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A Comparative Study of Sustainable Bacteria-Alccofine Concrete: Environmental Benefits and SEM Analysis

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ABSTRACT

The potential for creating unique, environmentally friendly, and cost-effective concrete via biomineralization is discussed in this research. Cement, a necessary component of concrete, is expensive and emits between 8 and 10% of the world's CO_2 emissions. Researchers have significant effects to identify alternatives that can reduce the burden of high costs, excessive energy use, and environmental repercussions. Manufactured sand (M-sand) completely replaced fine aggregate, and cement was replaced with alternatives such as Alccofine (AF) and Silica Fume (SF). The percentage at which it can be substituted for cement is, however, somewhat small. The goal of this study is to create an environmentally friendly AF and SF concrete mix by incorporating bacteria with the highest possible cell concentration. To evaluate the mechanical properties, concrete samples were tested for flexural strength, split tensile strength, and compressive strength at 7, 14 and 28 days post-curing. The microstructural analysis of sustainable concrete was performed using scanning electron microscopy (SEM) techniques. It was determined that 10% alccofine and 15% silica fume by volume of cement in the binary cementitious system provided the best mechanical characteristics for bacterial concrete using Bacillus megaterium. Similarly manner in the ternary cementitious system, the highest gain in compressive strength is seen when 10% alccofine is substituted with 10% silica fume in the cement mixture. Calcium carbonate precipitation validated the enhanced properties of bacterial concrete. The microorganisms used in the concrete are non-toxic and environmentally being. Results indicate that using Bacillus megaterium alongside AF and SF helps to reduce cement usage, lessens carbon dioxide emissions, and makes concrete more environmentally friendly. Using Scanning Electron Microscopy (SEM), the calcite precipitations in bio-additive mixed ternary admixture blended concrete were confirmed. The proposed regression equations produced minimal errors when compared to the experimental results, thus providing accurate and effective predictions of the flexural, split, and compressive strengths. The strength properties of these blends were validated through SEM studies.

INTRODUCTION

Concrete, a fundamental material in construction, is renowned for its impressive compressive strength but can exhibit vulnerabilities under tension, often resulting in the development of cracks. These cracks can arise from various factors such as heavy loads, shrinkage, excessive water-cement ratio, corrosion of reinforcement steel, and inadequate cover. Traditional methods for repairing concrete cracks are not only costly but also environmentally harmful. A novel repair procedure called concrete that heals itself has been devised by researchers in answer to this difficulty. This revolutionary technique incorporates bacteria into concrete either by directly adding bacteria while mixing or by embedding spores in shells (bacteria carriers) (Shanmuga Priya et al. 2019 and Zamani et al. 2020). Until cracks appear, these microbes lie latent in the self-repairing concrete. When a fissure forms, the combination of oxygen and moisture activates bacterial spores, which in turn start metabolic reactions that convert calcium lactate to carbonate of calcium (Schlangen & Senot 2013, Sohail et al. 2022). Therefore, the material's strength and durability are much improved when this precipitate of calcium carbonate seals the fissures (Aytekin et al. 2023).

In light of the environmental concerns associated with cement production, including high energy consumption and CO_2 emissions, exploring alternatives to cement in concrete structures presents a promising solution. The integration of supplementary cementitious materials (SCMs) represents a significant advancement in civil engineering. By harnessing the pozzolanic attributes of SCMs and combining them with cement, a wide range of concrete types with diverse strengths and enhanced durability can be produced. Incorporating SCMs as either substitutes for or in conjunction with cement can reduce cement consumption in concrete manufacturing and mitigate environmental contamination. Various SCMs, including fly ash, ground granulated blast furnace slag, silica fume, pond ash, limestone coarse, rice husk ash, and metakaolin, offer sustainable alternatives (Reddy & Meena 2018, Ansari et al. 2015, Chan et al. 2000).

SCMs are derived from the processing of waste materials discharged by factories and industries. Through appropriate modifications, these waste materials can be transformed into beneficial SCMs for construction purposes. Recycling industrial and factory waste materials not only offers economic benefits but also presents technical and environmental advantages. The global trend towards utilizing SCMs-based concretes is steadily growing due to their environmentally friendly attributes, strong performance, and energy-efficient characteristics (Kumar et al. 2016). SCMs play a significant role in fostering the creation of sustainable concrete, whether as mineral admixtures or partial replacements for cement (Suchithra & Malathy 2016, Umamaheswaran et al. 2015, Ushaa et al. 2015).

Incorporating SCMs into concrete development contributes to a reduction in cement consumption, thereby leading to decreased carbon dioxide emissions from cement production plants. Furthermore, this approach reduces the need for extensive excavation of raw materials essential for cement manufacturing while offering a solution for the responsible disposal of industrial waste.

Use of Alccofine and Silica Fume

Ambuja Cements Pvt Ltd, a leading cement company in India, has recently introduced a revolutionary micro-mineral SCM named Alccofine. Alccofine is available in three different forms; included in each set are alccofine-1101, alccofine-1203, and alccofine-1206. Their calcium contents differ. The amount of calcium silicate concentration in alccofine-1101 is the greatest of these kinds, while that of alccofine-1203 and alccofine-1206 is the lowest. The ability to make HPC and HSC is made possible by the latter two parts, which are SCMs, which can successfully substitute silica fume (Sharma et al. 2016, Ansari et al. 2015, Parveen et al. 2018, Jindal et al. 2017).

Rooted in low calcium silicate, Alccofine-1203 is a microfine substance with minimal environmental impact. It boasts high reactivity and a significant proportion of glass in its composition. Manufactured from GGBS, a byproduct of India's iron ore industries, Alccofine-1203 is a finely powdered material that enhances concrete flowability, workability, and compressive strength (Soni et al. 2013, Rajesh Kumar et al. 2015, Achal et al. 2009). Its tiny particle size allows it to efficiently fill the gaps between cement grains, resulting in greater compactness and strength (De Muynck et al. 2008, Chahal et al. 2012).

