

Life Cycle Assessment (LCA) of Microcapsule based self-healing in concrete

Sripriya Rengaraju^{1*} and Abir Al-Tabbaa¹

¹University of Cambridge, Dept. of Engineering, Cambridge, CB2 1PZ, United Kingdom

Abstract. Self-healing technologies provide the long-term resilience of concrete structures by enabling self-diagnose and self-repair of damages (aging cracks, cyclic load damages, and corrosion-induced cracks). However, self-healing technologies require special additives and materials in addition to the ones in conventional concrete. Hence, it is often perceived to have higher environmental impacts, and therefore, it is necessary to understand the same. This study is aimed to analyse the life cycle assessment (LCA) of concrete with microcapsules produced by different techniques to investigate the sustainability of these concretes. Two microcapsule techniques, namely complex coacervation and membrane emulsification, were studied at the laboratory scale and then projected to the industrial scale. The analysis shows that the concrete with microcapsules does not adversely impact the emissions in the production stage if supplementary cementitious materials are used. Further, if the beneficial effects of the self-healing technologies are considered in the use phase, the impacts are much lower. Thus, this assessment gives meaningful insights by identifying major impacts in the production of self-healing technologies and helps to improve their design and application in concrete.

1 Introduction

Concrete is the most widely used construction material in the world responsible for 8% of the world's anthropogenic greenhouse gas (GHG) emissions. Despite the advancements in concrete technology, deterioration is induced by ageing, and various environmental and physical factors, which results in crack formation, permeation of moisture and aggressive substances, reducing the structural safety and serviceability [1]. In the UK, repair and maintenance account for almost 45% of the expenditure in construction industry [2]. Repair and maintenance can add significantly to economic and environmental burden, and it is essential to find solutions to prolong the life of the structures. Self-healing concrete is an innovative concrete designed to repair itself in the event of crack formation reducing the possibility of further deterioration by external agents leading to reduced emissions and costs over the whole lifetime of the structure.

Many technologies are being developed in this context and microcapsules targeted at healing the crack formed have been successfully implemented in the sites as well [3]. Figure 1 shows the microcapsules in micro and macro scale visuals. Microcapsules essentially contain two phases, namely shell and cargo. The shell encapsulates the reactive component and prevents it from immediate reaction with cementitious matrix [4]. The shell has further requirement of withstanding the pressure due to mixing and open only during a crack formation. To address these requirements, a variety of

chemicals are added to stabilise the phases in various forms. All these essentially adds to the energy and emissions and hence, it is essential to understand them to justify the use of self-healing concretes from an environmental perspective over its entire life cycle.

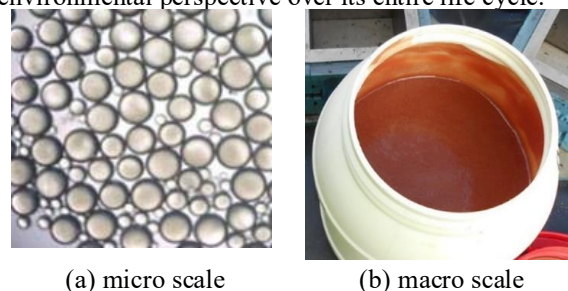


Fig. 1. Microcapsules – Visual observation [3,4]

Life cycle assessment (LCA) is one of the recognised tools to understand the environmental impacts from products as it accounts for the processes and the materials. The LCA methodology and framework are followed as per International Organization for Standardization (ISO) standards (ISO-14040, 2006a); (ISO-14044, 2006b) [5,6] following the four phases. In the first phase, the goal and the scope of the assessment defining the assumptions, functional unit (The basic unit considered for the calculation of impacts from the process and raw materials), and system boundary (the start and finish of the activities considered) are all defined. Sometimes, this phase is redefined based on the available data and its quality. Hence, it is first and an iterative process till the

* Corresponding author: sr973@cam.ac.uk

assessment becomes relevant and finalised. The next phase is inventory analysis in which data is collected about the type and quantity of materials and the processes which falls within the system boundary defined in the first phase. This phase is very critical for the quality and strength of the conclusions. The next phase is the impact assessment phase in which the impacts from the materials and processes are calculated. This phase has intrinsic calculations and conversion factors which in turn converts the energy and emissions to different impact categories based on the chosen impact assessment method. In this phase, the highest weightage is given to global warming potential, which is directly to CO₂ emissions irrespective of the chosen method. The final phase is the interpretation which involves assessment of data quality involving inconsistency and incomplete check, sensitivity analysis and then conclusions and recommendations.

