ANALYSIS OF THE INFLUENCE OF MINERAL ADDITIONS ON THE PROPERTIES OF SELF-HEALING CONCRETE

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The sustainability of buildings represents one of the biggest problems in the civil engineering industry from the point of view of global economy and ecology. The construction of structures requires a lot of energy and non-renewable resources that generate large amounts of CO_2 during their production, as well as high costs for the construction process itself. Annually, 2.5 tons of concrete are produced per person, and it is known that the main component in concrete is Portland cement. The process of obtaining the cement clinker results in the release of 1 ton of CO_2 for every ton of clinker produced if the calcination emissions and the fuel required for the rotary kiln are taken into account. Taking into account the fact that in 2022 4.1×10^9 tons of cement were produced and the CO_2 emissions from that cement were about 3×10^9 tons, which is assumed to be 5 - 7% of the total CO_2 emissions.

The current solution to this problem is to design structures with a longer lifespan, which is often overestimated due to the lack of maintenance of the structures, which leads to a shorter lifespan of the structures, and which ultimately leads to the need for new structures and thus new input energy and resource. The reason for this accelerated degradation of the structures is the biggest "enemy" of concrete, namely the cracks that are an inevitable part of it. The problem with cracks is that they represent a "shortcut" for aggressive agents that penetrates in the concrete and lead to the corrosion of the reinforcement, thus reducing the load-bearing capacity of the structure.

In such cases, the ability of concrete to heal its own cracks represents a huge opportunity in the field of sustainability of structures, meaning that the structure made of such concrete has an increased lifespan and increased sustainability of the structure. It is for these reasons that in this paper the possibility of self-healing of different concrete mixes will be experimentally investigated and their self-healing efficiency will be determined by monitoring different key parameters and conducting several tests.

Keywords: self-healing; concrete; cracks; durability

1. INTRODUCTION

Reinforced concrete structures often suffer from the problem of cracking, which leads to earlier degradation of properties than that predicted by the design life of the structure. The current practice responds to this problem by designing structures with a much higher quality, which means a higher initial cost of the structure. In addition to higher quality, an extensive and complex program for inspection and maintenance of the structures is also required, which is often very difficult and expensive due to the inaccessibility of some of the structures.

It is precisely for this kind of problem that it is necessary to develop a technology that can detect damage to the structure itself and at the same time repair that damage itself. If we are talking specifically about reinforced concrete structures, there is a possibility of applying technology that can detect the appearance of cracks in the concrete itself and heal them. Incorporating such technology into reinforced concrete raises the material to the level of smart materials.

2. DEFINITION OF SELF-HEALING

The field of self-healing is being researched my multiple world-renowned institutions, each with its own set of definitions for self-healing itself. In this paper the definitions were adopted from The International Union of Laboratories and Experts in Construction Materials, Systems and Structures “RILEM”.

Self-healing is a process that occurs in a material that results in its properties returning to a certain level and thereby improving the material's performance after they have been reduced by a previous action.

Autogenous self-healing is defined when the self-healing process is performed with components of the mixture that would otherwise be present in the material but not specifically intended for self-healing.

Autonomous self-healing is defined when the self-healing process is performed with components of the mixture that would not otherwise be present in the material, i.e., they are added specifically intended for the self-healing process.

Crack sealing is when the properties that affect durability or improve weather resistance (such as permeability) are restored.

Crack healing is when the properties that affect the strength properties are restored, i.e. they improve resistance to mechanical influences (mechanical properties).

3. MECHANISMS OF AUTOGENIOUS SELF-HEALING

As a result of theoretical approaches and experimental procedures, it was concluded that autogenous self-healing is the result of a complex interplay of physical, chemical and mechanical mechanisms within the cement matrix shown in Figure 1. In practice, it is difficult to achieve crack healing with only one of these mechanisms, but it is often possible to observe which of them is the dominant mechanism and what this is due to.