Bacillus bacteria, capable of serving as binding agents, contribute to reducing capillary pores in concrete, thereby enhancing its durability and strength. Certain strains of Bacillus bacteria produce the enzyme urease, facilitating the precipitation of calcite through biomineralization (Seshagiri Rao et al. 2012, Wu et al. 2012, Song & Saraswathy 2015, DeJong & Mortensen 2009, Achal & Mukherjee 2015). Notably, this bio-mineralization process does not affect concrete setting time, allowing bacterial concrete to adhere to existing mix design standards. This innovative approach, centered on bio-mineralization, holds the potential to significantly reduce maintenance expenses associated with bacterial concrete. By extending concrete lifespan, this technique aids in reducing atmospheric CO_2 emissions, mitigating global warming, and decreasing the demand for cement. Equations illustrating biochemical reactions responsible for calcium carbonate formation within cementitious materials, facilitated by ureolytic bacteria, align with findings presented in research (Achal et al. 2011, Tobler et al. 2011 and Yong et al. 2019).

Research Significance

A significant advancement in sustainable building techniques is the study of self-healing bacterial concrete and the incorporation of supplementary cementitious materials (SCMs). This innovative approach addresses the limitations of conventional concrete, which is brittle and has a significant environmental impact due to cement production. By adding bacteria such as Bacillus megaterium, the concrete can self-heal cracks through bio-mineralization, enhancing its durability and reducing maintenance costs. Additionally, the use of SCMs like Alccofine-1203, produced from industrial waste, improves the properties of concrete while reducing environmental harm by decreasing cement usage. This dual strategy, which promotes eco-friendly construction practices and optimizes concrete performance, aligns with global sustainability goals. This study aims to identify the optimal mix of SCMs and bacterial additives to enhance the mechanical properties, workability, microstructural characteristics, and overall sustainability of concrete.

MATERIALS AND METHODS

Bacteria Implementation Details

In this study, Bacillus megaterium, a rod-type strain found from the Microbial Type Values gathering and Gene Bank (MTCC), was utilized. The selection criteria for this bacterial strain adhered to established microbiological standards.

Preparation of Liquid Bacterial Cultures

Initially, pure cultures of Bacillus megaterium were preserved on nutrient agar slants (BC). Liquid bacterial cultures were prepared following precise protocols. A conical flask, previously sterilized, we occupied with 250 ml of water. Subsequently, peptone and meat or beef extract were added at a concentration of 5 $g.L^{-1}$ each. To adjust the pH level to 7, 20 $g.L^{-1}$ of urea was incorporated into the medium, as per the specified instructions. Additionally, 10 mg of MnSO4 x H2O was included to support bacterial growth. The medium underwent autoclaving for twenty minutes to ensure complete sterilization and elimination of any potential contaminants.

Inoculation Process

To introduce the bacteria into the nutritive media under sterile conditions, a loop was employed. Throughout the inoculation process, bacteria were transferred from their preserved state in a stock to a fresh medium to promote their further development. The closed loop containing the pure philosophy stock was carefully unlocked, 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.

Cultivation and Preservation:

The injected media were allowed to incubate for one day in an orbital shaking brooder at a temperature of 30 degrees Celsius and 250 revolutions per minute to facilitate bacterial growth. After incubation, the solution was chilled to 4 degrees Celsius for preservation, ensuring its viability for subsequent use in the concrete mixes (Fig. 1).

Binder

The binder in the concrete that was utilized to cast the requisite grade was OPC (53 grade), which had been employed in the production of the concrete. Table 1 presents its characteristics, and it satisfies the requirements of the International Standard 12269 (1987).

Coarse Aggregate (CA)

The present study utilized readily available local coarse material that was 20 millimeters in size and was conducted in compliance with the International Standard 383:1970. The results of certain preliminary testing are reported in Table 1, which includes its properties.

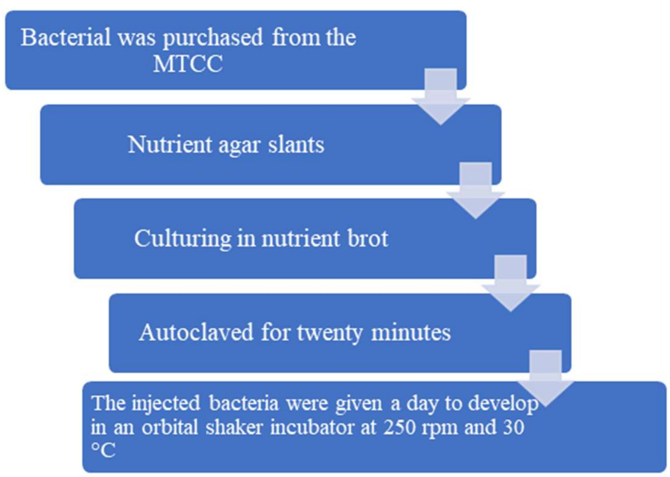

Fig. 1: Bacteria Cultivation.

Water

Concrete is being prepared and hardened with water from the faucet that is drinkable.

Manufactured Sand

The local M sand being evaluated for granularity and gradient according to IS: 383-1970 and the properties that are illustrated in Table 1, sand was utilized as a possible alternate material for fine aggregate.

Super Plasticizer

CONPLAST SP 430 was utilized as a water-reducing compound to achieve the desired level of functionality through the utilization of the most recent generation of improved sulfonated naphthalene polymers. Processing of substances was made possible as a consequence.

Alccofine

The study utilizes Alccofine 1203, which is an ultrafine tiny calcium silicate material that has a substantial amount of glass and a high degree of responsiveness. The material is obtained by the process of controlled granulation.

Silica Fume

The silica fume, which features an extremely thin sphere-like particle order, has a significant amount of amorphous silicon dioxide throughout its composition. In addition, magnesium, iron, and alkali metal oxides are discovered in minute quantities. Table 2 contains information regarding the physicochemical makeup of both alccofine and silica fume.

Constituents Used in M35 Grade Concrete

A mixture of concrete of M35 grade (1:1.79:2.57) was used,

Table 1: Physical (53 grade), CA, and M-Sand cement properties.

