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# Crack reactivity of ultra-high performance fibre reinforced concrete under the impact and immersion in geothermal water

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## ABSTRACT

It is well-known that the formation of cracks in concrete affects the durability in aggressive media due to the cracks contributing to the transport processes. However, the processes of interactions inside a crack are not well known and depends on parameters such as the aggressive media composition or the type of concrete. Besides, the self-sealing phenomena of the crack cannot be ruled out that modify the interaction with the aggressive environment. In the present work, the chemical interaction inside the crack of an ultra-high performance fibre reinforced concrete (UHPFRC) containing 45% blast furnace slag (BFS) and a crystalline admixture (CA) additive is analysed after 24 months exposure to the impact of simulated geothermal water (sgw) that contain sulphate and chloride. The obtained results confirm the interaction of the aggressive environment inside the crack, which varies with the deepness of the crack. Self- healing of the external part due to calcite precipitation while leaching of CSH crack wall and precipitation of ettringite inside the crack is appreciated.

**KEYWORDS:** *Concrete, Crack, Self-healing, Durability, Sulphates, Chloride*

## 1. Introduction

The main cause for loss of durability of concrete structures is related to the way they interact with the aggressive environment in service operating conditions. Advanced concretes employing UHPFRCs are undergoing continuous progress and development, Shi (2015), Cuenca (2022). High durability of UHPFRC in aggressive environment is considered, Wang, (2014), Son (2020), El-Joukhada (2021).
The damage expected from Cl interaction is mainly related to reinforcement corrosion, Song et al 2020, El-Joukhadar (2021) but also to the effect on steel fibres that affects the structural integrity of UHPFRC. The sulphates have a preferential interaction with cement paste forming new solid phases with higher volume causing expansions in the interior of the concrete.
The combined action of sulphates and chlorides have led to synergic interaction with cement paste, Some authors postulate reduction of Cl binding with preferential formation of ettringite, Alonso (2017), while others found enhancement of chemical absorption of Cl in presence of sulphates promoting the formation of Friedel's salt, Cheng (2019).
The presence of crack in concrete has demonstrated to reduce the service life of concrete due to the preferential entrance of the aggressive, Li (2019). The interaction of the crack with the environment can induce effect of self-healing reducing the transport of aggressive and benefit for service life extension (Maes et al 2016, Van-Belleghem, 2017).
Most of the processes related with the consequence of interaction of the crack with the environment are referred to what is observed on the surface with crack self-healing (Cuenca et al 2021, Van-Belleghem, 2017). However, the processes occurring in the crack and the consequence of the interaction with the local chemical composition of the water filling the crack is not well addressed (Gimenez et al, 2021).
In present paper, a microstructural study of the consequence of interaction on crack walls of UHPFRC exposed for 24 months of impact of simulated geothermal water rich in sulfates and chlorides is carried out. The interaction inside the crack in function to the distance from the surface is analysed.

## 2. Experimental

UHPFRC cylinders of Ø100x300 mm have been casted. The binder used was CEM I+45% BFS. The additive employed with the aim of modifying the concrete characteristics was CA. The w/b used was 0.18. The dosage of the concrete is included in Table 1.

Table 1. Dosage and composition of the concrete mix. in kg/$m^3$

| CEM I 52.5 R | BFS | Water | Steel fibres | Sand (0-2mm) | SP | CA |
|---|---|---|---|---|---|---|
| 600 | 500 | 200 | 120 | 982 | 33 | 4.8 |

The samples were cured in a moist room at 20 °C and 95 %RH for at least 2 months. Slices of Ø100x50 were obtained for testing. A notch of 5 mm was produced for crack generation, as shown in figure 1-left. Brazilian splitting tension test with a constant rate of 0.5 µm/s was used to obtain a single crack.

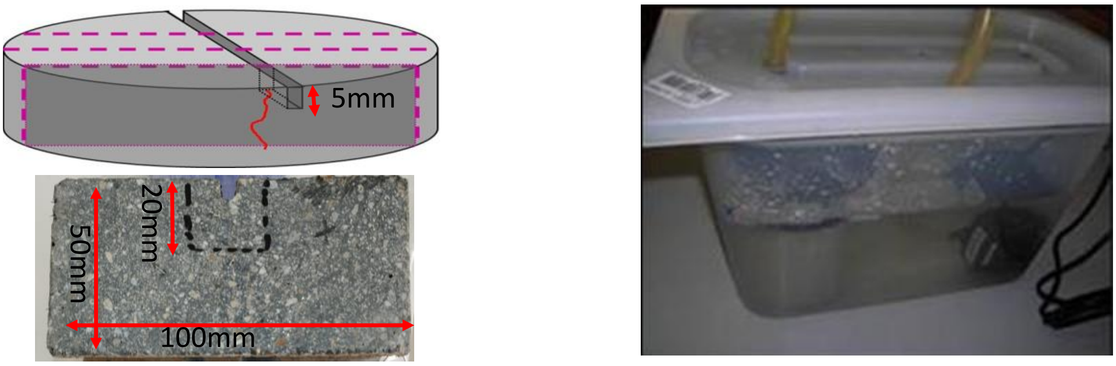


Figure 1. Left, cracked concrete sample and geometry used for testing. Right, set-up for the sgw impact test.

