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Durability and FTIR Characteristics of Sustainable Bacterial Concrete with Mineral Admixtures

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Abstract. The objective of this study is to optimize the concentrations of bacillus megaterium (BM), alccofine (AF), and silica fume (SF) in self-healing concrete while controlling the content of manufactured sand (M-sand). This research addresses the pressing need for sustainable alternatives to traditional cement as excessive energy consumption and environmental impacts continue challenging the construction industry. A novel "binary and ternary blended cementitious system" was developed, featuring twelve distinct mix proportions. M-sand was fully utilized as an acceptable aggregate substitute, with bacterial concentrations of (10–50)·10^5 cells/ml incorporated to mitigate crack formation. Cement was partially replaced with AF, and the M-sand content was adjusted from 0 to 20 % in 5 % increments. This study also uniquely evaluates the durability properties of the various cementitious systems, including water absorption, concrete density, porosity, long-term strength retention, and rapid chloride permeability – at intervals of 7, 14, and 28 days post-curing. Fourier transform-infrared spectroscopy (FTIR) was employed to analyze calcite precipitation, providing insights into the biochemical mechanisms. The results indicate that while SF demonstrates superior effectiveness compared to AF, combining both enhances durability compared to alternative mixes. The findings reveal that bacterial concrete incorporating zeolites can significantly improve structural strength and be a sustainable building material. Notably, incorporating additional cementitious materials with mineral admixtures increased strength by up to 10 % through optimized bacterial concentrations. The successful precipitation of calcium carbonate confirmed the beneficial properties of the bacterial agents, which are safe and non-toxic to the environment. Overall, this study contributes valuable knowledge on reducing cement usage and carbon dioxide emissions, positioning BM, alongside AF and SF, as a promising approach for environmentally friendly concrete solutions.

Keywords: environmental protection, CO_2 emission, calcite precipitation, durability, alccofine, silica fume.

1 Introduction

The demand for resilient and sustainable infrastructure is immense in rapidly developing nations like India. With the population overgrowing, the need for structures such as bridges, highways, residential buildings, and commercial spaces has skyrocketed. Concrete, a cornerstone material in modern construction, is indispensable in fulfilling these infrastructure needs. It is a composite material made of aggregates, cement, and water, which hardens over time to form a solid mass. Globally, about 5.5 billion tonnes of concrete are used every year [1], making it the most consumed material on earth after water.

Concrete owes its popularity to several factors: it is versatile, durable, and cost-effective. However, conventional concrete has significant environmental drawbacks, primarily due to the high CO_2 emissions associated with Portland cement production. Portland cement, the most common binder in concrete, is manufactured by heating limestone and other materials in kilns at temperatures exceeding 1400 °C, a process that releases significant amounts of carbon dioxide. The production of one tonne of cement generates roughly one tonne of CO_2 [2]. The cement industry contributes about 8 % of global CO_2 emissions, and this is a significant concern in an era of growing environmental consciousness.

While durable, concrete structures are susceptible to cracking over time due to shrinkage, temperature fluctuations, and loading conditions. Even hairline cracks can lead to the ingress of water, chemicals, and gases, accelerating the deterioration of reinforced concrete structures. This compromises the integrity of buildings and results in costly maintenance and repairs. With growing infrastructure needs, especially in countries like India, the industry faces a dual challenge: reducing environmental impact while improving the durability and longevity of structures.

2 Literature Review

As the global community increasingly focuses on sustainability, exploring and implementing alternative concrete materials is imperative. Researchers and engineers have directed their efforts toward reducing the environmental footprint of concrete by experimenting with supplementary cementitious material (SCMs) and alternative aggregates. For instance, manufactured sand (M-sand), derived from crushing rocks, has been identified as a viable substitute for natural river sand, which is rapidly depleting [3]. M-sand not only helps conserve natural resources but also improves the workability and strength of concrete [4].

Over the past few decades, the construction industry has grown interested in incorporating alternative materials into concrete to address environmental and resource challenges. The partial replacement of cement with SCMs, such as fly ash, silica fume (SF), and alccofine (AF), is gaining traction. These materials, often byproducts of industrial processes, can potentially improve the mechanical properties of concrete while reducing the carbon footprint associated with cement production [5, 6].

AF, for example, is a micro-fine SCM developed from the byproducts of the iron industry. It enhances concrete's workability, reduces water demand, and significantly improves compressive strength [7]. In addition, SF (a byproduct of silicon and ferrosilicon alloy production) has been found to improve the durability and strength of concrete. SF particles are much smaller than cement particles and can fill voids in the concrete matrix, resulting in denser and more durable concrete [8]. Studies have shown that concrete mixtures containing SF exhibit increased resistance to chemical attack, reduced permeability, and improved long-term durability [9].

One of the most promising innovations in the quest for sustainable and durable concrete is the development of bacterial concrete, a material that can repair its cracks. This concept of self-healing concrete was first explored in [10], representing a significant breakthrough in construction technology. The self-healing properties of bacterial concrete rely on introducing specific strains of bacteria into the concrete mixture, which can precipitate calcium carbonate to fill cracks and pores.

Bacillus megaterium (BM) and bacillus subtilis are two bacterial strains frequently used in bacterial concrete. When introduced into concrete in spore form, these bacteria remain dormant until cracks form and water seeps into the structure. Upon activation by water, the bacteria begin to feed on calcium lactate or other nutrients added to the mix, which produces calcium carbonate (calcite). This calcium carbonate fills the cracks, effectively "healing" the concrete and preventing further damage [10]. Studies have shown that bacterial concrete can heal cracks up to 0.5 mm wide, making it a viable solution for prolonging the life of concrete structures and reducing the need for frequent repairs [11].

Bacterial concrete not only addresses the issue of crack repair but also enhances the overall durability of structures. It reduces permeability, making the concrete less susceptible to water infiltration and chemical attack, particularly from chlorides and sulfates. This increases the concrete's resistance to corrosion, a common issue in reinforced concrete structures [12].

The development of bacterial concrete is significant not only for its self-healing properties but also for its potential environmental benefits. By reducing the need for extensive repairs and maintenance, bacterial concrete can extend the lifespan of structures, reducing the consumption of new construction materials and the energy associated with producing them. This contributes to a decrease in the overall carbon footprint of construction projects.

Moreover, bacterial concrete production requires fewer resources than traditional concrete. Since the bacteria used in the process can be cultivated in a laboratory and introduced into the concrete in small amounts, there is no need for large-scale industrial processes or significant energy inputs. Therefore, the overall environmental impact is lower, making bacterial concrete an attractive option for sustainable construction.

Despite its many advantages, bacterial concrete is still in the experimental phase, and further research is required to optimize its performance and understand its long-term behavior. One key area of investigation is determining the optimal dosage of bacterial solutions for different types of concrete applications. Researchers are also exploring the potential of using different strains of bacteria and alternative nutrients to enhance self-healing.

