IMPROVED COMPRESSIVE PERFORMANCE OF BIO-INDUCED SISAL FIBERS REINFORCED CONCRETE

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Abstract- The use of calcite-precipitating bacteria and fiber reinforcement has the potential to enhance the strength and crack-healing characteristics of cementitious materials. However, their impact on the compressive response of concrete is uncertain. This study evaluates the compressive response of Sisal Fiber (SisF) reinforcement in combination with *Bacillus Subtilis* (B.St) in concrete. The results demonstrate that SisF inclusion improves ductility, peak compressive strain, post-peak compression energy, and total compression energy, leading to a 1.43 increase in the toughness index. Direct incorporation of B.St due to the Microbial-Induced Carbonate Precipitation (MICP) process results in an 8.1% increase in compressive strength compared to the control mixture. Furthermore, combining fiber reinforcement and MICP leads to a substantial 14.0% increase in compressive strength while maintaining a toughness index of approximately 1.59. The successful synthesis of MICP is confirmed through Fourier Transform Infrared analysis. These findings establish the effectiveness of SisF and B.St, in enhancing concrete's compressive performance, thereby promoting the development of more resilient and sustainable construction materials.

Keywords- Bacillus Subtilis, Compressive response, Concrete composites, Sisal fiber.

1 Introduction

The use of bacteria in bioinspired cementitious materials has shown promise in improving the mechanical performance of concrete infrastructure. By incorporating bacteria, these materials can enhance concrete by facilitating biochemical processes that result in the production of calcium carbonate (CaCc). This CaCc acts as a mineral precipitate, filling voids and cracks in the concrete's microstructure, thereby enhancing its mechanical strength and long-term durability [1]. Research has demonstrated that incorporating various strains of bacteria, such as *Bacillus Subtilis* (B.St), into concrete positively impacts its microstructure, mechanical performance, and durability [2], [3]. Studies have shown that higher volumes of B.St result in increased CaCc production and improved compressive strength [4]. Immobilization techniques using carriers like lightweight aggregates, graphite nano-platelets, and iron oxide have been used to increase the longevity of bacterial spores within cementitious composites, resulting in enhanced compressive and tensile strengths [5]–[7]. Adding fibers to bacterial concrete further enhances its performance by distributing stresses, improving toughness, and providing a protective environment for bacterial spores. Fibers like basalt fiber, polyvinyl alcohol (PVA), polypropylene (PP), flax, coconut, jute, and coir have been incorporated, leading to increased compressive strength and reduced sorptivity [3], [8]–[10].

Sisal Fiber (SisF), derived from the sisal plant leaves, has been extensively studied for its potential in enhancing cementitious materials by reinforcing fibers, making it a promising material for sustainable construction [11]–[14]. Recent findings [15] have indicated its effectiveness as an immobilizer for B.St, resulting in improvements in compressive strength and tensile resistance. However, a thorough understanding of the stress-strain profile is needed to accurately predict fracture behavior and assess many engineering properties for designing modified concrete structures. Previous work using various bacterial strains and natural fibers has concentrated mainly on strength gains and self-healing effectiveness. According to Amjad et al. [15], compression strength increased by 14% while tensile resistance increased by 37%. The viability of several natural fibres, such as flax, coconut, and jute, as possible carriers for various strains of the Bacillus genus, including Cohnii, Subtilis, and Sphaericus, was also investigated in a related study [1]. It was discovered that these natural fibres offer improved preservation properties for immobilised bacteria because of their fibrillar and lamellar features. Coir fibre had been shown to have a 42% increase in compressive strength, indicating a substantial improvement. This research, on the other hand, presents a more comprehensive approach, assessing the compression response of bioinspired concrete supplemented with SisF and B.St as biomimetic agents.

2 Material and Methods

2.1 Preparation of the B.St

The preparation of the B.St involved the following steps as per the literature [15] with a detailed schematic method depicted in Figure 1:

a) B.St colonies were initially cultured on agar plates and subsequently transferred to Tryptone Soya Broth.

b) After 24 hours of shaking incubation at 37°C, the B.St cells exhibited significant growth.

c) A sporulation medium containing magnesium sulfate heptahydrate (1.01 mM), manganese chloride (0.01 mM), ferrous sulfate (0.001 mM), potassium chloride (13.4 mM), and calcium nitrate (1.0 mM) was added to the bacterial broth solution.

d) The mixture was further incubated for an additional 120 hours at 37°C with shaking at 150 rpm.

e) The endospores were harvested by centrifugation at 4000 rpm and 6°C for 20 minutes.

f) A sterile distilled water suspension was prepared for the collected endospores.

g) The optical density of the spore solution was adjusted to a concentration of 0.5, following previous studies.

