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Strength and durability characteristics of steel fiber-reinforced geopolymer concrete with addition of waste materials

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Abstract

In general, all countries in the world use ordinary Portland cement concrete for the construction purpose; this ordinary Portland cement (OPC) gives good mechanical properties and durability to the buildings. The binder cement and the filler aggregate are the ingredients widely used in the process of concrete. Natural resources are used to extract both filler and binder elements. In India, the fast-growing sectors like infrastructure, smart cities development, and real estate consume concrete in large quantity. Also, India is the second largest cement manufacturer in the world. The need of cement is increasing day to day, even though the country is manufacturing the cement more than the required demand. In an average, the cement manufacturing industries produce 6% of CO_2; for example, if industries produce 1 tonne of cement, they also emit 1 tonne of CO_2. This brings us environment changes and produces more pollution to the country. To handle this situation, after many research, geopolymer concrete has been developed. Geopolymer concrete (GC) is all about mixing of source materials to the alkaline solution. Fly ash (FA) that is collected from the power plant is used in GC. The FA-based GC gives more strength when compared to the normal OPC concrete. Under ambient and steam curing, the compression, flexural strength, and tensile strength of FAGC and steel-reinforced geopolymer (SFGC) were tested and results were compared with normal concrete. FAGC mix proportions were studied under different ratios for sodium hydroxide and sodium silicate with 10 M. When compared with normal cement, the strength given by FAGC achieved good strength under ambient temperature. FAGC was further tested for the acid, sulfate, water absorption, and sorptivity test and compared with OPC concrete.

Keywords Concrete · Fly ash · Nano silica · Micro silica · Granite waste · Compressive strength · Flexural strength

Introduction

OPC is very common binding material used in concrete because it has good strength and durability. The usage of cement is growing tremendously every day in construction industries. The manufacturing of cement involves direct extraction of natural materials and during the production of cement huge amount of energy is used to convert the natural materials to cement. Calcium carbonate, lime stone, and clay are the materials that are extracted from the natural resources. During this process, large amount of CO2 is emitted by the industries. Recent research said that during the manufacturing of 1 T of cement, the industries emit 1 T of CO2 (Abishek et al. 2015, Chithra et al. 2016, De Silva et al. 2007). Over this century, humans consume cement next to water. After China, India is the second largest manufacturer of cement. Due to this, environment gets polluted. In India, cement industries alone are responsible for 8% of CO2 emission (Azevedo et al. 2020), Bernal et al. 2010). Concrete is the most important material used in all construction works, but a huge amount of pollution is produces during its production. Due to the increase in population, the construction of structures also increases and vice versa. A large number of studies are carried out to reduce the usage of cement content. Geopolymers are new inventions (Hardjito et al. (2005, Hardjito and Rangan 2005, Hardjito and Wallah 2002), He et al.(2016) that are used as an alternative instead of cement Natarajan et al. (2022), Karthiga and Praveena (2022), Paija et al. (2019) in order to make the construction as green construction; as a result of which, the emission of carbon dioxide

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gets reduced in a very large manner (Mahendran and Arunachelam 2016, Marin-Lopez et al. 2009, Mehta and Siddique 2018). Nearly 35% of the fly ash is used in stuffing of landfills, embankment structures, and cement production. Fly ash is also used to produce this type of concrete Bhutta et al. (2017), Salih et al. (2015), Salihoglu and Salihoglu (2018). The mechanical and durability properties of this concrete are greatly influenced by the heat activation temperature with the dosage of sodium hydroxide solution. Geopolymerisation, a reaction between aluminosilicate oxides and alkali polysilicates, leads to the bonding of geopolymer concrete (Li and Xu 2009, Liu et al. 2009) (Neethu and Usha 2016), and its effects on the early strength and mechanical and durability properties. Many research works have been carried out using waste materials as a replacement material in concrete. Strength and the durability aspects of geopolymer concrete using fly ash when replaced for cement were found to give better results when the dosage and concentration of sodium hydroxide were in the range 0.67–1.0, and 10–20 M respectively (Neethu and Usha 2016). Effective use of admixtures, the appropriate mix design of GC Singh et al.(2015a, 2015b), the effect on axial compressive strength on columns (Islam et al. (2017), compressive strength and flexural strength Sarker (2011), Nath et al (2015),Raman et al. (2011), long- and short-term properties of FA-based GC , and minimal curing temperature that is used for curing Sreenivasulu et al, (2015, 2016, 2018a, 2018b) were studied in detail and it is shown that the alkali binder ratio at 1.0 gave better results.

