Performance Evaluation of Self-Compacted Geopolymer Concrete with Fly Ash Partially Replaced with Blast Furnace Slag

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ABSTRACT

The present study investigates the manufacturing process of Self-Compacted Geopolymer Concrete (SCGPC), an environmentally friendly and sustainable building material with a 76% aggregate composition. The raw material Fly Ash (FA) was substituted with Ground Granulated Blast Furnace Slag (GGBFS) by 10%, 20%, 30%, and 40% to produce ambient-cured SCGPC. SCGPC specimens containing 100% FA were heat-cured for 24 h at various temperatures, and then their Compressive Strength (CS), Split-Tensile Strength (STS), and Flexural Strength (FS) were tested after 3, 7, and 28 days. FA and GGBFS-based SCGPC were cured at room temperature, while the NaOH concentrations were kept constant at 8M, 10M, 12M, and 14M. The flowability of SCGPC was examined using EFNARC specifications, whereas the properties of hardened concrete were investigated using Indian Standard Codes. The SCGPC cube, cylinder, and prism specimens were cast to investigate how different parameters affected CS, STS, and FS, respectively. The results revealed that the CS, STS, and FS of SCGPC increased to 30% after the addition of GGBFS as a partial replacement of FA, and with an increasing NaOH concentration up to 12M after which they decreased. The SCGPC specimens were exposed to various Sea Water Concentrations (SWC) for 30, 180, and 365 days, which led to a reduction in strength and an increase in weight as both the exposure time and SWC increased. The Energy Dispersive X-Ray Spectroscopy (EDS) revealed that GGBFS improved the strength growth under ambient curing conditions, while the Scanning Electron Microscopy (SEM) showed dense structures with an early age setting and strength gain.

Keywords-Self-Compacted Geopolymer Concrete (SCGPC); split-tensile strength; environmentally friendly concrete; blast furnace slag

I. INTRODUCTION

Concrete is the most used building material, with Portland cement serving as the principal cementing agent. Ordinary Portland Cement (OPC) is the primary binder used in conventional concrete manufacturing, which contributes to 5%-7% greenhouse gas emissions and environmental challenges due to its high energy consumption for the cement manufacture [1]. However, cement remains a prevalent choice in the construction industry for its ability to bind aggregates when mixed with water, resulting in various sizes and forms. The cement output may rise from 3200 million tons in 2023 to 4397 million tons in 2050, indicating significant implications for the global warming indices. To ensure the sustainability of concrete production, an eco-friendly binder has been developed [2]. Moreover, byproducts from various sectors can be used to complement cementitious ingredients in concrete production. Geopolymerization is an alternative method for manufacturing eco-friendly concrete, as it provides an alternative resource for recycling and sustainability [3]. Geopolymers offer an alternative approach to eco-friendly concrete manufacturing, utilizing alkaline-activated Aluminosilicates (AS) of industrial by-products or natural clays, which consume less raw material energy and emit less carbon than OPC. The former do not require the formation of Calcium Silicate Hydrate (C-S-H) gel; instead, the formation of Sodium Aluminosilicate Hydrate (Na-AS-H) gel contributes to their durability [4]. GPC has a better cavity than OPC concrete, and the calcium content has a significant influence on the durability mechanism. Concrete constructions must be long-lasting and capable of withstanding the debilitating processes to which they are expected to be subjected [5].

Increasing the CS and ductility of high-strength GPC by using glass and carbon-fiber-reinforced polymers has demonstrated satisfactory durability characteristics, including resistance to drying shrinkage, penetration by chloride ions, water permeability, abrasion, and impact [6]. Authors in [7] explored the use of ground plastic waste, specifically Polyethylene Terephthalate (PET) bottles, to improve the

compressive and tensile strength of GPC. Residual CS is a critical durability feature of GPC. High temperature exposure has an impact on the surface properties, appearance, form, and color of concrete. The residual compressive resistance of four GPC types exposed to temperatures ranging from 20 to 1000°C for 2 h was evaluated, identifying 600°C as the maximum temperature threshold before strength loss occurs. The concrete specimens revealed that their CS reached 72 MPa after exposure to 205 °C, but it was reduced by 8.5, 44, 58, 56, and 91% at different temperatures [8]. A peak CS of 64.70 MPa after 300°C exposure was achieved. In [9], GP specimens produced with an alkaline activation process and high calcium (Class C) lignite FA as a precursor, assessed the Sulfuric Acid Resistance (SAR) of FA mixed GPC, exhibiting 8% lower mass loss after 18 months compared to OPC concrete specimens [9]. The SAR of FA-based GPC investigations revealed an average CS reduction of 14.91%. OPC concrete had a significantly lowered SAR compared to GPC [10]. FA and nano-silica combinations lead to the production of acid-resistant GPC [11].

Self-Compacted Concrete (SCC) is a novel breakthrough that has both environmental and practical benefits. Its primary characteristics are the flow, filling, and passing ability, all of which defy segregation [12]. This breakthrough includes SCGPC, which has both environmental and practical benefits [12]. However, further research is needed to confirm the usefulness of SCGPC in both fresh and hardened forms, as well as to produce materials for practical uses [13]. Supplementary cementitious materials, such as FA and slags, are commonly employed to minimize costs while improving concrete's workability and mechanical properties [14]. Drying shrinkage is a crucial property of concrete that influences its durability and long-term serviceability. Oven-cured GPC has a significantly lower drying shrinkage than ordinary concrete. There can be a small amount of water left in the hardened concrete's micro pores as the majority of the water produced during the chemical reaction in FA-based GPC evaporates during curing [15]. Conventionally cured GPC derived from FA offers high engineering performance and moderate drying shrinkage. However, because the slag-based GPCs activated with sodium silicate create silica-rich gel, they may result in larger shrinkage stresses than OPC concrete [15]. The SCGPC using FA as a foundation material revealed that longer curing time and higher temperatures led to greater CS, with concrete cured at 70°C showing the highest CS values compared to specimens cured at 60, 80, and 90°C [16]. The superplasticizer dose affected the CS and microstructure features of FA-based SCGPC's Interfacial Transition Zone (ITZ). The results indicated that increasing CS resulted in a thicker ITZ, which improved the concrete performance [17]. The impact of NaOH concentration ranging from 8M to 14M on the fresh characteristics and on the CS of SCGPC was investigated, revealing that the concentration change had a minimal effect [18]. The impact of superplasticizer and sodium hydroxide alkaline solution on the microstructure, workability, and CS of SCGPCs was examined in [19].

Coal is the primary source of electricity generation in many Asian countries, and its byproduct, FA, is available in abundant quantity. More than 226 tons of FA were produced in 2020, with 45% being used for construction and the remainder being disposed in ash ponds or lagoons [20]. Except for Class C FA, FA has no binding properties. Therefore, low calcium (Class F) FA may be activated using alkali activator solutions to generate a binding agent. This might allow for the entire replacement of OPC in concrete [21]. Alkali-activated binders, also known as geopolymers, have emerged as a relatively novel, sustainable, and cost-effective binding material that can be made using locally accessible industrial byproducts, such as FA and GGBFS [22]. Geopolymers are binders formed by polymerizing byproduct minerals, including silica and alumina, in high alkaline solutions [23, 24]. These byproducts, such as Class F FA and rice husk ash, might be geological or industrial in origin. Because of its chemical composition and general availability, low calcium (Class F) FA has been employed in the production of geopolymers [4, 25].

Heat-curing geopolymer is an energy-intensive method that cannot be used in cast-in-situ applications [26]. To solve this difficulty, an alternative geopolymer mix must be developed that can be cured at room temperature [26, 27]. The current experimental study seeks to assess the performance and properties of GPCs produced entirely from FA and GGBFS. The study's goals include producing oven-cured GPCs with FA as the only raw material. GGBFS is used to partially replace FA in the manufacture of ambient-cured GPCs. Understanding how SCGPC flows [28]. The study also investigated factors affecting the fresh and hardened properties of GP mortar and SCGPC, evaluating the features of GPCs in a new context, using SEM-EDS to investigate the microstructural behavior of SCGPC. The temperature resistance, fatigue resistance, and rutting performance were assessed using dynamic shear testing, zero shear viscosity measurements, and Multiple Stress Creep Recovery (MSCR) tests.

II. MATERIALS AND METHODS

A. Materials

The materials used in the preparation of SCGPC included low-calcium (Class F) FA, as seen in Figure 1(a), obtained from a thermal power plant in India, and GGBFS, as depicted in Figure 1(b), sourced from a steel plant in Pakistan [4]. The physical and chemical properties of the materials are presented in Table I.

TABLE I. PHYSICAL AND CHEMICAL PROPERTIES OF FA (CLASS F) AND GGBFS

Material		**FA**	**GGBFS**
Chemical composition	SiO_2	65.6	30.97
	Al_2O_3	24.53	17.41
	Fe_2O_3	5.19	1.13
	CaO	0.31	36.97
	MgO	0.76	5.81
	Na_2O	0.36	0.69
	K_2O	0.23	0.46
	SO_4	0.31	1.72
Physical	Specific gravity	2.28	2.8
	Loss on ignition	1.50	2.0
	Blain fineness (cm^2/g)	3098	425

Fig. 1. Materials used in preparation of SCGPC: (a) Low Calcium FA (Class F); (b) GGBF; (c) Sodium Hydroxide Pellets, and (d) Sodium Silicate Solution.

