MATEC Web of Conferences **378**, 06002 (2023) https://doi.org/10.1051/matecconf/202337806002
SMARTINCS'23

The sustainability profile of a biomimetic 3D printed vascular network to restore the structural integrity of concrete

Davide di Summa[1,2*], *Yasmina* Shields[1], *Vanessa* Cappellesso[1], *Liberato* Ferrara[2] and *Nele* De Belie[1]

[1] Ghent University, Department of Structural Engineering and Building Materials; MagnelVandepitte Laboratory, Tech Lane Ghent Science Park, Campus A, Technologiepark Zwijnaarde 60, B-9052 Ghent, Belgium
[2] Politecnico di Milano, Department of Civil and Environmental Engineering, piazza Leonardo da Vinci 32, 20133 Milan, Italy

Abstract. Among the various possibilities to tackle the issue of concrete damage within its structural service life, the biomimetic approach has favoured the development of innovative solutions such as the use of 3D printed vascular networks suitably incorporated into concrete structural elements to inject and convey the most suitable healing agent upon crack occurrence. These systems, able to cope with damage of different intensities, may lead to improvements of the structure's durability, through the closure of cracks, and a consequent reduction of the frequency of major maintenance activities. The present work investigates the environmental sustainability of the aforesaid self-healing technology through a Life Cycle Assessment (LCA) analysis. The attention has been also focused on the 3D printing process of the network due to the key role that it could play, in terms of environmental burdens, when upscaled to real-life size applications. The case study of a beam healed by means of polyurethane injected through the network and exposed to a chloride environment is reported to better predict the potential improvements in terms of overall durability and consequent sustainability within the pre-defined service life.

1 Introduction

Self-healing materials aroused a great interest within the recent past due to the possibility to extend the service life (SL) and reduce, at the same time, the need of human interventions to restore the normal functionality [1-2]. In this framework, exploiting a biomimetic solution analogous to the leaf venation and the human blood vascular system, the potential advantage of using a vascular network embedded in concrete structural elements to inject a healing agents upon occurrence has been investigated. Previous work on this topic has already outlined the potential advantages of such solution due to the possibility to indefinitely replenish the healing agent [3]. Nevertheless, the replication of a vascular network such as the ones present in nature, poses a challenge in terms of fabrication process. Due to this, 3D printed polymer hollow tube networks have been recently investigated because of their fast production as well as the various geometry that can be provided. The idea behind the system is that, upon cracking of the material in which the network is embedded, the agent is poured into the system and is then released through the network to favour the drawing of the agent into the open crack voids through the capillary forces [4-5]. Moreover, it must be highlighted that concrete is a material which is susceptible of the creation of cracks which represent a pathway for aggressive substances able to damage the reinforcement. To date, several self-healing technologies have been explored, but the literature is still quite scarce in terms of investigation of durability and sustainability performance of concrete with an embedded vascular network, when exposed to specific aggressive environmental scenarios (e.g. chloride or sulphate attack) [1, 6-9]. In view of this, the present work investigates the ecological profile of a structural element, i.e. a typical reinforced concrete beam, provided with a 3D printed vascular network to restore its functionality and exposed to a XS2 environmental scenario.

2 Case study

2.1 Description of the assessed structural element

Two concrete beams with dimensions of 0.15 m x 0.24 m x 1.27 m (W x H x L) with two 16 mm diameter reinforcement steel bars placed near the bottom, were assessed for the scope of this research. The concrete cover was designed equal to 45 mm as in accordance with a S4 structure (a structure with a service life of 50 years) and exposed to a XS2 environment. In order to assess the potential improvements coming from the employment of self-healing technologies in aggressive environments, the mix design detailed in Table 1, typical used for a XS1 environment has been employed. It foresees the use of CEM I 52.5 N cement with a water to cement ratio of 0.50 and limestone filler with a particle size <125 μm. Aggregates no larger than 8 mm

---

* Corresponding author: davide.disumma@ugent.be

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

were also chosen to easily pass between the branches of the 3D printed network and the mould. One beam, hereinafter referred as Ref_beam, was cast without any vascular network while a second one, named Vas_beam was built with an embedded 3D printed polylactic acid (PLA) vascular network. More specifically, the network itself, was assembled in 200 mm long sections and characterized by the presence of 1 mm diameter pores spaced at 10 mm and filled with gelatin gel. The gelatin had to protect the pores during the casting procedures and to be then removed through a flush of warm water right after the demoulding procedures. Figure 1 shows details of the geometry of the network. The network was placed in correspondence of the bending cracks formation area, within the cover zone and right below the reinforcement bars to which it was hooked by a metal wire. The employed healing agent was a polyurethane that can be used either as a one- or a two-component healing agent. Due to its properties, an expansive foaming reaction with a volume increase of up to 25–30 times occurs upon contact with moisture, favouring the crack filling.

