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**Title:** Self-healing capability of concrete with crystalline admixtures in different environments

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**Abstract:** The aim of this study is analyzing the self-healing effect of a crystalline admixture in four types of environmental exposure comparing with a reference concrete. Healing was studied by means of permeability tests on cracked specimens and physical closing of the crack was observed by optic microscope and quantified through crack geometrical parameters. The studied crack openings were under 300 μm and the time set for healing was 42 days. The results show a different healing behavior depending on the exposure and the presence of the crystalline admixture, demonstrating that the presence of water is necessary for the healing reactions.

**Keywords:** concrete, self-healing, autogenous, crystalline admixtures, permeability, durability

## 1. Introduction

Self-healing materials are those which have the capability of autonomously repairing small damages or cracks. The main reason for investigating the properties of self-repairing materials is that constructions built with them will have increased their service-life; likewise, structures with difficult or expensive reparations will benefit from self-healing their own damages [1]. Thus, self-healing concrete will lead to an increase of the sustainability of the structures built with this material.

Concrete has an inherent healing potential, called autogenous healing, which can take place in ordinary concrete elements but its power is limited and is not predictable. Neville in 1981 already mentioned this phenomenon and proposed the causes to autogenous healing [2]. He found out that fine cracks may heal completely under moist conditions and explained this phenomenon by both the delayed hydration of unhydrated cement and carbonation. Later, those processes were studied by Hearn (1998), Edvarsen (1999) and ter Heide (2005): all the authors agreed that the main processes responsible of self-healing were delayed hydration for young concrete while carbonation was more relevant for older elements [3][4][5]. Recent studies have compared the use of cement with different percentages of Portland cement and

additions in the autogenous healing process, obtaining better results with cements containing blast furnace slag or fly ash, which enhance the effect of delayed hydration, while carbonation precipitation remains similar for the different binder types [6][7][8]. Other studies were focused on the use of fibers in order to restrict crack width and enhance autogenous healing [9][10], using different fibers made of different materials [11] and analyzing the healing process under different environmental exposures [12].

In any case, autogenous healing is not a reliable phenomenon in order to get significant healing effects. That is the reason why several new "engineered healing concepts" have been investigated in the last years, such as the use of microencapsulated healing agents [13][14], bacterial concrete [15] or the use of crystalline admixtures [16].

Crystalline admixtures (CA) are a special type of permeability reducer admixtures (PRAs) as reported by the ACI Committee 212 [17]. In contrast to water-repellent or hydrophobic products, these materials are hydrophilic, and this makes them to react easily with water. When this reaction takes place, it forms water insoluble pore/crack blocking deposits that increase the density of Calcium Silicate Hydrate (CSH) and the resistance to water penetration. In this case, the matrix component which reacts is the tricalcium silicate ($C_3S$) and water presence is also needed. These products are formed by active chemicals contained in cement and sand which form modified CSH, depending on the crystalline promoter, and a precipitate formed from calcium and water molecules. Crystalline deposits become part of the matrix, unlike hydrophobic materials, thus being able to resist pressures as high as 14 bars [17].

Some authors studied the visual closure produced by different additives in mortar specimens comparing with a reference Portland mortar using fly ash, expansive admixtures, silica fume, crystalline admixtures and limestone powder with complete water immersion as healing exposure [18]. It was shown that crystalline admixtures improved self-healing processes at a higher rate than other types of additions, in the range of small cracks (less than 0.05 mm); however, they became inefficient for wider cracks. In other studies, the self-healing measured by means of the evolution of the permeability and visual closure was studied, comparing the effect of crystalline admixtures, expansive admixtures and a combination of both products. The limits were shown of the self-healing capability of crystalline admixture for cracks wider than 150 microns, while the combination of both agents achieved complete self-healing for cracks up to 400 microns after 30 days of water immersion [16]. Regarding to the recovery of mechanical properties, studying ordinary concrete and high performance fiber-reinforced concrete with crystalline admixtures, a better self-healing response was found for some parameters, such as the recovery of strength [19]. Other authors analyzed the healing effect of those admixtures under four different exposures (water immersion with/without renovation, wet/dry cycles, humidity chamber or air exposure) in terms of recovery of strength, obtaining the best results for the water immersion [19] or the wet/dry exposure [20].

The study of self-healing properties is based on the controlled creation of a specific damage (e.g. cracks) and the evolution of that damage under different conditions, which could be depicted by mechanical or durability properties. In recent years different procedures have been published to this purpose. Several methodologies have been proposed in order to analyze the permeability of cracked specimens, either simultaneously with the performance of load tests [21] or using independent tests for each phase [16]. In regards to the relation between the induced damage and the permeability properties, Edvardsen proposed a cubic relation between the water flow passing through a cracked concrete specimen and the crack width with an expression derived from Poiseuille Law [4].

## 2. Research objectives

The main objectives of this research can be summarized as follows:

- To analyze the effect of crystalline admixtures with reference to the enhancement of self-healing mechanisms.
- To determine the influence of the environmental exposure in self-healing of concrete with and without crystalline admixtures.
- To develop and compare methods for evaluating the self-healing properties of cracked specimens, based on the measure of the global permeability of the specimen and different geometrical characteristics of the crack before and after the self-healing period.

## 3. Experimental program and materials

### 3.1. Experimental program

In this study, it was decided to maintain the crack width always under 0.3 mm, as it is a common threshold for crack width in service state and it is potentially sealable by autogenous and CA healing, according to the available literature. The age of pre-cracking was fixed at 2 days, as most of the cracks due to shrinkage may occur few days after casting time. The initial permeability test was performed 1 day after pre-cracking, because of the needs related to the experimental procedure. Finally the time set for the self-healing process before the last permeability evaluation was 42 days; as a matter of fact, in most studies specimens got sealed in a smaller period of time when exposed to water immersion.

The experimental variables which were studied in this research are:

- Crystalline admixture dosage: 0% (control specimens), 4% by the weight of cement (CA specimens).
- Self-healing exposure: water immersion (WI), water contact (WC), humidity chamber (HC) and air exposure at laboratory conditions (AE)

This study includes both, a main study of permeability evolution and an analysis about the methodology for image evaluation of the crack. A total of eight groups of specimens were cast for permeability tests, each consisting of six

concrete specimens. Additional specimens were cast for some groups that required further exploration. Among all the specimens: three per each group were also employed for image evolution of crack parameters. An overview of the final number of cast specimens for each group is summarized in Table 1: as a whole 61 specimens were tested for permeability whereas image analysis of the cracks was performed on 24 specimens.

| Concrete | Exposure conditions | Number of specimens for permeability tests | Number of specimens for image analysis tests |
|---|---|---|---|
| Control | Water Immersion | 6 | 3 |
| | Water Contact | 7 | 3 |
| | Humidity Chamber | 8 | 3 |
| | Laboratory Conditions | 9 | 3 |
| CA | Water Immersion | 8 | 3 |
| | Water Contact | 8 | 3 |
| | Humidity Chamber | 8 | 3 |
| | Laboratory Conditions | 7 | 3 |

**Table 1. Number of specimens cast for each group**

### 3.2. Materials and mixture proportions

It was decided in this study to work with fiber-reinforced concrete. Since the focus of the project was to study the healing effects on pre-cracked specimens, fibers could provide an effective action both in controlling crack width during the pre-cracking process as well as in keeping fixed its value afterwards. The quantity of steel fiber was fixed at 40 kg/m$^3$ according to the criterion of making the crack opening easily controllable while avoiding excessive branching of cracks.

The cement used was CEM II/A-L 42.5 R from Elite Cementos S. L. The water/cement ratio used was 0.45 in both types of concrete. A dosage of 4% by the weight of cement of crystalline admixture in powder form was introduced in the CA Concrete whose behavior was compared with control specimens (without crystalline admixture). The two mix designs are shown in Table 2.

The criterion chosen for making concrete mixes with and without crystalline admixture is to maintain constant the sum of limestone powder and crystalline admixture, due to their similar effect on concrete workability. As a matter of fact they would both act as densifiers of the paste matrix phase. Superplasticizer, ViscoCrete 5720, dosage was adjusted in each different group in order to get similar slump (140 mm ± 20 mm).