Characteristics	Experiment-al Values of Cement	Experiment-al Values of CA	Experimental Values of M-Sand
Initial setting of the time	50 min	-	-
The setting of the final time	320 min	-	-
Specific gravity	3.15	2.8	2.2
Consistency	32%	-	-
Soundness	1.2 mm	-	-
Water Intake	-	3.5%	-
Level of density	-	-	-
surface texture	-	Smooth	-
Impact Value	-	14.2	-
Particle size, kg/m	-	-	576
Micron Density	-	-	0.1
Max. compressive stress (MPa)	32.8 at 28 days	-	-

Table 2: Comparative analysis of the chemical and physical properties of alccofine and silica fume.

Chemical Properties			Physical Properties		
Old Mineral	Composition (%)		Physical Possessions	Outcomes	
	AF	SF		AF	SF
SiO_2	34.2	92.1	Partial Size Distribution (in micrometer)		
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/gm)	-	-
CaO	34	0.5	Bulk Density (kg/m^3)	600	450
MgO	6.1	0.3	Particle Size (typical)	-	<1μm
Na_2O	-	0.3	Specific Surface	12000	2.22

(a) Alccofine

(b) Silica Fume

Fig. 2: Mineral admixtures.

which satisfies the IS 10262:2009 codal specification. The concrete is described in Table 3. A “chemical admixture” that ought to be used in concrete, with increments in cementitious material weights ranging from 0% to 1%, is revealed based on many experimental mixes. After the dry ingredients for the concrete mixes were combined, the proportions of superplasticizer (1% by weight) and water to cement (0.4 by volume) were adjusted according to the intended mix. Table 4 presents the binary and ternary blended systems that are used for mineral admixtures in their various forms.

Methodology Adopted

The methodology adopted has been presented graphically, as shown in Fig. 3.

Casting and Curing of Molds

Eighty one samples of binary cementitious concrete

Table 3: Description of concrete.

Mix ID	Description of concrete
AF0SF0	Controlled Mix
AF5SF0	Concrete in which alccofine accounts for 5% of the cement content
AF10SF0	Concrete in which alccofine accounts for 10% of the cement content
AF15SF0	Concrete in which alccofine accounts for 15% of the cement content
AF20SF0	Concrete in which alccofine accounts for 20% of the cement content
AF0SF5	Concrete in which 5 % Cement is replaced by silica fume.
AF0SF10	10 % Cement is replaced by silica fume.
AF0SF15	15 % Cement is replaced by silica fume.
AF0SF20	20 % Cement is replaced by silica fume.
AF5SF15	As a replacement for cement, concrete is made with 5% alccofine and 15% silica fume.
AF10SF10	As a replacement for cement, concrete is made with 10% alccofine and 10% silica fume.
AF15SF5	As a replacement for cement, concrete is made with 15% alccofine and 5% silica fume.

Table 4: Percentage of Alccofine (AF) and silica fume (SF) in BBS and TBS for 1-m^3 concrete.

Mix ID	FA	CA	Water	Cement	AF	SF	Workability
	(kg/m^3)						(mm)
AF0SF0	696	1253	156.6	436	-	-	85
AF5SF0	696	1253	156.6	412	22		76
AF10SF0	696	1253	156.6	392	44		74
AF15SF0	696	1253	156.6	370	66		72
AF20SF0	696	1253	156.6	350	88		74
AF0SF5	696	1253	156.6	412		22	78
AF0SF10	696	1253	156.6	392		44	76
AF0SF15	696	1253	156.6	370		66	74
AF0SF20	696	1253	156.6	350		88	72
AF5SF15	696	1253	156.6	350	22	66	70
AF10SF10	696	1253	156.6	350	44	44	75
AF15SF5	696	1253	156.6	350	66	22	71

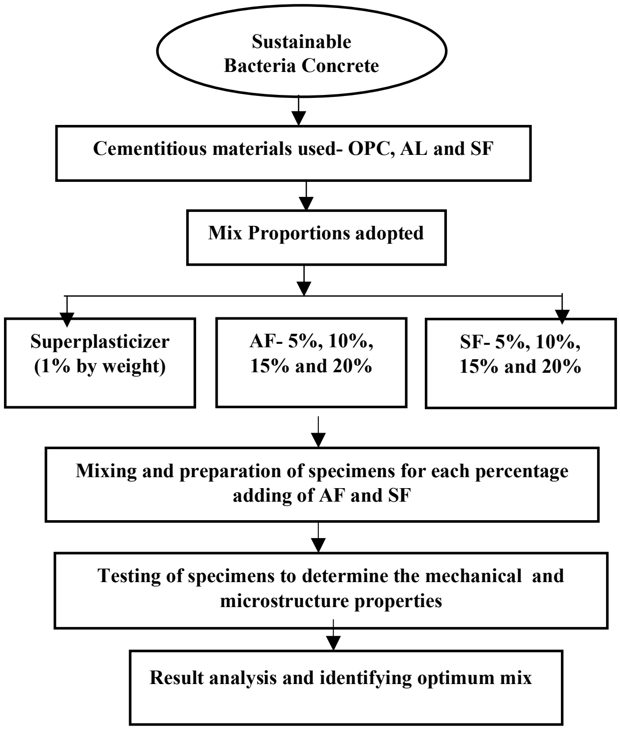

Fig. 3: Methodology.

Fig. 4: Failure mode Samples test.

were created utilizing the specified concrete mixture and conventional cubes. The specimens were evaluated in accordance with IS:516:1959 after being cast as spheres (150 mm), cylinders (100mm x 300 mm), and prisms (100 mm x 100mm x 500 mm). The curing tank is used to dry the concrete samples for seven, fourteen, and twenty-eight days. Though continuing a constant temperature of 27° C., Fig. 4 demonstrations the observed specimens. The entire project activity took 5 months to complete, which included 1 month for initial planning and material acquisition, 2 months for the casting process, and 2 months for testing and result analysis. The samples for SEM analysis were collected from the failure plane of specimens tested under compression. SEM examination was used to assess the dispersion characteristics and interactions with the cement matrix.

