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COUPLED EFFECT OF BACTERIA AND FIBERS ON SELF COMPACTING MORTARS

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Abstract: Concrete is a widely used construction material all over the world due to its high strength properties and relatively low cost. With a variety of advanced features, self-compacting concrete has been used for a variety of constructions and infrastructures as a new smart building material. However, the formation of cracks in concrete is inevitable. For this reason, fiber reinforced bacterial concrete is used to avoid cracks. The fibers reduce the crack width by the action of bridging and bacteria can develop a filling material in that bridging portion. Thus, a composite material is formed which can heal the cracks, thus improving the strength and durability of concrete. In this paper, coupled effect of bacillus subtilis bacteria and steel fibers on self-compacting mortars was examined. The replacement of cement in self-compacting mortars with supplementary cementitious materials, such as fly ash, GGBS, silica fume results in reducing the heat of hydration, decreasing efflorescence and producing cost-effective and eco-friendly concrete. The coupled effect of bacteria and fiber resulted in better mechanical properties, durability properties and improved self-healing/repairing efficiency due to the formation of $CaCO_3$. The results also confirmed the presence of calcium carbonate precipitate, which has been analyzed by micro-structural studies viz., SEM and EDS.

Index Terms - Self-compacting concrete, Bacteria, Fibers, Fly ash, GGBS, Silica fume, Strength, Durability, SEM, EDS.

1. INTRODUCTION

Concrete is the most widely used construction material as it resists high compressive load and is used for the development of infrastructure in every country. Cement is the major constituent of concrete. Self-compacting concrete (SCC) is a streaming solid blend which could self-unite under its own weight. The profoundly liquid nature of the SCC makes it reasonable to put them in troublesome conditions and in areas with congested reinforcement [3]. Concrete is brittle in nature and subjected to cracking under shear and tensile stresses. Concrete cracks under sustained loading, freeze-thaw and shrinkage lead to cracking in concrete. Due to the formation of cracks, water and gases easily enter inside the concrete and come in contact with reinforcement and leading to the corrosion of reinforcing bars. This leads to the decrease in strength and durability of concrete. Hence, a suitable repair mechanism is essential.

In olden days, to increase the strength and durability of the structure, the cracks were repaired by using epoxy injection or latex treatment or by giving extra reinforcement to the structure during the design to ensure that the crack width stays within a permissible limit [3]. But these traditional systems have the chance of thermal expansion and environmental issues. To avoid these issues, a new concept of a self-healing mechanism has been incorporated.

A recent new technique using microbiologically induced calcium or calcium carbonate precipitation is based on the concept of bio-mineralization (self-healing mechanism). By adding bacteria to concrete, it produces calcium carbonate crystals which block the micro-cracks and pores in the concrete. Hence, bacterially induced calcium carbonate precipitation has been proposed as an alternative and environmentally friendly crack repair technique by researchers. Different researchers used various types of bacteria to produce bacterial self-healing concrete, such as Bacillus pasteurii, Bacillus sphaericus and Bacillus subtilis. These bacteria remain dormant within the concrete for up to 200 years.

When a crack appears in concrete and water enters through it, the spores of the bacteria start microbial activities. In the process of precipitation of calcite, the soluble nutrients are converted to insoluble calcium carbonate, which solidifies on the crack surface and seals the crack. Use of different fibers in such self-healing concrete also improves compressive strength, tensile and shears strength. It is well known that the addition of fibers reduces the crack width and also the number of cracks in concrete by virtue of bridging action [5]. The coupled effect of bacteria and fiber could result in higher repair efficiency, better mechanical properties and water resistance recovery [1].

Self-healing concrete is usually outlined because of the ability of concrete to repair its cracks autogenously or autonomously. It is also known as self-repairing concrete or bacterial concrete. With the development of sustainable cement manufacturing, the self-healing/repairing properties of concrete have received widespread attention. In several studies, both microorganisms and fibers played a vital role in promoting the self-healing ability of concrete. Particularly, some recent studies have tried to load microorganisms with fibers to improve the self-healing ability of concrete; and these studies believe that the combination of fibers and microbes accelerates the self-repair method. However, this method has not been characterised and also the mechanism has not been explored [1].

To solve the problem of cracking, self healing concrete has been developed to alternate historical guide repair, owed to the excessive fee of manual repairs and also the lack of ability to discover cracks in time. Concrete has natural restoration functionality for cracks with widths below two hundred microns. The self-produced healing of concrete can be generally attributed to boost hydration of un-hydrated cementitious materials and carbonation of steel ions. Mineral admixture or microcapsule loading chemical binder or crystalline additive has been added to recover the self-recuperation effectiveness of concrete. Even though they have been of low fee and environmentally pleasant, these mineral or chemical additives may best be used as soon as, and they would react right away after leakage.