In total, 7 batches of control concrete and 6 of crystalline admixture concrete were cast. For each batch, three Φ150 x 300 mm cylindrical specimens were cast according to UNE-EN 12390-2 to determine the compressive strength at 28 days, as

per UNE EN 12390-3. All batches were also characterized by their workability with slump test as per UNE EN 12350-2:2009. These control tests were performed with the objective of verifying the homogeneity of specimens of different batches but belonging to a same mix group (either control or CA) and in order to compare the results between the two mix groups (control and CA). After averaging the results of all batches for each group, it was observed that CA concrete had a significantly better compressive strength, about 15% higher than control concrete. With reference to the slump test results, differences are slightly lower, since the average results are around 13 cm for control concrete and 15 cm for CA concrete, which are within the acceptable tolerance limits of slump tests according to the standards.

| Material (kg/m$^3$) | Control | CA Concrete |
|---|---|---|
| **Cement II/A-L 42.5 R** | 350 | 350 |
| **Water** | 157.5 | 157.5 |
| **Gravel (4-12 mm)** | 950 | 959 |
| **Natural sand** | 899 | 875 |
| **Fibers, Dramix 65/35** | 40 | 40 |
| **Limestone powder** | 50 | 36 |
| **Crystalline Admixture** | - | 14 |
| **Average Slump (cm)** | 13 | 15 |
| **Average Compressive Strength (MPa)** | 53 | 61 |

**Table 2 - Mix design of control and CA concrete**

## 4. Experimental methodology

The methodology used in this research to evaluate the effects of self-healing consists of four stages: first, the creation of controlled damage in the specimens; second, the measure of the recovery of certain properties, such as permeability or crack geometrical parameters; third, the simulation of the conditions or environmental exposure needed to achieve better healing results and, finally, the evaluation of the recovery of the same property measured in the second stage.

### 4.1. Creation of a damage: pre-cracking process

Each cylindrical specimen with dimensions of Φ150x300 mm was cut in half using a circular saw for concrete. In this way, the specimens' size for the permeability test was Φ150x150 mm. The edge faces of each Φ150x150 mm cylinder were then polished in order to eliminate mortar layers (in the bottom surface in contact with the moulds) and asperities (in the top free surface of the specimen as cast).

The specimens were pre-cracked at the age of 2 days, inducing, by means of a splitting test, a controlled damage (Figure 1): this was meant as the width of the diameter crack, which was set to reach a target value, controlled by a calibration

ruler. The measure of the crack width with the calibration ruler while performing the splitting test has been meant as good enough for the purpose of the campaign. As a matter of fact, though it is an approximate way to measure the crack width, it is also very simple and allows a larger amount of specimens to be cracked in a reasonable time. The calibration ruler has an inherent dispersion due to the human factor. Nevertheless it is a good method to obtain crack widths within a range of 0-0.3 mm. If higher precision is needed, however, other methodologies to control the crack width during the splitting test should be used.

**Figure 1 - Pre-cracking process of a concrete specimen**

Once cracked, specimens were kept in the healing exposure to let the self-healing agent to act for a specified period of time. The self-healing effect has been checked by analyzing the concrete permeability of cracked specimens before and after the self-healing process and with the evolution of geometrical parameters of cracks, namely its width and/or area.

### 4.2. Evaluation of properties: permeability test

A method based on the permeability test described in UNE-EN 12390-8 was employed in this study, but measuring the water flow instead of the water depth penetration. To guarantee the impermeability of the specimen lateral surface, the zones of the lateral surface which were in contact with the machine loading platens during the pre-crack splitting tests were sealed with an epoxy resin Sikadur 31-CF as shown in Figure 2. It should be noted that resin does not enter significantly inside the crack, since it is only placed externally.

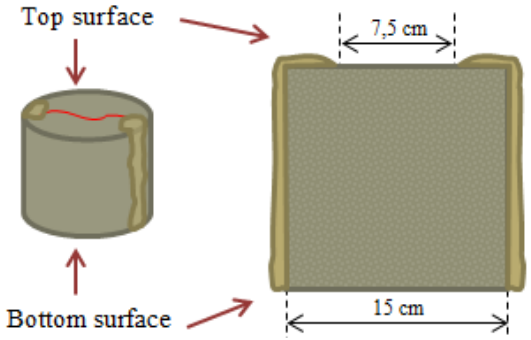



**Figure 2 - Lateral sealing of specimens with Sikadur**

The test was performed by applying a head water pressure equal to 2.00 bars. In practice, the initial pressure is set equal to 2.05 bars and as pressure decreases due to water flow, the permeabilimeter turns on again when a pressure of 1.95 bars is reached, recovering the 2.05 bars pressure. Therefore, water pressure is always kept between 1.95 and 2.05 bars. The quantity of water passing through the crack was measured during a 5 minutes testing time. This procedure results in higher water flows for larger crack widths. In this way, if a crack closes after the healing process, the water flow should have been diminished. The permeabilimeter used in the test and the different parts it consists of it are shown in Figure 3.

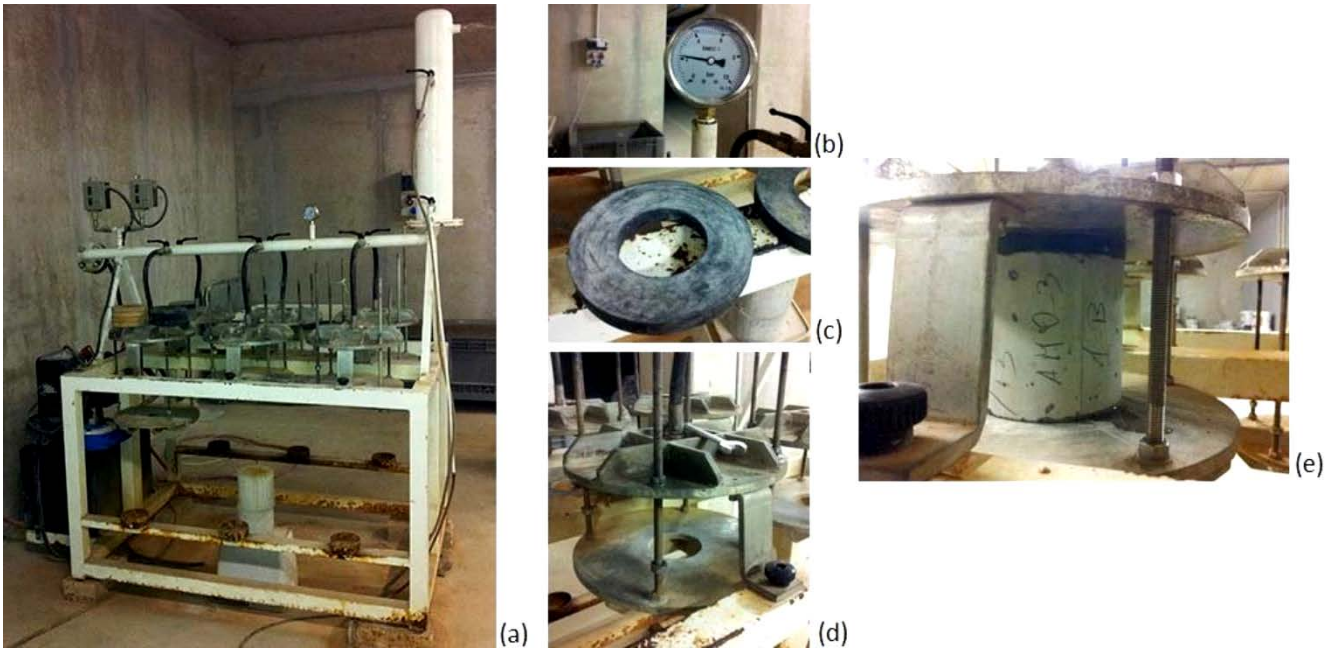



**Figure 3 - Permeabilimeter (a) and its parts: manometer (b), sealing ring (c), auxiliary structure (d), prepared specimen (e)**

### 4.3. Evaluation of properties: study of crack geometrical parameters

In addition, crack geometry parameters (width and area) were also measured to support measurements from permeability tests. The crack width/area measurements are based on the study of composed panorama pictures showing the cracks all along their length; the photography software Adobe Photoshop CS6 was used for image processing. The pictures were taken before and after the healing exposure, with a digital optical microscope (x60, x200). Before taking pictures all the specimens were cleaned with compressed air.