Given their ease of availability and inexpensive cost, NaOH, as illustrated in Figure 1(c), and Sodium Silicate (Na_2SiO_3), as portrayed in Figure 1(d), were utilized as activators of alkaline. NaOH was utilized as a pellet, while Na_2SiO_3 was employed as a liquid. Chemi Equip Ltd., based in Karachi, Pakistan, provided both materials. NaOH flakes were dissolved in water to form their solution; the quantity of flakes varied depending on the NaOH concentration. For example, 8M NaOH requires 320 g of NaOH flakes per L of water, but 10M, 12M, and 14M NaOH require 400 g, 480 g, and 560 g of NaOH pellets, respectively. Natural sand obtained from the river, as shown in Figure 2, was used as fine aggregate, while crushed stone aggregates up to 20 mm in size were utilized as coarse aggregates. With an increase in the FA quantity, a Poly carboxylic ether-based superplasticizer was utilized at various doses. In the NaOH solution, a 7.0 pH Viscosity Modifying Admixture (VMA) was deployed along with regular tap water. The mixture had no surplus water. SCGPC had coarse particles no larger than 16 mm. Of the aggregate mix, 35% passed through the IS 16 mm sieve and was retained on the IS 12.5 mm sieve, while 65% passed through the IS 12.5 mm sieve and was retained on the IS 4.75 mm sieve. According to these data, the aggregates fulfilled certain grading specifications. The physical properties of fine and coarse aggregates are presented in Table II.

Fig. 2. Natural sand obtained from the river.

TABLE II. PHYSICAL PROPERTIES OF FINE AND COARSE AGGREGATES

No.	Description		Fine	Coarse
1	Water absorption		1.20%	0.40%
2	Free moisture		0.26%	0.00%
3	Specific gravity		2.73	2.78
4	Bulk Density	Loose state	1580 kg/m^3	1550 kg/m^3
		Compacted state	1695 kg/m^3	1640 kg/m^3
5	Bulking of sand		11%	-
6	Fineness modulus		2.55	6.86

B. Production of Self-Compacting Geopolymer Concrete

1) Mixing, Casting, and Curing

SCGPC was prepared using a similar mixing mechanism (mixed in an electric concrete mixer) that includes dry mixing FA and fine aggregates in a laboratory mixer for 2 min before adding the coarse aggregate. The alkaline activator solution was prepared 24 h prior to the mixing operation in order to minimize the heat generation. The flakes of NaOH were diluted with tap water and left at room temperature for a day. The sodium silicate solution was added to the prepared solution while being thoroughly stirred. The alkaline activator solution was then added to the dry mixture (mix) and combined for 3 min. FA was chemically activated using four different concentrations of NaOH and Na_2SiO_3, with a 2.5 ratio. SCGPC was then prepared by adding a Poly-Carboxylic Ether (PCE)

based superplasticizer at 2.45% FA mass and was stirred for 2 min. To lower the mix viscosity, 1% mass of VMA was added. The alkaline liquid and superplasticizer solution were then progressively mixed into the dry mix for 4 to 5 min. Table III displays the mix proportions of the SCGPC mortar.

The mixes were examined while still in fresh condition, and the hardened state properties were measured by cast samples, which were stored for a day prior to being oven-cured for a full day at 85°C.

Moreover, to improve the ease of the mix settling without the need for an external vibrator, coarse aggregates with a maximum size of 16 mm were used. Of these, 35% passed through the IS 16 mm sieve and were retained on the IS 13 mm sieve, while 65% passed through the IS 13 mm sieve and were retained on the IS 5 mm sieve. The mixed proportion of SCGPC is summarized in Table IV. The mix description C represents a geopolymer mortar with 10%, 20%, 30% and 40% GGBFS content as a partial replacement of FA cured in ambient conditions at 35°C± 2°C.

TABLE III. MIX PROPORTIONS OF SCGPC MORTAR

Mix Code	C0	C1	C2	C3	C4
FA (%)	100	90	80	70	60
GGBFS (%)	0	10	20	30	40
Binder (kg/m^3)	450				
Gravel (kg/m^3)	800				
Sand (kg/m^3)	825				
Alkaline/Binder	0.5				
Molarity (M)	12				
Superplasticizer (%)	7				
Water (kg/m^3)	40				

TABLE IV. MIX SCGPC PROPORTIONS WITH DIFFERENT AMOUNTS OF AGGREGATES

Mix	1	2	3	4	5	5	7	8
C1	8	400	0	450	550	14	38	130
C2	8	360	40	450	550	14	38	130
C3	8	320	80	450	550	14	38	130
C4	8	285	120	450	550	14	38	130
C5	8	250	160	450	550	14	38	130
C1	10	400	0	450	550	16	35	130
C2	10	360	40	450	550	16	35	130
C3	10	320	80	450	550	16	35	130
C4	10	285	120	450	550	16	35	130
C5	10	250	160	450	550	16	35	130
C1	12	400	0	450	550	18	33	130
C2	12	360	40	450	550	18	33	130
C3	12	320	80	450	550	18	33	130
C4	12	285	120	450	550	18	33	130
C5	12	250	160	450	550	18	33	130
C1	14	400	0	450	550	21	30	130
C2	14	360	40	450	550	21	30	130
C3	14	320	80	450	550	21	30	130
C4	14	285	120	450	550	21	30	130
C5	14	250	160	450	550	21	30	130

1 = NaOH Conc. (M), 2 = FA (kg/m³), 3 = GGBFS (kg/m³), 4 = Coarse Aggregate (kg/m³) 18 mm, 5 = Fine Aggregate (kg/m³) 13 mm, 6 = NaOH Pellets (kg/m³), 7 = NaOH Water (kg/m³), 8 = Na_2SiO_3 Solution (kg/m³).

III. TESTING PROCEDURES USED FOR SCGPC

A. Slump Flow Test (SFT)

To assess the stability of SCGPC, the SFT developed in Japan was employed. It tests underwater and extremely flowable concrete by setting a traditional slump cone on a non-absorbent plate and filling it with fresh concrete without tamping. The horizontal spread and time necessary for concrete to spread to a 50-cm diameter were measured. A Visual Stability Index (VSI) was used to measure the stability of the concrete. For this study, VSI ratings of 0 or 1 were considered appropriate.

B. V-Funnel Test (V-FT)

V-FT was used for assessing the filling capability and segregating resistance of SCGPC. The test utilizes a V-shaped funnel, which is 425 mm high, 490 mm wide at the top, 65 mm wide at the bottom, and 75 mm thick. A rectangular section drops to 150 mm at its base. No vibration or tamping were used while filling the funnel with concrete, while the time taken for all of the concrete to flow out was noted. The concrete was added back into the funnel and was allowed to flow down for 5 min to assess the resistance of segregation. A longer flow duration indicates the susceptibility of concrete to segregation. SCGPC had a maximum flow time of 10 s, which was acceptable to avoid the segregation and filling resistance.

C. J-Ring Test (J-RT)

The J-RT was used to evaluate the filling capacity of SCGPC. As evidenced in Figures 3(a) and 3(b), the test setup consists of a 300 mm diameter open steel ring measuring 30 mm × 25 mm, with 100 mm long vertical holes designed to accept normal reinforcing bars. The bar spacing can be adjusted as required; however, it is proposed to maintain a spacing of three times the largest aggregate size. The test started with filling a slump cone with concrete and letting it spread horizontally across the gaps. Once the concrete sample had gone through the bar spacing and was settled, its horizontal spreading was determined. Four locations were used to assess the variation in height between the concrete outside and within the bars. The more passable the concrete was, the smaller was the difference.

D. L-Box Test (L-BT)

The L-BT, which was initially intended for undersea concrete, tests the capacity of SCGPC to fill and pass. The test originated in Japan and is currently used for testing extremely flowable concrete. The test involves laying concrete in an L-shaped box, which is 600 mm high and has a cross-section of 100 mm × 200 mm, and recording the time required for the concrete to reach the locations T20 and T40 along the box's horizontal half. The results are reported in the form of blockage ratio (H_2/H_1), with 1 being the ideal value for self-compacting concrete. Also, concrete with coarse particles is usually dispersed to the opposite end of the box's horizontal portion, showing a good resistance to segregation.

(a)

(b)

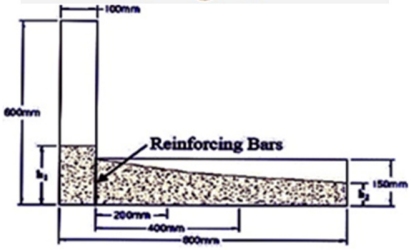


Fig. 3. (a) J-RT apparatus, and (b) L-BT apparatus.

E. SCGPC Mechanical Properties

The SCGPC specimens were examined for CS, STS, and FS at 3, 7, and 28 days of development before exposure to elevated temperature, marine, and acid conditions. The strength and weight variations were investigated using an average of three specimens for each combination.