Recent studies have focused on improving bacterial concrete's strength and healing efficiency through encapsulation techniques. In these studies, bacteria are encapsulated in protective shells to prevent premature activation and ensure that they remain dormant until cracks form [13]. This approach has promising results in laboratory tests and is expected to lead to the development of more robust and reliable self-healing concrete in the future.

Fourier-transform infrared (FTIR) spectroscopy has effectively investigated the chemical interactions and microstructural changes in concrete incorporating AF and SF. Horgnies et al. [14] demonstrated using Fourier transform infrared spectroscopy to study cementitious materials. Smarzewski [15] found that SFs significantly enhance concrete's mechanical properties. Narender Reddy and Meena [16] explored AF's properties and gave information about its behavior in concrete. Hamada et al. [17] highlighted the effect of SFs on the properties of sustainable cement concrete. Lastly, Jain et al. [18] employed FTIR to analyze the impact of SF on concrete.

As research progresses, integrating bacterial concrete into mainstream construction practices could revolutionize the industry. Its potential to reduce maintenance costs, improve durability, and minimize environmental impact makes it a desirable solution for modern infrastructure development challenges.

In conclusion, the development of bacterial concrete represents a significant advancement in the construction industry's pursuit of sustainable and durable materials. By addressing critical issues such as crack formation, durability, and environmental impact, bacterial concrete offers a promising solution for future infrastructure projects. As research continues, bacterial concrete will likely become a standard material in the construction industry, helping to reduce the environmental footprint of the built environment while improving the longevity and performance of concrete structures.

This study's originality lies in optimizing AF and SF content with bacterial cell concentration to develop a novel self-healing concrete. Unlike previous studies, which have focused on either bacterial concrete or using SCMs individually, this research uniquely integrates bacterial healing mechanisms with varying percentages of AF and SF to enhance durability properties. This approach explores the mechanical benefits and introduces an environmentally sustainable methodology by reducing the overall cement content and improving its longevity.

Additionally, this research conducts a comprehensive FTIR investigation to analyze the molecular-level interactions within the concrete matrix, providing new insights into the self-healing capabilities activated by bacterial calcite precipitation in conjunction with AF and SF. By determining the optimal bacterial concentration for concrete with varying AF and SF content, this study advances current knowledge on the synergistic effects of these materials, aiming to improve both the durability and sustainability of concrete structures.

Bacteria-based concrete exhibits efficient self-healing, utilizing actively metabolizing bacteria to process calcium nutrients. This metabolic activity releases carbon dioxide as part of the reaction [19]:

$$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O.$$

As a result of bacterial metabolism, the formation of calcium carbonate occurs, leading to the sealing of cracks through bacterial action [20].

A significant advancement in sustainable building techniques is developing self-healing bacterial concrete with SCMs. This approach addresses the brittleness and environmental impact of conventional concrete. By adding bacteria like BM, the concrete can self-heal cracks through bio-mineralization, improving durability and reducing maintenance costs. Using SCMs such as AF-1203, derived from industrial waste, enhances concrete properties and reduces cement usage. This dual strategy promotes eco-friendly construction and aligns with global sustainability goals.

The study aims to identify the optimal mix of SCMs and bacterial additives to enhance concrete's durability, microstructure, and sustainability.

3 Research Methodology

The rod-type BM strains were used in this investigation. They originated via the microbial kind cultures collection and gene bank (MTCC).

The selection criteria for this bacterial strain adhered to established microbiological standards. Culturing bacteria for use in concrete involves several detailed steps to ensure the bacteria are viable and effective. The bacterial strains were initially purchased from the MTCC, which provides high-quality microbial strains. These bacteria were first grown on a nutrient agar slant, a solid medium rich in essential nutrients to promote bacterial growth. The culture was transferred to a nutrient broth after establishing a sufficient colony on the nutrient agar slant. This broth is a liquid medium, allowing for more extensive bacterial multiplication. The nutrient broth was autoclaved for twenty minutes to maintain sterility and prevent contamination. Autoclaving involves heating the broth under high pressure to eliminate any unwanted microorganisms. The bacteria were introduced into this environment once the broth was sterilized and cooled. The inoculated nutrient broth was then placed in an orbital shaker incubator. This incubator maintains a controlled temperature of 30 °C and continuously shakes the culture at 250 rpm. The shaking ensures an even distribution of nutrients and oxygen throughout the broth, promoting optimal bacterial growth. The bacteria were allowed to develop in this incubator for one day, ensuring they reached a high concentration and were ready for application in concrete.

Initially, pure cultures of BM were preserved on nutrient agar slants. Liquid bacterial cultures were prepared following precise protocols. A conical flask, previously sterilized, was occupied with 250 ml of water. Subsequently, peptone and meat or beef extract were added at a concentration of 5 g/l each. To adjust the pH level to 7 and 20 g/L of urea was incorporated into the medium, per the specified instructions. Additionally, 10 mg of $MnSO_4 \cdot H_2O$ was included to support bacterial growth. The medium underwent autoclaving for twenty minutes to ensure complete sterilization and elimination of any potential contaminants.

A loop introduced the bacteria into the nutritive media under sterile conditions. Throughout the inoculation process, bacteria were transferred from their preserved state in a stock to a fresh medium to promote further development. The closed loop containing the pure culture stock was carefully opened, and the cut loop was sterilized using a flame for three seconds to prevent bacterial contamination. The sterilized loop was then placed atop the highest portion of the bacterial slant, ensuring that it did not come into contact with the edges of the tube. Subsequently, the bacteria-containing loops were gently immersed into the previously prepared growing media.

The injected media was allowed to incubate for one day in an orbital shaking incubator at 30 °C and 250 rpm to facilitate bacterial growth. After incubation, the solution was chilled to 4 °C for preservation, ensuring its viability for subsequent use in the concrete mixes.

Ordinary Portland cement (OPC, 53 grade) was used as the binder in the concrete for the required grade, meeting the specifications outlined in Table 1 and complying with the requirements of the Indian standard IS 12269:2013 “Ordinary Portland Cement, 53 Grade – Specification”. The present study utilized available local coarse materials that were 20 mm in size and complied with the standard IS 383:2016 “Coarse and Fine Aggregate for Concrete – Specification”. The preliminary testing results are reported in Table 1, including its properties.

