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STUDY ON MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE USING GGBS AND SILICA FUME

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ABSTRACT: Infrastructure plays an important role in the development of a country. Usage of concrete in constructions is increasing day by day. Mostly concrete made of Ordinary Portland Cement (OPC) is used in the construction sector. Production of Ordinary Portland Cement Concrete (OPCC) utilizes large quantities of energy and natural resources. A large amount of carbon dioxide is also produced in the manufacture of cement and concrete. Production of OPC causes environmental issues in the long run. In this scenario it is necessary to find alternatives for making environmental friendly concrete. Geopolymer concrete (GPC) came as an alternative to Ordinary Portland Cement Concrete (OPCC) in construction industry. At present GPC is an on-going research subject. GPC is manufactured by using the industrial by-products like Fly ash, GGBS, Metakaolin, and Silica fume etc. GPC is a combination of a source material and alkaline solution. The source material rich in Aluminium (Al) and Silicon (Si) when mixed with an alkaline solution, binders are formed by a process of polymerization. In this study GGBS based GPC was used. The mix design procedure for GPC is based on trial mixes. Based on the results from the trial mixes a better mix proportion was chosen. GGBS from the mix proportions was replaced with Silica Fume in percentages of 20%, 40%, 50%, 60%, 80%, and 100%. A total of 7 combinations were used in the study. For each combination cube, cylinder and beam(prism) specimens were casted as per IS specifications and studied for various properties like compressive strength, split tensile strength, flexural strength, modulus of elasticity, density and carbonation. This study mainly presents the mechanical properties of GGBS based GPC with silica fume as a partial replacement to GGBS. The different properties under the influence of silica fume were studied. It was observed that the properties like compressive strength, split tensile strength, flexural strength showed a significant reduction with the increase in silica fume quantity. Cost analysis shows the various costs and percentages of materials used.
Keywords: Geopolymer concrete, GGBS, Silica fume, Compressive strength, Split tensile strength, Flexural strength

I. INTRODUCTION

Concrete is one of the most important materials in construction industry. The traditional method of manufacturing concrete has put the advancement of this very important construction material in slow pace. The huge increase in demand from housing industry due to the population explosion has increased the gap between supply and demand. In order to meet the increasing demand, researchers have been trying to find out more sustainable alternative for construction material. Research have been undertaken in various parts of the world to manufacture concrete using industrial waste products like fly ash, Ground Granulated Blast furnace Slag (hereafter referred as GGBS), rice husk ash, metakaolin and silica fume. In the production of concrete cement plays a major role. Due to high emissions of carbon dioxide during the manufacturing of Ordinary Portland cement, researchers have tried to find more sustainable alternative to Portland cement. Cement production contributes to 7% of the global carbon dioxide emission. Dr. Joseph Davidovits coined the term ‘Geopolymer’ to refer binders made from alumino-slicate materials like Fly Ash, Rice husk ash, GGBS and Metakaolin. The constituents of geopolymer concrete are geopolymeric source materials (fly ash, ggbs, metakaolin, rice husk ash etc., and Alkaline activated liquids. The primary course of reaction is dissolution, condensation, polymerization and growth. This leads to formation of 3D1 structure similar to Zeolite. This makes it completely different from the C-S-H gel that is formed in Ordinary Portland Cement based binder. Research done in the area of geopolymer concrete identified geopolymer concrete to be more durable and are comparably superior to Ordinary Portland Cement concrete. The geopolymer concrete developed so far is based on fly ash cured at elevated temperature. GPC based on GGBS was found to attain full strength by curing at ambient temperature. Research on GPC based on GGBS is very limited. This thesis is the final result of humble effort made by the author to study the mechanical properties of GGBS based GPC by incorporating silica fume.

Silica Fume

Silica fume is an alternative cementitious material. It is also known as micro silica. It refers to materials that are used in concrete in addition to Portland cement. It is a by-product in the manufacturing of silicon metal and ferro silicon alloy in smelters with electric arc furnaces. It is an ultrafine material with spherical particles of 1μm diameter. This is used in the industrial production of aluminum, steel, computer chip fabrications and silicones. Silica fume when used in preparation of concrete with cement in varying proportions produces high compressive strengths. The rate of gain in strength is slow when silica fume is used in concrete with cement.

