Zurich, June 15-17 2016
Sustainable Built Environment (SBE) Regional Conference

Expanding Boundaries:
Systems Thinking for the Built Environment

SBE16 ZURICH

THE COST AND ENVIRONMENTAL IMPACT OF SERVICE LIFE EXTENDING SELF-HEALING ENGINEERED MATERIALS FOR SUSTAINABLE STEEL REINFORCED CONCRETE

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Abstract

To achieve higher sustainability of steel reinforced concrete structures, their service life should be extended. When subject to chloride induced steel corrosion, time dependent repair works are most probably inevitable. Evidently, this results in extra concrete manufacturing and thus more environmental impact. Cracks offering direct pathways for the corrosion inducing substances play a very detrimental role in this. This paper presents the potential of using self-healing concrete to cope with this problem. By incorporating a polyurethane (PU)-based healing agent that is adequately released upon crack occurrence, chloride ingress is hindered substantially and onset of active corrosion is postponed. The required number of repair actions within 100 years could then drop to zero. Nevertheless, the implementation of a self-healing mechanism comes along with a higher initial cost and additional environmental impacts. Therefore, the necessary cost and life cycle assessment calculations have been performed as well. It was found that the cost of the PU-based healing agent is very reasonable while the extra costs of the capsules are for the moment still unacceptable. Environmental burdens associated with the PU precursor filled capsules are negligible (0.1–4.8%) in comparison with the impacts related to regular concrete repair to meet the design service life of 100 years.

Keywords:

Self-healing concrete; service life extension; cost analysis; life cycle assessment

1 INTRODUCTION

The potential service life performance of a steel reinforced concrete structure highly determines its sustainability. This is easy to understand because a high susceptibility to, for instance, chloride induced corrosion of embedded reinforcing steel automatically implies regular repair actions in the course of time to maintain the integrity of the structure during its design service life [1]. Traditional concrete structures are almost never free of cracks and unfortunately, they serve as preferential pathways for chlorides. In previous research, it was shown by means of probabilistic service life prediction (cf. Visser et al. [2]) based on chloride diffusion tests at various exposure times and an assumed concrete cover of 50 mm, that the presence of cracks, 0.3 mm wide and 25 mm deep, reduces the time to chloride-induced steel depassivation from 104 to barely 8 years [3]. Therefore, it is certainly worthwhile to explore any possible strategy to cope with concrete cracking. One very promising strategy consists of implementing autonomous healing mechanisms in the concrete that are activated upon crack occurrence. Over the years, quite some research has been performed at the Magnel Laboratory for Concrete Research on the effectiveness of incorporating encapsulated PU precursors to achieve this self-healing. It resulted in a full proof of principle [4, 5]. A next important research phase consists in showing with how many years the service life of corrosion exposed steel reinforced concrete can indeed be extended and whether this can be done at an acceptable cost and without

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

substantial environmental burden. The service life issue has already been dealt with in Van den Heede et al. [3]. This paper mainly focuses on the economic and environmental aspects involved. It should be noted that only the material costs and impacts were considered in this study.

2 MATERIALS AND METHODS

2.1 Concrete mixture and slab

The studied concrete mixture is the same one that was used in Van den Heede et al. [3]. It is suitable for use in exposure class XS2 which corresponds with environments where concrete is permanently submerged in seawater. It meets the k-value concept of NBN B15-001. Per m³ of this concrete, this gives a CEM I 52.5 N content of 317.6 kg and a fly ash content of 56 kg for the binder fraction. A water content of 153 kg was assumed to achieve the required water-to-binder (W/B) ratio of 0.41. To ensure a sufficient workability (slump class S3) a polycarboxylic ether-based superplasticizer (SP) was added (dosage: 3.0 ml/kg binder). Regarding its inert fraction per m³, the concrete contained 696 kg river sand 0/4, 502 kg gravel 2/8 and 654 kg gravel 8/16. This composition with strength class C40/50 and ribbed steel bars with a diameter of 16 mm and steel quality 500 were used to design a slab (span: 5 m, width: 1 m) with a variable load of 5 kN/m². Design calculations done in accordance with Eurocode 2 showed that the slab thickness and required number rebars would need to amount to 0.17 mm and 6, respectively.