Materials and methods

OPC Grade 53 has been used for this investigation as per IS: 12,269–1987. The chemical properties of cement are listed as shown in Table 1. FA is a by-product from thermal power plants when coal is heated in electric furnaces. Coal is often crushed and pushed into the boiler's combustion with high pressure air, where it starts to burn instantly and start to produce heat and a mineral residue. The generated heat is extracted from the boiler with the help of boiler tubes, the extraction of heat helps to cool the flue gas, and the cooling of flue gas starts to solidify the mineral waste and create FA. FA is a lighter material collected from the bottom of the combustion chamber, while the coarse ash particles remain suspended in the flue gas. Fine aggregates are extracted directly by the ground mining technique. Fine aggregates are commonly taken from the natural sand particle at different sizes. Fine aggregates were made up of crushing of any stones to tiny particles. In this, we used M-Sand as a fine aggregate. Manufactured sand (M-Sand) is artificial building aggregates made by crushing the stones into smaller sand sized shaped particles, and then washed completely and graded them and used as construction aggregate. For building purpose, it is a preferable option to river sand. Control and geopolymer concrete were made with crushed aggregate sizes of 20 and 12 mm. The gradation test was performed in accordance with IS: 383–1970 (Reaffirmed 2016), and the coarse aggregate was classified as well-graded aggregate based on the test findings. The coarse aggregate was tested according to the method given in IS: 2386–1963 (Reaffirmed 2016). As an alkaline activator, sodium hydroxide pellets were used in geopolymer concrete, and sodium hydroxide of commercial grade with 96–98% purity was used in this experiment. The sodium hydroxide solution was created and employed as an alkaline activator based on the molarity of sodium hydroxide. To make geopolymer concrete, sodium silicate in the form of liquid gel was mixed with sodium hydroxide solution. The supplier delivered a Na_2SiO_3 solution with a SiO_2 content of 29.4% and a Na_2O content of 13.7%, as well as 55.9% water by mass. Low carbon cold drawn hooked end steel fibers having a modulus of elasticity of 2×10^5 MPa, the density of 7850 kg/m^3, and yield strength of 650 MPa were used in this research work. Table 1 gives the chemical properties of cement and FA that were used in this research work. Table 2 gives the details of the steel fiber used for the research work; Tables 3, 4, and 5 give the mix proportion of the concrete samples when nano silica (NS), micro silica (MS), and granite waste (GW) were used in certain percentages. The granite waste is dumped in the yards of Bannari Amman Sugars, in order to avoid the environmental issues; an attempt was made to replace it instead of FA. MS and NS are initially mixed with FA in a concrete mixer after which the alkaline is added and thoroughly mixed again and casted in moulds. MS and NS are added from 0 to 50% in this research work only to understand the variation in strength and durability aspects.

Table 2 Aspect ratio of steel fiber

S. No	Length (mm)	Diameter (mm)	Aspect ratio
1	35	0.75	45
2	50	0.75	65
3	60	0.75	80

Table 1 Chemical properties of materials used in the study

Particulars	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
Cement	19.2	5.2	4.8	65.4	2.67	1.2	-	-	1.3
FA	64.58	25.89	5.27	0.59	0.26	0.31	0.027	0.041	2.4
NS	99.8	0.005	0.001	0.62	-	0.78	-	-	0.660
MS	93.7	0.81	1.33	0.47	0.2	0.40	0.45	1.52	3.28

Table 3 Mix design of fly ash and nano silica

Mix Id	FA %	Nano Silica %	FA (kg/m^3)	Nano Silica (kg/m^3)	Steel Fiber %	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	NaOH (kg/m^3) 10 M	Na_2SiO_3 (kg/m^3)
GCNS0	100	0	405	0	0.5	683.13	1268.66	27.29	35.67
GCNS10	90	10	364.5	40.5	0.5	683.13	1268.66	27.29	35.67
GCNS20	80	20	324	81	0.5	683.13	1268.66	27.29	35.67
GCNS30	70	30	283.5	121.5	0.5	683.13	1268.66	27.29	35.67
GCNS40	60	40	243	162	0.5	683.13	1268.66	27.29	35.67
GCNS50	50	50	202.5	202.5	0.5	683.13	1268.66	27.29	35.67