Table 1 – Experimental values of OPC (53 grade), CA, and M-Sand

Characteristics	OPC	CA	M-Sand
Initial time setting, min	50	–	–
Final time setting, min	320	–	–
Specific gravity	3.15	2.8	2.2
Consistency, %	32	–	–
Water absorption, %	–	3.5	–
Surface texture	–	Smooth	–
Impact value	–	14.2	–
Bulk density, kg/m	–	–	576
Size, μm	–	–	0.1
Compressive strength on 2 days, MPa	32.8	–	–

The concrete is being prepared and cured with potable water from the faucet. As another fine aggregate material, local M-sand was utilized. This sand was subjected to refinement and grading tests per the standard IS 383:2016, and it exhibited the features detailed in Table 1. In order to attain the required level of workability, the most recent version of improved sulfonated naphthalene polymer compounds, known as Conplast SP 430, remained utilized as a water-reducing ingredient. This made the material easier to process.

The research project makes use of AF-1203, which is an ultrafine calcium silicate product that has a high glass content as well as a reaction. This product is produced via controlled granulation. A selection of mineral admixtures that is indicative of the whole can be found in Figure 1.

a b

Figure 1 – Sample of mineral admixtures: a – AF; b – SF

In addition to having an almost sphere-like particle shape, SF contains a high concentration of amorphous silicon dioxide. Magnesium, iron, and alkali oxides of metals are also found, albeit in minute quantities. Details regarding the physical properties of AF and SF are shown in Table 2.

Table 2 – Comparative analysis of the chemical and physical properties of AF and SF

Chemical properties			Physical properties		
Mineral	Composition, %		Possessions	Outcomes	
	AF	SF		AF	SF
SiO_2	34.2	92.1	Partial size distribution, μm		
SO_3	0.08	-	D_{10}	1.5	–
Al_2O_3	23.1	0.5	D_{50}	5	–
Fe_2O_3	0.8	1.4	D_{90}	9	–
K_2O	–	0.7	Specific gravity, g/cm^3	2.86	–
LOl	–	2.8	Fineness, cm^2/(g·m)	–	–
CaO	34	0.5	Bulk density, kg/m^3	600	450
MgO	6.1	0.3	Particle size, μm	–	< 1
Na_2O	-	0.3	Specific surface	$1.2 \cdot 10^4$	2.22

A concrete mix of M35 grade (1.00:1.79:2.57) was formulated, conforming to the standard IS 10262:2009 “Recommended Guideline for Concrete Mix Design” codal provisions. Various trial mixes were conducted, exposing the ideal concrete amount for the chemical admixture, ranging from 0 to 1 % in 0.25 % increments by weight of cementitious material.

Using mixers driven for 30 s in dry conditions, the OPC, fine aggregate, AF, SF, and coarse gravel are mixed in the planned proportions.

After all of the dry components have been combined to generate the concrete mixes, the superplasticizer, which is one percent, and the water-cement ratio, which is four percent, is then added to the design mix incrementally.

Information regarding binary and tertiary blended systems of mineral admixtures are presented in Tables 3, 4.

Figure 2 provides a visual representation of the testing of specimens.

The entire project spanned 5 months, encompassing 1 month for initial preparation and materials procurement, 2 months for the casting process, and 2 months for testing and result analysis. The flowchart of the research methodology adopted has been presented in Figure 3.

Table 3 – Percentage of SF and AF in BBS for 1 m^3 of concrete

Mix ID	Factors, %		FA	M-sand	CA	Water	Cement
	SF	AF	kg/m^3				
SF 0 AF 0	0	0	695	–	1254	157.6	435.0
SF 5 AF 0	5	0	–	695	1254	157.6	413.3
SF 10 AF 0	10	0	–	695	1254	157.6	391.5
SF 15 AF 0	15	0	–	695	1254	157.6	369.8
SF 20 AF 0	20	0	–	695	1254	157.6	348.0
SF 0 AF 5	0	5	–	695	1254	157.6	413.3
SF 0 AF 10	0	10	–	695	1254	157.6	391.5
SF 0 AF 15	0	15	–	695	1254	157.6	369.8
SF 0 AF 20	0	20	–	695	1254	157.6	348.0

Table 4 – Percentage of SF and AF in TBS for 1 m3 of concrete

Mix ID	Factors, %		FA	M-sand	CA	Water	Cement
	SF	AF	kg/m^3				
SF 5 AF 15	5	15	–	695	1254	157.6	391.5
SF 10 AF 10	10	10	–	695	1254	157.6	348.0
SF 15 AF 5	15	5	–	695	1254	157.6	304.5

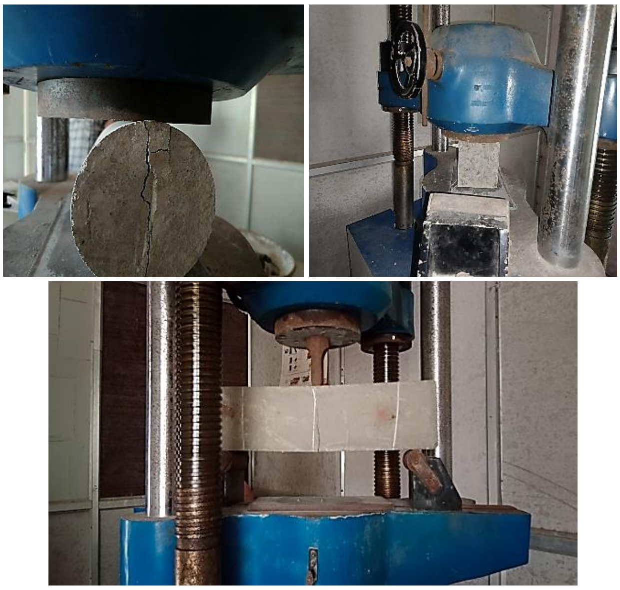

Figure 2 – Failure mode of tested specimens

Complying with the standard IS 456:2000 “Plain and Reinforced Concrete – Code of Practice”, 108 binary and tertiary cementitious concrete specimens were cast using the produced concrete mix. These specimens included normal cubes measuring 150 mm, cylinders measuring 100 mm by 300 mm, and prisms measuring 100 mm by 100 mm by 500 mm.

The standard IS 516:2018 “Hardened Concrete – Methods of Test” was utilized in order to investigate the specimens.

Following the casting process, the concrete specimens were allowed to soak in a curing tank at a temperature of 27 °C for varying amounts of time, including 7, 14, and 28 days.