Table 1. Mix design employed for the scope of this study.

Components	Quantities [kg/m^3]
CEM I 52.5 N	337.6
Sand 0-4 mm	742.9
Gravel 2-8 mm	1031.1
Limestone filler	58
Water	168.8
Superplasticizer MasterGlenium 27 (BASF)	2

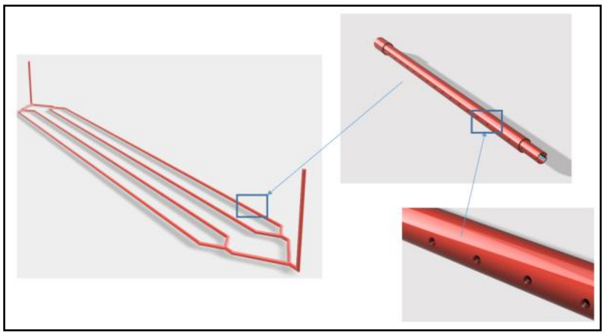


Fig. 1. 3D model of the vascular network used for the scope of this study.

After casting the two types of beams, they were stored in a curing room with a temperature of 20°C and a relative humidity >95% to be then demoulded after one day. Fig. 2 details the network assembled for the scope of this research while Table 2 provides information about the realization of the network, namely total number of pieces and printing time. These quantities will be used further on as part of the inventory for the Life Cycle Assessment (LCA) analysis.

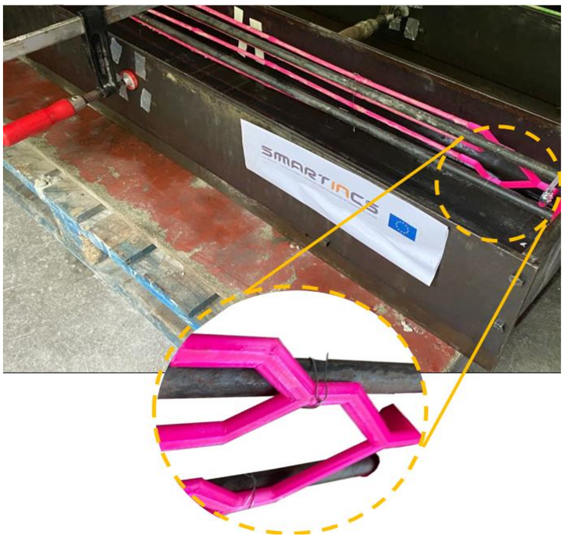
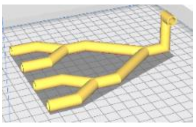
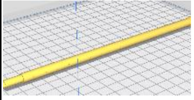


Fig. 2. Assembled vascular network.

Table 2. Details of the needed network elements per beam. The components have been printed separately and manually assembled.

Vascular network element	Quantities	Printing time
Branched ends 	2	1 h and 27 minutes
Channels (200 mm of length) 	20	29 minutes

To check the chloride penetration in the cracked and healed state, the beams with and without vascular network were loaded at the age of 28 days in sequential three-point bending over a span of 400 mm, with the aim of producing three cracks along the length of the beam. Loading was applied in displacement control at a rate of 0.001 mm/sec, with the crack width monitored using a crack mouth opening displacement (CMOD) clip gauge. The loading procedure was stopped once this reached a crack mouth opening of 0.5 mm. At three points along the corners of the beam 25 mm deep notches were made with a manual concrete saw-cutter to allow the crack to develop in the intended location. The beam with the vascular network was then healed with polyurethane (PU) that was pressurised up to 6 bar through the network. After 30 days, nine cores (100 mm of diameter) were extracted from the cracked and uncracked zone to be then immersed in an aqueous NaCl solution with a concentration of 33 g/L for three months after having coated the circumference with epoxy resin. Immediately after the removal from the solution, eight layers parallel to the exposed surface of concrete powders were collected by grinding material around the crack. The area of grinding was 18 mm wide with the crack in the middle and 50 mm in length along the crack. After having discarded the top layer of 1 mm, the 1st, 2nd and

