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Biobased Encapsulation Self-Healing Technique in Concrete Pavement

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Abstract
To reduce the carbon footprint of concrete infrastructure in the context of climate change, more sustainable, concrete pavements are required. Cracking under traffic strain severely damages concrete pavements and Cementous composites. The cost of rehabilitation and maintenance of concrete pavements is high. Although cracks are typically minor and do not always cause pavement collapse, they may reduce the life cycle and sustainability of pavements. The cost of rehabilitation and maintenance of rigid pavements is high. These concerns can be addressed by encouraging concrete self-healing processes via spore encapsulation. To enable such self-healing behavior without compromising the field performance of the concrete pavement, the needed microcapsules must be resilient against harsh environments, oxidation, and mechanical stress. For the first time, this study suggests the use of an exceptionally resistant biobased 2% (W/V of cement) spore suspension containing 10^6 cells/ml in 200 ml of sodium alginate solution for encapsulation in order to construct more durable self-healing pavements. Encapsulation contains the bacterial consortia *Bacillus flexus MK-FYT-3* and *Bacillus haynesii MK-NW-9*, endosporeforming bacteria capable of producing urease enzyme and growing at 60°C with optimum growth at 40°C (Mahmoud et al., 2022). SEM, visualized images, compressive strength, and indirect tensile strength tests were used to investigate the material properties and mechanical changes. Additionally, the healing levels of samples after cracking and the healing period were examined.
Keywords: Encapsulation - Self-Healing – Spore - Concrete Pavements - Bacterial Consortia

1. Introduction

Concrete has become one of the world's most widely used substances due to its special properties, which include good compressive strength, proximity, adaptability, economic suitability, suitability with a reinforced steel bar, flame retardancy, superior caloric weight, and the ability to be cast in specific designs and dimensions (Seifan, Samani, Berenjian, & biotechnology, 2016),(Luhar, Luhar, & Shaikh, 2022). Concrete, on the other hand, is prone to cracking, and some these cracks are not visible and, therefore, cannot be reached (Biondini, Camnasio, & Palermo, 2014).

Cracks grow in size and number as a result of material expansion, contraction, and penetration. As a result, infrastructure inspection and maintenance procedures are gaining popularity. Implementing continuous inspection and maintenance may be difficult, particularly in the case of large-scale infrastructures, due to the significant amount of investment required. Implementing continuous inspection and maintenance may be difficult, particularly in the case of large-scale infrastructures, due to the significant amount of money required. Other considerations, such as the location of the damage in the damaged structure, complicate repair (Hager, Greil, Leyens, van der Zwaag, & Schubert, 2010). Furthermore, repair work has a major negative environmental impact, particularly when full or partial structural replacement is required. It is well known that the manufacturing of 1 tone of Portland cement (PC), which is frequently used as the principal element in concrete, emits around 0.85–1.1 tone of CO_2 (Deja, Uliasz-Bochenczyk, & Mokrzycki, 2010). In 2014, around 3.6×10^9 metric tons of cement were manufactured worldwide (Oss, 2011). The CO_2 emissions linked with cement manufacture are large, accounting for 7% of global anthropogenic CO_2 emissions (Deja et al., 2010).As a result, the concept of autonomous repair, also known as the self-healing of these detrimental cracks with minimal labor as well as the capital requirements of the damaged structures, becomes quite appealing to academics. As a result of the low personnel and capital investment requirements, assessing self-healing efficiency using a variety of methods became appealing. In this context, multiple approaches are used to assess selfhealing efficacy. Self-healing efficiency is the return of a cement base material's functionality and desired quality criterion relative to its initial state (Hager et al., 2010).

The use of self-healing materials is becoming more common in civil engineering. The main objective of self-healing in the field of concrete materials is to increase the material's functionality and service life by regaining concrete strength, porosity, and water-tightness. In the field of concrete, self-healing mostly refers to the repair of cracks produced by the brittle character of the material. The process of self-healing is mainly carried out by two basic mechanisms: autogenous and autonomous healing, as illustrated in Figure 3. Autogenic healing is an intrinsic material healing property that occurs when unhydrated cement in the matrix hydrates, resulting in the development of calcium carbonates or hydroxides Figure 1 (a). Autonomic healing, on the other hand, involves the use of components that are not generally found in cement-based composites. This category normally refers to various types of materials included in the matrix, primarily in the form of encapsulated additions, which can either be bacteria-based Figure 1(b) or sticky materialbased Figure 1(c). Self-healing occurs when a crack forms, resulting in the rupture of the encapsulated system and the subsequent release of healing components. Microcapsules are an excellent choice for developing autonomic self-healing cement. Stress is used as a trigger for selfhealing by the microencapsulated healing agent. When damaged, the capsules break, causing the release and reaction of healing chemicals in the affected area (Rajczakowska, Habermehl-Cwirzen, Hedlund, & Cwirzen, 2019).