GGBS

GGBS means Ground Granulated Blast furnace Slag. It is an industrial by-product similar to fly ash. It can be used in production of concrete by mixing it with cement in varying proportions to form a durable and eco friendly concrete. A glassy granular product is produced by quenching of molten slag from blast furnace with water during the production of iron at about 15000C temperature. GGBS is obtained by grinding this glassy granular product. GGBS mainly contains silicate and aluminate impurities from the iron ore. The main constituents of GGBS are SiO2 (28-38%), Al2O3 (8-24%), CaO (30-50%) and MgO (1-18%).

Alkaline liquid
An alkaline liquid is used to react with silicon (Si) and aluminum (Al). The main constituents of alkaline liquid are Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) and Sodium Silicate (Na_2SiO_3) or Potassium Silicate (K_2SiO_3). Generally a combination of NaOH and Na_2SiO_3 are used as an alkaline liquid in the manufacture of GPC. This alkaline liquid when reacts with the source material of geological origin binders are produced. The chemical reaction that takes place in this process is called polymerization. A solution of 10M sodium hydroxide and sodium silicate were used in this study.

II. EXPERIMENTAL INVESTIGATION

General
The experimental investigation was done on the mechanical properties of the GGBS based GPC by incorporating silica fume at varying proportions to GGBS. The study includes industrial by-products like GGBS, silica fume and alkaline liquid. As there are no specific mix design guidelines for GPC the mix and proportioning is arrived by trial and error methods and by previous experience of the author in first phase of the project work. A preliminary study was conducted to identify the important parameters in order to get the proper consistency of the mix.

Constituents of GPC
The properties of different materials used in this were studied. The properties like Specific gravity, fineness and particle size distribution were studied. The different constituents used in this GPC are.

GGBS
The GGBS used in this study is from Vizag steel plant, Visakhapatnam, supplied by SVSS Enterprises Pvt. Ltd, Autonagar, Visakhapatnam.


Fig. GGBS used in the study

Table 2.1 - Properties of GGBS

S.NO	Particulars of test	Test results
1	Specific gravity	2.3
2	Fineness	4%

Table 2.2 - Composition of GGBS

Oxide	Mass percentage (%)
SiO2	35.47
Al2O3	19.36
FeO	0.8
CaO	33.25
MgO	8.69
Others	3.25

Silica Fume
The Silica Fume used in this work was supplied from BTL industries, Autonagar, Visakhapatnam

Table 2.3 - Properties of Silica Fume

S.NO	Particulars of test	Test results
1	Specific gravity	2.23
2	Fineness	2%

Table 2.4 - Composition of Silica Fume

Oxide	Mass percentage (%)
SiO_2	90
Al_2O_3	0.4
FeO	0.4
CaO	1.6
Others	7.6

Fine Aggregate
The fine aggregate used in this study is clean river sand, purchased from a nearby crusher in Visakhapatnam. The following tests are carried out on Fine aggregate as per IS 2386-1968 (Part 3)

Fig.Fine Aggregate used in the study

Table 2.5 - Properties of Fine Aggregate

S.NO	Particulars of test	Test results
1	Specific gravity	2.56
2	Water absorption (%)	1.4
3	Fineness modulus	3.4
4	Sieve analysis	Zone II

Coarse Aggregate

The coarse aggregate used in the present study is crushed stone of size 20 mm and down from Visakhapatnam and the following tests were done on the coarse aggregate.

Table 2.6 - Properties of Coarse Aggregate

S.NO	Particulars of test	Test results
1	Specific gravity	2.86
2	Crushing value (%)	25.92
3	Impact value (%)	17.56
4	Fineness modulus	7.23

Alkaline Liquid

The alkaline liquid used in this study was a combination of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). The sodium hydroxide and sodium silicate of laboratory grade were purchased from Guptha chemicals, Visakhapatnam. Sodium hydroxide is available in the form of flakes and sodium silicate is available in the form of liquid. Sodium hydroxide solution was prepared by dissolving flakes in distilled water. 10M concentration of sodium hydroxide was used for the entire study. The chemical composition of sodium silicate solution was Na_2O=15.23% by mass, SiO_2=35.67% by mass and remaining water.