The self-repairing technologies under microbial mineralization have distinctive benefits, as a result of microbial spores have greater resistance to harsh environments and may be kept for an extended time. It's importance mentioning that this technology has high self-repairing efficiency, especially due to the action of microorganism. In *Wang's* study, ureolytic microorganism spores might repair cracks with the crack width of 970 μm, and therefore the resistance of the repaired specimen to water improved 10 times. Sadly, in the development of urealysis of urea, ammonia gas is produced, which is unfriendly to the residents within the building. Another well-known technique is to use the respiration of micro-organisms to decompose organic matter and unleash the carbon to create carbonate. During this process of bio-mineralization, organic matter, like glucose and calcium lactate, is used as precursors. Moreover, the employment potency of metal ions also plays a very important role in the development of repairing effect [1].

In recent years, with the improvement of structural intelligence and biological science, microorganism self-healing technology for concrete cracks has become a research focus in our country and abroad [6]. The essential technique is to combine the microorganism self-healing agent meeting the necessities of cement-based materials in a very sure method. Once the cracks of cement-based materials occur, air and water within the surroundings enter into the cracks and activates the dormant microbes, and so calcium carbonate with definite bonding strength is induced by microbial mineralization, which is able to fill the cracks and block substance exchange between cement-based materials and external atmosphere.

Finally, the self-healing impact of cracks of cement-based materials is achieved [7-9]. Compared with ancient crack repair technologies, like surface treatment, grouting technology, epoxy resin or polymer mortar filling technique, a microorganism self-healing technology has the benefits of protecting the atmosphere, convenient operation and intellectualization [10, 11] the primary stated microbial mineralization method is used for the repair of concrete cracks, and also the strength and stiffness of repaired concrete improved to certain extent. However, once a micro-organism self-healing agent was directly added to the concrete, it had been tough for microbes to survive for an extended time as a result of the extremely alkaline atmosphere and the continuous compaction of pore structure within the concrete, therefore influencing the long-run self-healing effect of cracks. *Jonkers* et al., [7] directly added an alkalophilic bacillus into the concrete, and noticed that the number of existence of bacteria reduced by more than 90% in one month. He identified that the self-healing impact of concrete cracks by means of microbes could be greatly extended by the carrier technology. *Wang* et al., 12] used micro-encapsulated bacteria as a type of self-healing agent and carried out a self-healing impact in numerous environmental media with different proportions, and obtained the highest crack width that was healed up to 970 *μ*m. *Xu* and *Wang* [13] used low alkaline calcium sulpho aluminate cement doped with silica-fume as a protecting carrier for the bacterium. By embedding this bacteria-based self-healing method in concrete, the crack width of 417 *μ*m could be totally healed after water curing for 28 days. While positioned next with normal mortar, the regaining costs of compressive power and water tightness superior a 130% and 50% correspondingly.

Fibers are categorized into 2 types, i.e. natural fibers and artificial fibers. Fibers obtained from plants, animals, wood, wool etc. are thought as natural fibers. And the fibers which are man-made are thought as artificial or synthetic fibers and those are polyethylene, polyester, polyvinyl alcohol, asbestos fibers, ethylene vinyl alcohol etc. The employment of various types of fibers increases the mechanical properties of the concrete [14]. Several researchers have investigated the use of different types of fibers in self healing concrete. Kwon et al., [15] explained the crack healing capability of fiber reinforced cementitious materials by considering the various forms of fibers and results show that fiber reinforced cementitous materials precipitate crystalline particles into cracks and the air permeability ratio was also decreased.

Nishiwaki et al., [16] predicted the healing capacity of fiber reinforced cementitious materials by considering different kinds of fibers. Results show that the high polarity of the fiber composite features a higher rate of precipitate of calcium carbonate in a crack width equal to 0.3 mm. Also the water permeability reduced because of precipitation around fibers. *Snoeck*et al. [17] investigated the mechanism of self-healing of concrete materials when added with superabsorbent polymers and micro-fibers. Due to the addition of superabsorbent polymers, there was an increase in the healing properties of cracks.