A water impact tests was carried out, set up shown in figure 1-right. The test was specifically designed to simulate in the lab the real site interaction of the water used for the refrigeration of a tower in a geothermal power plant, with the concrete tank. The test arrangement consisted of a plastic container in which one specimen was placed over a plastic mesh to avoid immersion in the water. A pump was joined to a rubber tube allowing the recirculation of the water and the impact of the water with the specimen. The test conditions look for promoting the physical impact through the water movement, which recirculates from the bottom of the plastic container to the top with a flow rate of 70 ml/s and hit the concrete surface from a height of 20 cm.

Sulphate and chloride polluted water simulating the cooling water of a geothermal plant (sgw) was used for the physic-chemical interaction with the UHPFRC. The sgw chemical composition was: $SO_4^{-2}$ (2300 ppm), $Cl^-$ (300 ppm), $Na^+$ (1280 ppm). The pH was adjusted to 3 with $HNO_3$.

After 24 months of exposure, the samples were removed and sampling for the SEM characterisation. The samples for the microscopy were obtained from the slice of the concrete sample cut transversely to the crack. Pieces of around 20 mm were taken from the region of the crack (cross-sectional area in Figure 1 left shows how samples were obtained). To obtain the images, the pieces of UHPFRC were embedded into an epoxy resin, polished and coated with carbon. The samples were studied along the depth of the crack. For microstructure analysis the SEM in backscattered mode (BSEM) was used. EDX analyses were also carried out to identify the element composition differences.

## 3. Results and Discussion

The aim of the study is focused on the characterisation of the interaction of the walls of a crack due to the continuous impact of the sgw on the surface of the cracked concrete. The study has been done analysing along 20 mm inside the walls of the crack. In figure 2 the micrographies and mapping in two depths of the crack are shown. On the left-up of the figure 2, crack walls closest to the concrete surface is considered.

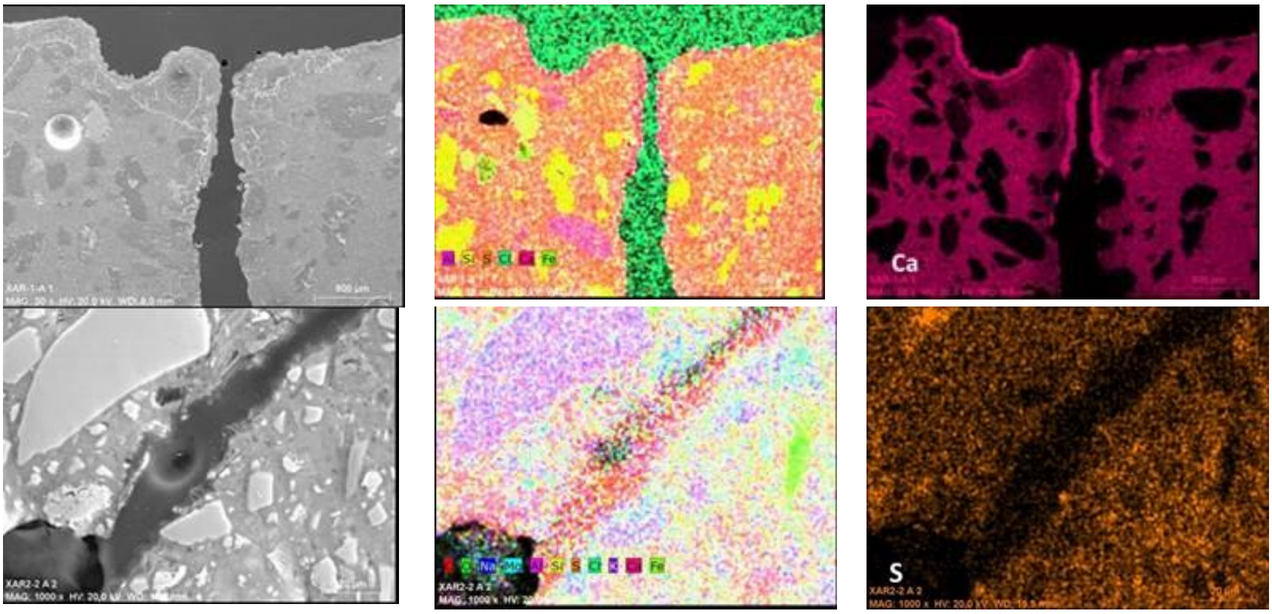


Figure 2. Micrographs and mapping showing the reactivity of walls of a crack of the UHPFRC with CA after 24 months exposure to the impact of sgw.