3rd layer had a thickness of 2 mm, the 4th, 5th, 6th layer of 3 mm, the 7th was 4 mm and the last (8th) was 5 mm. The layers were defined based on the EN 12390-11 (2010) The determination of the total chloride concentration consisted of an extraction in a nitric acid solution followed by a potentiometric titration against silver nitrate. First, in accordance to [10] and [11], the powders were dried at 105 °C until constant mass and, after cooling down at room temperature, 2 g of each powder were weighed in a 50 ml glass beaker to be mixed with 5 ml of nitric acid (concentration: 0.3 mol/L) and 40 ml demineralized water. The obtained solutions were then heated on a plate until they just started to boil. Then, after being cooled down, they were filtered and diluted with deionized water in a 100 ml volumetric flask to take, later on, through a pipette, 10 ml for the determination of the chloride concentration per layer. For such purpose, a titration apparatus Methrom (Salt Compact titrosampler by Metrhom Belgium) was used. The effective chloride profile was then determined for both the cracked and uncracked beams with and without the vascular network. Fig. 4 shows the profiles used to determine the effective chloride diffusion coefficients (D_{app}). The values are reported in Table 3 for both Ref_beam and Vas_beam and indicate that the PU was not able to prevent the chloride ingress in this case, in contradiction to what was found for some types of PU in our earlier research [12], maybe due to the different penetration of the healing agent. In this regard, further investigations will be needed in the future. Therefore, in the further analysis it will be considered that only where the PU fills the crack (as seen microscopically), it provides an effective sealing against chloride ingress.

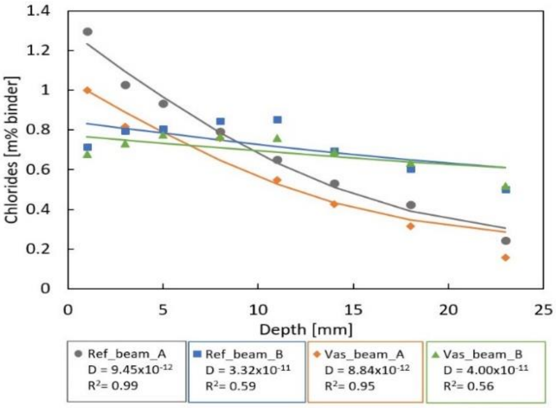


Fig. 3. Chloride profiles [m% binder] for Ref_beam and Vas_beam for both uncracked (Ref_beam_A and Vas_beam_A) and cracked state (Ref_beam_B and Vas_beam_B)

Table 3. Obtained D_{app} [m^2/s] and C_s [m% binder] values.

	Uncracked	**Cracked**
Ref_beam	D_{app} 9.45E-12 C_s 1.30	D_{app} 3.32E-11 C_s 0.84
Vas_beam	D_{app} 8.84E-12 C_s 1.12	D_{app} 4.00E-11 C_s 0.77

2.2 System boundaries of LCA analysis

The LCA analysis was carried out by employing a cradle-to-gate system boundary and supposing a service life of 50 years in total. Similarly to our previous works [13-14], the moment when the longitudinal bars lose 20% of their cross section area was assumed as serviceability limit state, considering the development of localized corrosion with the shape of a hemispherical pit. Exposure to a chloride concentration equal to 3.3% was considered, while the beams were supposed as initially cracked because of the loading conditions. Two different scenarios have been estimated for Ref_beam and Vas_beam, respectively. To predict the initiation time of the first one, the chloride diffusion coefficient equal to 3.32E-11 and the relative chlorides content at surface (C_s) were adjusted and employed within the second Fick's law. More specifically, D_{app} and C_s, being time dependent parameters, have been adjusted according to Equations 1 and 2 as in [15] where D_i and $C_{s,i}$ are the values obtained through the experimental results, t is the time of the years assumed equal to 5 (assumed as time reference as in [15] since no significant variations are expected after that timeframe), while m and n are empirical coefficients assumed as 0.44 and 0.47 respectively, because of the similar exposure conditions in the case study and in the reference [15]. 1.63 x 10^{-11} m^2/s and 1.7 m% binder have been obtained for D_{app} and C_s respectively.