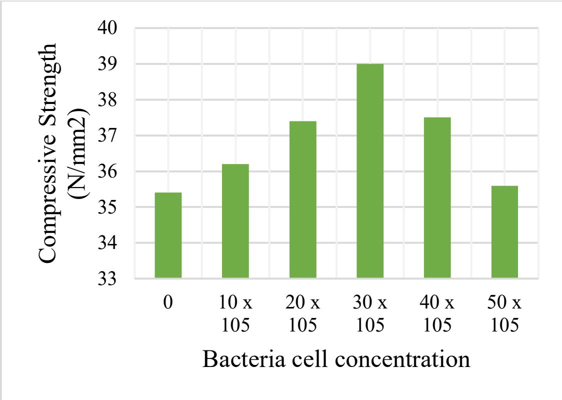

Fig. 5: Compressive strength of concrete cubes for different cell concentrations of Bacillus megaterium.

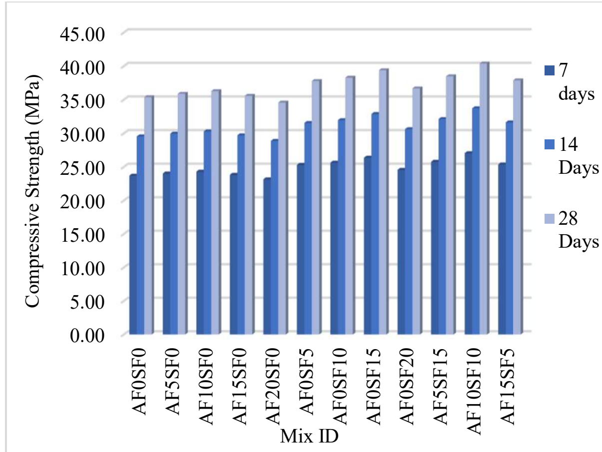

Fig. 6: Compressive strength (BBS & TBS).

RESULTS AND DISCUSSION

Optimum Bacterial Cell Concentration

Bacterial cell concentration is expressed as the number of bacterial cells per ml of mixing water. The optimum dosage of bacterial cell concentration corresponds to the cell concentration which will result in maximum compressive strength of concrete specimens. The compressive strength of concrete cube specimens of size 150 mm × 150 mm × 150 mm was measured at the age of 28 days using five different cell concentrations of Bacillus megaterium (from 10×10^5 to 50×10^5 cells /ml of mixing water). To cast concrete samples for strength and durability testing and to quantify crack healing, the ideal amount of bacterial cells needs to be used.

Fig. 5 shows that for all five strains of bacteria, the optimal cell concentration for maximal compressive strength is 30×10^5 cells/ml of mixing water. The four bacterial strains were added to the mixing water at a concentration of 30×10^5 cells/ml to produce the best microbial concrete specimens.

Workability

"Workability" refers to how easily the concrete can be laid, compacted, and finished. Reduce the amount of time and effort needed to finish the bacterial concrete using alccofine and silica fume by increasing its ability to work. The purpose of the crashing cone test is to find out how workable newly mixed concrete is. A number of concrete mixtures with various combinations are shown in Table 4, along with their slump properties.

Compressive Strength

The deformation strengths of the tested blocks on the Alccofine and silica fume microbiological concrete are

Table 5: Compressive strength of BBS and TBS.

Mix ID	Bacteria Concentration [cells.m^{-1}]	Average Compressive Strength [Mpa]			Compressive strength at 28 days compared to the control mix
		7th	14th	28th	
		Days			
AF0SF0	30 x 10^5	23.72	29.56	35.4	0.0
AF5SF0	30 x 10^5	24.05	29.98	35.9	1.4
AF10SF0	30 x 10^5	24.32	30.31	36.3	2.5
AF15SF0	30 x 10^5	23.85	29.73	35.6	0.6
AF20SF0	30 x 10^5	23.18	28.89	34.6	-2.3
AF0SF5	30 x 10^5	25.33	31.56	37.8	6.8
AF0SF10	30 x 10^5	25.66	31.98	38.3	8.2
AF0SF15	30 x 10^5	26.40	32.90	39.4	11.3
AF0SF20	30 x 10^5	24.59	30.64	36.7	3.7
AF5SF15	30 x 10^5	25.80	32.15	38.5	8.8
AF10SF10	30 x 10^5	27.07	33.73	40.4	14.1
AF15SF5	30 x 10^5	25.39	31.65	37.9	7.1

displayed in Table 5. As shown in Fig. 6, the compressive strength test outcomes for the binary blended cementitious solution (BBS) with the substitution of “alccofine and silica fume” are presented.

Table 5 and Fig. 6 illustrate the results of tests conducted on the compressive properties of bacterial concrete. The experiments were performed in and out of the presence of Alccofine, silica fume, and M sand, which were used as substitutes for the (BBS & TBS). The compressive values of the Bacterial concrete specimens in the Binary Integrated System, namely AF5SF0, AF10SF0, AF15SF0, and AF20SF0, were correspondingly 1.4%, 2.5%, 0.6%, and 2.3% higher/lower associated to that of the orientation mix AF0SF0, after 28 days of sampling. Similarly, the samples with silica fume replacement percentages of 5%, 10%, 15%, and 20% (referred to as AF0SF5, AF0SF10, AF0SF15, and AF0SF20, respectively) exhibited compressive strengths that were consistently better than the value of the control mix (AF0SF0) by +6.8%, +8.2%, +11.3%, and +3.7%, correspondingly. The compressive strengths of Bacterial Concrete in (TBS) specimens with alccofine and silica fume (AF5SF15, AF10SF10, and AF15SF5) at 28 days were respectively 8.8%, 14.4%, and 7.1% higher/lower compared to those of the untreated control mix (AF0SF0). The maximum compressive strength ratings (AF10SF0 & AF0SF15) can be found in bacterial concrete made with 10% alccofine replacement and 15% silica fume. Alccofine’s unique chemical makeup and ultrafine particles accelerated the soaking process between cement and alccofine, resulting in a stronger pozzolanic reaction. However, because the bacteria fill the holes in the concrete, the likelihood of cracking is drastically reduced. This means bacteria can be used in self-healing applications. The concrete strength was found to be reduced after 15% silica fume and 10% alccofine were added, but it was still greater than regular concrete mixtures. At a 15% alccofine replacement level, concrete’s compressive strength decreased due to insufficient cement hydration caused by a higher alccofine and silica fume concentration.

