INFLUENCE OF CRACK WIDTH ON HEALING PERFORMANCE AND MECHANICAL PROPERTIES OF MICRO-ORGANISMS BASED SELF HEALING CONCRETE

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Received: 12.05.2021 / Accepted: 02.06.2022 / Revised: 30.07.2022 / Available online: 15.12.2022

DOI: 10.2478/jaes-2022-0019

KEYWORDS: Self healing concrete, crack width, Micro-organisms, Healing rate, Compressive & tensile strength, SEM.

ABSTRACT:

Self healing concrete are the effective methods for solving concrete deterioration and improving durability. Keeping in this view, an experimental study is conducted to evaluate the strength and healing performance of concrete made with 4% fiber for all mixes and Effective Microorganism-1 (Expounded Cracks Healing Agent) of different percentages 0%, 2%, 4% and 6%, 8% and 10%. In this connection, 108 cylinders & 54 cubes of six mixes are prepared. Workability of six mixes lies between 1mm - 38mm which is increasing by the increase of EM-1.The workability of fresh concrete using W/C ratio 0.4 is evaluated. After performing slump test, mix the all ingredients of concrete and cast the cylinders and cubes. Poured cylindrical and cubical specimens are left for different curing ages at 7, 14 and 28 days. After curing, splitting tensile strength test is performed on cylindrical specimens only and compressive strength on hardened concrete cylinders and cubes are tested and then checked the air content ratio of all six mixes which is within the acceptable ranges. After testing the cubes and cylinders are again kept in water for curing to check rate of healing and then checked the microstructure by SEM images. Cracks are small due to the use of fiber addition. By the use of EM-1, cracks can be healed. Maximum healing of crack width is between 0.04 mm to 0.07 mm if cracks width exceeds from 0.20 then it is difficult to restore. Results concluded that microorganism based self healing concrete is suitable at 6% addition in concrete which is suitable for humid environment and hydraulic structures where high strength and voids less concretes are required. Chopped strand mat can be used where concrete can be used without reinforcement.

1. INTRODUCTION

Concrete is basically a manmade construction material that is commonly used in construction consists of cement, fine aggregate (sand), coarse aggregate (crushed stone) and specific amount of water. After adding water hydration process starts and release some energy as a result hardened concrete with the passage of time (Cuenca et. al., 2017; Durga et. al., 2021). Self healing concrete is a effective technology to heal the cracks and reduce crack width which happen after the application of loads. Different fibers react differently as the shape of fiber maters. Powder like fibers improve the binding and wrinkle properties but thread like fibers improve the strength and durability properties of concrete. By the addition of fibers, cracks can be reduced for a longer period if small cracks occur at a certain limit by the addition of micro-organisms can be healed (Feng et. al., 2019, 2021).

Cracks have been developed in Concrete-based structures which may cause so many reasons like loading, environmental issues. As a result of the impurity penetration, the cement's hardness is decreased to mix. (González et. al., 2020; Gupta, 2022). Concrete, for example, loses its durability as a result of cracking, making it more prone to corrosion (Huynh et. al., 2017).

Self-healing elements can be added to the concrete mix to help with this. By minimising the width of cracks, these materials will improve the durability of concrete (Hermawan et. al., 2021; Li, Victor C., et. al., 2017; Hamidah et. al., 2022).

