Effects of Microbial Inclusion on Mechanical Properties of Engineered Cementitious Composites

Vipul Solanki[1(✉)], Khadeeja Priyan[2], and Niteshkumar Mistry[3]

[1] CVM University, Vallabh Vidyanagar, Anand, Gujarat, India
vpsolanki@bbit.ac.in

[2] Civil Engineering Department, GCET Engineering College, Vallabh Vidyanagar, Anand, Gujarat, India
khadeeja.priyan@cvmu.edu.in

[3] Microbiology Department, Arts Science and R. A. Patel Commerce College, Bhadran, Gujarat, India

Abstract. Cementitious materials are the most common construction materials globally. The structural strength is compromised by the corrosion of the steel reinforcements brought on by the brittleness for high tension fractures of cementitious composites. Bacteria and fibres can be used to fix these issues. Addition of bacteria in concrete has a great potential on concrete crack self-healing by microbial-induced calcite precipitation (MICP). In this investigation, classic Engineered Cementitious Composites (ECC) M_{45} mix with *Bacillus Pumilus*, 3S Polyester fibre and class F fly ash were added with two different mix proportions. *Bacillus pumilus* is incorporated in 10^7 Cfu/g concentration and 3S Polyester fibre is used with 1% in ECC. Concrete samples were allowed to cure for 7 days and 28 days. Various tests to determine concrete mechanical strength such as compressive strength, tensile strength and flexural strength were conducted in varied curing periods. The test results show that 3S Polyester fibre and bacteria have the potential to enable excellent performance in the strength of concrete.

Keywords: ECC · *Bacillus Pumilus* · 3S Polyester fibre · MICP · Concrete Mechanical Strength

1 Introduction

In the current scenario of perpetual urbanization, concrete serves as the most important and versatile building material to fulfill the requirement for increasing built-in environment. Concrete is essential for infrastructural development, including residential, industrial, and commercial sectors. Cement production generates significant greenhouse gas emissions, accounting for 8% globally [1]. Other environmental concerns include number of illegal sand mining operations, harmful environmental effects such as increased surface runoff or the metropolitan heat island effect, and possibly harmful components. To create a circular economy, attempt to reduce emissions, or turn concrete into a source

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of carbon capture, research and development has been processing [2]. Traditional cementitious composites have several shortcomings mainly, reduced tensile strength leads to development of stress cracks, that lets dangerous gases and liquids seep in, eventually cause steel reinforcements to corrode [3]. A potentially effective way to deal with these problems is identified through the usage of bacteria. When calcium carbonate is added to cementitious composites, it has been discovered that some types of bacteria can participate, which is a regular occurrence in nature [4, 5]. Microbial techniques with cementitious composites, which has hailed as cost-effective and sustainable materials [6]. Even though microbial organisms can generate $CaCO_3$, current research has shown that only a few specialized bacterial species that survive in the alkaline atmosphere within concrete might be useful for enhancing the strength and durability of concrete structures [7]. Therefore, this study aims to ascertain how *Bacillus pumilus* precipitation affects the mechanical strength of concrete. An alkaline environment is ideal for the ubiquitous soil bacterium *B. pumilus* [8]. This bacterium is gram-positive, aerobic, and spore-forming bacteria. Except for the mutant strain ATCC 7061, *Bacillus pumilus* spores often provide impactful tolerance to the existence of oxidizers like hydrogen peroxide, exposure to UV radiation, desiccation, and other environmental stressor [9]. Microorganisms have been used successfully for microbial concrete, such as *Bacillus species* [10, 11] *Sporosarcina species* [12, 13] and *Shewanella species* [14], it is expected that *B. pumilus* will stay alive in the concrete and cause long-lasting calcite precipitation.