1) Compressive Strength (CS)

Three concrete specimens were evaluated at 3, 7, and 28 days of maturity using a 200-ton hydraulic compression testing equipment. The 100 mm cube specimens were tested for CS in accordance with the IS Code for concrete testing. The tests were performed on each mix and type, assuring reliable results and encouraging the growth of CS in concrete.

2) Split-Tensile Strength (STS)

STS is an indirect method for determining the concrete tensile strength by applying a compressive line load along the opposing generators of a concrete cylinder. Such tests were performed on cylindrical specimens with a diameter of 100 mm and a height of 200 mm.

3) Flexural Strength (FS)

FS, often called split modulus, bend, or fracture strength, is a mechanical characteristic of brittle materials. It evaluates a material's capacity to withstand the distortion under stress (load). The transverse bending test, which involves bending specimens until they fracture or yield, is often used to assess FS. FS is examined using prism specimens measuring 100 mm × 100 mm × 500 mm.

F. SCGPC Subjected to Marine Environments

The purpose of this test was to examine the effect of the Water Concentrations (SW) on the CS, STS, and FS of SCGPC specimens at varying doses of NaOH (8M to 14M). Following a 28-day exposure to maritime conditions, the specimens' weights were measured at 30, 180, and 365 days. To investigate the impact on these specimens, artificial saltwater with varying concentrations of NaOH was prepared. Throughout the test, the artificial seawater's salinity was checked and changed as required. Additionally, the chemical makeup of saltwater was investigated. Salt water samples (1000 grams) with 1N, 3N, and 5N concentrations were produced by dissolving the salts in ordinary water.

G. Microstructural Analysis

Microstructural analysis was conducted on the powder samples of the SCGPC. These samples with no coarse aggregate content were studied for the SEM-EDS analysis to investigate the reaction products and their behavior.

IV. RESULTS AND DISCUSSION

In this study, the SCGPC samples were made entirely of FA, rather than GGBFS. Experiments were carried out to investigate the CS, STS, and FS of SCGCP specimens at 3, 7, and 28 days of maturity. The specimens were exposed to 1N, 3N, and 5N concentrations of seawater for 30 days, 180 days, and 365 days, respectively. The microstructural properties were also investigated using XRD and SEM-EDS.

A. Properties of Fresh SCGPC

SCGPC's workability in its fresh form was evaluated in accordance with EFNARC criteria. The results of the tests, involving SFT, T50 cm flow, V-FT, L-BT, and J-RT, are shown in Figures 6(a)-6(e).

1) SFT and T50 cm Results

The properties of SCGPC in the fresh state were studied as per EFNARC standards. A decrease in the slump flow was noted for all SCGPC mixes with an increase in GGBFS content, irrespective of the NaOH concentration. This decrease is consistent with NaOH concentrations from 8M to 14M. Freshly mixed concrete is less workable when using GGBFS binders because they have a greater specific surface area than the FA binders and require more water while mixing. SCGPCs' slump flow values, with 0% and 40% slag concentration, were within the EFNARC limitations for the SF3 class. Nevertheless, SCGPC provides a superior surface quality compared to SCGC in the SF3 Class, as depicted in Figure 4(a).

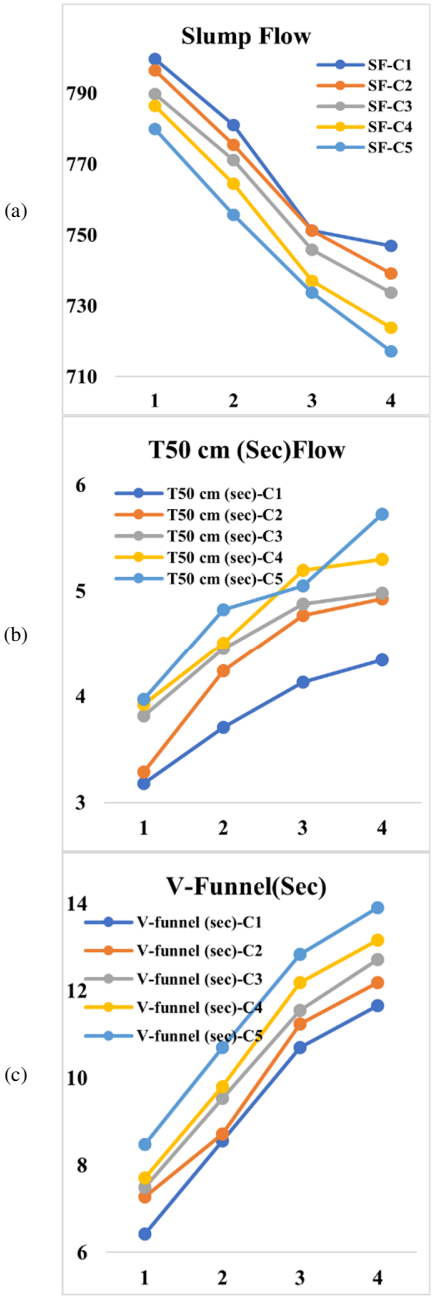
The time taken for SCGPC to flow for 50 cm increased with the increase in the NaOH concentration. The flow time for a 50 cm flow increased by 66.67%, from 3 s for 8M NaOH to 5 s for 14M NaOH concentration, as illustrated in Figure 4(b). This increase can be attributed to the mix's viscous character, which reduces the flowability of SCGPC. These findings emphasize the need for evaluating the viscous character of SCGPC blends when determining their workability.

2) V-FT Results

At an 8M NaOH concentration, the SCGC V-Funnel flow takes 6 s, but at 12M NaOH concentration, it takes 12 s, or 57% of the V-Funnel flow for filling ability. It takes longer for the SCGPC to pass through the funnel—13 s—when the NaOH concentration is increased further to 14M. Additionally, all of the SCGPC mixes exhibited the same pattern of longer flow times via V-funnels in response to increasing the NaOH concentrations, as displayed in Figure 4(c).

3) Results of L-Box Test

The filling capacity of SCGPC in the L-BT test was affected by the NaOH concentration, with a 4% drop in the L-Box ratio seen with every 2M NaOH concentration between 8M and 14M. This loss in workability is attributable to the viscous character of the alkaline activator solution, which causes the concrete to thicken and lose workability.



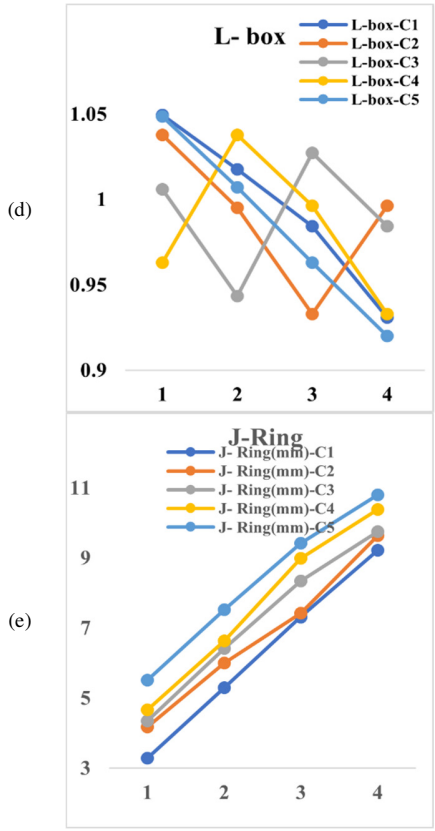


Fig. 4. Properties of fresh SCGPC (a) SFT; (b) T50 cm flow; (c) V-FT; (d) L-BT; and (e) J-RT under varying NaOH concentration.

The L-BT measures the mix's ability to pass through three-bar restricted apertures, with the test results ranging from 0.8 to 1.0, confirming the passage abilities according to EFNARC recommendations and the EN12350-10 standard. All mixtures had an acceptable passing capacity, with GGBFS-free blends having the greatest passing ability of 1.00. As the GGBFS content rises, the L-Box values fall, as presented in Figure 4(d).

4) Results of J-Ring Test

The J-RT assesses the distribution of fresh mixed SCGPC across the J-ring. The test results reveal that when the GGBFS content increases, the J-ring flow diameter shrinks. The results varied from 780 to 720 mm for 0% and 40% GGBFS concentration. The SCGPC mixtures may be divided into two classes based on the J-RT results: SF3 (0%-30%) and SF2 (30%-40%), with the test results being within the EFNARC accepted range, as demonstrated in [28]. Figure 4(e) shows that the difference in the heights of the J-RT increases by almost 50% as the NaOH concentration increases from 8M to 14M.

B. Mechanical Properties of SCGPC

Tests on hardened SCGPC samples were conducted to study the factors affecting the CS, STS, and FS of cube specimens having a size of 100 mm × 100 mm × 100 mm, cylinder specimens with a diameter of 100 mm and 150 mm height, and prism specimens with a size of 100 mm × 100 mm × 500 mm, respectively, at 3 days, 7 days, and 28 days of curing.