Table 6: Strength activity index.

Blended System	Mix ID	Strength Activity Index		
		7	14	28
		Days		
Binary	AF5SF0	1.01	1.01	1.01
	AF10SF0	1.07	1.07	1.07
	AF15SF0	1.10	1.10	1.10
	AF20SF0	1.03	1.03	1.03
	AF0SF5	0.98	0.98	0.98
	AF0SF10	1.07	1.07	1.07
	AF0SF15	1.01	1.01	1.01
	AF0SF20	1.00	1.00	1.00
Ternary	AF5SF15	1.04	1.04	1.04
	AF10SF10	1.15	1.15	1.15
	AF15SF5	1.09	1.09	1.09

Strength Activity Index

The strength action index was determined by comparing the compressive strength of concrete with mixed cementitious systems of two and three components to that of control concrete at ages 7, 14, and 28 days. This analysis was done for various degrees of AF and SF substitutes, and the results strength activity index was computed using the result.

Table 7: Tensile strength – BBS and TBS.

Mix ID	Bacteria Concentration (cells/ml)	Average Compressive Strength (Mpa)			Tensile strength at 28 days compared to control mix
		7^{th}	14^{th}	28^{th}	
		Days			
AF0SF0	30 x 10^5	2.80	3.49	4.18	0.0
AF5SF0	30 x 10^5	2.84	3.54	4.30	2.9
AF10SF0	30 x 10^5	2.87	3.58	4.51	7.9
AF15SF0	30 x 10^5	2.81	3.51	4.05	-3.1
AF20SF0	30 x 10^5	2.74	3.41	3.98	-4.8
AF0SF5	30 x 10^5	2.99	3.72	4.50	7.7
AF0SF10	30 x 10^5	3.03	3.77	4.61	10.3
AF0SF15	30 x 10^5	3.11	3.88	4.81	15.1
AF0SF20	30 x 10^5	2.90	3.62	4.29	2.6
AF5SF15	30 x 10^5	3.04	3.79	4.62	10.5
AF10SF10	30 x 10^5	3.19	3.98	4.86	16.3
AF15SF5	30 x 10^5	3.00	3.73	4.49	7.4

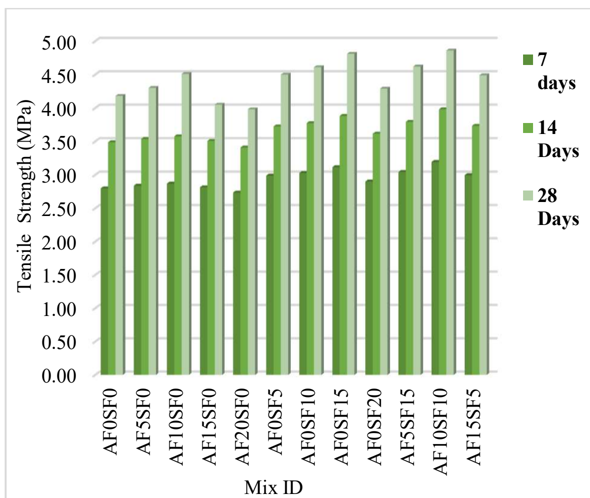

Fig. 7: Tensile strength between (BBS & TBS).

From Table 6, In a BBS, it was found that the activity index gradually decreased after Portland cement was replaced with AF and SF by 10% and 15% (AF10SF0 & AF0SF15), respectively. Similar to this, at TBS, the addition of Portland cement with AF and SF was gradually reduced to 10% (AF10SF10).

Split Tensile Strength

Table 7 and Fig. 7 illustrate the results of experiments conducted on the tensile strength of bacterial concrete, comparing samples regardless of the substitution of Alccofine, silica fume, and M-sand in the Binary Blended System (BBS). The samples of Bacterial concrete in the Binary Blended System, containing different proportions of Alccofine (AF5SF0, AF10SF0, AF15SF0, and AF20SF0), exhibited tensile strengths at 28 days that were accordingly 2.9% higher, 7.9% higher, 3.1% lower, and 4.8% lower compared to those of the untreated control mix (AF0SF0). Similarly, samples that had silica fume replacement levels of 5%, 10%, 15%, and 20% (referred to as AF0SF5, AF0SF10, AF0SF15, and AF0SF20, accordingly) exhibited tensile strengths that were consistently greater compared to that of the untreated control mix (AF0SF0) by 7.7%, 10.3%, 15.1%, and 2.6%, respectively. The Bacterial Concrete in Ternary Blended System (TBS) specimens, specifically AF5SF15, AF10SF10, and AF15SF5, showed tensile strengths at 28 days, which were correspondingly 10.5%, 16.3% and 7.4% higher or lower than the control mix (AF0SF0).

Based on the aforementioned experiment, it was initiated that "the tensile strength on the bacterial concrete of the split alccofine with silica fume" material decreased with increasing replacement owed to the calcium carbonate hastened by bacteria fills the tiny pores in concrete when Bacterial megaterium. Studies have shown that an extremely high percentage of alccofine and the splitting tensile strength was slightly increased by silica fume but not significantly, insignificantly beyond 10%. When the vacancies are initially filled with silica fume, the tensile strengths are significantly increased; however, the advantages become less significant as the level of silica fume increases. Because alccofine and silica fume increased pozzolanic reaction, lower heat of hydration, decreased permeability to concrete, and reduced segregation are all benefits of using this material, these factors probably contributed to a rise in the beginning stages of the strength of concrete.

