Effects of new generation of curing applications on self-healing in cement-bonded composites

[1]Lana Abdulateef, [2]Arife Akin

[1]Master student, [2]Doctor
[1]Civil engineering,
[1]Selcuk University, Konya, Turkey

Abstract: **Cement is the most widely used material for construction. However, cement production has a negative impact on the environment, as it is a contributor to global warming. Production of one ton of cement produces about one ton of carbon dioxide. This encourages the searchers to use environmentally friendly materials such as fly ash. The self-healing capacity of Engineered Cementitious Composites (ECC) materials used for new or repairing applications opens up difficult prospects for the use of building materials that can restore original durability levels, thereby ensuring longer service life for less-designed applications and less sensitive performance to environmental induced degradation. One of the possibilities for achieving self-healing capability mentioned above is the use of additives. These additives, when contact with water or air humidity, are capable of forming chemical compounds capable of closing the cracks and thereby ensuring the recovery of an initial level of mechanical performance. The self-healing behaviour of micro-cracks in composite materials was evaluated for the first time through the measurements of compressive and flexural strength tests'. It also focuses on the efficacy of the curing used by the Nano silica solution to stimulate self-healing. Finally, studies were carried out to assess the frequency and prevalence of the behaviour of ECC materials. In addition to the results of ECC studies, the high self-healing ability, which has also been confirmed by experimental results, is believed to contribute significantly to structural strength and sustainability.**

***Index Terms*:** **Engineered Cementitious Composites (ECC) materials, micro-cracks, nano silica, self-healing**

I. INTRODUCTION

All Cracking generally begins with the formation of micro cracks, which may later integrate into giant macro cracks. Cracks often allow moisture and harmful chemicals to cause problems such as frost-freezing damage and corrosion of the reinforcement; corrosion is particularly severe in salty environments such as marine applications or structures exposed to de-icing salts. This damage to concrete and steel can lead to reduced capacity and potential structural failure. The major problems with concrete is:

1. Durability: These issues come from their tendency to crack which is due to the brittle nature and low tensile strength. Characteristic that cause certain problems if the concrete is loaded in tension or flexure.

There are three essential ways in which crack widths can be reduced:
a) Reduce reinforcement stress.
b) Reduce bar diameters thus reducing bar spacing.
c) Increase the effective reinforcement ratio.

2. Sustainability: In addition to the durability problem, there are fundamental sustainability issues facing the cement and concrete industry, both economically and environmentally.

a) Environmental: It is estimated that for each ton of cement production, one ton of carbon dioxide is released into the atmosphere.
b) Economic: As a result of the durability issues described above, concrete structures require frequent inspection, maintenance and repair work, these works and cost of the initial construction of the structure are called the full cost of life of the structure. [10]

ECC is a special type of high performance concrete material that is the product of research to enhance the brittle behavior of traditional concrete. The micromechanics -based design supports the development of fiber-reinforced ECC, which is characterized by high ductility. The fiber content of this material, which is characterized by high tensile ductility and tight crack width, does not exceed 2% by volume. Moreover, regardless of the deformation applied, the width of tight cracks in ECC does not exceed 100 µm, in contrast to other concrete materials. These unique properties are the source of chemical and physical properties that make ECC a suitable material for self- healing. [3]

The self-healing phenomenon of cement-based materials has been observed in natural environments for many years. For civil infrastructure, for example, e.g. bridge decks, pavements and tunnel lining, where water and carbon dioxide are naturally available, its own damage with chemical products by itself. The main cause of self-healing is due to the formation of calcium carbonate, due to the interaction between calcium ion in concrete and dissolved carbon dioxide in water. Continuous hydration of unhydrated cementitious materials was another mechanism for self-healing. Due to the limited availability of self- healing products, control of the crack width was found to be essential in obtaining consistent behavior and self-healing in cementitious materials. To consistently control of the crack width, even with a steel reinforcement is relatively difficult in concrete. [9]

The application of nanotechnology in cement and concrete has attracted a lot of attention in recent years. This is gradually accepted by adding a fraction of nanoparticles, even at a very small dose, the features of cement-based material can be greatly improved in terms of workability, strength and durability. [8]

Nanotechnology has been explained by Drexler [4] as ‘‘the control of the structure of matter based on molecule-by-molecule control of products and by-products’’. Nanotechnology can be considered the most modern aspect of science and technology. As nanotechnology has great potential in the market and economic impact, the need for research and exploration in this field and its applications has increased significantly over the past few decades.