1) Compressive Strength Results

The study examines the performance of SCGPC mix C1 using FA as the only source material, which was cured in an oven at 90°C for 24 h. The highest 3-day CS of 33.07 N/mm^2 was attained with a 12M NaOH concentration, which achieved the maximum CS independent of the inclusion of GGBFS as a partial substitute for FA, as depicted in Figure 5(a). Mix C4 with 30% partial FA substitution by GGBFS at 12M NaOH concentration produced a maximum 3-day CS of 38.69 N/mm^2, whereas mix C5 with 40% GGBFS content resulted in a lower CS of 37.25 N/mm^2. The maximum 7-day CS of 38.80 N/mm^2 was attained for 12M NaOH concentration, whereas mix C4 with 30% fractional substitution of FA by GGBFS at 12M achieved a maximum 7-day CS of 43.14 N/mm^2. Increasing the GGBFS content to 40% in mix C5 resulted in a 1.45% drop in CS to 42.66 N/mm^2, as presented in Figure 5(b). The highest 28-day CS of 45.26 N/mm^2 was attained with a 12M NaOH concentration, while a 28-day CS of 51.97 N/mm^2 was achieved for mix C4 at a 12M NaOH concentration, as shown in Figure 5(c). Increasing the GGBFS content to 40% for mix C5 resulted in a 3.50% drop in CS to 50.15 N/mm^2 [4, 22, 28].

(a) (b) (c)

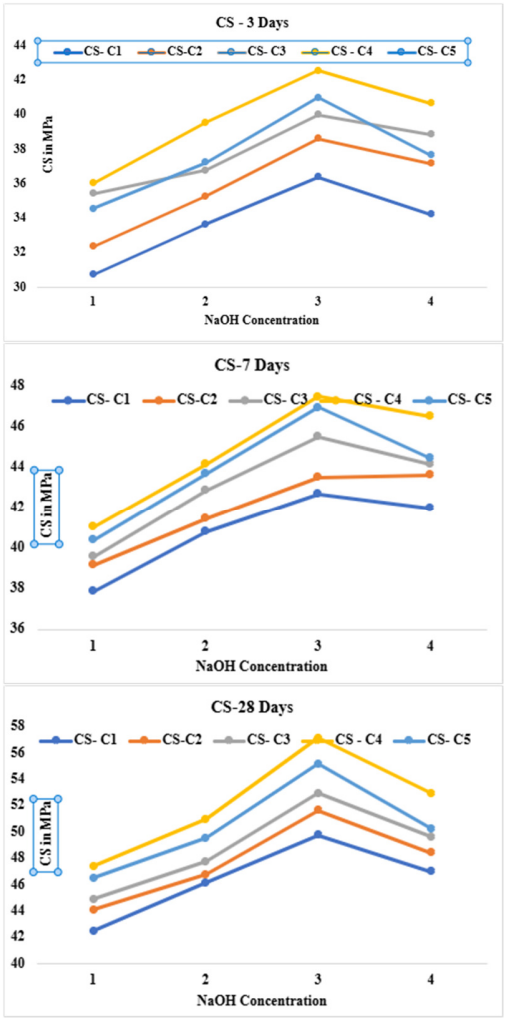


Fig. 5. CS of various mixes at :(a) 3 days, (b) 7 days, and (c) 28 days, under varying NaOH concentrations.

2) Split-Tensile Strength Results

The study analyzed the STS of SCGPC using three-cylinder specimens with dimensions of 100 mm in diameter and 200 mm in height. The results showed that SCGPC with a 12M NaOH concentration produced the highest STS, regardless of the inclusion of GGBFS as a partial replacement of FA. Mix C4 with 30% fractional substitute for FA by GGBFS at 12M achieved a maximum 3-day STS of 3.09 N/mm^2, while increasing the GGBFS content to 40% in mix C5 resulted in a 0.97% drop in CS of 3.06 N/mm^2, as seen in Figure 6(a). The study reveals that the STS of a material significantly influences its NaOH concentration. A 12M NaOH concentration yielded a maximum 7-day STS of 3.09 N/mm^2 for mix C1, while mix C4 produced a maximum STS of 3.44 N/mm^2, as illustrated in Figure 6(b).

(a) (b) (c)

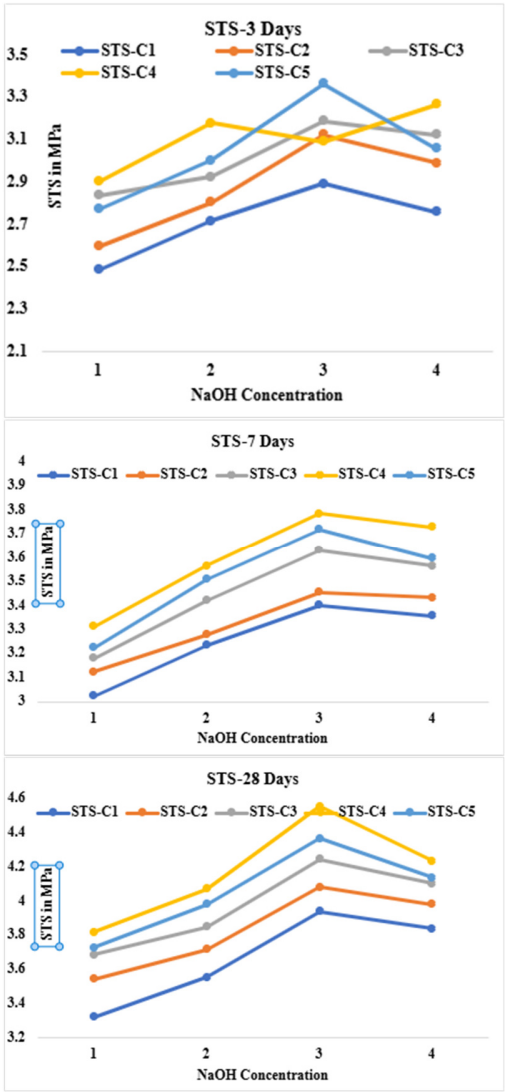


Fig. 6. STS of various mixes used to evaluate for (a) 3 days, (b) 7days, and (c) 28 days under varying NaOH concentration.

However, increasing the GGBFS content to 40% reduces CS by 1.74%. The SCGPC mix C1 with FA achieved a

maximum 28-day STS of 3.58 N/mm^2, while mix C4 at 12M NaOH yielded 4.14 N/mm^2, as depicted in Figure 6(c). Increasing the GGBFS content to 40% in mix C5 resulted in a 4.10% drop in CS (3.97 N/mm^2) [4, 5, 18].

3) Flexural Strength Results

The study focuses on the performance of the SCGPC mix C1 using FA as the sole source material, which was cured in an oven at 90°C for 24 h. The combination attained a maximum 3-day FS of 4.02 N/mm^2 at 12M NaOH concentration, as portrayed in Figure 7(a), and a maximum 7-day FS of 4.8 N/mm^2. Mix C4 at 12M NaOH achieved the highest 7-day FS of 5.05 N/mm^2. Mix C5 had a 1.3% drop in FS to 5.2 N/mm^2, as seen in Figure 7(b). When 12M NaOH was used, the highest 28-day FS for the SCGPC mix C1 was 5.2 N/mm^2. But mix C4 reached a maximum 28-day FS of 5.5 N/mm^2, as displayed in Figure 7(c). A 0.80% drop in FS was seen when the GGBFS content increased to 40% (mix C5) [20-22].

Up to 12M NaOH concentration, all SCGPC mixtures exhibited a comparable behavior in terms of increased CS, STS, and FS. However, increasing the NaOH content to 14M lowered the CS by 7.5%-11% across all combinations. This drop in CS above 12M NaOH can be attributed to the presence of excess hydroxide ions, which impede the geopolymerization process. The inclusion of GGBFS improved the early strength growth of SCGPC without requiring oven curing. CaO in GGBFS contributes to the initial strength rise of SCGPC, with 10%-40% GGBFS at a step of 10% content as a fractional substitute for FA.

C. Effect of Marine Environments

The study examines how SCGPC behaves under prolonged exposure to seawater in marine conditions. The test utilized three sets of 28-day matured specimens for each mix, with NaOH concentrations ranging from 8M to 14M, to analyze the impact of the exposure duration under different SWC. The research reveals that the CS of SCGPC decreases with a continued immersion in 1N, 3N, and 5N SWC. Notably, mix C1 experienced a significant 30-day CS reduction when submerged in SWCs of 1N, 3N, and 5N, dropping from 42.6 N/mm^2 to 4.2%, 5.2%, and 5.8%, respectively. Similarly, mix C5 at a 12M NaOH concentration exhibited an 8%, 8.3%, and 9.4% decrease compared to an initial CS of 55.2 N/mm^2, with corresponding Weight Gain (WG) values of 1.87%, 1.96%, and 2.15%.

Over a 180-day period, the CS of SCGPC mix C3 at an 8M NaOH concentration declined by 7%, 7.2%, and 8.9% compared to an initial CS of 45 N/mm^2 when submerged in 1N, 3N, and 5N SWC. The corresponding WG values were 2.4%, 2.5%, and 2.8% [4, 23]. Additionally, mix C5 at an 8M NaOH concentration experienced decreases of 11.6%, 13.7%, and 14.8%, while at a 10M NaOH concentration, the decreases were 7.4%, 7.8%, and 8.9% compared to the initial CS values. Moreover, over a 365-day period, mix C5 at a 10M NaOH concentration exhibited decreases of 11.65%, 13.94%, and 16%, while at a 12M NaOH concentration, the decreases were 12%, 15%, and 16% compared to the initial CS values. The corresponding WG values were 2.4%, 2.55%, and 2.9%. Finally, the SCGPC mix C4 at a 14M NaOH concentration showed reductions of 10.3%, 12.5%, and 13.95% compared to an initial CS of 53 N/mm^2 [24, 25].

