Kaunas University of Technology

CIVIL ENGINEERING AND ARCHITECTURE FACULTY

Physical and mechanical investigations of self-healing concrete after healed cracks

Master's Final Degree Project

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Supervisor

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Monzer Saleh

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Declaration of Academic Integrity

I confirm that the final project of mine, Monzer Saleh, on the topic „ Physical and mechanical investigations of self-healing concrete after healed cracks "is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarised from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this project.

I fully and completely understand that any discovery of any manifestations/case/facts of dishonesty inevitably results in me incurring a penalty according to the procedure(s) effective at Kaunas University of Technology.

____________________________ __________________

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Monzer Saleh. Savaime atsinaujinančio betono fizikiniai-mechaniniai tyrimai po plyšių užsitaisymo. Magistro baigiamasis projektas vadovas doc. dr. Algirdas Augonis; Kauno technologijos universitetas, statybos ir architektūros fakultetas.

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Kaunas, 2019 m. 63 p.

Santrauka

Betonas yra labai svarbi statybinė medžiaga, kuri yra esminė viešosios infrastruktūros ir daugumos pastatų dalis. Vis dėl to, mikro ir makro įtrūkimai betone kelia rimtą grėsmę jo stiprumui ir ilgaamžiškumui. Taip atsitinka dėl vandens ir drėgmės prasiskverbimo per plyšius, kas gali sukelti armatūros koroziją.

Siekiant preventyviai kovoti su šitomis betono problemomis, šiais laikais galima padidinti betono atsparumą dėl mikro ir makro pleišėjimo, į jo mišinio sudėtį pridedant kristalinių priedų arba bakterijų, kas leidžia savaime užtaisyti betono plyšius.

Šiame darbe yra tyrinėjama kristalinių priedų įtaka betono fizikinėms ir mechaninėms savybėms, taip pat betono savaiminio atsinaujinimo efektas naudojant vamzdžių metodą, stiprumo atsinaujinimas, savaiminio užsitaisymo galimybių ribos ir plyšių dydžiai, kurie gali užsitaisyti dėl šių priedų.

Monzer Saleh. Physical and mechanical investigations of self-healing concrete after healed cracks. Master's final project, supervisor, Algirdas Augonis; Civil engineering and architecture faculty, Kaunas University of Technology.

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Summary

Concrete is a vital building material that is an absolutely essential component of public infrastructure and most buildings. Macro and micro cracks form a serious threat on concrete strength therefore on construction lifetime. Due water penetration and humidity that seek through this crack to steel reinforcement and cause its corrosion.

To handle this threat a major important is given nowadays to improve resistance of concrete for this micro and macro crack by adding crystalline additives or bacteria to concrete mixture that can self-heal these concrete cracks.

In our work are studying the influent of crystalline additives on physical and mechanical properties of concrete, also the effect of healing using pipe method, strength recovery, limit of healing process and the dimension of crack that could be healed in the presence of this additives.

Task.

Actuality of research work.

Nowadays, the world is experiencing the creation and the use of special crystalline additive and bacteria which may lead to a self-healing concrete. A concrete that could weld the opened cracks itself once it will be in contact with water. This new property can increase the durability of concrete and extend its life time.

Research Objectives:

- Self-healing concrete and its properties

Main task:

To form the self-healing concrete with crystalline additive, create the special methodic to measure the efficiency of filling the cracks and examine the might of the concrete to recover strength.

The tasks:

- Analyses the studies and the research on self-healing and its properties.
- forming self-healing concrete specimens and measuring the physical and mechanical properties.
- To use and found new methods of measuring self-healing effects on cracks.
- To cast self-healing concrete cubes and prisms and investigate the possibility of recovering compressive and flexural strength.

Introduction:

In Lithuania as in the rest of the world at current time, more attention is given to possibilities to increase exploitation time of concrete construction and service life of all building. In all the world many constructions became problematic because of concrete cracks. This factor decreases concrete durability dramatically. The concrete erosion at the damaged areas in structures or cracks occurs more rapidly, because of water absorption from the environment, so the concrete and reinforcement corrosion speeds up. So, it is important for concrete to be watertight and to have no cracks, but the latter often occurs during exploitation due to the destructive environmental affect or/and mechanical loads. Through these cracks water transfers chemical elements, dissolves minerals and forms new compounds. Therefore, durability of the structures such as dams, reservoirs, parking lots or concrete floors can be reduced due to the effect of water. Diffusion of water vapor in concrete causes various problems. Kinetics of moister penetration, for example in the ground-floor, is variable event and highly depends on environment temperature. Constructional, groundwater, hydroscopic, condensational and exploitational humidity has an effect on this sort of structures. Moister kinetics in concrete depends on the raw material composition, newly formed structure (pore type, distribution and type of occurring cracks) and the exploitation environment.

On purpose to eliminate latter damages and improve production quality it is rational to use new type crystal additive or bacteria, which reacts with minerals occurring during hydration of cement and forms stable crystals, filling resident micro and macro cracks in the entire volume of sample and, most importantly, concrete self-heals. While crystal additive is filling capillaries, it minimizes structures water absorption, increases significantly water tightness, frost resistance, and concrete structure will be possibly more resistant to chemical effect i.e. it will be more durable by all aspects. According technical literature in Fig.1 it can be seen that self-healing concrete lets to increase building service life compared to traditional concrete

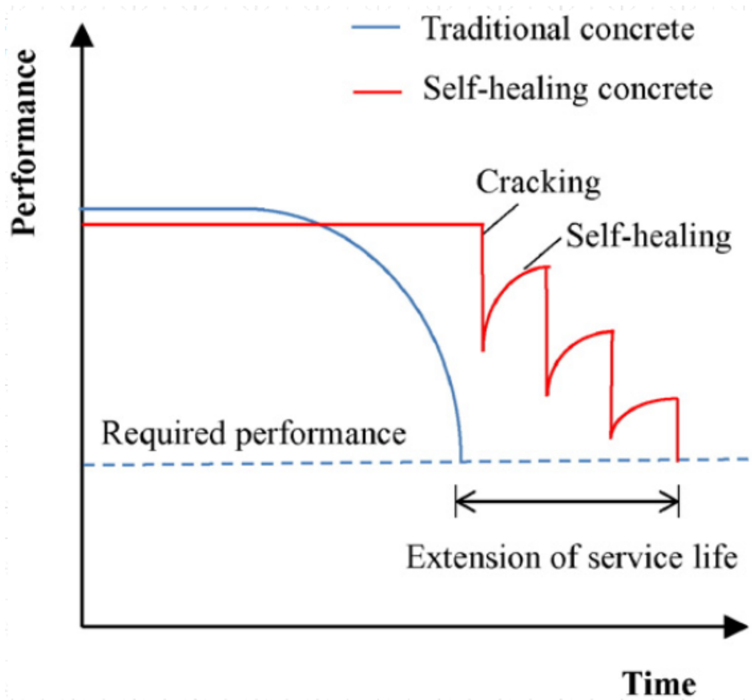


Figure 1: Self-healing effect on exploitation time of concrete construction

The main goal of this investigation – perform scientific research properly designing and investigating compatibility of crystal additive with locally used materials and evaluating influence of fresh and hardened concrete properties. Studying the recovery option of compressive and flexural strength.

Literature summary:

Approaches to Self-Healing

According to the approaches originated from self-healing of polymer [1]. We can classify self-healing concrete in three groups: intrinsic healing, capsule based healing and vascular healing. We found difference in the mechanism of each approach to achieve their goals in healing.

Intrinsic Self-Healing

Intrinsic self-healing is also divided in three categories: autogenous healing, improved autogenous healing and reaction of the polymeric substances inside polymer modified concrete. Which they all in general consist on the cement matrix. [2]

1-Autogenous Healing

Consist on healing mechanisms: hydration of anhydrous cement particles and dissolution and subsequent carbonation of$Ca(OH)_2$. At the time of cracking the age of concrete determines which mechanism is better. For young concrete the first mechanism is used due to the high amount of anhydrous cement particles, and the other will be the major mechanism for later age. For both mechanism water is essential. Autogenous healing is capable of healing cracks that's width 5 to 10 µm, 50 µm. In order to have more efficiency in healing we should make faces of cracks in contact by using compressive forces. [3;25;26]

2-Improved Autogenous Healing

In case of restricting cracks width autogenous healing is more effective. In this section we will list the mechanism of improving autogenous healing as: restriction of the crack width, water supply and improved hydration and crystallization. [4;27;28]

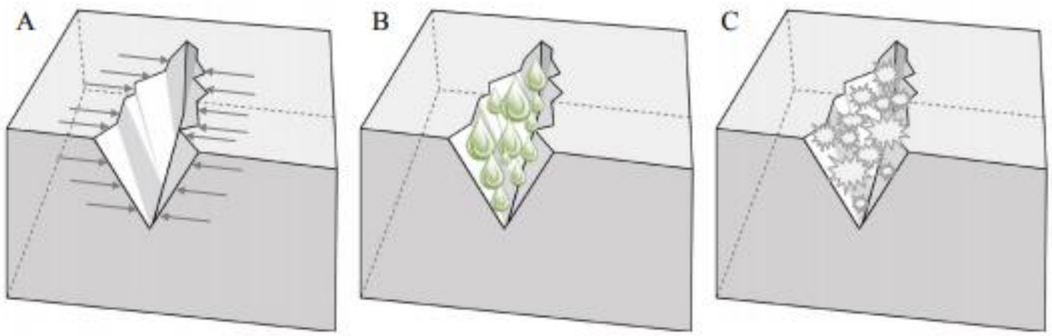


Figure 2 : Categories of Intrinsic self-healing [18]

Restriction of the Crack Width

On purpose to promote autogenous healing (ECC) fiber reinforced strain hardening engineered cementitious composite were used to restrict width. After that polyethylene(PE), poly vinyl alcohol (PVA) and steel cord (SC) fibers were used. (PVA) was more efficient in healing then the others specially (SC) and because corrosion of steel show less healing. The Hydroxyl attached to fiber structure catch the calcium ions which lead to the deposition of crystallization products. In case of usage of (PVA) with embedded tube contains healing agent, cracks with width higher than 200µm were perfectly healed because of the reaction of the agent with silica, in case of cracks with width lower than that, this mechanism is not efficient. [5;29]

Water Supply

This mechanism is based on providing water supply by adding hydrogels or super absorbent polymers(SAP) to the concrete mixture. SAP form insoluble gel by swelling and absorbing big amount of liquid, swelling capacity depend on the ionic concentration and the alkalinity of the solution therefore it reduces swelling when mixing with fresh concrete. After hardening, SAP release the absorbed water which conducts to the formation of small macro-pores and that reduces the strength of concrete. After the formation of cracks, water and the moisture seeking through, the water leads SAP to swell again and expand beyond the pore and physically blocked the cracks. Studies were made to modify the properties of swelling and made it work only in low PH values therefore stop swelling during the mixing of concrete where PH is 13. [6;7]

Hydration and Crystallization

Consist on adding agent which forms crystals and depose it in the cracks. Many attempts are made, one of them is replacing part of cement by fly ash which remains anhydrous, and due to their hydration later they promote autogenous healing. Other attempt is by using expansive agent such as calcium sulfa aluminates, which create crystals and filled the crack. But due to the notification of micro-cracks caused by the expansive reaction it's better to encapsulate the agents.