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The Self-Healing Process in Concrete may result by adding cementitious material with the ability to re-establish the strength of cracked materials (Islam et. al., 2022). To determine the healing rate at a percentage of EM-1, the healing agent (Microorganism EM-1) can be put to concrete in various proportions (Li, Victor C., et. al., 2007; Luo et. al., 2016; Menon et. al., 2019). Many studies have shown that implementing artificial techniques improves the self-healing phenomenon of concrete (Mousavi et. al., 2019; Mihas et. al., 2012). When crystalline admixtures are used in concrete, they produce better outcomes when subjected to water immersion circumstances (Mirshahmohammad et. al., 2022; Nodehi et. al., 2022). Many researchers have employed polymers and fibres with larger proportional ratios to improve the flexural strength of concrete (Reddy et. al., 2020; Rauf et. al., 2020). Microorganisms will be used as a healing agent in EM-1 (Effective Microorganism-1), a concrete built entirely of natural materials (Su, Qian, et. al., 2021). A microorganism will be employed as a healing agent named EM-1 in fibrous concrete, which is entirely constructed of natural materials (Shen et. al., 2021). Effective Microorganism is a unique combination of bacteria, yeasts and fungi used to activate and balance the naturally diverse microbiology of nature. With the passage of time, bacteria will be developed by this chemical process in concrete which will help to repair the concrete (Thao et. al., 2009). These microorganisms are entirely natural and can be found in the environment, with many of them also being used in food preparation (eg Lactic acid bacteria in Yoghurt) (Tan et. al., 2022). EM-1 is frequently employed in environment protection for waste decomposition and, most crucially, waste recycling, producing microorganisms in both solids and fluids (Zhang et. al., 2019, Xu et. al., 2018).

Yang D. et al. (2022) used Na_2SiO_3, colloidal silica, and tetraethyl orthosilicate as core materials to study the effects of self-healing microcapsules with different volume fractions on concrete by using the static mechanical test, ultrasonic measurement, capillary adsorption test, and optical microscope (Yang et. al., 2022; Yazici et. al., 2022; Yazici et. al., 2022. Zehtab et. al., 2022 also took Na_2SiO_3 as the core material, carried out adsorption measurement and X-ray diffraction analysis during the healing period, so as to quantify the crack self-healing effect and qualitatively describe the reaction between the core materials and cement base. The authors also designed the wall material, core material, and particle size of the concrete self-healing microcapsule and characterized its morphological structure and composition by scanning electron microscopy and energy-dispersive X-ray spectroscopy (Zaerkabeh et. al., 2022). We studied the influence of microcapsules on cement-based materials and the strength recovery performance of mortar materials under complete failure and analyzed the best factor combination of microcapsule self-healing concrete under different dosages (Zhu et. al., 2021).

However, previous studies mainly concentrated on obtaining the best factor combination of microcapsule self-healing concrete through the index of strength recovery. Although it combines the acoustic performance recovery of microcapsule self-healing concrete under high-damage conditions, the characterization index is single. It can be seen from some literatures that the healing time also has an important impact on the self-healing effect of concrete with Na_2SiO_3 as the healing agent (Zhang et. al., 2020).

2. MATERIALS

In this investigation, M-30 grade concrete was prepared with a required strength of 30 MPa (N/mm^2) which is determined by using the procedures recommended by the American Concrete Institute (ACI 211.1-91). The amount of water is needed to make 1 m^3 M30 concrete is estimated to be 172.42. According to clause 3.1.1 of IS 10262, the water-cement (W/C) ration is fixed at 0.4 based on the grade of cement employed in this study (2009).

2.1 Cement

Concrete is prepared with OPC of grade 43. The specific gravity of this cement was found according to ASTM C-188, the fineness of cement was found according to ASTM C-786c/786M, the consistency of cement was found according to ASTM C-187, and the setting times of cement were found according to ASTM C-191 which is shown in Table 1 and detail chemical composition of cement is given in Table 2.

Description	Values
Specific gravity	31.5
Fineness of cement	90%
Consistency	27%
Initial setting Time	105min
Final setting Time	505min

Table 1. Physical properties of Cement

Sr. No	Constituents	OPC % by weight
1	Lime (Ca O)	64.63
2	Silica(SiO_2)	21.28
3	Alumina(Al_2O_3)	5.60
4	Iron Oxide (Fe_2O_3)	3.36
5	Magnesia (Mg O)	2.06
6	Sulphur Trioxide (SO_3)	2.14
7	N_2O	0.05
8	Loss of Ignition	0.64
9	Lime Saturation Factor	0.92
10	C_3S (Calcium Tri-Silicate)	52.82
11	C_2S (Calcium Di-Silicate)	21.45
12	C_3S (Calcium Tri-Aluminate)	9.16
13	C_4AF (Calcium Tetra Alumina Ferrite	10.2

Table 2. Chemical composition of Cementitious material

2.2 Fine Aggregates

Lawrancepur sand with loose density 1437.41 Kg/m^3 (ASTM C-29/M-29), compacted density 1612.23 Kg/m^3 (ASTM C-29/M-29), fineness modulus of sand 2.35 (ASTM C-136), specific gravity 2.76 according to ASTM C-128 was found, water absorption 1.21 % according to ASTM C-128 and Voids 10.84 % (ASTM C29/M-29).