Flexural Strength

The outcomes of testing on the flexibility of alccofine and silica fume with M-sand replaced for (BBS & TBS) are presented in Table 8 and Fig. 8. The tensile strengths of Concrete in BBS specimens with Alccofine (AF5SF0, AF10SF0, AF15SF0, and AF20SF0) at 28 days were, respectively, 3.7% higher, 9.7% higher, 5.6% lower, and 7.1% lower than relate of the control mix (AF0SF0). Likewise, samples that had silica fume replacements of 5%, 10%, 15%, and 20% (referred to as AF0SF5, AF0SF10, AF0SF15, and AF0SF20, respectively) exhibited flexural strengths that were greater than the control mix (AF0SF0) by 9.7%, 11.6%, 15.3%, and 5.4%, respectively. Similarly, the flexural strengths of Concrete in (TBS) specimens with Alccofine (AF5SF15, AF10SF10, and AF15SF5 correspondingly) were, respectively, 9.2% higher, 17.2%

Table 8: Flexure strength of BBS and TBS.

Mix ID	Bacteria Concentration [cells.mL^{-1}]	Average flexure Strength (Mpa)			Variation in flexure strength at 28 days compared to the control mix
		7th	14th	28th	
		Days			
AF0SF0	30 x 10^5	3.32	4.14	4.65	0.0
AF5SF0	30 x 10^5	3.37	4.20	4.82	3.7
AF10SF0	30 x 10^5	3.40	4.24	5.10	9.7
AF15SF0	30 x 10^5	3.34	4.16	4.39	-5.6
AF20SF0	30 x 10^5	3.25	4.04	4.32	-7.1
AF0SF5	30 x 10^5	3.55	4.42	5.10	9.7
AF0SF10	30 x 10^5	3.59	4.48	5.19	11.6
AF0SF15	30 x 10^5	3.70	4.61	5.36	15.3
AF0SF20	30 x 10^5	3.44	4.29	4.90	5.4
AF5SF15	30 x 10^5	3.61	4.50	5.08	9.2
AF10SF10	30 x 10^5	3.79	4.72	5.45	17.2
AF15SF5	30 x 10^5	3.56	4.43	4.91	5.6

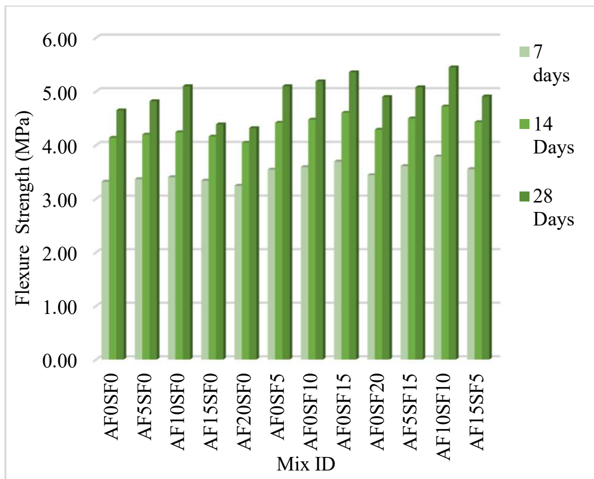

Fig. 8: Flexural strength comparison with BBS and TBS.

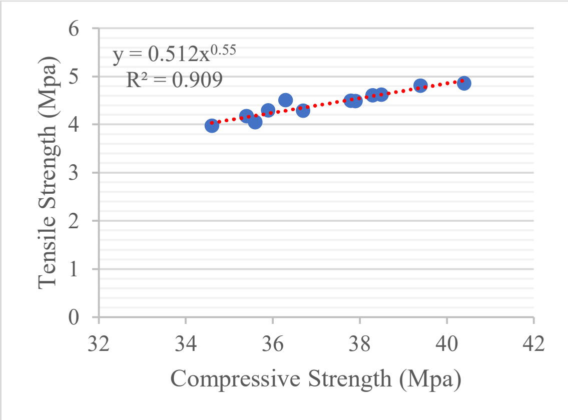

Fig. 9: Compressive Strength vs Tensile Strength.

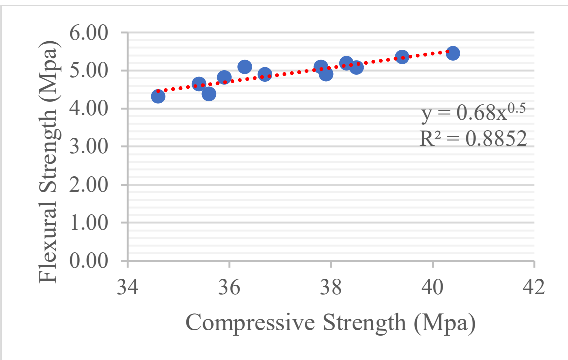

Fig. 10: Compressive Strength vs Flexural Strength.

higher, and 5.6% lower than those of the control mix (AF0SF0) after 28 days of testing.

The influence of alccofine and silica fume on the flexural strength of the material was more pronounced than the effects of these two substances on the tensile strength of the material. After precipitation, the flexural strength was greatly improved by the addition of silica fume and alccofine in concentrations of 10%. This was accomplished by supplying the organisms with the nutrients that are necessary for their continued existence.

It should have also been noticed that the flexural strength gradually decreased with increasing percentages of alccofine and silica fume substitution. This is something that should have been discovered. The incorporation of calcium oxide and silica into alccofine allowed for improvements to be made to the concrete's inherent mechanical properties.

Flexural, Tensile, and Compressive Strength Relationships

Alccofine and silica fume replacement BBS and TBS blended cementitious systems' flexural strengths, tensile, and compressive were resolute analytically, as demonstrated in Figs. 9 and 10.

The link between the compressive and tensile strength of the "BBS and TBS blended cementitious system" with AF and SM was derived from Fig 9.

$$f_t = 0.512\ f_{ck}^{0.55}\ (28\ \text{days}) \qquad \ldots(1)$$

Where, f_t signifies split tensile strength in N/mm^2 and f_{ck} represents compressive strength in N/mm^2

This equation is similar to the one developed by the ACI Committee 363 in 1993, which states that $ft = 0.59\ fck^{0.55}$ for concrete whose compressive strength is within the range of 21 to 83 N/mm^2. For concrete with a compressive strength of less than 84 N/mm^2, the researcher discovered that the relationship between the two variables is $ft = 0.462\ f_{ck}^{\ 0.55}$. According to the equations presented above, it is possible to deduce that the results of this education are consistent with the findings of other studies.