The best attempt was by replacing 10% of cement by expansive agents which expand with water, geo-materials which swell and chemical agents which precipitate crystals and close the cracks. Other researchers propose the usage of bacterial spores that we will explain later. [8;30]

Healing in Polymer Modified Concrete(PMC)

This mechanism consists on dissolution of organic polymers in the water mixed with concrete which film through concrete and heals in same way of traditional healing. Also healing can be occurred after long period because polymer react like membrane seals concrete and kept anhydrous cement in the matrix. One of these polymers was unhardened epoxy, which in contact with alkalis and hydroxide ions inside cracks hardened and healing occur. Another agent is ethylene vinyl acetate (EVA) a copolymer, which melt in the crack after heating specimens for 150 °C melt in the crack and fill it. [9;31]

Capsule Based Self-Healing

This process based on keeping healing agent inside capsules. Damaging the capsule trigged the self-healing mechanism, contact with moisture or air lunch the reaction of some agent, while other are lunched by contact with the cement matrix or another component present in the matrix. Capsules may have different shapes: spherical or cylindric…

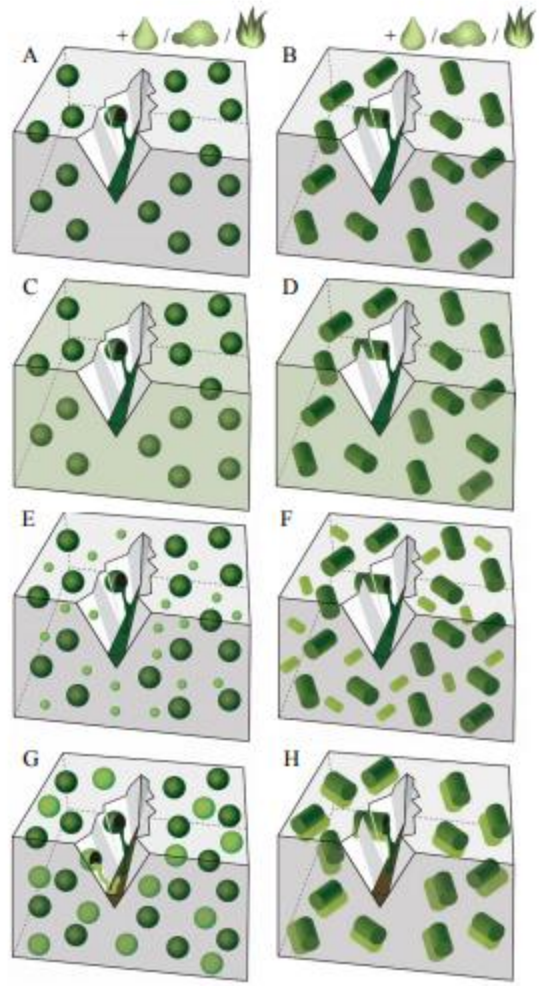


Figure 3: Capsular based self-healing [18]

Reaction due to Moisture, Air or Heat

For this approach, we can find many examples done by several researchers which contained numerous healing agents and several shape and material of capsules. First example is the usage of spherical microcapsules with gelatin shell contained tung oil or $Ca(OH)_2$. Result shows that many capsules were destroyed during mixing but the capsules which survived got ripped by the action of crack therefore the tung oil hardened because of their contact with air or $CaCO_3$ was formed by the reaction between $Ca(OH)_2$ and CO_2. Another example is using cylindrical capsules covered with wax contains methyl methacrylate(MMA), this example need the heat to melt the wax after crack appears so that (MMA) released and cured the crack. On that we add the example of cylindrical glass capsules contains cyanoacrylate (CA) which also cured in contact of air. [10;32]

Reaction with the Cementitious Matrix

This approach consists of the usage of expanded clay containing bacterial spores and calcium lactate as a nutrient. After the cracks appears the clay breaks, and its content healed it by precipitation of $CaCO_3$. Other researchers used sodium silicate solution which reacts with $Ca(OH)_2$and form calcium silicate hydrate and healing occur. [11]

Reaction with Second Component Present in Matrix

This approach consists on using healing agents inside the capsule which react after cracks occurs with another agent embedded in the matrix and cause repairing. For example, bisphenol-F epoxy unhardened used in spherical microcapsules, and a hardener embedded in the cement matrix after cracks appear and the capsule is broken, epoxy seeks in the crack and reacts with the hardener and cure the cracks. Also, this approach can be done by using tow type of capsules and tow type of agents which react together. [12;33]

Vascular Based Self-Healing

The healing mechanism is fulfilling by using the network of hollow tubes connecting the interior and the exterior of the structure and contains healing agents. This can be either by one channel or multi-channel vascular system.

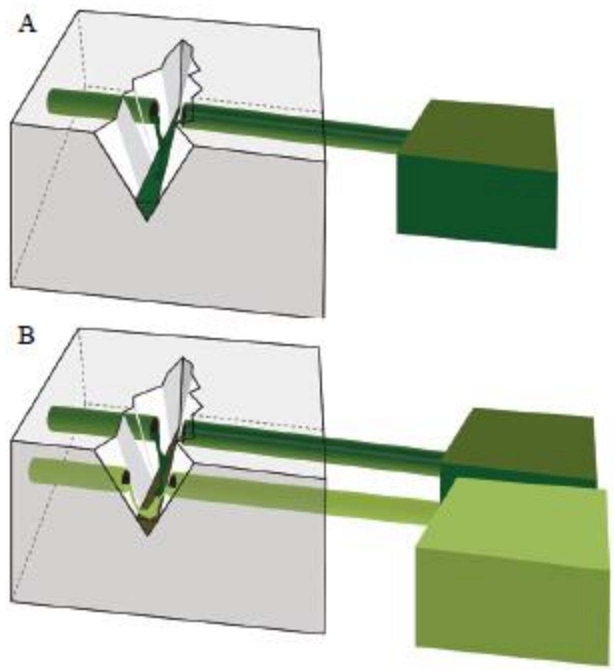


Figure 4: Vascular based self-healing [18]

One Channel Vascular System

Like the other, this approach consists of usage of healing agent, but it differs by using glass tubes to provide this agent in case of cracks. CA an air-curing agent is used, when cracks occurred the tube will be depleted and the agent leek and hardened in the crack. An additional agent is added by the end of the tube that should be opened and more healing could happen. Results show that this process can heal cracks up to 0.3mm. To accomplish this process we need human intervention, to avoid that, we can place tanks filled with the agent at a higher level connected to the tubes and provide healing agent where ever its need. [13;34]

Multiple Channel Vascular System

This approach is based on polymerization reaction resulted from tow agent provided by two glass tubes each one connected to a different tank. One tank contains epoxy and the second another agent. The procedure began after cracking, agent released because of the broken pipe and the healing occurred. [14;35]

Efficiency of Different Types of Healing Agents

Usually, Portland cement, water and other filling materials (sand, gravel…) are what concrete is made of. One month is the duration of the process of hardening after mixing with water, because the cement hydrates with water, the inevitable feature of ordinary concrete is micro-cracks, because of the tensile strength. The tensile strength increases when there are a lot of temperature differences. These micro-cracks reduce the durability of the concrete structure.

In ordinary concrete, this crack may be able to heal them self. After the hardens of the mixture, the non-reacting concrete molecule reacts with water that enters because of the cracks. That will cause the production of limestone which is able to heal cracks up to 0.20mm of width, but this process will be impossible if the cracks are larger. Recently in experiments the crystalline additives, bacterial spores, nutrients and calcium lactate have been used as self -healing agents. Concrete after adding healing agents is called self-healing concrete. There are several useable bacteria which can be added to the concrete. [15;36]

The Bacillus alkali nitrulicus: it is an alkali resistant soil bacterium which lives in extreme alkaline circumstances, in a temperature that range between 10 and 40 degrees Celsius and a ph. values range between 9 to 11.

A psychrophilic bacterium: As same as the bacillus alkali nutilicus, this bacterium lives in extreme circumstances, with a ph. that range between 9 to 11 but in a favorable temperature for living nigh to freezing point.

This healing bacteria can be added to the mixture as capsules. After the occurrence of the cracks, the water infiltrate inside and causes the activation of the bacteria that is created as spores while the living conditions were unfavorable. After the activation, the bacteria will start to react with nutrient and calcium lactate. This reaction can lead to the production of a limestone which will fill the cracks up to 0,80 mm. then the living condition will be unfovorable agian and it will reshape as spores. [16]

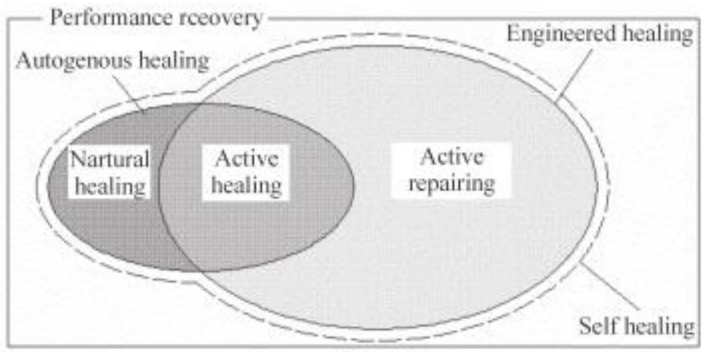


Figure 5: major types of self-healing [19]

The self-healing is divided to three major types: natural healing, active healing and active repairing. Water is the key element for the healing process in the first two division. The healing takes place as the precipitated CaCO3 or newly formed CSH. As well as the mineral additives are added to the mixture by following the same way of the bacteria process. After the occurrence of the cracks and hardening, the penetration of water especially in underground environment causes a physical-chemical reaction that produces CaCO3 and/or CSH and fill in the cracks until it close. [20;21;22]

There are three categories of additives classified to achieve autogenous heal so far according to the mechanism of healing: permeation-crystallization, expansion associated with crystalline effect and pozzolanic reaction.

The first category of additive provides CO_3^{2-} That react with Ca^{2+} found within environment to produce $CaCO_3$ that crystallize within the water and heal the crack. The other two categories consist on the growth by volume of the chemical shaped or by pozzolanic hydration. So a creation of hydration that heal the crack can be the result.

the acceleration of the process of healing is related to the understanding of the healing mechanism which is assessed by the characteristics of mortar specimens (elastic modulus, water permeability, compressive strength...). As time passed, several developments of the process of autogenously healing are achieved, the recent is the process of replacing a part of cement by mineral additives which is one of the categories mentioned above. The understanding of the healing process is related to the studying of the products that heal the cracks.

Therefor we have two major self-healing concrete process that depend the first on bacteria and the second on crystallin additives, which we are going to explain here after. [23;24]

Bacterial self-healing

Bacillus subtilis(JC3)

Bacillus subtilis is a gram-positive bacterium

It is easily grown in labs for minimum cost.

It is a non-pathogenic bacterium,

it doesn't harm humans (safe for use).

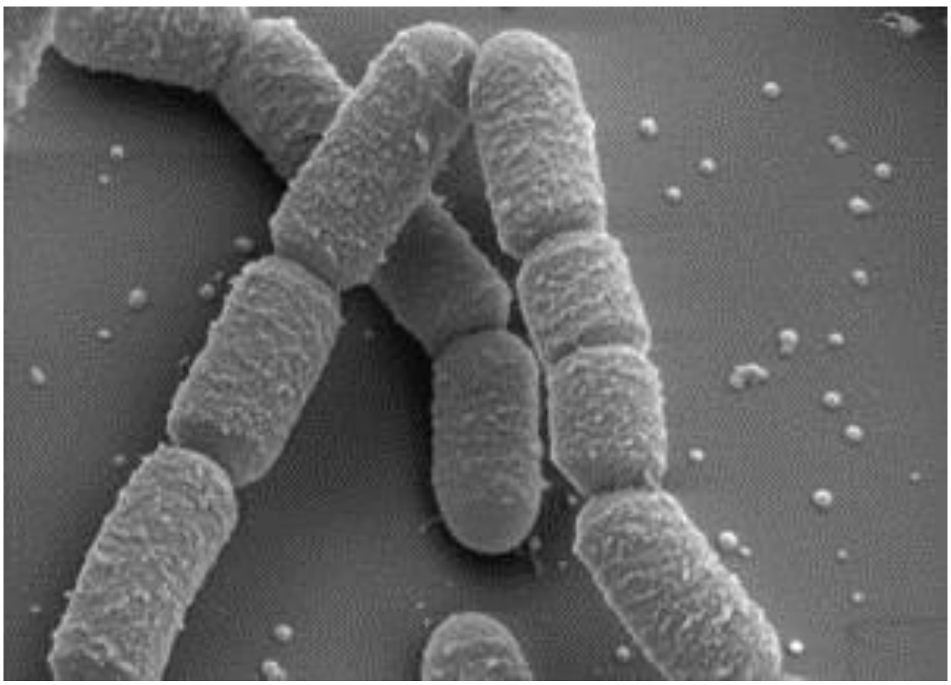


Figure 6: Bacillus subtilis [16]

Cracks meditation

Imitating seeds, after mixing the concrete the bacteria get into the dormant state. To activate their function, the bacteria strongly needs an exposure, therefore any crack would supply the initiation of it. Once the cracks are created, the shut bacteria need to precipitate calcite crystal. The broken concrete due to cracks permit water to seep through, this process is critical for the spore of bacteria to germinate. The calcium lactate from its basic nutrient once the bacteria is activated.

