EFFECT OF GGBFS ON FRESH AND HARDENED PROPERTIES OF SELF-COMPACTING GEOPOLYMER CONCRETE CURED AT AMBIENT TEMPERATURE.

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Abstract

The purpose of this research was to examine the fresh and mechanical properties of self-compacting geopolymer concrete (SCGPC) based on ground-granulated blast-furnace slag (GGBFS) cured at room temperatures. SCGPC was manufactured at various molarities of sodium hydroxide solution (8M, 10M, 12M, and 14M) and by replacing the GGBFS with fly ash at a fixed superplasticizer dose of 5%. For all SCGPC mixes, the total binder content was maintained at 440 kg/m^3, the water-to-geopolymer solid ratio of 0.23 and Sodium Silicate to Sodium Hydroxide ratio of 2.5, while the alkaline activator solution (AAS) to binder ratio was retained at 0.45 by mass. The fresh properties of SCGPC concrete for different mixes were examined, and hardened properties tests such as compressive strength test, flexural strength test, and split tensile strength test were executed. The findings of the investigations demonstrated that the concentration of sodium hydroxide solution and the GGBFS content had a significant effect on the efficacy of SCGPC. All mix proportions of SCGPC met the EFNARC (2005) workability standards (passing ability, flowability, and segregation resistance), and the GGC3 trial mix has the best compressive, split tensile, and flexural strengths at 28 days (44.28 MPa, 3.08 MPa, and 3.28 MPa, respectively).

Keywords: GGBFS, sodium hydroxide, molarity, sodium silicate, ambient curing, fly ash.

Highlights

- At ambient conditions, self-compacting geopolymer concrete based on GGBFS has been manufactured.
- The early strength of self-compacting geopolymer concrete has been improved due to GGBFS.
- Partial substitution of GGBFS with fly ash enhanced the fresh characteristics of SCGPC but diminished the hardened properties.
- The workability deteriorated as the molarity of the sodium hydroxide solution increased from 8M to 14 M.

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INTRODUCTION

The construction sector is rapidly increasing in parallel with urbanization. To satisfy the demands of urbanisation, infrastructure is being established, and so the need for concrete is expanding simultaneously. It is estimated that 40% of the infrastructure required for the globe until 2050 already exists, while the other 60% needs to be built [1]. Conventional concrete is mostly based on Portland cement, which is not environmentally friendly owing to environmental problems. For manufacturing of Portland cement, 1400°C to 1500°C temperature is required during the calcination of lime which consumes a huge amount of energy. Cement production not only releases substantial amounts of carbon dioxide but also depletes copious quantities of natural resources. About 0.4 tonnes of carbon dioxide liberates from the combustion of carbon-based fuels and 0.55 tonnes of chemical carbon dioxide is released from Portland clinkers during the production of 1 tonne of Portland cement [2]. It becomes vital to develop an alternative in order to make environmentally friendly concrete. Geopolymer concrete (GPC) is regarded as a novel and revolutionary innovation. GPC has sparked widespread interest due to environmental benefits such as reduced carbon dioxide emissions and natural resource use [3]. The carbon dioxide emissions from GPC binders are 5-6 times lower than those from Portland cement [4]. Geopolymer concrete does not need a lot of energy and is prepared from the polymerization of agricultural and industrial waste materials like rice hush ash, GGBFS, metakaolin, fly ash, silica fumes etc. containing high alumina and silica content [5]. At ambient temperatures, polycondensation transforms these aluminosilicate materials into a solid core mass through covalent bonding. These aluminosilicate materials are activated with the help of an alkaline solution (AS) which is formed from alkali hydroxides and alkali silicates [6]. Till date, the working mechanism of alkaline activator solution is unknown, and both the chemical composition of geopolymer binder and AAS play a key role in the development of geopolymer items. Several academics have proposed numerous techniques for the geopolymer formation procedure. According to Davidovits (1991), there are three distinct forms of three-dimensional crystalline alumina-silicate geopolymer structures. These three structures i.e., poly sialate [-Si-O-Al- O-], poly sialate siloxo [-Si- O-Al-O-Si-O-], and poly sialate disiloxo [-Si-O-Al-O-Si-O-Si-O-O-] are based on the silica to alumina ratio [7]. In alkaline circumstances, aluminosilicate oxides and AAS undergo a geo-polymeric reaction, ending in a polymeric Si–O–Al bond. Owing to this polymeric reaction, a stone-like material known as geopolymer concrete is produced [8]. As discussed above, GPC also entails the utilization of industrial and agricultural wastes, which are mostly utilized as landfill material and cause soil deterioration. The development of GPC will encourage the building industry to embrace sustainability and cleaner production by lowering the construction industry's dependency on Portland cement and enabling industrial wastes to be disposed of more efficiently and without negatively impacting the environment [9]. Compared to traditional concrete, GPC has superior thermal and mechanical qualities, and its pace of strength gain is exceptional. Due to the rapid pace of geopolymerisation, GGBFS-based GPC cures faster than ordinary concrete and achieves the majority of its strength within 24 hours [10].