Self-healing study of engineered cementitious composites showed that the fibers can develop the self-healing matrix by accelerating calcium carbonate precipitation [18, 19]. Glass fibers are light weight, cost-efficient and have high tensile strength [20]. Glass fibers in concrete are used since the 1950s. Use of glass fiber reinforced concrete (GFRC) considerably improves the architectural view of concrete buildings and is most cost effective when compared with other alternatives. Two basic materials, a concrete matrix, and excellent interaction make sure the notable mechanical properties of this material [21]. Several investigations were carried out to study the effect of steel fibers as a strengthening frame work on the mechanical properties and impact resistance [22]. Once steel fibers are integrated into concrete, they resist the circulation of cracks. Steel fibers triumph over any issues between close to surfaces of current micro-cracks, defer the break up improvement [23] and prevent damage unfold through reducing the damaged tip gap removal. This element is recognized as the spanning tool. The vitality of ingestion and feature an effect at the satisfactory of cement can be extended [24]. The addition of fibers in concrete to attenuate crack propagation [25] and to improve the tensile property [26] and also the technique of incorporation of bacteria for crack healing will aid to develop self-compacting concrete with improved mechanical and durability properties.

Based on the reported research, it is observed that there is less work done on the effect of coupled mechanism of bacteria and fibers on self-compacting concrete and mortar. Thus, in this study, investigations are carried out on self-compacting mortars with the addition of bacteria and fibers to understand the self-healing mechanism. Further, micro-structural analyses are also carried out. In this study, the self-compacting mortars with addition of supplementary cementitious materials, viz., fly ash of 25% and ground granulated blast furnace slag of 20% and silica fume of 5% along with optimum dosages of bacillus subtilis bacteria and steel fibers are prepared to carry out the investigations.

2. Experimental Program and Methodology

2.1 Materials and Mixes

Ordinary Portland Cement (OPC) of 53 grade was used. Here, OPC is replaced with some supplementary materials such as fly ash, GGBS (Ground Granulated Blast Furnace Slag), silica fume. Twenty five per cent of cement is replaced with fly ash, 20% with GGBS and 5% with Silica fume. Water to cement ratio of 0.45 is used in the mortar mixes for a slump range of 240 to 270mm.

In the present experimental investigation, Conplast SP 430 super plasticizer is used to improve the workability of fresh concrete. The physical properties and chemical composition of supplementary cementitious materials used in this study are represented in Table1 and Table2 respectively. Locally available fine aggregate with physical properties mentioned in Table3 was used. Potable water available in the laboratory was used for mixing and moist curing throughout the investigation. High tensile loose hook end steel fibers (SF) of length 35 mm, diameter 0.5mm and aspect ratio of 70 were used as mentioned in Table4. Bacillus subtilis bacteria, which is cultured in the college pharmacy laboratory, was used in liquid form. Bacteria are used in three different cell concentrations, namely 10^3, 10^5 and 10^7.

Table1: Physical properties of cementitious materials

Property	Cement	Fly Ash	GGBS	Silica Fume
Specific gravity	3.12	2.46	2.23	2.2
Normal consistency	32%	29%	42%	35%
Initial setting time	35 minutes	50 minutes	50 minutes	40 minutes

Table2: Chemical composition of cementitious materials

Oxide	Cement (%)	Fly Ash (%)	GGBS (%)	Silica Fume (%)
CaO	64.30	33.2	40.52	0.2
SiO_2	21.25	28.5	33	97
Al_2O_3	4.33	22.87	13.3	0.2
SO_3	3.70	4.67	8	0.15
Fe_2O_3	1.85	2.10	0.50	0.5
MgO	1.81	1.55	0.37	0.5
K_2O	0.71	0.94	-	0.5
TiO_2	0.13	0.62	-	-
Na_2O	0.17	0.35	-	-

Table3: Physical properties of fine aggregate

Physical test of Fine Aggregate	Results
Specific Gravity	2.66
Fineness Modulus	2.64
Zone	II
Bulk Density (Loose, Compacted) (kg/m^3)	1550, 1670

Table4: Steel fiber properties

Type of Fiber	Length (mm)	Diameter (mm)	Aspect Ratio (l/d)	Density (kg/m^3)
Steel Fibers (Hooked-end)	35	0.5	70	7850

Mix design of self compacting mortar was done by using the method proposed by S. Rao [27], [28], [29], which includes trail mixes and also followed European guidelines. For casting, cube specimens of size 70.6 x 70.6 x 70.6 mm were used. Mix details of the specimens are mentioned in Table5. For every mix, fresh properties (mini slump cone & mini v-funnel) were carried out and then mortar cubes were casted.

After 24hours, specimens were demoulded and tested. Fresh properties were listed in Table6. After curing for 28 days, specimens were tested for obtaining mechanical properties, durability properties and micro-structural analysis.