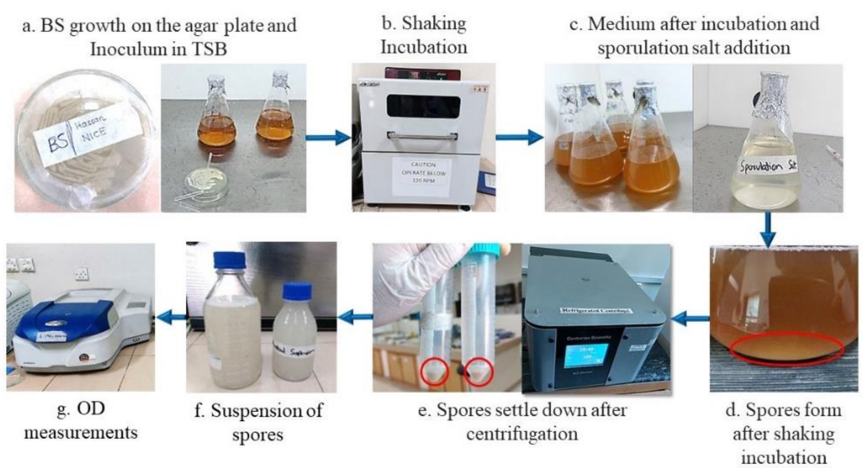

Figure 1: Preparation of the B.St

2.2 Concrete Constituents

The materials included Bestway Cement Type-1 Ordinary Portland Cement, Lawrencepur sand as the fine aggregate, and locally available Margalla crush as the coarse aggregate, meeting ASTM guidelines [16]–[19]. Table 1, and Table 2 provide the chemical constituents of the cement, properties of the fine aggregates, and properties of the coarse aggregate, respectively.

Table 1: Chemical Composition of Bestway Cement

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O
64.52	21.25	4.96	3.15	2.81	2.51	0.62	0.18

Table 2: Properties of fine and coarse aggregate

	Fineness Modulus	**Absorption (%)**	**Bulk Specific Gravity (SSD)**
Sand	2.90	2.04	2.75
Coarse aggregate	-	0.92	2.68

2.3 SisF

SisF, in the optimal size of 25 mm, was incorporated into the concrete mixture based on previous research [3], [15]. Figure 2 provides a visual of SisF:

Figure 2: Visual appearance of SisF

2.4 Mix Formulations

Four different formulations were investigated, as summarized in Table 3**.** In plain concrete, Mix-1 and Mix-3 had a mix design proportion of 1 for cement and 2.2 and 2.4 for fine and coarse aggregates, respectively. A water-to-cement ratio of 0.45 was chosen for the design. Fibrous mixes, Mix-2 and Mix-4, had similar proportions but included an additional superplasticizer to achieve workable mixtures within the desired slump range of 40-50 mm, as mentioned in the literature [15]. Based on the optimal dosage for concrete, 1.0 wt % SisF was incorporated into the fibrous mixes according to previous studies [12], [20]. In Mix-4, for the immobilization of bacterial spores, SisF was immersed in the biomimetic agent for one hour before being integrated into the concrete. To ensure homogeneity, calcium lactate pentahydrate, a mineral precursor, was added to all mixes. The formulations are categorized into four different mixes. The first mix, Mix-1, serves as the control mix and does not contain any SisF or biomimetic agent. In Mix-2, it is a fibrous control mix where only SisF is added at a concentration of 1.0 wt %. On the other hand, Mix-3 consists of a bacterial mix, which includes only the biomimetic agent at a concentration of 6x108 cells/cm3.

