Construction and Building Materials 173 (2018) 763–774

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Effect of a crystalline admixture on the self-healing capability of high-performance fiber reinforced concretes in service conditions

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## HIGHLIGHTS

- Study on self-healing capability of reinforced concrete tie-specimens.
- Effects of fiber and crystalline admixture (CA) in concrete were investigated.
- Initial permeability (*Kwi*) decreased by 60% in concrete, 100% with fibers and CA.
- Reloading to reach again *Kwi* was 60 MPa in rebar of concrete, 115 MPa with fibers and CA.
- Healing products were calcite and ettringite without CA, aragonite with CA.

## ARTICLE INFO

*Article history:*
Received 21 July 2017
Received in revised form 5 February 2018
Accepted 1 April 2018
Available online 24 April 2018

*Keywords:*
Self-healing
Crystalline admixture
Fiber reinforcement
Crack openings
Water permeability
Mechanical recovery
SEM observations
Calcite
Aragonite

## ABSTRACT

In presence of water, cracks of reinforced concrete structures can heal naturally or with the help of admixtures. The project aimed to measure the water permeability and self-healing of a high-performance concrete (HPC), a HPC with fibers (HPFRC) and a HPC with fibers and crystalline admixture (HPFRC-CA). Under monotonic loading, HPFRC and HPFRC-CA showed maximal crack widths 39% lower and water permeability 3.1 times inferior than HPC. Under a 7-day constant loading and a continuous water flow, cracks of HPFRC and HPFRC-CA were completely healed in comparison to 60% for those of the HPC. The self-healing kinetics was slower for the HPFRC-CA than for the HPFRC, but a higher load had to be applied in the HPFRC-CA to reach again the initial permeability. SEM observations of self-healed products allowed identification of calcite and ettringite in the HPFRC in comparison to aragonite in the HPFRC-CA.



## 1. Introduction

Reinforced concrete structures deteriorate due to various stresses and deformations from internal, mechanical or environmental loadings. This deterioration enhances different transport properties of concrete, such as permeability, diffusion and capillarity suction, resulting in higher water, gas and aggressive agents ingress through concrete [1–3] and thus in a reduced durability. The premature durability problems (corrosion of reinforcing steel, alkali-aggregates reactions, etc.) reduce the service life of concrete structures and increase their rehabilitation costs including indirect costs linked to the socioeconomic and environmental impacts of these activities. In this context, durability of concrete structures has become main priority for owners, stakeholders, governments and standards. Permeability, defined as the flow of a fluid through a porous saturated medium under a pressure gradient, is a predominant transport mechanism in concrete particularly at vicinity of cracks. The crack represents a preferential path for water ingress and the permeability is proportional to the cube of the crack width [4]. The permeability coefficient is thus a meaningful durability indicator for cracked concrete. As permeability is closely influenced by crack widths, it is necessary to better control their opening to build durable structures. This can be achieved by adding rebar or fibers into concrete as shown in some researches [5–7].

In addition to reducing the crack opening, permeability can also decrease with time due to the self-healing potential of concrete in presence of water. Different physico-chemical phenomena can explain cracks self-healing, as formation of calcium carbonate

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https://doi.org/10.1016/j.conbuildmat.2018.04.003
0950-0618/

$CaCO_3$ (generally the main phenomenon for mature concrete) [1,2,8–10], formation of additional hydrates due to the presence of residual clinker in the matrix [11] and presence of water impurities or concrete particles stuck into the crack [12]. Studies about self-healing proved that thinner cracks heal faster than larger cracks [5,13] and that the crack width is the predominant controlling parameter in the self-healing kinetics (much more than the water to binder ratio (w/b) of concrete). Because inclusion of steel macrofibers into concrete results in thinner cracks, steel fiber reinforced cracked concrete presents higher rates of self-healing than conventional concrete and requires a greater additional loading after self-healing to reach the same permeability level as before self-healing occurred [5].

In recent years, researchers tried to enhance the healing capacity of concrete through different ways as mineral additions (fly ash, silica fume, limestone powder) [14–17], chemical additions (crystalline admixture, expansive additive, adhesive agents and encapsulated polymers) [18–20] and finally biological additions [21,22]. Because self-healing depends on many parameters (cracking procedure and terms, storage conditions, crack width and amount of addition) and the diversity of testing methods using to evaluate self-healing, it is difficult to classify self-healing techniques according to their efficiency. However, some self-healing techniques are more straightforward to set up with products easily available on the market. It is the case of crystalline admixture.

Crystalline admixture is a powder made of active chemicals provided in a carrier of cement and sand, it is added in the concrete mix like other components. The ACI Committee 212 indicated that the active chemicals react with water and cement to generally produce modified calcium silicate hydrates and/or pore-blocking precipitates in the concrete porosity and cracks [23]. Pore-blocking precipitates may take form of calcium carbonate [24,25] or fibrous products similar to hydration product [26].