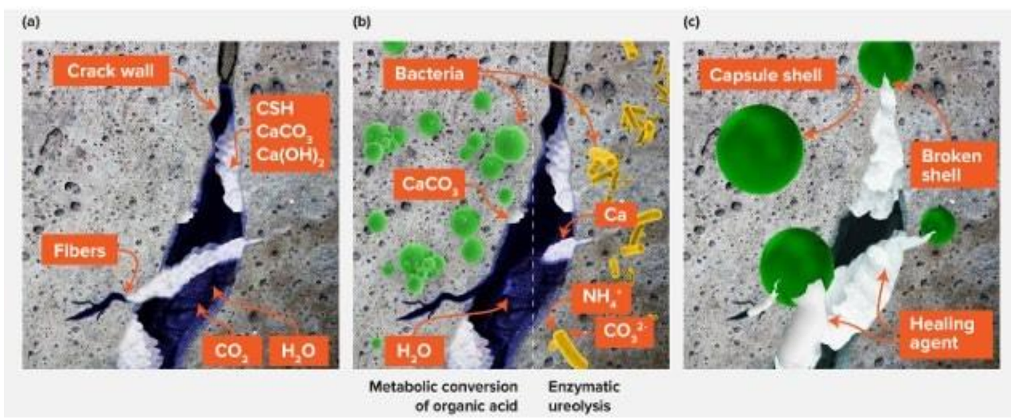

Figure 1. Self-healing mechanisms: (a) autogenous; (b) autonomous bacteria-based; and (c) autonomous capsule-based (Orlov, 2021).

Efficient self-healing is obtained when the sealing is long-lasting and can be maintained over the system's lifespan. Based on the microbial-induced formation of calcium carbonate precipitation (MICP), it has evolved into an intelligent and environmentally friendly approach to repairing concrete cracks. As a result, bacterial survival is critical. However, if bio-agents are applied directly to concrete, the survival of bacteria may be limited due to the high-alkali environment in concrete. When bacterial spores are injected directly into the mixture, the life of untreated spores is restricted to only two months, according to research, and only young samples have efficiently self-healed (Roy, Rossi, Silfwerbrand, & Jonkers, 2020). Encapsulation-based self-healing begins with the formation of cracks and develops through the chemical reaction of released self-healing chemicals in the cracks, which are stored in capsules (Xue, Li, Li, Tam, & Ye, 2019).

There are several methods for encapsulating bacteria:

- Polymeric encapsulation: hydrogel, sodium alginate, calcium alginate, rubber particle, melamine microcapsule, silica gel (SG), polyurethane (PU), and peroxide tablets
- Lightweight aggregate encapsulation: expanded clay (EC), leca aggregates, expanded perlite (EP), ceramist
- Mineral encapsulation: diatomaceous earth (DE), zeolite

- Nanomaterial encapsulation: graphene nanoplatelets (GNP), granular activated carbon (GAC), and iron-oxide nanoparticles (IONPs).
- Cementitious encapsulation: metakaolin-geopolymer covering, limestone powder (LSP), calcium sulpho aluminate powder (CSA), volcanic ash.
- Biochar encapsulation in waste-derived biomass (Roy et al., 2020).

The main objective of this study is to evaluate and optimize the crack healing efficiency of encapsulated bacteria in concrete pavements.