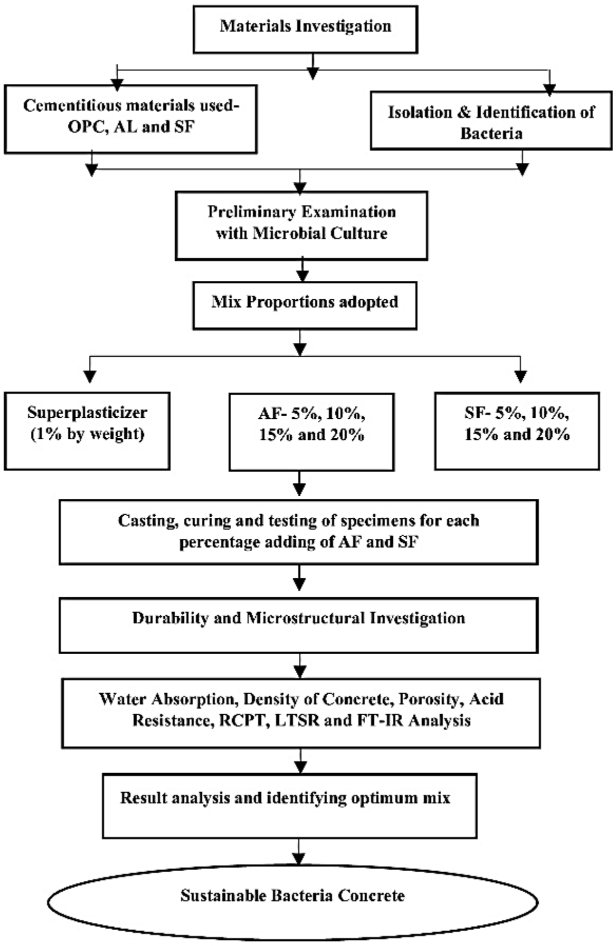

Figure 3 – A flowchart of the research methodology

4 Results

4.1 Water absorption

Concrete can take in water because of its porosity, and the amount of water taken in is inversely related to the amount of pore space present. Evaluations of water absorption were conducted according to the test method described in the standard IS 1124:1974 "Methods of Test for Determination of Water Absorption, Apparent Specific Gravity and Porosity of Natural Building Stones".

A concrete test sample (150×150×150 mm) with varying replacement percentages of pozzolanic AF and SF materials (from 0 to 20 %) and BM were designated for testing. The sample was considered before submersion in water and left submerged in distilled water for 24 hours. Water absorption examinations were achieved after curing for 7, 14, and 28 days. The weight before immersion W_1 and after immersion W_2 were recorded, and A calculation was made using the following equation to get the percentage of water absorption:

$$WA = \frac{W_2 - W_1}{W1} \cdot 100\%, \quad (1)$$

where WA – the proportion of water that has been absorbed, %; W_1, W_2 – the starting weights of the specimen prior to and following an immersion period of 24 hours, respectively.

Water absorption tests were conducted on microbial concrete both with and without AF, SF, and M-sand as replacements for the binary blended system (BBS), and the results are shown in Table 5 and Figure 4.

Table 5 – Water absorption of BBS

Mix ID	The initial weight of a sample before immersion W_1, kg	Weight of the sample after 24 hours of immersion W_2, kg			Percentage of water absorption, W_A, %		
		7	14	28	7	14	28
		days			days		
AF0SF0	8.06	8.10	8.08	8.05	0.56	0.34	0.11
AF5SF0	7.66	7.95	7.94	7.93	3.77	3.65	3.54
AF10SF0	7.76	8.10	8.08	8.08	4.36	4.08	4.04
AF15SF0	7.57	7.79	7.79	7.77	2.95	2.83	2.59
AF20SF0	7.17	7.34	7.33	7.31	2.47	2.22	1.97
AF0SF5	7.58	7.81	7.80	7.79	3.09	2.97	2.85
AF0SF10	7.32	7.52	7.51	7.50	2.64	2.52	2.40
AF0SF15	7.67	7.98	7.97	7.96	4.06	3.94	3.71
AF0SF20	7.08	7.24	7.23	7.21	2.25	2.12	1.87

At 28 days after testing, the water absorption rates of the control mix (AF0SF0) were 3.5, 4.0, 2.6, and 2.0 % higher, respectively, for bacterial concrete in the integrated blending systems samples with AF (AF5SF0, AF10SF0, AF15SF0, and AF20SF0).

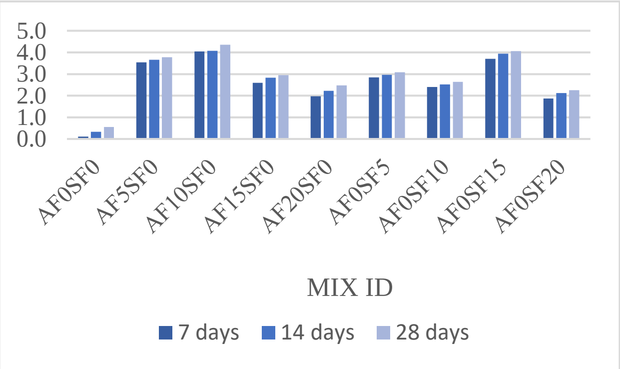

Figure 4 – Water absorption compared with BBS

Compressive strength values were also higher in samples with SF replacement levels of 5, 10, 15, and 20 % (AF0SF5, AF0SF10, AF0SF15, and AF0SF20) compared to the control mix. (AF0SF0) by 2.9, 2.4, 3.7, and 2.0 %, respectively.

Similarly, Figure 5 and Table 6 show the outcomes of tests on the water absorption of bacterial concrete with and without AF, SF, and M-sand substituted for ternary blended system (TBS).

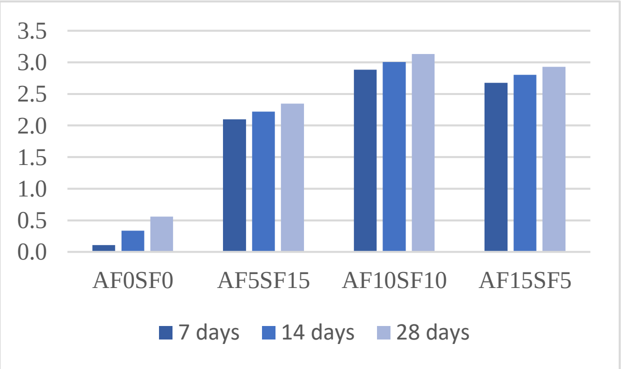

Figure 5 – Water absorption compared with TBS

Bacterial concrete in TBS specimens with SF and AF (AF5SF15, AF10SF10, and AF15SF5 correspondingly) had compressive strengths at 28 days following testing that were, correspondingly, 2.1, 2.9, and 2.7 % greater than those of the control mix (AF0SF0).

Table 6 – Water absorption of BBS

Mix ID	The initial weight of a sample before immersion W_1, kg	Weight of the sample after 24 hours of immersion W_2, kg			Percentage of water absorption, W_A, %		
		7	14	28	7	14	28
		days			days		
AF0SF0	8.06	8.10	8.08	8.05	0.56	0.34	0.11
AF5SF15	7.37	7.54	7.53	7.53	2.35	2.22	2.10
AF10SF10	7.26	7.49	7.48	7.47	3.13	3.01	2.88
AF15SF5	7.14	7.35	7.34	7.33	2.93	2.80	2.68

The highest water absorption ratings (AF10SF0 and AF0SF15) are observed in bacterial concrete with 10 % AF replacement and 15 % SF. The results indicate decreased water absorption values with increasing curing age and replacement level. AF enhances pozzolanic activity over time, reducing connections between pores. The fineness of AF (average particle size of 4 μm) contributes to sealing pores and microcracks, further lowering water absorption. AF and SF contribute to reducing water absorption in concrete due to their large specific surface area. The impact of pozzolanic and micro-filler properties results in decreased water absorption values for concrete mixtures with increased SF replacement.