There are many inherent sustainability issues associated with the use of concrete, which will be discussed in the following sections. These problems are exacerbated only by the tendency of the concrete to crack and the subsequent reduction in the durability and life of the structure. Any means of reducing cracking and improving durability will have an immediate positive impact on the sustainability of concrete.

The research in this paper is to improve sustainability within construction industry, particularly the cement and concrete industries. Improving the durability of concrete structures will reduce maintenance requirements and build new structures to replace the old ones, reducing demand for cement and concrete and improving overall economic and environmental sustainability. And the research is to better understand the behavior of materials at the nanoscale level as well as to determine how to improve the microstructure of cement materials. Self-healing cement is a potential solution to this durability issue.

2. EXPERIMENTAL METHOD

This paper focuses on the self-healing behavior of cement-bonded composites. For this purpose, two different types of ECC mixtures have been produced with two different types of fly ash (type F and C).

2.1. Materials

The materials used were Ordinary Portland cement, standard CEM I 42.5R with the specific weight 3.06 and the Blaine grade is 325 m2/kg, two different types of fly ash type F that obtained from bituminous coal/ Çatalağzı and having a total SiO_2 + Al_2O_3 + Fe_2O_3 percentage of more than 70%, type C that obtained from Soma Thermal Power Plant via Batıçim Cement Plant with specific gravity 2.27 and chemical composition of SiO2, Al2O3 and Fe2O3, quartz sand with an average grain size of about 200 µm and a maximum grain size of 400 µm, Super Plasticizer of the acrylic based polycarboxylic ether type Glenium 51, produced by BASF Construction Chemicals with specific weight of 1.1 kg/dm^3 , tape water that is suitable for drinking, Polyvinyl-alcohol (PVA) fibers (The properties of the PVA fiber are shown in detail in table1) and nano silica solution from (Biyotez factory) with 30% concentration, then the concentration of the solution have been reduced by adding water to get the value we want which is (2%) in order to use it for curing.[5]

Table 1. Properties of PVA fiber

Fiber type	**PVA**
Nominal tensile strength (Mpa)	1620
Density (Kg/m3)	1300
Length (mm)	8
Diameter (µm)	39
Young’s modulus (GPa)	42.8
Rupture –Elongation Rate (%)	6.0
Specific weight	1.3

2.2. Mix proportions and samples perpetration

The ratios of materials used in ECC blends are shown in table 2.

Table 2. Proportions of materials used

Mixing Ratios	**ECC-F (1.2)**	**ECC- C (1.2)**
Cement (PC)	1	1
(FA-F)/PC	1.2	-
(FA-C)/PC	-	1.2
Water /(FA+PC)	0.32	0.32
Sand /(FA+PC)	0.36	0.36
SP (kg/m3)	4	11.5
PVA Fiber (Volume, %)	2	2

Firstly, all components were weighed before mixing. Dry mixing of Portland cement, fly ash and quartz sand with low speed (100 cycles/min) except PVA fibers for 1 minute. After that, water was added mixing continued for 2 minutes with speed (100 cycles/min), with speed of (150 cycle/min) super plasticizer were mixed with water and added to the pervious mix (mixing for 3 minutes) then PVA fiber were added and mixing continued for 3 minutes.

The prepared mixtures casted in 40 x 40 x 160 mm prism for flexural test and 50 x 50 x 50 mm cube for compressive strength test.

After casting, the samples were stored in the mold for 24 hours, then transferred to plastic bags for 28 days at 23 ± 2 ° C and 95 ± 5% humidity conditions.

On the 28th day, the maximum strength value of 3 samples was found under compressive loads and 3 samples under flexural loads. By applying a load of up to 85% of the average strength found, the maximum strength values were obtained by applying load-unload-load to on 3 samples. The rest of the samples: half of them were submitted to the pre-damage level by the load of the pre-damage and half were left without damage. Damaged and undamaged samples were cured in water as a reference and with 2% Nano silica solution for 7, 30, 60 and 90 days. At the end of the specified curing periods, at least 3 samples were removed at each time to determine whether the strength values of the damaged samples were approaching the undamaged strength values of the damaged samples and the strength values of the undamaged samples were increased.