2. Materials and Methods

2.1. Encapsulated Concrete Mix

The concrete component is composed of cement, fine aggregate, coarse aggregate, and water in a weight ratio of 1:1.55:3:0.36, respectively. The preparation process of self-healing microcapsules was performed as illustrated in Figure 1, in an exceptionally resistant biobased 2% (W/V of cement) spore suspension containing 10^6 cells/ml in 200 ml of sodium alginate solution for encapsulation in order to construct more durable self-healing pavements as in Figure 2. For this combination, two sets of mortar cubes, along with two sets of mortar cylinders, were prepared. The mechanical properties of these specimens were characterized by compressive and tensile strength tests. The specimens were cracked with widths ranging from 0.8 to 1 mm, maintained in a temperatur econtrolled environment at 30°C for a day until the surface dried, and subjected to 28 wet/dry c ycles, Once the wet/dry cycles were completed, the specimens were tested to determine the strength recovery. One Cylinder specimen with 1cm height were cracked, and subjected to 28 days of wet/dry cycles in which crack width was visually monitored.

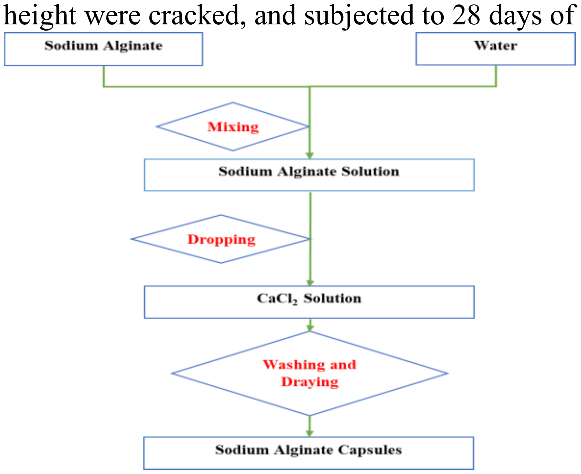

Figure 1. Schematic encapsulated bacteria preparation process.

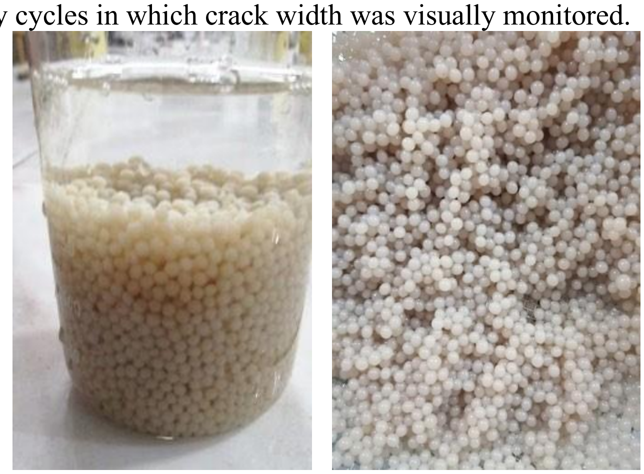

Figure 2. Encapsulated bacteria in concrete mix.

2.2. Self-Healing Performance Test

As an additive, calcium alginate capsules are mixed into concrete mortar. The use of capsules should increase concrete mortar's self-healing performance without affecting its mechanical properties. While the density and strength of capsules differ substantially from those of aggregates, their incorporation may have a significant impact on the pavement performance of concrete. Furthermore, image analysis and scanning electron microscopy are conducted to visualize crack healing, determine crack filling, and characterize the healing material.

2.2.1. Mechanical Properties Recovery

Several macro-scale examinations have been conducted to assess the efficacy of self-healing to regain compressive, and other mechanical properties. When self-healing process initiates and the healing agent completely hardens, the self-healing concrete containing microcapsules was compared with normal concrete (reference) after microcracking is loaded to measure the strength based on compressive strength test. The compressive strength procedure was adapted in reference to ASTM C39 (C39M-17a., 2017) for cube specimens with 7.5cm× 7.5cm× 7.5cm dimensions.

The testing machine was equipped with steel bearing plates with faces larger than the size of the samples as in Figure 3. The rate of load, or stress, ranged from 0.2 to 0.4 MPa/s. The initial compressive stresses were determined with three replicates by applying stress on samples until they reached failure. Succeeding experiments of replicates of three were performed.

Figure 3. Compressive strength recovery: a) compressive strength machine, b) control mortar specimen, c) mortar cubes with encapsulated bacteria specimen.

2.2.2. Microstructural Evaluation

Scanning electronic microscopy was used to assess the cracks healing process after curing for 28 days using Quanta FEG 250 scanning electron microscope (FEI Company, USA) (Prošek, Nežerka, Plachý, Bartoš, & Tesárek, 2022). Secondary digital image is predominant method for visualizing and evaluatiog self-healing behavior and process, such as crack width.