Table 4 Mix design of fly ash and micro silica

Mix Id	FA %	Micro silica %	FA (kg/m^3)	Micro silica (kg/m^3)	Steel Fiber %	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	NaOH (kg/m^3) 10 M	Na_2SiO_3 (kg/m^3)
GCMS0	100	0	405	0	0.5	683.13	1268.66	27.29	35.67
GCMS10	90	10	364.5	40.5	0.5	683.13	1268.66	27.29	35.67
GCMS20	80	20	324	81	0.5	683.13	1268.66	27.29	35.67
GCMS30	70	30	283.5	121.5	0.5	683.13	1268.66	27.29	35.67
GCMS40	60	40	243	162	0.5	683.13	1268.66	27.29	35.67
GCMS50	50	50	202.5	202.5	0.5	683.13	1268.66	27.29	35.67

Table 5 Mix design of fly ash and granite waste

Mix Id	FA %	Granite waste %	FA (kg/m^3)	Granite waste (kg/m^3)	Steel fiber %	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	NaOH (kg/m^3) 10 M	Na_2SiO_3 (kg/m^3)
GCGW0	100	0	405	0	0.5	683.13	1268.66	27.29	35.67
GCGW10	90	10	364.5	40.5	0.5	683.13	1268.66	27.29	35.67
GCGW20	80	20	324	81	0.5	683.13	1268.66	27.29	35.67
GCGW30	70	30	283.5	121.5	0.5	683.13	1268.66	27.29	35.67
GCGW40	60	40	243	162	0.5	683.13	1268.66	27.29	35.67
GCGW50	50	50	202.5	202.5	0.5	683.13	1268.66	27.29	35.67

Mix design of geopolymer concrete

By using trial and error method mix design was performed and proper percentage of waste materials were obtained for preparing the test samples. After the samples are prepared two types of curing methods such as ambient curing and oven curing are carried out. Finally the samples are tested for checking the mechanical and durability properties as given below.

Test results

Mechanical tests-compressive strength

The samples casted with NA, MS, and GW were cured in ambient conditions for a period of about 28 days and when tested for compression strength were found to have a strength of 33.9 MPa, 38.2 MPa, and 41.6 MPa respectively. In the same samples when oven curing was performed, the compression at 28 days was found to be 35.9MPs, 34.2MPs, and 36.7 MPa respectively as shown in Fig. 1. The ambient cured steel fiber-reinforced geopolymer concrete with 0.50% of steel fiber was found to have greater compression strength with aspect ratio of 80 when compared to 45 and 65 aspect ratios. Also, the compression strength of SFGC was found to be more when compared to controlled concrete (CC). The abbreviations used in this research work are NC for nano silica concrete, MC for micro silica concrete, GC for geopolymer concrete, ONC for ordinary nano silica concrete, OMC for ordinary micro silica concrete, OGC for cement used geopolymer concrete, and SFGC1, SFGC2, and SFGC3 for steel fiber used geopolymer concrete in certain proportions.

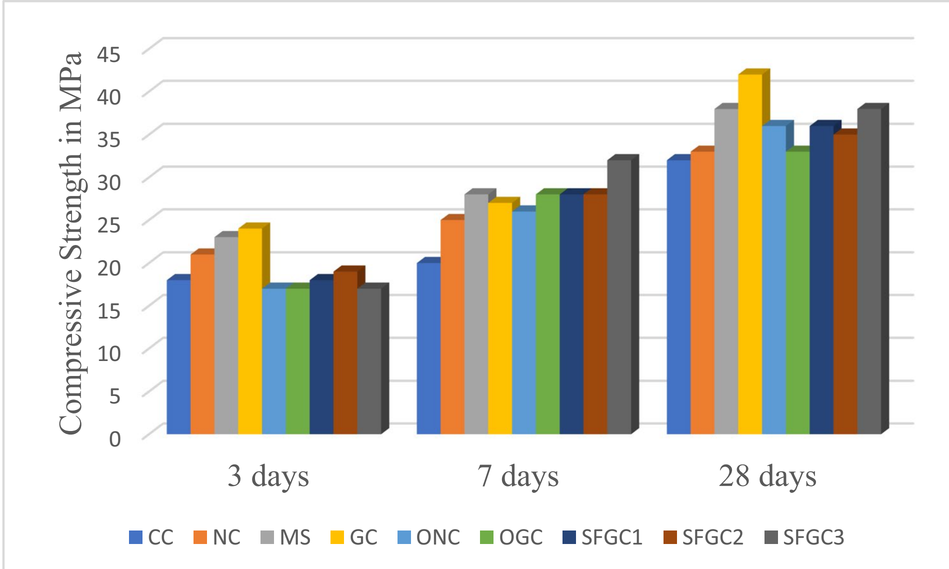

Fig. 1 Compressive strength

Split tensile strength

The split tensile strength of FAGC and controlled concrete (CC) mixture at different ages is shown in Fig. 2. The ambient cured sample shows good split tensile strength with 14.9%, 17.8%, and 7.8% increase in split tensile strength at 28 days when compared to the oven cured samples at 28 days.