SCGPC is novel concrete which offer the combined benefits of self-compacting concrete (SCC) and geopolymer concrete. Very little study has been conducted on SCGPC cured at room temperature to yet. SCGPC accomplishes advantages like the improvement of concrete quality, the saving of construction time, the easy pouring of concrete mix through mobbed reinforcing bars, homogenous compaction, and good bond strength, as well as the elimination of noise pollution due to the absence of vibrating equipment [11]. It reduces total expenses and creates a safe working environment for masons. SCGPC is prepared with the same constituents as GPC, but in different quantities, and requires supplemental mineral and chemical admixture [12]. SCGPC often requires a greater volume of ultra-fine powder and has good flowability due to viscosity modifying agent and superplasticizer. Cementitious and mineral ingredients are utilised to increase workability and mechanical characteristics while also lowering building costs [13]. The use of SCGPC manufactured without high temperature curing has the potential to grow beyond precast concrete. This also reduces the cost and energy consumption involved with high temperature curing [14]. Thus, the purpose of this research is to construct SCGPC cured at room temperature.

MATERIALS USED FOR PREPARING SCGPC

1. FLY ASH AND GGBFS

Fly ash is a fine powdery material made of spherical particles with pozzolanic properties, predominantly consisting of reactive aluminium oxide (Al_2O_3) and silicon dioxide (SiO_2). The rest is calcium oxide (CaO) and other oxides [15]. In this work, F-class fly ash procured from the Rajpura thermal plant was used. The GGBFS utilized in this study was obtained from a Chennai-based commercial provider. Table 1 outlines the physical characteristics of GGBFS and fly ash, while table 2 details their chemical makeup. As illustrated in Fig. 1, the SEM micrograph of fly ash particles reveals that they are smooth and round hollow spheres termed cenospheres. GGBFS particles are elongated, lengthy, and flaky in form as depicted in Fig. 2.[16].

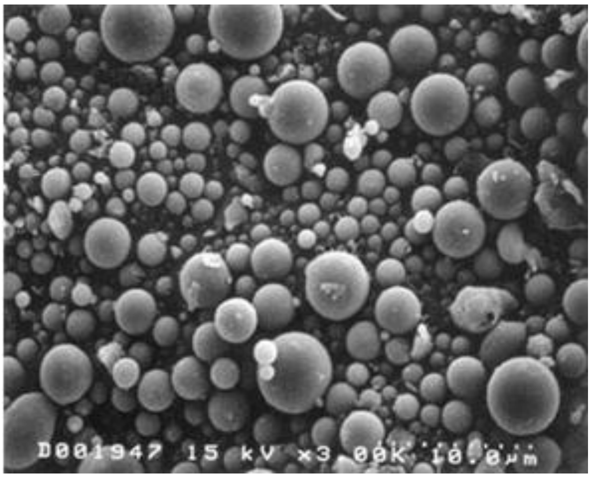

Figure 1: Fly ash SEM image

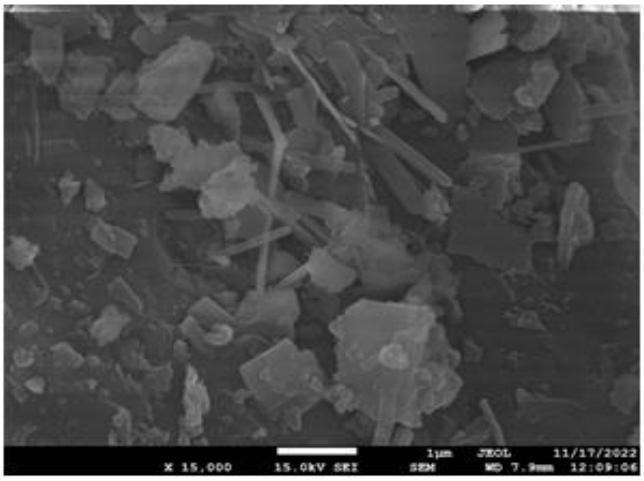

Figure 2:GGBFS SEM image

Table 1: Physical characteristics of GGBFS and fly ash.

Sample	Specific gravity	Fineness m^2/kg	Particle size micron	Bulk density kg/m^3	Colour
GGBFS	2.9	386	Avg. 45	1180	Off-white
Fly ash	2.21	280-300	1-150	540-860	Dark grey

Table 2: Chemical composition of GGBFS and fly ash.

Sample	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	MnO	Na_2O	K_2O	LOI*
GGBFS	34.81	17.92	37.63	0.66	7.80	0.51	0.21	-	-	0.05
Fly Ash	51.76	34.52	1.4	6.22	1.35	0.04	-	0.28	1.32	0.68

LOI: Loss of ignition

2. AGGREGATES

Crushed stones with a nominal size of 12.5 mm and locally available river sand of zone II in accordance with IS: 383-2016 were utilized [17]. In a saturated surface dry situation, coarse aggregates were employed (SSD). Table 3 lists the physical characteristics of both fine and coarse aggregates. In order to prevent the blocking effect in SCGPC, the big size coarse aggregates were constrained. According to EFNARC (2005) recommendations, the quantity of coarse aggregates in SCGPC mixes was maintained lower than in traditional concrete [18].

Table 3: Physical characteristics of fine and coarse aggregates.