A reduction of the crack width is attributed to the interaction of the crack wall with the external environment, identified as the self-healing of a crack observed from the surface (Cuenca, 2022). This self-healing is appreciated to penetrate less than 1mm depth in the crack. The composition of the crack edges affected by the self-healing process is appreciated in the mapping of figure 2middle-up that highlights the element distribution (Si, Ca, S and Cl). The composition of the external sealing product is rich in Ca, as shown in figure 2right-up associated with the precipitation of calcite. The explanation found for this is related to the initial acid pH of the sgw which favours the dissolution cement paste, the CSH and portlandite, releasing $Ca^{+2}$ ion to the sgw and increase of pH, as it was demonstrated in Gimenez et al (2021). Soon after the Ca ions are captured by the $CO_2$ dissolved in the sgw facilitating in this way the calcite precipitation. Below this self-healing region, figure 1left-up the crack width remained not affected. At deeper level of the crack, figure 2-left-down, more precipitated product occupy the internal part of the crack. The mapping of figure 2middle-down and right suggest enrichment in S, Ca and Al.
The processes that characterise the internal interaction of the water in the crack with the walls of the crack suggest to type of event taking place. Regions of the crack walls with no product precipitation but alteration of the CSH, as shown in figure 3, with changes in $SiO_2$ and CaO content typically associated with a leaching process of concrete in contact with water (Alonso, 2017).

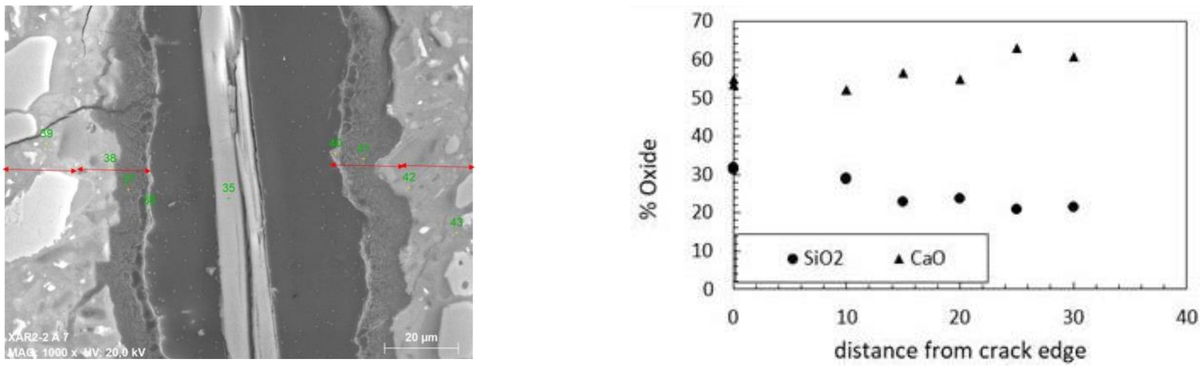


Figure 3. left, microstructural alteration of cement paste from the crack edges, right, variation of % of $SiO_2$ and CaO from the crack wall edge.

Inside the crack, regions filled with precipitated products, as shown in figure 4-left are taken place. This product has been identified to be related with the precipitation of ettringite (figure 4-ringht), what confirms the penetration of sulfates from the sgw in the crack. The CSH at the edges of the crack also shows leaching. The differences in the reactivity of the walls of the crack suggest changes in the internal water composition filling the crack and the outer part.

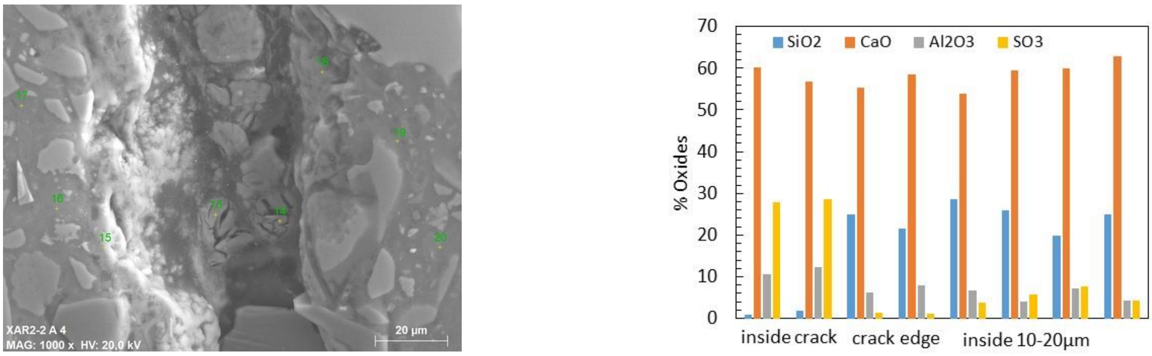


Figure 4. Left, microstructure of the internal filling of the crack. Right, Ettringite and CSH alteration.

## 4. Conclusions

The results observed in the analyses of the walls of the crack suggest different chemical processes of the interaction of the simulated geothermal water inside the crack, which varies with the deepness the crack. Self- healing of the external part due to calcite precipitation, while leaching of CSH crack wall and precipitation of ettringite inside the crack.


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