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Applying a biodeposition layer to increase the bond of a repair mortar on a mortar substrate

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ABSTRACT

One of the major concerns in infrastructure repair is a sufficient bond between the substrate and the repair material, especially for the long-term performance and durability of the repaired structure. In this study, the bond of the repair material on the mortar substrate is promoted via the biodeposition of a calcium carbonate layer by a ureolytic bacterium. X-ray diffraction and scanning electron microscopy were used to examine the interfaces between the repair material and the substrate, as well as the polymorph of the deposited calcium carbonate. The approximately 50 μm thick biodeposition film on the mortar surface mostly consisted of calcite and vaterite. Both the repair material and the substrate tended to show a good adherence to that layer. The bond, as assessed by slant shear specimen testing, was improved by the presence of the biodeposition layer. A further increase was found when engineering the substrate surface using a structured pattern layer of biodeposition.

1. Introduction

Concrete is one of the most widely used construction materials on Earth. It is an ideal material to resist compressive forces, but when sufficient tensile forces are present, concrete may crack. And, without repair of the cracks, the durability can be critically compromised. One can decide to use a self-healing concrete during the design phase of construction [1–3], but repair of existing concrete structures will still often be needed. This manual repair should be made with care and precautions should be taken to assure that the repair is long-lasting, durable and efficient. If the bond between repair product and concrete substrate is not sufficient, delamination or spalling may occur. Therefore, one needs to make sure that the surface treatment of the substrate is properly executed. A striking statistic is that, 20%, 55% and 90% of the repairs of concrete structures are unsatisfactory after only 5, 10 and 25 years, respectively [4]. For patch repair, 30% of the failures are due to cracking, 25% due to debonding, 25% due to corrosion issues and 20% due to other failure mechanisms [4]. Debonding thus is a major factor in the overall failure of repair works [5].

One way of improving the bond between a concrete substrate and a repair material is by introducing a primer on the substrate. For example, incorporating fly ash into a primer between both materials or using neat cement paste, expansive paste, cement mortar or a water-dispersible epoxy resin as a primer are existing solutions [6]. A silane coupling agent can be applied as well [7]. But, the bond of the coupling agent itself should also be good and the practitioner would thus benefit from a solution where the bond is not a possible issue. Also, proper surface preparation, as characterized by cleanliness, roughness, and saturation level, is of major importance [8–10].

Another way of increasing and engineering the bond between the repair material and the concrete substrate could be the use of a biodeposition treatment, which is based on bacterially induced $CaCO_3$ precipitation in/on the substrate. One of the first patented applications on biodeposition was the protection of ornamental stone by a microbially deposited carbonate layer [11,12]. The formed bacterial $CaCO_3$ layer works as an extra barrier to resist degradation and/or as a consolidant to cement the loose particles, and hence the surface properties of historical materials can be greatly enhanced in the aspects of a decrease of water permeability, an increase of freeze-thaw resistance, and an improvement of

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surface strength, etc. [13–15]. This biodeposition technique has also been applied on cementitious materials resulting in an increased resistance of mortar specimens towards chloride penetration, freeze/thawing and carbonation [11,15–18]. It should merely be considered as a coating system as carbonate precipitation is mainly a surface-controlled phenomenon due to the limited penetration of bacteria into the microporous cementitious matrix. Thin-section analysis revealed that the thickness of the bacterial layer was typically within the range of 10 μm–40 μm; in which larger crystals up to 110 μm could be found [11]. This layer may be a promising route to engineer the substrate surface for optimal bond strength characteristics.

The bond between the concrete or mortar substrate and the repair material usually represents the weak link in the repaired structure if no special action is undertaken. Several tests are currently available to measure the bond of the repair material to the substrate. The main tests under tensile stress are pull-off tests, direct tension tests, and splitting tensile tests. Direct shear methods are also used. A combination of both shear and compression can be used as well. An example is the slant shear test where two identical halves bonded at an angle of 30° are tested under axial compression. Depending on the method, different quantitative values may be obtained for the bond strength [8,19]. The slant shear test has become one of the most-widely accepted tests.

In this paper, the bond strength was assessed by slant shear testing. Specimens with and without a biodeposited layer were studied and the crystal composition and morphology were examined. Different partial pattern-type biodeposition layers were studied to further increase the bond strength between a mortar substrate and a repair material. The formed biodeposition products were studied by means of X-ray diffraction, scanning electron microscopy and thin section analysis.

