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EXPERIMENTAL INVESTIGATION ON BENEFITS OF INCORPORATING BACTERIA FOR ENHANCING WORKABILITY AND STRENGTH CHARACTERISTICS OF GEOPOLYMER CONCRETE.

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Abstract
Cement is widely used as a key raw material in construction projects across the globe. To meet the growing demand from the construction sector, significant quantities of cement are produced annually, leading to substantial CO2 emissions. With rising concerns about global warming, Geopolymer Concrete (GPC), an inorganic polymer binder, has been developed as an alternative to Ordinary Portland Cement (OPC) concrete. Recently, research has focused on improving the viscosity and workability of GPC, leading to the development of Self-Consolidating Geopolymer Concrete (SCGC). This experimental study explores the impact of Bacillus Pseudofirmus and Bacillus Licheniformis bacteria on the workability, strength, and durability of SCGC. Three different SCGC mixes were created using these bacteria at a concentration of 3% of the total binder content, and various workability and strength tests were conducted. The results indicated that the SCGC mix containing Bacillus Pseudofirmus exhibited superior workability with a slump value of 706 mm and achieved a maximum compressive strength of 53.38 MPa after 28 days of ambient curing. Furthermore, the hardened SCGC mix with Bacillus Pseudofirmus demonstrated greater resistance to acid and alkali attacks and had the lowest water absorption rate.

Keywords: *Bacterial concrete; Bacillus Pseudofirmus; Bacillus Licheniformis; Self-consolidating; Geopolymer concrete.*

1. Introduction

The construction industry has experienced significant growth in modern times, driven by the development of infrastructure such as bridges, buildings, and roads. Concrete and steel are heavily utilized in this sector. Notably, the cement industry ranks as the second-largest emitter of carbon dioxide. Concrete, the world's most widely used construction material, is responsible for nearly 8% of global CO2 emissions due to the production and use of Portland cement. The CO2 emissions from concrete production are directly linked to the amount of cement used in the mix, with 900 kg of CO2 released for every ton of cement produced. This accounts for 88% of the emissions in a typical concrete mix. The primary issue arises during the calcination of limestone, where each molecule of calcium oxide, or "quicklime," results in the release of one molecule of carbon dioxide.

Given the global annual production of approximately 4.5 billion tons of cement, this process generates about 2.7 billion tons of CO2.

The urgent need for alternative binding materials to mitigate environmental impacts has become evident. One notable innovation is Geopolymer Concrete (GPC), developed by Prof. Joseph Davidovits in 1978. GPC is an eco-friendly alternative that utilizes industrial by-products like fly ash (from thermal power plants) and ground granulated blast furnace slag (from iron production) as a complete replacement for cement in concrete. This material not only reduces cement usage but also offers superior strength and durability compared to Portland Cement Concrete (PCC). By decreasing reliance on PCC, the adoption of GPC in the construction industry can significantly reduce environmental pollution.

Since SCGC can flow under its own weight, manual compaction is no longer required. It can fill all gaps in formwork, even in areas with dense reinforcement. Using SCGC in construction enhances overall quality and significantly reduces long-term maintenance costs.

Concrete deterioration often results from naturally occurring cracks. These cracks within the hardened concrete matrix can be effectively sealed by incorporating Bacillus species bacteria, eliminating the need for external chemicals. These bacteria can survive in harsh conditions. This project investigates the impact of Bacillus species on the workability, strength, and durability of SCGC. Research on bacteria-infused SCGC is still limited. However, studies have shown that incorporating bacteria enhances concrete by filling cracks with calcite and improving the mechanical properties of geopolymer concrete.

