Special Lecture delivered by Dr. Nele De Belie, Ghent University, Belgium on "Healing and Self-Healing of Concrete and Stone"

1.0 Introduction

Concrete plays a major role in the construction industry. For a durable structure, good quality concrete must be used. In the life cycle of a structure, concrete and stone gets affected by physical, chemical and environmental factors. Concrete structures are affected by cracking, spalling, etc. The cracks are formed by thermal expansions, external loads, temperature variations and other environmental factors.

Prof. Nele De Belie has shown during her presentation how repair and consolidation of mineral phases of building materials and the healing and self-healing of concrete with the help of bacteria is possible.

2.0 Healing and Self-Healing

2.1 Consolidation of Mineral Phases of Building Material

Consolidation means reduction of the porosity of the structure and densification of the structure. The building materials deteriorate due to weathering actions such as physical, chemical and biological actions. The building materials also deteriorate due to interaction of micro-organisms with stone and concrete. Micro-organisms play a crucial role in pedogenesis, transformation of minerals and exchange of elements in structures. This also includes transformation of hard rocks to soft soil, which supports plant growth and is a positive process in nature. However, when this rock is used as a building block or a constituent of concrete, this biodegradation process is far from positive. The building materials may be protected by traditional systems such as coatings and hydrophobic sealers or with organic dispersions, but this has the following disadvantages:

- The surface layer will have a different thermal expansion coefficient compared to concrete.
- Formation of incompatible surface film.
- Environment and health hazards.

On the other hand the micro-organisms such as bacteria, cyanobacteria, algae, lichens, yeasts, fungi and mosses etc., which are omnipresent and omnipotent, are responsible for metabolism action that results in a microbial deposition of a protective $CaCO_3$ layer. Also, this process results in re-establishment of the cohesion between particles of mineral building materials and protects against further decay of stone material. To prove the positive effects of microbial $CaCO_3$ precipitation, the micro-organisms were applied on concrete or stone samples by a subsequent immersion with following procedure:

- The sample is immersed up to 1 cm depth for 1 day in bacteria culture.
- Subsequently placed for 3 days in biodeposition medium.
- Lastly treated for 7 days by drying at 28°C.

This treatment results in precipitation of carbonate crystals which can be seen by a scanning electron microscope or thin section (Fig. 1). This precipitation of carbonate crystals was not limited to the outer surface only, but could be observed at depth greater than 1 mm and bacterial cells could be observed clearly.

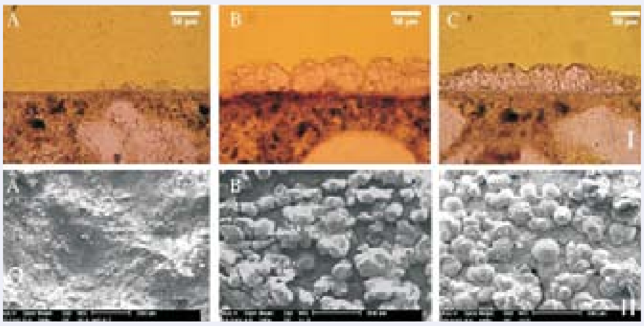

Fig. 1: Thin sections (top) and scanning electron microscopic views (bottom) of (A) untreated (B) biodeposition with $CaCl_2$ and (C) biodeposition with Ca acetate

The increase in porosity in concrete leads to increase in capillary water uptake, increase in gas permeability along with higher carbonation rate, higher chloride migration and freeze-thaw damage. But precipitation of carbonate crystals by using Bacillus Sphaericus isolates with calcium acetate or calcium chloride as a calcium source (Bac.sph. Ca Ac & Bac.sph. $CaCl_2$) helped to decrease the capillary water uptake in concrete up to 65-90% (Fig. 2) and minimized the water absorption. It helped to decrease porosity and gas permeability. Also, biodeposition of micro-organisms (Bac.sph. Ca Ac & Bac.sph. $CaCl_2$) helped to increase the resistance towards carbonation and the rate of carbonation decreased up to 25-30 % (Fig. 3) and the decrease in chloride migration amounted up to 10-40%. All these helped to achieve a durable structure.

