BIO-HEALING FOR MICRO-CRACK TREATMENT IN CEMENTITIOUS MATERIALS: TOWARD A QUANTITATIVE ASSESSMENT OF BACTERIAL EFFICIENCY

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Keywords: mortar, bio-healing, self-healing, *Bacillus cohnii*, calcium lactate

ABSTRACT

Bio-healing is a promising approach to enhancing natural self-healing and thus completely heal large micro-cracks (> 200 µm) in cementitious materials. The aim of this research is to better understand bio-healing of cementitious materials in order to accelerate the healing kinetics and maximize sealing efficiency of large micro-cracks. The bio-healing approach generally consists in soaking micro-cracks in a culture medium containing a bacterial strain. However, it is difficult to precisely assess the efficiency of the bacterial-mediated precipitation in the bio-healing process with respect to the impacts of natural self-healing and precipitation induced by the culture medium. The aim of this work is to study the healing of well-defined micro-cracks on mortars subjected to more and more complex healing mechanisms. First, cracked mortars were subjected to natural self-healing, then to a precursor solution (calcium lactate), and finally, to a culture medium containing a bacterial strain. However, before this last step, an important part of this study focused on assessing the growth kinetics of a bacterial strain: *Bacillus cohnii*. Mortars specimens (W/C = 0.485) were submitted to controlled cracking at 28 days (under sustained load) using a mechanical expansive core. Two micro-crack categories were created (100 ± 5 µm and 195 ± 30 µm). The healing kinetics was evaluated from air-flow measurements that were used to compute the evolution, over time, of the apparent crack opening (1, 3 and 6 months of conservation at 23°C and 100% R.H.) Overall, self-healing was faster and more complete when cracks were soaked in calcium lactate solutions compared to natural healing. Thus, precursor solutions significantly improved the healing kinetics of the larger micro-cracks (> 150 µm). On the other hand, the optimum growth conditions for *Bacillus cohnii* were evaluated at different nutrient concentrations and pH values. Finally, a method was developed in order to evaluate the bacterial activity semi-quantitatively.

1. INTRODUCTION

Bio-healing is a promising approach to enhancing natural self-healing and thus completely heal large micro-cracks (> 200 µm) in cementitious materials. One bio-healing approach consists in soaking micro-cracks in a culture medium containing a bacterial strain. Bio-healing proceeds from a combination of several mechanisms that include: 1- precipitation of calcium carbonate and cementitious hydrates by natural self-healing [1]; 2- precipitation of specific reaction products formed by the precursor solution [2]; 3- precipitation of products formed by the bio-healing process (calcium carbonates and other specific products formed by the bacterial activity in the crack) [3]. The development and optimization of bio-healing approaches require a better understanding of the individual contribution of these mechanisms and their combined effects on the precipitation of healing products in cracks.

The first part of the experimental program aimed at studying the mechanisms and kinetics of natural self-healing in mortar samples, as well as the impact of calcium lactate, a precursor solution containing calcium ions in order to enhance calcite formation. The second part aimed at evaluating the optimum growth conditions of a bacterial strain, *Bacillus cohnii,* involved in bio-healing at different pH values and in the presence of calcium lactate. This inoculated culture medium would be later injected into cracks formed in mortar samples.

2. MATERIALS AND METHODS

The kinetics of natural self-healing was evaluated according to a procedure developed by Gagné et al. [4]. Air-flow measurements through a crack were used to calculate an effective crack opening (W_{ef}). The evolution of the effective crack opening is used to assess self-healing evolution over time. Mortar specimens (W/C = 0,485) were submitted to controlled cracking at 28 days (under sustained load) using a mechanical expansive core [4]. Two micro-crack categories were created (100 ± 5 µm and 195 ± 30 µm). Samples cracked under sustained deformation, were stored in a fog room at 23°C and 100% R.H. for 1, 3 and 6 months.

Three test conditions were used with the cracked mortars samples: 1- natural self-healing (no culture medium injected in the crack); 2- calcium lactate impregnation in the crack. Crack impregnation was achieved by submerging the mortar samples for 24 hours in a solution containing calcium lactate close to its solubility level (79 g/L).