This method is more precise and reliable than the measurements which can be obtained by using the transparent calibration ruler since through the use of the graphical software is possible to choose the real width bypassing the error related to the human eye, which in smaller cracks, as those studied in this research, becomes more relevant.

The measurement of crack geometrical parameter has been performed with a twofold purpose: first, to seek a correlation with the water flow measured in the permeability tests; and, second, to analyze the significance of the evolution of the

same geometrical parameters as indicators of self-healing. To this twofold purpose, the ratios between final and initial values of the water flow and of crack geometrical parameters were calculated. Water permeability is considered the reference value in order to compare the different methods for quantifying self-healing, since the main objective of closing a crack is to avoid the entrance of liquids, contaminants and aggressive agents.

Crack geometrical parameters can be divided in two groups: the measure of crack width and the measure of crack area. The measure of crack width is the most used method to analyze geometrical evolution of cracks, because of its simplicity. However crack area was expected to be a better indicator of the physical closing, because it would include the crack width all along the whole length of the crack. Four crack geometrical parameters were measured in this paper:

- Two measures of crack width:
  - $w_{max}$, maximum crack width: by means of graphic software, the maximum crack width is determined in millimeters.
  - $w_{avg}$, average crack width: by means of graphic software, crack width (in millimeters) is determined in five fixed positions and averaged.
- Two measures of crack area:
  - $A_{est}$, estimated from average crack width $w_{avg}$: using the five measures of crack width and multiplying by their associated lengths, in squared millimeters.
  - $A_{px}$, measuring black pixels: by using graphic software, black pixels in the image are counted, which indicate crack area.

With reference to the measure of the crack width, the maximum width $w_{max}$ was calculated searching the highest value of width all along the whole crack length in the high-resolution panoramas. For instance, the average width $w_{avg}$ was calculated averaging five width measurements, taken at prescribed positions along the crack, thus decreasing the uncertainty of the measurement itself. A grid was prepared to overlap on the panorama pictures, after bringing the grid at the same scale of the picture (Figure 4). Precisely, two grids were used, one for the top cracks and the other for the bottom cracks, because of the different crack length in each surface (7.5 cm in the top crack and 15 cm in the bottom).

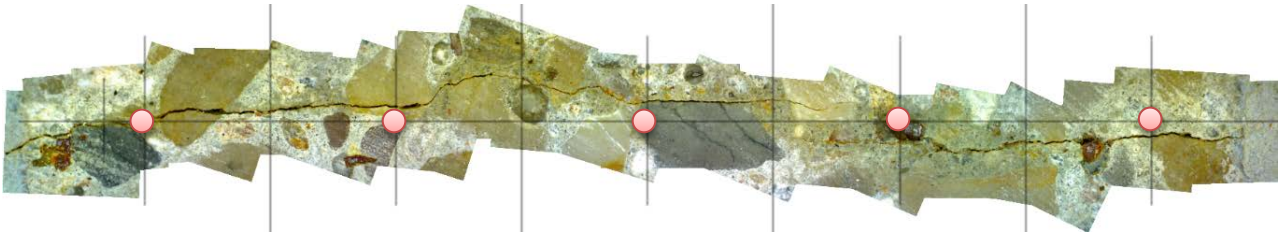


**Figure 4 - Panorama of a top crack and grid marking the measuring points**

The second group consists of the measurement of an averaged crack area and the measure of black pixels in an image. By means of the same approach used to calculate $w_{avg}$, the area of the cracks is estimated by multiplying the five measured widths, in millimeters, by their associated lengths obtaining the area in squared millimeters $A_{est}$. In this way, the resulting area is approximated as the sum of the areas of five rectangles. The second method to calculate the area of the cracks involves the use of the graphical software to quantify the number of black pixels inside the pictures. The basic concept is that the cracks are shown as a black area, thus a higher number of black pixels corresponds to a greater area of the crack. In order to avoid that pores or other dark parts of the pictures affect the quantification of black pixels, all the panoramas were cleaned by a specific tool of the software (Figure 5).

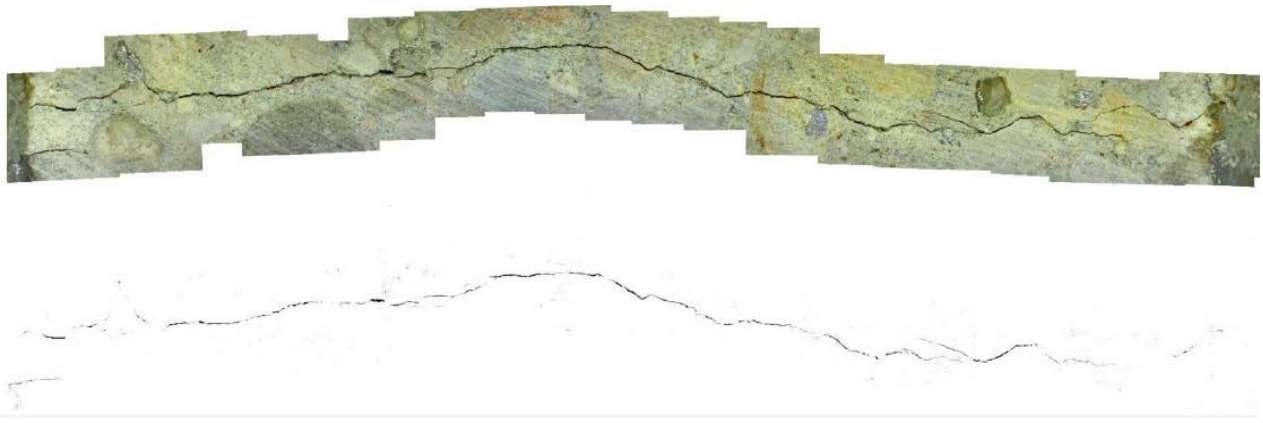


**Figure 5 - Panorama of a top crack and its black pixels (before cleaning).**

Each specimen has got two cracks (top and bottom), denoted according to the orientation of the same specimen in the permeability test, and the water contact exposure. The relationship between water flow and the geometrical crack parameters was studied. In this case, it is expected that a wider crack parameter leads to a bigger water flow result. It has been studied if the geometrical crack parameter that should be considered is the value corresponding to: the top/bottom crack, the maximum/minimum crack or the average of the two cracks.

### 4.4. Exposure simulation

Four environmental exposures were studied in order to determine the effect of humidity on the self-healing capability of the tested specimens, comparing the reference concrete with the crystalline admixture concrete (Figure 6).

a. WI (Water immersion): continuous immersion in tap water at laboratory conditions without renewing the water during the healing period (temperature of water, 15-16ºC)

b. WC (Water contact): a layer of water with a head pressure of 2 cm-water on the top crack, and storage in humidity chamber at 20ºC and 95±5% relative humidity. Additional water was supplied when necessary in order to maintain the 2 cm water layer.

c. HC (Humidity chamber): storage of the specimens inside a standard humidity chamber at 20ºC and 95±5% relative humidity.

d. AE (Air Exposure): storage of the specimens in normal laboratory conditions inside a room without exterior influences.

(a)  (b) 

(c)  (d) 

**Figure 6 - Four exposures: water immersion (a), water contact (b), humidity chamber (c) and air exposure (d)**

Each type of healing exposure has been designed with the objective of simulating real conditions. WI simulates underwater concrete elements; WC simulates situations with a face directly exposed to water with a very low pressure and the other unexposed to it, such as buried walls under the water table; HC simulates concrete elements without direct contact with water but constructed in a high humidity environment and AE concrete elements without direct contact with water and average humidity levels. With these four environmental conditions, it is intended to discern if the self-healing will be powerful enough for constructions in several types of environments as above, including those without direct contact with water and those elements in contact with it, either having a small amount of water in contact or totally immersed.