$$D(t)=D_i \cdot t^{-m} \qquad (1)$$

$$C_s(t)=C_{s,} \cdot t^{n} \qquad (2)$$

This leads to an estimated initiation time of 4.65 years by employing the second Fick' law. For the propagation of the corrosion, in accordance to the work of Van Belleghem [10], a time of 7.5 years was calculated to develop a pit which reduces the cross section of the reinforcement bars with 20% (corresponding to a volume of the pit equal to 388 mm^3). Thus, at the age of 12.15 years the first maintenance activities are supposedly carried out for Ref_beam. Then, hypothesizing a reasonable structural loading scenario for the beam with a load combination resulting in 22.10 kN/m it has been verified that the acting bending moment exceeds the value of the one corresponding to the first cracks creation (M_{cr}) according to the Eurocode and calculated equal to 4.061 kNm. What above, considering 1.14 kN/m as weight of the beams, 0.38 kN/m as the incidence of a railing, 9 kN/m as crowd load and 11.58 kN/m as deck load (considering for both the crowd load and the deck a tributary area of 2.5 m) load. Thus, assuming a perfect adhesion of the repair layers to the concrete substrate, they have been assumed as immediately cracked as well, reason why all the consequent maintenance activities have been supposed to be carried out every 12.35 years, which means for a total of 4 times within 50 years of SL. A different scenario was figured out for Vas_beam since the injection of the PU was executed immediately at day one to prevent the ingress of the harmful substances from outside. Supposing a perfect sealing of the cracks up to

37 mm away from the vascular network towards the crack mouth, based on the spread of PU in the crack observed by microscope analysis (meaning a remaining crack depth of 8 mm) this thickness has been assumed as the new cover depth to calculate the initiation time for Vas_beam. The uncracked D_{app} equal to 8.84 x 10^{-12} m^2/s which has been adjusted as well, together with Cs (resulting in 4.35x10^{-12} m^2/s and 2.3 m% binder), according to equations 1 and 2, have been used in this case. This leads to an initiation time of 35 years in total to which 7.6 years for the propagation must be added, resulting in 42 years in total to lose 20% of the cross section of the reinforcement bars. With regard to the maintenance activities, they consisted for both Ref_beam and Vas_beam in the removal of the concrete cover and of the damaged rebars with their consequent replacement. In this respect, it must be highlighted that while all of the concrete debris coming from the maintenance activities were considered to be treated as waste material, the steel scraps were accounted as recycled in respect to the current European regulations. Due to the scarcity of data regarding the PLA in the existing libraries or environmental product declarations (EPDs), the LCA has been carried out with the assumption that the polymer material is nylon instead of PLA 3D printing filament, which has similar mechanical characteristics and is a suitable vascular network wall material. The software SimaPro with Ecoinvent 3.6 has been employed as data source for all of the raw components. Moreover, the environmental footprint has been calculated by employing the CML-IA impact method. Ten impact indicators were assessed in total ranging from the local scale, up to the regional and global one: global warming (GWP); acidification (AP); ozone depletion (ODP); photochemical oxidation (POCP); eutrophication (EP); abiotic depletion potential (ADP); human toxicity potential (HTP); freshwater aquatic ecotoxicity potential (FAETP); marine aquatic ecotoxicity (MAETP) and terrestrial ecotoxicity potential (TETP).

3 LCA outcomes

Due to the capacity of the PU to partially heal the cracks, different performance has been observed for Ref_beam and Vas_beam because of the different amount of maintenance activities to be carried out, namely four for the first one and only one for the second. Another difference is represented by the fact that for Vas_beam, besides the repair consisting of the removal and replacement of the damaged concrete layer and reinforcement bars, also the burdens referred to the vascular network itself and to the polyurethane (considered as injected under pressure) must be added. As expected and outlined in previous research [16], the highest impacts are due to the cement and reinforcement content that create, for example, 42% and 46 % of the Global Warming impact respectively for the case of Vas_beam. For all of the other indicators the incidence of the reinforcement is always higher than 35% (up to 86% for the case of HTP) while cement ranges between 6 % (HTP) and 42 % (GWP). The influence of the vascular network is between 6% (HTP) and 20% (ODP). Fig. 4 presents the details for the ten impact indicators of Vas_beam.