Fig Sodium Hydroxide (NaOH) flakes used in the study

The sodium hydroxide solution must be prepared 24 hours prior to casting and sodium silicate must be mixed with sodium hydroxide solution 1 hour prior to casting. The ratio between sodium hydroxide to sodium silicate was maintained as 2.5. Additional may be added for workability without exceeding limit.

Water

The water used in this study was potable water. Distilled water was used for dissolving sodium hydroxide flakes to prepare sodium hydroxide solution. Normal potable water was used as additional water for the mixing of concrete.

Mix Design

- The Mix design process for GPC is illustrated as below.
- Assume the density of GPC between 2200 to 2400 Kg/m^3.
- Take the volume of combined aggregate by weight between 70 to 80% of the density of GPC.
- Source material and alkaline liquid comprise 20 to 30% of the assumed density.
- Assume alkaline liquid to source material ratio from 0.3 to 0.5 and calculate their quantities.
- Consider the ratio of sodium silicate to sodium hydroxide as 2.5 and calculate their individual quantities from the quantity alkaline solution.
- Based on the molarity of sodium hydroxide the amount of sodium hydroxide flakes in the solution changes.
- The sodium hydroxide solution must be prepared 24 hours prior to the mixing of GPC.
- Sodium silicate could be added 1 to 3 hours before the mixing.
- If required additional water is considered for mixing of GPC.

Mix Proportions

The design mix used for this research work is 1: 1.35: 2.03. The water to source material (GGBS and silica fume) is 0.41. To study the mechanical properties of GGBS based GPC 7 different proportions were prepared with different percentages of silica fume by weight. GGBS in the concrete was replaced with silica fume from 0-100% by weight (0, 20, 40, 50, 60, 80 and 100). In each mixture 6 specimens were prepared 3 were tested for 7 days and 3 for 28 days.

Table 2.7 Geopolymer concrete mix proportions

GGBS/Silica fume (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	Water (Kg/m^3)	Water/Solids
496.6	672	1008	202.92	0.41

Table 2.8 GPC design replacement mix proportions

Ingredients (Kg/m^3)		Different mixes						
		G1 0%	G2 20%	G3 40%	G4 50%	G5 60%	G6 80%	G7 100%
GGBS		496.6	397.3	298	248.3	198.6	99.3	0
Silica fume		0	99.3	198.6	248.3	298	397.3	496.6
Fine aggregate		672	672	672	672	672	672	672
Coarse aggregate	20mm	705.6	705.6	705.6	705.6	705.6	705.6	705.6
	10mm	302.4	302.4	302.4	302.4	302.4	302.4	302.4
Sodium silicate (Na_2SiO_3)		159.6	159.6	159.6	159.6	159.6	159.6	159.6
Sodium hydroxide (NaOH)	Solids	19.79	19.79	19.79	19.79	19.79	19.79	19.79
	Water	44.05	44.05	44.05	44.05	44.05	44.05	44.05
Additional water		158.7	158.7	158.7	158.7	158.7	158.7	158.7

Mixing Procedure
The mixing procedure employed in this research work is pan mixing followed by hand mixing. As the setting time of this concrete is much less concrete was hand mixed as quickly as possible after pan mixing. Mixing was continued until the entire mix becomes homogeneous and uniform in appearance. The entire period of mixing is not more than 3 minutes.

Test for Workability
Concrete was tested for workability after mixing. Every mix of concrete was checked for slump. Care must be taken to place concrete in the moulds as quickly as possible after testing for slump. After the slump is checked concrete is mixed again uniformly and placed in the moulds. Re-mixing of concrete must be as fast as possible as the setting time is short but the mix must be homogeneous and uniform.

Size of the Specimens
Cube specimens used for testing were of size 100 x 100 x 100 mm^3. The size of the cylindrical specimens were 150mm diameter and 300 mm length, generally their length are twice the size of their diameter. The beam specimens used were 500 mm length and the dimensions of the cross section were 100 mm x 100 mm. These dimensions are according to IS: 10086-1982.