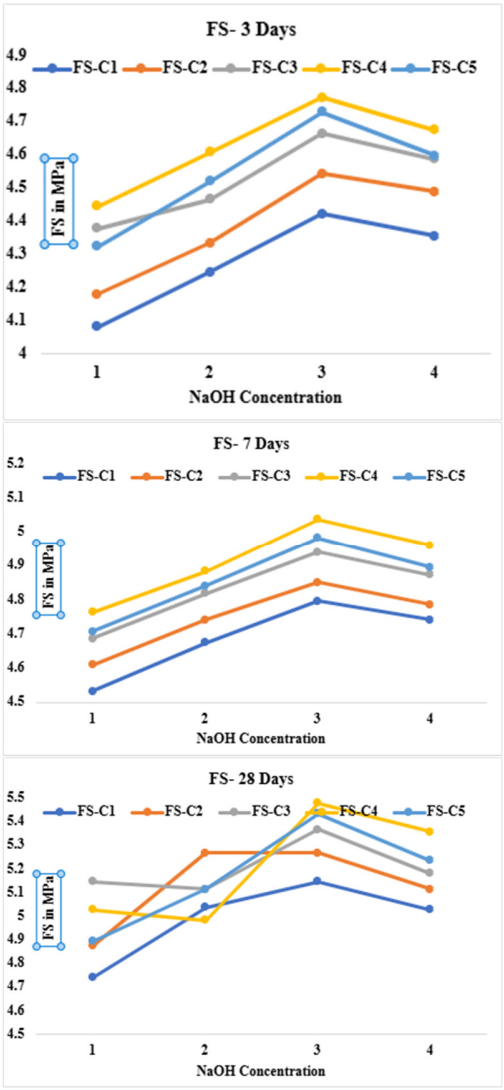
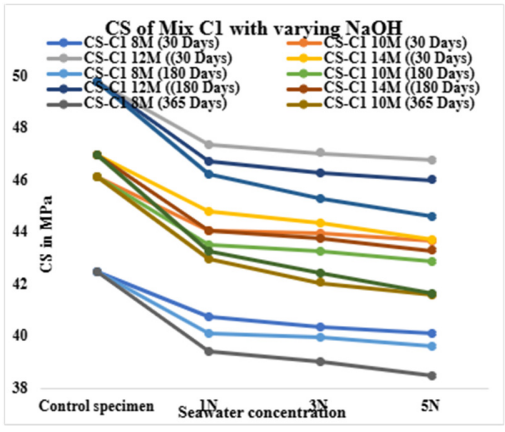
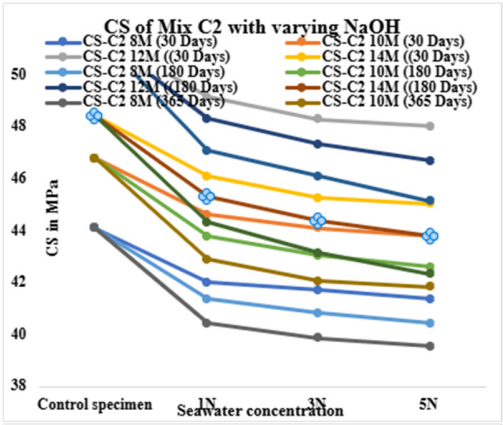


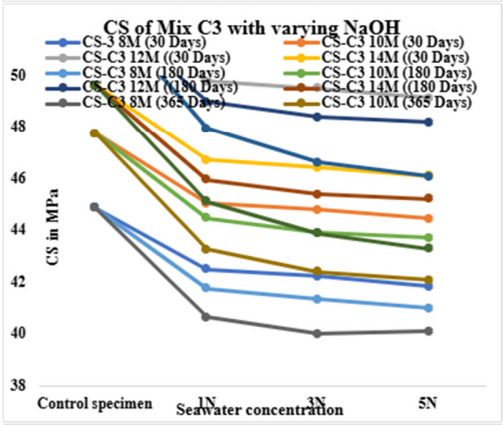
Fig. 7. FS of various mixes used to evaluate for (a) 3 days, (b) 7days, and (c) 28 days under varying NaOH concentration.



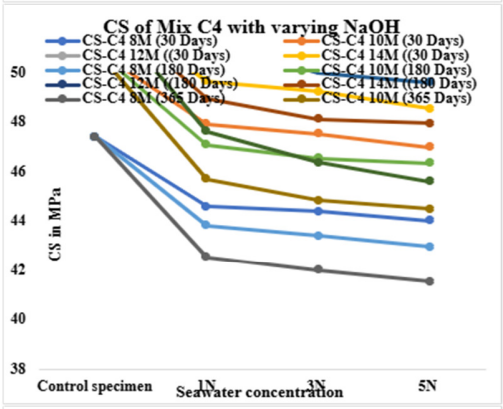
(b)



(c)



(d)



(e)

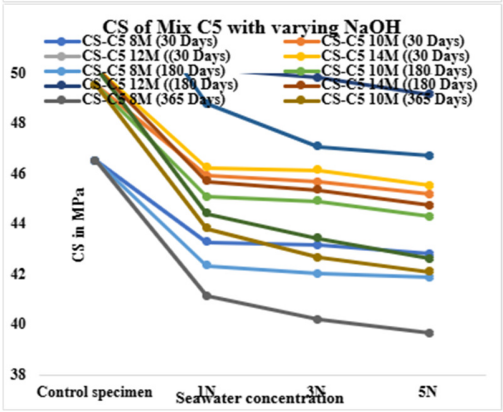


Fig. 8. CS of specimens exposed to the marine environment: (a) C1, (b) C2, (c) C3, (d) C4, and (e) C5, under varying SWC concentrations.

1) Results of the Split-Tensile Strength Test

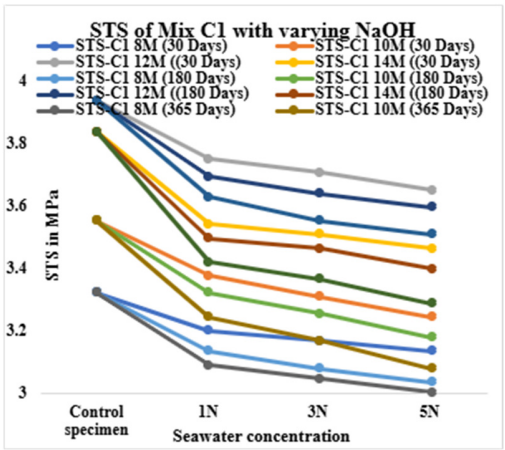
The study investigates the resilience and efficacy of SCGPC samples when exposed to seawater solutions. Over a 30-day period, the STS of SCGPC gradually decreased with a prolonged immersion in saltwater, dropping significantly for mix C1 to 3.43 N/mm^2. Simultaneously, the WG of SCGPC specimens submerged in saltwater consistently increased, with percentages of 1.55%, 1.65%, and 1.76%, with the highest one observed in the SCGPC mix C5, containing 8M NaOH and being submerged in SWC with a concentration of 5N. After 180 days, the STS of SCGPC mix C3 at an 8M NaOH concentration decreased by 6.95%, 8.75%, and 10.3% compared to the initial STS of 3.7 N/mm^2. The corresponding WG values for the same exposure period were 2.34%, 2.5%, and 2.8%.

Similarly, the 365-day STS of the SCGPC mix C5 at an 8M NaOH concentration declined by 9.82%, 11.9%, and 13.4% compared to the initial STS of 3.75 N/mm^2, with corresponding WG of 3.2%, 3.35%, and 3.45%. Moreover, the 180-day STS of SCGPC mix C4 at a 10M NaOH concentration decreased by 8.65%, 10.85%, and 13.6%, with corresponding WG values of 1.95%, 2%, and 2.2%. Likewise, the 365-day STS of SCGPC mix C2 at a 10M NaOH concentration dropped by 10.4%, 12.5%, and 14.65% compared to the initial STS of 3.73 N/mm^2.

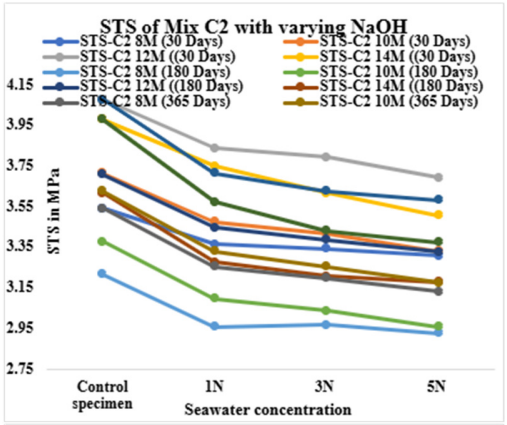
2) Results the Flexural Strength Test

The FS of the SCGPC mixes showed a decline with increasing SWC and longer exposure durations. Mix C1 initially achieved an FS of 4.85 N/mm^2, but after 30 days, it declined by 4.8%, 5.8%, and 6.3%. The WG of 1.42% was recorded during this early stage, reflecting initial surface absorption. The extended exposure for 180 and 365 days led to weight reductions of 7.4% and 18.9%, indicating leaching and microstructural degradation. Prior to leaching taking over, the comparable WG values were 2.4%, 2.6%, and 2.85%.