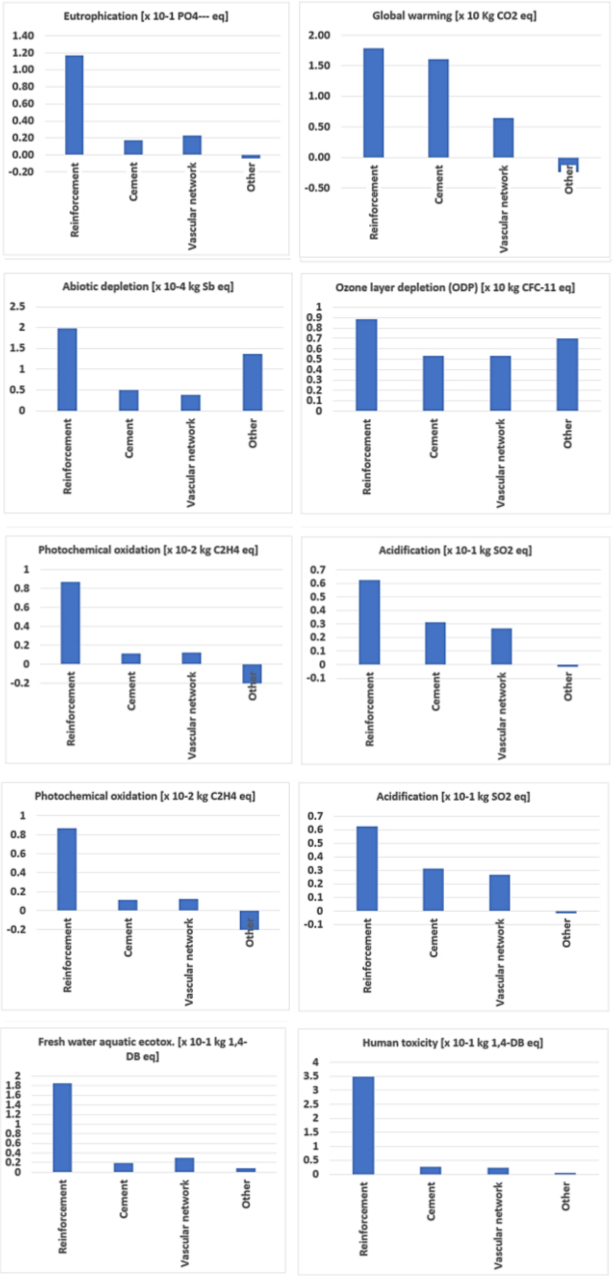


Fig. 4. 10 CML_IA impacts of Vas_beam. "Other" includes also the treatment of the concrete debris and recycling of the steel scraps, reason why it is here displayed with a negative value.

Note that the category "other" includes also the treatment of the concrete debris and recycling of the steel scraps. As a matter of fact, a material that is recycled has a negative numerical impact value which, for the case of this study, exceeds the positive impacts related to all of the remaining components included in the "other" category (e.g. gravel, water, limestone etc). In general, as summarized by Figure 5, when exposed to the same environmental conditions, Vas_beam compared to Ref_beam, presents lower impacts for all of the ten indicators, sometimes reaching reductions higher than 45% as for FAETP and HTP.

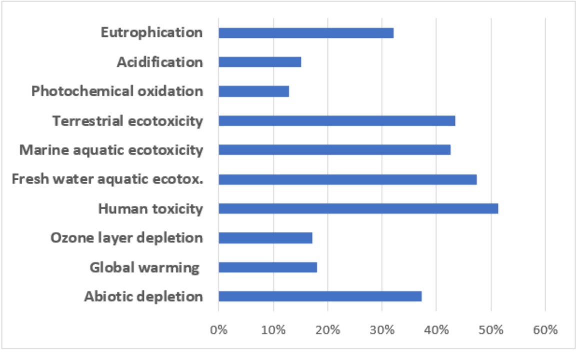


Fig. 5. Impacts of Vas_beam relative to Ref_beam.