Placing of Concrete
The uniformly mixed concrete was placed into the moulds in three layers. After placing the first layer a tamping rod was used to give 25 blows.

Compaction by Vibration
Concrete in the moulds was compacted by using a vibrating table. The moulds were kept on the vibrating table and vibrated. The time taken for vibration was much less yet sufficient to allow concrete to settle evenly all over the mould. Top of the moulds were treated for a smooth finish and were removed from the table and allowed for setting.

Curing
After demoulding the concrete specimens were kept for curing. As there will be no heat of hydration in GPC the specimens were not water cured. There are two types of curing for GPC, namely ambient curing and heat curing. In ambient curing the specimens are cured at ambient temperature. In heat curing the specimens are cured at a specified temperature in oven by covering the specimens with polythene covers in order to restrict the humidity. In this research work ambient curing was done in practical point of view. Specimens were cured for 7 and 28 days at ambient temperature.

Tests on Specimens
The specimens were tested for compressive strength, split tensile strength, flexural strength, modulus of elasticity, and carbonation for 7 and 28 days as per Indian Standards.

Age of Specimens at Test
The specimens were tested after 7 and 28 days of curing. Here specimens were allowed to cure at ambient temperature for 7 days and 28 days and then tested.

Number of Specimens Tested
For each mix at least 3 specimens were tested for compressive strength, split tensile strength, flexural strength and modulus of elasticity at 7 days and 28 days.

III. PRESENTATION OF RESULTS

In this chapter the experimental results are presented and discussed. Except mix design all the methods used to prepare and test the concrete specimens are as per their respective Indian standard codes. Various tests have been done on GGBS, silica fume, fine aggregate and coarse aggregate to know whether they are suitable in making geopolymer concrete. As there is no standard for the mix design of GPC proportioning was done based on trial mixes. Different trial mixes with varying constituents were laid and based on their results a suitable mix design was approached. GPC is based on GGBS and it is replaced with silica fume in different varying proportions. The concentration of sodium hydroxide was kept constant as 10M. The variations of compressive strength, split tensile strength, flexural strength with respect to percentage of silica fume are discussed in the results section. The experimental setup and procedures for conducting various tests on concrete are discussed below.

Table 3.1 Compressive strength at 7 days of ambient curing

Mix.No	Different mixes	Compressive strength (MPa)
1	100% GGBS	62.6
2	80% GGBS and 20% Silica Fume	55
3	60% GGBS and 40% Silica Fume	44.33
4	50% GGBS and 50% Silica Fume	32.33
5	40% GGBS and 60% Silica Fume	20.66
6	20% GGBS and 80% Silica Fume	15.66
7	100% Silica Fume	11.66

Table 3.2 Compressive strength at 28 days of ambient curing

Mix.No	Different mixes	Compressive strength (MPa)
1	100% GGBS	65.33
2	80% GGBS and 20% Silica Fume	58.33
3	60% GGBS and 40% Silica Fume	47.33
4	50% GGBS and 50% Silica Fume	33
5	40% GGBS and 60% Silica Fume	22
6	20% GGBS and 80% Silica Fume	17
7	100% Silica Fume	13.33

Casting and Testing for Split Tensile Strength of GPC

The GPC cylinder used for testing was of size 150 mm diameter and 300 mm length. The cylinder specimens were tested according to IS: 5816-1999. The moulds of the cylinder were cleaned and oiled well before casting of cylinders. Application of oil to the moulds helps in the easy removal of specimens from moulds without any deformations. The GPC was mixed thoroughly and poured throughout its depth. The moulds were placed on the vibrating table and compacted.