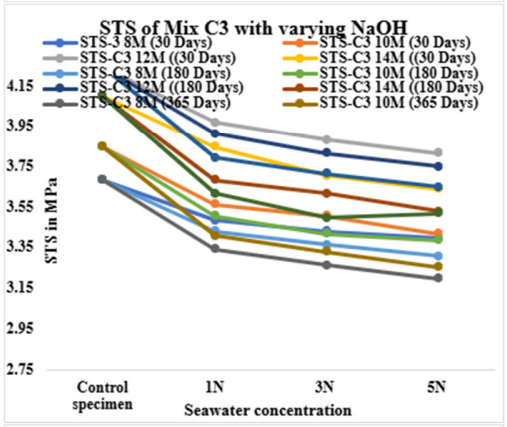
(a)



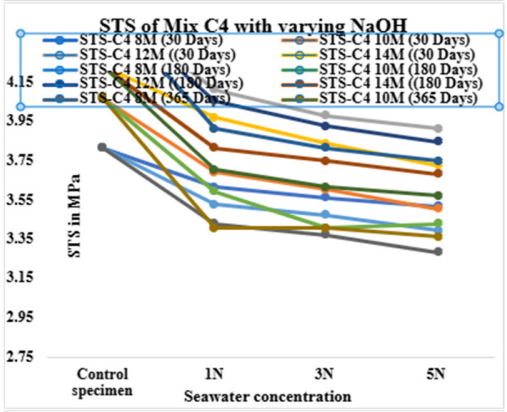
(b)



(c)



(d)



(e)

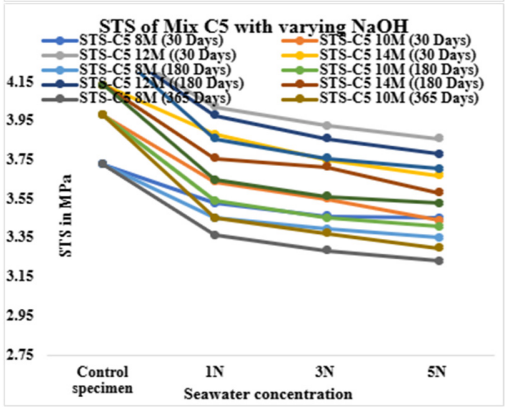
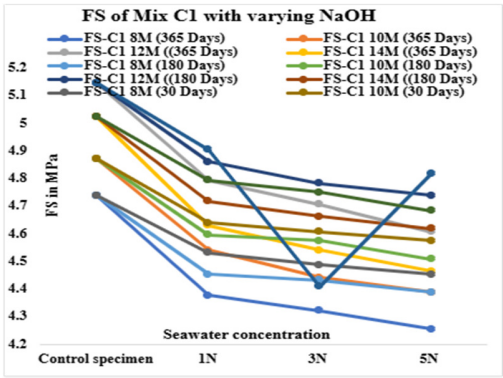


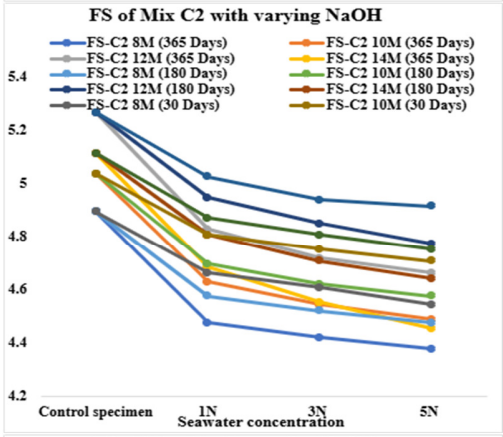
Fig. 9. STS of specimens exposed to the marine environment: (a) C1, (b) C2, (c) C3, (d) C4, and (e) C5, under varying SWC concentrations.

The study shows that increased concentrations of saltwater increase the breakdown rate of FS due to the aggressive ions of sulfate and chloride breaking the bonds and causing microcracking in the geopolymer matrix. Mix C5 (starting FS = 5.2 N/mm^2) showed FS reductions of 9.6%, 10.75%, and 11.5% at the same SWC after 180 days. The durability comparison is determined by using enhanced concentration solutions (3N, 5N) and regular saltwater (1N). The accelerated aging test is a dual technique that assesses both the long-term durability under harsh settings and practical field performance. Normal seawater represents actual marine exposure conditions, while higher concentrations speed up the degradation mechanisms.

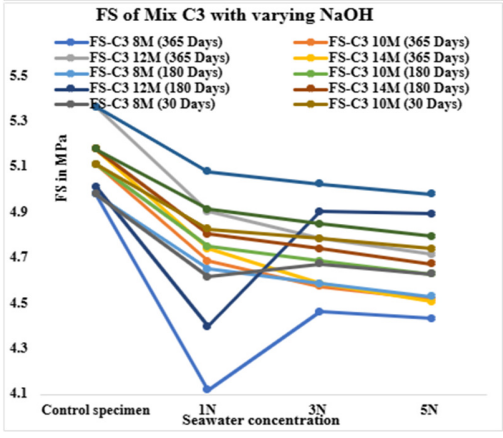
(a)



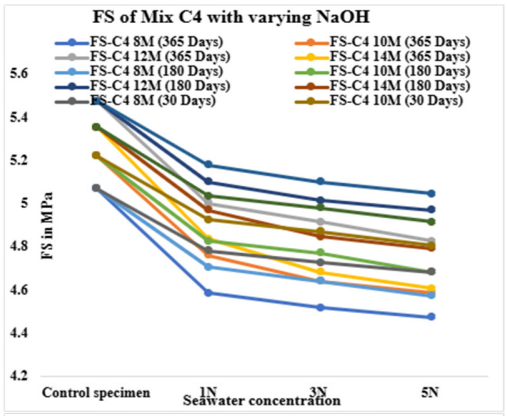
(b)



(c)



(d)



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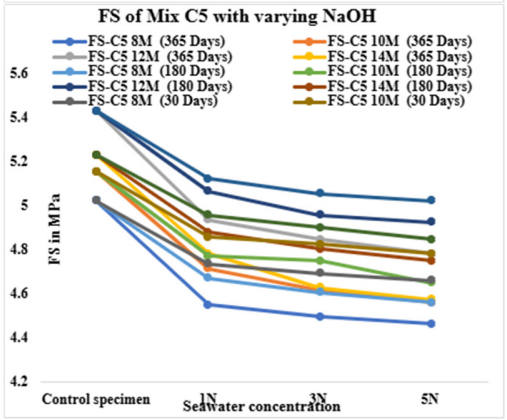
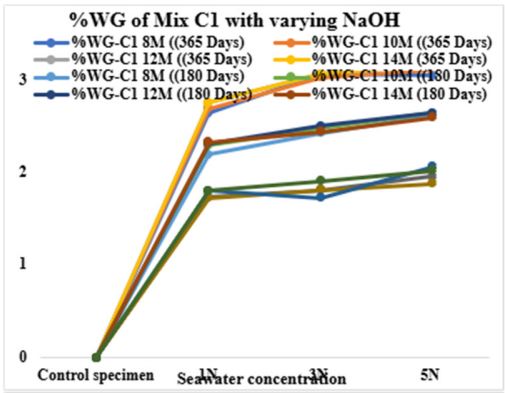


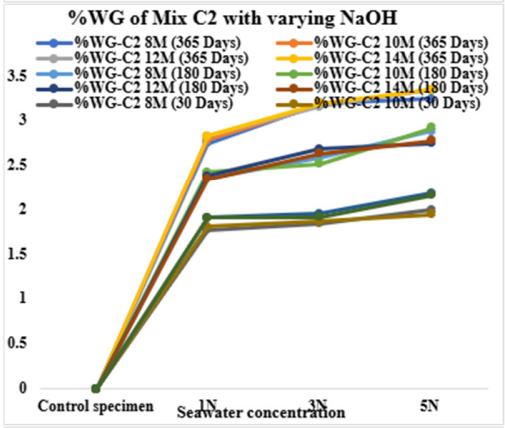
Fig. 10. FS of specimens exposed to the marine environment: (a) C1, (b) C2, (c) C3, (d) C4, and (e) C5, under varying SWC concentrations.

The current study explored the water absorption characteristics of various SCGPC mixes under different conditions. Mix C3, when exposed to an 8M NaOH solution for 180 days, exhibited WG of 2.35%, 2.5%, and 2.8%. Similarly, mix C5, over 365 days, showed WG of 3.25%, 3.33%, and 3.45%. In a separate trial, the 30-day WG of mix C5 in a 10M NaOH solution under specific loading conditions was found to be 1.95%, 2.1%, and 2.21%. Mix C2 experienced a noticeable increase in WG over 365 days, with percentages of 2.53%, 2.9%, and 3.15%, while mix C1, immersed in a 12M NaOH solution, demonstrated WG of 1.67%, 1.71%, and 1.89% over 180 days. Mix C5 also showed varying WG after 180 days in solutions with different concentrations (1N, 3N, and 5N SWC), ranging from 2.64% to 3.15%. Additionally, mix C4 exhibited WG of 3.14%, 3.33%, and 3.45% over 365 days in the same SWC concentrations. Mix C5, subjected to a 10M NaOH concentration, showed WG of 2.7%-3.12% over 180 days, while mix C3 had WG of 2.92%-3.32% over 365 days. Finally, mix C1 recorded WG of 2.31%-2.53% over 180 days in a 12M NaOH solution.