The studied strain, *Bacillus cohnii,* was provided by the German Collection of Microorganisms and Cell Cultures (DSMZ, Germany). This bacteria was cultured in the growth medium recommended by DSMZ, Nutrient Broth (NB) medium (3 g/L at pH=9.7). The growth kinetics of this bacterial strain was also measured at different initial pH values equal to 7.5, 8.0, 9.5, 10.5, and 11.5, to assess the impact of mortar alkalinity on bacterial activity. The bacterial growth was indirectly evaluated by biological oxygen demand (B.O.D.), using the Oxitop® system. The system uses gas pressure measurements over a bacterial suspension placed in a sealed container. The vacuum created by the oxygen consumption is used to compute the B.O.D. expressed in mg of O_2 per litre of solution. The B.O.D. was monitored during 6 days at 30°C under continuous agitation.

The effect of calcium lactate on bacterial growth was also investigated: 9.7 g/L of calcium lactate was added to the Nutrient Broth (NB) medium. The impact of a source of nitrogen (NH_4Cl) was also checked. The bacterial growth and the lactate concentration were monitored during 36 days at 30°C under continuous agitation.

3. RESULTS AND DISCUSSION

It appears that natural self-healing is systematically faster during the first month (Figure 1-A). After 6 months, natural healing is more advanced for small cracks (100 ± 5 µm) leading to an apparent effective opening of 50%. For large cracks (195 ± 30 µm), effective opening is only reduced by 30%. These results are similar to those obtained by Gagné and Argouges [4]. The main product formed in cracks is calcite. Influence of the precursor (calcium lactate) on healing kinetics is shown in Figure 1-B. The healing is faster and more complete for large cracks. On the other hand, the healing of small cracks was not influenced by the precursor.

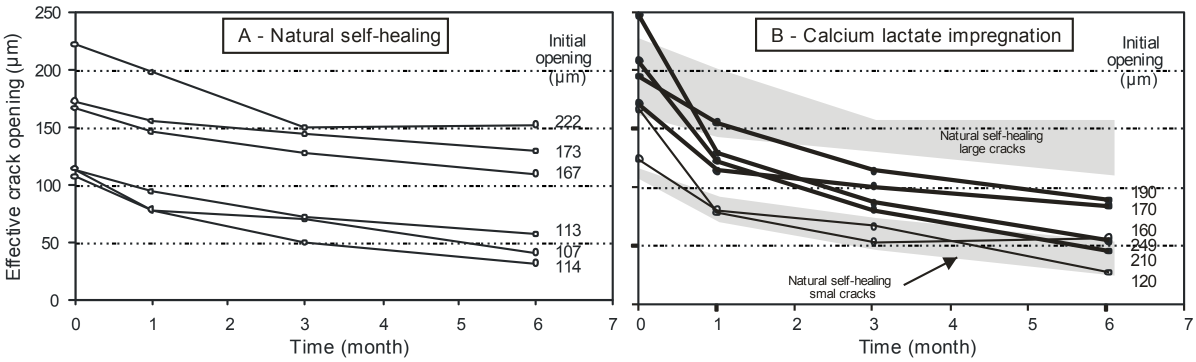

Figure 1: Evolution of the effective crack opening: (A) Natural self-healing; (B) Calcium lactate impregnation in the cracks

Using bacteria appears to be one of the most promising ways of improving healing capacity in cementitious materials. Figure 2 shows the bacterial activity in the NB medium at initial pH values ranging between 7.5 and 11.5. The bacterial activity, monitored by using the Oxitop system, showed that *Bacillus cohnii* grows rapidly in pH values between 7.5 and 10.5, which are the pH of a carbonated or leached concrete surface. No significant activity is noticed at a pH value of 11.5.