After 24 hours the specimens were demoulded and kept in ambient curing for 7 and 28 days. After curing the specimens were tested for split tensile strength on a compression testing machine of 200 ton capacity. The ultimate load is taken and split tensile strength of the specimen is calculated using the following equation.

$$\text{Split tensile strength of concrete} = \frac{2 \times \text{Ultimate split load } (N)}{\pi \times \text{Length} \times \text{Diameter (mm square)}}$$

Fig. Cylinder specimen on compression testing machine

Table 3.3 Split tensile strength at 7 days of ambient curing

Mix.No	Different mixes	Split Tensile strength (MPa)
1	100% GGBS	3.57
2	80% GGBS and 20% Silica Fume	2.92
3	60% GGBS and 40% Silica Fume	2.4
4	50% GGBS and 50% Silica Fume	1.73
5	40% GGBS and 60% Silica Fume	1.5
6	20% GGBS and 80% Silica Fume	1.17
7	100% Silica Fume	0.85

Table 3.4 Split tensile strength at 28 days of ambient curing

Mix.No	Different mixes	Split Tensile strength (MPa)
1	100% GGBS	3.82
2	80% GGBS and 20% Silica Fume	3.3
3	60% GGBS and 40% Silica Fume	2.44
4	50% GGBS and 50% Silica Fume	2.12
5	40% GGBS and 60% Silica Fume	1.64
6	20% GGBS and 80% Silica Fume	1.36
7	100% Silica Fume	1.04

The modulus of rupture or flexural strength is the tensile strength of concrete beams. The concrete beams used for the flexural strength were casted and tested in accordance to IS: 516-1959. The size of the specimens used was 100 X 100 X 500 mm.

The beam moulds shall confirm to IS: 10086-1982. The moulds of the beams were cleaned and oiled well before casting. Oil is applied throughout the moulds for easy removal without any damage to the specimens. The GPC was mixed thoroughly and poured along the length of the beams evenly. The moulds were placed on the vibrating table and compacted.

The specimens were demoulded after 24 hours of casting and kept in ambient curing. After curing the specimens were tested at 7 and 28 days for flexural strength or modulus of rupture on a universal testing machine of 40 ton capacity. The ultimate load is taken and flexural strength of the specimen is calculated using the following equation.

The flexural strength of the specimen shall be expressed as the modulus of rupture fb, which, if ‘a’ equals the distance between the line of fracture and the nearer support, measured on the centre line of the tensile side of the specimen, in cm, shall be calculated to the nearest 0.5 kg/sq cm as follows:

$$f_b = \frac{p \times l}{b \times d^2}$$

when ‘a’ is greater than 20.0 cm for 15.0 cm specimen, or greater than

$$f_b = \frac{p \times l}{b \times d^2}$$

13.3 cm for a 10.0 cm specimen, or

when ‘a’ is less than 20.0 cm but greater than 17.0 cm for 15.0 cm specimen or less than 13.3 cm but greater than 11.0 cm for a 10.0 cm specimen

where

b = measured width in cm of the specimen,

d = measured depth in cm of the specimen at the point of failure,

l = length in cm of the span on which the specimen was supported, and p = maximum load in kg applied to the specimen.

If ‘a’ is less than 17.0 cm for a 15.0 cm specimen, or less than 11.0 cm for a 10.0 cm specimen, the results of the test shall be discarded.

Fig.3.4 Beam specimen on universal testing machine (UTM)

Fig.3.5 Beam specimens after testing for flexural strength

Table 3.5 Flexural strength at 7 days of ambient curing

Mix.No	Different mixes	Flexural strength (MPa)
1	100% GGBS	4.13
2	80% GGBS and 20% Silica Fume	3.36
3	60% GGBS and 40% Silica Fume	2.56
4	50% GGBS and 50% Silica Fume	2.24
5	40% GGBS and 60% Silica Fume	2.08
6	20% GGBS and 80% Silica Fume	1.92
7	100% Silica Fume	1.36

Table 3.6 Flexural strength at 28 days of ambient curing

Mix.No	Different mixes	Flexural strength (MPa)
1	100% GGBS	5.12
2	80% GGBS and 20% Silica Fume	3.52
3	60% GGBS and 40% Silica Fume	2.72
4	50% GGBS and 50% Silica Fume	2.4
5	40% GGBS and 60% Silica Fume	2.24
6	20% GGBS and 80% Silica Fume	2.08
7	100% Silica Fume	1.6

Determination of the Modulus of Elasticity.
The test specimens shall consist of concrete cylinders 150 mm in diameter and 300 mm long. The test specimens shall be prepared in accordance to IS: 516- 1959 and cured in ambient temperature. Normally this test shall be made when the specimens reach the age of 28 days.