2.2 Self-healing mechanism

The concrete can be given self-healing properties by incorporating cylindrical borosilicate glass capsules (inner diameter: 3.00 mm, outer diameter: 3.35 mm, length: 35 mm) filled with a one component PU precursor cf. Van Tittelboom et al. [5]. They are characterized by a high brittleness. As such, they break easily upon crack occurrence. A major drawback of these capsules is that they do not easily survive the concrete mixing process. PMMA-based alternatives for these capsules with a time-varying brittleness are for the moment still under investigation.

The healing agent was a non-commercial PU precursor which was developed within the framework of SHEcon, another research project on self-healing concrete [6]. The polymer can be compared with a typical flexible PU foam of which the precursor essentially consists of methylene diphenyl diisocyanate (MDI) and a polyether polyol. This precursor reacts with water to create the foam that heals the cracks. The moisture content of the concrete itself counts as the main water source.

Regarding a possibly recommended dosage for this encapsulated PU precursor, Van Belleghem et al. [7] incorporated three capsules with a 20 mm spacing to heal an artificially induced crack, 0.3 mm wide, 25 mm deep and 60 mm long. With the potential number of cracks and their location known, a more precise dosage could be defined. Two possible scenarios were considered in this theoretical case study.

Firstly, it was assumed that capsules were placed only in the zone where tensile stresses and thus cracks are to be expected. In case of a concrete slab (length: 5 m, width: 1 m, thickness: 0.17 m), capsules could then for instance be placed only near the bottom side of the mold (12.5 mm from the mold surface) prior to concrete casting. To be able to heal 0.3 mm wide and 25 mm deep cracks over the entire 5 × 1 m² bottom surface of the slab, 4150 capsules filled with PU-based healing agent would be needed in that zone.

Secondly, as cracks in the tensile zone of a slab usually have a depth higher than 25 mm, extending beyond the location of the rebars, the encapsulated PU-based healing agent should maybe be treated as bulk addition to concrete. When added in sufficient quantities during concrete mixing, the capsules would be well distributed over the entire slab volume. In that case the original number of capsules needs to be multiplied by 7 to have 4150 capsules in each ± 25 mm layer of the 170 mm thick slab. This gives 29050 capsules in total for the second scenario.

It should be noted that the two scenarios considered still require further investigation and optimization regarding their practical feasibility. Further experimental research on easy-to-use techniques for incorporating encapsulated PU precursors in prefabricated concrete elements is for the moment still ongoing at our laboratory.

2.3 Cost of the slab components

Based on the prices of all its constituents, the concrete would cost around 65 €/m³. A Belgian metal work supplier sells the applied rebars at a price of a little less than 1 €/m. The price of the borosilicate glass capsules equals 0.3 €/capsule, while the amount of PU precursor needed to fill one capsule would only cost 0.0005 €. The cost of time-dependent rehabilitation actions of traditional concrete without self-healing properties was taken into account by including the cost of the required concrete repair volume within a 100 year timespan, again at a price rate of 65 €/m³. Within Section 3.2, the absence of repair actions for self-healing concrete will be substantiated further on with results of previously conducted service life calculations.

2.4 Life cycle assessment

Cf. ISO 14040, the LCA consisted of four major steps: definition of goal and scope, inventory analysis, impact analysis and interpretation.

Definition of Goal and Scope

This LCA was conducted to quantify the reduction in environmental impact that could be achieved by using the proposed PU-based self-healing

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DOI 10.3218/3774-6, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

concrete instead of a traditional concrete in a submerged marine environment. To do this correctly, the LCA study takes into account the difference in service life between traditional (cracked) concrete and the same concrete with self-healing properties. Therefore, a reinforced concrete slab with a variable load of 5 kN/m² and a design service life of 100 years was chosen as functional unit (FU). As such, the extra material needed to repair the slab as soon as steel corrosion is at risk was considered. For a slab repair, an extra concrete volume representing the 50 mm cover on top of the rebars plus the thickness of these rebars was taken into account.