Table 3: Mix Design of different mixes

Materials	**Mix-1**	**Mix-2**	**Mix-3**	**Mix-4**
Cement (kg/m^3)	392	392	392	392
Fine aggregate (kg/m^3)	863	863	863	863
Coarse aggregate (kg/m^3)	941	941	941	941
Water/cement ratio	0.45	0.45	0.45	0.45
Bacterial spores content ($cell/cm^3$)	0	0	6×10^8	6×10^8

Lastly, Mix-4 is the fibrous bacterial mix, containing both SisF at a concentration of 1.0 wt % and the biomimetic agent at a concentration of 6x108 cells/cm3. These mixed formulations provide a basis for investigating the effects of different components on the experimental outcomes.

2.5 Specimen Preparation and Experimentation

All materials were carefully weighed according to the designated mix design and then dry-mixed in an electronic concrete mixer for a period of 2 to 3 minutes. Water was subsequently added, and the wet mixing process was continued for an additional 2 to 3 minutes. For each formulation, six P.C.C. cylinders measuring 100 mm in diameter and 200 mm in height and rectangular beamlets measuring 100x100x400 mm³ were cast. After casting, the samples were left to dry-cure in molds for 24 hours, under a temperature of 20±2 °C. At the end of the 24-hour curing period, the specimens were removed from their respective molds and then placed in a water curing tank, maintained at a relative humidity of 100% at room temperature (23±2°C), and left to cure for the respective days.

Standardized specimens were prepared according to ASTM-approved specifications for testing purposes. This included cylindrical specimens with a diameter of 100 mm and a height of 200 mm for evaluating the compressive response behavior. To ensure reliable results, a minimum of three specimens were prepared for each material and test. Testing of the formulated concrete mixes in compression loading was conducted to investigate strain vs stress plots, compressive strength, elastic modulus, pre and post-cracking energies, and toughness index, following ASTM C-39 guidelines [21]. In addition, Fourier-transform infrared spectroscopy (FTIR) was employed to assess any crystallographic variations in the concrete matrix resulting from microbially induced calcite precipitation (MICP).

3 Results and Discussion

3.1 Compressive Performance

Figure 3 illustrates the stress-strain plot of the investigated concrete mixtures under compression loading. The compressive strength is determined by the highest stress value obtained from the curve, while the corresponding strain value is known as the peak compressive strain (Figure 3 b). Pre-peak compression energy is calculated by integrating the response curve up to the highest stress value, while post-peak compression energy is obtained by integrating the response curve from the highest stress value to the failure point. The total compression energy, representing the area under the response curve, is derived by combining the pre-peak and post-peak compression energies. Figure 3 c shows the pre-peak, post-peak, and total compression energy of the formulated concrete mixes. The toughness index for compression, which is the ratio of total to pre-peak compression energy, is depicted in Figure 3 d to demonstrate ductility. Another significant property, the elastic modulus, is shown in Figure 3 e, which is derived using the chord technique according to ASTM C469 [22]. This technique involves establishing a chord through 40% of the peak stresses and strains at 0.05%, where the chord gradient reflects the elastic modulus of the concrete.

The behaviour of the concrete mixes is affected by the incorporation of SisF and B.St due to the composite nature of the concrete. SisF has a more ductile effect compared to B.St intrusion. While SisF has a minimal impact on compression strength (approximately 2.8%), it significantly increases the peak compressive strain (around 15.0%) in Mix-2 compared to Mix-1. This can be attributed to the confinement effect of the fiber, which delays crack formation and propagation, leading to increased peak compressive strain [23]. Mix-2 also shows significant improvements in post-peak compression energy, total compression energy, and a toughness index value of 1.43, indicating the effectiveness of fiber bridging in restraining crack widening.Mix-3, which incorporates B.St directly, exhibits an 8.1% increase in compressive strength due to the MICP process. This process fills voids and cracks, stiffening the compression behavior of the concrete and reducing the peak compression strain by 15.0%. The MICP-induced densification of the microstructure reduces compression strain and increases compressive stress [24]–[26]. The MICP does not have a prominent effect on total compression energy and compression toughness index, as it does not provide resistance to brittleness and lateral crack opening. However, the elastic modulus of Mix-3 is 22.3% higher than that of Mix-1 due to the pore refinement resulting from MICP [23].