Modulus of elasticity or Young's modulus is a measure of resistance of an object which is deformed elastically. It is generally measured from the slope of the stress-strain curve. Modulus of elasticity of concrete in compression is determined by using an extensometer. The extensometer is attached parallel to the axis of the cylinder. The specimen must be placed in the testing machine and accurately centered. The load should be applied continuously and the corresponding dial gauge readings must be noted for different loads. Stress and strain must be calculated for respective deflection and load. The stress values are to be plotted against the strain and the slope is measured for modulus of elasticity.

The following are stress and strain values of cylinder specimens at 28 days

Table 3.14 Modulus of Elasticity (or) Young's modulus for different mixes

Mix.No	Different mixes	Modulus of elasticity (Mpa)
1	100% GGBS	9733.33
2	80% GGBS and 20% Silica Fume	9433.3
3	60% GGBS and 40% Silica Fume	8500
4	50% GGBS and 50% Silica Fume	7566.6
5	40% GGBS and 60% Silica Fume	7500.6
6	20% GGBS and 80% Silica Fume	5675.3
7	100% Silica Fume	4275

IV. RESULTS AND DISCUSSION

There is a lot of research on Fly ash based GPC but there is not enough research done on GGBS based GPC. To use GGBS based GPC for construction purpose it is necessary to study the complete mechanical properties of concrete. In this study Silica fume is replaced partially with GGBS at percentages of 20%, 40%, 50%, 60%, 80% and 100%. The mechanical properties like compressive strength, split tensile strength, flexural strength, modulus of elasticity, carbonation and density were tested.

The following graphs show the variation of average compressive strength of different mixes at 7 and 28 days of ambient curing. In the graph on X-axis different mixes are shown and on Y-axis compressive strength is shown in Mpa.

Compressive Strength

The following graphs show the variation of average compressive strength of different mixes at 7 and 28 days of ambient curing. In the graph on X-axis different mixes are shown and on Y-axis compressive strength is shown in Mpa.

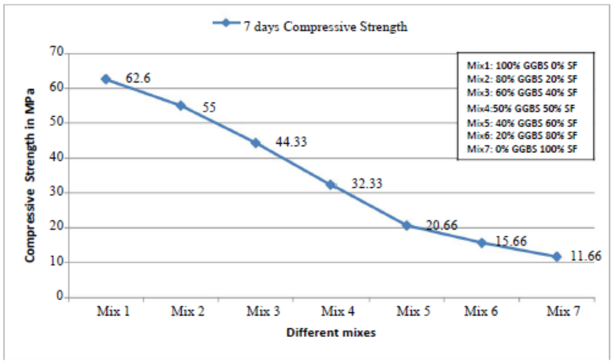

Fig.4.1 Variation in the compressive strength of GPC at 7 days of ambient curing

Figure 4.1 shows the variation of 7 days ambient cured average compressive strength of GPC specimens. From the graph it is observed that GGBS based GPC has high early strength of 62.6 MPa at 7 days of ambient curing which is 40% more than required. The compressive strength is decreased with the increase in silica fume replacing GGBS. Reduction in strength is continuous and significant from 20% to 60% of replacement, which is from 55 MPa to 20.66 MPa. However from 60% to 100% replacement the reduction is gradual from 20.66 MPa to 11.66 MPa. The compressive strength was reduced due to the increase in the remaining free water in the mix in excess than required for source material and for proper compaction of fresh GPC. The excess free water content in the different mixes increases with the increase in silica fume content. This may cause the particles of the constituents to separate by leaving minute pores in the hardened concrete which consequently causes reduction in the concrete strength.