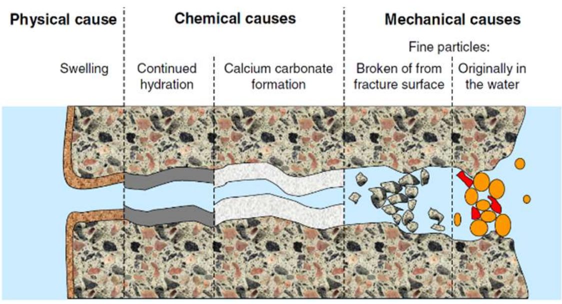

Figure 1. Mechanisms of autogenous self-healing.

The mechanisms can be separated in three groups: physical, chemical and mechanical.

The most dominant physical mechanism is swelling of concrete when the crack surfaces is in contact with the water, it should be noted that this mechanism is theoretically reversable.

There are two dominant chemical mechanisms: continued hydration and formation of $CaCO_3$. When the crack surfaces are in contact with the water, the un-hydrated cement particles start the hydration process and produce C-S-H gel that has bigger volume than the cement particles and seals the crack. Calcium carbonate ($CaCO_3$) forms when calcium hydroxide ($Ca(OH)_2$) which is a product from hydration, reacts with carbon dioxide (CO_2) in the presence of water (H_2O), so the calcium carbonate particles than latch onto the walls of the crack.

The mechanical mechanism represents a blockage of the crack with particles from the crack walls or from the water. This type of healing is unpredictable and is reversible.

4. EXPERIMENTAL REASERCH OF SELF-HEALING CONCRETE

4.1 MIX DESINGS

For the purposes of this experiment, a total of three concrete mix designs were made, all three of which were made with CEM I 52.5R. The first sample was with only cement as a binder, without materials that replace cement, i.e. sample R1. In the second sample 16% of the cement was replaced with mechanically activated fly ash, i.e. sample R1LP16HK1, while in the third sample 10% of the cement was replaced with finely ground dolomite, i.e. sample R1D10HK1. The corresponding mix designs are given in Table 1.

Table 1. Mix design of samples with CEM I 52.5R

Mix design	CEM I 52.5R	Water	Aggregate	Fly ash	Dolomite	Hidrofob Kristal	PP Fiber	Super-plasticizer
R1	360 kg	200 kg	1840 kg	/	/	/	12 kg	5.40 l
R1LP16HK1	302.40 kg	200 kg	1840 kg	57.60 kg	/	3.60 kg	12 kg	5.40 l
R1D10HK1	324 kg	200 kg	1840 kg	/	36 kg	3.60 kg	12 kg	5.40 l

All samples have a superplasticizer with a dosage of 1.5% in relation to cement in order to increase the workability of the concrete. Due to the need to open a crack and keep the crack opening stable in all samples, without causing failure of the concrete samples, polypropylene (PP) fibers with a length of 50 mm were added with a dosage of 0.5% in relation to the weight of the concrete. A water-cement factor of 0.55 was maintained in all mix designs. To increase the efficiency of self-healing in all samples except in the standard sample R1 a crystal-forming additive Hidrofob Kristal (ADING) was added with a dosage of 1% in relation to cement. In order to maintain the same amount of Hidrofob Kristal and superplasticizer, the initial amount of cement, i.e. 360 kg, was always taken when calculating the dosage. Each sample consists of twelve test specimens, namely nine prisms with dimensions 10/10/40 cm and three cubes with sides of 15 cm.

Figure 2. Test examples.

4.2 EXPERIMENT COURSE

After casting the specimens according to the mix design, ultrasonic pulse velocity (UPV) was measured longitudinally and transversely of the specimen at age of 7 and 28 days. At age of 28 days the mechanical i.e. compressive strength and bending strength of the concrete were determined in accordance with the standards MKC EN 12390-3:2019 and MKC EN 14651+A1:2010 respectively.

After 28 days of age a crack was created in six of nine specimens, the UPV was measured again to see the effect of the crack and also the crack width was measured with digital microscope camera. After that three of the cracked specimens were fully submerged in water to promote self-healing. During this period at 2, 7 and 28 days after submerging the crack width was measured in the same places as before. After 28 days of treatment the specimens were removed from the water and are dried for 7 days to a constant weight, then the UPS was measured to determine the effect of the self-healing.

Following these, all nine specimens were coated with epoxy resin except a surface of 10x5 cm on the bottom of the specimen and the specimens were submerged in water for a depth of 2 ± 0.5 cm to achieve capillary water absorption according to standard MKC EN 13057:2009. The weight of the capillary absorbed water was controlled after 15 min, 30 min, 1h, 2h, 4h, 8h and 24h. This data was used to determine the efficiency of self-healing.