"Engineered Cementitious Composite" (ECC), also known as "Strain Hardening Cement-Based Composites" (SHCC) or "flexible concrete" or "bendable concrete," specifies to a concrete-based composite which can be easily molded and reinforced with arbitrarily chosen short fibres [15–18]. Due to the micromechanical design and microfibre bridging framework, the typical crack width in ECC can be limited to between 60 and 80 μm [19], making it particularly suitable for producing microbial-based ductile concrete without the need for specialized carriers. Strain capacity increases by the use of ECC; therefore it acts as a ductile material rather than brittle material [20–22]. Filling larger fissures with calcium carbonate produced by bacterial precipitation would be particularly desirable, alternatively, it is also interesting to investigate how the presence of modest concentrations of bacteria might alter the fibre/matrix interface and mortar matrix characteristics of ECC, hence influencing the macroscopic mechanical properties of the material [23]. As previously stated, this research focuses on ECC's mechanical properties impregnating with *Bacillus pumilus* and 3S Polyester fibre. The overall performance of ECCs is described, including their compressive, tensile, and flexural strengths.

2 Materials and Method

In the present study, materials such as 53-grade Ordinary Portland Cement (OPC) wonder cement, locally available river sand as fine aggregate, *Bacillus pumilus* for ECC self-healing, and mineral admixtures like fly ash, 3S Polyester fibre was used. The concentration of *Bacillus pumilus* is 10^7 Cfu/g and 3S Polyester fibre is 1%. The characteristics of the materials are explained below.

Table 1. Physical Properties of Cement

Test		Value	Requirement as per IS 12269:2013
Initial setting time (minutes)		40	30
Final setting time (minutes)		190	600 maximum
Compressive Strength(N/mm^2)	3 days 7 days 28 days	36.80 43.82 55.78	27 minimum 37 minimum 53 minimum
Soundness(mm)		1	10 maximum
Standard consistency (%)		27.25	25–35 (IS: 4031-Part 4-1998)

2.1 Cement

As a binding substance, Wonder OPC 53 grades restricted to IS 12269:2013 [24] was used. Several experiments were carried out on cement to determine its physical characteristics and compared the results as per IS: 12269-2013. The physical properties of cement are shown in Table 1.

2.2 Fine Aggregate

Sand collected from the riverbank was used as the fine aggregate and it is classified into four grading zones as per IS: 383–2016 [25] and this classification is based on the fine aggregate's particle size distribution, which can be determined by performing sieve analysis. Based on the findings of the sieve analysis, the cumulative percentage weight passing of sand for all below mentioned sieve sizes in Table 2 falls under Zone II category (Table 3).

Table 2. Fine Aggregate's Sieve Analysis

Sieve size (mm)	Weight retained (gram)	Cumulative weight retained (gram)	Cumulative % weight retained	Cumulative % weight passing
10	0	0	0	100
4.75	66	66	6.6	93.4
2.36	60	126	12.6	87.4
1.18	180	306	30.6	69.4
600 micron	360	628	62.8	38
300 micron	276	942	94.2	5.8
150 micron	60	995	99.5	0.05
Pan	5	1000	100	0

Table 3. The Physical Characteristic of Fine Aggregate

Characteristics	Fine Aggregates
Fineness modulus	3.0
Specific gravity	2.670
Water Absorption (%)	0.9
Size (mm)	4.75 max
Moisture content (%)	1.8
Zone of sand	II

Table 4. Chemical Composition of Fly Ash

Details	Test Result	Requirement acc. to IS 3812 (Part-I)
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	84.13	>70.00
SiO_2 (%)	65.31	>35.00
MgO (%)	1.72	<5.00
SO_3 (%)	1.13	<3.00
Cl (%)	0.021	<0.05
Loss on ignition (LOI) (%)	0.83	<5.00
Total alkali as Na_2O	0.167	Max 1.5

2.3 Water

For the casting of the ECC and the curing of the specimens, salt-free portable water that complied with IS 456:2000 was used with water/cement ratio of 0.55–0.56. Utilizing contaminated water, sewage water, or industrial wastewater is not recommended to create composites or concrete.

2.4 Fly Ash

A by-product created when coal is burned in a thermal power station is typically called fly ash. Fly ash is divided into two forms, low calcium fly ash (class F fly ash) and high calcium fly ash(class C fly ash), depending on the amount of calcium present in it. Class F fly ash was employed in the investigation and confirmed to IS: 3812-1987 [26]. In fly ash, the specific gravity was 1.98. Table 4 provides a breakdown of the chemical composition of fly ash.

