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Enhancing the Mechanical Properties of Concrete and Self-Healing Phenomena by adding Bacteria, Silica fume and Fibres

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ABSTRACT. *Concrete which is the most useable material in the world after the water has flaws, it is susceptible to cracking over time. These cracks occur in the form of shear cracks, flexural cracks, tension cracks, shrinkage cracks etc. With these cracks, some hair-like cracks also occur in concrete which are not visible during the visual inspection. The propagation of these cracks in concrete allows the water and many other chemicals to seep inside the concrete and leads to a decrease in its properties. Such properties include decreasing durability, erosion of rebars, and progressive failure in the concrete strength. Therefore, the repair of hair-like cracks is also essential for the long-term safety of structures. In the present study the Silica fume, and Polypropylene fibres are added to a rich concrete along with the bacteria named Bacillus Subtilis and Calcium Lactate for enhancement of its mechanical properties and self-healing phenomena. The effect of bacteria in the healing phenomenon and other properties is compared to normal concrete by casting the cylinders and beams. The slump, compressive strength, tensile strength, and self-healing phenomena are tested and found the increase in mechanical properties of concrete. The self-healing phenomena of cracks is observed by the Scanning Electron Microscope (SEM).*

Keywords: Self-Healing, Bacillus Subtilis, Mechanical Properties, Concrete.

1. INTRODUCTION

Concrete is widely used as a construction material because it is inexpensive, long-lasting, and has a high compressive strength for its weight. However, many concrete structures will inevitably degrade and deteriorate over time. This is the result of water penetrating the concrete, which has a negative impact on its performance [1]. Despite its numerous benefits, concrete is prone to cracking as a result of tensile stress. Due to cracks in the concrete, the life span of the structures may be reduced, or they may fail [2]. A physical approach of repairing the cracks is used to remediate the structures, however this method is limited in its use due to factors like the location (such as outside of skyscrapers), the availability of manpower, the risk of accidents and injuries, and so on. To overcome the aforementioned limitations, a unique method of repairing incorporating bacteria, polymeric compounds, and fibres is being developed. Microbial precipitation of microorganisms and metabolic activity enhances the overall behavior of concrete. Precipitated calcite acts as a healing agent to repair cracks in structures as illustrated in Fig -1 [3]. Bacillus Subtilis is capable of healing cracks in concrete surfaces, hence boosting the strength and durability of a concrete building or component. Since Bacillus Subtilis is a non-pathogenic and non-toxigenic bacterium, it poses no threat to human health or the environment. Introducing the Bacillus Subtilis bacterium into the concrete matrix during the mixing process confers self-healing properties. Cracks in the concrete's surface allow water to seep, where it reacts with bacteria to produce calcium carbonate ($CaCO_3$), the primary ingredient in lime. Given the fact that bacteria require food to survive, we choose Calcium lactate as the chemical precursor to perform the task [4]. Self-healing concrete has the potential to reduce maintenance costs and increase the lifespan of structures, especially in harsh environments, such as marine environments, where corrosion and cracking are common problems. It can also improve the durability and sustainability of concrete structures by reducing the need for repairs and replacement. However, self-healing concrete is still a developing technology and there are some challenges that need to be addressed, such as the cost and scalability of the production process, and the effectiveness and long-term durability of the healing mechanisms.

Fig -1: Healing of Crack [2]

The emergence of cracks in concrete is a common occurrence that allows various chemicals and water to seep inside, reducing the durability of the concrete and eventually leading to collapse [5][6]. Therefore, in this study, a bacterium named bacillus subtilis, along with calcium lactate, is introduced in concrete to self-heal cracks after cracks' propagation by filling the lime $CaCO_3$, and its chemical reaction is given in equation (1). The silica fume and polypropylene fibres are also added along with bacteria to enhance other mechanical properties of concrete and make it economical. The self-healing concrete has the potential to improve the performance and longevity of concrete structures, making them more reliable, durable, and sustainable. Self-healing concrete can reduce construction time by eliminating the need for repairs after the concrete has been poured. This technology is still being developed, but it holds great promise for the future of the construction industry.

$$Ca\,(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \qquad (1)$$

Where, $Ca\,(C_3H_5O_2)_2$ is Calcium Lactate and $CaCO_3$ is lime.