4.2 Density of concrete

The density of concrete, a weight measurement, divides it into two categories: ordinary and lightweight. A concrete specimen of M35 grade was selected for the tests. The specimen had the following dimensions: 150×150×150 mm and could have SF material substitution levels between 0 and 20 % along with BM. The specimen is considered to be the same weight as before immersion.

Next, the following equation is used to get the density while considering the volume of the concrete:

$$\rho = \frac{M_{c.s.}}{V_{c.s.}} \qquad (2)$$

where ρ – density, kg/m^3; $M_{c.s.}$ – mass of concrete specimen, kg; $V_{c.s.}$ – volume of concrete specimen, m^3.

Figure 6 and Table 7 display the results of tests conducted on the bulk density of bacterial concrete.

The experiments compared samples with and without AF, SF, and M-sand in a BBS. In the samples with AF, the water absorption at 28 days was 3.6, 4.9, 6.0, and 11.0 % lower than the control mixture (AF0SF0) for AF5SF0, AF10SF0, AF15SF0, and AF20SF0, respectively.

The samples with SF replacements of 5, 10, 15, and 20 % (AF0SF5, AF0SF10, AF0SF15, and AF0SF20) had lower compressive strengths than the control mix. (AF0SF0) by 4.8, 6.0, 9.1, and 12.1 %, respectively.

Similarly, Figure 7 and Table 8 show that the bacterial concrete in TBS specimens with AF and SF (AF5SF15, AF10SF10, and AF15SF5, respectively) had compressive strengths at 28 days following testing that were, respectively, 9.5, 11.0, and 12.2 % lesser than those of the control mix (AF0SF0).

Density has decreased due to the influence of specific gravity. The control mix exhibits lower density as cement has a lower specific gravity than AF and SF.

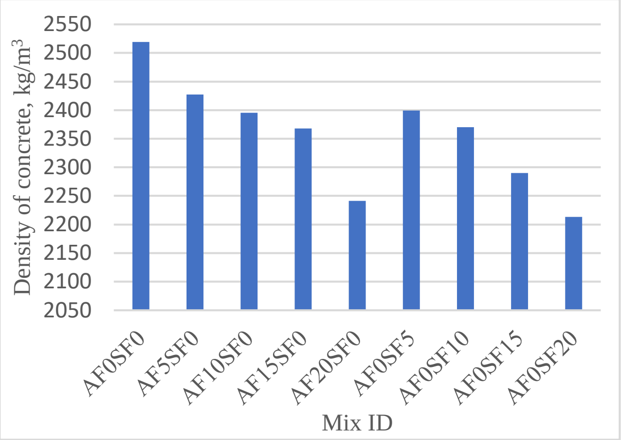

Figure 6 – Density of concrete compared with BBS

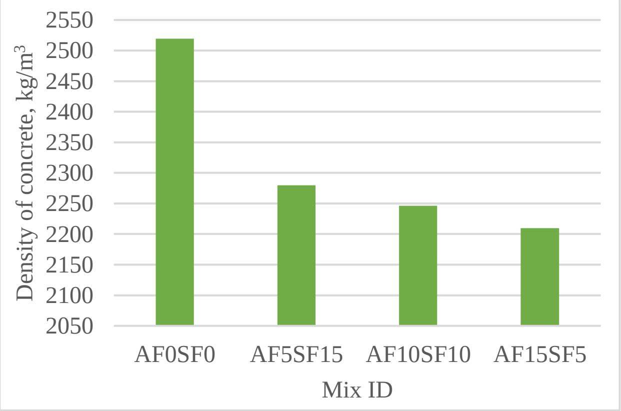

Figure 7 – Density of concrete compared with TBS

Tables 12, 13 and Figures 6, 7 show the outcomes of the concrete's density tests where the binder system was binary and tertiary blended with AF and SF instead of the cementitious system.

Table 7 – Mass, volume, and density of BBS

Mix ID	Mass of specimen, kg	Volume of specimen, m^3	Density, kg/m^3
AF0SF0	8.503	0.003375	2519
AF5SF0	8.193	0.003375	2427
AF10SF0	8.084	0.003375	2395
AF15SF0	7.991	0.003375	2368
AF20SF0	7.565	0.003375	2241
AF0SF5	8.098	0.003375	2399
AF0SF10	7.999	0.003375	2370
AF0SF15	7.728	0.003375	2290
AF0SF20	7.470	0.003375	2213

Table 8 – Mass, volume, and density of TBS

Mix ID	Mass of specimen, kg	Volume of specimen, m^3	Density, kg/m^3
AF0SF0	8.503	0.003375	2519
AF5SF15	7.695	0.003375	2280
AF10SF10	7.581	0.003375	2246
AF15SF5	7.458	0.003375	2210

4.3 Porosity

The test was conducted following the procedure outlined in IS 1124:1974 on concrete cubes of standard size. Concrete cubes measuring 100×100×100 mm were cast for all mix IDs. The weight of each specimen was measured to determine porosity, and the calculations were discussed.

Here are the findings of the porosity tests conducted on different concrete mixtures at 28 days of age (Tables 9). Figures 8, 9 show how the porosity of concrete mixes is affected by the addition of M-sand to red mud and SF and how the porosity varies with varying percentages of these two materials in binary and ternary blended cementitious systems.

At 28 days after being tested, concrete in a BBS system with 5, 10, 15, and 20 % AF replacement (AF5SF0, AF10SF0, AF15SF0, and AF20SF0, respectively) had effective porosity at 28 days ranged from 2.5 to 3 % that was 7.6, 15.1, 22.9, and 28.7 % reduction in porosity compared to of the control mix AF0SF0, respectively.

Similarly, specimens with 5%, 10 %, 15 %, and 20 % SF replacement (AF0SF5, AF0SF10, AF0SF15, and AF0SF20, respectively) had effective porosity at 28 days ranged from 2.4 to 2.90 was 10.4, 17.1, 28.7, and 35.0 % reduction in porosity compared to of the control mix (AF0SF0) shown in Table 9 and Figure 8.

Table 9 – Porosity of BBS

Mix ID	Porosity at 28 days, %	Reduction in porosity*, %
AF0SF0	3.2	–
AF5SF0	3.0	7.580
AF10SF0	2.8	15.09
AF15SF0	2.6	22.88
AF20SF0	2.5	28.69
AF0SF5	2.9	10.37
AF0SF10	2.7	17.06
AF0SF15	2.5	28.69
AF0SF20	2.4	34.99

* compared to standard concrete at 28 days.