This kind of bacteria can remain robust up to 200 years waiting for an appropriate environment to germinate due to their thick cell wall.

During this phenomenon, the bacteria consume all the oxygen and the insoluble limestone which is converted from soluble calcium lactate. This solidification process on the surface lead to sealing the cracks. [17]

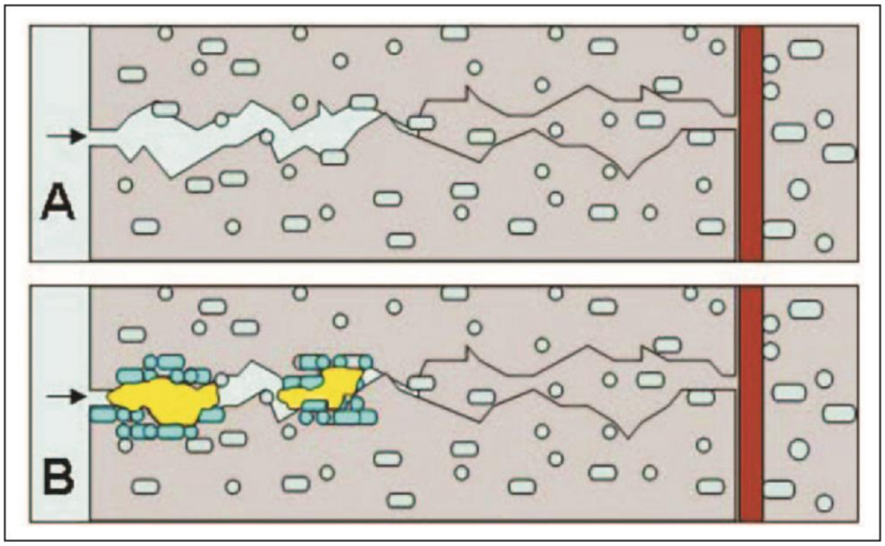


Figure 7: Crack sealing [16]

Oxygen consumption

the activation of the bacteria plays a vital role in increasing the durability of steel reinforced concrete construction that is due to the consumption of the oxygen which is an important element for corrosion. We tend to add that the concrete which contains bacteria have higher strength regain and a lower chloride and water penetration. So, we can declare that the bacteria are the key component in the self-healing process whether it is wise enough to understand that the task is accomplished, especially the alkaliphilic spore-forming bacteria. [16]

Chemistry of the process

Due to negative charge of cell surface, the microorganisms draw cations from the environment and let deposit on cell surface such as Ca^{2+}as shown in the equation. That help bacteria to act as nucleation site, which conduct to the precipitation of calcite that is going to plug the concrete cracks. B subtilus produces urea, which react as part of the process and produce $CO_2$and ammonia, that increase the PH of the environment surrounding and helped the precipitation of $CO_3^{2-}$and Ca^{2+} as $CaCO_3$. The process of healing continues by expansion of the calcium carbonate crystals until filling the entire gapes. The chemical reaction below explains the process. [16]

$$Ca^{+2} + cell \longrightarrow cell\text{-}Ca^{+2}$$

$$cell\text{-} Ca^{+2} + CO_3^{-2} \longrightarrow CaCo_3$$

Experimental program

The aim of the present experiment is to obtain specific experimental data, lead us to understand the crack healing performance of Bacterial concrete and its characteristics. This experimental program can be divided into four phases:

Phase1: Culture and Growth of Bacillus subtilus

Phase2: Evaluation of compressive strength

Phase3: Evaluation of Durability

Phase4: Microscopic analysis of CaCo3 precipitation in Bacterial concrete specimens

Materials Used

The following are the details of the materials used in the investigation:

Cement: Ordinary Portland cement available in local market is used in the investigation. The cement used has been tested for various properties as per IS:4031-1988 and found to be confirming to various specifications of IS: 12269-1987 having specific gravity of 3.0.

Fine Aggregate: Locally available clean, well-graded, natural river sand having fineness modulus of 2.89 was used as fine aggregate.

Coarse Aggregate: Crushed granite angular aggregate of size 20 monomial size from local source with specific gravity of 2.7 was used as coarse aggregate.

Water: Locally available potable water is used.

Microorganisms: Bacillus subtilis JC3**,** a model laboratory Soil bacterium which is cultured and grown was used.

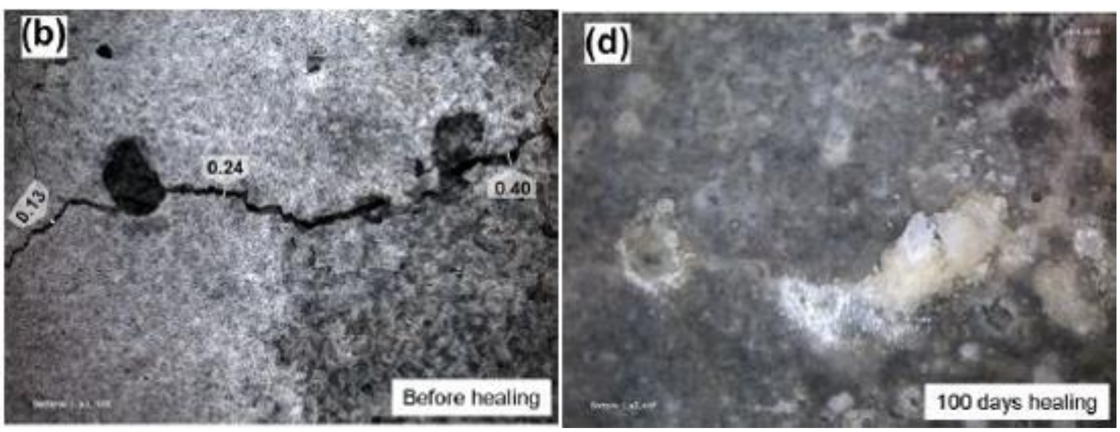


Figure 8: Crack before and after healing [16]

In table 1 we can find the result of testing the compressive strength of specimens containing a different concentration of Bacillus subtilus measured after 3days, 7days and 28 days of mixing. The highest improvement occurs in specimens with concentration 10^5cells/ml for all ages which reach 16.5% at 28 days. This improvement is due to the chemical process explained before which allows to the microorganism cell to react and plug the pores. After healing it is expected that the extracellular growth to increase more the compressive strength this is why the biggest improvement is found after 28 days. [17]

Table 1: Effect of Bacillus subtilis, JC3 bacteria Cell Concentration on Strength [17]

Cell concentration/ml of mixing water	Compressive strength of cement mortar in MPa					
	7 days	% increase	14 days	% increase	28 days	% increase
Null (control)	37.32	-	44.10		51.81	
10^4	41.68	11.68	45.23	2.56	58.02	11.99
10^5 (optimum)	45.02	20.63	49.21	11.59	61.79	16.15
10^6	43.09	15.46	47.69	8.14	57.21	10.42
10^7	40.11	7.48	45.97	4.24	54.66	5.51

for furthermore studies, cubes (100mm x 100mm x 100mm) are prepared with and without bacteria and we tested their compressive strength for ordinary concrete, standard concrete and high grades concrete and the results are in the table 2. The results show increasing of 23% for the specimens with bacteria for all kind of concrete. [16]

Table 2: Effect of the Bacillus subtilis, JC3 bacteria addition on Compressive Strength [17]

Age (no. of days)	Compressive strength (MPa) at 28 days		
	Controlled concrete	Bacterial concrete	% increase
Ordinary grade concrete	28.18	32.74	16.18
Standard grade concrete	51.19	60.17	17.54
High grade concrete (M60)	72.61	94.21	29.75
High grade concrete (M80)	93.8	119.2	27.08

Materials and methods.

Mixes and markings of concrete samples with crystal additive.

To evaluate the influence of the crystal additive for fresh concrete mix and mechanical and physical properties of hardened concrete four mixture compositions were designed. One mixture was done without crystal additives, two mixtures with one type of crystal additive with different percentage called W, and one mixture was prepared with other type of crystal additive called Y. The compositions of the concrete mixtures are given in table 3

Table 3: The compositions and marking of the concrete mixes.

Concrete components for 1 m^3	Control	1% W	2% W	1% Y
Portland Cement CEM I 42,5R, kg	350	350	350	350
Water, l (W/C=0.45)	157.5	157.5	157.5	157.5
Sand (0/4mm), kg	861	861	861	861
Gravel (4/16mm), kg	1031	1031	1031	1031
Superplasticizer Sika ViscoCrete D187, kg	2.98 (0.85% f.c.m.)	2.98 (0.85% f.c.m.)	2.98 (0.85% f.c.m.)	2.98 (0.85% f.c.m.)
Crystal additive, kg W	-	3,50 (1.00% f.c.m.)	7,00 (2.00% f.c.m.)	-
Crystal additive, kg Y	-	-	-	3,50 (1.00% f.c.m.)

To conduct the experiment CMOD, two mixture composition were designed. One of the mixtures was done with propylene fibre and the other with metal fibre, we use W as crystalline additives for both compositions. The composition is mentioned in the table 4.

Table 4: Composition of concrete mix

Concrete components	With polypropylene fiber (for 30 L)	With metal fiber (for 33 L)
Portland Cement CEM I 42,5R, kg	10.5	11.55
Water, l (W/C=0.45)	4.74	5.19
Sand (0/4mm), kg	25.83	28.41
Gravel (4/16mm), kg	30.93	34.02
Superplasticizer Sika ViscoCrete D187, g	90 (0.85% f.c.m.)	99 (0.85% f.c.m.)
Crystal additive, g W	105 (1.00% f.c.m.)	115.5 (1.00% f.c.m.)
Plastic micro fiber, g	18	19.8
Metal fiber, g	-	825

Figure 9 : steel fibre used in experiments

Mixing and addition of concrete components sequence:

1) Pouring all aggregates (sand and gravel) and 1/3 of water;
2) Mixing for 30 s;
3) 1 min pause;
4) Pouring all the cement;
5) Mixing for 30 s;
6) Pouring rest of water;
7) Mixing for 1 minute while superplasticizer is added;
8) Pouring in crystal additive powder and mixing for 30 s.

Figure 10 : Cement used in experiment

Figure 11: Concrete mixing in “Zyclos” mixer

Physical properties of fresh concrete.

Slump, temperature, air content, and density were measured to evaluate crystal additive influence on the concrete mixtures physical properties with different types of cement. The slump was measured twice – immediately after mixing and after 60 minutes (to find out if the crystal additive has any side-effect on concrete mix left for a longer time without any mechanical intervention). The concrete mixtures were mixed in 50 l volume concrete mixer “Zyclos”.

When the concrete mixtures were ready, slump, temperature, density, and air content was measured.

Compressive strength.

The concrete samples for the investigation of various physical and mechanical properties were formed according to the concrete compositions given in table 3. For compressive strength testing 9 cubes (measurements 100×100×100 mm) for each composition were formed. The Samples were demoulded after 1 day and for the rest days were kept in water ($20\pm2^{o}C$). The concrete compressive strength test was carried out after curing for 1, 7, 14 and 28 days. The compressive strength test results and density values are given in table 6.

Water permeability

3 cubes for each composition were formed (150×150×150 mm) to determine the influence of the crystal additive on concrete's water impermeability. Their water impermeability was determined after curing for 28 days in (sample's water absorption depth was measured). During the test, the concrete samples were placed in the special frame (see fig. 12) and exposed to an enlarged water pressure of 1,4 MPa (on bottom samples side).