4.3 METHODS OF DETERMINING THE EFFICIENCY OF SELF-HEALING

One of the main challenges in the field of self-healing concrete is the lack of standardization, which hinders the advancement of research to a higher level. This has resulted in a variety of experimental approaches and the use of different self-healing indices to quantify healing efficiency, often leading to inconsistent results and conclusions in literature. The general approach adopted by researchers involves testing a physical or mechanical property of the concrete before and after crack healing. By comparing these stages—the premises are expressed as a percentage or self-healing index—the healing efficiency is determined. In the following only those relevant to this paper will be presented.

When self-healing is monitored via optical microscopy, crack width can be measured from processed images. The healing efficiency is quantified using the Crack Closure Index (ICS), defined as:

$$ICS = \frac{w_{pre-healing} - w_{post-healing}}{w_{pre-healing}} \quad (1)$$

where $w_{pre-healing}$ is the crack width before treatment, and $w_{post-healing}$ is the crack width after treatment.

Similarly, the Self-Healing Index (ISH) can be applied when healing efficiency is evaluated through a capillary absorption test. In this case, the parameter of interest is the amount of water absorbed through specimens with unhealed cracks and specimens with healed cracks. The index is then calculated as:

$$ISH_{sorptivity} = \frac{S_{crack.,unhealed} - S_{crack.,heale}}{S_{crack.,unhealed}} \quad (2)$$

where $S_{cracked}$ is the sorption coefficient of unhealed specimens and S_{healed} corresponds to healed specimens.

5. TEST RESULTS

5.1 MECHANICAL PROPERTIES

5.1.1 Compressive strength

Compressive strength was tested on cubes with a side of 15 cm, according to the standard MKC EN 12390-3:2019 at an age of 28 days, as shown in Figure 3.

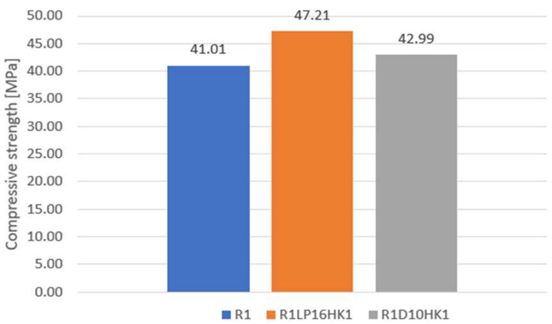

Figure 3. Compressive strength of specimens.

The results show that the sample with mechanically activated fly ash has the highest compressive strength, as the finer particle size increases reactivity compared to ordinary fly ash. The strengths of the cement-only sample and the one with dolomite are similar. It is also evident that the crystal-forming additive does not reduce compressive strength, which is an important property.

5.1.2 Bending strength

The bending strength was tested on prisms with dimensions of 10/10/40 cm, using a three-point flexure test, according to the standard MKC EN 14651+A1:2010 at an age of 28 days. The results are shown on Figure 4.

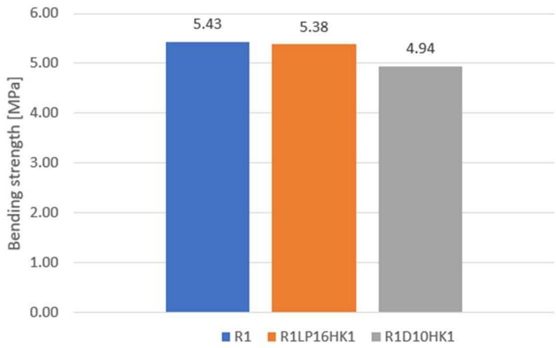

Figure 4. Bending strength of specimen.

The results show that the sample with only cement and the one with fly ash have the same flexural tensile strength, while the sample with dolomite shows slightly lower values but still within the same range, indicating that the type of additive does not significantly affect flexural tensile strength.