2. BACKGROUND STUDY

Luhar et al. examined the effectiveness of encapsulated bacteria's capacity to self-heal cracks and restore a variety of mechanical and durability attributes in bacterial concrete and concluded that the bacillus subtilis has the ability to heal the cracks by filling the lime [7]. Neeladharan et al. found that, after 28 days, the compressive and tensile strength of a 10 ml specimen of M25 grade was 33.72 N/mm^2 and 5.51 N/mm^2 higher than the standard specimen of M25 grade, respectively. Therefore, it is recommended to employ both the 10ml bacterial concrete procedure and the standard specimen cured in bacterial solution. Also, it is recommended to utilize M25 grade bacterial concrete rather than M30 normal concrete. They cast cubes for compression testing and cylinders for tensile testing, both of which serve the function of healing [4]. Lagazo et al. showed that the addition of bacterial solution-Bacillus Subtilis to concrete improves the compressive quality, split tensile strength, water absorption, and flexural quality of concrete due to the growth of microscopic organisms. As long as the bacteria are contained in a research facility, they are extremely safe and pose no threat to human health. Utilizing this form of bacteria for concrete's self-healing mechanism can result in strong or durable constructions that are both cost-effective and long-lasting, according to the study that was conducted [8]. Hussein et al. concluded that the decrease in water absorption of (15-38%) and the decrease in compressive strength of (10% loading) concrete specimens of (23-41%) relative to control concrete. Concrete specimens with a concentration of 106 cells/mm had the highest reduction. Concrete specimens aged 7, 28, 60, and 90 days showed increases in compressive resistance of (6-20%), (6-17%), (8-22%), and (7-20%), respectively. In comparison to control specimens without bacteria, concrete specimen loading 10% of compressive strength increases are (25-34%) and (34-39%) after 60 and 90 days. Increased density, calcite carbonate deposition in voids, and fissure closure by layering of calcium carbonate were all noted by scanning electron microscope [9]. Cracks in concrete can compromise the structural integrity of a building, leading to potential safety hazards. Self-healing concrete can help prevent these hazards by repairing cracks before they become a safety issue [6].

Manish et al. concluded that bio concrete only fixes surface-level microcracks and stops concrete from crumbling. Additionally, utilizing the bacteria, it is simple to determine how concrete's compressive, tensile, and fracture strengths have increased in comparison to regular concrete [10]. Sudha et al. concluded that self-healing mechanisms can be done by introducing microorganisms to concrete to increase its strength. It has been observed that adding more bacteria to the mix increases the strength of concrete [11]. Vijay et al. tested the effect of calcium lactate on bacterial concrete. The concrete was treated with both spores and cultures of the bacteria. The results indicated that the presence of bacteria in either form precipitates $CaCO_3$. The results indicate that calcium lactate should be added to concrete at a lower concentration to boost compressive strength [1]. Ramakrishnan et al. concluded in 'a concrete for the future' that a common soil bacterium was used to cause the precipitation of calcite. This approach is particularly favorable since the mineral precipitation resulting from microbial activity is both natural and pollution-free. By comparing the compressive strength and stiffness of bacteria-remediated cracked specimens to those of control specimens, the efficacy of this approach was assessed (without bacteria). Experiments were also conducted to test the strength recovering capacity (modulus of rupture) of cracked beams remedied with various bacterial concentrations. This study also discusses the results of a study on the durability of cement mortar beams exposed to alkaline and acidic environments and treated with bacteria [12]. Nele et al. described how bacteria can aid in the repair and consolidation of mineral phases of construction materials, as well as the healing and self-healing of concrete. In structures, microorganisms play a crucial role in pedogenesis, mineral processing, and element exchange. This also includes the change of hard rocks into soft soil, a natural process that encourages plant growth. However, the biodegradation process is not favorable when this rock is employed as a building block or component of concrete. Traditional methods such as coatings and hydrophobic sealants, in addition to organic dispersions, can be utilized to protect building components [13].

The ratios, quantities, and other mixtures used in various studies are listed in table 1 to identify the gap.

Table -1: Literature Review

Researchers	**Mix Ratio C : S : A**	**Bacteria + Admixtures**	**Quantities**
Vijay and et al. [1]	1 : 1.25 : 2.5	Bacillus + Calcium Lactate	2.25, 4.5 kg/m3 + 2.25, 4.5, 6.75, 9, 11 kg/m3
Chithambar and et al. [3]	1 : 1.25 : 2.5	Bacillus + polypropylene fiber	105 cells/ml + 0.45%
Neeladharan and et al.[4]	1 : 1 : 2	Bacillus Subtilis	0, 10, 20, 30 ml
Lagazo and et al. [8]	1 : 3 : 6	Bacillus Subtilis + Nutrient Agar	0, 30 ml + 105 cells/ml
Hussein and et al. [9]	1 : 1.5 : 2	Superplasticizer	0, 1, 1.5, 2, 2.5 l/100kg Cement
Manish and et al. [10]	1 : 1.5 : 2.2	Silica fume + Calcium Lactate	1, 1.5, 2, 2.5 %
Sudha and et al. [11]	1 : 1.25 : 2.5	Bacillus	0, 10, 20, 30, 40 ml
Nguyen and et al. [14]	1 : 2 (mortar) 1 : 2 : 4	Bacillus + urea + Nutrient broth	1.26 % of cement
Tziviloglou and et al. [15]	1 : 2 : 2	Genus Bacillus + Calcium Lactate + Yeast	10^8 spores/L + 200 g/l + 4 g/l
Mohd and et al. [16]	1 : 2.5 : 1.5	Bacillus + Urea + calcium + yeast	2, 4, 6 % + 2% + 0.3%