Figure 12: Water impermeability test in special frame

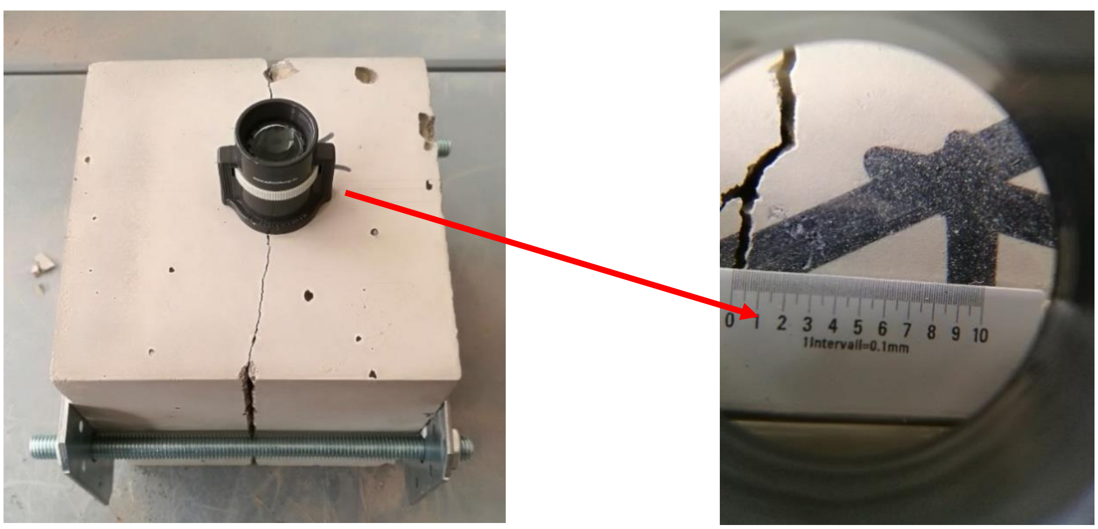
The samples placed in the frame were gradually (by 0.2 MPa step) exposed to the water pressure for 7 days until it reached 1,4 MPa. After the testing, it was noted that samples, haven't let any water through the top of all samples and it fitted the requirements of W14 water impermeability class.

Because all samples passed W14 class (probably due to low W/C and high cement amount), it was made decision to keep such water pressure (1,4MPa) for 28 days. Water pressure for the testing should be kept 500 ± 0,50 kPa for 72 ± 2h, so keeping 1400kPa gives 2,8 times higher water pressure to samples.

After the 28days and 1,4MPa pressure test, samples have been split in half to measure depth of water penetration. The depth of water penetration in the samples with crystal additive wasn't as deep as in the control samples. Therefore, it can be concluded that crystal additives increases concrete's water impermeability. The results are shown in the Table 7.

Self-healing effect by using pipes method.

The special test methodology was used to evaluate self-healing properties of concrete with the crystal additive, where an artificial crack was affected with water (0,5 m water column) for 28 days. The artificial crack was created by cutting the concrete sample and then joining both parts with the special clamps leaving the ≤0,4 mm width. Later water was released to flow through the crack until the crack was filled up with new crystals and water couldn't penetrate. So, after 28 days of normal curing, the samples were split in half and tested as shown in Fig. 13.



a) Tightened sample till ≤0,4 mm width crack for the self-healing testing

b) Zoom view of tightened sample till ≤0,4 mm width crack

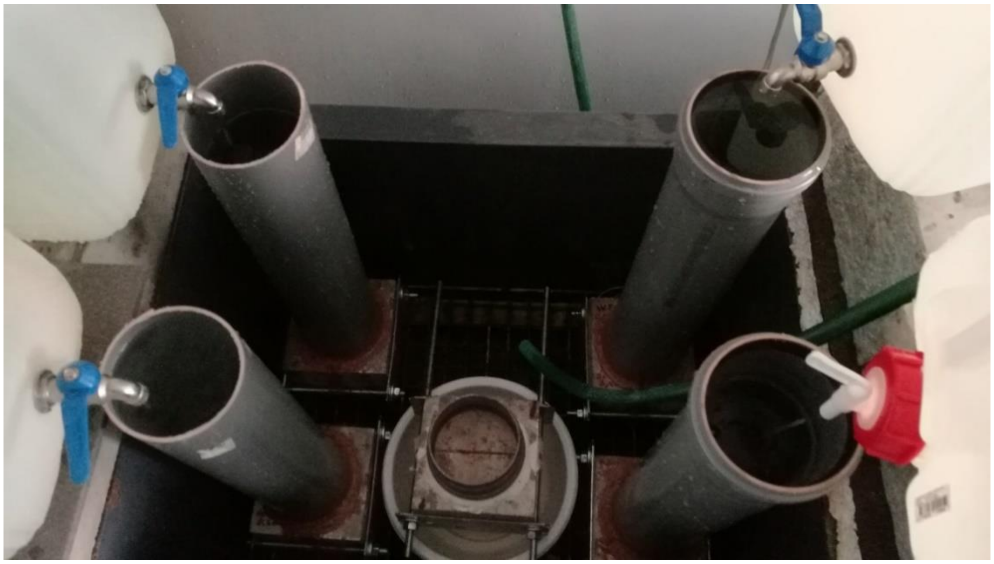


Figure 13: Testing procedure of crack healing effect

Although it is known that the crystalline additives are able to fill open concrete cracks (as demonstrated by studies of this work), it is not known what water pressure is still able to fill the crack. Also it is not known what water pressure can resist the crystal-filled crack. These issues are becoming more and more relevant in construction sites under soil water pressure.

Figure 14: Testing procedure of crack healing effect with 5-meter high water column pressure (is about 0.5 atmospheric pressure on specimen).

We concluded that such a testing method needs to be updated because it cannot reflect real object conditions, where water column pressure is much higher. So, we have done testing with always 5meter water column pressure (see Fig 13). Results after 35 days of water filtering through the crack in the concrete with 5meter water column pressure have shown very promising results, it stops in some stage of water column pressure (filled crack hold some stage of water level in pipe), but these results will not be given so far, because needs more research and more statistical data's. This could be done in future works.

Self-healing efficiency by using 5m Hight pipes

After the end of the previous experiment, we took the specimens that were affected with 0.5 m of water tube and has positive results, and we put them under 5m water tube. we observe and measure the quantity of water left in the tube. that quantity indicates the efficiency of self-healing in this case and if the healed crack can sustain the pressure of water of 5m. By using of 5 m height water column on the specimens is created 0.5 atmospheric pressure.

Like the previous experiment, each healed cube was put in metallic plaque and fixed that they don't break. Then a 5 m tube was glued over each cube by silicon to hold the water pressure. The 5m tube was filled with water and left for 24 hours. After this time, we measured the quantity of water remains in each tube. the result is given in the table 9.

Compressive strength recovering.

Compressive strength is a very important feature in concrete properties. It stands for the capacity of concrete to withstand load. Therefore, based compressive strength concrete is classified. Since the cracks that we attempt to limit it and heal it, weaken concrete by decreasing its compressive strength. The healing process that we seek should end up by recovering the original compressive strength of the concrete tested in the experiments or regain more.

Therefore, in the experiment 4, testing cubes from the first composition were used one as the control without any crystalline additives and tow cubes with "W" added as a crystalline additive but the percentages are different in each one. The fourth have "Y" as the crystalline additive. This experiment is made after at least one month of the moulding of concrete to ensure that the cubes are completely dry.

As it is shown in picture below the cube were crushed by the pressing machine but not totally damaged (the compressive load was stopped almost at

Figure 15 : Specimen fixed to 5m tubes.

90% of final compressive strength after 28 days hardening) until we see the first fissure. The compressive strength of each cube was taken. After crushing this cube were put in water fully immerge in to ensure that the water submerge the entire cube. The control cube is put in different water of the cubes that contained additives so that the additive does not shift to it and help it in the healing process.

The cubes were left in water for one month and then taken out and left for 48 hours to let them dry from water. After this time the compressive strength of this cubes is retested after healing. The results are given in the table 10.

Figure 16: Crushing the cubes before putting in water.

Crack mouth opening displacement “CMOD”.

The specimens casted from the second composition are use in this experiment. With steel fibre we had made 2 small (100×100×300 mm with notch of crack 10 mm depth) and 5 big (150×150×600 mm with notch of crack 25 mm depth), also with polypropylene fibre 4 small (100×100×300 mm with notch of crack10 mm depth) specimens. This experiment consists on creating an artificial crack in each specimen with different crack width then launching the healing process by putting the specimen in contact with water for 30 days. After that, monitoring the results and its effect on the flexural strength. To establish this experiment, we used the “Toni Technik” press machine.

By using a cutting machine, we cut each specimen in the middle of its surface by 25 mm (for big specimens) or 10 mm (for small specimens) of width. Then we use the small press machine to create load on the small specimen (432N/min), and the big press machine for the big specimen (0.2mm/min). The specimen was put on two support (28cm for small, 50 cm for big). Detectors are glued to the specimen and connected to the computer to control the value of the maximum load and the width of crack created.

In the first loading are the value of crack width (100µm, 150 µm, 250 µm, 300 µm, 400 µm) was choosing to attempt for big specimens. A second loading was attempt on each specimen to be sure that there is a difference of loading graph between the first and the second loading. One more loading show that its curves not changed at the same load.

After this procedure all the specimens were put in water to initiate the process of healing, then they were taken out after 30 days, and the third attempt of loading was done on each specimen. A graph was drowned for each attempt of loading for each specimen and the value of maximum load was taken to examine the capability of self-healing to recover strength of concrete.

Experiment results.

Physical properties of fresh concrete

Table 5: Slump, temperature, air content and density of concrete mixtures

	Control	W 1%	W 2%	Y 1%
Slump, mm	75	110	155	60
Slump after 1h, mm	70	110	175	50
Temperature, ^0C	18.0	17.5	17.1	17.6
Temperature after 1h, ^0C	18.1	17.6	17.8	18.0
Density, kg/m^3	2369	2363	2376	2382
Air content, %	2.8	3.0	2.8	2.6

As we see in table 5, application of the crystal additives hasn’t got any practical influence on the temperature of the concrete mixture, air content or density, but has some influence on concrete mixture slump. The concrete without crystal additive we have got S2 slump class, while with W crystal additive the slump was increased by one class – from S2 to S3 and slump increased more as W additive amount was increased. Using second type crystal additive Y we have got no practical influence on slump and slump was even lower, compared to control mixture (75mm control and 60mm with 1% F.C.M. Y). After 60 min concrete slump tendencies were similar as concrete slump measured after mixing. Slump after 1h of control specimens has shown the same value as slump measured after the mixing, while concrete specimens with crystalline additive W and 2% from cement amount, slump values after 1h already fulfilled S4 concrete requirements. It can be concluded, that both crystalline additives have no influence or small influence on fresh concrete properties like temperature, density, and air content, while it influences fresh concrete consistency. W have a positive effect and it increases concrete consistency while adding Y we have got no positive effect on this parameter.

Compressive strength

Table 6: The concrete compressive strength and density after 1, 7, 28 days of curing

Concrete composition	Compressive strength after 1 day, MPa	Density after 1 day, kg/m^3	Compressive strength after 7 days, MPa	Density after 7 days, kg/m^3	Compressive strength after 28 days, MPa	Density after 28 days, kg/m^3
Control	27.2	2377	50.0	2402	56.3 (σ=1.9)	2385
W 1%	27.8	2395	53.4	2389	65.7 (σ=0.5)	2398
W 2%	23.6	2386	55.9	2384	67.7 (σ=0.7)	2419
Y 1%	20.2	2428	51.5	2406	59.2 (σ=0.8)	2408

As shown in table 6, the application of the Y crystal additive or higher dosages of W has an influence on concrete's early strength i.e. after 1 day of curing it can be lower down from 25 % till 13% accordingly (W 1% have no effect on early strength). Concrete manufactures should consider that application of the crystal additive reduces concrete early compressive strength, so this should be considered preparing a demoulding schedule and working in winter conditions.

