MIDWEST TRANSPORTATION CENTER MTC

Development of an Eco-Friendly, Cost-Effective Biogrout for Concrete Crack Repair

tech transfer summary

Due to the environmental and economic benefits, biocementation resulting from a microbiologically induced calcium carbonate precipitation process is being increasingly used to enhance civil infrastructure—through stone surface protection, sand cementation, soil consolidation, crack remediation, and so forth.

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RESEARCH PROJECT TITLE
Development of an Eco-Friendly, Cost-Effective Biogrout for Concrete Crack Repair

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Problem Statement

More study is needed in order to improve and apply microbiologically induced calcium carbonate precipitation (MICP) technology to field concrete repair applications.

Background

Cement-based materials have often been used for infrastructure construction and repair. The production of conventional Portland cement is energy-consuming and environmentally unfriendly. For example, production of one ton of Portland cement generates approximately one ton of carbon dioxide (CO_2) from calcining limestone and fuel use. It is estimated that cement production contributes 7% of total global CO_2 emissions.

In recent years, an alternative material called biocement has been developed through an MICP process. Biocement is generally made of calcium salt (most commonly calcium chloride or $CaCl_2$), a small amount of urea, and urease-producing bacteria (UPB).

However, looking specifically at the calcium salt used in the MICP process, not only is $CaCl_2$ expensive, but excessive $CaCl_2$ in concrete can alter its properties and be harmful to human health and agriculture (Chung et al. 2014). Some studies have already been performed to replace $CaCl_2$ with different calcium sources like calcium hydroxide ($Ca(OH)_2$), calcium nitrate ($Ca(NO_3)_2$), calcium acetate ($Ca(CH_3COO)_2$), and eggshells in vinegar (Choi et al. 2016).

Although some work has been done, the study of concrete repair using MICP technology is still very limited. Studies have indicated that MICP can contribute to crack repair via several mechanisms: (1) filling cracks with biogenic calcium carbonate ($CaCO_3$), microbial biomass, and polysaccharides (formed through enzyme-catalyzed condensation); (2) bonding loose materials with biogenic $CaCO_3$, microbial biomass, and polysaccharides; and (3) forming salt bridges between particles and/or colloids mediated by microorganisms.

It is expected that after being repaired with biocement/grout, cracked concrete can resume its integrity and have proper mechanical properties and water penetration resistance. Although the concept of MICP is promising, the repair materials and procedure used vary widely in different studies. The effect of crack width on MICP repair effectiveness is still not clear.

Project Objectives

- Produce a soluble calcium source for MICP utilizing an industrial by-product, limestone fines, an agricultural by-product, and an acetic acid-rich fraction of biomass pyrolysis product
- Study the influences of bacterial quantity, available nutrients, and water content on the MICP process and maximize the biogenic $CaCO_3$ productivity
- Evaluate the crack-healing effectiveness and ensure that the concrete/mortar repaired with the newly developed biogrout has improved engineering properties

Research Approach and Methodology

A deeper study of possible soluble calcium solutions leading to the development of a new biogrout was needed. The approach included two main tasks: biogrout development and mortar crack repair analysis.

The biogrout development included three major steps:

1. The preparation of materials and solutions for the MICP tests included selection of a urease-producing bacteria, *bacillus sphaericus (sp.),* to produce the urease enzyme. Calcium ions were produced in a solution using limestone fines and acetic acid-rich stage fraction 5 (SF5) instead of the conventionally used $CaCl_2$ for the MICP process.

2. To test for sand cementation, sand samples were compacted to a total unit weight of approximately 1.70 g/cm^3. Twelve samples were prepared, with six used to test unconfined compressive strength (UCS) and six used to test splitting tensile strength (TS). UPB and urea-$CaCl_2$ solutions were then added to the biocemented sand samples.

3. The properties of the biocemented sand samples (the amount of $CaCO_3$, water permeability, UCS, and TS) were then evaluated. Small pieces of the broken samples were also collected for examination of their microstructures under a scanning electron microscope (SEM).

To study crack repair, mortar cylinder samples were prepared and subjected to different levels of splitting loads, thus generating different sizes of cracks (i.e., different crack areas and widths) in the samples. The repair technique was optimized by applying, in different orders, the amount of UPB and calcium solutions to the cracked mortar samples under varying environmental conditions. To investigate the effectiveness of the biogrout repair or crack healing, the repaired mortar samples were tested for water permeability and splitting tensile strength.

The mortar crack repair analysis included three major steps:

1. A series of 20 mortar samples were made of ordinary Portland cement (OPC), river sand, and distilled water. A single straight crack was then made in each mortar sample.