4 Conclusions

This study has investigated the environmental performance of a concrete structural element realized with an embedded vascular network to inject polyurethane upon occurrence of cracks with the aim to restore its functionality. The conducted experimental campaign outlined the potential advantages of Vas_beam when compared to Ref_beam and exposed to an aggressive environmental scenario rich in chlorides. This is mainly due to diffusion of the chlorides into the material which is of the same order of magnitude for both. Despite the reduced initiation time caused by the high chloride diffusion coefficient and the consequent need to reiterate 4 maintenance activities for Ref_beam and 1 initial PU injection plus 1 maintenance activity for Vas_beam, the sustainability analysis outlined interesting results, posing the basis for future investigations. As matter of fact, the impact of the vascular network itself registered values always lower than 22%. Nevertheless these impacts come from the use of the nylon, the production of which is strongly dependent on the use of fossil fuels. This means that a different and more sustainable materials such as PLA suitable for the same purpose, could lead to consistent advantages due to the fact that the material itself is derived from renewable and organic sources. Moreover, the durability characteristics employed to carry out the LCA analysis are strongly dependent on the healing agent which has been chosen for the injection (polyurethane), meaning that different and more performant products, able to better penetrate the cracks, could lead to better results when the structure is exposed in a chloride scenario, due to the potential extension of the initiation time. As matter of fact, supposing the need of the same raw materials for the construction of the element, only a reduced maintenance frequency of one solution in comparison to the other, can lead to consistent environmental and cost benefits. Additionally, in line with the most recent literature, better results could also be achieved in the future combining the potential advantages of the vascular network with the ones coming from the use of recycled concrete as aggregate and as partial replacement of cement. In this framework, the current work points out which are the parameters that need to be governed when such technologies are scaled-up to a structural level and exposed to real environmental scenarios to favour their large uptake by the market. In terms of environmental performances, the material of the network itself and the healing agent to be employed are key factors to get advantageous results when a holistic sustainable vision is aimed to be pursued.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860006.

References

1. De Belie N., E. Gruyaert, A. Al-Tabbaa, P. Antonaci, C. Baera, D. Bajare, A. Darquennes, R. Davies, L. Ferrara, T. Jefferson, C. Litina, B. Miljevic, A. Otlewska, J. Ranogajec, M. Roig-Flores, K. Paine, P. Lukowski, P. Serna, J.-M.M. Tulliani, S. Vucetic, J. Wang, H.M. Jonkers, Adv. Mater. Interfaces. 5 (17), 1–28 (2018)
2. Cappellesso V., D. di Summa, P. Pourhaji, N. Prabhu Kannikachalam, K. Dabral, L. Ferrara, M.C. Alonso, E. Camacho, E. Gruyaert, N. De Belie, Submitt. to Int. Mater. Rev. (2023).
3. Li Z., L.R.D. Souza, C. Litina, A.E. Markaki, A. Al-Tabbaa, Mater. Des. 190 (2020).
4. Shields Y., T. Van Mullem, N. De Belie, K. Van Tittelboom, Sustain. 13 (23), (2021)
5. Selvarajoo T., R. Davies, B. Freeman, A. Jefferson, Constr. Build. Mater. 254 119245 (2020)
6. Tsangouri E., In: Sustainable Construction and Building Materials. IntechOpen (2019).
7. Belleghem B.V., P. Van den Heede, K.V. Tittelboom, N.D. De Belie, Materials (Basel). **10** (1), (2017).
8. Li M., R. Ranade, L. Kan, V.C. Li, 2nd Int. Symp. Serv. Life Des. Infrastruct. (1), 773–781 (2010).
9. van Breugel K., In: roceedings of the First International Conference on Self Healing Materials. , Noordwijk aan Zee, The Netherlands (2007).
10. Van Belleghem B., PhD Thesis. Ghent University, Belgium (2018)
11. Heede V. Den, Ghent University (2014)
12. Van Belleghem B., S. Kessler, P. Van den Heede, K. Van Tittelboom, N. De Belie, Cem. Concr. Res. 113 130–139 (2018).
13. Kannikachalam N.P., D. di Summa, R.P. Borg, E. Cuenca, M. Parpanesi, N. De Belie, L. Ferrara, Submitt. to ACI Mater. J. (2022).
14. di Summa D., J.R. Tenório Filho, D. Snoeck, P. Van den Heede, S. Van Vlierberghe, L. Ferrara, N. De Belie, J. Clean. Prod. 358 (2022).
15. Stipanovic Oslakovic I., D. Bjegovic, D. Mikulic, Mater. Struct. Constr. 43 (10), 1397–1412 (2010)
16. Colangelo F., A. Forcina, I. Farina, A. Petrillo, Buildings. 8 (5), (2018).