2.3 Coarse Aggregates

Crushed stone (Coarse Aggregate) with loose density 1494.88 Kg/m^3 and compacted density 1611.83 Kg/m^3 and voids 10.84 % are found according to ASTM C-29/M-29, fineness modulus of sand 6.93 according to ASTM C-136, specific gravity 2.73 according to ASTM C-128 was found, water absorption 1.81 % according to ASTM C-128.

2.4 Water

Water is the necessary part of construction. If the building's water quality isn't maintained, it will quickly deteriorate and become obvious like sulphate attack and chlorine effect. The core material of concrete is cement in construction. In the manufacture of cement concrete, water plays an important function. All parameters of concrete like hydration process, strength, workability, and general durability are all governed by water. One of the most essential aspects of sustainable concrete is its durability. Curing has played a vital role in the formation of microstructure. Salts and solid materials should be removed from water by sedimentation. Concrete is typically made with tap water.

2.5 Chopped Strand Mat (Fiber)

Chopped strand mat AC 200 is used which bound, specifically designed for "corrosion resistant" application and where maximum laminate clarity weather-ability and durability are required. Density of fiber is 300g/m3 and nominal weight per kg is 32kg. The best quality is a random fiber mat that provides equal strength in all directions and provides a good binding ability in hydraulic structures. Fiber is shown in Figure 1.



Figure 1. Microscopic View of Chopped Strand Mat (Fiber)

2.6 Effective Micro-Organisms

EM-1 is used as a healing agent in this study because it is essentially for soil and concrete conditioner that improves the structure durability which is shown in Figure 2.



Figure 2. Sample of Effective Micro-Organism

3. METHODOLOGY

In this study, different mechanical properties are evaluated like workability, compressive strength and tensile strength of concrete by adding the EM-1 with different percentages (0%, 2%, 4%, 6%, 8%, 10%) and 4% fiber (chopped strand mat) for all mixes. Also check the rate of healing at each level.

3.1 Mix Design

Two types of molds were prepared. Type I mold with dimension (6"x6"x6") were casted for compression test. Type II mold 6" dia. x12" was casted to investigate the crack behaviour from compression and tensile test. Mixing ratio which is derived after a calculation according to ACI 211.1 for this mix is 1:1.25: 2.25 with w/c ration 0.5.

where:

1= Cement by weight
1.25 = Fine Aggregate (F.A)
2.25 = Crushed Stone (C.A)

3.2 Mix Proportion

Mixing detail of six mixes with different ratios is shown in Table 3.

Mix Type	C (%age)	Fiber (%age)	F.A (%age)	C.A (%age)	EM-1 (%age)	W (%age)
M1	%	4	100	100	0	0.4
M2	%	4	100	100	2	0.4
M3	%	4	100	100	4	0.4
M4	%	4	100	100	6	0.4
M5	%	4	100	100	8	0.4
M6	%	4	100	100	10	0.4

Table 3. Mix Proportions

Where c is cement, F.A. fine aggregates (lawrancepur sand), C/A. coarse aggregates, EM-1 effective micro-organisms, Fiber chopped strand mat.

4. EXPERIMENTAL PROGRAM

After evaluating the physical properties of all materials and perform mix design, materials are measured as the required quantity and mixed it properly.

4.1 Slump Test

After mixing, slump test is performed (ASTM C-39) on fresh concrete to check workability of concrete which is shown in Figure 3.



Figure 3. Slump Test on Fresh Concrete

4.2 Air Content Test

Air content property is effective to address the crack width. Air content represents the presence of voids if voids are there in concrete automatically strength parameters affects and concrete face cracks in a shorter period.