Aggregate	Specific gravity	Fineness modulus	Absorption %	Bulk density Kg/m^3	zone	Grade mm
Fine aggregate	2.60	2.69	0.80	1668	II	-
Coarse aggregate	2.65	6.14	0.61	1568	-	12.5

3. SODIUM HYDROXIDE

Commercial-grade sodium hydroxide pellets with a Specific Gravity of 2.13 and a purity of 97% were used in this experiment. In water, sodium hydroxide pellets were dissolved at concentrations of 8 M, 10 M, 12 M, and 14 M. It was prepared 24 hours in advance of use [19].

4. SODIUM SILICATE

The ratio of sodium silicate to sodium hydroxide was maintained at 2.5:1. In the current work, a liquid gel sodium silicate containing 55.52 % water, 29.46 % SiO_2, and 14.73 % Na_2O was used. The molecular weight and specific gravity of sodium silicate are 184.04 and 1.39, respectively.

5. SUPERPLASTICIZER

In this research, Brocrete SCC superplasticizer was used, and its relative density is 1.08. It is a modified polycarboxilic ether-based super-plasticizer created to enhance the workability, performance, and durability of self-compacting concrete. It is compatible with all types of cement since it lacks alkali and chlorides.

MIX PROPORTIONS

The mix design in case of SCGPC is inverse to that of conventional concrete. As there is no proper mix design procedure for SCGPC. In this research, mix design was prepared with the help of Taguchi Approach [20] and EFNARC (2005) guidelines of SCC [18]. The mass ratio of water to geopolymer solids (W/G's) was kept at 0.23 and the total binder content was controlled at 440 kg/m^3. To achieve the desired workability of SCGPC, an additional 20 % water content and a superplasticizer dose of 5 % by mass of binder were used [21]. The ratio of alkali activator solution to binder (AAS/B) was maintained at 0.45 for all SCGPC mixes. Based on the preceding conversations, three groups of eight distinct proportions have been created. In the first group, GGBFS was used as the only binder, while the concentration of sodium hydroxide was varied by a factor of 2 from 8M to 14M. In the second group, GGBFS was replaced with fly ash by 25, 50, and 75% by mass, but the sodium hydroxide molarity remained constant (12M). In the third group, GGBFS was replaced entirely with fly ash and the sodium hydroxide molarity was maintained at 12M. The SCGPC mix proportions and ingredient descriptions are shown in Table 4.

Table 4: Mix design of SCGPC mixes.

Mix	Molarity (M)	GGBS (Kg/m^3)	Fly Ash (Kg/m^3)	Fine Aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	Sodium Hydroxide (Kg/m^3)	Sodium Silicate (Kg/m^3)	Super plasticizer (%)	Extra water (%)
GGC1	8	440	-	920	840	56.57	141.43	5	20
GGC2	10	440	-	920	840	56.57	141.43	5	20
GGC3	12	440	-	920	840	56.57	141.43	5	20
GGC4	14	440	-	920	840	56.57	141.43	5	20
GGC5	12	330	110	920	840	56.57	141.43	5	20
GGC6	12	220	220	920	840	56.57	141.43	5	20
GGC7	12	110	330	920	840	56.57	141.43	5	20
GGC8	12	-	440	920	840	56.57	141.43	5	20

PREPARATION, CASTING AND CURING OF SPECIMEN

The mixing procedure consisted of two distinct phases. At the beginning, the fine aggregate, coarse aggregate in saturated surface dry condition (SSD), and binder (GGBFS and fly ash) were combined for 2.5 minutes in a concrete mixer. After the conclusion of dry mixing, a well-shaken and pre-mixed liquid combination including alkaline solution, superplasticizer, and additional water was added to the concrete mixture, and 3 minutes of wet mixing were performed [22]. To ensure the consistency of the mixture, fresh SCGPC was blended for a further two to three minutes. After completing the workability tests, raw SCGPC was once again mixed and cast into cube, cylinder, and prism moulds without any compaction to fill the voids of the moulds by self-weight. For compressive strength testing, nine 150 mm x 150 mm x 150 mm cubes were cast for each fraction of the mix. To conduct a split tensile strength test, 9 cylinders with a 150 mm diameter and 300 mm height were cast for each mix proportion. And for flexural strength testing, nine 150 mm x 150 mm x 700 mm prisms were cast for each proportion of the combination [23]. After 24 hours of curing at room temperature, specimens were demoulded and stored at room temperature until the testing date.

RESULTS AND DISCUSSION

FRESH PROPERTIES

As stated in Table 5, the workability parameters of all SCGPC mixtures were evaluated in accordance with EFNARC (2005) Guidelines [18]. When the concentration of sodium hydroxide based alkaline solution increased from 8 M to 14 M, the passing and filling abilities dropped due to the faster setting and hardening caused by the enhanced polymeric reaction rate. In contrast, when the fly ash content was raised while maintaining the same molarity of 12M, filling and passage abilities improved.