2.5 3S Polyester Fibre

The properties of 3S Polyester fibre make it a suitable material to serve as reinforcement in cementitious composites. 3S Polyester fibre, a product of Jogani Reinforcement

Fig. 1. 3S Polyester Fibre

Table 5. Properties of 3S Polyester fibre

Properties	Values
Fibre Length(mm)	12
Fibre Diameter(µm)	38
l/d proportion	315.78
Nominal tensile strength (Mpa)	1250
Melting point (˚C)	250–265
Specific Gravity	1.34–1.39

is shown in Fig. 1. Its appealing qualities include a high modulus of elasticity, great durability, high tensile strength, extremely high alkali resistance, high UV resistance, excellent acid and chemical resistance, and a high bonding strength with a concrete matrix. Table 5 displays the 3S Polyester fibre characteristics.

2.6 *Bacillus pumilus* Bacteria

The self-healing ECC material was examined in this study using *Bacillus pumilus* from the Aum Enzymes, INDIA. *B.pumilus* produces calcium carbonate more effectively than other species, and it can also tolerate high alkali and the harsh conditions of the mortar matrix. Table 6 shows the Properties of Bacteria. Figure 2 depicts the culture of *Bacillus pumilus*.

Fig. 2. Culture of *Bacillus Pumilus*

Table 6. Properties of *Bacillus Pumilus*

Test	Specification	Result
Characteristics	Aerobic, rod-shaped, Gram-positive, and spore-forming bacteria	
Base of Enzyme	Lime	
Appearance	Free flowing powder	Complies
Colour	Off white- to – white powder	Complies
Odour	Natural	Complies
Taste	Natural	Complies
Particle size	100% passage through 80 mesh	Complies
Loss of drying	Not more than 8%	5%
Solubility in water	Partly soluble	Complies
Viable spore count	Not less than 1 x 10^7 Cfu/g	> 1 x 10^7 Cfu/g
Pathogens	Absent	Absent
Other organisms	Not more than 1% of the labeled viable spore count	Complies
Storage	Store in airtight poly bags, in cool and dry place	

3 Preparation of Bacterial Culture

Nutrient broth (NB) is the medium used to cultivate bacteria. The nutrient broth was used to make a sufficient amount of liquid broth. Further, it was sterilized in an autoclave for 30 minutes, so there were no pollutants in the solution. The top of the conical flask was completely wrapped with thick cotton, and the cap was just loosely fastened. The material was autoclaved at 121 °C and allowed to cool at room temperature. After opening the flasks, 1 ml of the microorganism is added using nichrome wire to the sterilized flask and shaken at a pace of 150–200 rpm for 24hrs. A foggy haze in the media identified a fully-grown bacterial spore that resembled a whitish, yellowish, turbid solution after the incubation period and was tested to see how the growth was progressing. Glycerol stock was used to keep the bacterial solution for an extended time. Calcium lactate was added to the bacterium spores to give them life, and when an environment conducive to bacterial growth was present, the bacteria were nourished. These spores can survive up to 200 years while waiting for more hospitable conditions for germination because of their significantly thicker cellular walls. Food is readily available, water enters the structure, and spores will be triggered as the concrete begins to crack. Calcium lactate and bacterial spores are added to the concrete mix in varying concentrations (Fig. 3).

4 ECC Casting Procedure

In the present study, *Bacillus Pumilus* bacteria and 3S Polyester fibre were added to two traditional ECC M_{45} mixtures, and detailed mechanical characteristic analysis was carried out. The concentration of *Bacillus pumilus* incorporated is 1x10^7 Cfu/g. 3S