4.3 Casting and curing of Molds

108 cylinders and 54 cubes were prepared for six mixes with same water cement ratio for all mixes. 54 cylinder is casted for tensile testing; 54 cylinder and 54 cubes for compression testing. After casting of molds, remove the concrete specimen from the mold and place in curing tanks at 7, 14 and 28 days as shown in Table 4 which is specially designed for the curing purposes.

4.4 Process of Introducing Damage

Concrete is heterogeneous material and the method is to overcome the damage is quite challenging task. Different concrete structures behave differently under loading. Concrete is not enough bonded material which can be deteriorated and cracked under loading. Healing of cracks is a difficult task but it can be controlled within the limits by adding some microcapsules or any bacterial content. Cracks occur on concrete surface with different width under instant and continuous loading. Cracks are of two types: natural cracks and artificial cracks. In both cases a small cracks occur around the major cracks. When initials cracks occur and not cured initially then structures faces more damage and increase in cracks width. When biological content in concrete meets water, improvement of strength can be attributed to the microbiologically induced special growth within the pores of concrete. More crack width can not be healing by using some microcapsules or any other content.

4.5 Compression Test

This test is performed (ASTM C-39) on hardened concrete at different curing ages like 7 days, 14 days & 28 days separately as shown in Figure 4. After compression test cracks appears on cylinders which is shown in Figure 5.



(a) (b)

Figure 4. Performing compression test on (a) Cube (b) Cylinder

4.6 SEM Analysis

SEM images have been taken to check the pore distribution. Chopped strand mat fiber is added in concrete for the proper mixing and bonding which shows that particles are properly connected with each other and void ratio are within the acceptable ranges.



(a) (b) (c)

Figure 5. Microscopic view of cracks on concrete samples (a) 4% addition of EM-1, (b) 6% addition of EM-1 and (c) 8% addition of EM-1



(a) (b) (c)

Figure 6. SEM Images of crushed concrete samples (a) 4% addition of EM-1, (b) 6% addition of EM-1 and (c) 8% addition of EM-1

Figure 5 shows that concrete cracks appear on samples and shown different behaviour at different percentages which is taken by the microscope for detail integration of the ingredients of concrete. And Figure 6 had shown the integration of cracked samples at different percentages of EM-1. Cracked samples have been taken from compression test and then perform SEM analysis for the integration of concrete materials.

4.7 Split Tensile Test

Split tensile test is performed (ASTM C-39) on hardened concrete at different curing ages 7, 14 and 28 days is shown in Figure 7.



Figure 7. Performing Tensile Test on Concrete Specimen

4.8 Again Curing after Compression Test

After applying compression test, cracks found on concrete surface and then place specimen to water again for self-healing purpose for same days curing and re-apply the compression test after measuring the self-healing rate. Measuring of crack width is shown in Figure 8.



Figure 8. Concrete Specimen in curing Tank for healing

4.9 Measuring Rate of Healing

After performing the compression test, samples are again immersed in water tank to check the rate of healing. First measure the crack width before healing at 7, 14 and 28 days which is shown in Figure 9, Figure 11, Figure 13 respectively and then after again curing and performed compression test again to check the crack width after healing at 7, 14 and 28 days shown in Figure 10, Figure 12, Figure 14 respectively.