3. EXPERIMENTAL STUDY

3.1. Methodology

The proposed methodology for this study comprises several steps, as illustrated in Fig -2. After the literature review, the materials selected will be used for this study. The bacteria are cultured and then converted into liquid form for addition to the concrete after passing through several processes. After that, the casting and curing of cylinders are to be done. Then the slump test, compressive strength, split tensile strength, and self-healing phenomena are tested after 28 days.

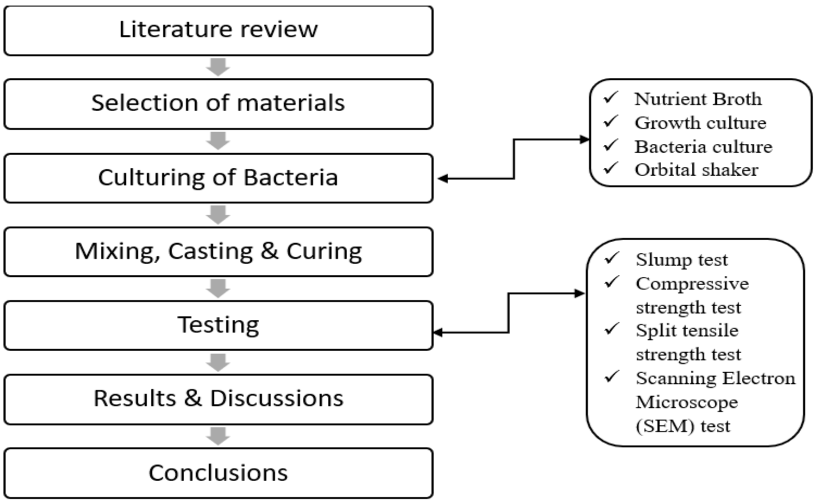

Fig -2: Proposed Methodology

3.2. Selection of Materials and Tests

In this study, four types of specimens are cast according to the addition of different materials, as given in Table 2. The cylinders-1 types are the standard concrete cylinders, and a total of 06 cylinders are cast, 03 for the Compressive Strength test and 03 for the split tensile strength test. The cylinders-2 type is bacterial cylinders, including the bacillus subtilis bacteria and calcium lactate. The 09 cylinders are cast of this type, 03 cylinders for compressive strength test, 03 for split tensile test and 03 for SEM test to check the healing phenomena. The cylinders-3 type is also bacterial cylinders, but it includes the Silica fume and bacteria to enhance the strength of concrete. The 06 cylinders are cast for this type, 03 for compressive and 03 for the split tensile strength test. The cylinders-4 types include polypropylene fibres and bacteria; also, 06 cylinders are cast for this type. The slump test is conducted for all types of cylinders. The compressive strength and split tensile strength tests are performed after 28 days.

Table -2: Detail of Specimens

Sr no.	Specimen	Mixtures	Mix Ratio	No. of Cylinders
1	Cylinders-1	Normal Concrete	1 : 1 : 2	6
2	Cylinders-2	Concrete + Bacteria + Calcium lactate	1 : 1 : 2	9
3	Cylinders-3	Concrete + Bacteria + Calcium lactate + Silica fume	1 : 1 : 2	6
4	Cylinders-4	Concrete + Bacteria + Calcium lactate + Polypropylene Fibers	1 : 1 : 2	6

3.3. Material Quantities

The water-cement ratio is kept constant at 0.45 for all cylinders. In recent research, the optimum quantity of the bacteria used is 10 ml, at which the maximum strength of the concrete is achieved, and the fixed quantity of bacteria 10ml per cylinder is added to specified specimens in this study. The optimum quantity of calcium lactate is added 0.5% of cement weight, fixed for all types of specified cylinders as given in Table 3. And 0.4% of the cement volume of polypropylene fibres is added to selected cylinders to achieve maximum strength.

