. The water reduction did
519 not impede plant development.

520 Irrigation was unexpectedly cut-off for four-months for the testing site's winterization. In the
521 interim the walls received half-a-dozen waterings by hand using a spray bottle. Nevertheless,
522 the plants regrew after winter and irrigation resumption. A technical problem in April led to
523 three-week irrigation stoppage, apparently killing the plants. In the hope of their regenerating,
524 the irrigation was repaired and the flow increased to 2 liters/m²/day for one month.

525 Fortunately, despite the interruption, the plants regrew – except the majority of grass plants;

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

528 3.7.6. Exterior water analysis

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

536

537 3.7.7. Perenniality validation

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

544 3.7.8. Cost analysis

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

Description	Unit	Labor		Material	Unit	Material			Total (€/m ²)
		Labor (h/m ²)	Total labor (€/m ²)			Quantity	Cost (€/m ²)	Total Material (€/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.	m ²	0,52	15,60					28,60	44,20
								Total Cost (€/m ²)	192,70

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

550

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

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

558 4. Conclusions

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

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

571 A new construction methodology was invented and vetted: the pervious concrete layer is cast
572 before the structural backup layer and becomes its wall form, locking the two concretes
573 together. A chemical analysis of water irrigated through concrete was presented. The study
574 shows fertilizer is not necessary for living walls to survive. The exterior tests proved that the
575 germination and perenniality achieved in the indoor trials is possible outdoors. However, lush
576 vegetation indoors was not achieved outdoors. The outdoor tests showed water consumption
577 can be 1 l/m²/day if runoff is recycled.

578 A conservative analysis shows living concrete costs ~200€/m² – half the cost of the least
579 expensive contemporary systems, validating the approach of rethinking the additive living
580 wall paradigm to encourage their proliferation.

581 **5. Discussion**

582 The study resulted in the development of a new living material for interior and exterior
583 architectural and green infrastructural applications. And the first cast-in-place living wall: the
584 innovation of vertically-cast pervious concrete. The trials also validate growing living wall
585 plants from seed in-situ. The interior and exterior trials validated the repeatability of
586 germination, formulas, and construction methodologies of a concrete living wall. Still

587 flourishing after three years, the interior trials show the perenniality of living concrete given
588 the right conditions.

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

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

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

605 Several watering lessons were learned. A concrete living wall consumption can average 1
606 liter/m²/day. More water is needed for initial germination and spring regeneration.

607 Furthermore, homogenous plant coverage requires running irrigation until moistening the
608 entire substrate, thus defining the event's duration. If internal irrigation moistens completely,
609 supplemental watering is unnecessary for germination. Evidently, the height between the

610 irrigation pipe and collection point will dictate the event's duration. Future tests are
611 recommended to validate usage data in closed-circuit irrigation (recycled water).

612 Concrete living wall durability and structural potential foretell its use for green infrastructure,
613 but also portent its weight disadvantage compared to contemporary additive living walls, such
614 as Patrick Blanc's lightweight felt system or heavier-weight modular-cell systems. For
615 example with retrofitting. The proposed system is for new construction only, limiting its use.
616 However, alternative solutions for retrofitting are detailed in the dissertation on this subject
617 [79]. In these cases, weight may become an adverse factor: a 5 cm layer of living concrete
618 weighs nearly 88 kg/m².

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

628 Consideration was given to the system's potential to host pests such as mosquitos, which in
629 turn could harbor Vector borne diseases, e.g., the Zika virus in Europe [80]. The
630 interconnected pores of the living concrete are unconnected to outside air by the seeded-
631 substrate. Thus, exposure is limited to water distribution and collection points. Here, covers,

632 insect screens, and adequately pitched collection trays are necessary to allow access to
633 irrigation or standing water.

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

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

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

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677

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A close-up photograph of a vertical concrete wall covered in a dense layer of green moss and small, colorful succulent plants. The plants are in various shades of green, yellow, and pink. The background is a blurred wall of white, porous concrete blocks. The text 'Living Concrete' is overlaid in the center of the image.

Living Concrete