Thus, for a single mixture in total 54 samples for flexural and 54 samples for compressive tests were produced. For each mixture, a total of 108 samples were produced so for the two mixtures a total of 216 samples were produced.[5]

3. RESULTS AND DISCUSSION

There are several potential causes of the self-healing/sealing phenomena:

- Formation of calcium carbonate or calcium hydroxide.
- Blocking of cracks by impurities in the water and loose concrete particles as a result of crack spalling.
- Hydration of previously unhydrated cementitious materials.
- Expansion of the hydrated cementitious matrix in the crack flanks. [10]

The compressive strength of ECC samples decreases with increasing fly ash content. This is because the percentage of cement in cementitious material decreases, leading to a reduction in the quantity of products that dominate compressive strength. However, fly ash is usually considered as a useful component of long-term strength development in concrete due to its pozzolanic properties. Secondary hydration of fly ash is very slow, so it only reaches a very limited reaction level at the age of 28 days. Thus, fly ash may remain in the system as inactive in the initial phase. In later ages, the contribution of fly ash to compressive strength may become more pronounced. [11]

After curing (water and nano silica immersion) half samples where submitted to the pre damage load and half remain without damage then all the samples where cured in water and nano silica for (7, 30, 60 and 90 days).

At the ages of 7, 30, 60 and 90 days, the compressive strength test for cubic specimens were applied following ASTM procedures. [6]. Table 3 and 4 shows the compressive strength results for samples made with FA/F 1.2 and FA/C 1.2.

It can be seen from the tables 3 and 4, the compressive strength of samples in 28 days for all the preloaded and unloader samples that made with FA/C1.2 shows higher result that samples made with F1.2 and at the ages 60 and 90 days high amount of strength gain was achieved by both FA/F and C but still FA/C is showing the highest result, this because the advance in hydration and pozzoline reactions of FA in general and due to the small particles size of FA than cement which can fill the space among the cement grains (filler effect), improving the particles distribution of cementitious system and forming dense micro-structure. However, the highest strength gain was 57.27 Mpa (for undamaged samples) from FA/C 1.2 mixture and 47.83 Mpa (for damaged samples) from FA/C 1.2 mixture after 90 days of curing with nano silica. The high strength should be correlated not only to fineness but also to the self – cementitious activity of class C fly ash. The lime content of FA seems to contribute to the strength of ECC mixture. Nerveless, all mixtures exceeded the nominal compressive strength for normal concrete (30Mpa) at the age of 28 days which is an acceptable value for most of construction practices.

The tensile test is to be the most accurate method to confirm the strain hardening behavior of composite as quasi – brittle fiber reinforced composite can potentially show apparent strain – hardening behavior under flexural loading depending on the specimen geometry. However, previous studies demonstrate that deflection capacity under bending can be correlated with tensile strain capacity when the material is truly strain hardening [6], therefore in this study, it was decided to use the three point bending test to investigate the flexural strength and ductility of ECC mixtures. During the three -point bending test, in all ECC specimens, the first crack was observed at the tensile face in the mid-span. As flexural stress increased, multiple cracks with small spacing and tight widths developed and propagated from the first cracking point. When the fiber bridging strength is reached for one of the micro cracks, bending failure resulting in localized deformation occurred at that part of ECC specimen. As the modulus of rupture (MOR) was approached, one of the cracks inside the mid-span started to widen leading to complete failure.

The test results in terms of flexural strength (MOR) and ultimate mid-span deflection at the peak stress at the end of 7, 30, 60 and 90 days of curing are displayed in Table 5 (for FA class F1.2) and Table 6 (for FA class C1.2). The flexural performances of ECC mixtures were calculated by the results of three-point bending measurements.

It is important to note that the flexural strength test results varied 12.68 Mpa (for F class FA) and 10.45 Mpa (for C class FA) after 90 days of curing with nano silica solution for undamaged samples and 10.48 Mpa (for F class FA) and 9.57 Mpa (for C class FA) after 90 days of curing with nano silica solution for damaged samples, this showing that increase in the values of flexural strength of C_ECC was not so drastic compared to the values of F_ECC as in the compressive strength test results. Moreover, for all specimens, no significant flexural strength gain was observed. The most probable reason for this trend may be attributed to the fact that flexural strength is governed by more complex material properties, such as tensile first cracking strength, ultimate tensile strength and tensile strain capacity, particularly in the case of strain hardening cementitious materials [6]. Among all the supplementary cementitious materials, F_ECC showed the highest deflection capacity, therefore ductility, at all ages. The improvement in the mid-span beam deflection capacity with the use of Class-F FA can be attributed to the fact that the addition of Class-F FA has a tendency to reduce PVA fiber/matrix interface chemical bond and matrix toughness while increasing the interface frictional bond, in favor of attaining high tensile strain capacity. However, although it is not sure, the overall decrease in the mid-span beam deflection capacity for C_ECC specimens might be associated with higher lime content which in turn causes enhanced fracture toughness, bond strength and the chemical bond between mortar matrix and fibers.[6]

Table 3. Compressive strength results for ECC-F1.2.