2. The cracked mortar samples with different crack sizes were treated with UPB solution and urea-$CaCl_2$ solution.

3. To evaluate the effectiveness of the crack repair method, permeability of the cracked mortar samples was tested at 0, 7, 14, and 21 cycles of the MICP treatment. TS of the samples was measured after the permeability test at 21 cycles. The split surfaces of these samples were then examined under a SEM.

Key Findings

The researchers drew the following conclusions about the development of a new soluble calcium solution for MICP:

- A soluble calcium solution can be achieved from dissolving a limestone powder into an acetic acid-rich SF5 solution, which was derived from a pyrolysis and bio-oil fractionation system.

- The properties of the soluble calcium solution for MICP were optimized from the study of different limestone powder-to-SF5 ratios, potential for hydrogen (pH) values of the obtained solutions, and procedures for applying the UPB and urea-$CaCl_2$ solutions for $CaCO_3$ precipitation. The optimal 0.3 M calcium solution obtained from this study consists of a limestone:SF5:NaOH:distilled water ratio of 1:8:0.045:13 (by weight).

- The permeability of the biocementated sand ranged from 8.17E-6 to 1.52E-6 m/s, UCS ranged from 858 to 1,111 kPa, TS ranged from 137 to 197 kPa, UCS/TS ratios ranged from 4.6 to 6.9, and the modulus of elasticity (E_{50}) was 38.3±1.7 MPa for compression and 24.3±2.7 MPa for tension.

- There are close relationships between the engineering properties (permeability, UCS, TS, UCS/TS ratio, and E_{50}) of the biocemented sand samples and the $CaCO_3$ content in the samples. Generally, the permeability decreased and strength and E_{50} increased with increasing $CaCO_3$ content.

The researchers drew the following conclusions about the study of mortar crack repair using MICP technology:

- After 7 cycles, most small cracks (<0.52 mm) were healed. After 21 cycles, all cracks (0.15 to 1.64 mm) were healed with 1/16 to 1/8 in. of precipitated $CaCO_3$ layers on the top surfaces of repaired cylinders.

- The MICP repair technique can significantly reduce water permeability of cracked samples. Before any MICP treatment, the cracked mortar samples, with crack sizes ranging from 0.15 to 1.64 mm, had permeability values ranging from 3.027E-3 to 9.237E-6 m/s. After being treated with MICP for 7 cycles, permeability decreased to the range of 8.254E-5 to 2.046E-6 m/s. After being treated with MICP for 21 cycles, permeability of the mortar samples was only about 1.000E-6 m/s or less.

- The TS of the MICP-repaired samples ranged from 32 to 386 kPa, and the maximum strain of the samples ranged from 0.22 to 2.17% after 21 treatment cycles. Most of the samples had a maximum strain larger than 1.0%, compared to 0.3% for most intact conventional concrete/mortars, and their stress-strain behavior was generally linear. However, the water-treated mortar samples were all broken into two pieces after demolding, and they therefore were unable to be tested for TS.

- There was no clear relationship between TS and the $CaCO_3$ content, because the samples had an average crack width of ≤0.5 mm. However, a clear relationship was observed for the sample average crack widths >0.52 mm, where TS increased with $CaCO_3$ content.

- The SEM study suggested that there were two different forms of $CaCO_3$ in the cracked mortar samples: one form consisted of flower-shaped clusters made with well-arranged thin (plate/sheet-like) hexagon $CaCO_3$, which might be vaterite, and the other was the granular clusters made with thick (coarse) hexagon $CaCO_3$, which was probably calcite. The $CaCO_3$ crystals had a size ranging from 5 to 20 µm, and they formed a porous matrix that filled in the cracks.

Implementation Readiness and Benefits

The development of a new eco-friendly, cost-effective biogrout for concrete crack repair could have transformable impacts on the environment, as it could potentially be used instead of current biogrout made with environmentally harmful $CaCl_2$.

- The developed soluble calcium solution can effectively replace $CaCl_2$ in the MICP process, because it can provide desirable $CaCO_3$ precipitation.

- The properties of the sand samples biocemented using the newly developed soluble calcium solution are comparable to those of the sand samples biocemented using $CaCl_2$ as a calcium source for MICP.

- Cracks in the mortar samples repaired using the MICP technology gradually healed with an increasing number of treatment cycles.

Future Research

- In this study, the limestone powders and the acetic acid-rich SF5 solution were obtained from given sources. The properties of these raw materials from different sources may vary. The effects of the variations in the raw materials on the properties of the resulting soluble calcium solution should be further studied.

- In addition to soaking, different treatment methods (e.g., injection and spraying) should be investigated, as they are commonly used repair methods in construction.

- An in-depth study should be conducted to find out why different forms of $CaCO_3$ (calcite and vaterite) were observed in a given sample.

References

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