The specimens immersed in water during the healing period, were divided in two different water recipients, in order to avoid interferences between control concrete and concrete with crystalline admixtures. The immersed specimens were placed on two 3 cm wide wood strips ensuring a separation between specimens of at least 5 cm between the cracked faces and 1 cm between the lateral surfaces, in order to let the water act in the whole specimen.

The setup for the 2 centimeters water contact environment is shown in Figure 7. In this group, water remains in the upper PVC ring and enters inside the specimen through the crack and does not exit from it because of the lower sheets of insulation and wood.

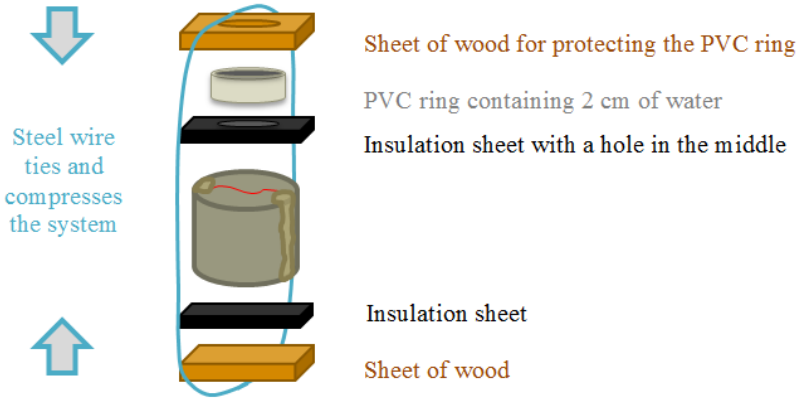



**Figure 7 - Setup of the 2 cm water head exposure**

## 5. Results and discussion

### 5.1. Morphology of healed cracks

Concerning the visual observation of the panoramas, several aspects can be studied in addition to the crack geometry parameters, such as the formation of precipitates inside the crack under different conditions.

As a first and most immediate aspect of the occurred crack sealing, it is worth noticing the whitish formations in control and CA specimens when immersed in water, which can be clearly seen in Figure 8. For specimens conditioned in the "water contact" environment, those white precipitates were only formed on the top face of the specimens, *i.e.*, on the face in direct contact with water. This fact indicates that the transportation of water through the crack with a water head of 2 cm is not enough for ensuring healing of both faces, *i.e.* a complete healing throughout the thickness of the specimen. However, despite the smaller reaction of the bottom crack, specimens stored in WC exposure got fairly good results according to the healing rate achieved.

The formations were located all along the surface of the specimens in contact with water (for WI and WC exposures), not only inside the crack, and were frequently accumulated also in some pores. In some cases, the precipitates were slightly yellowish, which is supposed to be originated by the oxidation of steel fibers.

Another interesting aspect that could be studied through the analysis of the complete crack pattern panoramas is determining whether the healing occurred only when the crack was in the cement paste or if it also occurred when the crack broke through an aggregate or in the paste-aggregate interface. In the specimens with sealed or almost sealed cracks this aspect was analyzed, and it was concluded that most formations were originated in the cement paste: this is logical, because crystalline admixture is dispersed in concrete matrix among with the cement particles. Anyway, it was

also powerful enough to transport the healing products inside small cracked aggregates, which is an indicator of the effectiveness of the self-healing agent.

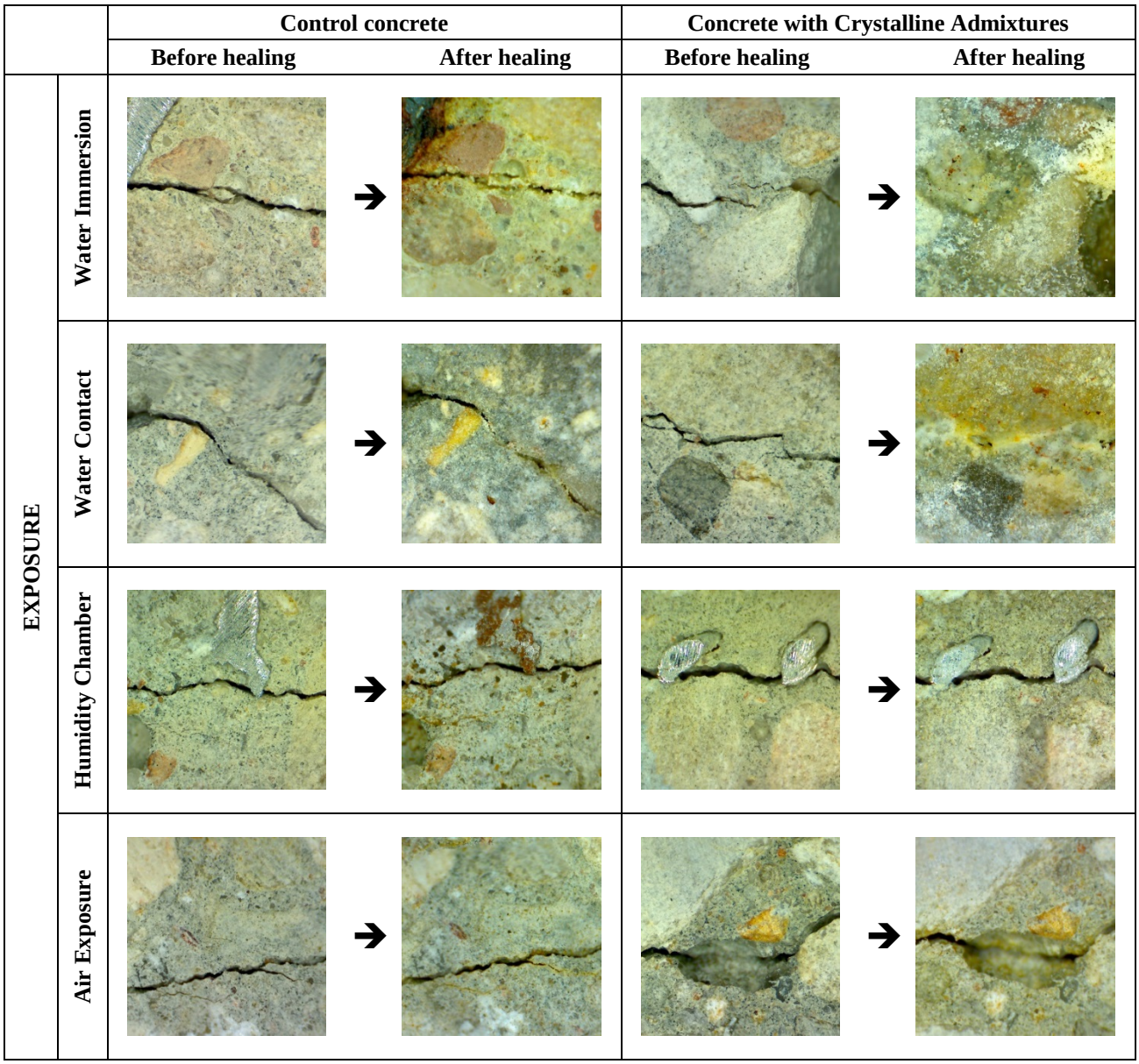



**Figure 8 - Comparison between crack aspect at 0 days and after 42 days of healing, for control and CA specimens exposed to the four environments: water immersion (WI), water contact (WC), humidity chamber (HC) and air exposure (AE).**

### 5.2. Self-healing results: water flow vs. crack geometry parameters

When representing water flow versus the four crack geometry parameters obtained from image analysis of crack pattern panoramas (as detailed in section 4.3), it has to be observed that the best correlations were obtained from the relation between water flow and the $A_{mm}^{2}$ (Figure 9c) and with the averaged crack width $w_{avg}$ (Figure 9a). The chosen trend lines are cubic functions depending on the crack geometry parameter: as explained from the literature, the water flow in a cracked specimen depends on the cube power of the crack width [7]. On the other hand, the correlation between water

flow and $w_{max}$ (Figure 9a) and $A_{px}$ (Figure 9d) were highly dispersed and therefore these crack geometry parameters are proved to be worse indicators of the level of damage of the cracked specimens and the resulting self-healing.