ECC-F1.2(28)				
	Damaged		***Undamaged***	
	Water	***NS***	***Water***	***NS***
28	28.46	28.46	28.46	28.46
28+7	34.36	34.87	37.69	38.73
28+30	42.27	42.85	43.82	45.78
28+60	42.76	43.18	44.21	47.28
28+90	43.18	43.72	44.92	49.87

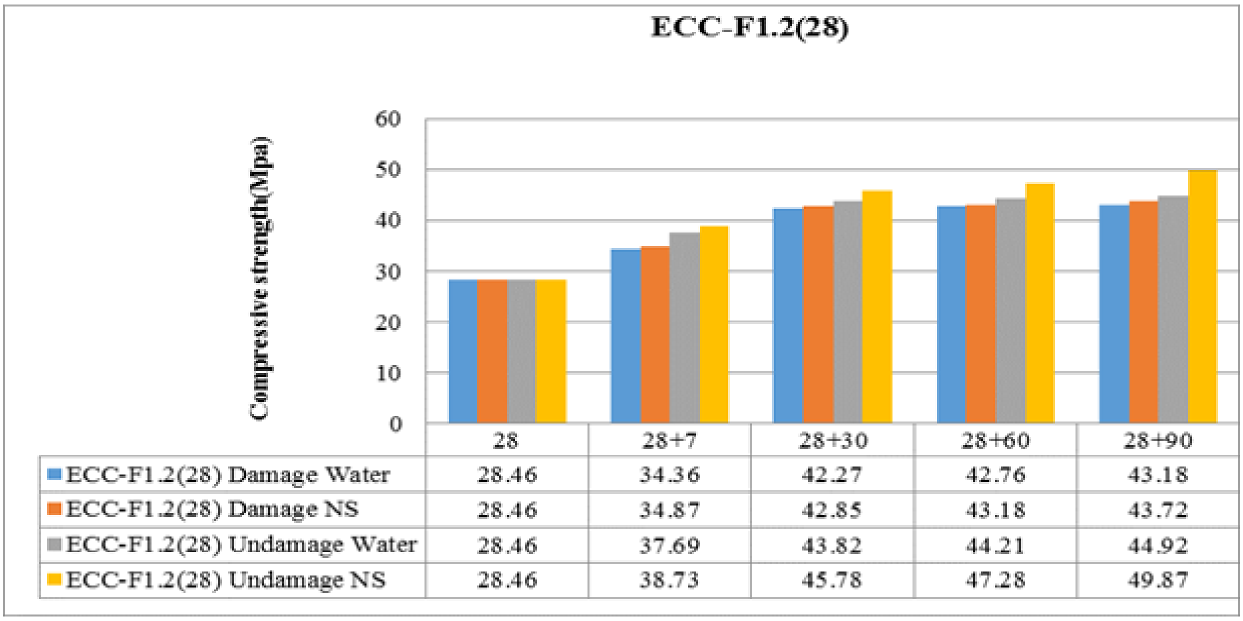

Fig 1. Compressive strength values of ECC-F (1.2) samples

Table 4. Compressive strength results for ECC-C 1.2.

	ECC-C1.2(28)			
	Damaged		***Undamaged***	
	water	***NS***	***Water***	***NS***
28	36.84	36.84	36.84	36.84
28+7	37.6	38.45	39.36	41.91
28+30	38.36	43.86	45.51	49.93
28+60	43.13	47.26	51.28	53.29
28+90	46.52	47.83	52.89	57.27