In TBS, at 28 days, effective porosity of concrete with 5 % AF and 15 % SF, 10 % of both AF and SF, 15 % AF and 5 % SF replacement (AF5SF15, AF10SF10, and AF15SF5) gave 31.8, 28.7, and 25.7 % reduction in porosity compared to of the control mix AF0SF0, respectively.

The effective porosity test results substituted the ternary blend binder system for red mud and SF in the ternary blended cementitious system shown in Figure 9 and Table 10.

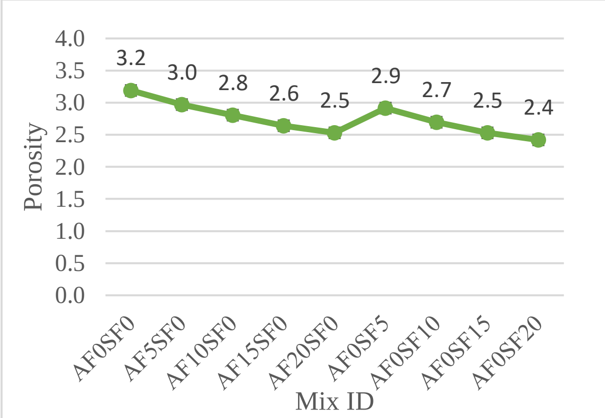

Figure 8 – Porosity comparison with BBS

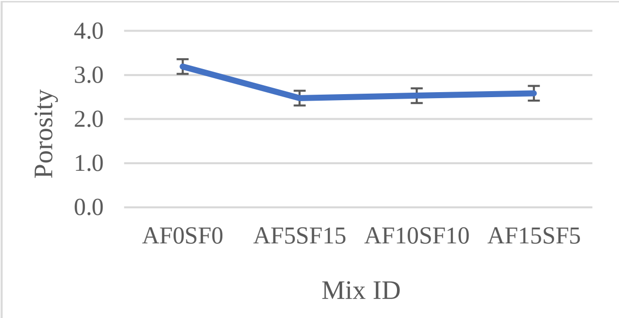

Figure 9 – Porosity comparison with TBS

Table 10 – Porosity of TBS

Mix ID	Porosity at 28 days, %	Reduction in porosity*, %
AF0SF0	3.19	-
AF5SF15	2.475	31.768
AF10SF10	2.53	28.688
AF15SF5	2.585	25.74

* compared to standard concrete at 28 days.

4.4 Tests on acid resistance and rapid chloride permeability

The cubes of concrete of all mix IDs were evaluated for their resistance to the acid according to the process stated in the standard ASTM C642-1 "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete", and the findings were presented.

A comparison is made in Figure 10 between the visual appearance of control concrete cubes and concrete cubes that have been admixed with AF and SF and have been submerged in a solution of 5 % sulfuric acid for 8 weeks.

The control specimens exposed to sulfuric acid exhibited significant surface erosion, with a thick white paste formation, possibly attributed to the high calcium content in cement. In contrast, the SF and AF admixed concrete displayed minimal erosion, attributed to their high pozzolanic content. Surface damage increased with a more extended exposure period.

Figure 10 – Visual appearance of concrete after exposure to sulphuric acid during 4 weeks

A decrease in compressive strength measured after 4 weeks of exposure is displayed in Table 11 and Figure 11, respectively.

Table 11 – Result on compressive strength for specimens soaked in sulphuric acid solution

Mix ID	Compressive strength, MPa		% loss in compressive strength
	before immersion	after immersion	
AF0SF0	35.40	29.88	15.6
AF5SF0	35.90	33.07	7.89
AF10SF0	36.30	33.08	8.88
AF15SF0	35.60	31.27	12.2
AF20SF0	34.60	30.47	11.9
AF0SF5	37.80	36.65	3.05
AF0SF10	38.30	35.81	6.50
AF0SF15	39.40	35.31	10.4
AF0SF20	36.70	32.44	11.6
AF5SF15	38.50	34.93	9.26
AF10SF10	40.40	36.85	8.78
AF15SF5	37.90	35.03	7.56

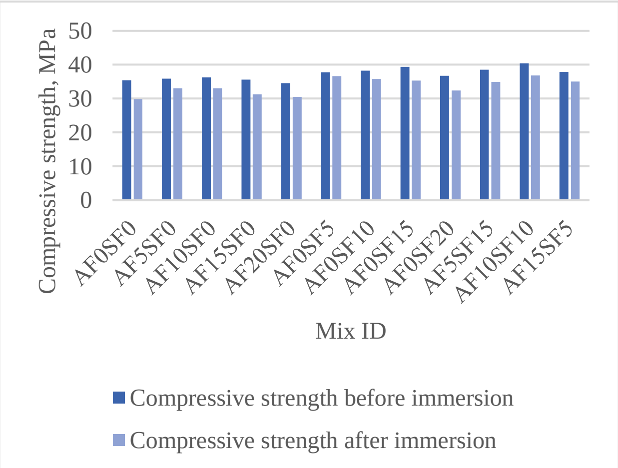

Figure 11 – Comparison of compressive strengths

It has been demonstrated by the results of the tests that the concrete specimen displayed a decrease in compressive strength by 15.6, 7.9, 8.9, 12.2, 11.9, 3.1, 6.1, 10.4, 11.6, 9.3, 8.8, and 7.6 % for AF0SF0, AF5SF0, AF10SF0, AF15SF0, AF20SF0, AF0SF5, AF0SF10, AF0SF15, AF0SF20, AF5SF15, AF10SF10, and AF15SF5, respectively, after 4 weeks all in comparison to the control specimen.

The RCP test measures one of the durability properties, i.e., penetrability. The charge passed is the measure of penetrability expressed as RCP.

Table 12 depicts the charge passed of SF and AF mixes at all ages 28 days.

Table 12 – Rapid chloride permeability test

Mix ID	The passed charge, C	Chloride penetration
SF 0 AF 0	4256	high
SF 0 AF 10	1300	low
SF 15 AF 0	1936	moderate
SF 10 AF 10	875	very low

Mix with 10 % SF and 10 % AF exhibited a significantly lower RCP. The rate of chloride penetration decreased with age for all mixes. The rate of chloride penetration decreased with the increase in SF and AF. Hence, it can be concluded that 10 % SF and 10 % AF mixes exhibited lower RCP.

4.5 FTIR analysis and relationship between water absorption and compressive strength

From the previous tests and experimental results, the mixes AF 0 SF 0, AF 10 SF 0, AF 0 SF 15, and AF 10 SF 10 exhibited the highest compressive strength, and these samples were selected for FTIR analysis, as shown in Figure 12.