As a matter of fact, it can be observed that the measure of black pixels proved the worst one. There are two possible reasons for this behavior: a) the three-dimensional effect of the interior part of cracks, which makes crack pixels turn grey in the photographs while still being part of the crack; and b) the small interferences of black pixels outside the crack, though they were cleaned for minimizing this effect.

For the two best methods, polynomial cubic trend lines were calculated by applying the boundary conditions of zero flow in correspondence of zero damage and horizontal tangent at zero flow. Adjusted R-squared ($R^2_{adj}$) was used in order to evaluate the goodness of fit of the model.

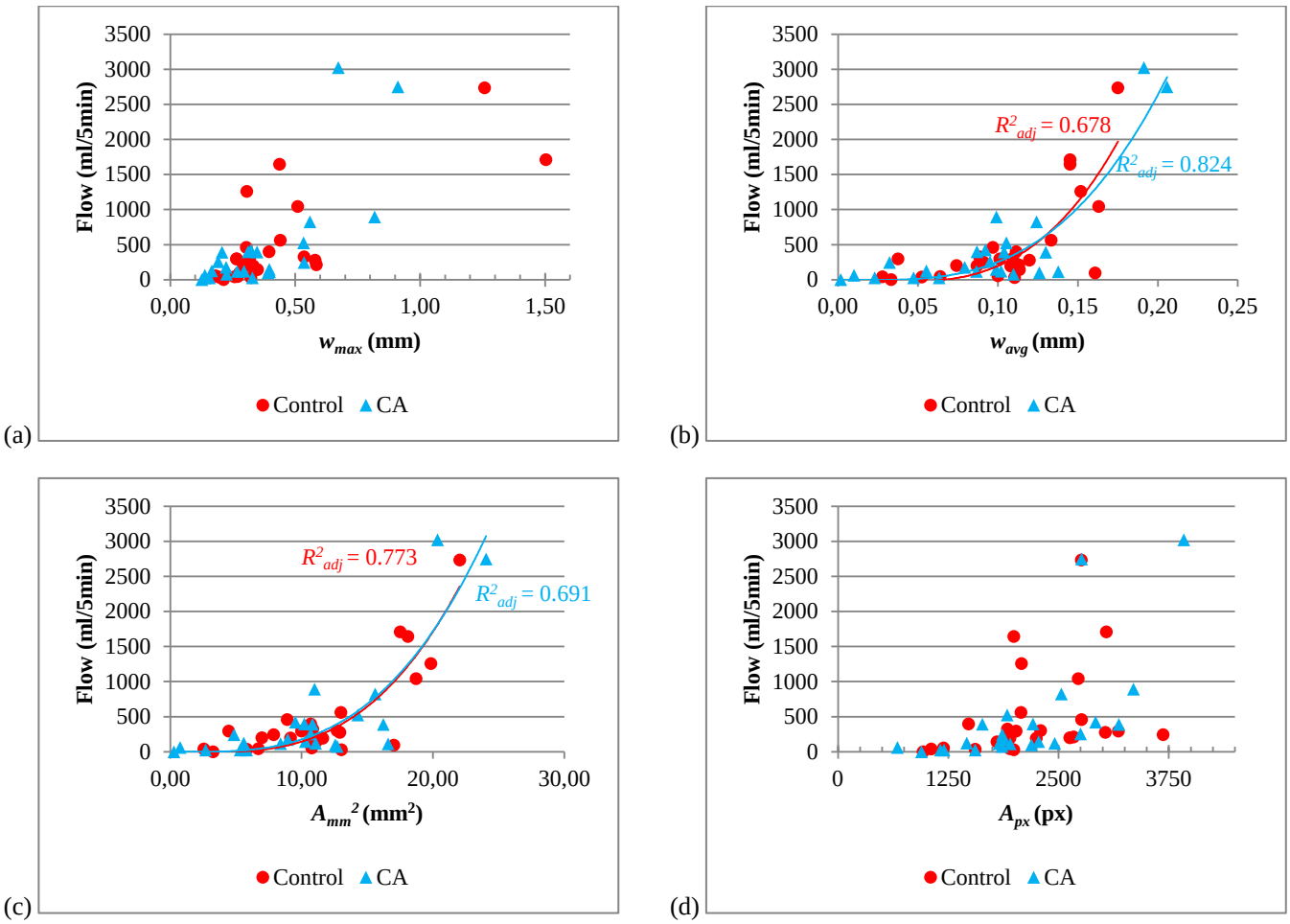
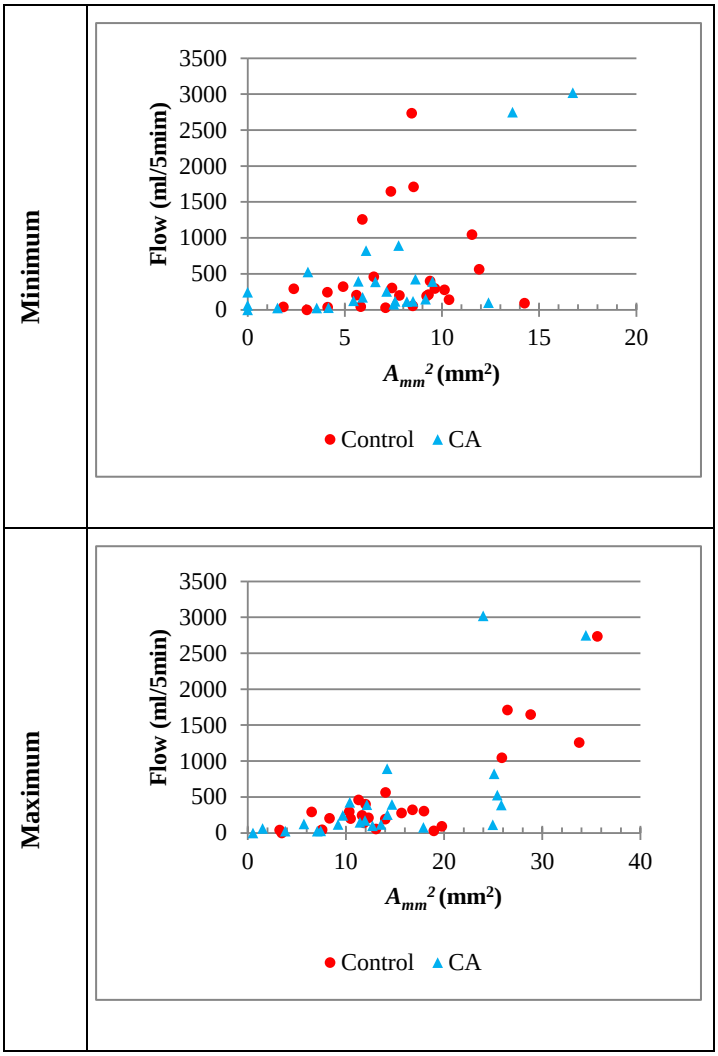



**Figure 9 - Relation between water flow and the geometrical parameters: (a) maximum crack width $w_{max}$, (b) averaged crack width $w_{avg}$, (c) estimated crack area $A_{mm}{}^2$, (d) amount of black pixels $A_{px}$**

It is important to remark that in each specimen two cracks were formed, on the top and the bottom surface. When choosing the value of the crack geometry parameter in order to study its relation with water flow, several options could be considered: the value of the parameter for the top/bottom crack, the minimum or the maximum, the average value, etc.