Table5: Mix design details of normal mix, bacterial mix, fibers mix, bacteria+fibers mix

Mix Designation	Binding Material
NM	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)
SF 0.3	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+SF (0.3)
SF 0.6	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+SF (0.6)
SF 0.9	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+SF (0.9)
SF 1.2	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+SF (1.2)
SF 1.5	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+SF (1.5)
B 10^3	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+B (10^3)
B 10^5	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+B (10^5)
B 10^7	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+B (10^7)
B 10^5 + SF 1.2	OPC (50%)+GGBS (25%)+FA (20%)+S.F (5%)+B (10^5)+SF (1.2)

2.2 Bacteria Culturing Process

2.2.1 Preparation of Nutrient Broth:

- Firstly, 1.3 grams of nutrient broth powder (agar) was weighed and transferred into a clean conical flask.
- Nutrient broth was dissolved in sufficient quantity of water and overall volume was made to 100 ml with water.
- Cotton plugs were applied to conical flask. Sterilization was done in autoclave at 121°c under 15 lb pressures for 15 minutes.
- Allowed the autoclave to cool. Removed the conical flask from the autoclave and stored at the room temperature.

2.2.2 Preparation of Bacteria:

- After the preparation of nutrient broth, very tiny quantity of bacteria (Bacillus Subtilis) was added into the conical flask and mixed thoroughly.
- Conical flask was placed in the incubator for the period of 24 hours.
- After 24 hours the conical flask was taken out from the incubator so that the bacterium was cultured (in liquid form).
- Bacillus subtilis bacteria cultured in liquid form is as shown in Fig.1
- Finally, cultured liquid bacteria were taken in required cell concentrations.

Fig.1 Cultured bacteria in liquid form (Bacillus Subtilis)

3. Results and Discussions

3.1 Fresh Properties

3.1.1 Mini Slump Cone

The mini-slump cone test is the most common method to check deformability. This test was carried out before casting the specimens using fresh self-compacting mortar mix. The mini-slump cone had a diameter of 100mm and 70 mm and a height of 60 mm.

Fig.2 Mini slump cone used in the experiment

Slump flow details of various mixes are presented in Table 6. FromTable6, it is observed that nominal mix showed better workability than mixes with the addition of steel fibers. In particular, the slump flow diameter for the mixes with steel fibers ranging from 0.3% to 1.5% was reduced. This decrease in workability may be attributed to micro scale particles of fibers and increasing the cohesiveness of fresh mortar. By using bacteria with different cell concentrations, slum results did not show much difference. So, we can conclude that bacteria addition does not affect the fresh properties (slump flow).

3.1.2 Mini V-Funnel

The mini V-funnel test is the most common method to check the viscosity. This test was carried out before casting the specimens using fresh self-compacting mortar mix. The mini V-funnel lasted for 7-12 sec. Results obtained are presented in the Table6.

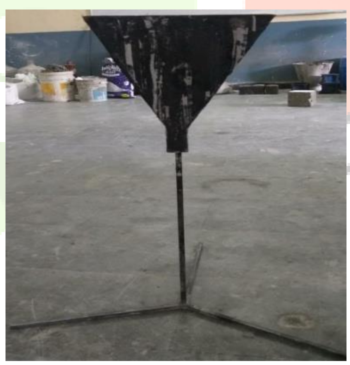

Fig.3 Mini V-Funnel used in the experiment

From the results, it is observed that slump flow time varies between 6 to 12 sec. We can say that the addition of supplementary materials caused better flowability than the mixes with the addition of fibers. With increasing fiber content, the flow time of the mix has been increased.

The insertion of fibers reduced the flowability, as expected. It is conceivable to conclude that using additives with a specific surface area greater than that of a cement particle (fibers), requires less water and super plasticizer is required to maintain the same degree of flow as an equal mix without fibers. By means of the use of bacteria with unique cellular concentrations, effects did not show lots distinction. So, we can conclude that bacteria addition does not have an effect on the fresh properties (flow time).

Table6: Fresh properties results

Mix	Slump flow (mm)	V-Funnel (sec)
NM	270	6
SF 0.3	265	8
SF 0.6	260	8.5
SF 0.9	250	10
SF 1.2	250	12
SF 1.5	245	13
B 10^3	260	11
B 10^5	265	11.5
B 10^7	265	12

3.2 Compressive Strength

The results of compressive strength of mortar obtained, when OPC is replaced with the ideal quantity of supplementary cementitious materials, and by adding steel fibers in five dosages (0.3, 0.6, 0.9, 1.2 &1.5) and bacteria in three different cell concentrations (10^3, 10^5& 10^7) are presented in Table 7 and Fig.4.

From results presented in Table 7, it is observed that when compared to the normal mix, addition of fibers and addition of bacteria gave good compressive strength. With the increase of the steel fiber percentage from 0.3 to 1.2, the compressive strength increased. After the addition of 1.5 percentage of steel fiber, the compressive strength decreased.