Mix	**Slump flow (mm)** (650-800)	**T_{50cm} Slump flow (sec)** (2-5)	**V-funnel flow time (sec)** (6-12)	**V-funnel T_{5min} time (sec)** (± 3)	**L-box ratio (H_2/H_1)** (0.8-1)	**J-Ring test (mm)** (0-10)
GGC1	710	3.4	8	11	0.95	3
GGC2	702	3.9	9.5	12	0.92	5
GGC3	693	4.2	12	14	0.90	5
GGC4	679	4.9	13	16.5	0.86	7
GGC5	698	4	11.5	13.5	0.91	6
GGC6	700	3.8	11.5	13	0.92	6
GGC7	703	3.6	11	12.5	0.92	5
GGC8	705	3.5	10	12	0.93	4

1. SLUMP FLOW AND T_{50CM} SLUMP FLOW TEST RESULTS

Figure 3 illustrates the results of slump flow for several SCGPC mixes. A slump flow value of 710 mm was recorded for the control mixture GGC1. The mix proportion GGC4 at 14M molarity exhibited the lowest slump, 679 mm. When the concentration of Sodium Hydroxide rises from 8M to 14M, the viscosity of the SCGPC mixture increases, which reduces its flowability and, therefore, the slump flow value [19]. Figure 4 also displays the results of the T_{50cm} slump flow test for several SCGPC mix proportions. During the slump flow test, the time required for the concrete mix to blowout to a diameter of 500mm was recorded. The range for the T_{50cm} slump flow test is two to five seconds. The lowest T_{50cm} slump flow time observed for the GGC1 mix was 3.4 seconds. At 14M sodium hydroxide concentration, a maximum slump flow duration of 4.9 seconds was measured for GGC4 mix.

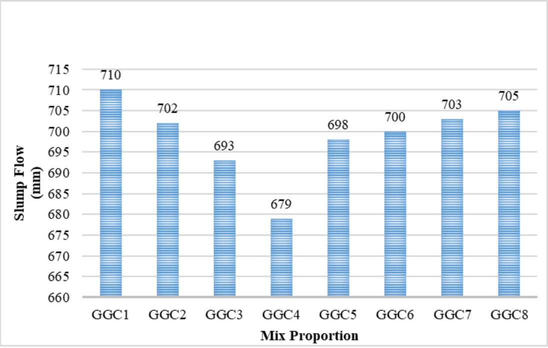

Figure 3: Slump Flow Graph

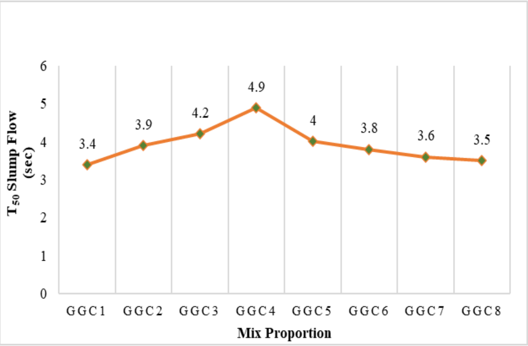

Figure 4: T_{50cm} Slump Flow Graph

2. V-FUNNEL FLOW AND V-FUNNEL T5MIN TEST RESULTS

SCGPC mixes' flow ability and stability were evaluated using V-funnel flow and V-funnel T_{5min} tests. Figures 5 and 6 represent the results of the V-funnel flow test and the flow time for V-funnel T_{5min}. The V-funnel test is used to evaluate the filling ability of concrete mixes, whilst the V-funnel T_{5min} test is used to evaluate the mix's resistance to segregation. Minimum V-funnel flow time of 8 seconds was observed for the GGC1 mix of 8M sodium hydroxide concentration. However, a maximum V-funnel flow duration of 13 seconds was measured for the mix GGC4 of 14M Sodium Hydroxide concentration. With a rise in sodium hydroxide content, the flowability and fluidity of SCGPC concrete decreased, resulting in an increase in flow time. Yet, the flowability improves as the proportion of fly ash increases [24]. Additionally, a minimum flow duration of 11 seconds was reported during the V-funnel T_{5min} test for GGC1 with 8M sodium hydroxide. Although a maximum flow time of 16.5 seconds was observed for GGC4 with a concentration of 14M sodium hydroxide.

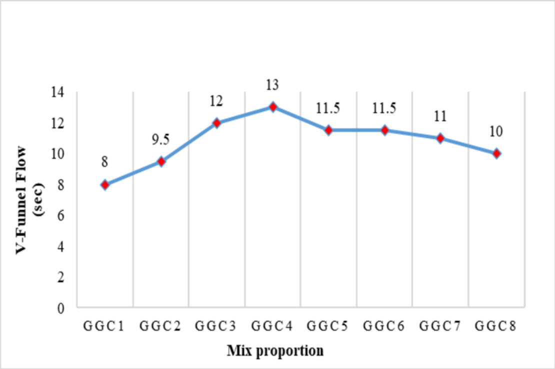

Figure 5: V-Funnel Flow Graph

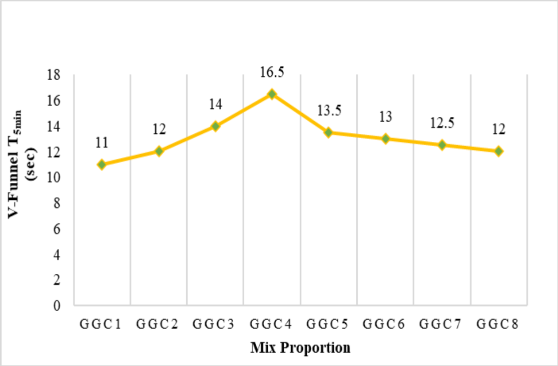

Figure 6: V-Funnel T5min Graph

3. L-BOX AND J-RING TEST RESULTS

Figures 7 and 8 represent the results of the L-box test and J-ring, respectively. In accordance with EFNARC (2005) rules, a fresh concrete is considered acceptable in terms of its capacity to fill and pass if the L-box ratio falls between 0.8 and 1.0. L-box ratio diminishes when the concentration of sodium hydroxide increases from 8M to 14M. Nevertheless, it rises as the proportion of fly ash increases. Mix GGC1 of 8M sodium hydroxide concentration had the greatest L-box ratio of 0.95, while mix GGC4 of 14M NaOH concentration had the lowest L-box ratio of 0.86. Furthermore, according to EFNARC (2005) criteria, the recommended range for J-Ring testing is 0 to 10 mm. The J-Ring values of all SCGPC mixtures fell within the EFNARC (2005) guidelines [18].