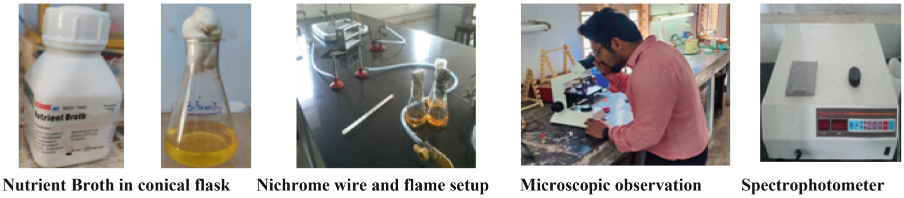

Fig. 3. Preparation of Bacteria Culture

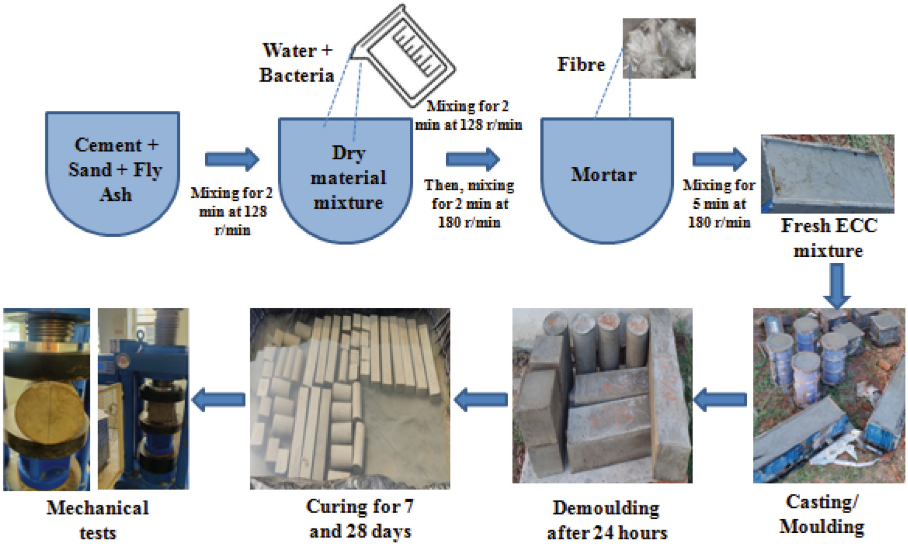

Fig. 4. ECC Casting Procedure

Polyester fibres of 1% were added in ECC. Concrete samples were allowed to cure for 7 days and 28 days. Two different mix design proportions M1 and M2 for ECC were carried out. Figure 4 shows the pictorial representation of ECC casting procedure.

5 Mechanical Characteristics of ECC

The hardened ECC concrete's mechanical characteristics were identified. The concrete mould size of the cube was 150 x 150 x 150 mm. The compressive strength test was carried out at ages 7 days and 28 days, respectively, under IS 516-1959 [27]. The mould size of the beam was 150 x 150 x 700 mm. By flexing a beam of plain concrete under a transverse force, the flexural strength test was carried out to ascertain the flexural behavior of concrete. The test was conducted under IS 516-1959 at 7 days and 28 days of age. A cylindrical sample of 150 mm in diameter and 300 mm in length underwent a split tensile test to assess its tensile strength. After 7 days and 28 days, the test procedures were carried out on the specimen under IS 5816-1999 [28]. Figure 5 shows mechanical testing of ECC.

Fig. 5. Compressive Strength, Tensile Strength and Flexural Strength Testing of ECC respectively

6 Results and Discussion

In this experimental study, the mechanical tests were carried out on the specimens for Mix design-1 and Mix design-2. For each of the Mix designs, specimens were casted for Normal mortar, Normal mortar with Fly ash (C + W + FA), ECC with Fibre, ECC with Fibre and Bacteria. Figures 6, 7 and 8 shows the Compressive Strength, Tensile Strength and Flexural Strength test results.

Compressive Strength of M1FFB increases by 21.46% and 27.04% than M1F after the age of 7 days and 28 days respectively. Compressive Strength of M2FFB increases by 25.89% and 30.2% than M2F after the age of 7 days and 28 days respectively.

Tensile Strength of M1FFB increases by 22.63% and 39.4% than M1F after the age of 7 days and 28 days respectively. Tensile Strength of M2FFB increases by 24.3% and 42% more than M2F after the age of 7 days and 28 days respectively.

Flexural Strength of M1FFB increases by 30% and 42.2% more than M1F after the age of 7 days and 28 days respectively. Flexural Strength of M2FFB increases by 37% and 45.28% more than M2F after the age of 7 days and 28 days respectively.