2. Materials and Methodology

2.1. Materials Used

The binder materials used for preparing Self-Consolidating Geopolymer Concrete (SCGC), including GGBFS, Alccofine, and Fly Ash, were sourced from the Ultratech Ready Mix Concrete plant in Peenya, Bangalore. The physical properties of these binders are detailed in Tables 2 and 8, while the chemical properties of Fly Ash, GGBFS, and Alccofine are outlined in Tables 6 and 7. Bacillus Pseudofirmus and Bacillus Licheniformis bacteria, obtained in solution form from the National Centre for Microbial Resource (NCMR) in Pune, were incorporated into the SCGC mixes. The characteristics of these bacteria are shown in Table 1. The alkaline activator liquids used in the SCGC mixes included commercially available Sodium Hydroxide (NaOH) flakes with 94% purity and a Sodium Silicate (Na2SiO3) solution containing 55% water. Table 3 presents the properties of the Na2SiO3 solution. Locally sourced M-sand was used as the fine aggregate, while coarse aggregate under 20mm in size, procured from a local vendor, was used in the mix. The physical properties of both aggregates are listed in Table 4. BASF Master Glenium 8233, a superplasticizer acquired from a local supplier, was used to prepare the mix, with its properties detailed in Table 5.

Table1. Bacillus Pseudofirmusand Bacillus Licheniformis Bacterium properties (Data source: NCMR, Pune)

NCMR Accession Number	MCC 2183	MCC 2819
Taxonomic Designation	Bacillus Licheniformis (Ehrenberg 1835) Cohn 1872	Bacillus Pseudofirmus
Strain Designation	LS-1	LAP217
Source of Isolation	Lonar lake soil sample	Lonar Lake water sample
Medium Name and Number	72a (Horikoshi and Akiba Agar (HAA)/Broth (HAB)	34C (Alkaline Nutrient Agar)
pH of Medium	12	10
Temperature of Growth in 0C	30	28-30
Incubation Period	1 Day	2 Days
Risk Group	--	Do not Know
Oxygen Requirement	Aerobic	Aerobic

T**able 2:** Physical Properties of GGBFS and Alccofine

Physical Requirements	Specific Gravity	Slag Activity Index in %		Fineness (m2/kg)
		7 Days	14 Days	
GGBFS	2.9	72.4	382	110.4
Alccofine	2.91	73.3	383	114
Requirements as per IS 16715:2018	--	60 (Min)	320 (Min)	75 (Min)

Table 3: Properties of Na_2SiO_3 solution

Properties	Specifications
Solids to Liquid Ratio	48:52

Colour	Colorless
Density (g/cc)	2.7

Table 4: Physical properties of Aggregates

Test Data		Fineness Modulus	Water Absorption (%)	Specific Gravity
Fine Aggregate		3.61	0.4	2.7
Coarse Aggregate	20 mm	6.4	0.4	2.8
	12.5 mm	2.82	1.5	2.7

Table 5: Properties of Superplasticizer

Test Data	pH	Relative Density	Aspect	Chloride ions
Superplasticizer	>6 at 250C	1.1 to 0.01 at 250C	Dark Brown Liquid	<0.18%

Table 8: Physical Properties of Fly ash

Physical Requirements	Soundness	Lime Reactivity (N/mm2)	Fineness (m2/kg)	Specific Gravity	Residue on 45 Micron Sieve in %
Results	0.032	6.1	371	2.4	17.1
Requirements as per IS 3812:2013					
Part 1	0.8 (Min)	4.5 (Min)	320 (Min)	--	34 9 (Max)
Part 2	0.8 (Max)	--	200 (Min)	--	50 (Max)

Table 6: Chemical Properties of Fly ash

Chemical Requirements	SiO2	Na_2O	MgO	SO3	SiO2+Al2O3 + Fe2O3	Total Chlorides	Loss of Ignition
Content in %	52.72	0.80	1.94	0.23	87.56	0.004	3.2
Requirements as per IS 3812:2013							

Part 1	Siliceous Pulverized Fuel Ash in %	35.0	1.5	5.0	3.0	70.0	0.05	5.0
	Calcareous Pulverized Fuel Ash in %	25.0	1.5	5.0	3.0	50.0	0.05	5.0
Part 2	Siliceous Pulverized Fuel Ash in %	35.0	1.5	5.0	5.0	70.0	0.05	7.0
	Calcareous Pulverized Fuel Ash in %	25.0	1.5	5.0	5.0	50.0	0.05	7.0