The FTIR spectra revealed prominent peaks at 3767 cm^{-1} for the control specimen and 3783 cm^{-1} for the others, indicating the presence of carbonate phases in the samples. These peaks suggest the existence of $Ca(OH)_2$ in the concrete matrix, along with strong C-H, C-F, NO_2, C-O, and C-N bonds in addition to C-S-H.

Bands at 972, 957, 956, and 965 cm^{-1} correspond to Si-O bonding, while peaks at 1426 and 1418 cm^{-1} are notable C-H ones.

The high noise effect in the low-wavenumber range further supports these findings. FTIR analysis highlights the complex nature of the bacteria's self-healing properties due to calcite precipitation in the cement.

Figure 13 illustrates the relationship between compressive strength and water absorption percentages in concrete.

The test results indicate an inverse correlation between compressive strength before immersion and water absorption. The incorporation of AF and SF led to an increase in both compressive strength and water absorption. Specifically, replacing up to 10% of the cement with AF and SF significantly improved compressive strength while increasing water absorption. Compared to the control mix, this increase in both properties is attributed to the formation of additional C-S-H gel from the reaction of Portlandite and stratlingite with silica during later hydration, resulting in a denser matrix with fewer microcracks, lower Ca/Si ratios, and higher amounts of larnite and alite.

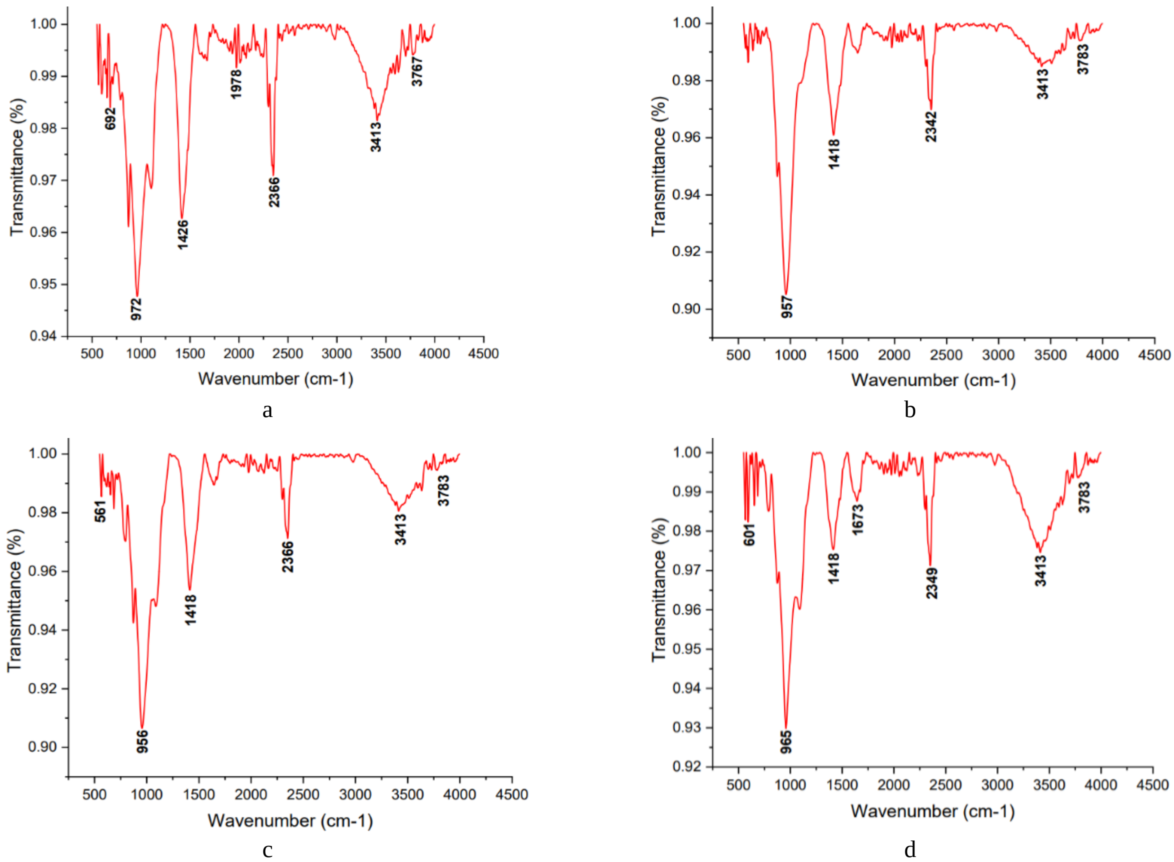

Figure 12 – FTIR analysis: a – AF 0 SF0; b – AF 10 SF 0; c – AF 0 SF 15; d – AF 10 SF 10