After 7 and 28 days of curing, compressive strength increases comparing with control mixtures. These tendencies also can be seen in Figure 17. We can see that control specimens average compressive strength value is 56,3MPa, while using W 1% and 2% dosage strength was increased 65,7MPa and 67,7MPa accordingly (9,4MPa and 11,4MPa strength increase). Using Y crystalline additive and 1% dosage compressive strength was increased by 2,9MPa (till 59,2MPa), compared to control specimens. We can estimate that control concrete fulfils C40/50 concrete class requirements, concrete with W 1% and with W 2% fulfils C50/60, concrete with Y 1% fulfils C45/55 concrete class requirements.

According to table 6, we can see that crystal additive influence on concrete density have changed slightly. We can see higher density values with Y compared with control specimens.

The graphic view of concrete compressive strength test results after 1, 7, 14 and 28 days is given in the fig. 17.

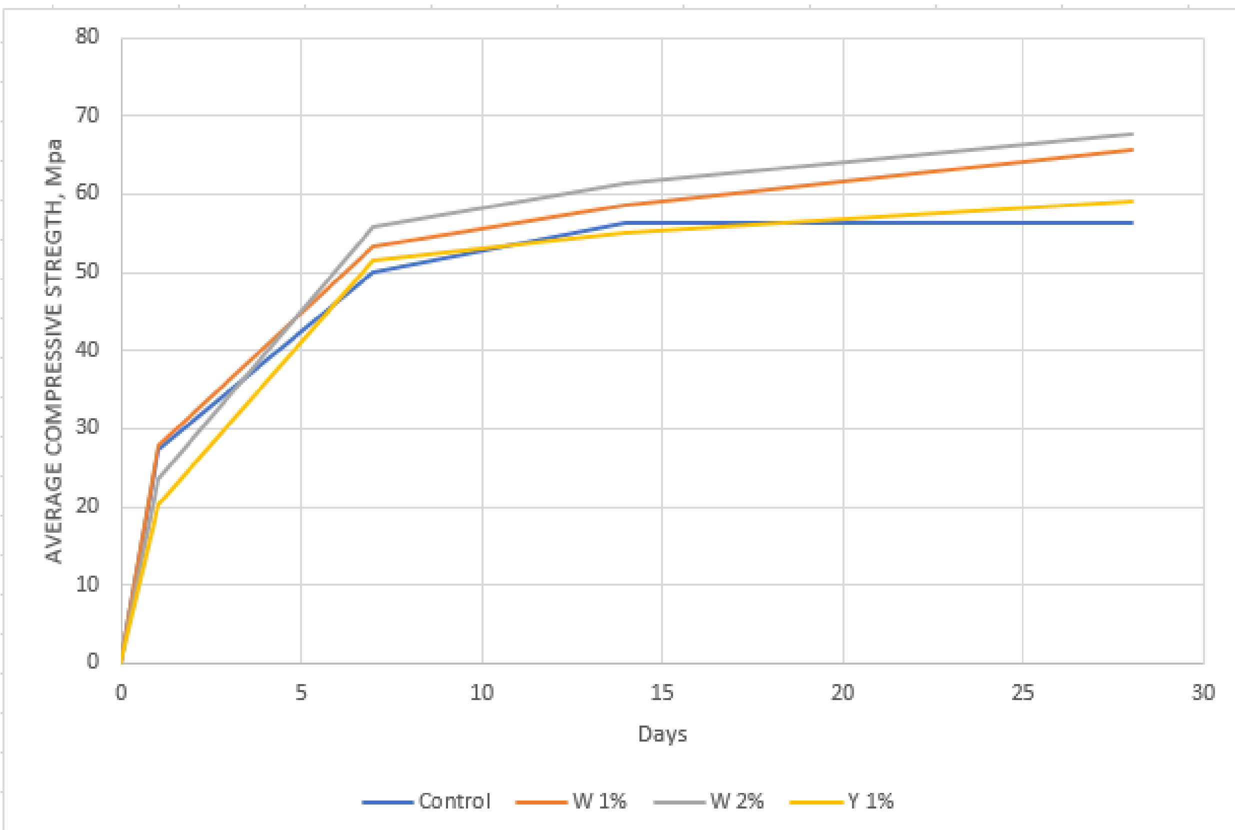


Figure 17: The compressive strength tests results after 1, 7, 14 and 28 days of curing with crystal additive

Water permeability

Table 7: Measurement of the maximum depth of penetration under the 28 days and 1400kPa pressure test.

	Control	W 1%	W 2%	Y 1%
Maximum depth of water penetration, mm	31,75	21,28	17,41	20,54
Limits, 30mm	not passed	passed <30mm	passed <20mm	passed <30mm

As shown in table 7, applications of crystal additives reduce water penetration depth more than 33-45 %. According to given limits for Watertight Concrete, water penetration depth should not exceed <30 mm when specimens are tested. In our case, we can see that this value was passed in all specimens with crystalline additives, while control specimens value exceed <30 mm. Also, it could be noticed that water pressure values were kept much higher so this conclusion is subjective.

self-healing effect by using pipes method.

According to the procedure shown in Fig 13, the decision was to keep maximum testing time 4 weeks. According to the technical literature, usually, after such period cracks should be healed. Results are given in table 8. It can be seen that leakage stops in all specimens with crystalline additives. Fastest self -healing effect was obtained in a specimen with W 1%. Specimens with W 1% after one week testing water flowability to sample decreased from small water stream till water drops and after 2 weeks it was not leaking anymore. Specimens with W 2% and with Y 1% were obtained similar tendencies only the leakage stops later - after 3 weeks. While control specimens due all testing time (4 weeks) water leakage does not stop and it could be concluded that the control specimen did not pass the self-healing testing.

Table 8: Self-healing effect.

	Control	W 1%	W 2%	Y 1%
Self-healing testing	Not passed	Passed (after 2 weeks)	Passed (after 3 weeks)	Passed (after 3 weeks)

Figure 18: Testing procedure of crack healing effect (view of crack filling by crystals in the bottom of concrete specimens after the test)

Self-healing efficiency by using 5m Hight pipes

Table 9: Depth of water remains after 24 hours in 5m tubes.

	W 2%	W 1%	Y
Depth of water remain after 24 h (cm)	0	30	83

As it is seen in table 9 the distance of water remain in 5 m tubes was 0 for specimens with W 2% additives, 30 cm for specimens with W 1% additives and 83 cm for specimens with Y additives. So we can conclude that the newly formed cracks cannot handle pressure with value 0.5 atmospheric.

Compressive strength recovering.

Figure 19: Specimen after 30 days in water.

Table 10: Compressive strength of cube before and after self-healing.

Composition	Compressive strength for dry cubes after 28 days hardening tested until 90% its final strength		Compressive strength after healing the same specimens for 30 days in water		Percentage of changes
	KN	Mpa	KN	Mpa	%
control	1350.1	60	1336.3	59.39	-1
W 1%	1490.1	66.21	1628.8	72.3	+9.19
W 2%	1515.6	67.35	1546.4	67.72	+0.5
Y	1542	68.53	1415.4	62.8	-8.3

As it is shown in table 10, which express the compressive strength of cubes when we crushed them then their compressive strength of same cubes after putting in water for 30 days then dry them for 48 hours. The result in the table shows us a decrease of 1% for the control cube which is normal because it does not contain any crystalline additives help him in healing. Control recover 99% of its strength due to autogenous healing which can happened in concrete that don't contains any healing additives.

Therefore, an increase of 9.19% is showed for the compressive strength of cube with W1% and 0.5% for cube with additive W2%. This increase due to the crystalline additives used in the composition of these two cubes which shows that it could be a very effective additive.

As for the last cube we can see a decrease by 8.3% of its strength and that due to failure of the additives to complete its task of healing.

By conclusion of this test we can say that crystalline additives is not effective to recover compressive strength, because obtained recovering effect is unstable by deviation

Crack mouth opening displacement “CMOD” using bending test

to begin our experiment each specimen is prepare by the following steps.

- Using a cutting machine to make a longitudinal fissure in the bottom.
- Clean the area around the fissure.
- Glue two metallic plate on the two side of the fissure which are going to hold the detector
- The plate that hold the detector is glued for 2.5 cm from the fissure
- The other plate which hold the tope of detector is glued for 0.5 cm of the fissure
- Place the specimen in the load machine. It is placed on two metallic support (distance between two support 50cm for big, 25cm for small).
- Place a metallic bar on the top of the specimen in the middle parallel to the fissure.
- Make sure that the detector work and is connected properly.
- Start the load make sure to keep safety distance from the press machine.

Figure 20: Cutting the fissure for specimen.

Figure 21: Placement of plats that hold the detector

Figure 22: Final step of each specimens before starting the load.

After finishing the preparation of specimen, we start by creating an artificial crack.

Figure 23: Crack start to shows.

During the third attempts of loading after healing, the result of load (Mpa) was taken in function of the opening of crack (μm). For the two small specimens, the load in the first two attempts was stopped when the crack mouth reaches 50 μm (before healing). then we repeat the third attempts after taking out of water and we got the graph 1 and 2

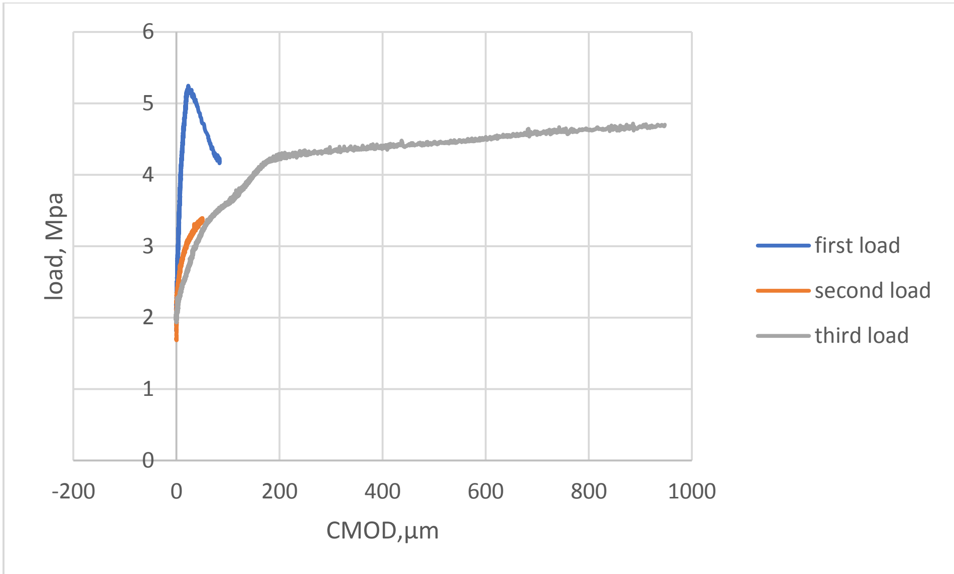


Figure 24: Variation of load according to CMOD (small specimen 1) until CMOD (50µm).