Table 7: Chemical Properties of GGBFS and Alccofine

Sl No	Chemical Requirements	Requirements as per IS 16715:2018	Alccofine	GGBFS
1.	Al2O3	--	18.13	17.68
2.	MgO	(Max) 17.0%	7.1	8.3
3.	CaO	--	36.59	38
4.	MnO	(Max) 5.5%	0.42	0.3
5.	SiO2	--	32.44	32.65
6.	SO3	(Max) 3.0%	0.4	0.1
7.	Loss of Ignition	(Max) 3.0%	0.3	0.2
8.	S (Sulphide Sulphur)	(Max) 2.0%	0.5	0.56
9.	Insoluble Residue	(Max) 3.0%		0.2
10.	Glass Content	(Min) 85%	88	98
11.	Moisture Content	(Max) 1.0%	0.2	0.2
12.	(CaO+MgO+Al2O3)/SiO2	(Min) 1.0%	1.93	1.9
13.	Cl (Chloride)	(Max) 0.1%	0.02	0.007

2.2 Methodology

Bacillus Pseudofirmus and Bacillus Licheniformis bacteria used in this study were cultured in the laboratory at M S Ramaiah University of Applied Sciences, Bangalore, using Luria Bertani (LB) broth medium. The LB broth contained Tryptone (10 g/L), Yeast Extract (5 g/L), and NaCl (5 g/L). The bacteria were cultured at 30°C with continuous shaking for 24 hours. After this period, bacterial cell density per milliliter of medium was manually counted using the Quadrant Plate technique. Three different Self-Consolidating Geopolymer Concrete (SCGC) mixes were prepared: one control mix without bacteria and two mixes containing Bacillus Pseudofirmus and Bacillus Licheniformis, each at a cell concentration of 3% of the total binder content. The binder content for all SCGC mixes was consistently maintained at 450 kg/m³. The proportions of the binder components—GGBFS, Class F Fly Ash, and Alccofine were fixed at 65%, 30%, and 5%, respectively. All mixes used a 13M NaOH solution, with the Na2SiO3 to NaOH ratio set at 1. The amount of free water and superplasticizer was also kept constant at 12% and 1% of the total binder content, respectively. Ambient curing was applied to all SCGC mixes. Mix identification details are provided in Table 9.

Table 9: SCGC mix identification

Mix Description	Mix ID		
	M1	M2	M3
GGBFS (%)	65	65	65
Fly Ash (%)	30	30	30
Alccofine (%)	5	5	5
Type of Bacteria	No Bacteria	Bacillus Pseudofirmus	Bacillus Licheniformis
Bacteria Cell Concentration (%)	3	3	3

2.3 Mix Design:

The Self-Consolidating Geopolymer Concrete (SCGC) mixes used in this study were designed based on prior research, as no standard guidelines are available for SCGC mix design. The workability of the mixes was enhanced by adding superplasticizer and free water. The optimal percentages of these additives were determined through slump flow and Marsh cone tests. Table 10 shows the slump flow test results, while Figure 1 illustrates the Marsh cone test outcomes. The proportions of binder components and the molarity of the NaOH solution were initially established by performing compressive strength tests on SCGC cubes after 7 days of curing. The mix design used in this study was influenced by the research of Nishanth and Dr. Nayana N. Patil (2022), based on the initial test findings. Details of the mix design for all SCGC mixes are provided in Table 11.