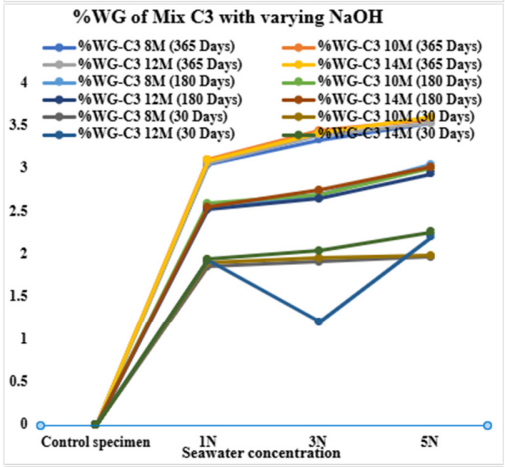
(a)



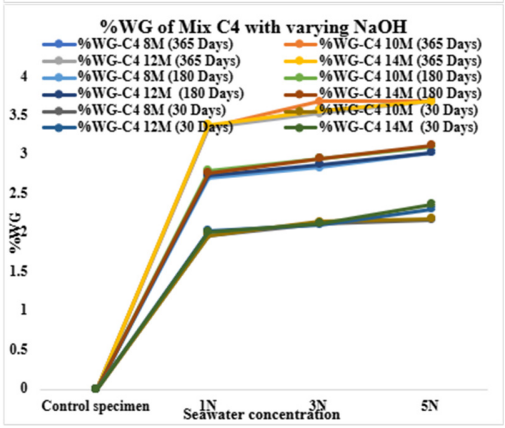
(b)



(c)



(d)



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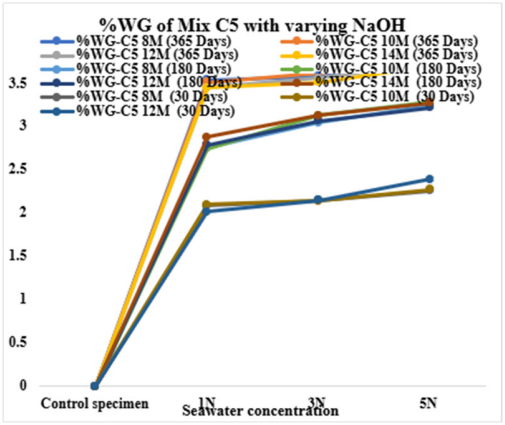
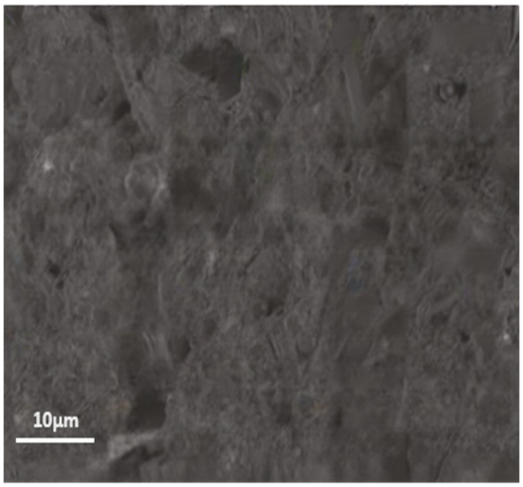


Fig. 11. WG in specimens exposed (a) C1; (b) C2; (c) C3; (d) C4; and (e) C5 under varying SWC.

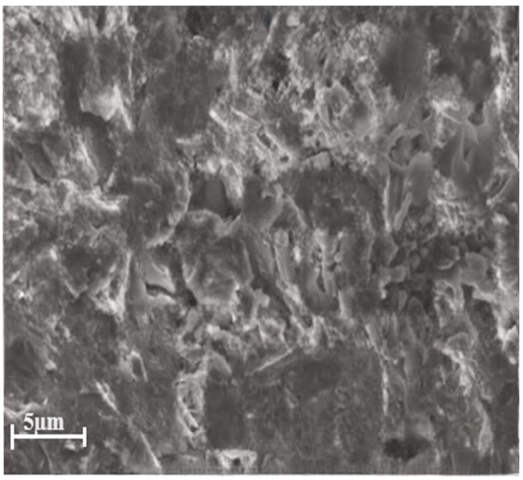
D. Scanning Electron Microscopy Analysis

The research focuses on the microstructure of SCGPC made from FA as the sole source material. All SCGPC mixes underwent analysis by SEM-EDS, which revealed the presence of alumina, silica, calcium, and other components. The use of GGBFS as a partial replacement for FA improves the mix's ability to create a dense structure with an amorphous AS gel. The SEM pictures show cavities, which indicate a porous structure. The presence of calcium in an EDS picture indicates the existence of GGBFS. The inclusion of GGBFS enhanced the intensity of calcium in the matrix, resulting in a gel that is more akin to Ca-AS-H [15]. The inclusion of GGBFS boosted the calcium content, resulting in early age setting and strength growth of the SCGPC specimens in cube, cylinder, and prism specimens at 3, 7, and 28 days of maturity. SEM investigation demonstrated that GGBFS partial substitution increases the density of the mix and the presence of amorphous aluminum-silicate gel. Crystalline particles containing Si and Al may be attributed to the AS gel, along with additional light grey angular particles classified as GGBFS unreacted residues.

(a)



(b)



(c)

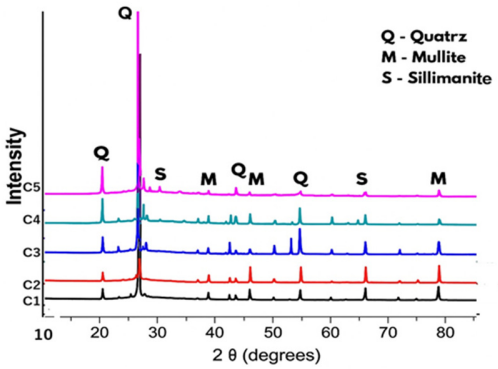


Fig. 12. SEM analysis of SCGPC mix: (a) C3 at 10M; (b) C4 at 12M and at 5N; and (c) XRD results of SCGPC mixes having mixes C1 to C5 at 12M NaOH concentration and at 5N.

The cavities in the SEM pictures imply a porous structure [20, 22]. The calcium in the EDS pictures also indicates the existence of GGBFS. GGBFS contains calcium, which works as a reaction germ, speeding up the process and allowing for an early strength increase. Thus, the inclusion of GGBFS enhanced the calcium content, resulting in early age setting and higher strength of SCGPC.

V. CONCLUSIONS

The performance of Self-Compacted Geopolymer Concrete (SCGPC) under varied mix parameters and exposure situations was investigated in this paper. According to EFNARC requirements, all SCGPC mixes showed sufficient flowability and passing ability. The mixes continued to self-compact, but the workability declined with increasing NaOH concentrations, as evidenced by shorter T50 cm flow durations and lower J-Ring values.

SCGPC has been shown to perform better flexurally and to have a higher curing strength than regular concrete. The early strength gain and faster setting were facilitated by the microstructure's refinement due to the partial replacement of Fly Ash (FA) with Ground Granulated Blast Furnace Slag (GGBFS). More calcium was present in the denser matrix, which encouraged the production of Ca-Al-Si-H type gel. Up to 12M, SCGPC consistently improved its flexural

performance and curing strength with the NaOH concentration; however, at 14M, there was a minor reduction. The 30% GGBFS replacement and 12M NaOH produced the best CS, surpassing the matching conventional mix design after 28 days.

Under the three-point bending test, SCGPC demonstrated enhanced Flexural Strength (FS), greater resilience against cracking, and superior load redistribution. Up to 30% more FS was achieved with the inclusion of GGBFS. Even though the Compressive Strength (CS), Split-Tensile Strength (STS), and FS gradually decreased over time (30 days, 180 days, and 365 days), SCGPC showed resilience against the saltwater exposure, with corresponding increases in the water gain. Nevertheless, it demonstrated a slower rate of strength loss, suggesting that it was more resistant to the sulfate and chloride attack. With sufficient workability, self-compaction, and regulated setting durations, SCGPC outperformed ordinary concrete in terms of the flexural performance and curing strength. Its resilience in the marine environment bolsters its promise as a strong and sustainable substitute material in concrete.

REFERENCES

[1] C. Heidrich, H.-J. Feuerborn, and A. Weir, "Coal Combustion Products: A Global Perspective," presented at the 2013 World of Coal Ash (WOCA) Conference, Lexington, KY, Apr. 2013.

[2] A. M. Rashad, "A Comprehensive Overview About the Influence of Different Admixtures and Additives on the Properties of Alkali-activated Fly Ash," *Materials & Design*, vol. 53, pp. 1005–1025, Jan. 2014, https://doi.org/10.1016/j.matdes.2013.07.074.