No consensus exists presently on the benefit of CA on the self-healing of cracked concrete. It is probably explained by the variety of composition of concretes studied with CA, the difference of composition of the CA itself, the differences of CA content introduced in the concrete, and the various testing periods and methods considered in projects (mechanical or durability tests). These parameters can influence the type of self-healing product, its growth rate and thus the efficiency of the CA to seal cracks. Self-healing of cracks in presence of CA is better or similar to the concrete without CA. It was generally found that presence of water is critical for the self-healing process in presence of CA or not [18]. Thus some researchers found that CA did not favor cracks self-healing at 95 ± 5% of relative humidity [18], although others found that CA can even enhance self-healing in air exposure [26].

Until now, the healing potential of concrete with crystalline admixture was evaluated with different methods as observation of the effective crack opening evolution [16–18], evaluation of mechanical properties of healed specimens with and without additive [26] or evaluation of durability with permeability tests [24,25]. In these studies, the concrete specimens were generally unreinforced, were unloaded after the cracking procedure and presented a single crack. These conditions differ strongly from real concrete structures which are steel-reinforced, randomly cracked and loaded.

This project aims to determine the effect of the inclusion of fibers and crystalline admixture on the mechanical behaviour, permeability and healing potential of reinforced concrete tie-specimens in service condition. Standard flexural tests were first performed to better understand the mechanical behaviour of concrete containing crystalline admixture. Then a permeability device developed at Polytechnique Montreal [6,27] was used to perform water permeability and crack openings measurements simultaneously with the application of monotonic and constant tensile loadings. The constant loading was applied to evaluate the self-healing potential of reinforced concrete structures at a loading representative of services conditions.

## 2. Methodology

### 2.1. Materials

Three concrete mixtures were used to study the mechanical behaviour, permeability and self-healing capability of reinforced concrete (Table 1): a high-performance concrete (HPC), a high-performance fiber reinforced concrete (HPFRC) with 0.75%-vol of steel macrofibers with hooked end ($l_f$ = 35 mm and $\phi_f$ = 0.55 mm) and the same HPFRC with the addition of 2%-mass of crystalline admixture (HPFRC-CA) per cement content as recommended by the CA manufacturer. The CA used in this project was the WT-250 commercialized by Sika. All concretes were made with a water to binder ratio (w/b) of 0.43.

The workability and mechanical properties measured for each material are summarized in Table 2 and Fig. 1. The spread was measured by the slump flow test according to ASTM C1611 [28]. The compressive strength ($f_c$) and the Young's modulus ($E_c$) were determined at 28 days and 50 days (age of the permeability tests) in accordance with ASTM C39 [29]. The HPFRC and HPFRC-CA tensile strengths ($f_t$) were evaluated at 50 days through dogbone specimens subjected to uniaxial tensile loading according to Polytechnique procedure [30] based on RILEM TC 162-TDF standard [31]. The HPC tensile strength was assessed at 28 days and 50 days through splitting tests in accordance with ASTM C496 [32]. Besides, the grade 400 W steel rebar along the longitudinal axis of the tie-specimens had a Young's modulus of 210 GPa as well as yield and ultimate strengths respectively equal to 470 MPa and 580 MPa.

### 2.2. Experimental programs

#### 2.2.1. Preliminary program

Before evaluating the permeability and self-healing capability of concretes under load, a preliminary program was performed on six unreinforced notched prisms specimens (550 × 150 × 150

**Table 1**
Composition of concretes (0.75% vol. of fibers).

| Material | HPC | HPFRC | HPFRC-CA |
|---|---|---|---|
| Cement (kg/m$^3$) | 550 | 550 | 550 |
| Crystalline admixture (kg/m$^3$) | – | – | 11 |
| Water (kg/m$^3$) | 230 | 229 | 229 |
| Superplasticizer (l/m$^3$) | 9.7 | 10.5 | 10.5 |
| Viscosity agent (l/m$^3$) | 0.7 | 0.7 | 0.7 |
| Sand (kg/m$^3$) | 814 | 814 | 808 |
| Coarse aggregate (kg/m$^3$) | 678 | 658 | 653 |
| Steel fiber dosage (kg/m$^3$) | – | 58.5 | 58.5 |
| Water/binder ratio (–) | 0.43 | 0.43 | 0.43 |

**Table 2**
Properties of concretes.

| Properties | Date (days) | HPC | HPFRC | HPFRC-CA |
|---|---|---|---|---|
| $f_c$ (MPa) | 28 | 48.2 | 60.7 | 58.5 |
| | 50 | 54.7 | 63.1 | 58.3 |
| $f_t$ (MPa) | 28 | 3.31 | – | – |
| | 50 | 3.42 | 3.90 | 3.01 |
| $E_c$ (MPa) | 28 | 33 500 | 32 220 | 32 800 |
| | 50 | 34 500 | 33 640 | 34 100 |
| Slump flow (mm) | 0 | 610 | 530 | 540 |