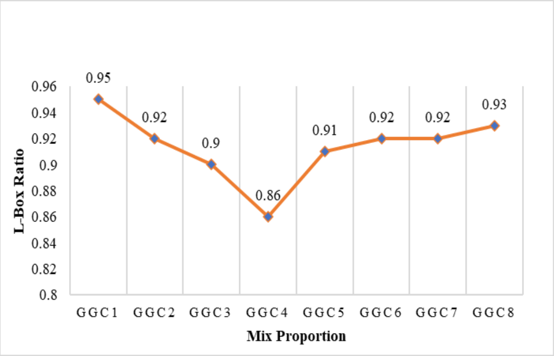

Figure 7: L-Box Ratio Graph

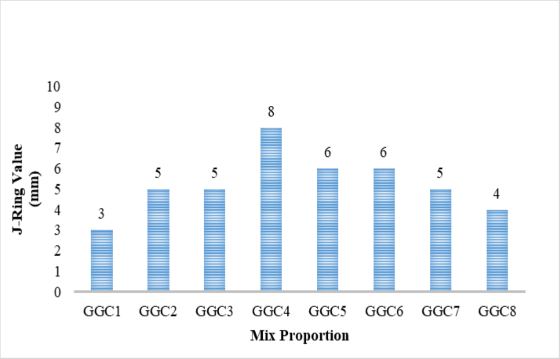

Figure 8: J-Ring Graph

HARDENED PROPERTIES

To assess the hardened characteristics of SCGPC, tests such as compressive strength, splitting tensile strength, and flexural strength were carried out. IS 516 (1959) was the testing standard used for SCGPC specimens [23]. The results of SCGPC's hardened characteristics are provided in Table 7. In terms of hardened aspects, the GGC3 mix of 12M sodium hydroxide concentration with GGBFS as the only binder yields the best results compared to other mix proportions.

Table 5: Hardened characteristics of SCGPC mixes

Mix	Compressive strength (MPa)			Split tensile strength (MPa)			Flexural strength (MPa)		
	7Days	21Days	28Days	7Days	21Days	28Days	7Days	21Days	28Days
GGC1	33.12	35.25	37.57	2.30	2.43	2.58	2.73	2.84	2.90
GGC2	36.54	38.43	40.04	2.43	2.72	2.81	2.86	2.94	3.03
GGC3	38.45	41.63	44.28	2.71	2.94	3.09	2.95	3.05	3.28
GGC4	36.83	39.75	42.36	2.54	2.79	2.95	2.91	3.01	3.12
GGC5	34.69	37.42	39.27	2.37	2.62	2.77	2.82	2.89	3.00
GGC6	29.32	32.88	35.95	2.30	2.38	2.45	2.54	2.67	2.80
GGC7	24.25	26.52	28.81	2.06	2.19	2.27	2.28	2.41	2.52
GGC8	17.95	19.39	21.23	1.61	1.76	1.83	1.85	1.92	1.98

1. COMPRESSIVE STRENGTH

Sodium Hydroxide is crucial for stimulating the alumino-silicate base material in order to produce geopolymer concrete. The increase in sodium hydroxide concentration enhances the solubility of alumino-silicate components and the bonding process, hence boosting the compressive strength of SCGPC [25]. The compressive strength of SCGPC specimens improved as Sodium Hydroxide molarity grew from 8M to 12M but decreased as Sodium Hydroxide molarity increased beyond 12M. At 14M, more hydroxide ions accumulate in aluminosilicate gel at an early stage of geopolymerisation, delaying the next reaction phase and resulting in poorer strength [26]. While in case of fly ash as a secondary binder, compressive strength decreases with increase in percentage of fly ash content. Figure 9 illustrates the compressive strength of each SCGPC mix proportions. At 7, 21, and 28 days, the GGC3 mix with 12M molarity of NaOH obtained maximum compressive strengths of 38.45MPa, 41.63MPa, and 44.28MPa, respectively. It was observed that 6.57%, 17.85%, and 12.27% improvement in compressive strength of GGC2, GGC3 and GGC4 mixes with respect to compressive strength of controlled mix GGC1 at 28 days. However, when the amount of fly ash increases, the compressive strength begins to decrease in a consistent manner. It was due to presence of less alumina (Al_2SiO_3) and the incomplete polymeric reaction at room temperature [27].