Figure 9. Measuring cracks of Concrete Specimen before healing at 7 days

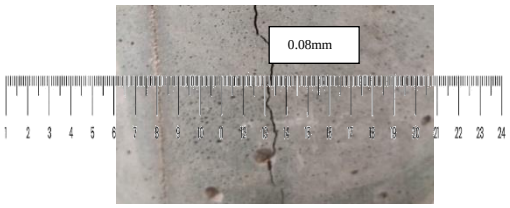


Figure 10. Measuring cracks of Concrete Specimen after healing at 7 days

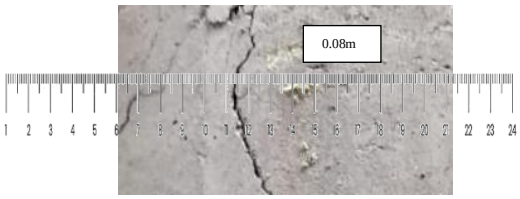


Figure 11. Measuring cracks of Concrete Specimen before healing at 14 days

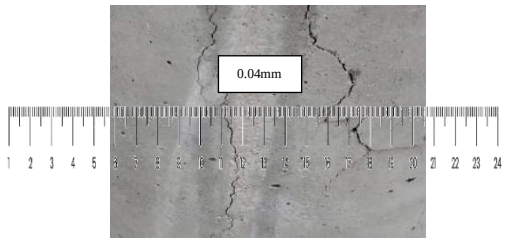


Figure 12. Measuring cracks of Concrete Specimen after healing at 14 days

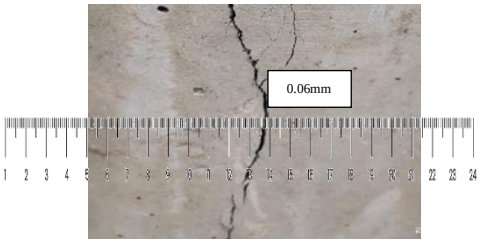


Figure 13. Measuring cracks of Concrete Specimen before healing at 28 days

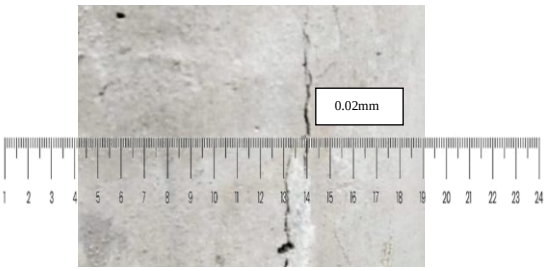


Figure 14. Measuring cracks of Concrete specimen after healing at 28 days

5. RESULTS AND DISCUSSIONS

5.1 Effect of Fiber and EM-1 on workability

Before pouring cylinders & cubes, Slump Test is performed on fresh concrete to check the workability of concrete which is shown in Table 4. By the addition of fiber and EM-1, workability increases. EM-1 is in liquid state and fiber is in powder form that covers the demand of water and maintains the quantity of water.

Sr. No	Mix Type	Slump Value (mm)
1	M1	1
2	M2	5
3	M3	9
4	M4	19
5	M5	27
6	M6	38

Table 4. Slump Test Results

W/C ratio is same of all the six mixes, but by using different percentages of EM-1 the slump increases by the increase of EM-1 because EM-1 is in liquid form, binding property of concrete is increased due to the mixing of fiber which is shown in shown in Figure 15.

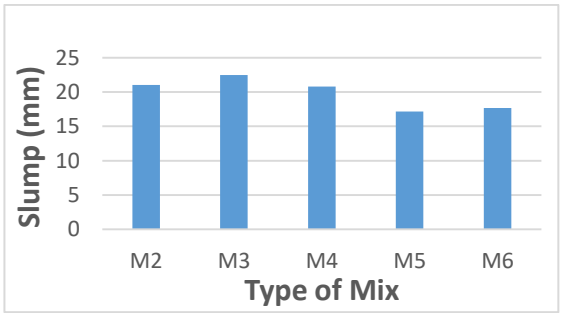


Figure 15. Slump Test Results

5.2 Effect of Fiber and EM-1 on Strength properties of concrete

Compressive strength is measured on both cylindrical and cubical specimens at 7 days, 14 days and 28 days. Compressive strength is increases by the addition of fiber and EM-1 which are equally beneficial for concrete strength.

5.3 Compressive Behaviour

5.3.1 After performing the compression test, cracks appear on concrete surface was very less in width and crack width is not more than 0.10. All cracks are longitudinal in direction.

5.3.2 Compressive strength (Cylindrical & Cubical) at 7 day. Results shows that the compressive Strength of cylindrical specimens is slightly decreased by the increase of EM-1 at 7 days and at 6% addition of EM-1 strength increased after that again strength decreases by the increase of EM-1. And compressive strength of cubical specimens is also decreased at 7 days when the amount of Fiber and EM-1 in increasing gradually then the value of Compressive strength slightly same as compare to control mix. Comparison of cylindrical and cubical specimen is shown in Figure 16.