Flexural strength

The flexural strength of FAGC with granite waste was 34% higher than the conventional concrete at 28 days. It is noted that flexural strength of granite waste mix at 7 and 28 days in ambient curing was higher when compared to conventional concrete is as shown in Fig. 3. From past research studies it was found that the flexural strength of concrete increases with increase in compressive strength.

Modulus of elasticity

The modulus of elasticity of the FAGC and CC were tested under both ambient and oven curing with different ratios of admixture. The modulus of elasticity of FAGC with granite waste was 7% higher than the conventional concrete at 28 days as shown in Fig. 4. It is noted that the modulus of elasticity of granite waste mix at 7 and 28 days in ambient curing was higher when compared to conventional concrete.

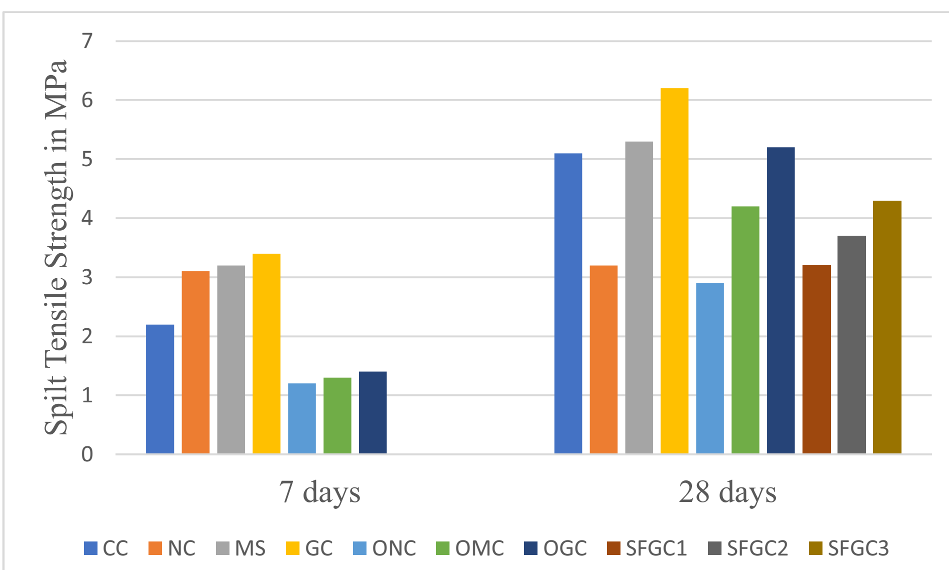

Fig. 2 Split tensile strength

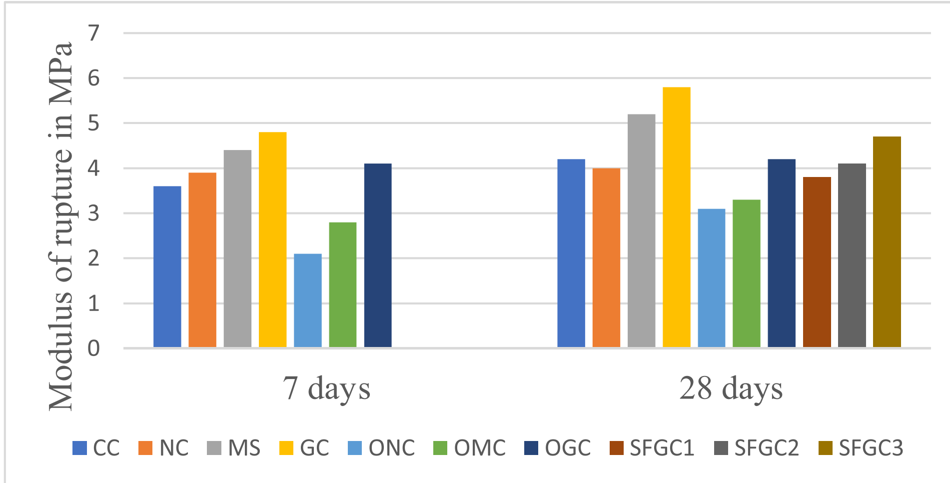

Fig. 3 Flexural strength

Durability properties

Acid resistance test

The degree of acid attack was evaluated based on the strength and weight loss results. The weight and loss in strength of FAGC, steel-reinforced GC, and conventional concrete due to acid attack at 7 and 28 days are given in Fig. 5. The weight loss in conventional concrete was found to be increased to about 66.9% and 63.5% at 7 and 28 days respectively when compared to the FAGC and SFGC. At the same time, there was a decrease in compressive strength in CC to about 8 and 14.1% respectively as shown in Fig. 6.

Sulfate resistance test

The effect of sulfate absorption affects the expansion and degradation of RC buildings. In general, sulfate accumulation is found in aggregate, ground water, soil, sewage, and sea water. The samples of CC, FAGC, and SFGC are immersed in 5% magnesium sulfate.

The loss of weight in conventional concrete was increased to 53% and 57.8% at 7 days and 28 days when compared to the FAGC and SFGC whereas in the case of conventional concrete, the strength was found to decrease to about 49% at 7 days and 37.9% at 28 days respectively as shown in Figs. 7 and 8.