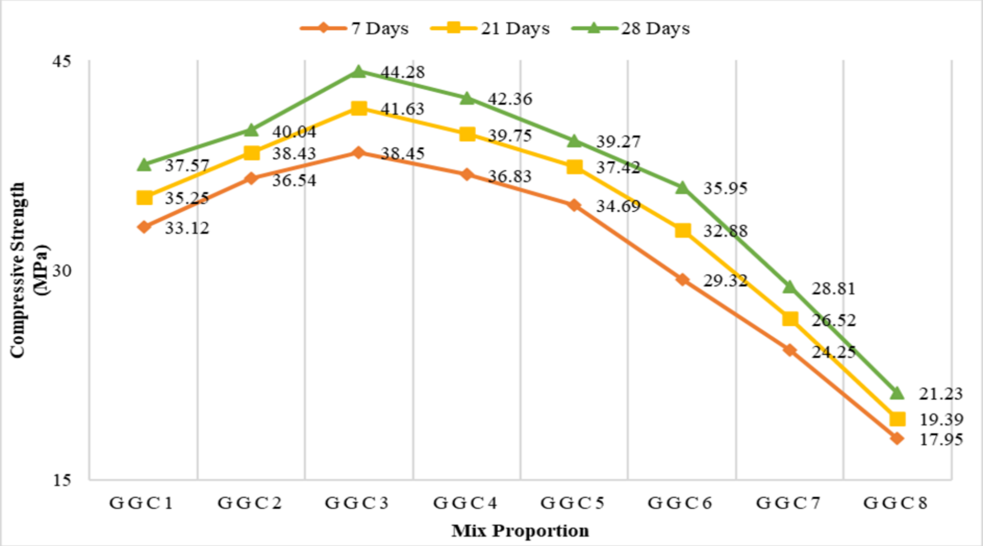

Figure 9: Compressive Strength Graph

2. SPLIT TENSILE STRENGTH

Tensile strength is an essential mechanical parameter utilized in several structural design processes, including shear and anchoring reinforcement [28]. Figure 10 displays the splitting tensile strength results of SCGPC mixes. It improves with the age of concrete. Due to early geopolymer reaction facilitated by heat of hydration of Calcium hydroxide component in GGBFS, gain in split tensile strength is rapid in the first seven days. During 28 days of ambient curing, the SCGPC mix GGC3 with 100% GGBFS achieved the highest split tensile strength of 3.09MPa. The strength of mix GGC3 improved by 14.02 % from 7 to 28 days at ambient curing, but the strength of the controlled mix GGC1 increased by just 12.17 % from 7 to 28 days. As demonstrated in Figure 10, the increase in split tensile strength of SCGPC mixes GGC2, GGC3, and GGC4 at 28 days with respect to the control mix GGC1 is 8.91%, 19.76%, and 14.34%, respectively. At 28 days of ambient curing, 2.77MPa, 2.45MPa, 2.27MPa, and 1.83MPa were measured for the GGC5, GGC6, GGC7, and GGC8 mixes, respectively.

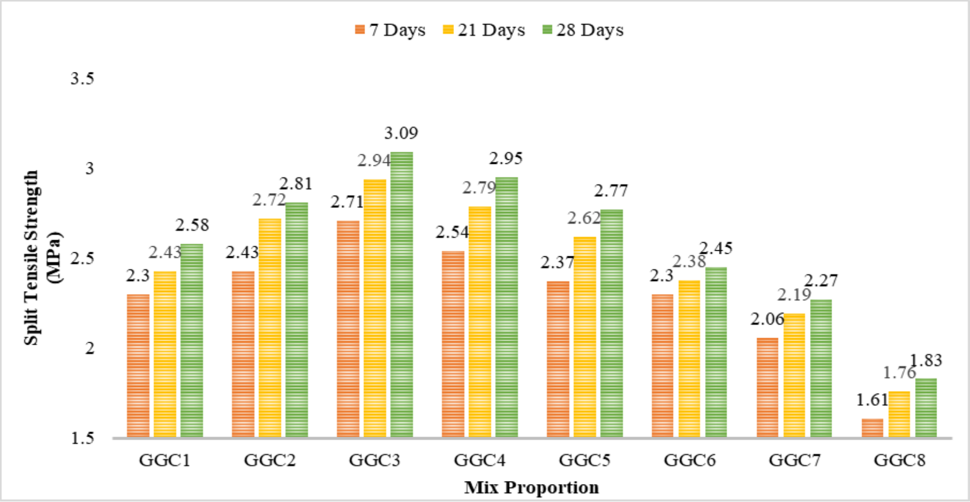

Figure 10: Split Tensile Strength Graph

3. FLEXURAL STRENGTH

Figure 11 depicts the flexural strength of SCGPC mixes with various sodium hydroxide concentration and fly ash content. Similar to compressive strength, increase in the concentration of sodium hydroxide from 8M to 12M enhanced the flexural strength of SCGPC but retards at 14M. It is due to rapid geopolymerisation while in case of high concentration of sodium hydroxide (14M), an excess hydroxide ion slowdown the geopolymerisation. The utilisation of fly ash generally improves the workability of SCGPC mix and retards the flexural strength due to less content of Al_2SiO_3 [29]. The GGC3 mix achieved the maximum flexural strength at 28 days, 3.28 MPa, whereas the GGC8 mix recorded the lowest, 1.98 MPa. At 7, 21, and 28 days, the control mix GGC1's flexural strength of 2.73, 2.84, and 2.90 MPa was noted, respectively. For mix GGC3, a percentage rise of 11.18% was seen from 7 to 28 days of ambient curing, but for control mix GGC1, only 6.22% of flexural strength increased during this time.

