Preparation and optimization of bio-based and light weight aggregate-based healing agent for application in concrete

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ABSTRACT

The innovative technology of self-healing concrete allows the material to repair the open micro-cracks that can endanger the structure's durability, due to ingress of aggressive liquids. Various concepts of self-healing concrete use encapsulation techniques, in order to immobilize and protect the healing agent during mixing and setting. In this paper the bio-based healing agent, consisting of alkaliphilic bacterial spores and organic mineral compounds (feed), is encapsulated into light weight aggregates (LWA). Although, the concept of shielding the healing agent in LWA capsules is simple and effective, there are some challenges regarding the incorporation procedure. In this study a method for efficient incorporation of healing agent into the LWA is developed. The results obtained in the current study show that the optimized method increases considerably the amount of healing agent embedded into LWA, in comparison with what was achieved in a previous study. As a consequence, the LWA treated with the new incorporation procedure are likely to provide better crack sealing and therefore enhanced durability protection for concrete.

1. INTRODUCTION

Self-healing concrete excels of the ordinary concrete, since it has the ability to seal cracks beyond the limits of crack width that can be repaired through autogenous healing. In fact, it has been shown that in ordinary concrete fine cracks up to 150 μm, exposed to moist conditions can sometimes close completely [1]. On the other hand, in self-healing concrete it has been reported that larger cracks up to 500 μm can be efficiently sealed [2]. This property of self-healing concrete prevents the ingress of aggressive liquids through open micro-cracks. By this means, durability-related risks are decreased and the material's life span is extended.

Several self-healing concrete concepts use to encapsulate the healing agent, in order to immobilize and protect it during mixing and setting. The healing agent can be encapsulated into hydrogels [2], into glass or ceramic tubes [3] or into other alternative carriers. In this study the bio-based healing agent, consisting of alkaliphilic bacterial spores and organic mineral compound, is encapsulated into porous light weight aggregates (LWA).

The present study focuses on optimizing the incorporation procedure of the healing agent into the LWA suggested in [4], in order to increase the healing material found in the pores of the LWA. The functionality of the healing agent system (LWA-bacteria-feed) is also validated by oxygen concentration measurements reflecting bacterial metabolic activity.

2. MATERIALS AND METHODS

2.1. Healing agent optimization

The bio-based healing agent consists of spores derived from alkaliphilic bacteria of the genus *Bacillus*, calcium lactate (nutrient for the bacteria) and yeast extract (vitamins for the bacteria) embedded in expanded clay particles, Liapor 1/4 mm (Liapor GmbH Germany). The LWA are impregnated with a solution containing the feed and the spores. For the optimization procedure three variables were considered: a. the amount of feed in the solution, b. the impregnation type and c. the drying method. The following table presents the approach of the previous study [4] and the improvements attempted in this study.

Table 1: Healing agent incorporation approach.

Variable	Previous study	Current study	Sample
Amount of feed	Calcium lactate: 80 g/L Yeast extract: 1g/L	Calcium lactate: 80 g/L Yeast extract: 1g/L	L[(1)]
		Calcium lactate: 200 g/L Yeast extract: 4g/L	H[(2)]
Impregnation type	Vacuum application	Without vacuum application	NV-L[(3)], NV-H
		Vacuum application	V-L[(4)], V-H
Drying temperature	Drying in 36° C	Drying in 36° C	$V\text{-}H_{36° C}$
		Drying in 20° C	$V\text{-}H_{20° C}$
		Drying in 4° C for 24h and then in 20° C	$V\text{-}H_{4° C}$

(1) L : Low content of calcium lactate

(2) H: High content of calcium lactate

(3) NV-: Without vacuum application

(4) V-: With vacuum application

2.2. Oxygen concentration measurements

In the presence of oxygen and water the dormant bacterial spores are activated. Later, the active bacteria cells convert the calcium lactate ($CaC_6H_{10}O_6$), present in the healing agent into $CaCO_3$ (see equation below) by using oxygen.

$$CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$$

Therefore, by conducting oxygen concentration measurements on loaded LWA (with healing agent) submerged in carbonate-bicarbonate buffer (0.1 M, pH=10.5), it was possible to evaluate the effectiveness of the healing agent system. $V\text{-}H_{20° C}$ samples were used for this test. The oxygen concentration was monitored in sealed glass flasks via optical oxygen sensors (Fibox 4 & Fibox 4 trace, Germany). Four different samples were tested: a. unloaded (without any healing agent), b. impregnated only with calcium lactate (CaL), c. impregnated with calcium lactate and yeast extract (CaL+YE) and d. impregnated with healing agent (H-A).