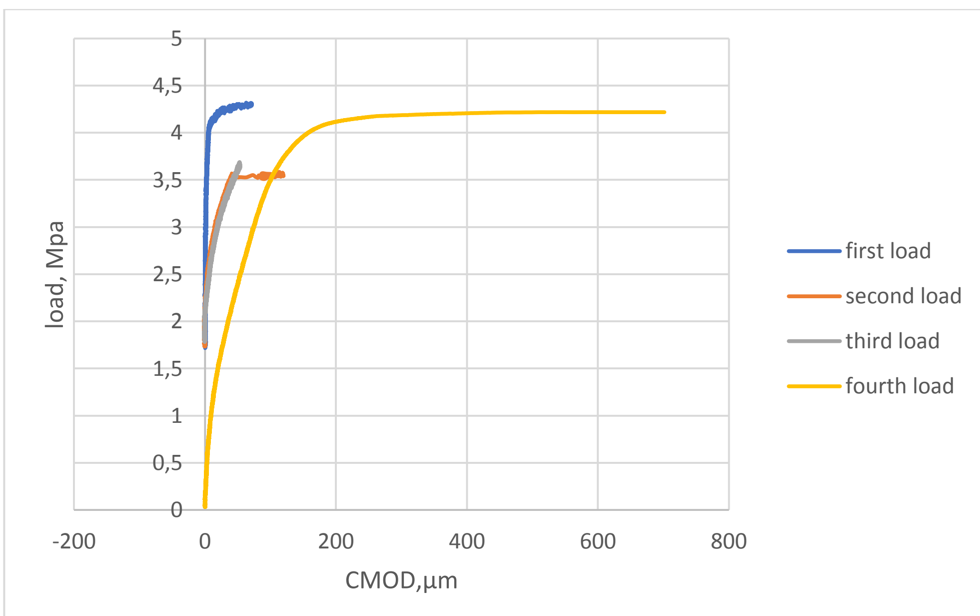


Figure 25: Variation of load according to CMOD (small specimen 2) until CMOD (50µm).

As seen in figure 25, 4.5Mpa was the load necessary to reach 50 µm of crack mouth opening. Then in the second attempt the same value of opening needed to 3.3 Mpa and that is a signe that the concrete is been weeker in this place and the opening of same cracke needed less power. After the 30 day in water the third attemp was made and

Big specimen with steel fiber.

In the case of big specimen, the load was stopped consequently when the crack mouth reaches 100 µm, 150 µm, 250 µm, 300 µm et 400 µm

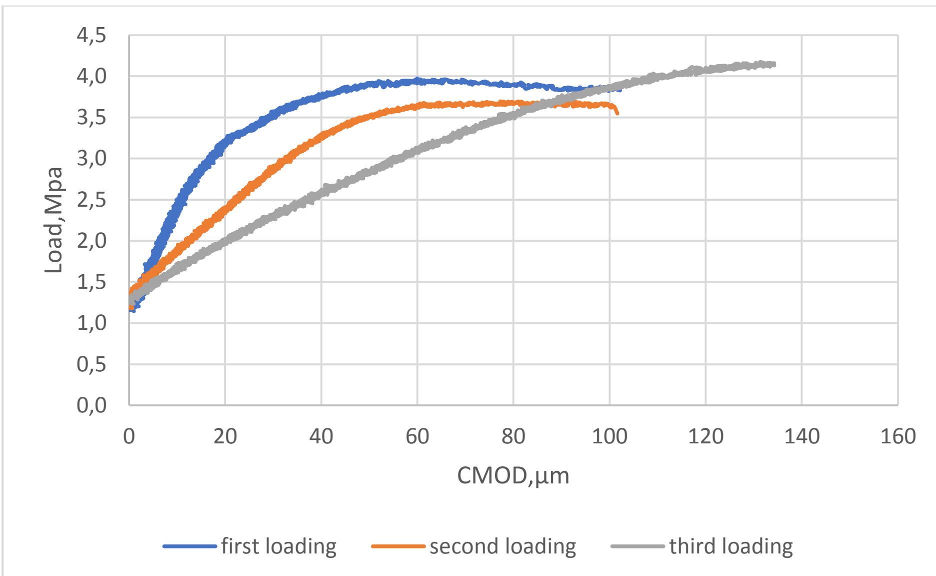


Figure 26: Variation of load according to CMOD (big specimen N'1) until CMOD (100µm).

As it is seen in figure 26, we stop the load when the crack mouth achieves 100 µm. For the first load, this opening of the crack needed 3.8 Mpa to reach 100 µm. the second attempt the load needed to 100 µm decrease to 3.5 Mpa which indicated a weakness happened in concrete caused by the crack. After the healing process, the same crack mouth opening 100 µm needed 3.9 Mpa which indicate a recovering in concrete strength by means of self-healing.

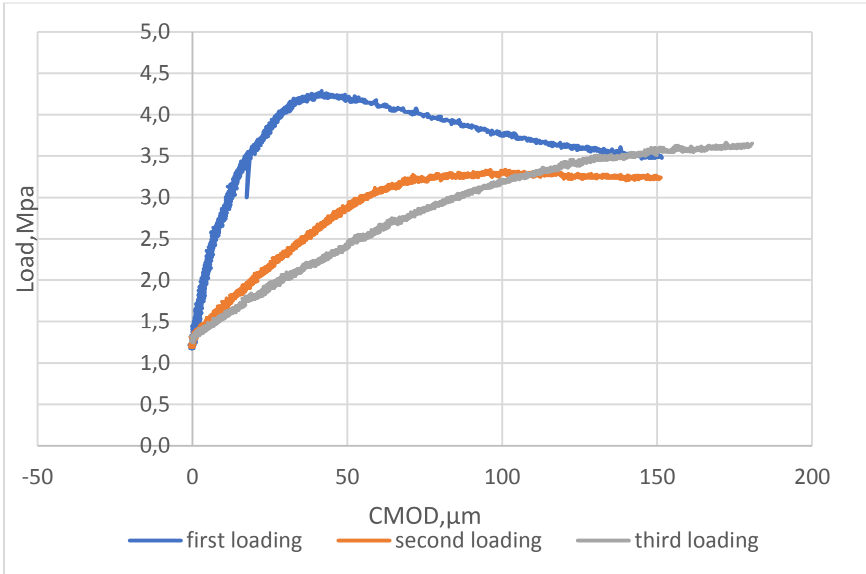


Figure 27: Variation of load according to CMOD (big specimen N'2) until CMOD (150µm).

In the case of the second specimen, the opening mouth intended to reach is 150 µm. In the first attempt, the opening of crack the load needed to reach it was 3.5 Mpa. The second attempt and after the crack is done and the concrete is weakened 150 µm took 3.2 Mpa, however this value increases to 3.6 Mpa after the healing process.

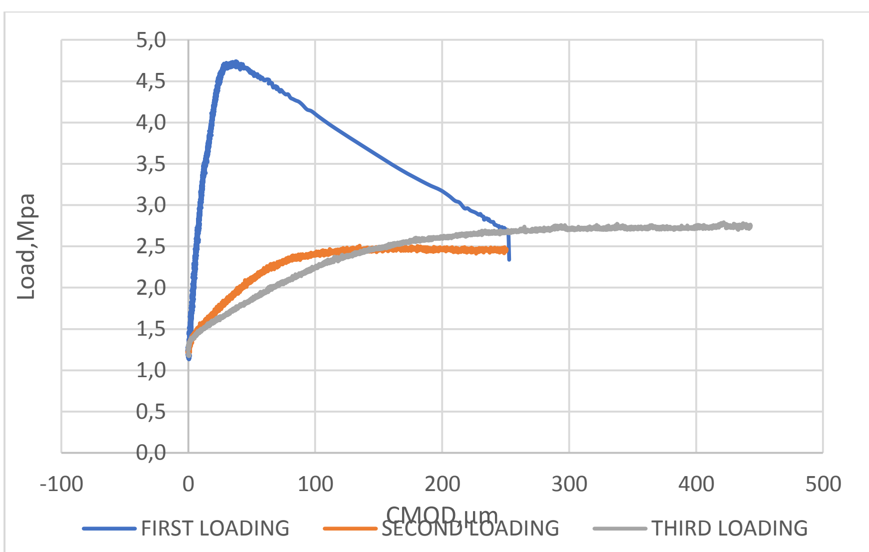


Figure 28: Variation of load according to CMOD (big specimen N'3) until CMOD (250µm).

For the third specimen we intended to stop the crack mouth opening at 250 µm. first load to reach this value was 2.7 Mpa. The second try the load to reach 250 µm was 2.4 Mpa. After the healing happened the same opening needed 2.7 Mpa as load.

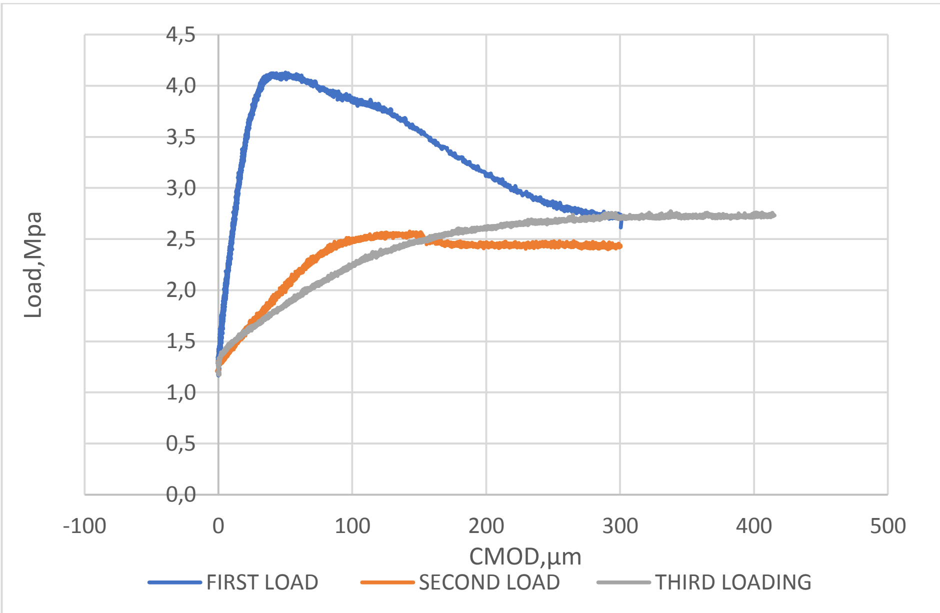


Figure 29: Variation of load according to CMOD (big specimen N'4) until CMOD (300µm).

For the fourth specimen we intended to stop the crack mouth opening at 300 µm. first load to reach this value was 2.8 Mpa. The second try the load to reach 250 µm was 2.4 Mpa. After the healing happened the same opening needed 2.8 Mpa as load.

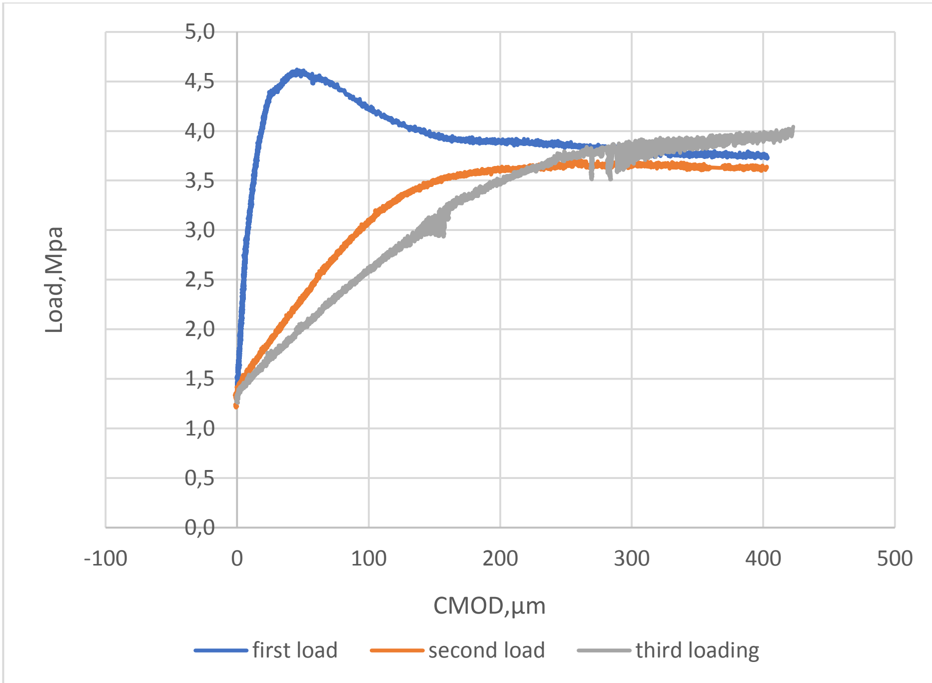


Figure 30: Variation of load according to CMOD (Big specimen N'5) until CMOD (400µm).