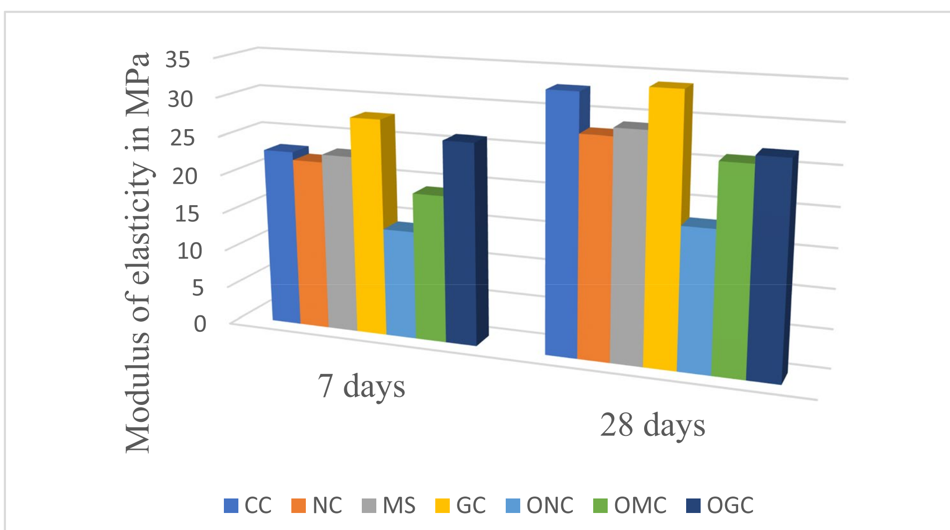

Fig. 4 Modulus of elasticity

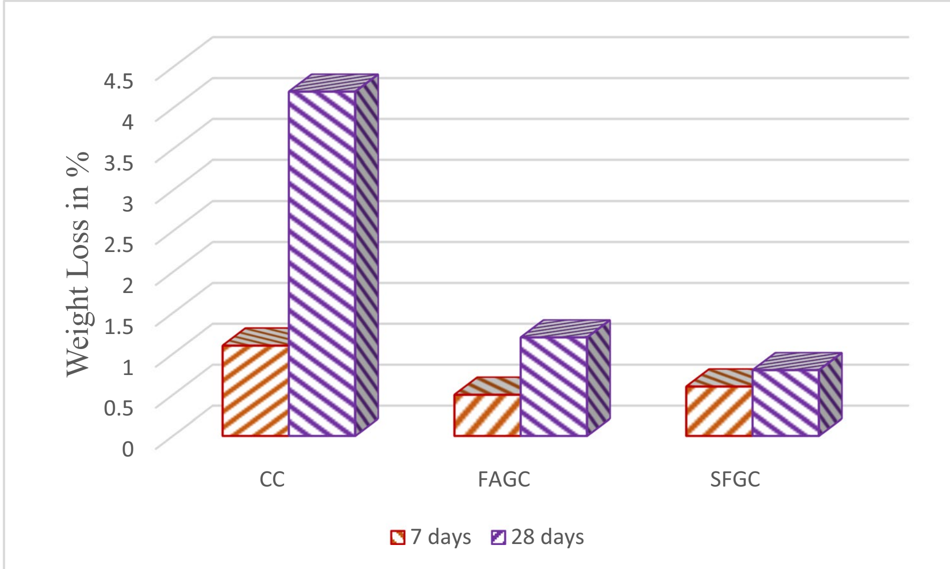

Fig. 5 Weight loss in acid attack

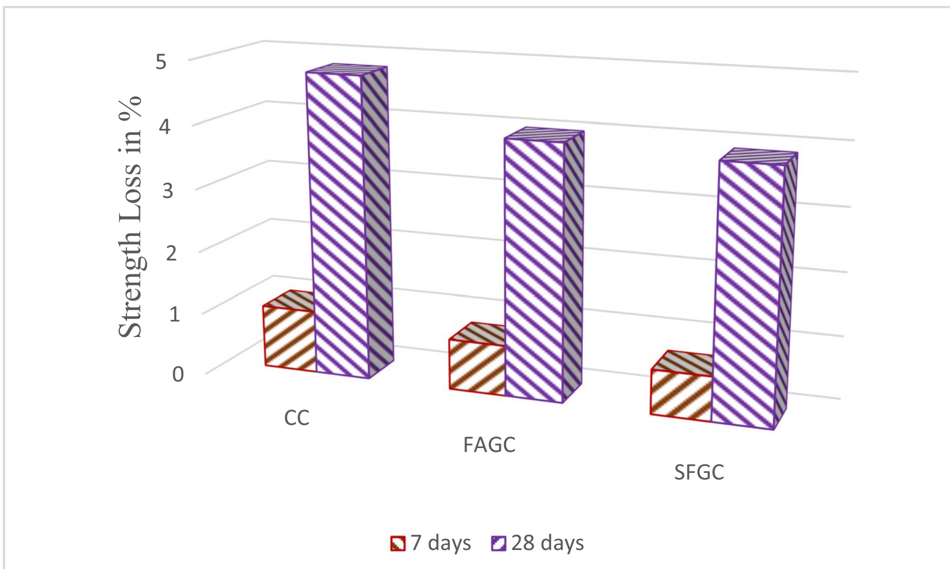

Fig. 6 Strength loss in acid attack

Salt resistance test

External parameters such as sea water, seashore breeze, dirts from the environment, and components of minerals in the ground water include salts that can degrade the quality of concrete. As per IS: 456:2000, the permissible limit of chloride content for construction purpose is up to 500 ppm. The samples were tested at 3.5% of NaCl.

The weight loss in conventional concrete was increased to 34.2% and 47.1%; at the same time, there was a decrease in compressive strength to about 78.5% and 27.7% at 7 and 28 days respectively when compared to the FAGC and SFGC as represented in Figs. 9 and 10.

Sorptivity

The rate of absorption of water and the time calculated at every interval gives the sorptivity of the concrete. It is observed that in the GPC and SFGC mix sorptivity level was measured 3 times lesser than the normal OPC concrete and is given in Table 6.

Water absorption

The water absorption of CC, FAGC, and SFGC at different ages is tabulated in Table 7. The amount of water