[3] I. Ismail, S. A. Bernal, J. L. Provis, R. San Nicolas, S. Hamdan, and J. S. J. Van Deventer, "Modification of Phase Evolution in Alkali-activated Blast Furnace Slag by the Incorporation of Fly Ash," *Cement and Concrete Composites*, vol. 45, pp. 125–135, Jan. 2014, https://doi.org/10.1016/j.cemconcomp.2013.09.006.

[4] S. J. Chithambaram, S. Kumar, and M. M. Prasad, "Thermo-mechanical Characteristics of Geopolymer Mortar," *Construction and Building Materials*, vol. 213, pp. 100–108, July 2019, https://doi.org/10.1016/j.conbuildmat.2019.04.051.

[5] M. E. Gülşan, R. Alzeebaree, A. A. Rasheed, A. Niş, and A. E. Kurtoğlu, "Development of Fly Ash/slag Based Self-compacting Geopolymer Concrete Using Nano-silica and Steel Fiber," *Construction and Building Materials*, vol. 211, pp. 271–283, June 2019, https://doi.org/10.1016/j.conbuildmat.2019.03.228.

[6] B. R. Arun, P. S. Nagaraja, and J. M. Srishaila, "An Effect of NaOH Molarity on Fly Ash—Metakaolin-Based Self-Compacting Geopolymer Concrete," in *Sustainable Construction and Building Materials*, vol. 25, B. B. Das and N. Neithalath, Eds. Singapore: Springer Singapore, 2019, pp. 233–244.

[7] M. Ganeshan and S. Venkataraman, "Durability and Microstructural Studies on Fly Ash Blended Self-compacting Geopolymer Concrete," *European Journal of Environmental and Civil Engineering*, vol. 25, no. 11, pp. 2074–2088, Sept. 2021, https://doi.org/10.1080/19648189.2019.1615991.

[8] H. L. Muttashar, M. A. M. Ariffin, M. N. Hussein, M. W. Hussin, and S. B. Ishaq, "Self-compacting Geopolymer Concrete with Spend Garnet as Sand Replacement," *Journal of Building Engineering*, vol. 15, pp. 85–94, Jan. 2018, https://doi.org/10.1016/j.jobe.2017.10.007.

[9] B. Narendra Kumar, A. Bhargavi, and G. Vinod Kumar, "An Experimental Study on Self Compacting Geo-polymer Concrete Containing Metakaolin at Ambient Curing Condition," *Materials Today: Proceedings*, vol. 62, pp. 1873–1878, 2022, https://doi.org/10.1016/j.matpr.2022.01.012.

[10] S. Al-Rawi and N. Taysi, "Performance of Self-compacting Geopolymer Concrete with and Without GGBFS and Steel Fiber," *Advances in concrete construction*, vol. 6, no. 4, pp. 323–344, Aug. 2018, https://doi.org/10.12989/ACC.2018.6.4.323.

[11] R. Alzeebaree, A. Çevik, B. Nematollahi, J. Sanjayan, A. Mohammedameen, and M. E. Gülşan, "Mechanical Properties and Durability of Unconfined and Confined Geopolymer Concrete with Fiber Reinforced Polymers Exposed to Sulfuric Acid," *Construction and Building Materials*, vol. 215, pp. 1015–1032, Aug. 2019, https://doi.org/10.1016/j.conbuildmat.2019.04.165.

[12] S. Saha and C. Rajasekaran, "Enhancement of the Properties of Fly Ash Based Geopolymer Paste by Incorporating Ground Granulated Blast Furnace Slag," *Construction and Building Materials*, vol. 146, pp. 615–620, Aug. 2017, https://doi.org/10.1016/j.conbuildmat.2017.04.139.

[13] G. Saini and U. Vattipalli, "Assessing Properties of Alkali Activated GGBS Based Self-compacting Geopolymer Concrete Using Nano-silica," *Case Studies in Construction Materials*, vol. 12, June 2020, Art. no. e00352, https://doi.org/10.1016/j.cscm.2020.e00352.

[14] M. Chi and R. Huang, "Binding Mechanism and Properties of Alkali-activated Fly Ash/slag Mortars," *Construction and Building Materials*, vol. 40, pp. 291–298, Mar. 2013, https://doi.org/10.1016/j.conbuildmat.2012.11.003.

[15] P. Astuti, R. Afriansya, E. A. Anisa, and J. Randisyah, "Mechanical Properties of Self-compacting Geopolymer Concrete Utilizing Fly Ash," presented at the 1st International Conference on Technology, Informatics, and Engineering, Malang, Indonesia, 2022, Art. no. 020028, https://doi.org/10.1063/5.0094463.

[16] Y. J. Patel and N. Shah, "Development of Self-compacting Geopolymer Concrete as a Sustainable Construction Material," *Sustainable Environment Research*, vol. 28, no. 6, pp. 412–421, Nov. 2018, https://doi.org/10.1016/j.serj.2018.08.004.

[17] R. Manjunath and R. V. Ranganath, "Performance Evaluation of Fly-ash Based Self-compacting Geopolymer Concrete Mixes," *IOP Conference Series: Materials Science and Engineering*, vol. 561, no. 1, Oct. 2019, Art. no. 012006, https://doi.org/10.1088/1757-899X/561/1/012006.

[18] N. Bheel, P. Awoyera, T. Tafsirojjaman, N. Hamah Sor, and S. Sohu, "Synergic Effect of Metakaolin and Groundnut Shell Ash on the Behavior of Fly Ash-based Self-compacting Geopolymer Concrete," *Construction and Building Materials*, vol. 311, Dec. 2021, Art. no. 125327, https://doi.org/10.1016/j.conbuildmat.2021.125327.

[19] N. A. Eren, R. Alzeebaree, A. Çevik, A. Niş, A. Mohammedameen, and M. E. Gülşan, "Fresh and Hardened State Performance of Self-compacting Slag Based Alkali Activated Concrete Using Nanosilica and Steel Fiber," *Journal of Composite Materials*, vol. 55, no. 28, pp. 4125–4139, Dec. 2021, https://doi.org/10.1177/00219983211032390.

[20] I. Faridmehr, M. L. Nehdi, G. F. Huseien, M. H. Baghban, A. R. M. Sam, and H. A. Algaifi, "Experimental and Informational Modeling Study of Sustainable Self-compacting Geopolymer Concrete," *Sustainability*, vol. 13, no. 13, July 2021, Art. no. 7444, https://doi.org/10.3390/su13137444.

[21] S. İpek, O. A. Ayodele, and K. Mermerdaş, "Influence of Artificial Aggregate on Mechanical Properties, Fracture Parameters and Bond Strength of Concretes," *Construction and Building Materials*, vol. 238, Mar. 2020, Art. no. 117756, https://doi.org/10.1016/j.conbuildmat.2019.117756.

[22] S. Sasui, G. Kim, J. Nam, T. Koyama, and S. Chansomsak, "Strength and Microstructure of Class-C Fly Ash and GGBS Blend Geopolymer Activated in NaOH & NaOH + Na2SiO3," *Materials*, vol. 13, no. 1, Dec. 2019, Art. no. 59, https://doi.org/10.3390/ma13010059.

[23] A. F. H. Sherwani, K. H. Younis, R. W. Arndt, and K. Pilakoutas, "Performance of Self-Compacted Geopolymer Concrete Containing Fly Ash and Slag as Binders," *Sustainability*, vol. 14, no. 22, Nov. 2022, Art. no. 15063, https://doi.org/10.3390/su142215063.

[24] Q. Shen, W. Chen, C. Liu, W. Zou, and L. Pan, "The Tensile Strength and Damage Characteristic of Two Types of Concrete and Their Interface," *Materials*, vol. 13, no. 1, Dec. 2019, Art. no. 16, https://doi.org/10.3390/ma13010016.

[25] B. Bhushan Jindal, P. Jangra, and A. Garg, "Effects of Ultra Fine Slag as Mineral Admixture on the Compressive Strength, Water Absorption and Permeability of Rice Husk Ash Based Geopolymer Concrete," *Materials*

Today: Proceedings, vol. 32, pp. 871–877, 2020, https://doi.org/10.1016/j.matpr.2020.04.219.

[26] R. Caron, R. A. Patel, and F. Dehn, "Extension of the FIB MC 2010 for Basic and Drying Shrinkage of Alkali-activated Slag Concretes," *Structural Concrete*, vol. 23, no. 6, pp. 3960–3973, Dec. 2022, https://doi.org/10.1002/suco.202100901.

[27] D. Sood and K. M. A. Hossain, "Strength, Shrinkage and Early Age Characteristics of One-Part Alkali-Activated Binders with High-Calcium Industrial Wastes, Solid Reagents and Fibers," *Journal of Composites Science*, vol. 5, no. 12, Nov. 2021, Art. no. 315, https://doi.org/10.3390/jcs5120315.

[28] A. Adesina and S. Das, "Drying Shrinkage and Permeability Properties of Fibre Reinforced Alkali-activated Composites," *Construction and Building Materials*, vol. 251, Aug. 2020, Art. no. 119076, https://doi.org/10.1016/j.conbuildmat.2020.119076.