For the fifth specimen we intended to stop the crack mouth opening at 400 µm. first load to reach this value was 3.8 Mpa. The second try the load to reach 250 µm was 3.6 Mpa. After the healing happened the same opening needed 4 Mpa as load.

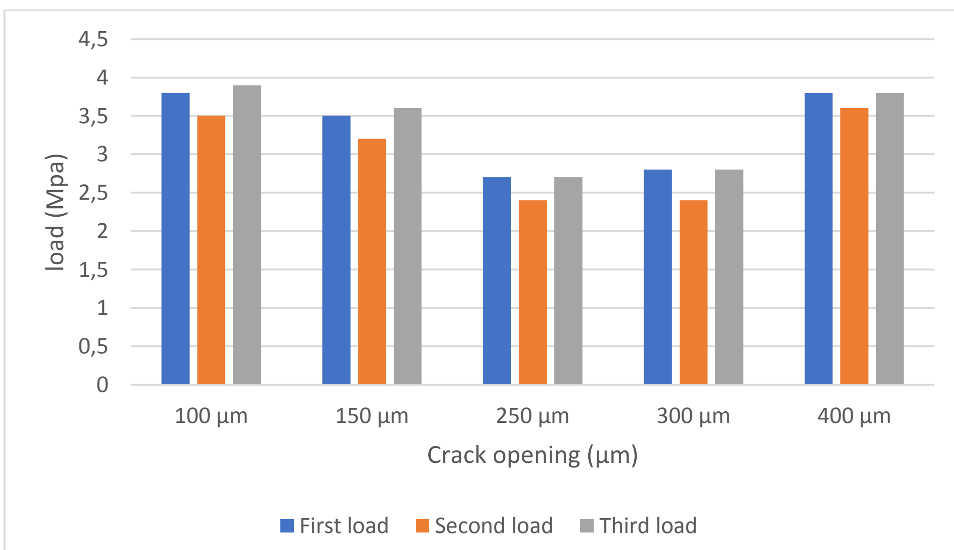


Figure 31: Changing of loads by different crack mouth opening (steel fiber).

Table 11: Difference in percentage for each load (steel fiber)

Specimen number	Load and crack mouth opening (µm)	Value of load (Mpa)	Difference (%)
Big N 1	First load (100)	3.8	100
	Second load (100)	3.5	92
	Third load (100)	3.9	102.6
Big N 2	First load (150)	3.5	100
	Second load (150)	3.2	91
	Third load (150)	3.6	102.8
Big N 3	First load (250)	2.7	100
	Second load (250)	2.4	88
	Third load (250)	2.7	100
Big N 4	First load (300)	2.8	100
	Second load (300)	2.4	85
	Third load (300)	2.8	100
Big N 5	First load (400)	3.8	100
	Second load (400)	3.6	94
	Third load (400)	3.8	100

As it is seen in the figure 31 and the table below, after healing the load needed to achieve certain crack mouth opening displacement increase in all cases. For the 100 µm and 150 µm after healing we notice that the strength needed for this crack recover and gained 2% more. As for 250, 300 and 400 µm the recovery in load was 100 % which is a good sign for the additive used in the self-healing range.

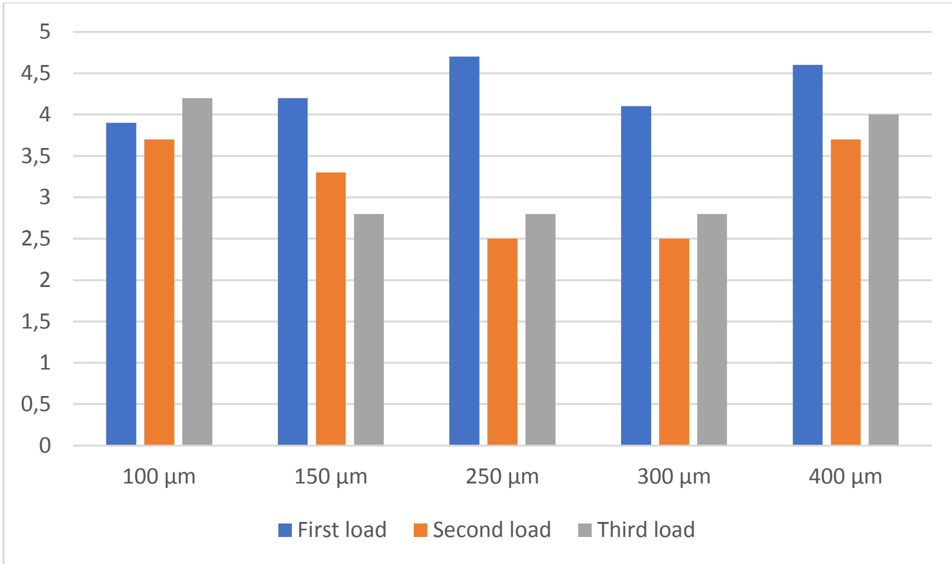


Figure 32: Maximum load for each attempt for different specimens (steel fiber)

Table 12: Difference of percentage for maximum value of load for each specimen

Specimen number	Load and crack mouth opening	Value of maximum load (Mpa)	Difference (%)
Big N 1	First load	3.9	100
	Second load	3.7	9
	Third load	4.2	107.6
Big N 2	First load	4.2	100
	Second load	3.3	78
	Third load	3.7	88
Big N 3	First load	4.7	100
	Second load	2.5	53
	Third load	2.8	59
Big N 4	First load	4.1	100
	Second load	2.5	60
	Third load	2.8	68
Big N 5	First load	4.6	100
	Second load	3.7	80
	Third load	4.0	87

As we can see in figure 32 and table 12, the maximum load for all CMOD was the first load except for 100 μm the maximum load was the third load after healing. Therefore, we can conclude that the perfect healing can happen when the crack width is not more then 100 μm, although there is healing and recovering in strength for all the other CMOD.

Table 13: Different percentage of load on the peak between first and third load.

Specimen		Load, Mpa	CMOD, μm	Difference at the same CMOD (%)
1 (100 μm)	Load at peak first load	4	60	100
	Third load at same CMOD	3.2	60	80
2 (150 μm)	Load at peak first load	4.2	30	100
	Third load at same CMOD	2.2	30	52
3 (250 μm)	Load at peak first load	4.6	50	100
	Third load at same CMOD	2	50	43
4 (300 μm)	Load at peak first load	4.6	40	100
	Third load at same CMOD	1.9	40	41
5 (400 μm)	Load at peak first load	4.6	50	100
	Third load at same CMOD	1.8	50	39

As we can see in the table 13 that the recovery of load increase when the crack decrease. So, we can conclude more the crack is small more the recovery is higher.

Big specimen with polypropylene.

As for the specimen with polypropylene only, the load was stopped consequently when the crack mouth reaches 16 µm, 22 µm, 25 µm and 28 µm.

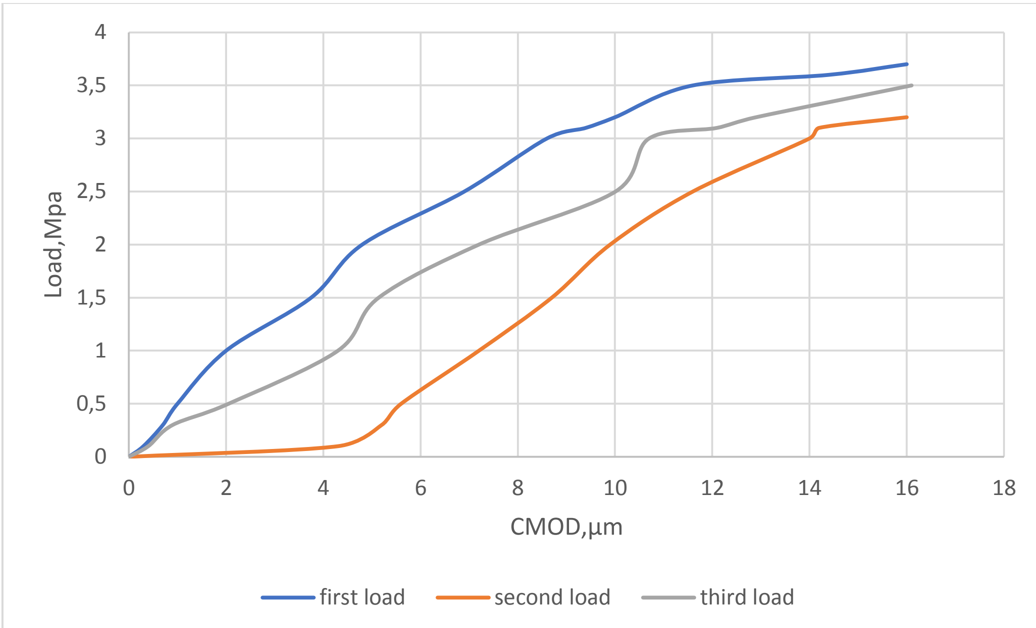


Figure 33: Variation of load according to CMOD (propylene specimen N'1) until CMOD (16µm).

As it is seen in figure 33, we stop the load when the crack mouth achieves 16 µm. For the first load, this opening of the crack needed 3.7 Mpa to reach 16 µm. the second attempt the load needed to 16 µm decrease to 3.2 Mpa which indicated a weakness happened in concrete caused by the crack. After the healing process, the same crack mouth opening 16 µm needed 3.5 Mpa which indicate a recovering in concrete strength by means of self-healing.

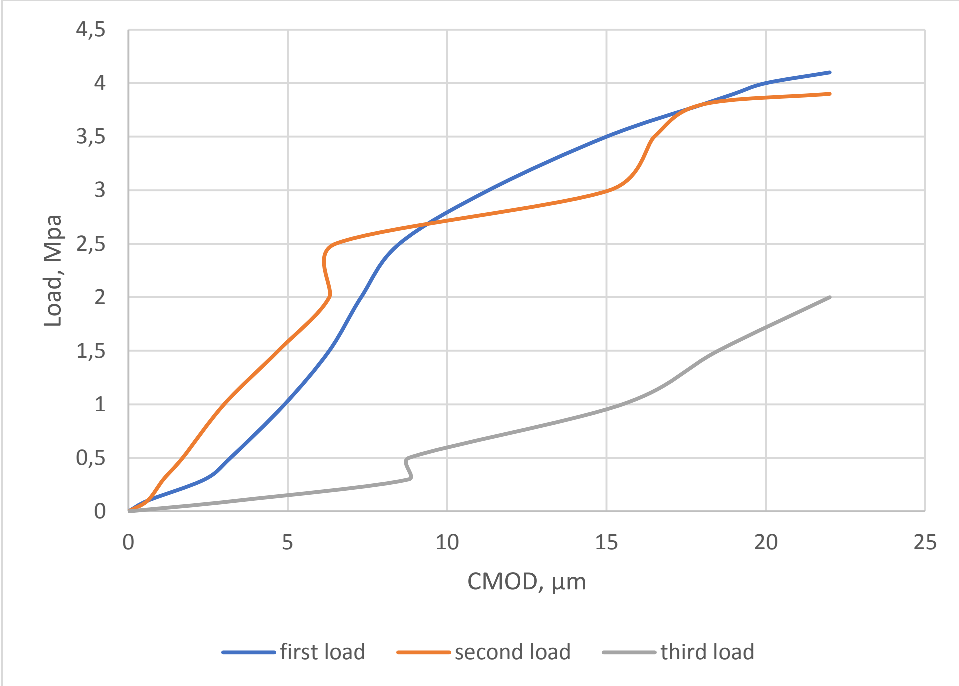


Figure 34: Variation of load according to CMOD (propylene specimen N'2) until CMOD (22µm).

For the second specimen figure 34, we stop the load when the crack mouth achieves 22 µm. For the first load, this opening of the crack needed 4.1 Mpa to reach 22 µm. the second attempt the load needed to 22 µm decrease to 3.9 Mpa which indicated a weakness happened in concrete caused by the crack. After the healing process, the same crack mouth opening 22 µm needed 2 Mpa.