With the addition of bacteria, the compressive strength results did not vary but give good results when compared to that of normal mix. From the B10^3 dosage to B10^5, compressive strength increased. After that, the strength decreased at B10^7.

So, finally, from the results, it can be concluded that the compressive strength values increased till the optimum dosage. After reaching optimum dosage point, there is a decrease in compressive strength values.

The coupled effect, i.e., due to the combination of optimum dosages of bacteria and steel fibers gave higher compressive strength when compared to all mixed proportions (normal mix, mix with bacteria and mix with steel fibers).

Table 7: Compressive Strength results at 28 days

Mix Designation	Compressive Strength (MPa)
NM	35.52
SF 0.3	38.89
SF 0.6	40.22
SF 0.9	43.54
SF 1.2	46.65
SF 1.5	44.35
B 10^3	44.74
B 10^5	46.75
B 10^7	45.42
B + SF	52.5

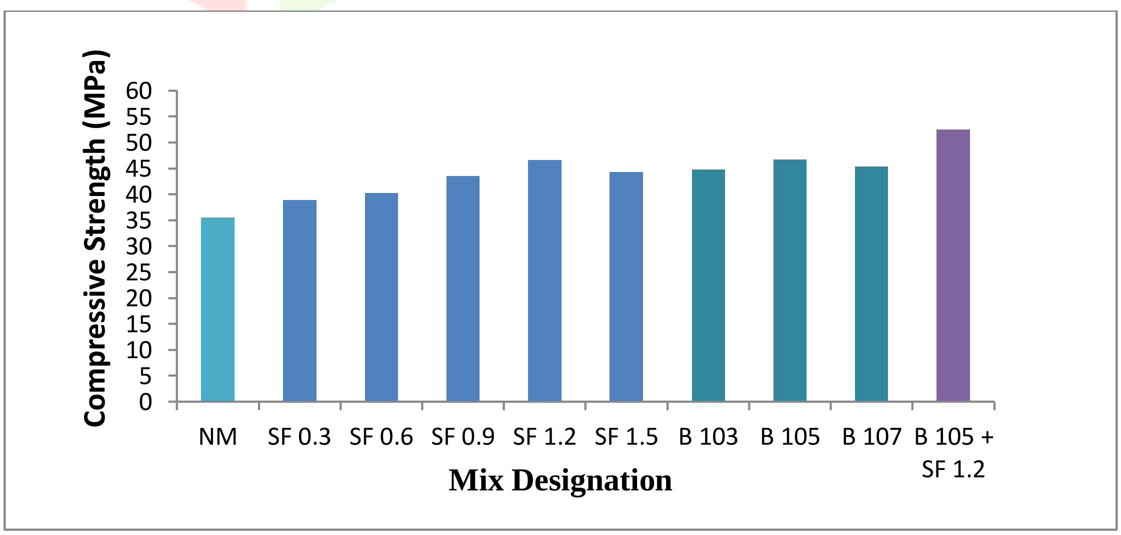

Fig.4 Compressive Strength results at 28 days

3.3 Self-Healing Observation Tests

3.3.1 Ultrasonic Pulse Velocity

UPV tests are conducted on the mortar samples with combination of bacteria and fibers. The UPV tests are conducted on un-cracked samples, pre-cracked samples before healing and after healing, for the ages of 28 days and 56 days under three different curing conditions (wet curing, dry curing and wet & dry curing conditions). Results are presented in Table 8 which showcases the self-healing properties of the samples.

From the results of the UPV tests, it is clear that wet cured samples gave better results when compared to dry cured and wet & dry cured samples. Un-cracked samples were compared with pre-cracked samples before healing and after healing. The pre-cracked samples which were healed gave nearly equal values to those of un-cracked samples. And also, the 56 day healed samples performed more healing properties compared to the 28 day healed samples as can be seen from Fig.5.

Finally, it can be concluded that the addition of bacteria showed a healing nature because of the formation of calcium carbonate precipitate. This could be also visually observed from Fig.6.

Table 8: UPV test results

Curing conditions	Before pre-cracking	After pre-cracking	After healing	
			28 days	56 days
Wet cycle	4.25	3.74	4.06	4.12
Dry cycle	4.20	3.53	3.99	4.02
Wet & dry cycle	4.11	3.20	3.52	3.58