It was found that there is a correlation between compressive and flexural strengths of binary and ternary blended cementitious systems with AF and SM, which was derived from Fig. 10 and the equation for this relationship is as follows:

$$f_{cr} = 0.68\ f_{ck}^{0.5}\ (28\ \text{days}) \qquad \ldots(2)$$

The following group of scholars has made some suggestions on equations that relate the flexural strength of concrete to its compressive strength:

Burg and Ost (1992), $f_r = 1.03\ f_{ck}^{\ 0.5}$

IS: 456 -2000, $fr = 0.7\ f_{ck}^{\ 0.5}$

The equations resulting from the AF and SF mixes in this examination are inside the range established by previous investigators.

Equivalent CO_2 Gas Emission and Energy Factor

Associated with cement production, the manufacture of alternative fuels (AF) and supplementary fuels (SF) emits less CO_2 into the atmosphere. The CO_2 emissions from AF and SF manufacturing (100 kg of CO_2 per ton of AF produced and 16 kg of CO_2 per ton of SF produced) are primarily caused by raw material extraction and kiln operation rather than chemical reactions. In contrast, cement manufacturing releases CO_2 through the decarboxylation of calcium carbonate, resulting in higher emissions (521.5 kg of CO_2 per ton of cement produced). Additionally, AF and SF require less thermal energy during production compared to cement (1.90 GJ per ton of AF, 0.36 GJ per ton of SF, and 4.65 GJ per ton of cement).

Table 9: Sustainability balance of binary cementitious energy saved per $1m^3$ of concrete.

Mix ID	Energy (GJ)			
	OPC	AF	SF	Total
AF0SF0	2.35	0.00	-	2.35
AF5SF0	2.23	0.52	-	2.74
AF10SF0	2.12	0.96	-	3.07
AF15SF0	1.98	1.36	-	3.35
AF20SF0	1.88	1.85	-	3.72
AF0SF5	2.21	-	0.072	2.292
AF0SF10	2.12	-	0.126	2.236
AF0SF15	1.98	-	0.196	2.19
AF0SF20	1.88	-	0.236	2.106
AF5SF15	1.88	0.52	0.196	2.586
AF10SF10	1.88	0.96	0.123	2.953
AF15SF5	1.88	1.36	0.072	3.302

Table 10: Sustainability balance of binary and ternary cementitious - CO_2 emissions.

Mix ID	CO_2 Emission (kg)						
	Extraction & Kiln			Chemical reaction			Total
	OPC	AF	SF	OPC	AF	SF	
AF0SF0	243	0	0	261	0	0	504
AF5SF0	234	2.5	-	248	0	0	484.5
AF10SF0	222	5	-	235	0	0	462
AF15SF0	228	7.5	-	228	0	0	464
AF20SF0	196	10	-	221	0	0	427
AF0SF5	243	-	0.35	248	0	0	492
AF0SF10	234	-	0.7	235	0	0	470
AF0SF15	222	-	1.05	228	0	0	451
AF0SF20	196	-	1.4	221	0	0	419
AF5SF15	196	2.5	1.05	221	0	0	420.55
AF10SF10	196	5	0.7	221	0	0	423
AF15SF5	196	7.5	0.35	221	0	0	425

The CO_2 emission, including the emissions associated with the movement of raw materials, is determined (Cassagnabere et al. 2010) by the calculation of chemical processes and the use of energy for 1 tonne of cement and AF with SF. Table 9 presents an assessment of the environmental impact of the binders (cement + AF + SF) in terms of CO_2 emissions and energy consumption. The calculation of CO_2 emissions and energy savings was performed using Equations (1) and (2):

$$\text{Energy saved (\%)} = (Ei-Eo)/Eo \times 100 \quad \ldots(1)$$

Where,

Eo equals the amount of energy that is consumed by the control mix.

The term "Ei" refers to the amount of energy that is consumed by binary and ternary ceramic systems.

$$CO_2 \text{ Emission (\%)} = (Ci-Co)/Co \times 100 \quad \ldots(2)$$

Where,

Co = The amount of carbon dioxide that is released by the control mixture

CO_2 emissions from BSS cementitious systems are denoted by the symbol Ci.

Economic Feasibility of Metakaolin

Alccofine typically falls between the cost of silica fume and cement in concrete production expenses, offering similar performance enhancements alongside silica fume. While Alccofine and silica fume share similar production processes, slight variations may exist in energy consumption and processing costs. Both Alccofine and silica fume contribute to sustainability by utilizing waste materials, contrasting with the high environmental impact of cement production. Ultimately, the choice among Alccofine, silica fume, and cement hinges on project requirements, cost considerations,

Table 11: Sustainability balance of ternary cementitious energy saved per $1m^3$ of concrete.

Mix ID	Energy (GJ)				Environmental benefit regarding	
	OPC	AF	SF	Total	Energy (%)	CO_2 emission (%)
AF0SF0	2.35	0.00	-	2.35		
AF5SF0	2.23	0.52	-	2.74	-2.1	-5.1
AF10SF0	2.12	0.96	-	3.07	-3.1	-10.1
AF15SF0	1.98	1.36	-	3.35	-4.8	-13.2
AF20SF0	1.88	1.85	-	3.72	-8.2	-16.5
AF0SF5	2.21	-	0.072	2.292	-1.8	-5.1
AF0SF10	2.12	-	0.126	2.236	-2.4	-10.2
AF0SF15	1.98	-	0.196	2.19	-3.1	-14.5
AF0SF20	1.88	-	0.236	2.106	-4.7	-18.5
AF5SF15	1.88	0.52	0.196	2.586	-5.7	-17
AF10SF10	1.88	0.96	0.123	2.953	-6.35	-17
AF15SF5	1.88	1.36	0.072	3.302	-7.8	-17