Table 10: Slump Flow Test Results

Mix ID	S0	S1	S2	S3	S4	S5	S6	S7

% of Free Water	0	2	4	6	8	10	12	14
Slump Flow (mm)	39	156	262	393	480	551	675	811

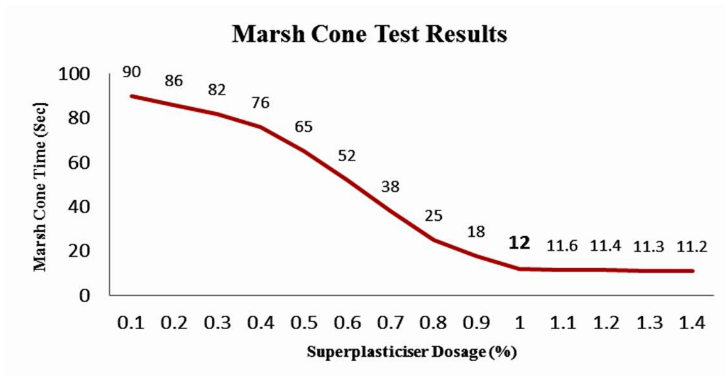


Fig 1: Marsh Cone Test Results

Table 11: Mix Design Details

Mix ID	Molarity	NaoH solids (kg/m^3)	Sodium silicate (kg/m^3)	GGBFS (kg/m^3)	Fly ash (kg/m^3)	Alccofine (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	SP (%)	Extra Water (kg/m^3)
M1	13M	135	135	292.5	292.5	292.5	925	925	1	54
M2	13M	135	135	135	135	135	925	925	1	54
M3	13M	135	135	22.5	22.5	22.5	925	925	1	54

3. Test Results and Discussion

3.1 Test results of fresh concrete

According to EFNARC guideline, the self-compacting ability of Self-Consolidating Geopolymer Concrete (SCGC) is defined by its filling ability, segregation resistance, and passing ability. SCGC should achieve high workability without compromising its strength properties. Workability test results are presented in Table 12. The results showed that the SCGC mix without bacteria exhibited the lowest slump flow due to the intensified polymeric reaction caused by the high molarity of the NaOH solution and reduced water content, which accelerated the concrete's hardening. In contrast, the SCGC mixes containing bacteria demonstrated improved passing and filling abilities, likely due to the increased water content from the addition of the Luria Bertani (LB) broth medium with bacteria. The addition of the LB broth medium delayed the polymeric reaction due to the reduced molarity of the NaOH solution, which extended the concrete's hardening time. Among the mixes, SCGC mix M2 with Bacillus Pseudofirmus bacteria displayed the best workability. It is important to note that all SCGC mixes met the EFNARC guidelines.

Table 12: Workability test results

Sl.No	**MIX ID**	**TEST RESULTS**				
		Slump Test (mm)	T- 50 Slump (Sec)	L- Box Test (mm)	V- Funnel Test(sec)	J – Ring Test(mm)
1	M1	692	4.8	0.83	9.74	8.1
2	M2	735	3.5	0.86	5.61	4.5
3	M3	706	2.3	0.95	6.25	5.2
Acceptable Values AS PER EFNARC						
Minimum Values		650	0	0.80	6	0
Maximum Values		800	6	1.0	12	10

3.2 Hardened concrete test results

Compression, split-tensile, and flexural tests were conducted at 7, 14, and 28 days, following IS 516-1959, to assess the strength characteristics of the hardened SCGC mixes. The test results are shown in Table 13, with graphical representations in Figures 2, 3, and 4. SCGC mix M2, which contained Bacillus Pseudofirmus bacteria at a 3% cell concentration of the total binder content, achieved the highest compressive strength of 53.38 MPa, split-tensile strength of 5.12 MPa, and flexural strength of 3.89 MPa after 28 days of ambient curing. The high strength gain in this mix is attributed to the formation of a tetrahedral alumina-silicate structure, resulting from the development of geopolymeric gels such as C-S-H, C-A-S-H, and N-A-S-H. These gels are formed through an exothermic reaction driven by the high CaO content in Alccofine and GGBFS. On the other hand, SCGC mix M1, which did not contain bacteria, exhibited the lowest compressive strength of 43.87 MPa, split-tensile strength of 3.12 MPa, and flexural strength of 3.67 MPa after 28 days of ambient curing.