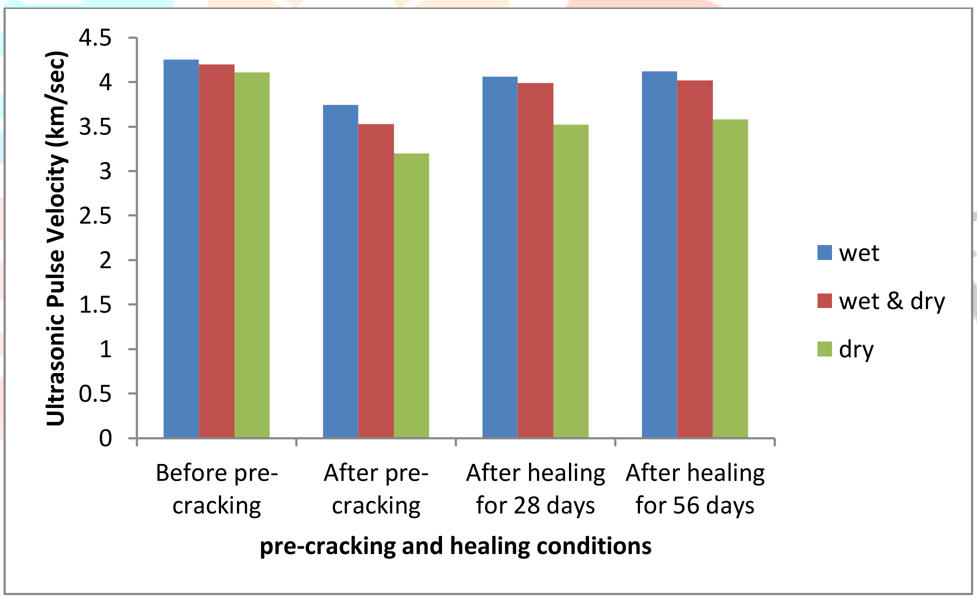

Fig.5 UPV results for pre-cracked and healed specimens under different curing conditions

3.3.2 Visual Observation

The presence of $CaCO_3$ is observed visually and photographic images are shown below in Fig.6.

Fig.6 Self-healing of concrete (formation of calcium carbonate)

3.4 Durability Properties

3.4.1Rapid Chloride Permeability Test

At the age of 28 days, according to ASTM C-1202 the resistance of specimens to salt attack was measured by rapid chloride penetration test (RCPT). 60V potential is maintained across the three specimens of 100mm diameter and 50mm thickness for 6hours duration. To evaluate the chloride permeability of each mixture, the total charge passed through the specimens was measured and the results are presented in Table 9.

RCPT test shown good results for bacterial mix. When compared to normal mix, more amount of charge is passed through the bacteria mix. In case of fiber reinforced bacterial mix, due to the addition of fibers less amount of charge is passed as can be seen from Fig.7. The reason is that, when the fibers are added, porosity increases, which can cause a lower resistance to ion penetration than in a specimen with a normal mix or a mix with bacteria. For the combination of bacteria and fibers, the RCPT value is less in the bacterial mix, but is more compared to a normal mix because the bacteria form a healing material on the surface of fibers.