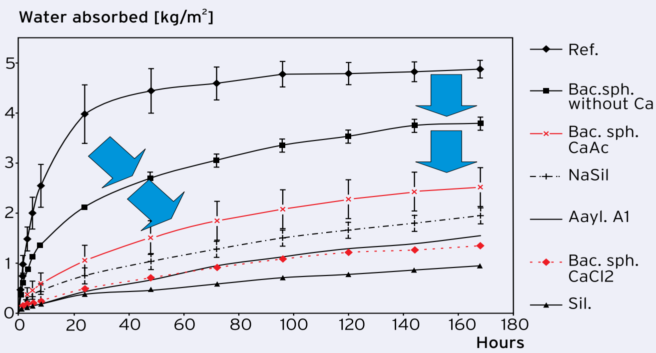

Fig. 2: Biodeposition resulted in decrease in capillary water uptake in concrete

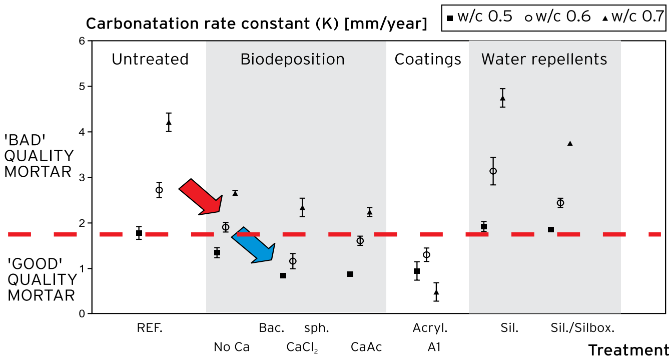

Fig. 3: Biodeposition increased resistance towards carbonation

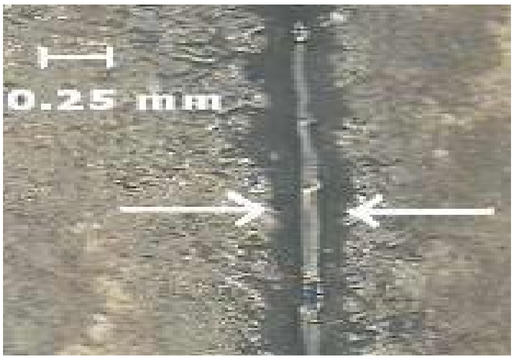

Fig. 4: Crack repaired with epoxy

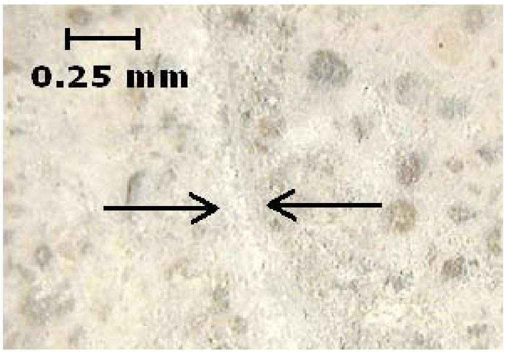

Fig. 5: Crack repaired with bacteria in Sol-gel medium

2.2 Healing of Cracks in Concrete

For remediation of cracks, usually traditional repair methods such as grouting or epoxy injection (Fig. 4) are being used. But the latest development of bacterial treatment is more useful. In the bacterial treatment, the solution medium used was of equimolar concentration of urea (20g/l) and $CaCl_2$ or $Ca(NO_3)_2$ for 3 days and thereafter dried for 3 days at 28°C. The bacteria used were B. Sphaericus(BS). But to protect these bacteria from the strong alkaline environment in concrete, they were immobilized in Silica Sol-gel (Fig. 5). The treatments were applied by placing the samples on plastic rods in the treatment solution, where the liquid level was 10 mm above their lower side. Remediation of cracks could be possible by formation of biocers (in contact with a salt, the silica sol becomes a silica gel, creating a biological ceramic material) together with carbonate precipitation inside. By this process the cracks up to 10 mm deep could be completely filled (although this could not seal a 20 mm deep fissure completely). This also helped to decrease the water permeability.

2.3 Self-Healing of Cracks in Concrete

In concrete, cracking is a common phenomenon due to the relatively low tensile strength of this material. As these cracks function as an entry channel for potentially aggressive liquids and gases, which may cause concrete attack and reinforcement corrosion, they need to be repaired. However, large costs are involved in maintenance and repair of concrete structures. Besides, indirect costs are even 10 times higher than the direct costs of maintenance and repair.

Therefore, it would be interesting to design the material in such a way that it repairs the damage all by itself. Self-healing properties may be obtained when encapsulated healing agents are dispersed through the concrete matrix. Once a crack appears, the capsules break and the healing agent is released into the crack, resulting crack repair. The other method of self-healing is introducing healing agents in glass tubes dispersed through the concrete matrix. Cracks form in the concrete matrix wherever damage occurs and subsequently these cracks break the glass tubes, releasing both components of the healing agent into the crack plane through capillary action. When both components come into contact, the polymerization reaction is triggered and the crack faces are bond together.

The concrete can be provided with a self-healing mechanism by using healing agents such as polyurethane. The concrete has to be filled throughout the matrix with polyurethane in capsules. The capsules used were made of ceramic tubes of 3 mm dia. and 100 mm long or glass tubes of 2 mm or 3 mm dia. having the same internal volume (Fig. 6). The components used as healing agents were prepolymer of polyurethane on the one hand and a mix of accelerator and water on the other hand. Upon polymerization reaction (Fig. 7), the concrete regained its mechanical properties due to crack healing as confirmed by bending test. Due to crack healing water permeability also decreased.