Inventory Analysis. Per concrete constituent, the life cycle inventory (LCI) data was collected from the Ecoinvent database [8] (Table 1).

Constituent	LCI description Ecoinvent
Sand	Sand, at mine/CH U
Gravel 2/8 & 8/16	Gravel, round, at mine/CH U
CEM I 52.5 N	Portland cement, strength class Z 52.5, at plant/CH U
Fly ash	partially contains: 'Electricity, hard coal, at power plant/BE U', through economic allocation
Water	Tap water, at user/CH U
Glass capsule	Glass tube, borosilicate, at plant/DE U
PU-based healing agent	Polyurethane, flexible foam, at plant/RER U (modified)

Table 1: Overview of the Ecoinvent life cycle inventory (LCI) data used.

For the allocation of impacts related to the industrial by-product fly ash, the economic allocation coefficient as proposed by Chen et al. [9] was applied. This is 1.0% of the impact of the coal fired electricity production corresponding with the production of 1 kg fly ash. SP inventory data were obtained from an environmental declaration published by the EFCA [10]. The transport of each constituent to the concrete plant was not incorporated in the LCA since its environmental impact is always very case specific. The impacts related with the production process at a concrete plant were included by the partial assignment of the following LCI from Ecoinvent: 'Concrete, normal at plant/CH U'. It comprises the whole process of producing 1 m³ of ready-mixed concrete, including all internal processes (transport, wastewater treatment, etc.).

As indicated above, the existing LCI for PU flexible foam was somewhat modified to make it more representative for the PU that was used in this research. One important change relates to the fact that the toluene diisocyanate (TDI) needed to be replaced with methylene diphenyl diisocyanate (MDI). Another distinct modification was the removal of the water for reaction with the PU precursor from the LCI, as this water is being provided by the moisture content of the concrete. The PMMA sealant that was used to close the glass tubes once filled was so small that this component could be omitted from the LCI.

Impact Analysis and Interpretation

The CML-IA impact method was used. It gives an eco-profile with ten baseline impact indicators regarding abiotic depletion (ADP, MJ fossil fuels), global warming (GWP, kg CO_2 eq), ozone depletion (ODP, kg CFC-11 eq), human toxicity (HTP, kg 1,4-DB eq), freshwater aquatic ecotoxicity (FAETP, kg 1,4-DB eq), marine aquatic ecotoxicity (MAETP, kg 1,4-DB eq), terrestrial ecotoxicity (TETP, kg 1,4-DB eq), photochemical ozone creation (POCP, kg C_2H_4 eq), acidification (AP, kg SO_2 eq) and eutrophication (EP, kg PO_4 eq).

3 RESULTS AND DISCUSSION

3.1 Maintenance scenarios

Based on earlier conducted service life predictions for PU-based self-healing concrete and traditional (cracked) concrete [3], two different maintenance scenarios were considered (Table 2).

Scenario 1	**Time-dependent repair of traditional (cracked) concrete**
Estimated service life	8 years [3]
Time-dependent maintenance	Replacement of the concrete cover
Number of repairs within a 100 year timespan	12
Scenario 2	**Repair-free PU-based self-healing concrete**
Estimated service life	104 years [3]
Time-dependent maintenance	None
Number of repairs within a 100 year timespan	None

Table 2: Overview of the maintenance scenarios considered.

The earlier obtained service life performance for PU-based self-healing concrete in marine environments only applied to the option with incorporation of capsules in one layer [3]. The bulk addition approach is for the moment still under investigation. Although the estimated service life performance of the latter option probably differs from the first, the same service life of 104 years was taken into consideration for now.