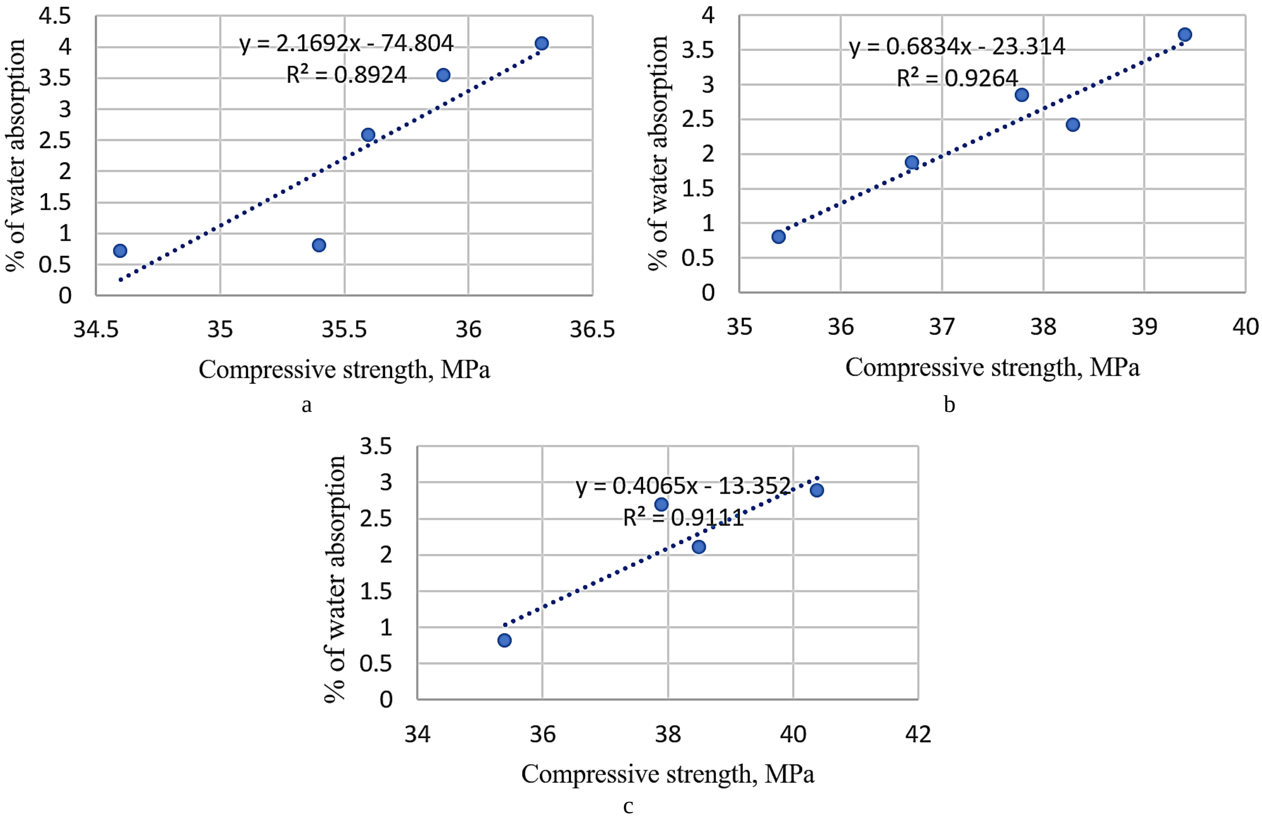

Figure 13 – Relationship between compressive strength and percentage of water absorption for concrete with AF (a), SF (b), and combiner AF and SF (c)

5 Discussion

The concrete specimens incorporating 10 % AF and 10 % SF exhibited significantly higher strength values at 90 days than those at 28 days [21–23]. This observation underscores the enduring enhancement of mechanical properties by including these mineral admixtures in concrete. The prolonged monitoring of compressive strength over 90 days highlights the concrete's ability to maintain structural integrity and mechanical performance over an extended duration [24].

The increased strength retention observed with AF and SF is likely due to their contribution to pozzolanic reactions, which continue over time, refining the pore structure and reducing permeability. This process enhances matrix densification, ensuring prolonged strength development and durability. Furthermore, these admixtures contribute to the concrete's resistance against deleterious reactions such as alkali-silica, further improving its long-term performance.

While these results suggest significant potential for long-term durability and resilience, further investigation is warranted to assess the performance over extended periods (e.g., 180 days, 1 year, or more). The impact of environmental factors such as temperature, humidity, and exposure to aggressive agents on long-term strength retention should be explored.

Field studies and real-world applications of these formulations would provide valuable insights into their suitability for sustainable construction practices. In conclusion, 10 % AF and 10 % SF show promising long-term strength retention results, supporting their sustainable construction use. However, ongoing research is essential to understand and fully optimize their long-term effects on concrete performance.

The results of this study demonstrate significant improvements in bacterial concrete performance with the addition of AF and SF, which align with global research findings. Water absorption rates were notably reduced, consistent with [25, 26], due to bacterial calcite filling pores and healing cracks. As noted in [27], reduced density and porosity indicated enhanced durability. As supported in [28], long-term strength retention confirmed the material's robustness over time.

Resistance to acids is consistent with [29]. It showed improved chemical durability. Furthermore, the rapid chloride penetration test and FTIR analysis corroborate the findings, showing reduced chloride ion permeability and the presence of calcite, which enhances concrete durability. These comparisons substantiate the reliability of the research methodology and the outcomes obtained.

Given the promising results, further studies are needed to optimize the proportions of AF and SF for different concrete applications and to assess their long-term performance under various environmental conditions. Investigating the effects of different bacterial strains on concrete's mechanical and durability properties could also provide valuable insights.

6 Conclusion

After conducting all the experimental work, the following conclusions are formulated.

First, the water absorption of the bacterial concrete mixes showed an increase of 4.0, 3.7, and 2.9 % compared to the control concrete for the AF10SF0, AF0SF15, and AF10SF10 mixes, respectively. Due to the impact of the pozzolanic and micro filler, the water absorption values of the concrete mixtures replaced with SF decreased as the amount of silica replacement increased.

Second, in contrast, the density of the AF20SF0, AF0SF20, and AF5SF15 mixes decreased by 11.0, 20.0, and 12.2 %, respectively, compared to the control, indicating that higher specific gravity materials contribute to reduced density. Furthermore, the porosity of these mixes was significantly lower, with reductions of 28.7, 35.0, and 32.2 %, which suggests improved structural integrity due to decreased pore size.

Third, the compressive strength tests revealed a decrease for all specimens after 4 weeks, with reductions of 15.6, 7.9, 8.9, 12.2, 11.9, 3.1, 6.1, 10.4, 11.6, 9.3, 8.8, and 7.6 % for the AF0SF0, AF5SF0, AF10SF0, AF15SF0, AF20SF0, AF0SF5, AF0SF10, AF0SF15, AF0SF20, AF5SF15, AF10SF10, and AF15SF5 mixes, respectively, when compared to the control specimen.

Fourth, the decrease in compressive strength is more pronounced in specimens containing AF and SF than in the control specimen. The control specimen shows a higher potential for gypsum and ettringite formation due to its higher $Ca(OH)_2$ and C_3A content. The filling of concrete pores with gypsum and ettringite enhances short-term compressive strength. Concrete using AF showed better resistance to an acidic environment than SF due to the excess release of hydrated calcium silicate in the transition zone.

Also, the AF0 SF0, AF10 SF0, AF0 SF15, and AF10 SF10 mixes, which exhibited the highest compressive strength, were chosen for FTIR analysis. The FTIR results identified several chemical phases and bonds, highlighting the complex nature of the cement's bacterial self-healing properties resulting from calcite precipitation.

Moreover, SF is a highly reactive pozzolanic chemical with unique characteristics, including roughness, a high content of amorphous silica, and ultrafine particles. These properties enhance the hydration process and pozzolanic reaction of AF. The combined action of BM and characteristic materials like AF and SF generates porosity by forming C-S-H gel. This porosity improves strength, workability, and resistance to chemical attacks. Additionally, bacteria fill concrete voids, reducing the likelihood of cracking and functioning as a natural antibiotic.

Finally, considering the promising results, the widespread use of AF and SF presents an opportunity to mitigate the adverse effects of conventional cement manufacturing and usage on both the environment and the economy. Adopting the binary and TBS not only leads to eliminating greenhouse gas emissions but also results in a substantial reduction in concrete costs.

AF and SF present significant advantages, including enhanced strength, reduced permeability, and improved durability, contributing to more sustainable construction practices. However, potential drawbacks include increased production costs and the need for careful mix design to maintain workability and consistency. Understanding the long-term effects of these materials under different exposure conditions remains crucial for widespread adoption.

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