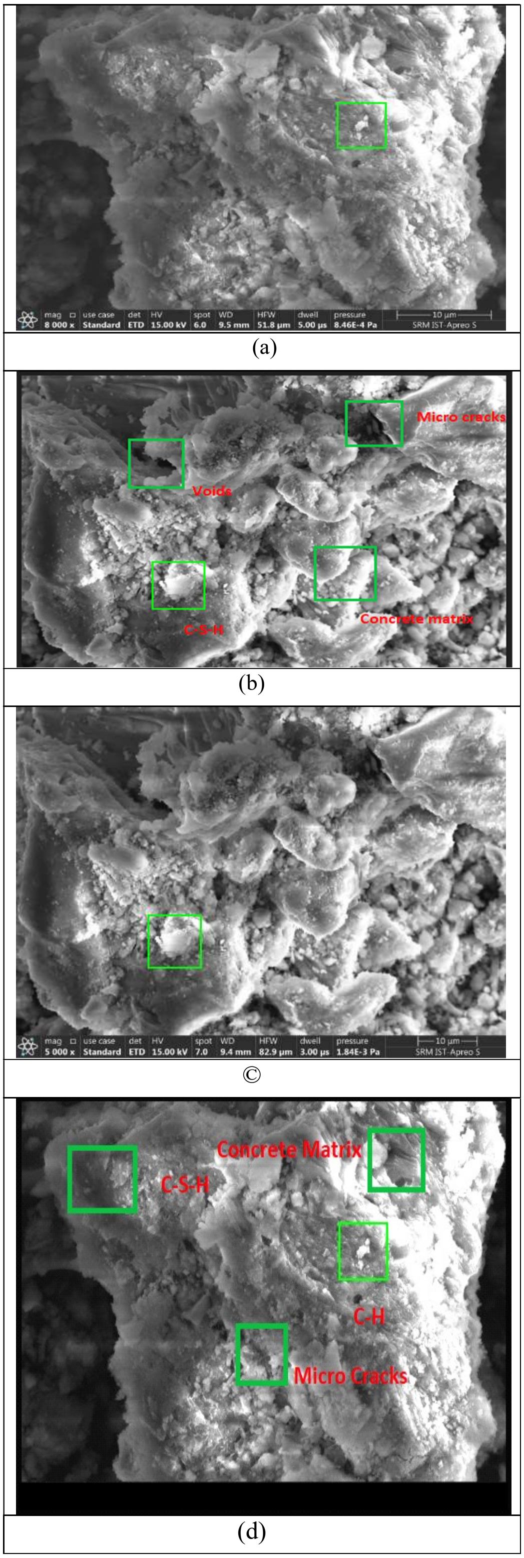

Fig. 11: SEM Images of (a) Control, (b) AF10SF0, (c) AF0SF15, and (d) AF10SF10.

and performance expectations, with the economic analysis serving as a pivotal factor in decision-making.

SEM Analysis

From the over-dried samples, a suitable one has been selected for each mix for the SEM analysis. The SEM images of all the mix binders are shown in Fig. 11. SEM images showed micro-cracks, concrete matrix, voids, and C-S-H in all mix binders. The inclusion of AF and SF improves the hydration products, which increases the mechanical strength. In the specimens with AF and SF, the micro-cracking region was able to be extended due to a strong enough contact with the concrete matrix. The presence of AF and SF reduced the number of pores as they filled the microcavities. They also play a dual role by acting as a filler, increasing the density, and engaging in enhancing the strength properties by initiating an early hydration process and formation of extra C-S-H gel. SEM observations revealed that the formation of additional C-S-H gel increased along with an increase in the percentage of AF and SF replacement levels, and the number of voids and micro-cracks appeared to be less than up to 10% replacement of cement with AF and SF.

CONCLUSIONS

Following are the results that have been reached after all of the experimental work has been completed.

- According to the results of the BCC tests, the maximum compressive strengths of the AF10SF0, AF0SF15, and AF10SF10 mixes were correspondingly 36.30 $N.mm^{-2}$, 39.40 $N.mm^{-2}$, and 40.40 $N.mm^{-2}$. The highest compressive strengths were 2.5%, 11.3%, and 14.4% higher than the value of the control concrete.
- The results of the break tensile tests conducted on BCC showed that the AF10SF0, AF0SF15, and AF10SF10 mixes had the highest split tensile strengths of 4.51 $N.mm^{-2}$, 4.81 $N.mm^{-2}$, and 4.86 $N.mm^{-2}$, correspondingly. These values were 8%, 15.1%, and 16.3% higher than the control concrete.
- The highest flexural strength of BCC at 28 days for the AF10SF0, AF0SF15, and AF10SF10 combinations, utilizing 10%, 15%, and 17% more than the control concrete, had flexural values of 5.10 MPa, 5.36 MPa, and 5.45 MPa, correspondingly.
- Using the method of regression, two correlation equations were created: one involved split tensile and compressive strength, and the second involved flexural and compressive strength. Both models were built to compare and contrast performance. It was determined

that the error ranges that were forecasted were enough when the models were tested.

- SEM observations revealed that the formation of additional C-S-H gel increased along with an increase in the percentage of AF and SF replacement levels, and the number of voids and micro-cracks appeared to be less than up to 10% replacement of cement with AF and SF.
- "Silica fume" refers to a highly reactive pozzolanic chemical. In particular, the hydration process and pozzolanic reaction of "alccofine" are enhanced by its unevenness and better satisfaction of amorphous silica content and ultrafine particles with a unique chemical makeup. However, because the bacteria fill the holes in the concrete, the likelihood of cracking is drastically reduced. Therefore, microorganisms can function as a natural antibiotic.
- Given the promising findings, alccofine and silica fume can be used on a massive scale to offset the negative effects of conventional cement manufacturing and usage on the environment and the economy. Finally, the elimination of greenhouse gas emissions and a significant decrease in concrete costs came from the binary and ternary blended system.

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