Table 9: RCPT results

Mix Designation	Charge Passed (Coulombs)
NM	2018
B	2059
B+SF	2032

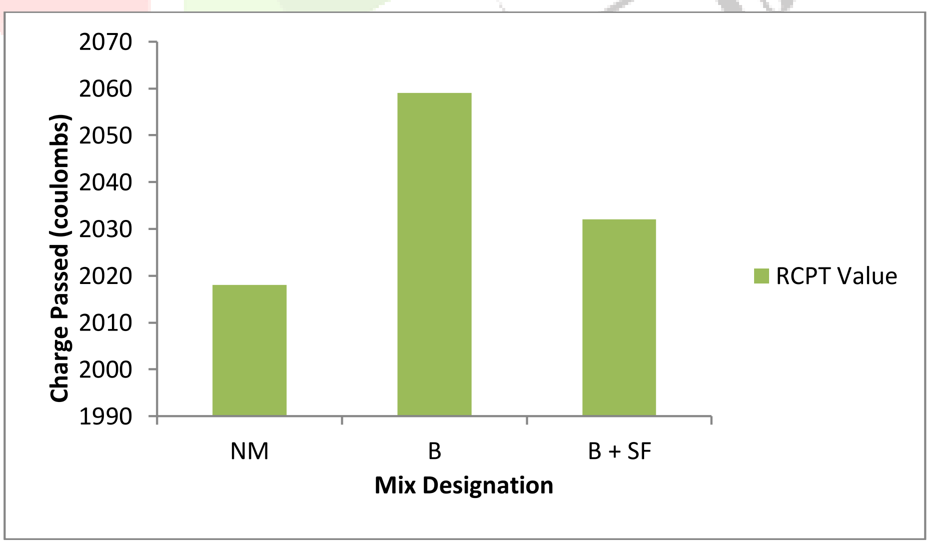

Fig.7 RCPT results

4.5 Micro-structural Properties

4.5.1 Scanning Electron Microscopy

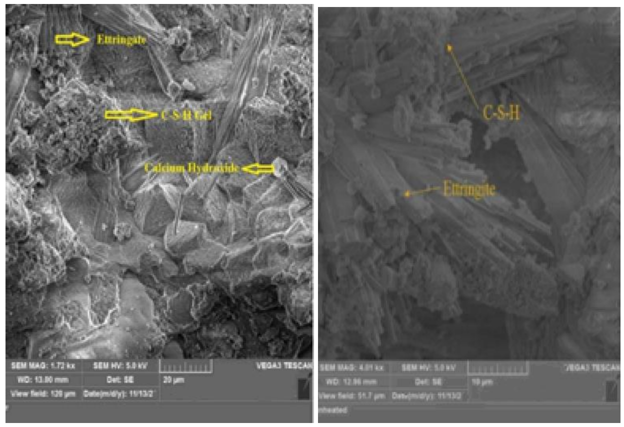

Fig.8 SEM observations on normal mix (a) 20µm, (b) 10µm

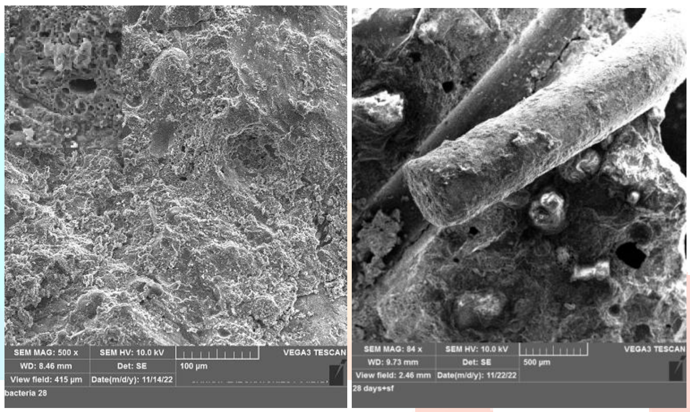

Fig.9 SEM observations of presence of (a) bacteria, (b) fiber

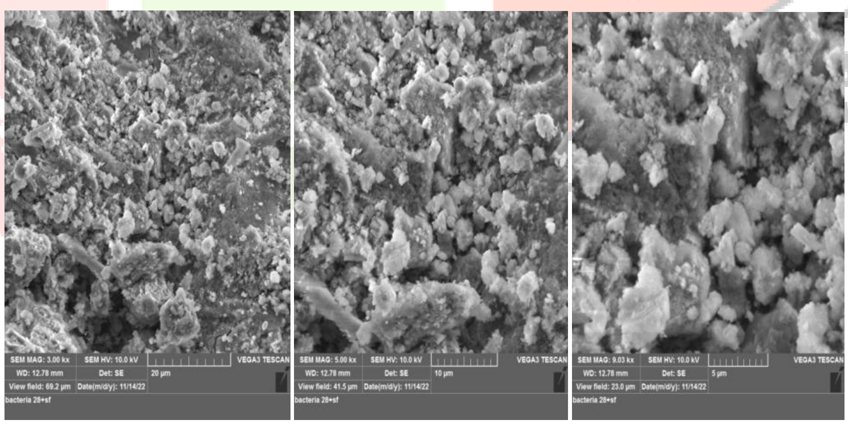

Fig.10 SEM observations on formation of calcium carbonate (a) 20µm, (b)10 µm, (c)5 µm

When cement is added to water it undergoes hydration by interaction of calcium, sulphate, aluminate, and hydration ions and the needle shaped calcium tri-sulfoaluminate hydrate called Ettringite is first appeared. In addition, a well hydrated cement paste shows the C-S-H gel and C-H (Portlandite gel). C-S-H Gel occupies about 50 to 60% of total volume of well hydrated cement paste which plays a key role in maintaining long term strength and durability. While C-H gel makes 20 to 25%, the contribution of strength is less compared with C-S-H gel.

SEM results obtained are presented in Figs.8-10. Figs 8 shows the SEM images of Normal mix. Fig. 9 shows the presence of bacteria and steel fibers. Fig.10 shows the presence of calcium carbonate precipitates due to the action of bacteria and fibers forms a bridge like structure which reduces cracks and leading to formation of self-healing structure.