Fig. 6: Capsules of ceramic tubes

Fig. 7a: PU healing agent before polymerization

Fig. 7b: PU healing agent after polymerization

For self-healing of concrete, concrete beams with and without autonomous crack healing properties were tested. The concrete beams had size (500 mm X 110 mm X 50 mm) with a 20 mm-deep notch in the middle and the self-healing beams contained the tubular capsules filled with a mix of accelerator and water and prepolymer of polyurethane. Concrete beams were subjected to three-point bending test, which resulted in crack formation and healing. For comparison, some beams were made without self-healing properties and the cracks were repaired manually. In case of manually-healed cracks, the crack should be injected by polyurethane after the bending test and in case of autonomous crack healing, the polyurethane was released automatically during the bending test. The beams were reloaded in three points bending to determine the amount of regain in strength due to crack healing. Due to autonomous crack healing, 90% strength regain and 60% regain in stiffness were obtained (Fig. 8) This also helped to decrease the water permeability.

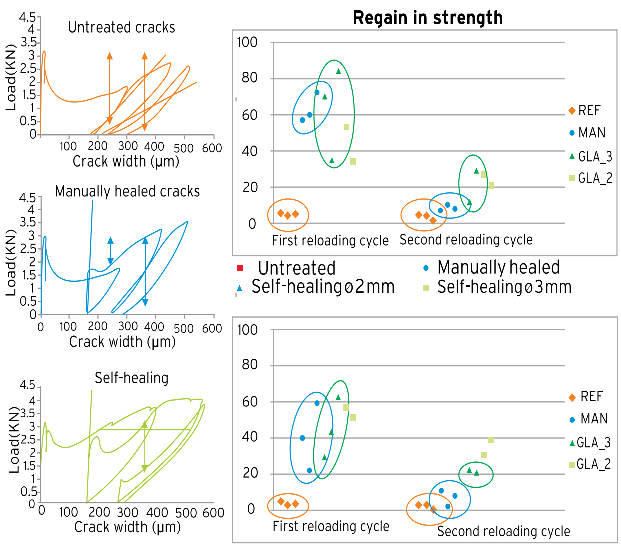

Fig. 8: Regain in mechanical properties due to crack-healing

REF: Untreated samples

MAN: Manually healed cracks

GLA_2: Self-healing by 2 mm φ glass tube

GLA_3: Self-healing by 3 mm φ glass tube

After the first reaction of healing, a second reloading can be carried out and a second healing action can be feasible with a liquid healing agent or polyurethane foam. To prove the crack healing efficiency by means of acoustic emission measurements, the beams were subjected to a crack width controlled bending test, while acoustic emissions were captured and, upon crack healing, the beams were reloaded to test the possibility to prove crack healing again by means of acoustic emission test.

As another option for self-healing of concrete, bacteria spores were used. To protect the bacteria from higher alkalinity of the concrete, the carrier materials used in tubes were PU (Polyurethane) and SG (Silica Gel). The components used for self-healing were the following:

- Bacteria to precipitate $CaCO_3$ crystals – Bacillus Sphaericus
- Calcium source / salt for gel formation – $Ca(NO_3)_2$
- Nutrients – Urea
- Protection against concrete envelope – SG/PU
- Trigger mechanism – Breakage of glass tubes

Argex and Lava were also used to test as other suitable carrier materials in self-healing action of concrete. Lava could improve the performance where as in case of argex the strength reduced in comparison with standard reference specimen for testing compressive and tensile strength of such samples. By self-healing of concrete, strength regained after cracking and cracks were sealed immediately by which aggressive substances would not enter through the cracks and more durable concrete structures could be obtained.

3.0 Conclusion

Crack repair with a biological treatment in which a *B. sphaericus* culture is incorporated in a gel matrix is most effective. Silica gel can be used to protect the bacteria against the high pH in concrete. This helps to decrease in water permeability. Precipitation of these crystals inside the gel matrix also enhances the durability of this repair material. The use of this biological treatment is highly desirable because the mineral precipitation induced as a result of microbial activities is pollution-free and natural. Self-healing of cracks in concrete is due to embedding encapsulated healing agents in concrete resulting following:

- Strength regain after cracking
- Cracks are immediately sealed
- Aggressive substances will not enter the cracks
- More durable concrete structures
- Regain of water impermeability could still be improved

Biological approach for healing and self-healing of cracks in concrete and consolidation of building materials can be possible by adopting this latest green technology, which makes the structures durable and environment friendly.

[Lecture was delivered on Healthy Construction Lecture Series organised by Dr. Fixit Institute of Structural Protection & Rehabilitation, Mumbai by Prof. Nele De Belie, Magnel Laboratory for Concrete Research, Dept. of Structural Engineering, Ghent University, Belgium at Kolkata and New Delhi on 23rd and 24th September, 2010 respectively]