2. Materials and methods

2.1. Mortar specimens

The standard followed to prepare the mortar substrates was ASTM C882/C882M-13 on 'Bond strength of epoxy-resin systems used with concrete by slant shear'. Three portland-cement mortar cylinders with a standard mixture composition as described in the Standard EN 196-1 were cast (510 kg/m^3 CEM I 52.5 N, 1530 kg/m^3 silica sand 0/2, and 255 kg/m^3 water) per series. The specimens' diameter and height were 75 mm and 150 mm, respectively, and each had a diagonally cast bonding area at a 30° angle from the vertical, as per the ASTM standard. The specimens were cast against a polymeric half-cylinder substrate with the same dimensions, demoulded after one day and stored for 28 d in a moist room at 95% ± 5% RH and 20 °C ± 2 °C; all reported uncertainties represent one standard deviation, unless stated otherwise.

A total of five series were cast. The specimens were manually ground (bonded surface) by means of a sand paper until the desired roughness was reached. The International Concrete Repair Institute (ICRI) has a set of "roughness" surface profile chips [20]. An intermediate profile, similar to the CSP-5 chip, was targeted at an age of 28 d. All prepared surfaces were visually similar. Three out of five surfaces were used for the bacterial treatment (BAC, BACX and BAC#, see later on). One series was used for reference samples (REF). One series of three specimens were not manually ground and the casting surface was used in further testing. These smooth specimens served to study the influence of the roughness (SMO).

2.2. Bacterial strain and cultivation condition

Bacillus sphaericus LMG 22257 (Belgian coordinated collection of microorganisms, Ghent) was used in this study. The bacteria were grown aseptically in the growth medium (400 mL per batch) that consisted of a blend of yeast extract (20 g/L) and urea (20 g/L). The culture was incubated at 28 °C on a shaker at 10.5 rad/s [100 rpm] for 24 h. Subsequently, the bacterial cells were harvested by centrifugation (733.0 rad/s [7000 rpm], 7 min) of the 24 h old grown culture and were re-suspended in sterile saline solution (NaCl, 8.5 g/L). The concentration of the bacteria in the suspension typically varied from $1.5 \cdot 10^9$ cells/mL to $2 \cdot 10^9$ cells/mL. The obtained bacterial suspension was stored in a 4 °C refrigerator for further experimental use.

2.3. Biodeposition treatment

Three different biodeposition patterns were studied. These include a continuous layer, a non-continuous layer with two thirds of the surface covered by biodeposition and a non-continuous layer with only one third of the surface covered by biodeposition. For this purpose, the mortar substrate surfaces were taped with aluminium tape in a distinct way (Fig. 1). In an eventual biodeposition, a film would be deposited both on the mortar surface and the tape. By removing the tape after the biodeposition, only the uncovered parts of the mortar substrate would have been treated. In that way, the three different series with 100% biodeposition ☐ (BAC), 66% biodeposition ▦ (BACX) and 33% biodeposition ▦ (BAC#) were made.

Mortar specimens (BAC, taped BACX and taped BAC#) were partially immersed in a precipitation medium that consisted of urea (0.5 mol/L), calcium nitrate (0.5 mol/L) and yeast extract (5 g/L) for 24 h and had a pH of 6.1. The medium level was approximately 10 mm above the immersed surface (elliptical surface for applying repair material) of the mortar specimens. After that, the specimens were taken out from the precipitation medium and put upside down until surface dry at 60% ± 5% RH and 20 °C ± 2 °C. Subsequently, bacterial suspension was sprayed (approximately 0.5 mL/cm^2) all over each elliptical surface every 6 h for 4 times. In the end, the biodeposition layer was seen on all samples (Fig. 2). After 3 days, the repair mortar was applied.

2.4. Repair material application and slant shear testing at 28 d

The repair material (Sika MonoTop-412 N)[1] was mixed for 3 min. It is a cement-based single component fiber reinforced repair mortar with low shrinkage and with R4 classification according to EN 1504-3. The prepared bonding surface (mortar half cylinder) was put inside of a cylindrical mould (as replacement of the polymeric half-cylinder substrate) and the repair material was applied next, filling the cylindrical mould. The complete specimen was demoulded the day after. The entire cylinder was put in a moist room at 95% ± 5% RH and 20 °C ± 2 °C until the repair product achieved an age of 28 d. Prior to testing, the loading surfaces of each cylinder were ground to produce a smooth and parallel testing surfaces. The composite specimen was loaded in compression (Fig. 3) and its strength was recorded, as described in the Standard ASTM C882/C882M – 13. The bond strength was determined by dividing the load carried by the specimen at failure by the area of the bonded surface. The area of the bonded surface was reduced by that of any visible voids found in the bond layer on inspection after

[1] Certain commercial products are identified in this paper to specify the materials used and the procedures employed. In no case does such identification imply endorsement or recommendation by Ghent University or the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.