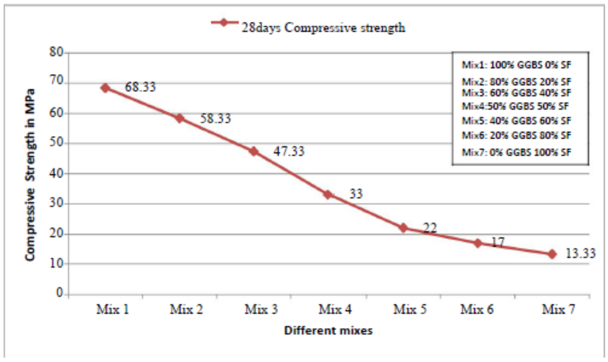

Fig.4.2 Variation in the compressive strength of GPC at 28 days of ambient curing

Figure 4.2 shows the variation of 28 days ambient cured compressive strength of cube specimens. There is an increase in strength between respective mixes from 7 to 28 days of ambient curing. However the decrease in strength can be seen with the increase in silica fume replacement. From the graph it is observed that the compressive strength of GPC at 0% replacement is 68.33 MPa and 100% replacement is 13.33 MPa.

Split Tensile Strength

The following graphs show the variation of split tensile strength of different mixes at 7 and 28 days of ambient curing. On X-axis different mixes were taken and on Y-axis Split tensile strength was taken in MPa. Figure 4.3 shows the variation in the split tensile strength of GPC cylinders at 7 days of ambient curing. The split tensile strength is decreased with the increase in silica fume replacing GGBS. Reduction in split tensile strength is continuous and significant from 0% to 50% of replacement, which is from 3.57 MPa to 1.73 MPa. However from 50% to 100% replacement the reduction is gradual from 1.73 MPa to 0.85 MPa. The split tensile strength was reduced due to the increase in the remaining free water in the mix than required for source material and for proper compaction of fresh GPC. The excess free water content in the different mixes increases

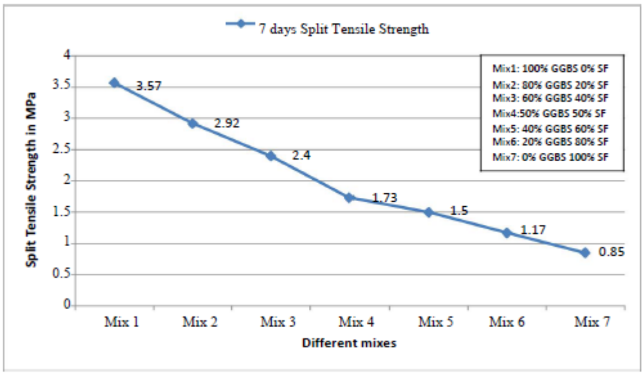

Fig.4.3 Variation in the split tensile strength of GPC at 7 days of ambient curing

with the increase in silica fume content. This may cause the particles of the constituents to separate by leaving minute pores in the hardened concrete which consequently my cause reduction in the split tensile strength.

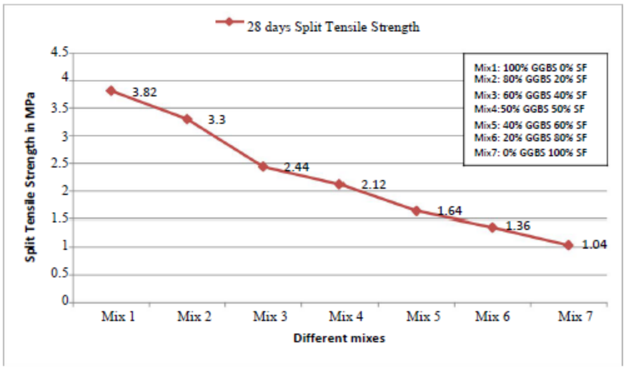

Fig.4.4 Variation in the split tensile strength of GPC at 28 days of ambient curing

Figure 4.4 shows the variation in split tensile strength of GPC cylinders at 28 days of ambient curing. There is an increase in the split tensile strength between respective mixes from 7 to 28 days of ambient curing. However the decrease in strength can be seen with the increase in silica fume replacement. The reduction in split tensile strength is significant between 0% and 40% of replacement, which is from 3.82 MPa to 2.44 MPa. From 40% to 100% the reduction is gradual from 2.44 MPa to 1.04 MPa.

Flexural Strength

The below graphs show the variation in flexural strength of GPC beam (prism) specimens at 7 and 28 days of ambient curing. Different mixes were taken on X-axis and flexural strength was taken on Y-axis.