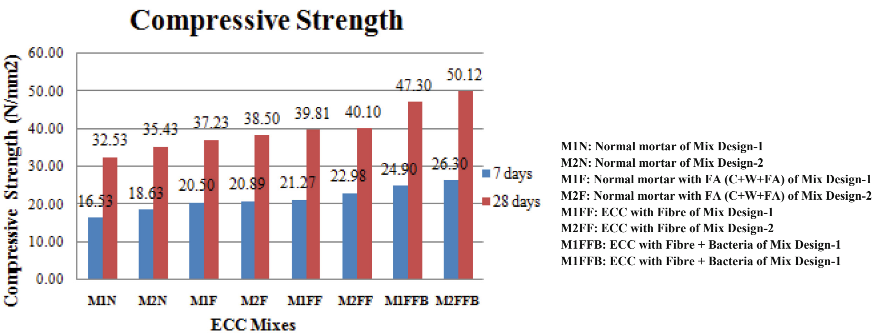

Fig. 6. Analysis of Compressive Strength

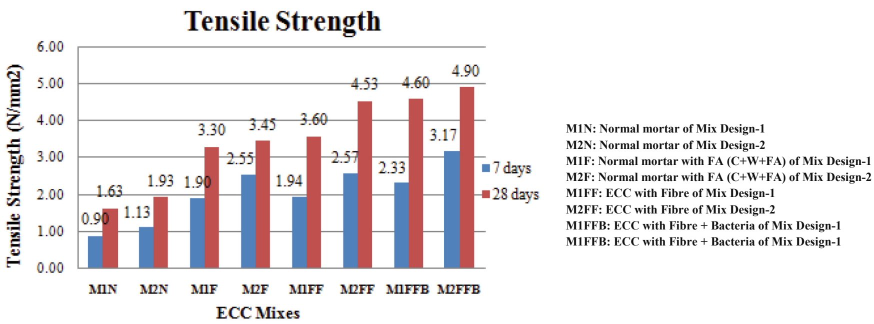

Fig. 7. Analysis of Tensile Strength

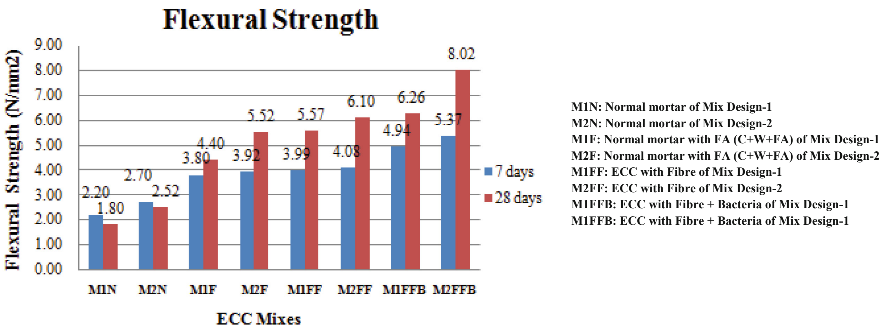

Fig. 8. Analysis of Flexural Strength

7 Conclusion

In this investigation, the mechanical characteristics of ECC reinforced with 1% of 3S Polyester fibre and 1x10^7 Cfu/g concentrations of *Bacillus Pumilus* bacteria were tested. Following observations are observed:

- Compressive, Tensile and Flexural Strength of M1FFB are increased by 27.04%, 39.4% and 42.2% respectively, as compared to M1F at the age of 28 days.
- Compressive, Tensile and Flexural Strength of M2FFB are increased by 30.2%, 42% and 45.28% respectively, as compared to M2F at the age of 28 days.
- Mix Design-2 shows favorable results as compared to Mix Design-1 in terms of better mechanical strength due to higher addition of Fly ash in Mix-Design-2.
- The addition of Fly ash which is a by-product, can significantly increase the bonding performance linking fibres, fill voids, enhances compactness and overall performance.
- Addition of fibres boosts the mechanical strength compared to Normal mortar with Fly ash in both Mix-designs. Incorporation of 3S Polyester fibres to concrete offers many benefits, such as prevention of sudden failure, reduction of crack width due to high bridging ability, increases flexural, tensile strength and toughness.

- Bacteria integration has major effects on the mechanical performance of ECC, including compressive strength, flexural strength and tensile characteristics. Addition of bacteria in concrete results in the precipitation of calcium carbonate ($CaCO_3$) among the voids of the concrete, resulting in enhancing the strength of the concrete and reducing its permeability.
- As the coarse aggregates are not used in ECC, the overall weight of ECC is significantly reduced.

Hence, the bacteria inclusion in ECC can emerge as a future trend in construction sector which requires more research.

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