Mix-4 exhibits stronger fiber reinforcement and MICP compared to other mixtures. The immobilization of B.St enhances both MICP potential and the interfacial bond between SisF and the cementitious matrix [15], [27]. Mix-4 shows a 14.0% increase in compressive strength and a 6.2% increase in strain compared to Mix-1. It also demonstrates significant improvements in post-peak and total compression energies, with a toughness index value of 1.59 indicating enhanced fiber reinforcement. The addition of SisF makes the behavior of Mix-4 more elastic, resulting in a 5.7% reduction in elasticity compared to Mix-1. Although these findings contradict a previous study [2] conducted on stress-strain behavior of bacterial concrete however the results are well aligned with the literature that explored the coupled effect of fibers and microstructural densification of concrete structures [10]. However, for typical structural members as reported in the previous literature, the minimum compression capacity of 17.24 MPa is usually recommended [26].

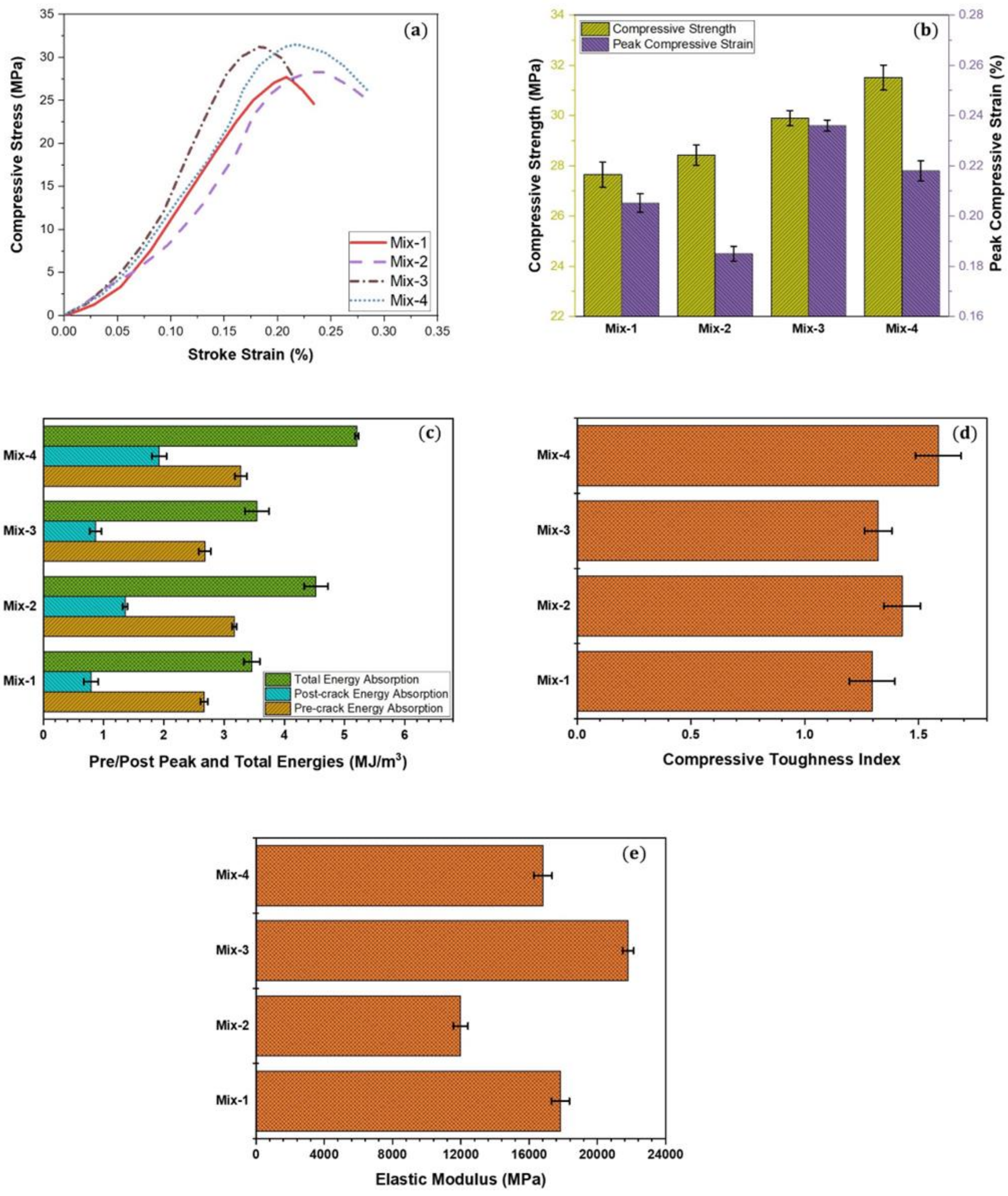

Figure 3: Compressive performance (a) compressive response behaviour (b) peak compressive strength and strain (c) pre- and post-peak compressive energies (d) compressive toughness index (e) elastic modulus