4.5.2 Energy Dispersive X-ray Spectroscopy (EDS)

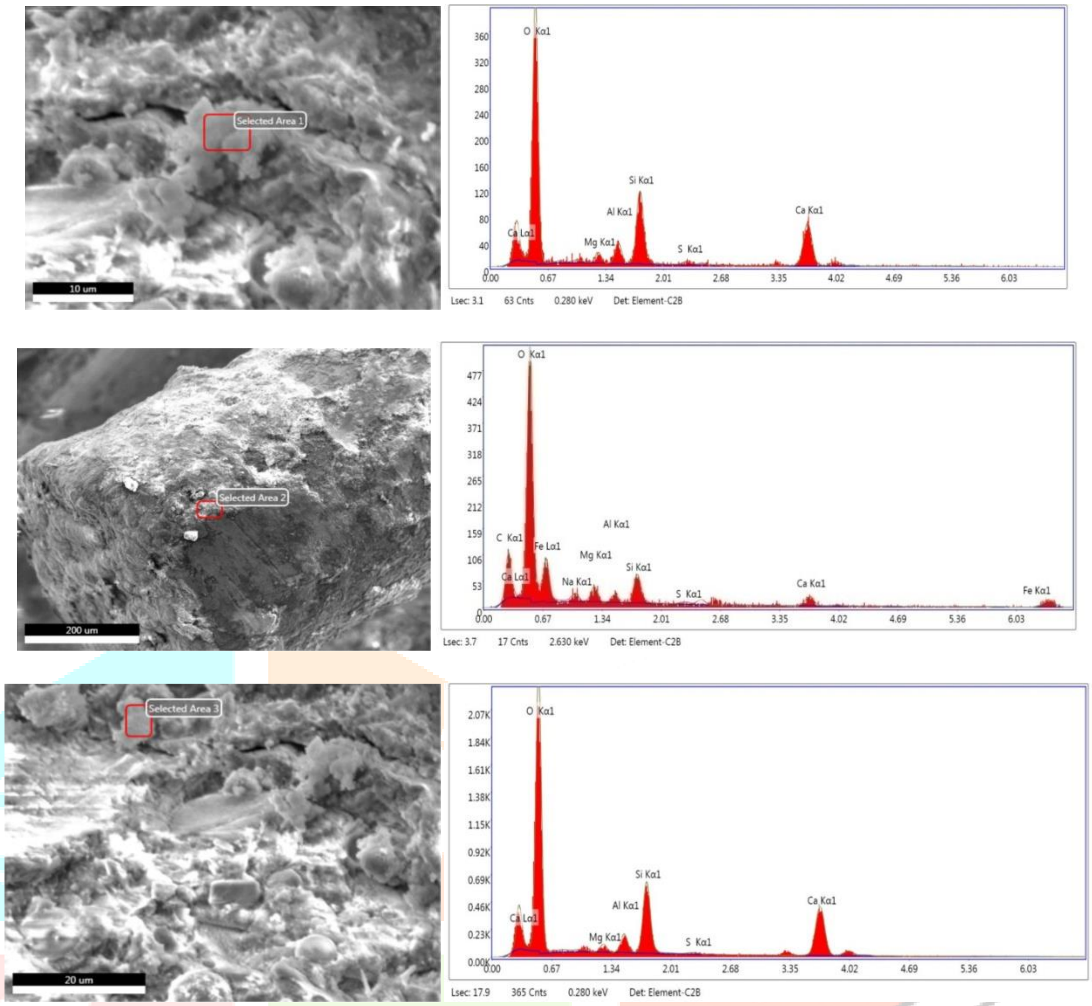

Fig.11 SEM observation with EDS of deposits induced by bacteria+fibersurfaces (a) SEM observation of precipitation, (b) EDS spectrum of precipitation

EDS technique shows the chemical composition of the materials. EDS analysis of the specimens with bacteria+fibers shows that the particularly formed precipitates were comprised of three main elements: C, O and Ca, confirming that the mineral precipitates were calcium carbonate based. The high calcium amounts shown in the EDS analysis confirm that calcite was present in the form of $CaCO_3$ due to the microbial-induced calcite precipitation.

5. Conclusions

- From the results, it is clear that compared to normal mix and bacterial mix, the mix containing bacteria and fibers gave good mechanical properties.
- The higher compressive strength results at 28 days obtained for the mixes with bacteria-10^5 and steel fibers-1.2 i.e. 46.75 MPa and 46.65 MPa respectively.
- The compressive strength result for the combination of bacteria-10^5 and steel fibers-1.2 at 28 days is 52.5 MPa.
- Self-healing of concrete is observed due to the effect of bacteria.
- The formation of calcium carbonate is observed visually as white colour precipitate.
- Among three types of curing conditions wet cycle gave the good results for self-healing.
- Mix containing bacteria and fibers shown highest resistance to chloride ion penetration.
- SEM analysis shows the micro-structural view of formation of calcium carbonate.
- Finally, it can be concluded that the coupled effect of bacteria and fibers resulted in better mechanical & durability properties and demonstrated higher self-healing/repairing efficiency.

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