The minimum crack and the averaged crack were expected to be the best parameters in order to represent the damage comparing with the permeability results, the first option because the minimum section may restrict water flow and the latter because it is an estimation of the 3D volume of the crack considering it as a pyramidal frustum. The results in Figure 9 were represented using the averaged result from both top and bottom surface cracks. Other relations were also analyzed and they showed notably worse results, as it can be seen in Figure 10 for the cases of choosing the minimum, maximum and averaged value of cracks, for one of the best parameters, $A_{mm}^2$. Choosing the top or the bottom crack as parameter did not showed any stable trend. Very similar results were achieved when analyzing the averaged crack width parameter $w_{avg}$. Thus, it can be assumed from the results in Figure 10 show that the averaged crack geometry parameter is the parameter that performs better.



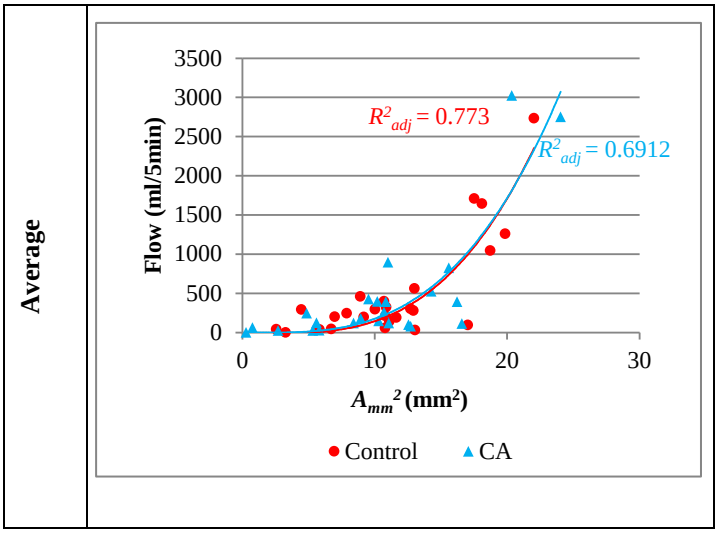
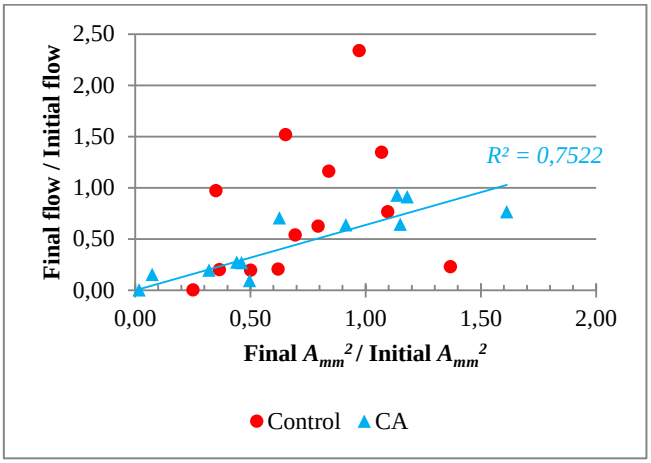



**Figure 10 - Initial water flow versus minimum, maximum and averaged estimated crack area $A_{mm}^2$**

The results of the relationship between the obtained ratios of final and initial water flow and the ratios from the final and initial values of the crack geometry parameters (averaged from the top and bottom cracks for each specimen) can be seen in the graphs in Figure 11. As expected higher water flow ratios correspond to higher crack geometry parameter ratios. Control specimens got significantly high dispersion while CA group showed a highly linear behavior for both methodologies of evaluating the crack geometry.

(a)




(b)

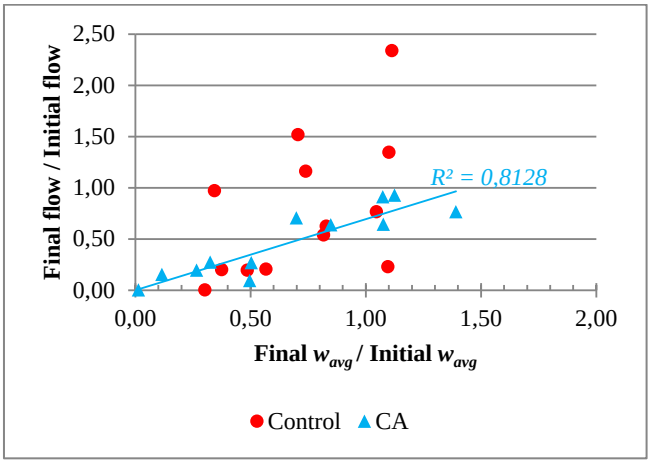



**Figure 11 - Relation between water flowratio and estimated crack area $A_{mm}^2$ ratio (a) and water flow ratio and averaged crack width $w_{avg}$ ratio (b)**

The dispersion obtained in the results of this research could be caused by healing in different points of the interior of the crack since crystallization could start easily in the zones with lower crack width. Figure 12 represents a simplification of some of the possible interior morphologies of a crack in a concrete specimen, and the points that might be more suitable in order to start the precipitation of crack healing products. If the morphology of the crack is a concave volume, the interior of the crack may be healing while the visible crack would stay immutable, which could distort the calculated ratios and affecting the results.

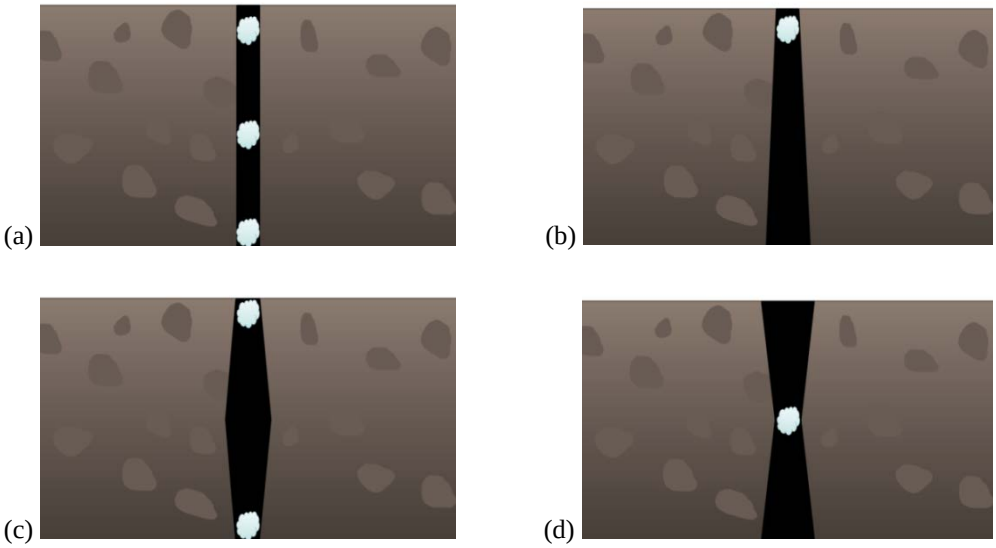



**Figure 12 - Simplification of different possibilities for crack geometry in depth: uniform crack, pyramidal frustum, convex and concave forms and their most feasible points for precipitates**

In few words, comparing the previous results of the crack geometry parameters obtained from image analysis of crack pattern panoramas, it can be said that the measurements that most closely reflect the self-healing as evaluated by means of permeability recovery are the measure of crack area, averaged from crack width measured at different locations, ($A_{mm}^2$) and the averaged crack width ($w_{avg}$), as they minimize the dispersion. The dispersion in the correlation relationships between the healing ratio by permeability and healing ratio by crack geometry parameters could be caused by self-healing taking place inside a crack but not on the surface of the specimen, where the crack geometry parameters are measured.

### 5.3. Self-healing results: permeability

The self-healing properties based in the evolution of permeability are evaluated by means of the healing rate, which is defined as:

$$Healing\ Rate = 1 - \frac{Final\ Flow}{Initial\ Flow} = 1 - \frac{Q_{42}}{Q_0}$$

With:

$Q_0$ the initial water flow

$Q_{42}$ the final water flow for a healing time of 42 days

When the final flow is similar to the initial flow, the healing rate would tend to 0; and when the final flow is 0, the healing rate would be 1. Negative values of the healing rate would show a reopening of the crack. The healing produced depending on the initial level of damage can be analyzed by representing the healing rates obtained for each specimen versus its initial water flow.