Very few studies involve the process involved in production of microcapsules and most focus mainly on cradle to gate emissions from the concrete involving the self-healing additives [7]. In addition, with the NetZero targets in the UK, there is a requirement for the manufacturers of construction materials to calculate and publish the environmental impacts of their products. However, there are invisible barriers such as commercial confidentiality, makes data on such innovative materials scarce [8]. Hence, this paper presents the LCA of microcapsules produced by two different methods and discusses their advantages and disadvantages with respect to concrete.

2 Life Cycle Assessment Methodology

In this section, the detailed process for production of microcapsules using two techniques is first explained and then followed by LCA methodology. The goal and scope are defined, and data related to the raw materials and energy required for the production process was collected. Then, the impact assessment was done for the LCA.

2.1 Detailed process of microcapsules production

Two types of microcapsule production were considered for LCA study, namely complex coacervation and membrane emulsification. These two techniques were chosen as they are commonly employed to produce the microcapsules in large scale production.

In complex coacervation, two opposite charged particles are added together in an aqueous solution and in due course of time, they form coacervates (lumps) forming interface thus leading to microcapsule formation as shown in Figure 2. For preparing the inner phase, sodium silicate and gelatine are dissolved in deionised water at 45°C separately for 15 mins and then mixed and cooled to ambient temperature. The mineral oil is then added to the mixture and kept separately. For the outer phase, a combination of gelatine and acacia gum are added together to deionised water at 45°C for 15 mins. Then sodium hydroxide is added to the solution

to bring pH to 9. After this pH is adjusted with acetic acid to the desired pH. The mixture (outer phase) is then added to the inner phase. The two phases are then mixed, and stabilising agent glutaraldehyde is added, and the mixture is kept at 40°C to enable microcapsules formation. Once microcapsules are formed, they are cooled, filtered, and harvested. This type of microcapsule formation is done in batches [9]. The main disadvantage of this method is the formation of microcapsules is not in uniform size and there is a huge distribution of size. Additionally, the information about wastage cannot be predicted easily as they depend on the variety of factors such as batch size, mixing process, temperature, and sequence of operation. Hence, in this study, due to the unknown quantity, the wastage is not considered.

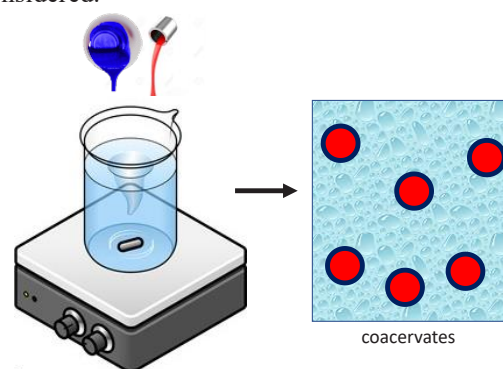


Fig. 2. Complex coacervation process

The membrane emulsification technique is a simple and efficient process where the inner phase is continuously pushed to the outer phase through a membrane at a predetermined rate. The sodium silicate solution is mixed with acrylate oil + photo initiator) for 3 mins and pushed via a membrane into the stirrer containing 1% PVA (outer phase). In laboratory scale, stirrer cell as shown in Figure 3 is used [10]. This cell was used just for ensuring the proof of concept and working principle. However, for large scale industrial production, there is a possibility of continuous operation using cross flow membrane and there is no limitation on the quantity produced per unit time as the quantity of microcapsules depends on the membrane type and flow rate. Additionally, the waste is almost nil due to greater efficiency. Moreover, the energy requirement is also very less in this process.

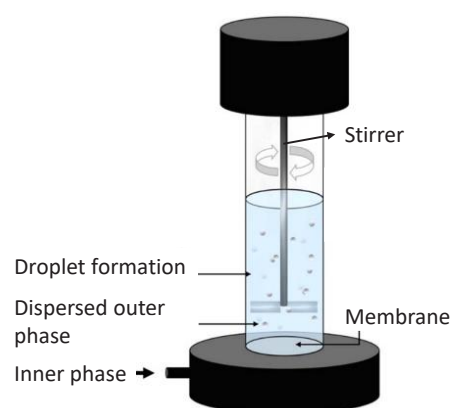


Fig. 3. Stirrer cell for membrane emulsification

2.2 System boundary and Assumptions

The scope of the study involves cradle to gate of microcapsule production. The functional unit is 1 kg of microcapsules. This functional unit was selected as it is commonly used in the construction industry to calculate the composition of the concrete mix per m³ and to quantify the environmental impact, making this study easily comparable to others. The place of production was assumed as the UK. The laboratory process is considered for quantity of materials and industrial scale production is considered for energy requirements. The raw materials which were of negligible amount (1% or less by quantity) were not considered for impact calculations.