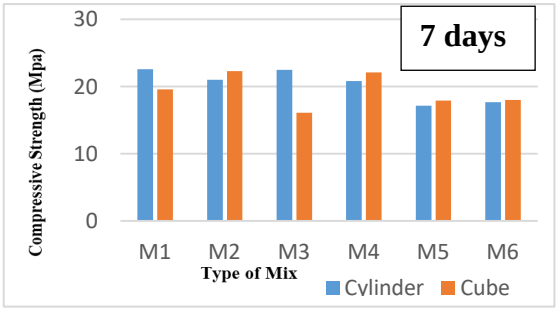


Figure 16. Compressive Strength of Concrete (cylinder & cube) at 7 Days

5.3.3 Compressive strength (Cylindrical & Cubical) at 14 day. Results concluded that compressive Strength of cylindrical specimens at 14 days by the addition of amount of Fiber and E.M-1 in increasing gradually then the value of Compressive strength is being gradually decreased which shows in table 6 that it is not more suitable for concrete work. It is better only for soil stabilization. And Compressive strength of cubical specimens at 14 days when the amount of Fiber and EM-1 in increasing gradually then the value of Compressive strength is gradually being decreased due to EM-1 properties which are not let to improve Compressive strength of concrete which is shown in Figure 17.

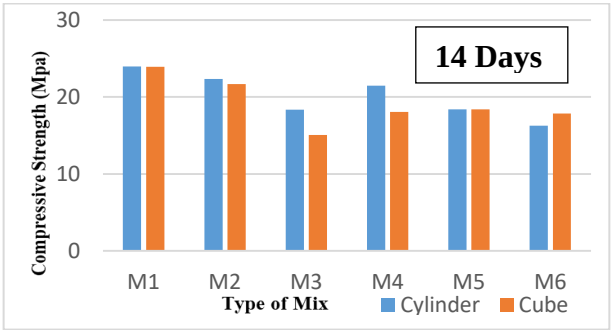


Figure 17. Compressive Strength of Concrete (cylinder & cube) at 14 Days

5.3.4 Compressive strength (Cylindrical & Cubical) at 28 days. Compressive Strength of cylindrical specimens at 28 days by the addition of amount of Fiber and EM-1 in increasing gradually then the value of Compressive strength is gradually decreased which show that combination of fiber with EM-1 is not good for concrete structure as shown in Figure 18. And Compressive strength of cubical specimens at 28 days when the amount of Fiber and EM-1 in increasing gradually then the value of Compressive strength is not sustained which is not good for concrete structure.

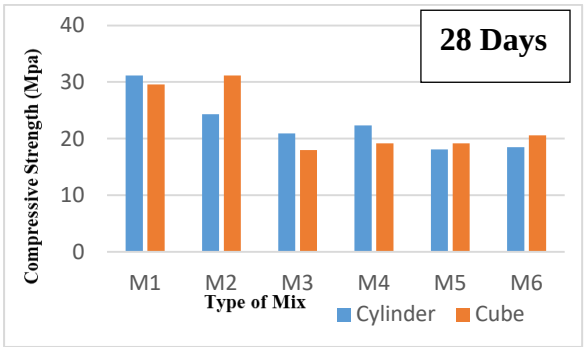


Figure 18. Compressive Strength of Concrete (cylinder & cube) at 28 Days

5.4 Tensile Behaviour

As tensile behaviour is concerned, cracks are wide and width is also bigger in size. It is very difficult to cure and heal. The only solution is to provide reinforcement to reduce the chance of cracks. As we all know, concrete is too weak in tension so that it is negligible in concrete structure designing in tension zone. To bear the tension we provide different type of steel bars at different spacing required in design. But in this research we measure the Tensile Strength of this fibrous concrete. There are different types of mix of concrete were prepare to test and to make graph for analysis. That graphs are being shown in Figure 19.