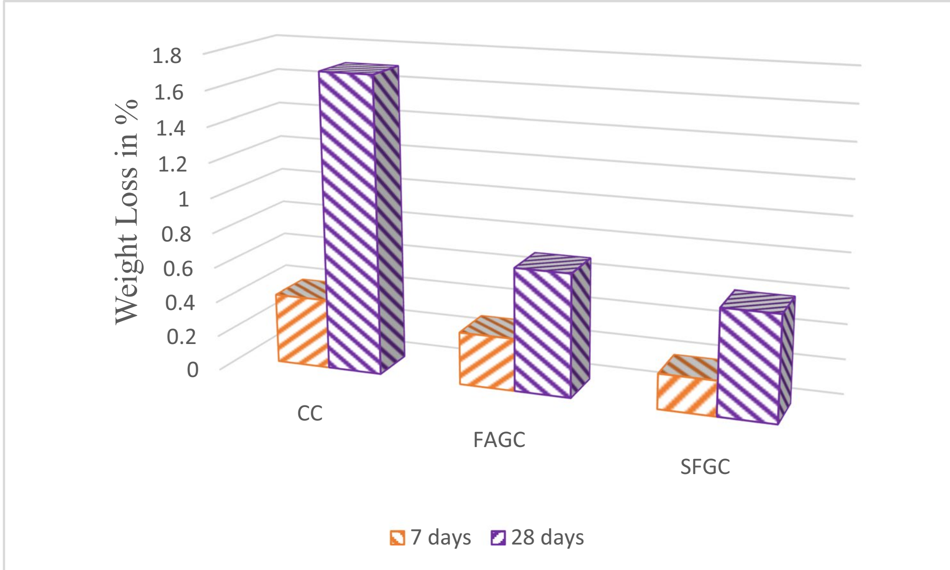

Fig. 7 Weight loss due to sulfate attack

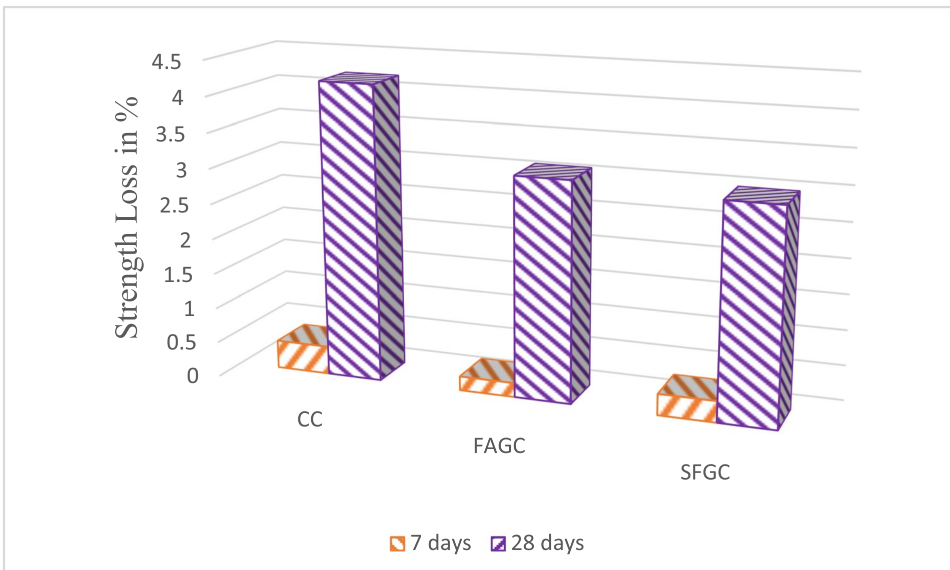

Fig. 8 Strength loss due to sulfate attack

absorbed in 7 days and 28 days for CC, FAGC, and SFGC is 3.27%, 1.77%, and 1.96% and 1.92%, 1.7%, and 1.79% respectively. Water absorption by FAGC and SFGC was found to be less when compared with CC as the GC has dense microstructure.

Conclusions

At all ages, the ambient and oven cured mix of granite waste geopolymer concrete with alkaline liquid performed better than CC in terms of compressive strength. Mechanical properties of FAGC mix with ambient curing alone, such as compressive strength, split tensile strength, flexural strength, and modulus of elasticity, clearly performed better than conventional mix. The experimental result shows the granite waste GC was identified as ideal mix proportions for making fly ash geopolymer concrete based on trial findings. This ideal mix fraction is also used to investigate the flexural behavior and durability features of FAGC.

i. From the experimental compressive strength test results, it was found that there was an increase in compressive strength to about 5.5%, 10.4%, and 11.7% when the samples were oven cured that ambient curing at 3 days respectively. But there was no significant change in compressive strength at 7 and 28 days because due to the application of heat it gives rise to the formation of a stronger polymer chain bonding.