2.3 Inventory of the required chemicals

Table 1 shows the list of raw materials and their quantity required for the complex coacervation process for production of 4.75 kg microcapsules. This quantity of raw materials is then scaled for the industrial scale production of 1000 kg for LCA analysis. However, the energy required for the production is considered in industrial scale.

Table 1. Requirements for complex coacervation process [9]

Raw materials	Quantity
Mineral oil	2320 g
Water	1356 g
Pig Gelatine	156 g
Sodium metasilicate	168 g
Pig Gelatine	314 g
Gum Arabic	314 g
Glutaraldehyde	128 g
Sodium Hydroxide (4M)	13.7 g
Acetic Acid (20%)	3.89 g
Preheat and homogenisation	36.681 kWh

Similarly, Table 2 shows the list of materials and energy required for membrane emulsification technique. The membrane emulsification in industrial scale is assumed to be done using a crossflow membrane with peristaltic pumps for controlling the continuous and dispersed phase.

Table 2. Requirements for membrane emulsification technique [10]

Raw materials	Quantity
Sodium silicate	3.75 ml
Acrylate oil/TMPTA*	11.25 ml
photo initiator	1% by wt. of TMPTA
Water	85 ml
Poly vinyl alcohol (PVA)	1% by wt. of water
Hot plate	1.65 kWh
Pumping	2 kWh
UV polymerisation	6 kWh

*TMPTA - Trimethylolpropane triacrylate

2.4 Life cycle assessment

Calculations were performed using the free software OpenLCA 1.10.3 and Ecoinvent v3.7.1. The impact assessment was performed using IPCC GWP 100a method in which global warming potential is calculated. This method was chosen as the carbon footprint is the most important aspect of life cycle assessment and is an indicator of immediate climate change requirements.

3 Results and Data interpretation

This section presents the results generated for the impacts associated with the production of microcapsules. Then, a comparison is also done with CEM I to understand the effects of the impacts in a better manner.

3.1 Comparison of GWP

Figure 4 shows the difference in global warming potential (GWP) during the production of 1 kg of microcapsules in comparison to 1 kg of CEM I.

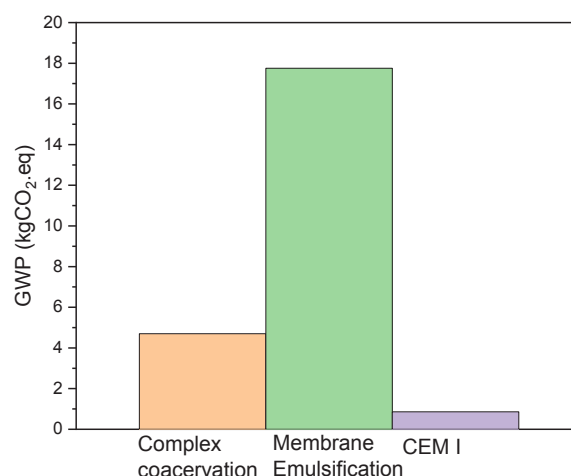


Fig. 4. Comparison of GWP of 1kg of cement and microcapsules

Here, the results indicate that the production of 1 kg of CEM I is less carbon intensive than the production of 1 kg of microcapsules. This result brings couple of questions – How much quantity of microcapsules is needed for 1 m³ of concrete? Does the carbon-intensive microcapsules production process make the concrete less eco-friendly in the long run too? To understand the emissions better and the chose the alternatives, it is essential to understand the process contribution.

3.2 Process contribution

Figure 6 shows the process contribution analysis where the results of the microcapsules produced using complex coacervation indicate that the main emissions are coming from gelatine. In case of gelatine, it can be easily substituted by vegetable-based alternatives such as xanthan gum, agar agar, and guar gum with some research on plant based/ less energy process [11].