3.2 FTIR Examination

Figure 4 depicts the FTIR examination of the investigated concrete mixes to analyze the crystallographic shifts and identify molecular vibrations. Specific peaks were observed, indicating various molecular vibrations within the concrete mixture. Table 7 presents the identified molecular vibrations and their corresponding wavelengths (cm-1).

The O-H stretching vibrations are represented by peaks in the range of 3425-3430 cm^{-1}. H-OH and C-H bending vibrations are observed in the range of 1640-1645 cm^{-1}. Si-O stretching vibrations are identified in the range of 1075-1080 cm^{-1}. C-O stretching vibrations are observed in the range of 970-980 cm^{-1}, and additional peaks related to molecular vibrations can be seen at 1405-1410 cm^{-1}, 870-875 cm^{-1}, and 710-715 cm^{-1}. The presence of portlandite, which is associated with O-H stretching, has been established in previous studies [28], [29]. The H-OH and C-H bending vibrations and Si-O stretching vibrations are indicative of the presence of C-S-H gel [30],[31]. The spectra of bacterial mixtures, specifically Mix-3 and Mix-4, show significant peaks related to carbonate, confirming the presence of biomineralized calcium carbonate (CaCc). These findings align with prior research on biomineralization in concrete [15].

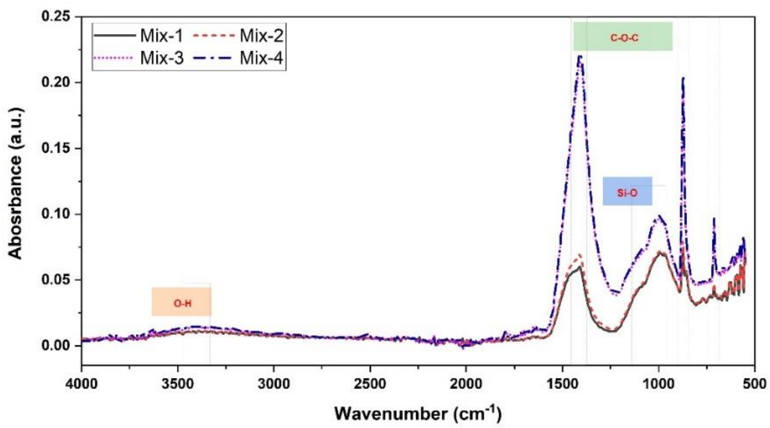

Figure 4: FTIR examination of the investigated concrete mixes

4 Conclusions

Thus using bio-triggered sisal fiber-reinforced concrete offers enhanced fracture resistance of concrete in various construction applications. It can be used in building and infrastructure construction, retrofitting existing structures, and construction in seismic-prone areas. The use of sisal fibers promotes sustainable construction practices by utilizing renewable and bio-based materials, reducing environmental impacts, and providing cost-effective solutions. The following conclusions have been derived from the experimental results:

1. The addition of B.Sb to the concrete increases its stiffness, whereas the addition of SisF increases its ductility.
2. Mix-2 containing SisF exhibits a 15% increment in peak compressive strain compared to the control mixture. Furthermore, Mix-2 demonstrates significant improvements in post-peak compression energy and total compression energy, the toughness index of the resulting concrete improved by 1.43, respectively.
3. Mix-3 containing B.St only undergoes the MICP process and exhibits an approximate 8.1% increase in compressive strength compared to the control mixture. Whereas, Mix-4 containing both fiber reinforcement and B.St shows a substantial increase of approximately 14.0% in compressive strength compared to the control mixture. Moreover, the toughness index, indicating the ratio of total to pre-peak compression energy, is approximately 1.59 for Mix-4, highlighting the enhanced toughness compared to the control mixture.
4. The FTIR examination confirms the successful synthesis of MICP.

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