5.2 ULTRASONIC PULSE VELOCITY

A total of 531 measurements were carried out on nine prisms and three cubes from three concrete mix designs. Only the characteristic results relevant for drawing conclusions are presented below. The UPV for the specimens in three states: 28 days age before crack, 28 days age after crack and after 28 days treatment as shown in Figure 5.

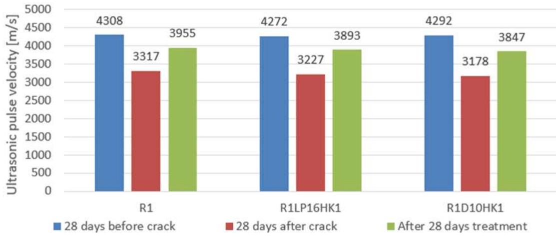

Figure 5. UPV in three states measured longitudinally.

The same results can be shown on a graph for a better representation as shown in Figure 6.

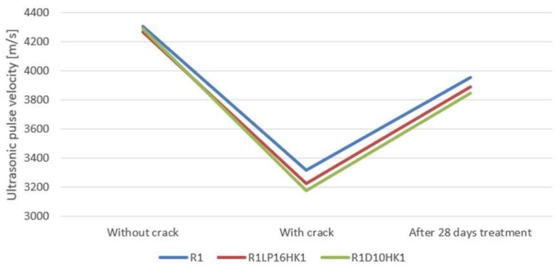

Figure 6. UPV in three states measured longitudinally.

From the results, it can be concluded that there is a clear trend of decreasing direct wave propagation velocities after the appearance of a crack, followed by a partial recovery to the range of reference values (before cracking) after 28 days of treatment.

In the next graph as shown in Figure 7, a correlation is made between the measured crack width with ultrasonic pulse velocity, before and after treatment of the specimens. The data for the crack width is taken from Figure 8.

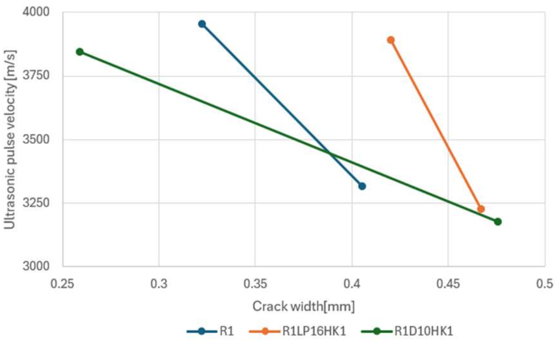

Figure 7. Correlation of UPV in longitudinal direction with the crack width before and after treatment.

The presented results clearly show the correlation between crack width and ultrasonic pulse velocity through the specimen, as the crack width decreases due to self-healing, the ultrasonic velocity increases.

5.3 MICROSCOPIC MONITORING

The self-healing process was also monitored on the surface with a microscope camera at six measurement points on three sides of the prism.

In Figure 8 the average healed and unhealed crack width is shown. The crack width is measured on three prisms that were under treatment, before and after the treatment on the bottom side of the prism in two points (K5 and K6).

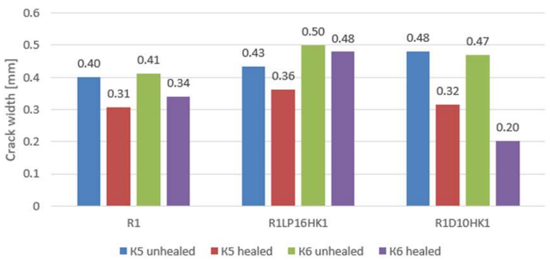

Figure 8. Measured crack width before and after treatment.

The graph shows the self-healing of the crack in every mix design and on both measuring points, but due to the localized effect of crack sealing this type of data cannot be used to determine the efficiency of the self-healing.

5.4 CAPILLARY ABSORPTION

Three uncracked specimens, three specimens with an unhealed crack, and three specimens with a healed crack were coated with two layers of epoxy on the entire bottom surface and up to half of the side surfaces, leaving an uncoated area of 5 × 10 cm on the bottom side. This uncoated part was designated for water absorption and where the crack is located.