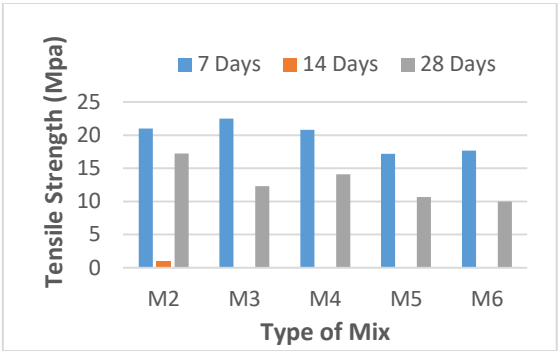


Figure 19. Split Tensile strength of concrete at different curing ages

5.5 Again Curing of Specimens after Cracks

Put all samples into water to re-curing and self-healing purposes. We found some cracks like columnar, shear in concrete specimens like cylinder and cube. Here we are going to analysis of cracks and strength which is measured before putting samples in water after producing cracks by applying a gradually load on samples. This load is applied by a machine

made by Controls which has a capacity of 2000 KN load. This machine has a zero error and was calibrated in April 2021, after one year it is compulsory to calibrate the machine and remove error if found.

5.6 Comparison of Compressive strength before and after healing at 7days, 14days and 28days

Compression test is performed on concrete cylinders then place again for curing to heal the cracks. After curing again compression test is performed and then get the percentage difference of concrete samples before healing and after healing at different curing days 7days, 14 days and 28 days which is shown in Figure 20.

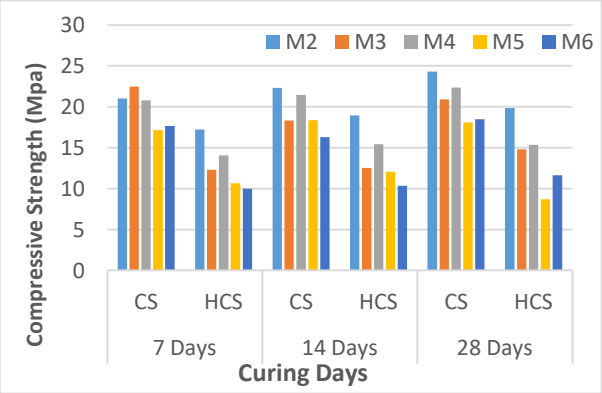


Figure 20. Comparison of compressive strength before and after healing at 7 days, 14 days and 28 days

Where: HS used for compressive strength before healing and HCS is used as healed compressive strength. In Figure 20 all strength shows and strength increased at 6% by the addition of fiber before and after healing which is concluded as the comparison of control mix.

5.7 Comparison of Compressive strength before healing and after healing at 7days, 14days and 28days

Difference between compressive strength before healing and after healing at 7days, 14 days and 28 days are shown in Table 5, Table 6 and Table 7 respectively.

Type of Mix	Compressive Strength Before Healing	Compressive Strength after Healing	Difference in Compressive Strength(%)
	Curing Days (7 days)		
M1	22.6	-	-
M2	21.01	17.23	56.44
M3	22.49	12.31	54.76
M4	20.81	14.08	67.66
M5	17.16	10.65	62.09
M6	17.68	9.98	56.4

Table 5. Difference between compressive strength before healing and after healing

Type of Mix	Compressive Strength before Healing	Compressive Strength after Healing	Difference in Compressive Strength(%)
	Curing Days (14 days)		
M1	23.98	-	-
M2	22.33	18.95	94.88
M3	18.39	12.55	68.51
M4	21.46	15.45	72.03
M5	18.38	12.05	65.58
M6	16.28	10.34	63.53

Table 6. Difference between compressive strength before healing and after healing

Type of Mix	Compressive Strength before Healing	Compressive Strength after Healing	Difference in Compressive Strength(%)
	Curing Days (28 days)		
M1	30.18	-	-
M2	24.30	19.87	81.77
M3	20.90	14.82	70.94
M4	22.35	15.34	69.15
M5	18.11	8.71	48.09
M6	18.49	11.66	63.08

Table 7. Difference between compressive strength before healing and after healing

5.8 Comparison of Crack width before healing and after healing at 7days, 14days and 28days

Crack width is measured before healing and after healing at different curing days which is shown in Figure 21.