The specimens immersed in water (Figure 13a) and in contact with 2 cm of water layer (WC, Figure 13b) achieved higher healing rates. The exposure which showed the best healing behavior was water immersion, in which crystalline admixture specimens showed slightly better behavior than the control group. The importance of the presence of water for the self-healing reactions is proved. Nevertheless, the specimens stored in humidity chamber (Figure 13c) and in laboratory conditions (Figure 13d) showed lower results, with healing rate values generally lower than 0.5. It is worth noting that a more stable self-healing rate was achieved for specimens made with concrete containing the crystalline admixture (CA) than for control specimens, which show high dispersion as the amount of available water is reduced.

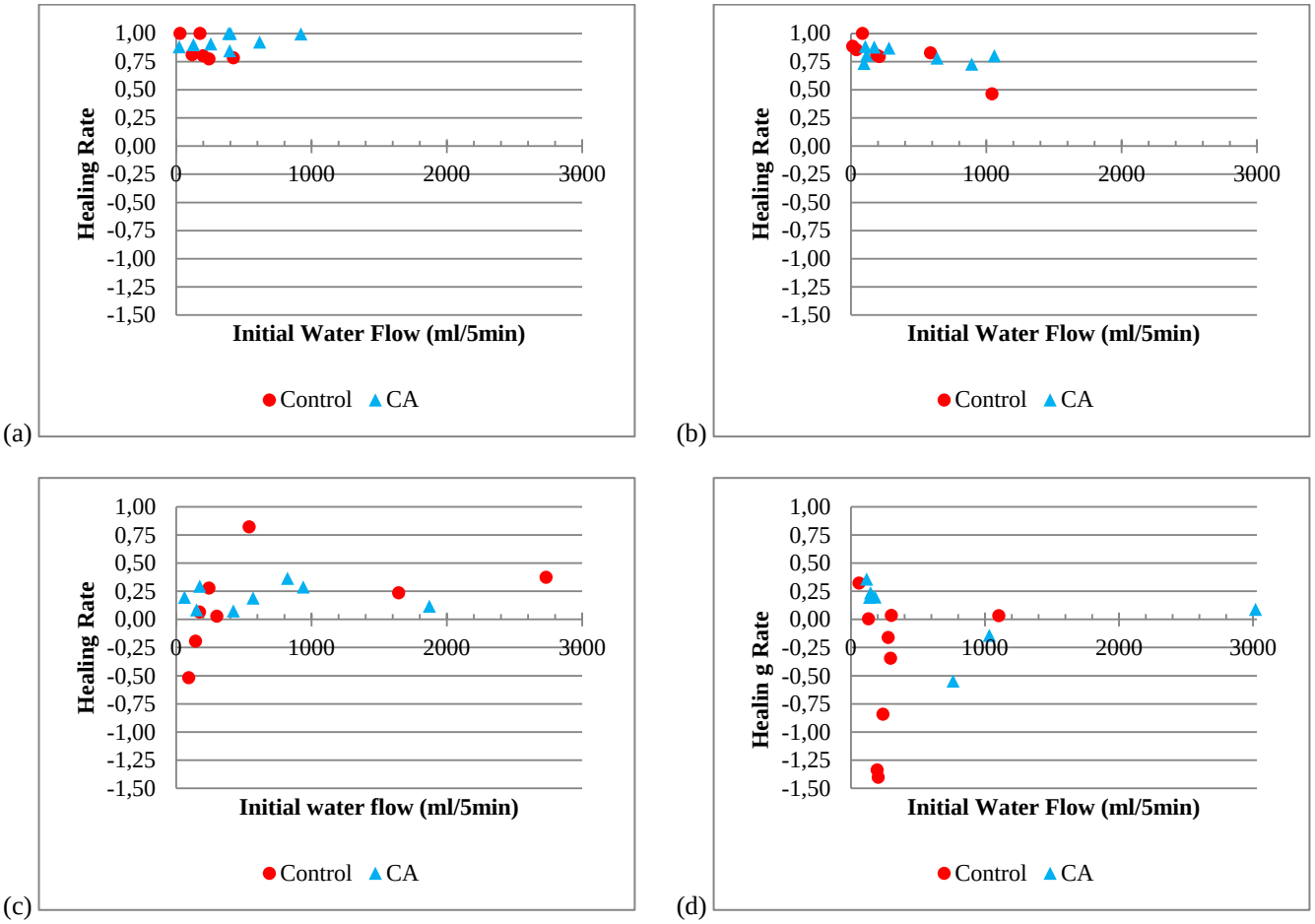



**Figure 13 - Control and CA concrete in the four exposures: water immersion (a), water contact (b), humidity chamber (c) and air exposure (d)**

In detail, specimens immersed in water showed values of healing rate between 0.75 and 1, those from the CA group showing higher values. For specimens in WC exposure there is a clear overlapping between the control and CA groups. In the HC group, control specimens showed higher dispersion, even reaching negative values of healing rate. It should be noted that in the group of laboratory exposure conditions, AE, there are several specimens with negative healing rates as well. This particular behavior can be caused by shrinkage, as specimens are young and the exposure has not enough humidity to compensate for the water loss, making the crack width even larger.

The same results, but classified depending on the type of mixture, are shown in Figure 14a (for control concrete) and Figure 14b (for CA concrete).

In the case of control specimens (Figure 14a), the results show a high dispersion. However, a clear tendency of better healing rates when increasing the available water can be observed. Moreover, no notable differences were observed between the specimens immersed in water immersion and those in water contact conditions.

On the other hand, for CA concrete (Figure 14b), the results can be clearly gathered in two groups: those in direct contact with water, either immersed or with a moderate head pressure, and those exposed to air humidity, either controlled or natural. Again, the more water available for the specimen, the higher healing rate is achieved. In the case of crystalline admixtures concrete, the results are clearly concentrated around the values of 0.93 for WI, 0.81 for WC; 0.21 for HC and 0.17 for AE. This remarks the need of direct contact with water for the self-healing reactions to occur.

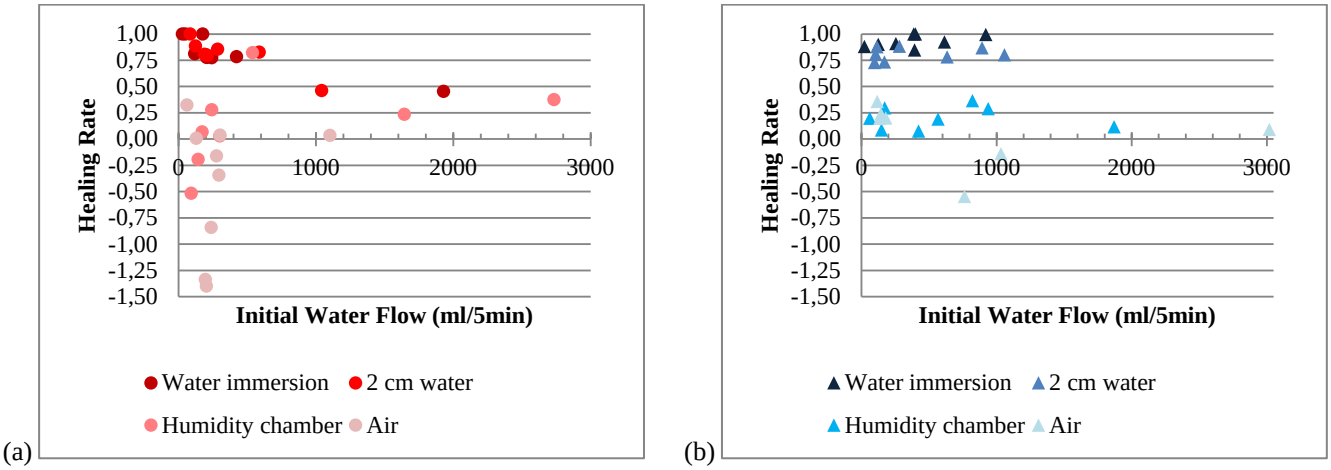



**Figure 14 - Behaviour of control concrete (a) and CA concrete (b) for the four different exposures**

Averaging the results of healing rates for the specimens with an initial water flow lower than 1000 milliliters per 5 minutes (Figure 15), it can be clearly seen that the groups with higher healing rates are the groups with direct contact with water (WI and WC). In contrast, the specimens in humidity chamber showed a slightly better result with CA than for control concrete, but there is a significant difference with the previous groups. It can be hence argued that natural environmental humidity is not enough for complete self-healing to take place, even when using CA. However, it should be noted that when exposed to an environment with a lower humidity there is a big difference between the specimens made with concrete containing the crystalline admixture and the control concrete specimens. This is most likely due to drying shrinkage: in humidity chamber (HC) the water loss would be compensated, but not in the laboratory conditions (AE). In this case, the CA would act as a shrinkage compensator and the cracks, even if not healed, would at least be kept from growing.