Mix ID	Compression strength (MPa)			Split-tensile strength (MPa)			Flexural Strength (MPa)		
	7 Days	14 days	28 Days	7 days	14 days	28 Days	7 days	14 days	28 Days
M1	41.76	41.79	43.87	2.6	2.79	3.12	3.17	3.23	3.6

									7
M2	49.24	51.81	53.38	3.88	4.08	5.12	3.24	3.34	3.89
M3	46.18	50.93	51.29	3.58	3.69	4.78	3.21	3.27	3.76

Table 13: 7, 14 and 28 days strength tests results

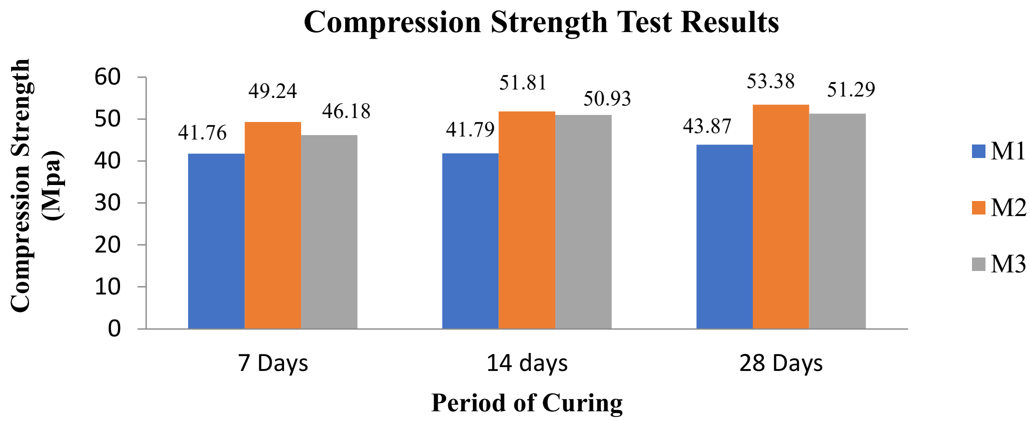


Fig 2: Compression strength test results

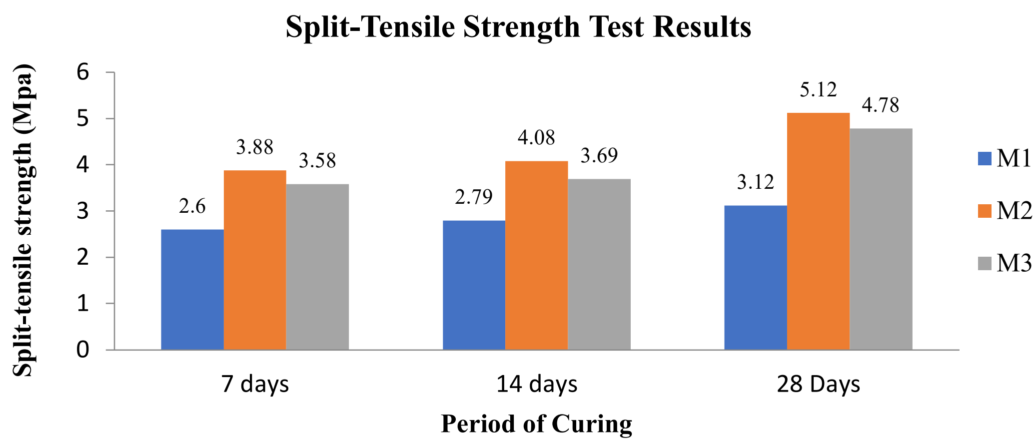


Fig 3: Split-tensile strength test results

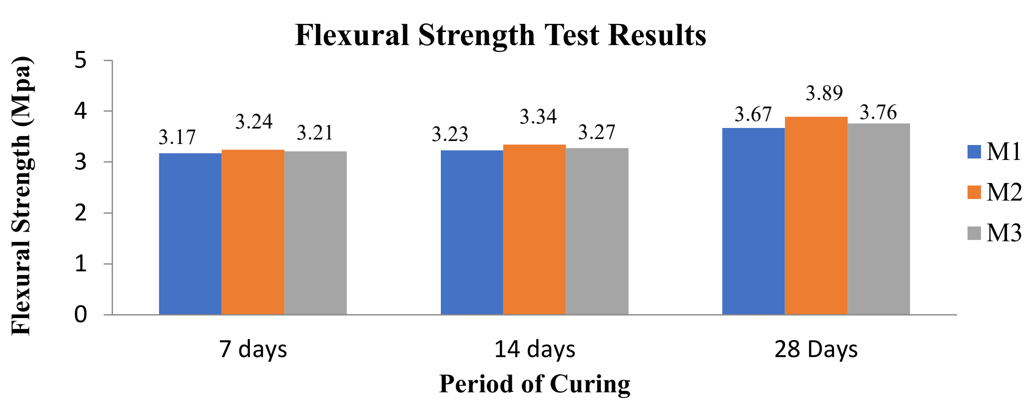


Fig 4: Flexural strength test results

3.3 Durability tests

3.3.1 Acid attack test

An acid attack test was performed by immersing cylindrical specimens measuring 100mm in diameter and 150mm in height in a 3% sulfuric acid (H_2SO_4) solution for 28 days to assess changes in weight and strength. Figure 5 shows the weight changes, while Figure 6 illustrates the strength changes after 28 days of acid exposure. The SCGC mix M1, which did not contain bacteria, experienced the highest weight loss of 4.63% and the greatest strength reduction of 5.1% after 28 days of immersion. The test results are detailed in Table 13.