The procedure for testing capillary water absorption followed the standard MKC EN 13057:2009 ,with slight modifications regarding specimen geometry and immersion depth. All prisms were placed inside a closed container of water on spacers, so that there was a gap between them and the bottom of the container, allowing free circulation of water. The immersion depth was 2.0 ± 0.5 cm. At intervals of 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours, and 24 hours, the masses of the prisms were measured, and the amount of absorbed water was calculated over time.

Water uptake per unit area (kg/m^2) was calculated as:

$$i = \frac{W}{A} \tag{3}$$

where W is the absorbed water (kg) over a given time interval and A is the exposed surface area (m²).

The sorption coefficient (S) was determined as the slope of the linear relationship between *i* (kg/m^2) and the square root of immersion time ($h^{0.5}$). One of the graphs is shown on Figure 9.

Self-healing efficiency (*SE*, %) was quantified by comparing cracked–unhealed and cracked–healed sorption coefficients, using:

$$SE = \frac{S_{crack.,unhealed} - S_{crack.,heale}}{S_{crack.,unhealed}} \tag{4}$$

where $S_{cracked}$ is the sorption coefficient of unhealed specimens and S_{healed} corresponds to healed specimens.

With such measurements, the entire self-healing process can be quantified, allowing a clearer evaluation of the effect of different mineral additives on self-healing, as well as the possibility to compare them with each other.

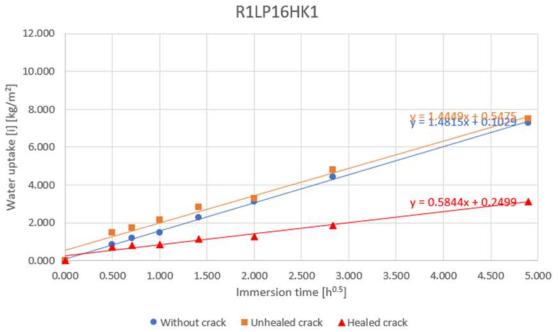

Figure 9. Capillary absorption of samples from R1LP16HK1 mix design.

Based on this and all other graphs, summary results are shown on Figure 10 for all mix designs.

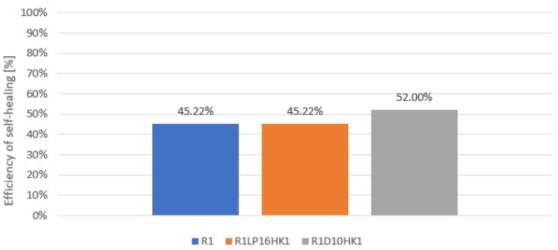

Figure 10. Summary results on self-healing efficiency.

The results indicate that self-healing also occurred in mix design R1 without mineral additions or crystalline admixtures. For mix design R1LP16HK1, the same level of self-healing efficiency as in R1 was observed, due to the short treatment period of 28 days. For mix design R1D10HK1, the highest self-healing efficiency was observed after 28 days of treatment.

6. SUMMARY

This study evaluated the influence of mineral additions (fly ash, dolomite) and a crystalline admixture on the mechanical behaviour, ultrasonic pulse velocity, and self-healing efficiency of concrete. The results showed that mineral additions and the crystalline admixture had little effect on flexural tensile strength, while the highest compressive strength was achieved in the mix with fly ash (R1LP16HK1) due to its increased reactivity, followed by R1 and R1D10HK1, the latter influenced by the expansive behaviour of MgO from dolomite hydration. The crystalline admixture itself had no significant effect on mechanical properties.

Ultrasonic testing confirmed the presence of self-healing, with an initial decrease in velocity after cracking and a subsequent recovery after 28 days of water treatment, consistent with crack filling.

Microscopic monitoring revealed localized deposition of healing products. However, capillary absorption testing quantified healing efficiency: the highest value (52.0%) was recorded for the dolomite mix (R1D10HK1), due to the high calcium ion availability from CaO and the effect of the crystalline admixture. The reference mix (R1) also showed considerable efficiency (45.2%), attributed to un-hydrated cement and calcium hydroxide, while the fly ash mix (R1LP16HK1) showed comparable, though slower developing, healing due to the delayed pozzolanic reaction.

Overall, the results demonstrate that self-healing occurs in all mixes, with efficiency depending on the type of mineral additive and available calcium sources. Longer curing periods are recommended to better assess the continued effect of fly ash and crystalline additives over time.

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