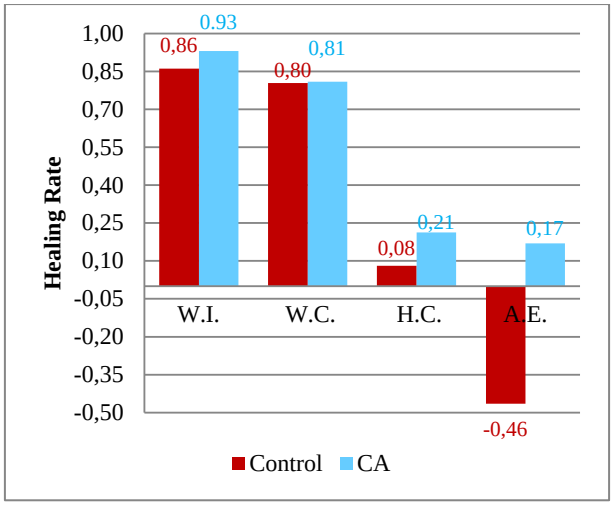



**Figure 15 - Averaged Healing Rate for each group**

## 5.4. Discussion

Edvardsen proposed a model based on Poiseuille Law [4], which is expressed in equation (1), for water at 20ºC, viscosity $v=\eta/\rho$=1.00 mm$^2$/s) and a visible crack length of 1 meter; where $q_0$ is the water flow per meter length of crack, I is the hydraulic gradient in meters of water head per meter, $w_{avg}$ is the mean value of crack width and $k_t$ is a correcting parameter for temperature.

$$q_0\left(\frac{liters}{m}\right) = 740 * I * w_{avg}^3 * k_t \qquad (1)$$

This expression can be adjusted to the parameters of the present research by changing units and the length of the crack (considered as 75 mm), resulting in the expression (2).

$$Q\ (liters) = 740 * \frac{20}{0.15} * w_{avg}^3 * 1 * 0.075 \qquad (2)$$

The obtained experimental results of water flow and averaged crack width in this research (shown previously in Figure 9) fit reasonably well in the theoretical predictions given by equation (2) as displayed in Figure 16. The lower values obtained in this research might be due to the presence of fibers which could help blocking water flow inside the crack.

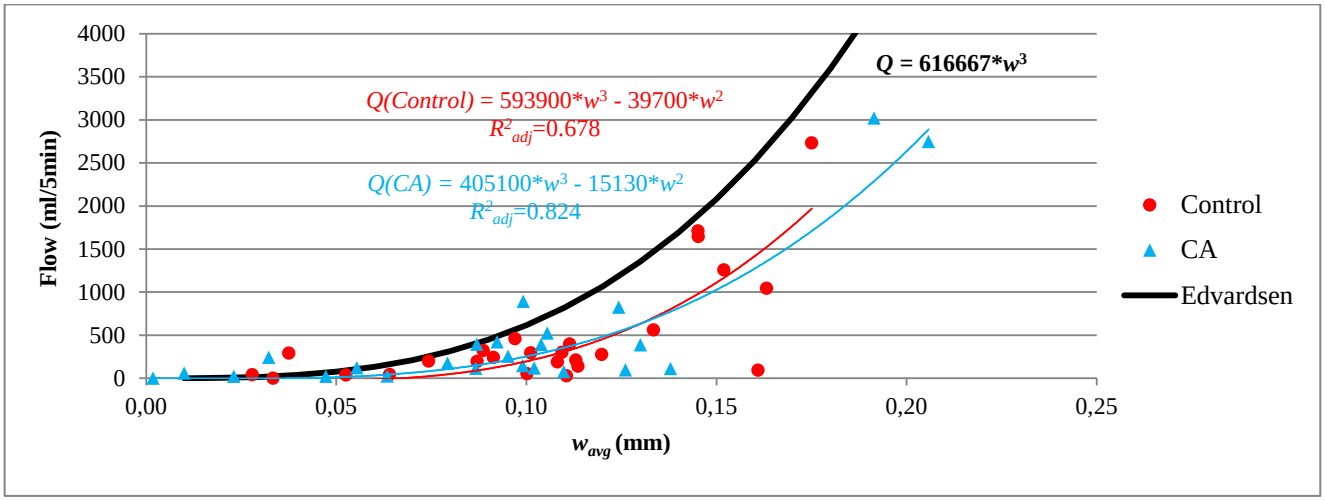


**Figure 16 - Comparison between experimental and theoretical water flow and crack width results**

With reference to the healing rates, similar values have been registered by other authors for permeability properties [16], mechanical parameters or [19][20] closure of crack width [16][18] for specimens under water immersion exposure, with values of effectiveness usually around 90% of recovery, or even higher. The enhancement of effectiveness by crystalline admixtures specimens under water immersion comparing with results of control specimens has been also confirmed by other studies [19], with results similar to those obtained in this work, increasing the healing capability about 7-10% with respect to control concrete. The higher results of specimens from both groups (control and CA) under water immersion WI compared to indoor or air exposure AE specimens obtained in this work are similar to those obtained studying the recovery of mechanical properties in other studies [20].

## 6. Conclusions

This paper has presented the results of a research comparing different methodologies for quantifying the self-healing capacity of fiber reinforced concrete and the effectiveness of crystalline admixtures as self-healing agent in four different environmental exposures.

The following conclusions can be drawn from the obtained results:

With reference to the test methodology and to the parameters adopted to define and quantify the healing process rate:

1. Self-Healing Rate, calculated from the results of the modified permeability test designed in this research, is a reliable indicator of the recovery of durability properties. The evaluation of permeability is, as a whole, the best methodology in order to evaluate the damage in a concrete specimen.
2. The crack geometry parameters evaluated through image analysis have a clear relation with the water flow results when comparing flow with the averaged crack area or the averaged crack width. This indicates that the two aforementioned crack geometry parameters can be considered as alternative to water permeability measurement tests. However, when correlating flow rates and crack geometry parameters in order to evaluate the outcomes of self-healing processes, the dispersion is always higher for control specimens.
3. Still with reference to crack geometry parameters, the quantification of crack area through measurement of black pixels of a crack panorama was the method which resulted in the highest dispersion of the values, probably because of the three-dimensional effect of the depth of the cracks.

With reference to the influence of concrete composition and exposure conditions:

4. Self-healing process has been confirmed for both cases: autogenous healing of control concrete and healing caused by crystalline admixtures reactions.

5. Specimens cast with concrete containing crystalline admixtures and stored under water immersion achieved the highest self-healing rates, with values around 95% even for the larger initial crack width. Specimens with crystalline admixtures showed a more stable and reliable behavior in healing tests showing lower dispersion and clearer trends.
6. The presence of water is critical for the self-healing to take place for both reference concrete and crystalline admixture concrete, leading to self-healing rates above 80-90% respectively. The two exposures with direct contact of water had significantly higher healing rates than those under different values of air humidity, confirming the need of water for the reaction.
7. The presence of a layer of 2 cm of water in one crack is enough to make the self-healing rate to increase to levels of 80%, with low differences between both types of concrete.

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