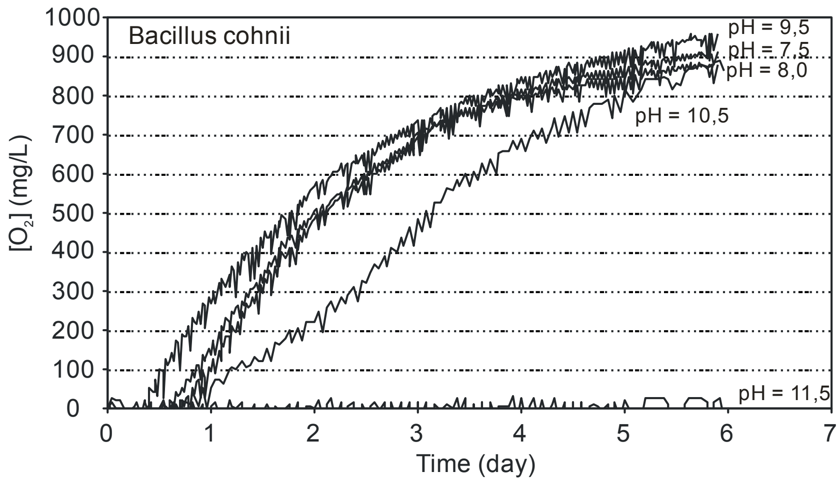

Figure 2: Oxygen consumption of *Bacillus cohnii* in NB medium at different pH

The bacterial growth was also observed in media containing calcium lactate in addition to NB. Moreover, a decrease in the lactate concentration was observed, indicating that the bacteria can use lactate as a nutrient (Figure 3). The lactate disappears in less than 20 days. However, it is important to notice that no significant bacterial activity is observed in the medium containing only calcium lactate without others nutrients. *Bacillus cohnii* seems to be unable to decompose lactate without the presence of other nutrients. The nitrogen source added (NH_4Cl) does not impact the calcium lactate consumption nor the bacterial growth.

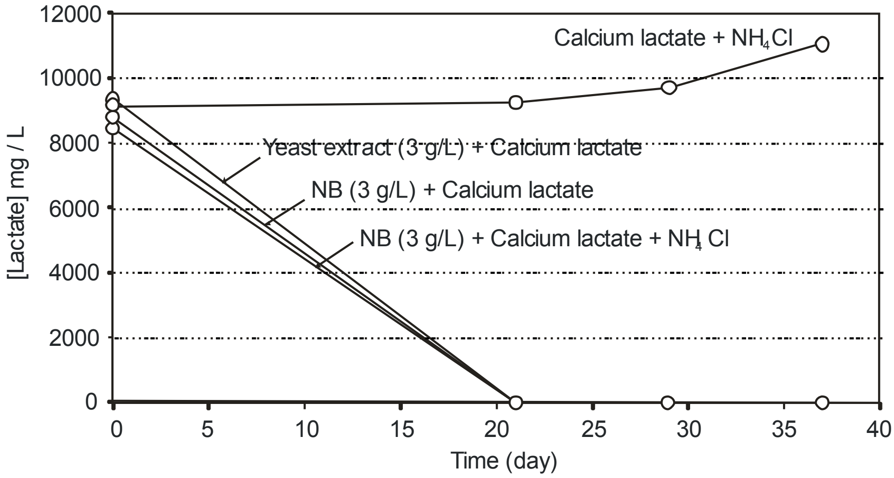

Figure 3: Evolution of the lactate concentration by *Bacillus cohnii* growth in different media

4. CONCLUSION

Self-healing naturally occurs in cracked cementitious materials. The most important effect is observed for small cracks (≈ 100 µm). The use of a calcite precursor, containing calcium, such as calcium lactate, significantly improves the healing of large cracks, even in the absence of bacteria. However, calcite mediated precipitation by bacteria is expected to enhance crack healing even further. Amongst possible bacterial strains, *Bacillus cohnii* shows an interesting potential. It has been demonstrated that it can grow in pH values ranging from 7.5 to 10.5 and that calcium lactate can be one of its nutrient. However, *Bacillus cohnii* is unable to decompose lactate without the presence of other nutrients such as Nutrient Broth (NB) medium. These results are a first step toward the development of a bacterial repair technique. The next step will be to inject the cracks with bacterial media in order to evaluate the additional improvement of healing thanks to the microbiological activity leading to the formation of greater amounts of calcite.

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