Table 13: Acid Attack Test Results

Mix ID	Change in Weight			Change in Strength		
	Before Immersion	After Immersion	% Loss in Weight	Before Immersion	After Immersion	% Loss in Strength
M1	3.693	3.522	4.63%	3.12	2.96	5.1%
M2	3.703	3.624	2.13%	5.12	4.96	3.1%
M3	3.693	3.564	3.5%	4.78	4.56	4.6%

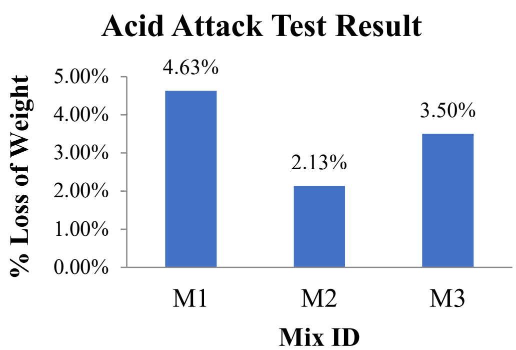


Fig 5: Change in Weight

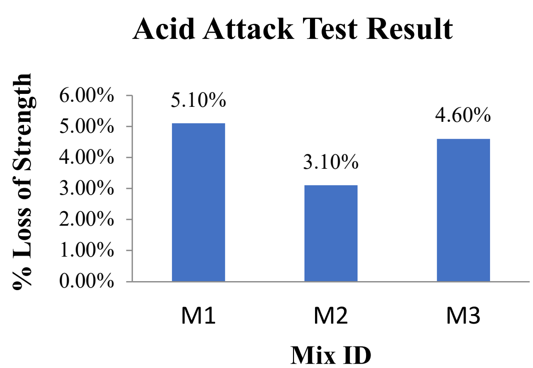


Fig 6: Change in Strength

3.3.2 Sulphate attack test

A sulphate attack test was conducted by immersing cylindrical specimens measuring 100mm in diameter and 150mm in height in a 5% magnesium sulphate ($MgSO_4$) solution for 28 days to evaluate changes in weight and strength. Figure 7 displays the weight changes, and Figure 8 shows the strength changes after 28 days of exposure to the alkaline environment. The SCGC mix M1, which did not contain bacteria, exhibited the highest weight loss of 2.6% and the greatest strength reduction of 2.2% after the 28-day immersion period. The test results are summarized in Table 14.