Table -3: Quantities of Materials

Sr no.	Specimen	W/C Ratio	Bacteria	Calcium Lactate	Silica fume	Polypropylene Fibers
1	Cylinder-1	0.45	0	0	0	0
2	Cylinder-2	0.45	10 (ml) / cylinder	0.5 % of cement	0	0
3	Cylinder-3	0.45	10 (ml) / cylinder	0.5 % of cement	10% of cement	0
4	Cylinder-4	0.45	10 (ml) / cylinder	0.5 % of cement	0	0.4 % of cement volume

4. RESULTS AND DISSCUSSIONS

4.1. Mechanical Properties Results

The four types of cylinders are cast, cured, and tested of M25 concrete in the present study. The compressive strength, split tensile strength, and SEM test are conducted after 28 days to check the strength and the slump test is performed to check the workability. Standard concrete's compressive strength and split tensile strength are obtained at 24.79N/mm^2 and 2.47N/mm^2. After adding the Bacteria and calcium lactate, the compressive strength and split tensile strength increased to 29.63N/mm^2 and 2.83N/mm^2, which is more than standard concrete, and the workability of concrete also increased. By adding the silica fume to the bacterial concrete, the compressive strength increased up to 32.45N/mm^2, split tensile strength 2.92N/mm^2, and the slump was obtained 100mm, as given in Table 4. The split tensile strength enhanced up to 3.13N/mm^2, and the compressive strength was 30.50N/mm^2 by adding the polypropylene fibres. So, adding bacteria, silica fume, and fibres makes the concrete durable for an extended period and increases its workability.

Table -4: Results of Slump, Compressive Strength and Split Tensile Strength Test

Sr no.	Specimens	Testing Age	Slump	Compressive Strength	Average	Split Tensile Strength	Average
		(Days)	(mm)	(N/mm2)	(N/mm2)	(N/mm2)	(N/mm2)
1	Cylinders-1	28	100	24.87	24.79	2.40	2.47
				25.30		2.40	
				24.20		2.60	
2	Cylinders-2	28	105	28.90	29.63	2.75	2.88
				30.10		2.90	
				29.90		3.00	
3	Cylinders-3	28	100	33.15	32.45	3.10	2.92
				32.80		2.70	
				31.40		2.95	
4	Cylinders-4	28	98	30.50	30.50	3.30	3.13
				31.20		2.90	
				29.80		3.20	

4.2. Self-Healing Test

Self-healing concrete is a type of concrete that has the ability to repair itself when cracks or damage occur. The concept behind self-healing concrete is to mimic the natural healing process of bones and tissues in the human body. The self-healing property is observed using a Scanning Electron Microscope (SEM), which reveals the deposition of calcite carbonates in the voids and the healing of the crack through calcium carbonate precipitation. The addition of bacterial $CaCO_3$ increases the strength of concrete by clogging the pores within the concrete cylinders, as illustrated in Fig -3. The layer of $CaCO_3$ will help guard against structural reinforcement corrosion and enhance the strength and durability of structures.

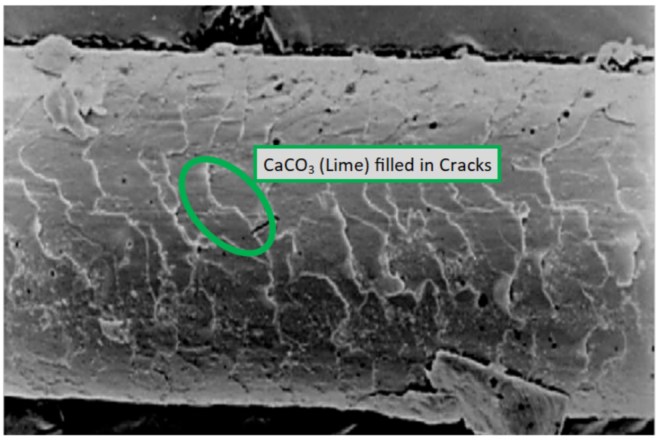

Fig -3: SEM Test of Healing

The concreting day in the construction industry has the most significance. Maintaining the workability and serviceability of the concrete while pumping is an arduous task, and after concreting, the inspection became challenging. Therefore, by adding the bacteria, silica fume, and fibres, the workability, serviceability, and strength of the concrete improve and the hair-like cracks, which may be ignored during the visual inspection, self-healed after crack propagation.

5. CONCLUSIONS

There are different approaches to creating self-healing concrete. One common approach is to embed capsules or filled with a healing agent, such as bacteria or chemicals, into the concrete mixture. When a crack occurs, the capsules rupture, releasing the healing agent into the crack, which then reacts with the surrounding material to form a seal and repair the crack. This research investigates the self-healing potential of Bacillus Subtilis bacteria combined with silica fume, polypropylene fibre, and calcium lactate in concrete. Cultured bacteria were incorporated into the concrete. The results show that by adding 10 ml of bacillus subtilis bacteria, the compressive strength is enhanced to 29.63 N/mm^2, which is 5 N/mm^2 more than standard concrete, and the split tensile strength is increased by 0.4 N/mm^2. Furthermore, self-healing phenomena were also observed. The compressive strength of bacterial concrete is enhanced to 32.45 N/mm^2 when adding silica fume. After adding polypropylene fibres, the split tensile strength reaches 3.13 N/mm^2. Due to its eco-friendly nature, self-healing capabilities, and increase in durability, bacterial concrete technology has proven to be better than many conventional technologies.

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