3. Results

With respect to self-healing recovery, encapsulated concrete specimens displayed superior healing efficiency after being subjected to wet/dry cycles, and no significant difference was noted among the reference specimens.

3.1. Mechanical Tests Results

Microscopy indicated a high concentration of calcium-rich crystals as calcium carbonate, indicating bacterial activity after the capsules were discharged. Based on the best-performing mortar samples, scale-up concrete research was carried out and compared to reference concrete specimens. The concrete analysis results show that the inclusion of encapsulated bacteria increased the compressive and tensile strength of the concrete, as shown in Figures 4 and 5. In contrast, after wet and dry cycles, the concrete reference specimen demonstrated less healing efficiency.

Therefore, based on the test results presented After healing the microcracks in concrete, the results showed that the significant increase of compressive and bending strengths manifested the self-healing ability of the microcapsules in concrete (Tan, Keung, Choi, Lam, & Leung, 2016). The results are similar to previous research in which the precipitates were analyzed by Achal et al. demonstrated an improvement in compressive strength when bacteria were employed in combination with admixtures in concrete (Achal, Mukherjee, & Reddy, 2011). Furthermore, compressive strength increased by 36% (Achal et al., 2011). It has been demonstrated that, following self-healing, compressive strength can be restored to up to 60%. Furthermore, after selfhealing, ultrasonic pulse velocity increases (Muhammad et al., 2016). Up to now, many researches are still ongoing, where bacteria are being applied in concrete purposefully for more strength and durability improvement.

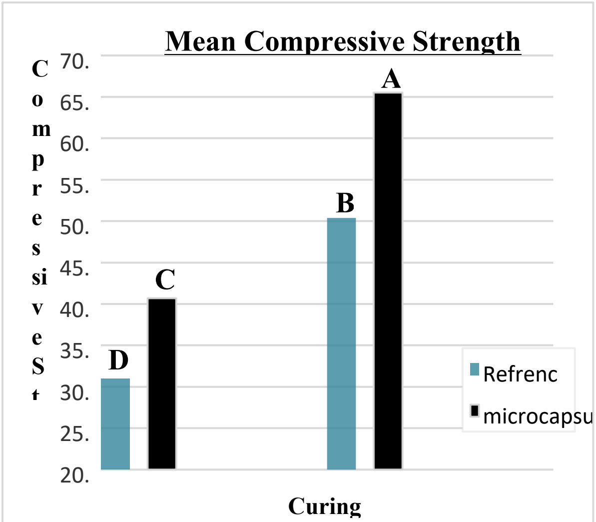

Figure 4. Mechanical compressive strength of microcapsules concrete mortar.

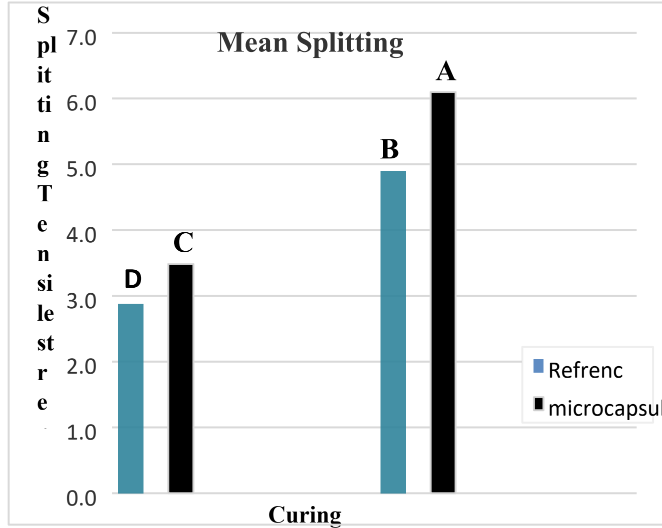

Figure 5. Mechanical tensile strength of microcapsules concrete mortar

3.2. Microstructural Results

SEM was the most popular technique adopted among the researchers for verifying the precipitated crystals by healing agents, followed by visualization image of the crack healing. In order to confirm the reliability of the results, microstructural tests like SEM can be adopted to identify and characterize the presence of precipitated products in the crack specimens. SEM microscopy was used to obtain detailed information about the microstructure and cracking using precipitated $CaCO_3$. Figure 6 illustrates images of calcite crystals detected by SEM.