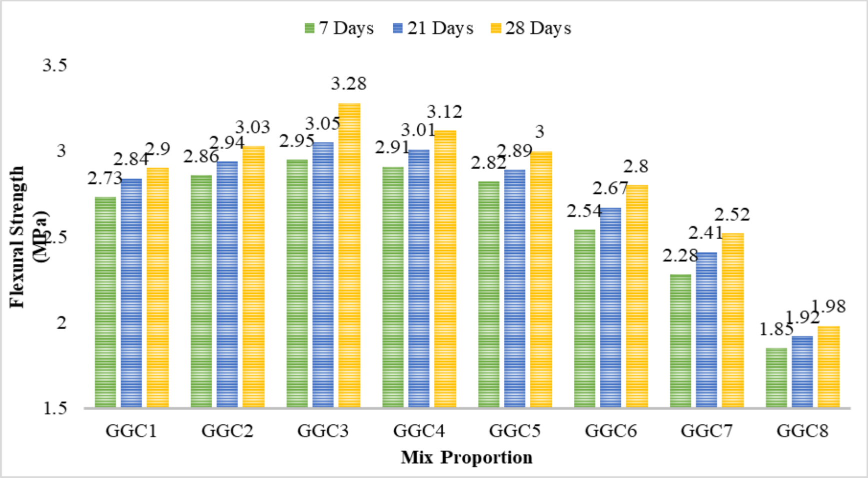

Figure 11: Flexural Strength Graph

CONCLUSION

- Under ambient curing conditions, the SCGPC with a binder content (GGBFS) of 440 kg/ m^3, an AAS/B ratio of 0.45, an SS/SH ratio of 2.5, and a NaOH molarity of 12 M had the maximum compressive strength after 28 days (44.28 MPa).
- During ambient curing, SCGPC produced using 100% fly ash as a binder failed to attain the requisite strength at 7, 21, and 28 days owing to inadequate geo-polymerisation in the absence of heat.
- When the molarity of NaOH solution increased from 8M to 14M, the workability of GGBFS-based SCGPC declined. Moreover, it improves as the amount of fly ash used as a partial substitute for GGBFS increases.
- The hardened characteristics of SCGPC enhances when the molarity of NaOH solution increased up to 12M. In contrast, its rate

decreases when the molarity of sodium hydroxide increases above 12M.

- To increase the setting time of geopolymer concrete under ambient curing conditions, a combination of GGBFS with FA can be a possible solution, as the blend of GGBFS with FA achieved longer setting time.

References

1. L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang, “Carbon emission of global construction sector,” Renew. Sustain. Energy Rev., vol. 81, no. June, pp. 1906–1916, 2018, doi: 10.1016/j.rser.2017.06.001.
2. G. U. Fayomi, S. E. Mini, O. S. I. Fayomi, and A. A. Ayoola, “Perspectives on environmental CO2 emission and energy factor in Cement Industry,” IOP Conf. Ser. Earth Environ. Sci., vol. 331, no. 1, 2019, doi: 10.1088/1755-1315/331/1/012035.
3. R. Dharmaraj, “Experimental study on strength and durability properties of iron scrap with flyash based concrete,” Mater. Today Proc., vol. 37, no. Part 2, pp. 1041–1045, 2020, doi: 10.1016/j.matpr.2020.06.290.
4. J. Davidovits, “Geopolymer cement to minimizecarbon-dioxde greenhouse-warming,” Ceram. Trans. ·, vol. 37, no. 1, pp. 165–182, 1993, [Online]. Available: https://www.researchgate.net/publication/284682578_Geopolymer_cement_to_minimize_carbon-dioxde_greenhouse-warming
5. S. K. Rautaray, D. K. Bera, and A. K. Rath, “Utilization Of Industrial Waste For Production Of Self Compacting Geo-Polymer Concrete,” vol. 9, no. 06, 2020.
6. 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,” Sustain., vol. 14, no. 22, 2022, doi: 10.3390/su142215063.
7. J. Davidovits, “Geopolymers - Inorganic polymeric new materials,” J. Therm. Anal., vol. 37, no. 8, pp. 1633–1656, 1991, doi: 10.1007/BF01912193.
8. A. M. Mustafa Al Bakri, H. Kamarudin, M. Bnhussain, I. Khairul Nizar, A. R. Rafiza, and A. M. Izzat, “Chemical reactions in the geopolymerisation process using fly ash-based geopolymer: A review,” Aust. J. Basic Appl. Sci., vol. 5, no. 7, pp. 1199–1203, 2011.
9. M. N. H. Alhashimi, F. A. Jasim, G. N. Ahmed, and W. A. Najim, “Performance of Self-Compacting Geopolymer Concrete Containing Nano Silica and Ground Waste Ceramic Tiles as a Fine Aggregate,” J. Southwest Jiaotong Univ., vol. 54, no. 5, 2019, doi: 10.35741/issn.0258-2724.54.5.6.
10. S. V. Patil, V. B. Karikatti, and M. Chitawadagi, “Granulated Blast-Furnace Slag (GGBS) based Geopolymer concrete - Review Concrete - Review,” Int. J. Adv. Sci. Eng., vol. 5, no. 1, p. 879, 2018, doi: 10.29294/ijase.5.1.2018.789-885.
11. T. G. Ushaa, R. Anuradha, and G. S. Venkatasubramani, “Performance of self-compacting geopolymer concrete containing different mineral admixtures,” vol. 22, no. August, pp. 473–481, 2015.
12. P. U. Praveen and K. Srinivasan, “Self-compacting geopolymer concrete - A review,” IOP Conf. Ser. Mater. Sci. Eng., vol. 263, no. 3, 2017, doi: 10.1088/1757-899X/263/3/ 032024.
13. C. Jithendra and S. Elavenil, “Role of superplasticizer on GGBS based Geopolymer concrete under ambient curing,” Mater. Today Proc., vol. 18, pp. 148–154, 2019, doi: 10.1016/j.matpr.2019.06.288.
14. B. C. Indian Concrete Institute, “Geopolymer Concrete Applications: Challenges and Opportunities,” Smart Tech. Solut. Ecofriendly Sustain. Constr., pp. 1–67, 2020, [Online]. Available: http://icikbc.org/docs/ICIBC-Seminar20200218-GP-Proceedings.pdf
15. S. K. Rahman and R. Al-Ameri, “A newly developed self-compacting geopolymer concrete under ambient condition,” Constr. Build. Mater., vol. 267, p. 121822, 2021, doi: 10.1016/j.conbuildmat.2020.121822.
16. B. S. Divsholi, T. Y. D. Lim, and S. Teng, “Durability Properties and Microstructure of Ground Granulated Blast Furnace Slag Cement Concrete,” Int. J. Concr. Struct. Mater., vol. 8, no. 2, pp. 157–164, 2014, doi: 10.1007/s40069-013-0063-y.
17. IS:383, “Is:383,” Indian Stand. Coarse Fine Aggreg. Concr. Specif., no. January, pp. 1–21, 2016.
18. E. BIBM, CEMBUREAU, ERMCO, EFCA, “The European Guidelines for Self-Compacting Concrete,” Eur. Guidel. Self Compact. Concr., no. May, p. 63, 2005, [Online]. Available: http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf
19. F. A. Shilar, S. V. Ganachari, V. B. Patil, T. M. Y. Khan, and S. Dawood Abdul Khadar, “Molarity activity effect on mechanical and microstructure properties of geopolymer concrete: A review,” Case Stud. Constr.