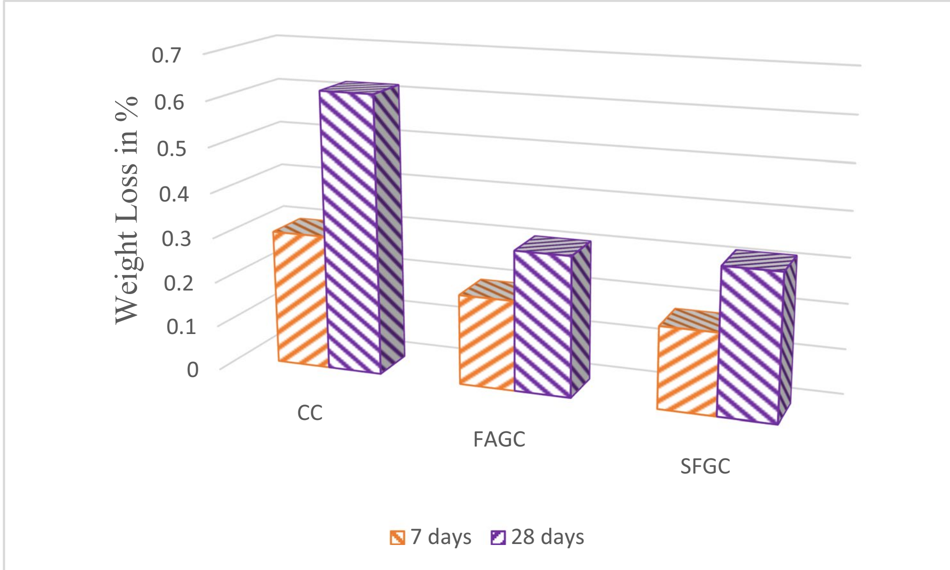

Fig. 9 Weight loss in salt resistance test

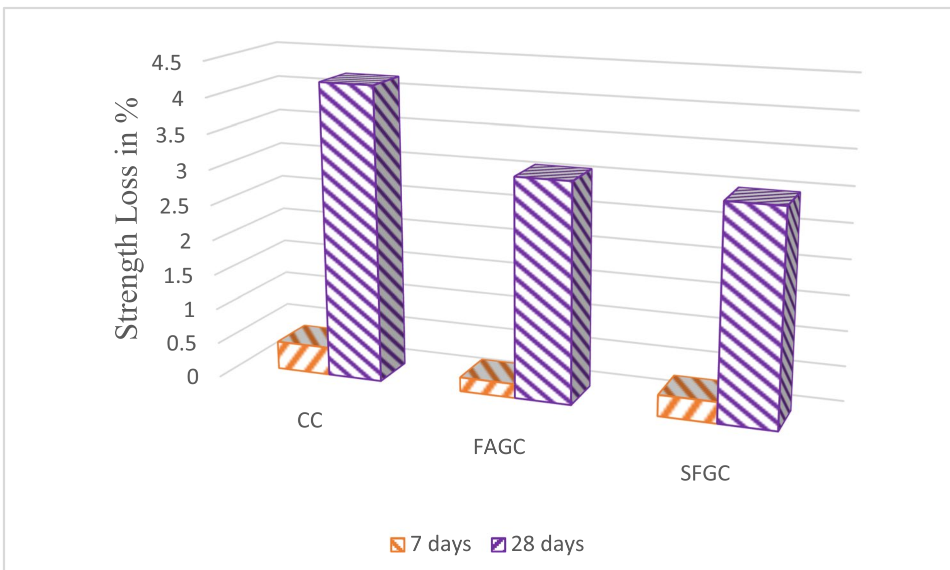

Fig. 10 Strength loss in salt resistance test

Table 6 Sorptivity test

Mix	Sorptivity (cm/min½) × 10^{-3}	Chloride penetration depth (cm)
CC	6.75	2.8
FAGC	2.56	1.5
SFGC 0.5	2.39	1.4

Table 7 Water absorption of prepared samples

Mic Id	Dry weight (kg)	Wet weight (kg)	% of water absorption
7 days			
CC	2.445	2.525	3.27
FAGC	2.489	2.530	1.77
SFGC	2.480	2.529	1.96
28 days			
CC	2.497	2.545	1.92
FAGC	2.526	2.569	1.7
SFGC	2.510	2.555	1.79

ii. The split tensile strength of SFGC increases to about 0.50% when the aspect ratio is at 80 when compared to other aspect ratio such as 45 and 65 respectively. The split tensile strength of GW geopolymer mix shows remarkable increase of 55.6% and 21.6% at 7 and 28 days split tensile strength when compared with conventional concrete.
iii. It was clear that FAGC performed better than CC as FAGC was found to be permeable and all the aggregate pores were completely occupied by geopolymer paste and FAGC has no calcium compounds.
iv. As the percentage of NS is added to a larger extent, it was found that there was decrease in strength.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-22360-x.

Author contribution Karthiga Shenbagam Natarajan, have equally contributed for this work.

Data availability All the necessary data are given in the paper in detail.

Declarations

Ethics approval This is the work done by me and it is not published anywhere else by us.

Consent to participate All the authors of this paper have given their consent to participate and act as one of the authors.

Consent for publication I, the author, give my consent for the publication of identifiable details, which can include photograph(s) or case history and details within the text

Competing interests The authors declare no competing interests.

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