In contrast, the sealed rate in the case of reference specimens is smaller, which is consistent with autogenous fracture repair without the use of healing agents. The crack width reduction was also used as an indication of the degree of self-healing observed in each specimen group. Figure 7 shows the images taken before repair, after 7, 14, and 28 days under room conditions. After 28 days, the precipitates in white are plainly visible in the case of the encapsulated bacteria mixture. As expected, the crack width reduction increased over time for all specimen groups. all samples containing alginate beads exhibited higher crack width reductions which surpassed the reference specimens. Kawaai et al. (2022) presented the results of the images taken by microscope before repaired, after a week, and after the exposure tests of 56 days. Demonstrate that, the calcite precipitation in gel films formed in crack is highly effective in sealing crack in mortar specimen. In addition, the Bacillus subtilis (natto) could reduce the concentration of dissolved oxygen in concrete, which is found to contribute to reduction of the macro cell corrosion (Kawaai, Nishida, Saito, & Hayashi, 2022). Proek et al. (2022) studied the structure of precipitated $CaCO_3$ crystals due to SHA activity after 90 days of self-healing using SEM-SE microscopy at 3000 magnifications, and the microscopy images indicate differences in the sizes of $CaCO_3$ crystals formed spontaneously during autogenous remediation of a cementitious matrix and when *Bacillus pseudofirmus* was present. bigger crystals, while bacterially-induced $CaCO_3$ precipitation produced tightly packed, smaller crystals (Prošek et al., 2022).

As a result, specimens containing encapsulated bacteria that play an important role in microcrack repair were able to seal larger cracks than control specimens.

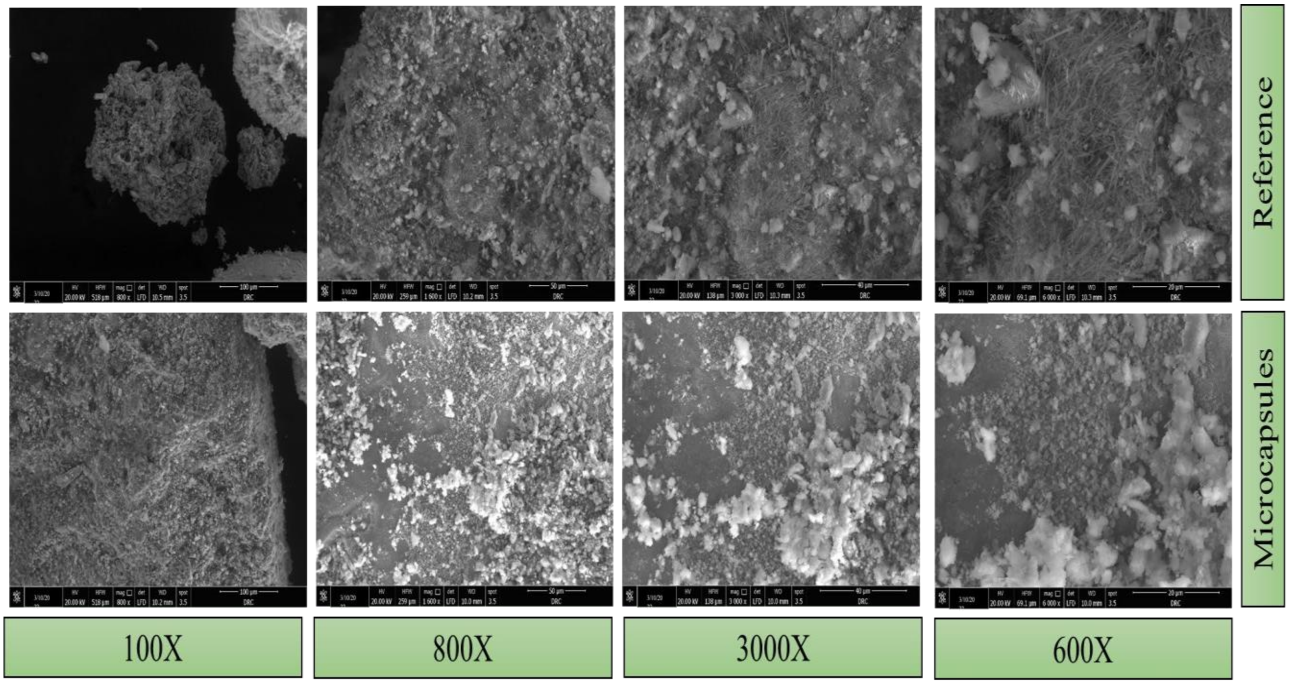

Figure 6: SEM Image of microcapsules and reference concrete specimens at 100, 800, 3000, and 6000X magnification.