3.2 Cost analysis

Given the unit prices of the different slab components (Section 2.3), the regular (cracked) steel reinforced concrete slab (span: 5 m, width: 1

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m, thickness: 0.17 m) would cost around 85 €. Incorporation of one layer of 4150 PU filled capsules would add 1373 € to this price. When adding the capsules in bulk to ensure their presence over the entire concrete volume, no less than 9605 € extra would need to be spent. The major contributors in these high extra costs are the borosilicate glass capsules which are – as stated earlier – not really feasible from a practical point of view anyway. When only considering the extra costs inherent to the PU precursor, the extra costs are much more acceptable, especially when their presence would avoid slab repair within the lifespan it was designed for. Adding PU precursor in only one layer would cost only 2.1 € extra, while adding the PU precursor in bulk, would add 14.7 € to the price of the steel reinforced slab. Thus, in comparison with the price (= 21 €) of one concrete repair volume (= 0.32 m³), a slab with self-healing properties holds an economic benefit. Given the fact that in presence of 25 mm deep cracks the expected time to chloride-induced steel depassivation would only be 8 years [3], this benefit would even be much more pronounced because the concrete repair volume would need to be applied 12 times. This means that one would need to spent 253 € extra to guarantee the integrity of the concrete slab for 100 years. On the other hand, when using a concrete that can be considered free of 0.3 mm wide cracks, chloride-induced steel depassivation would take no less than 104 years [3] and the costly rehabilitation actions would not be necessary at all. Thus, once a sufficiently cheap and practically feasible type of capsule for the PU-based healing agent would become available and a 100% healing capacity can be assured as such, contractors would most probably be willing to pay the slightly higher, PU precursor attributed production cost of the self-healing concrete.

3.3 Life cycle assessment

As can be seen in Fig.1, the impacts associated with the required twelvefold repair for a traditional steel reinforced concrete slab within a 100 year timespan are substantial. For all ten baseline impact categories, the environmental burdens related to the concrete needed for all repair works are usually at least two times higher than the impact of the concrete and steel needed for the initial construction of the slab. On the other hand, the incorporation of 4150 PU filled capsules in one layer at the bottom of the slab to ensure autonomous healing of 0.3 mm wide and 25 mm deep cracks, brings along very little extra environmental burden.

Depending on the category indicator, their impact contribution amounts to only 0.1–0.7% of the one of the required concrete volume for 12 repairs in the course of time. When adding 29050 PU precursor filled capsules over the entire slab volume, the impact only increases slightly to 1.0–4.8% of the concrete repair volume related impact. Still, this looks very acceptable. Thus, if a 100% autonomous healing efficiency could indeed be achieved with this encapsulated PU-based healing agent, ensuring a repair-free 100 year service life in exposure class XS2, the environmental benefits of self-healing concrete easily overcome the burdens of the PU precursor filled capsules. It indicates that this novel concrete type indeed has a high sustainability potential.

4 CONCLUSIONS

A cost analysis for PU-based self-healing concrete demonstrated that the extra costs related to the PU precursor alone are very acceptable. It would increase the overall price of the slab with only 2.1–14.7 €. This is much lower than the 253 € that would need to be spent on repair works within a time period of 100 years without self-healing mechanism present in a submerged marine environment. The price of the now applied borosilicate glass capsules is far more critical. Nevertheless, these are not the type of capsules that will be used eventually as they do not survive the mixing process. A feasibility study of alternative PMMA-based capsules with a time-varying brittleness is for the moment still ongoing.

In terms of environmental impact, the PU-based self-healing concrete is far more beneficial than ordinary (cracked) concrete when exposed to chloride-induced corrosion. For all ten CML baseline indicators the impact is less than half, both when the capsules are added in only one layer of the slab and when added in bulk. Without self-healing properties, a twelvefold repair is required within a time span of 100 years. The impacts related to the extra concrete manufacturing extensively exceed those of producing the required quantity of PU precursor filled glass capsules (up to 29050) to ensure self-healing.