Mater., vol. 16, no. January, p. e01014, 2022, doi: 10.1016/j.cscm.2022.e01014.

20. S. Karthik and K. S. R. Mohan, “A taguchi approach for optimizing design mixture of geopolymer concrete incorporating fly ash, ground granulated blast furnace slag and silica fume,” Crystals, vol. 11, no. 11, 2021, doi: 10.3390/cryst11111279.
21. F. A. Memon, M. F. Nuruddin, S. Demie, and N. Shafiq, “Effect of superplasticizer and extra water on workability and compressive strength of self-compacting geopolymer concrete,” Res. J. Appl. Sci. Eng. Technol., vol. 4, no. 5, pp. 407–414, 2012.
22. S. Indexed, T. Nadu, and T. Nadu, “SELF-COMPACTING GEOPOLYMER CONCRETE WITH AN ALKALINE ACTIVATOR,” vol. 09, no. 13, pp. 1877–1882, 2018.
23. IS 516, “Method of Tests for Strength of Concrete,” Bur. Indian Stand., pp. 1–30, 1959.
24. M. U. Hossain, J. C. Liu, D. Xuan, S. T. Ng, H. Ye, and S. J. Abdulla, “Designing sustainable concrete mixes with potentially alternative binder systems: Multicriteria decision making process,” J. Build. Eng., vol. 45, no. November 2021, p. 103587, 2022, doi: 10.1016/j.jobe.2021.103587.
25. A. Bouaissi, L. yuan Li, M. M. Al Bakri Abdullah, and Q. B. Bui, “Mechanical properties and microstructure analysis of FA-GGBS-HMNS based geopolymer concrete,” Constr. Build. Mater., vol. 210, pp. 198–209, 2019, doi: 10.1016/j.conbuildmat.2019.03.202.
26. K. S. Surekha and B. P. Patil, “ECG signal compression using parallel and cascade method for QRS complex,” Indian J. Sci. Technol., vol. 11, no. 1, pp. 1–6, 2018, doi: 10.17485/ijst/2018/v11i1/117698.
27. B. R. Arun, P. S. Nagaraja, and S. J. Mahalingasharma, “Combined Effect of Flyash & GGBS on Workability and Mechanical Properties of Self Compacting Geopolymer concrete,” Int. J. Pure Appl. Math., vol. 119, no. 15, pp. 1369–1380, 2018.
28. A. Balasubramanian and S. Patil, “Experimental Investigation on Strength Properties of Geo- polymer Concrete,” Set Conf., vol. 37, no. 2, pp. 872–876, 2018.
29. A. M. Henigal, M. A. Sherif, and H. H. Hassan, “Study on Properties of Self-Compacting Geopolymer Concrete,” vol. 14, no. 2, pp. 52–66, 2017, doi: 10.9790/1684-1402075266.