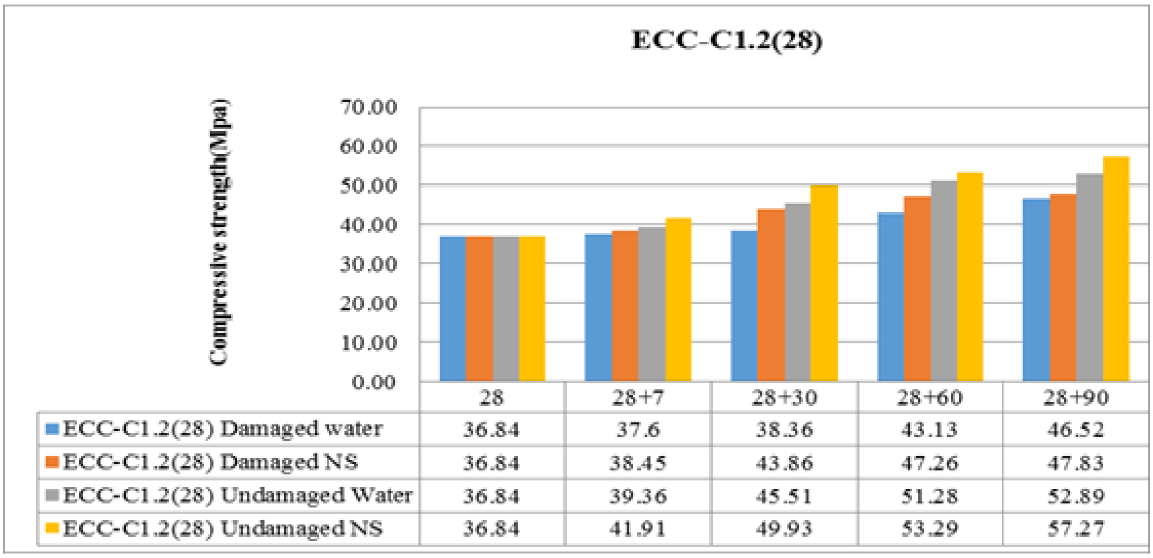

Fig 2. Compressive strength values of ECC-C 1.2 samples

Table 5. Flexural strength results for ECC-F 1.2.

	ECC-F1.2(28)			
	Damaged		***Undamaged***	
	Water	***NS***	***Water***	***NS***
28	9.67	9.67	9.67	9.67
28+7	9.82	10.14	10.25	10.52
28+30	10.08	10.27	10.38	11.53
28+60	9.84	9.95	11.11	11.81
28+90	10.44	10.48	11.75	12.68

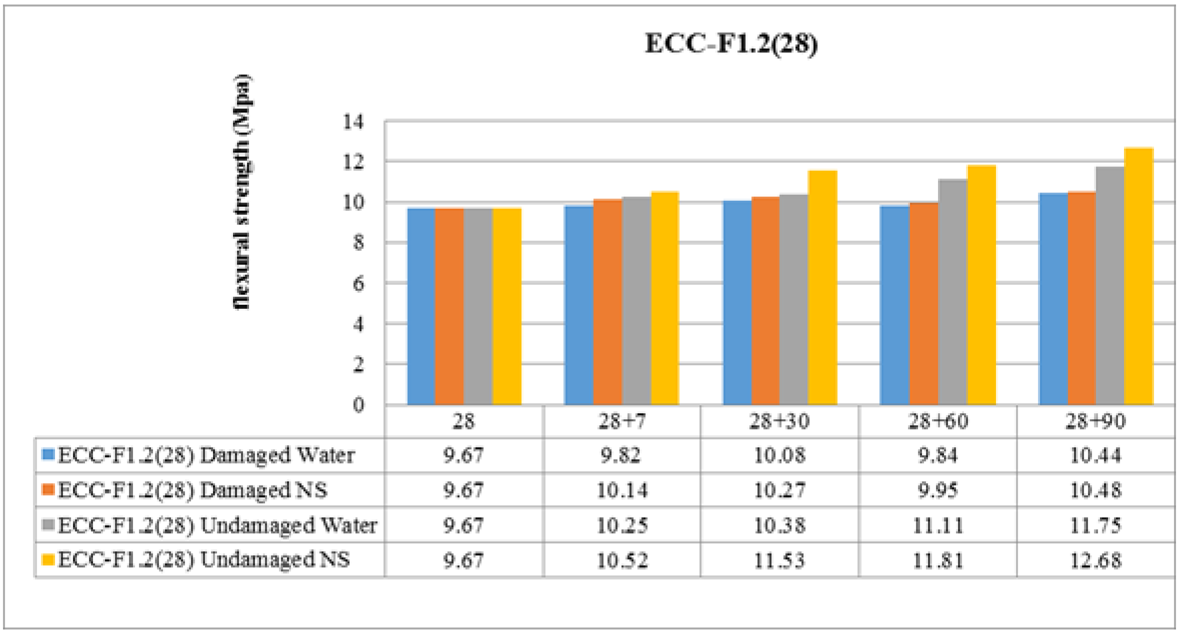

Fig 3. Flexural strength values of ECC-C 1.2 samples

Table 6. Flexural strength results for ECC-C 1.2.