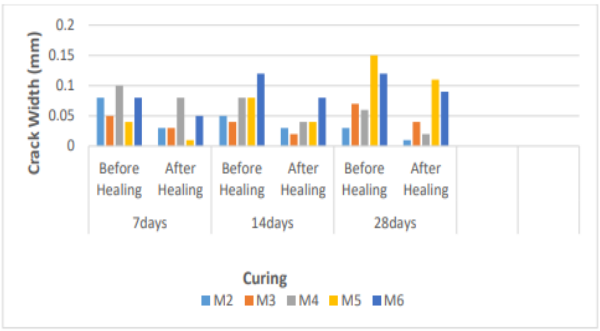


Figure 21. Comparison of Crack width before healing and after healing at 7days, 14days and 28days

5.9 Effect of Fiber on air content of concrete

The main evaluation indexes of the air content are to check the voids in the presence of fiber. By the use of fiber, cracks and are very thin and reduced. Measuring the air content is effective property to address the crack width which is shown in Figure 22. Fiber was added in concrete to improve the strength and binding properties. If voids are less, air content is reduced

in the presence of fiber as compared to the normal ordinary concrete.



Figure 22. Measuring air content on fresh concrete

Fiber is same for all the mixes so air content is almost same and no major effect of microorganism on air content. Air content is measured by filling the container and then dial gauge show the reading by pressing and pulling the gauge. Air content percentage is shown in Figure 23 which is not more than 2.5%. It can be measured by the formulae:

$$\text{Air Content (ac)} = \frac{Va}{Vv} \text{x } 100$$

where:

Va = Volume of air
Vv = Volume of voids

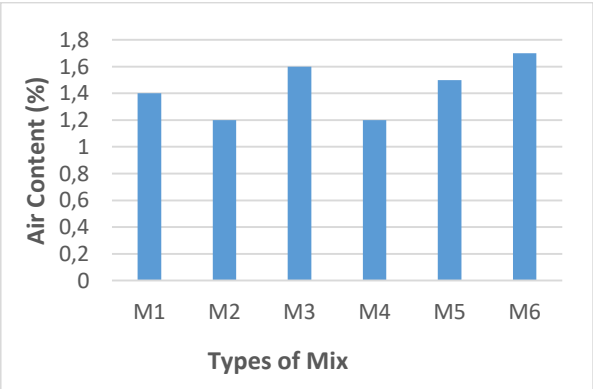


Figure 23. Measuring air content on fresh concrete

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Few results of this study have been drawn the following conclusions:

- Slump value of M1 is 1mm which indicates the lower workability of because of low w/c like 0.4. It is not much easier to work on this type of concrete. It is observed that the range of slump of M1 to M6 is between 1 mm to 38 mm which shows that concrete is much workable. By the increase of fiber and EM-1content, the workability was being improved gradually due to the EM-1.

- Compressive strength of concrete at 7 days are gradually increasing by the addition of EM-1. Maximum strength is observed at the replacement of 6% but the rate of healing is zero at 7 days. The loss of strength is 8% as compared to the ordinary concrete but healing response is good for all ages. At 14 and 28 days, strength is observed decreasing gradually by the addition of EM-1. Maximum strength is achieved at 6% EM-1 but healing rate is gradually increasing at 14 days and 28 days. Maximum healing is observed 13mm at 7 days and 23mm at 28 days of 10% addition. No major strength difference is observed at all ages after healing. Healed cracks are observed in crystalline form. After healing cracks, the comparison of compressive strength before healing and after healing cracks have been healed and reduce the crack width.

- Splitting tensile strength is not more than 1.75 MPa which is totally negligible in any case of designing a portion or element of concrete structure. It observed in this study is nearly equal to same which is adequate for concrete member.

- Fiber can be make a constant and increase the ration of EM-1 because fiber is not changing the strength of concrete and EM-1 is continuously changing healing rate of expounded cracks.

6.2 Recommendations

Further research and testing is recommended of self healing concrete by the addition of different fiber in addition of EM-1. It also recommended increasing the addition of EM-1 and fiber to get the better strength behaviour and healing performance of concrete.

6.2.1 Summary. Results concluded that the rate of healing will give the better response by the use of EM-1 in concrete and suitable for construction for healing of small cracks without compromising its strength. This type of concrete is used only in hydraulic concrete structure where crack is being produced and difficult to handled. These cracks are self cured by the micro-organism based concrete.

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