

Damage management of concrete elements by crack mitigation and self-healing strategies

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Abstract. Small cracks in concrete elements that are allowed by structural design codes will not hamper the functionality of the element initially, but do provide an easy access for aggressive agents into the concrete and to the reinforcement. Therefore, cracks will lead to an acceleration of degradation processes and reduce the service life and sustainability of concrete structures. Crack mitigation strategies like the incorporation of superabsorbent polymers, and self-healing methods can help to reduce the maintenance frequency and increase service life, however, their efficiency in realistic environments needs to be properly evaluated.

1 Occurrence of cracks in concrete

The occurrence of small cracks in concrete is almost unavoidable. Shrinkage phenomena and temperature effects can induce early age cracks and at later ages the intrinsic brittleness and low tensile strength of the material in many cases leads to cracking in service. For many structural elements, this results in the need to introduce reinforcement, mostly steel rebars. In design codes, cracks of limited width (200-300 μm) are allowed for most structural elements if water tightness is not a prerequisite. Fib Model Code 2020, Eurocode 2 and ACI 318, propose equations to calculate crack widths as a function of reinforcement bar diameter and reinforcement area ratio, concrete cover, concrete tensile strength, steel-concrete bond strength and the induced stress in the reinforcement. Small cracks will not hamper the functionality of the element initially, but do provide an easy access for aggressive agents into the concrete and to the reinforcement. Therefore, cracks will lead to an acceleration of degradation processes and reduce the service life and sustainability of concrete structures. Recently developed high performance and extremely low porosity concrete types are mostly even more brittle and sensitive to early age cracking than normal strength concrete. Degradation models rarely include the crack pattern as a durability parameter, because the effects of cracks on the kinetics of the degradation mechanisms are generally not well-known or too complex to introduce into simple calculation models.

2 Effect of cracks on concrete durability

It is clear that the presence of cracks in the concrete cover zone provides easier access for various aggressive agents. For instance, it has been found that cracks above a certain critical crack width allow a faster penetration of chloride ions into the matrix. This critical width could be around 10 to 50 μm , as stated by Maes [1] and Van den Heede et al. [2] respectively. Based on in situ inspections on a concrete bridge, Kušter Marić et al. [3] mentioned that above the crack width of 100 μm the time to depassivation of the reinforcement was significantly reduced, independent of the cover thickness. Cracks can also increase the CO_2 penetration through the concrete cover, thus triggering an earlier start of the reinforcement corrosion. Alahmad et al. [4] found that CO_2 penetrated freely in cracks with a width above 60 μm , while the carbonation rate in the crack decreased for smaller crack widths. Also, Van Mullem et al. [5] showed that carbonation was significantly affected by the crack tortuosity for crack widths below 100 μm .

3 Crack mitigation and self-healing strategies

To increase durability and the service life of the structure, different mitigation and crack treatment methods can be applied. Superabsorbent polymers (SAPs) possess the ability to take up a significant amount of liquids from the environment and due to

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their ability to absorb and retain water from the cementitious mixture, they have been successfully used as internal curing agents preventing self-desiccation and reducing autogenous shrinkage. In a recent study [6], commercial acrylate based and in-house developed NaAMPS (2-acrylamido-2-methyl-1-propanesulfonic acid sodium salt) based superabsorbent polymers have been proven to effectively eliminate early age shrinkage cracks in reinforced concrete walls (14 m x 2.75 m x 0.80 m), while reference walls without SAPs presented through-going cracks in the first 7 days after casting.

The so-called passive crack treatments are manually applied if inspection indicates that crack widths have exceeded allowable values for the structure and environment in which it has to function. They only treat surface cracks and the application is dependent on the accessibility of the affected area. Active methods on the other hand are incorporated at the construction stage. Those methods, also called self-healing techniques, will be activated when the cracks are formed and may fill both interior and surface cracks.

3.1 Autogenous and autonomous healing

A further distinction can be made between autogenous healing and autonomous or autonomic healing. Autogenous healing relies on the conventional constituents of the concrete matrix, and is mainly induced by continued hydration of yet un-hydrated binder particles near the crack walls, and precipitation of calcium carbonate crystals in the crack. Methods to limit crack width (fibre addition), provide the water that is needed for hydration reactions to occur (e.g. addition of superabsorbent polymers), or enhance hydration or crystallization (e.g. by mineral additions or crystalline admixtures) can be used to stimulate or improve autogenous healing. Autonomous healing uses unconventional engineered additions to provide the self-healing function and includes the application of encapsulated minerals and polymeric healing agents, and of encapsulated or granulated micro-organisms. Various microbes have been shown to induce precipitation of CaCO_3 as a result of their metabolism and the nucleation properties and zeta-potential of the cell wall. Regarding encapsulated agents, micro-encapsulation, macro-encapsulation, and vascular networks have been applied. The choice will determine the magnitude of the healable damage, the repeatability of healing, and the recovery rate. In these systems, the formation of the crack is mostly the trigger to activate the self-healing, because it ruptures the capsules and releases their content.

3.2 Self-healing under realistic conditions

Several review papers have been published, giving an overview of the different autogenous and autonomous technologies [7], test methods to assess their effectiveness [8] and models to predict the result of the self-healing process [9]. However, many of the results were obtained in ideal conditions, often environmental conditions in laboratories. At the moment, there is a need for further insights into the behaviour of self-healing concrete in real service scenarios, including cases where structures are functioning in extreme or aggressive conditions and in the case of dynamic cracks. An overview of the current knowledge regarding the efficiency of self-healing concrete under realistic conditions has been recently compiled [10].

Ideal conditions vary according to the considered self-healing mechanism. For (improved) autogenous self-healing to happen, liquid water should be available. SAPs can capture moisture from the air and in this way activate autogenous healing [11]. The swelling of SAP particles in contact with moisture leads to immediate crack sealing and the release of water to yet unhydrated binder particles at the crack faces activates autogenous healing. The efficiency of bacterial self-healing will depend on the characteristics of the microorganisms that are used. Aerobic bacteria are not only in need of water, but also of oxygen, of which the availability could decrease from the crack mouth to the crack tip. This could be overcome by using nitrate-reducing bacteria together with nitrate as an alternative electron acceptor that enables bacterial CaCO_3 precipitation without O_2 being available. These bacteria could provide the added functionality of corrosion inhibition by nitrite produced as an intermediate metabolite [12]. Other autonomous mechanisms, based on encapsulated polymeric healing agents, may be independent of water availability. Still, one-component polyurethane precursors need humidity to polymerize [13]. On the other hand, in unsaturated specimens, the release and distribution of healing agent can be positively affected by the capillary action of the crack. Temperature changes will affect the rate of chemical and enzymatic reactions and lead to a variation in polymer viscosity thus affecting the crack filling efficiency [14]. Therefore, the best self-healing strategy will depend largely on the conditions in which the concrete element will function.

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