	ECC-C1.2(28)			
	Damaged		*Undamaged*	
	Water	*NS*	*Water*	*NS*
28	7.09	7.09	7.09	7.09
28+7	7.66	7.94	8.49	9.77
28+30	7.95	8.02	8.76	9.92
28+60	8.28	8.64	9.27	10.18
28+90	8.54	9.57	9.91	10.45

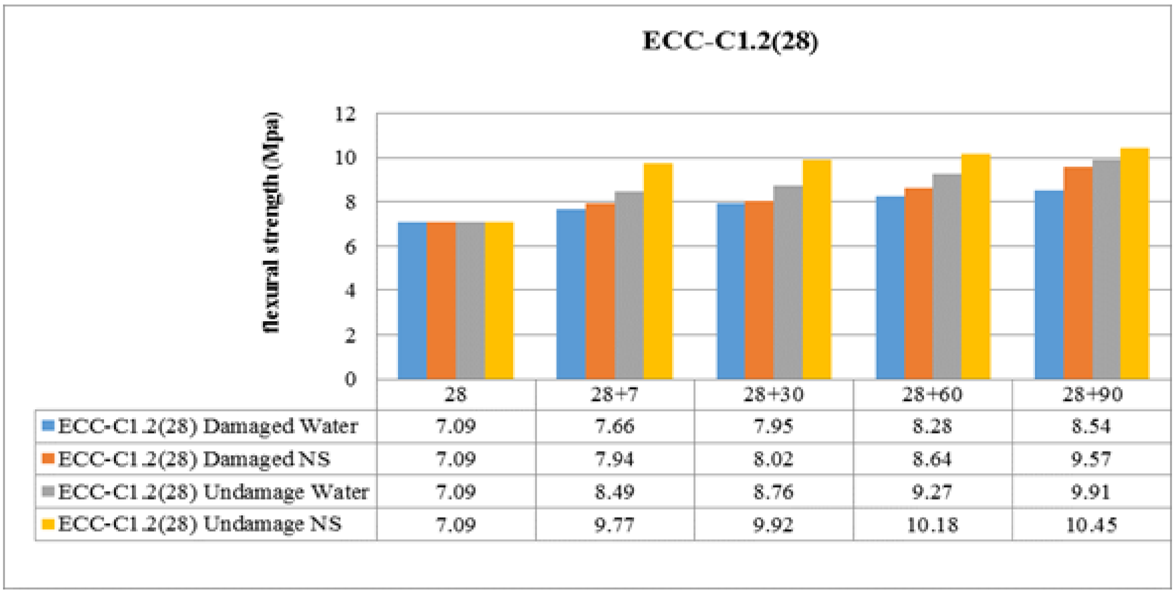

Fig 4. Flexural strength values of ECC-C 1.2 samples

5. CONCLUSION

Self- healing cementitious materials have the ability to significantly improve the durability and design life of concrete structures. This in turn will reduce the environmental impact of the cement and concrete industry by reducing global demand for cement and reducing the full cost of life of concrete structures by reducing the need for inspection, maintenance and repairs. For this reason, the self-healing behavior of a series of pre-cracked ECC specimens incorporating different SCMs (Class-C and Class-F fly ashes) investigated in this paper. To generate micro cracks, the compressive and flexural test with preloading deformation levels were chosen and up to failure. The pre-determined deformation levels were introduced to ECC mixtures at the age of 28 days, and specimens were further exposed to water curing conditions and Nano silica curing conditions up to 28 +7, 28+30, 28+60 and 28+90 days. In order to observe the effects of different SCMs on the self-healing capability of ECC mixtures.

As a matter of fact, this could confirm the assumption that self-healing capacity of cementitious composites does not represent only the capacity to seal/heal the crack but as promotes the increasing of the bonding capacity of the fibers with the cement paste due to the increasing of the fracture energy to pull-out a single fiber. At the end of the specified curing periods.

The main idea of this study is to determine whether the strength values of the damaged specimens are approaching to the undamaged strength values and whether the strength values of the undamaged specimens increased.

The results indicate that the role of nano-silica is not limited to the effects of pozzolanic or filler effects, but it also makes the hydration faster due to its ultrafine nature.

II. ACKNOWLEDGMENT

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