3. RESULTS AND DISCUSSION

Weight measurements on wet LWA after impregnation with and without vacuum application revealed that the use of vacuum increases substantially the incorporated amount of healing agent. In addition, by increasing the amount of feed in the solution, the healing agent content inside Liapor particles was 67 % higher. An overview of the weight increase results can be found in Table 2.

Table 2: Results in weight increase from different impregnation types.

Sample	Weight increase on wet LWA after impregnation (% per initial dry weight)	Estimated healing agent content (% per initial dry weight)
NV-L	20.0	1.6
V-L	70.8	5.7
NV-H	22.3	4.55
V-H	86.2	17.6

The results above were supported by light microscope pictures. Figure 1 shows that there is no visible white spot (i.e. healing agent) in particles NV-L and NV-H, implying that the estimated healing agent content stays only on the outer surface of the particles. In VL particle only few white spots are found in the pores near the surface. The case is different for the V-H particle that the healing agent spots are easily identifiable and spread thought-out the inner mass of the sample.

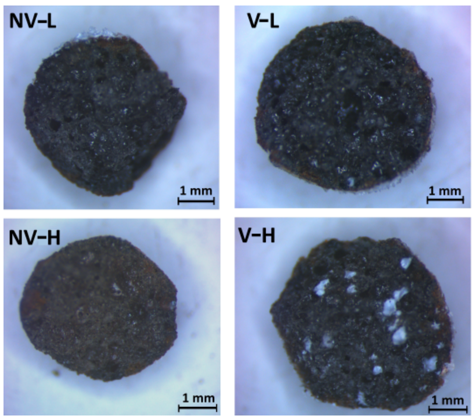

Figure 1: Liapor particles with different impregnation type

Furthermore, the weight comparison on dried LWA (Table 3) revealed that the most efficient drying method is the one with the intermediate cooling phase (V-$H_{4^\circ C}$). During cooling, the solubility of calcium lactate drops and water evaporates leaving the maximum amount of the feed inside the pores of the particles.

Table 3: Results in weight increase from different drying methods.

Sample	Weight increase per initial dry weight (%)
V-$H_{36^\circ C}$	8.59
V-$H_{20^\circ C}$	11.27
V-$H_{4^\circ C}$	12.24

Oxygen concentration measurements (Figure 2) on impregnated Liapor particles revealed that only the samples containing the bacteria spores showed bacterial activity, i.e. oxygen consumption. The results prove that the oxygen consumption originated only from the activated bacteria existed in the healing agent. Thus, the bacteria are active in relatively high pH conditions, which means that the healing agent can be functional when incorporated in concrete.

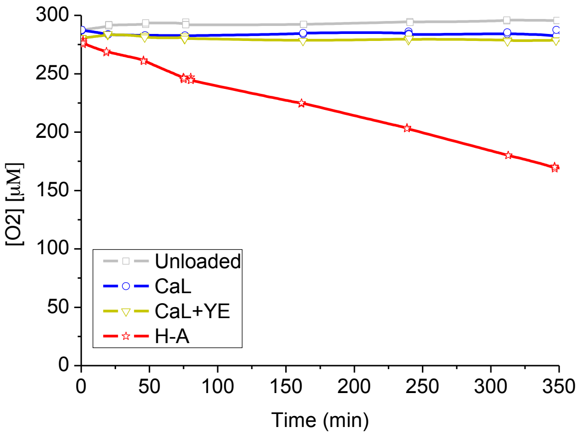

Figure 2: Oxygen concentration measurements on unloaded and loaded Liapor particles

4. CONCLUSIONS

In the current study, the bio-based healing agent encapsulated into LWA has been optimized, by improving the impregnation procedures. The amount of healing agent, embedded into LWA, has increased almost three times compared to the previous study. Moreover, the whole system is functional in high pH conditions, therefore, it can be used in concrete and provide the material with self-healing properties.

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