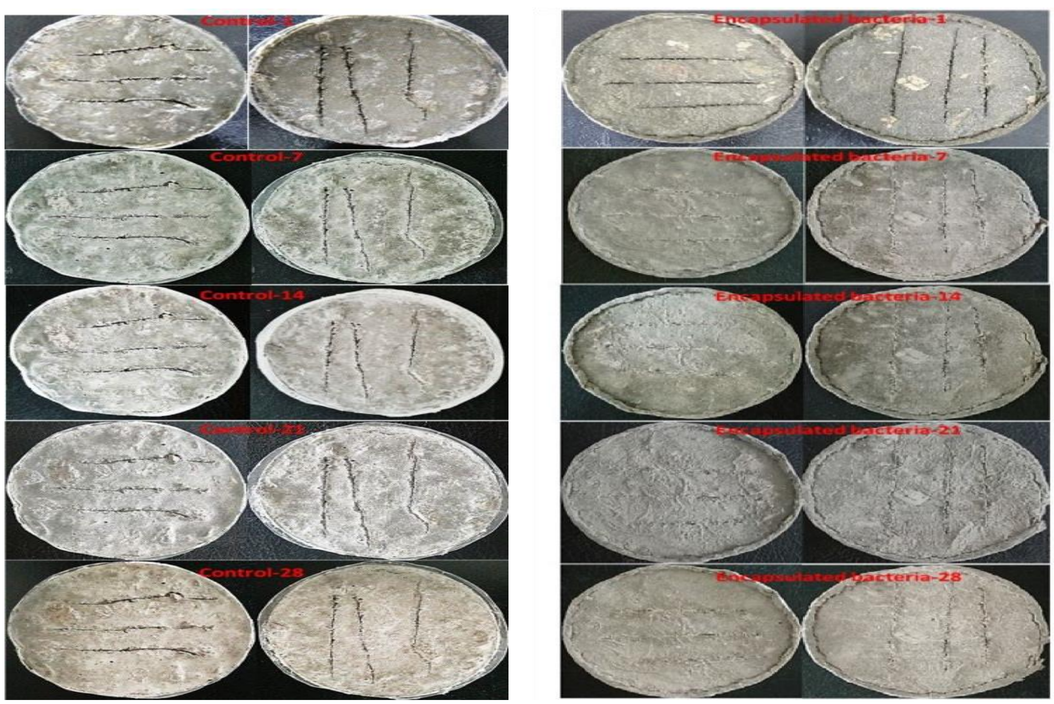

Figure 7. Visualization imaging concrete mortar regain

4. Conclusion

This study examined the suitability of concrete mortar containing encapsulated bacteria compared to reference specimen regarding rate and efficiency in sealing microcracks. The encapsulated concrete mortar was utilized to evaluate the efficacy of encapsulated bacteria in producing $CaCO_3$ precipitation for crack sealing while protecting bacteria spores and nutrients. Crack healing occurred in water and was monitored for 28 days.

The results from the study of healing the microcracks in concrete revealed a significant increase in compressive and tensile strengths, demonstrating the self-healing potential of the microcapsules in concrete. In addition, after microcracking using SEM microscopy, imagine visualization with camera photographs. The most common techniques for achieving effective self-healing are Muhammed et al. (2016), which produce additional cementing materials, polymers, and microorganisms. The major challenge is determining the influence of self-healing on successfully closing the crack width. So far, cracks with a maximum size of 0.95 mm have been repaired. The basic techniques for determining the diameter of filled fractures are visual observation using a microscope, and digital imaging (Muhammad et al., 2016). Mechanical strength recovery is clearly the most direct indicator of remediation degree and acts as an appropriate combination of microstructure observations.

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