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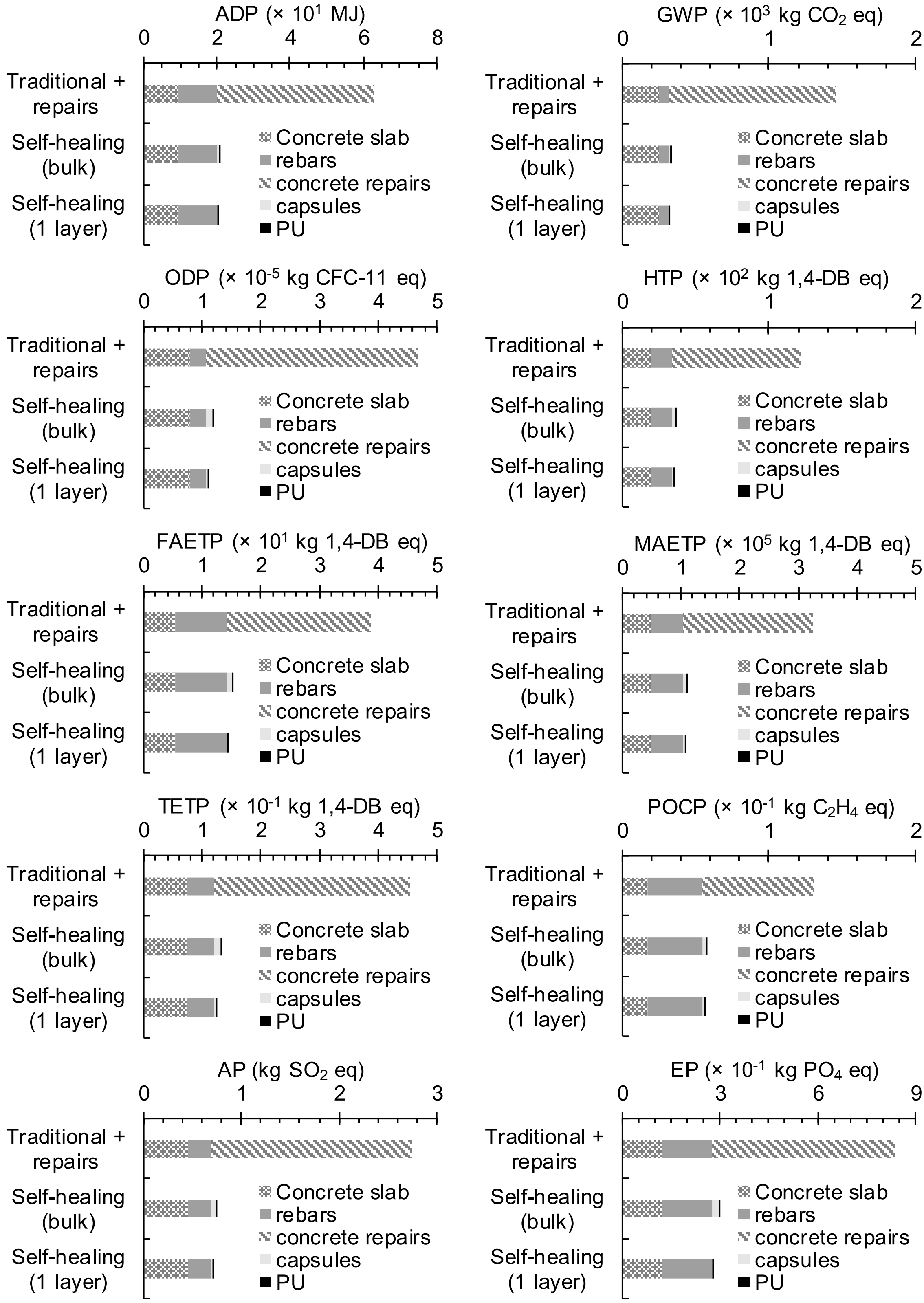

Fig. 1: Comparison in environmental impact (ADP, GWP, ODP, HTP, FAETP, MAETP, TETP, POCP, AP, EP) between traditional (cracked) and self-healing concrete slabs.

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5 ACKNOWLEDGMENTS

This research under the program SHE (Engineered Self-Healing materials), project ISHECO (Impact of Self-Healing Engineered materials on steel COrrosion of reinforced concrete) was funded by SIM (Strategic Initiative Materials in Flanders) and IWT (Agency for Innovation by Science and Technology). The financial support from the foundations for this study is gratefully acknowledged.

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DOI 10.3218/3774-6, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html