Table 14: Alkali Attack Test Results

	Change in Weight	Change in Strength

Mix ID	Before Immersion	After Immersion	% Loss in Weight	Before Immersion	After Immersion	% Loss in Strength
M1	3.693	3.598	2.6%	3.12	3.05	2.2%
M2	3.703	3.682	0.6%	5.12	5.04	1.6%
M3	3.693	3.622	1.9%	4.78	4.69	1.8%

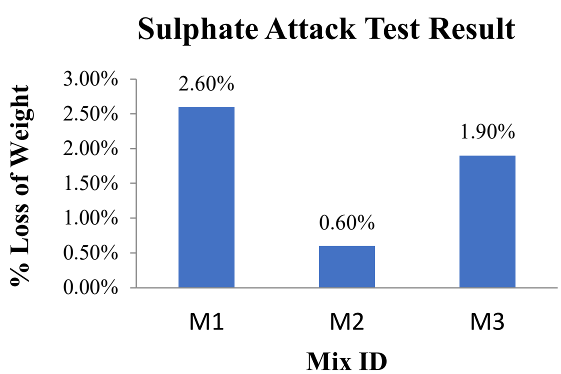


Fig 7: Change in Weight

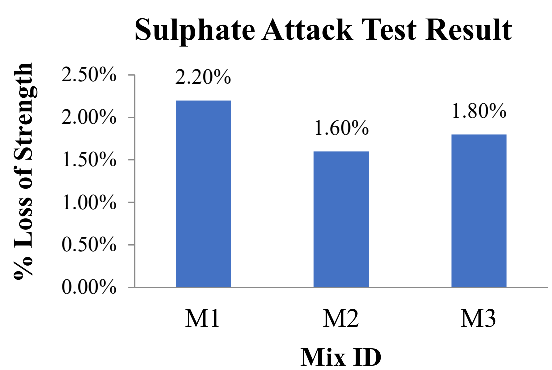


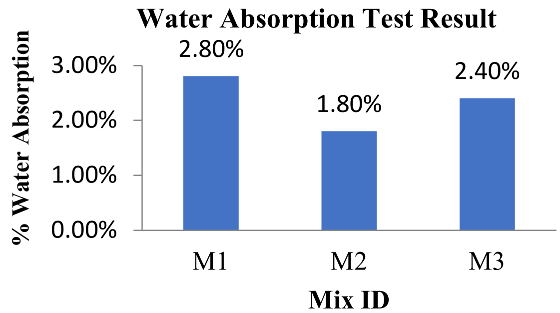
Fig 8: Change in Strength

3.3.3 Water absorption test

The water absorption test was carried out by immersing oven-dried cylindrical samples, measuring 100mm in diameter and 150mm in height, in water for 24 hours to measure the change in weight. After 24 hours, the specimens were removed, patted dry, and weighed. Figure 9 presents the test results. The SCGC mix M1 showed the highest water absorption rate of 2.8% after 24 hours of immersion, likely due to the porous nature of the concrete. The test results are detailed in Table15.

Table 14: Water Absorption Test Result

Mix ID	Change in Weight		
	Before Immersion	After Immersion	% Gain in Weight
M1	3.693	3.798	2.8%
M2	3.703	3.769	1.8%
M3	3.693	3.784	2.4%



Conclusion

This experimental study examines the impact of Bacillus Pseudofirmus and Bacillus Licheniformis bacteria on the workability, strength, and durability of Self-Consolidating Geopolymer Concrete (SCGC). The inclusion of Bacillus Pseudofirmus bacteria at a cell concentration of 3% of the total binder content significantly improved the workability, strength, and durability of SCGC. The results show that adding Bacillus Pseudofirmus increased slump flow by 6.1%, compressive strength by 21.7%, split-tensile strength by 64.1%, and flexural strength by 6%. The incorporation of this bacteria reduced the porosity of SCGC, as demonstrated by durability tests, which in turn enhanced the concrete's strength characteristics. Therefore, bacteria-infused SCGC emerges as a sustainable and eco-friendly alternative to Ordinary Portland Cement (OPC) concrete.

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