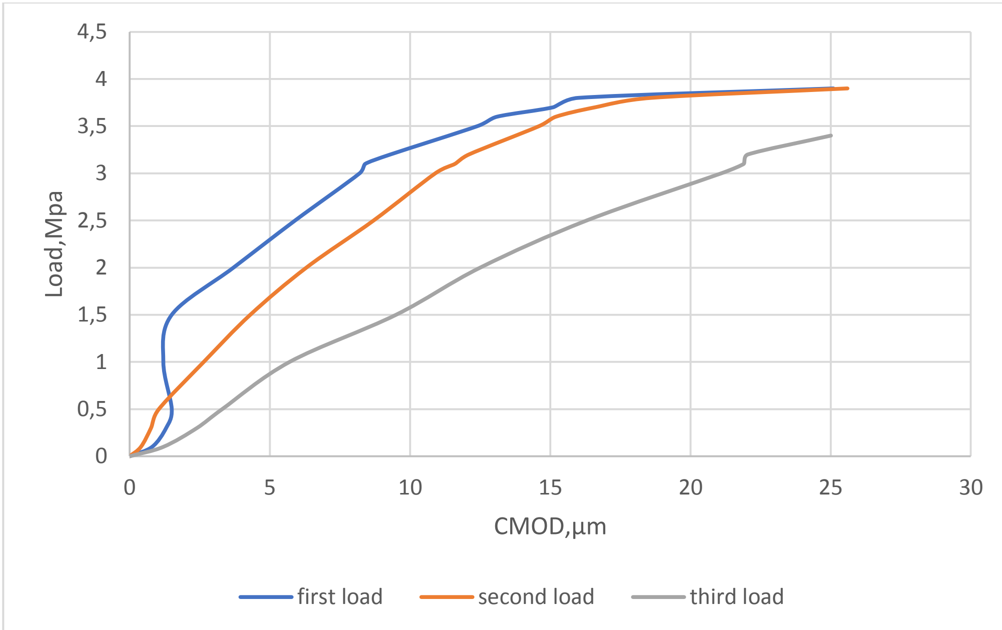


Figure 35: Variation of load according to CMOD (propylene specimen N'3) until CMOD (25µm).

For the third specimen figure 35, we stop the load when the crack mouth achieves 25 µm. For the first load, this opening of the crack needed 3.9 Mpa to reach 25 µm. the second attempt the load needed to 25 µm decrease to 3.9 Mpa which indicated a weakness happened in concrete caused by the crack. After the healing process, the same crack mouth opening 25 µm needed 3.4 Mpa.

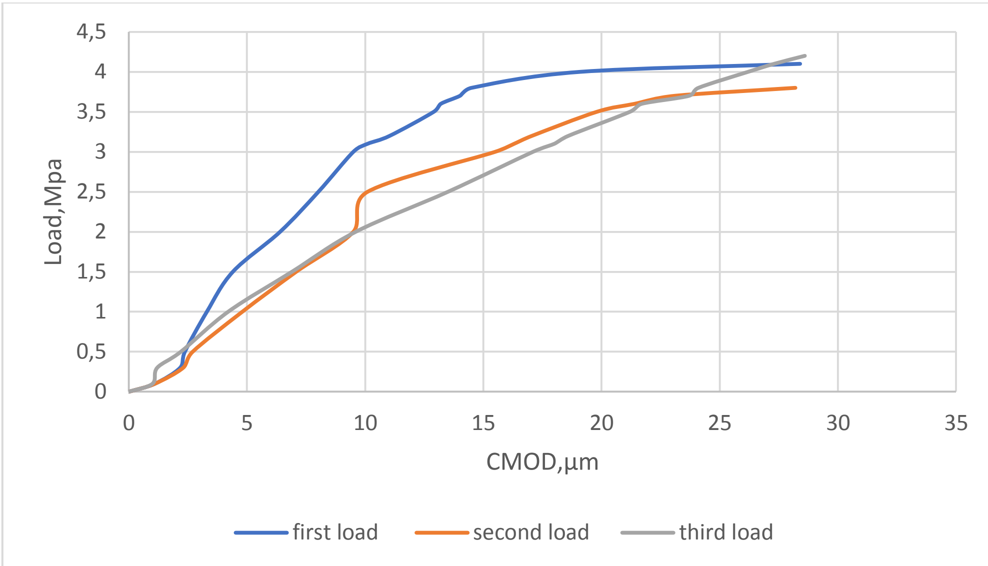


Figure 36: Variation of load according to CMOD (propylene specimen N'4) until CMOD (28µm).

As for the fourth specimen figure 36, we stop the load when the crack mouth achieves 28 µm. For the first load, this opening of the crack needed 4.1 Mpa to reach 28 µm. the second attempt the load needed to 28 µm decrease to 3.8 Mpa which indicated a weakness happened in concrete caused by the crack. After the healing process, the same crack mouth opening 28 µm needed 4.2 Mpa which indicate a recovering in concrete strength by means of self-healing.

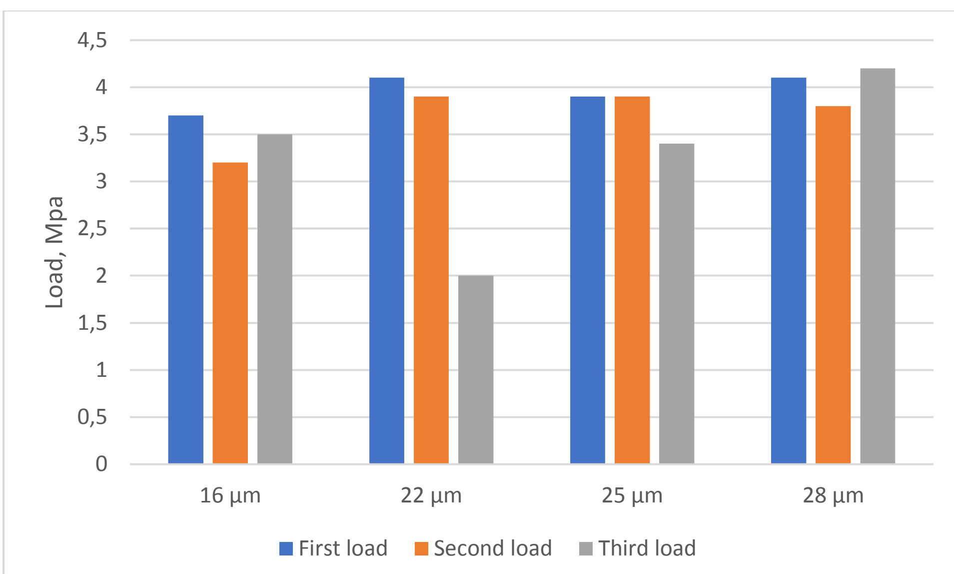


Figure 37: Changing of loads by different crack mouth opening (propylene fiber).

Table 14: Difference in percentage for each load (propylene fiber)

Specimen number	Load and crack mouth opening (µm)	Value of load (Mpa)	Difference (%)
Big N 1	First load (16)	3.7	100
	Second load (16)	3.2	86
	Third load (16)	3.5	94
Big N 2	First load (22)	4.1	100
	Second load (22)	3.9	92
	Third load (22)	2	47
Big N 3	First load (25)	3.9	100
	Second load (25)	3.9	100
	Third load (25)	3.4	87
Big N 4	First load (28)	4.1	100
	Second load (28)	3.8	92
	Third load (28)	4.2	102

As it is seen in the figure 37 and the table below, after healing the load needed to achieve certain crack mouth opening displacement increase in some cases and decrease in other. For the 16 µm after healing we notice that the strength needed for this crack recover 94% of its original strength. As for 22 µm the recovery in load was 47 %. For 25 µm the recovery in strength was 87%. For 28 µm we notice full recovery in strength and gain of 2% which is a good sign for the additive used in the self-healing range. Therefor we can conclude that self-healing can be done but it is hard to control the crack, because crack goes to much.

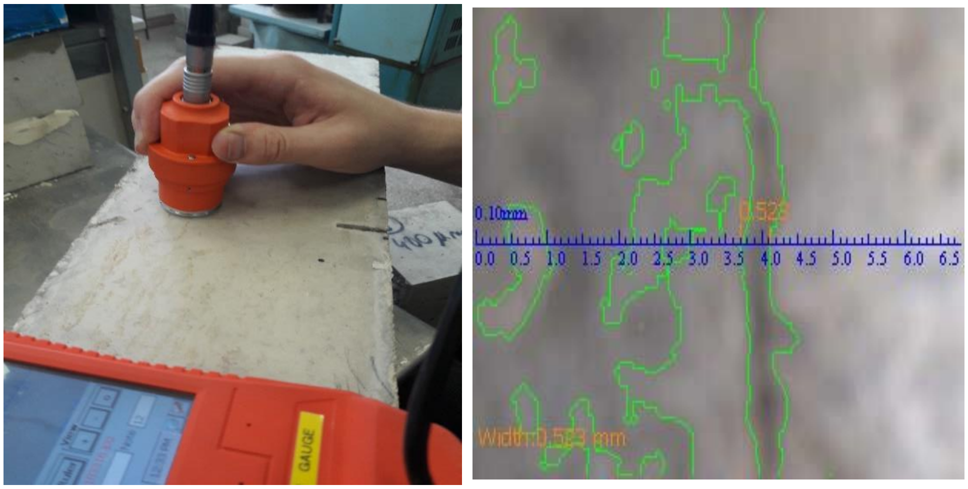


Figure 38: Digital microscope picture of cracks after healing

Measuring CMOD during experiments with steel fiber reinforced concrete according three-point bending test with notched cracks before and after self-healing, we concluded that there is some recovering effect on flexural strength depending by the width of the preloading cracks. During preloading crack until 100 μm of CMOD and after healing, the flexural strength was recovered until 80 percent of the maximum load. But then the preloaded cracks were bigger (150 μm, 200 μm, 300 μm. 400 μm), after the healing in water for 28 days, the maximum flexural strength recovered less by tendency (from 52 to 39 percent). This kind of experiments could be very important in the future research during preloading test with CMOD less than 100 μm, because in reality concrete structures the crack occurs with less dimensions and grows slow, so probably it could be in time to recover.

Conclusions.

1. The experiments have shown that the crystalline additive does not affect temperature of the concrete mixture, density or content of entrained air, however it changes the slump (depending on type of crystalline additive, see the table 3), so it should be considered.
2. The compressive strength tests after 1, 7 and 28 days have shown that the crystalline additive reduces the early strength of the concrete up to 25% after 1 day (depending on the type of crystalline additive, see table 4), but after 7 and 28 days the compressive strength increase 20 % when 2 % f.c.a. of "W" additives was used. Also, the additives didn't have any negative influence on density.
3. As for water permeability test with 1.4 MPa water pressure for 28 days the specimens of the all composition classified as W14, but the concrete with the crystalline additive was 30 % less permeable and water penetration depth did not exceed 30mm.
4. In this research work the pipes method with water was used to show self-healing effect. Experiments showed that water stopped go through the cut concrete specimens (through the crack) with crystalline additives (1 or 2 % by mass) respectively after 14 and 21 days. After that, the cracks with 0,3-0,4mm widths was filled.
5. In the experiment of self-healing 5 meters height of pipes was used also to see the self-healing effect of concrete under pressure of water column (0.5 atmospheric pressure). The self-healing effect always holding this high pressure of water was poor. Therefore, we need more studies concerning this.
6. Measuring CMOD during experiments with steel fiber reinforced concrete according three-point bending test with notched cracks before and after self-healing, we concluded that there is some recovering effect on flexural strength depending by the width of the preloading cracks. During preloading crack until 100 μm of CMOD and after healing, the flexural strength was recovered until 80 percent of the maximum load. But then the preloaded cracks were bigger (150 μm, 200 μm, 300 μm. 400 μm), after the healing in water for 28 days, the maximum flexural strength recovered less by tendency (from 52 to 39 percent). This kind of experiments could be very important in the future research during preloading test with CMOD less than 100 μm, because in reality concrete structures the crack occurs with less dimensions and grows slow, so probably it could be in time to recover.

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