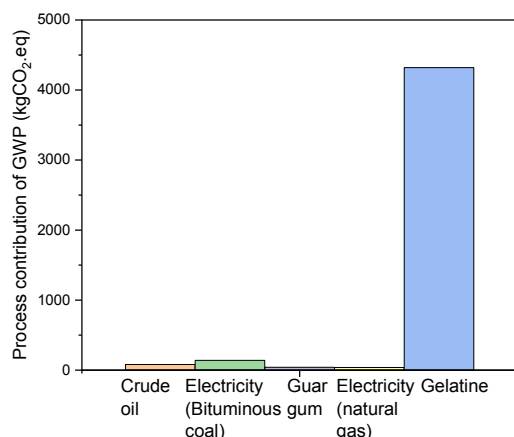


Fig. 5. Process contribution – Complex coacervation

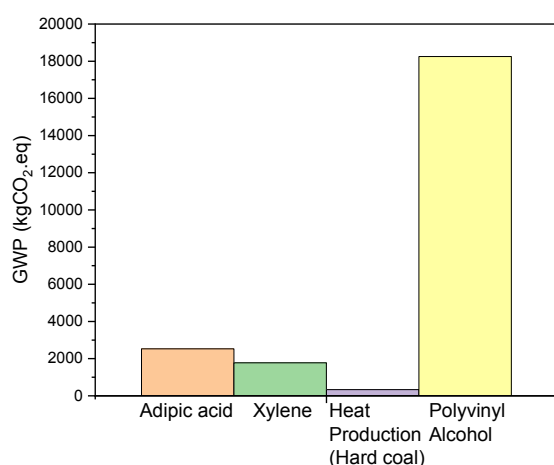


Fig. 6. Process contribution – Membrane emulsification

Similarly polyvinyl alcohol (PVA) used in membrane emulsification is the biggest source of carbon emissions as shown in Figure 6. In the case of PVA, bio-degradable and water resistant PVA with less carbon is researched upon and it will be better to use that as an alternative to reduce the carbon [12]. In addition, the ingredients used for stabilisation (TMPTA) is the second major contributor in the membrane emulsification process which uses xylene and adipic acid. So, it is necessary to find alternatives to the stabilising agent. It is to be noted that even when alternatives are used, the carbon emissions from the microcapsules could be slightly higher than the production of CEM I when the system boundary of cradle to gate considering only the production process is included for the LCA analysis. This is because the very essence of adding the microcapsules in the concrete production, which is the extension of service life by healing the cracks is not captured in LCA system boundary. Thus, this comparison of carbon does not justify the addition of microcapsules and the system boundary should be extended to the use phase of the structure where cracks and other deterioration occurs.

3.3 Extension of LCA till use phase

Figure 7 shows the comparison of overall emissions from the self-healing concrete and the traditional concrete for a design life of 50 years. A 40 MPa concrete

mix design with 376 kg of cement and microcapsules - 12% volume fraction by weight of cement as self-healing additive is considered [13]. For traditional OPC concrete, 360 kg of cement is considered for making 40 MPa concrete. CC represents the concrete (Binder: 50% OPC and 50% Slag) admixed with microcapsules produced by complex coacervation, ME represents the concrete (Binder: 50% OPC and 50% Slag) admixed with microcapsules produced by membrane emulsification technique and CEMI is traditional concrete (100% OPC) without any admixtures. Only the major contributors of emission which arises from cement and additives are shown here. The emissions from other ingredients of concrete such as aggregates, water, and electricity used for mixing are not shown as it is common for all types of concrete.

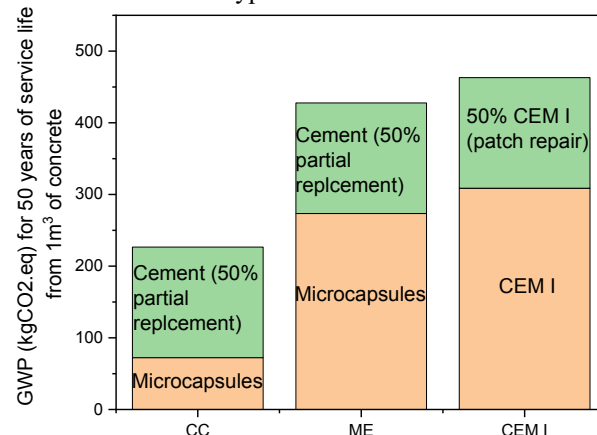


Fig. 7. GWP from cradle to gate including use phase

It is estimated that about 10% structures fail within 10 years of service life due to various construction related failures [14]. If such a structure is designed for 50 years, then the concrete consumed in patch repair is estimated as 50% of the original concrete in such failure cases. This increase in emission due to patch repair can be eliminated completely when self-healing additives are used. In addition, it is recommended to use the supplementary cementitious materials such as slag as partial replacement to CEM I along with these additives to reduce the carbon. In such cases, where the partial replacement of CEM I is done, emissions from self-healing concrete is less compared to the exclusive cement-based concrete for 50 years of service life. In this way, the increase in capital carbon (embodied energy) is compensated by the increase in service life and thus the overall emissions from the use of microcapsules are lesser than the traditional cement indicating that the self-healing additives (microcapsules) along with the supplementary cementitious materials are beneficial to the environment.

4 Conclusions

The following conclusions are made based on the LCA analysis of the self-healing concrete.

1. The capital carbon (carbon emissions calculated from production) is high for the self-healing additives and alternatives to the carbon

- intensive process/products should be found to make it less intensive.
2. The technique adopted to produce these additives play a significant role in the energy required and in turn affect the emissions. Hence, innovative techniques for reducing such emissions should be encouraged.
3. Self-healing additives (Microcapsules) are beneficial to environment when admixed with supplementary cementitious material as it enhances the repair-free service life.

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