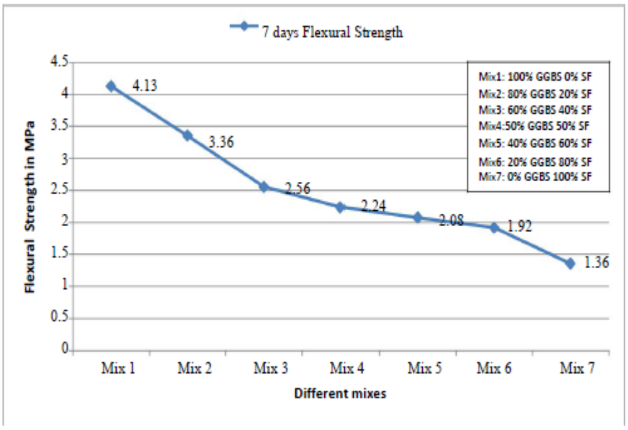

Fig.4.5 Variation in the flexural strength of GPC at 7 days of ambient curing

Figure 4.5 shows the variation in the flexural strength of GPC beam (prism) specimens at 7 days of ambient curing. The flexural strength is decreased with the increase in silica fume replacing GGBS. Reduction in flexural strength is continuous and significant from 0% to 40% of replacement, which is from 4.13 MPa to 2.56 MPa. However from 40% to 100% replacement the reduction is gradual from 2.56 MPa to 1.36 MPa. The flexural strength was reduced due to the increase in the remaining free water in the mix than required for source material. The excess free water content in the different mixes increases with the increase in silica fume content. This may cause the particles of the constituents to separate by leaving pores in the hardened concrete which may cause reduction in the flexural strength

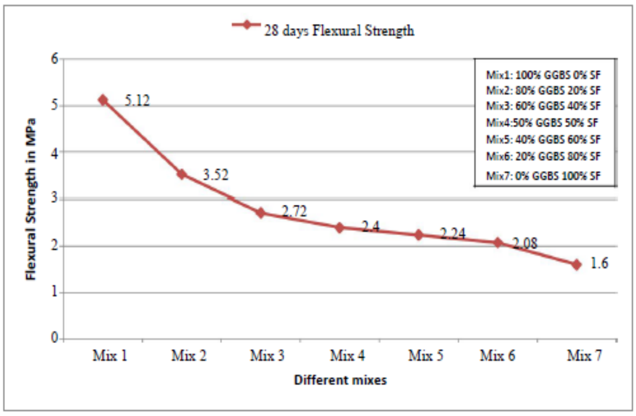

Fig.4.6 Variation in the flexural strength of GPC at 28 days of ambient curing

Figure 4.6 shows the variation of 28 days ambient cured flexural strength of beam (prism) specimens. There is an increase in strength between respective mixes from 7 to 28 days of ambient curing. However the decrease in strength can be seen with the increase in silica fume replacement. From the graph it is observed that the flexural strength of GPC at 0% replacement is 5.12 MPa and 100% replacement is 1.6 MPa.

Modulus of Elasticity

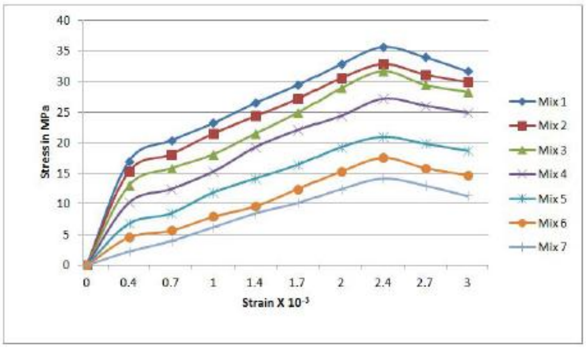

Fig.4.7 Variation in the Stress-Stain curves of GPC

Figure 4.7 shows the variation in stress-strain curves of GPC cylinder specimens. On X-axis strain values are taken and on Y-axis stress values are taken. From the graph it can be observed that up to certain limit stress value increased with the increase in corresponding strain value. Beyond a certain point with the increase in strain the stress value decreased. In general compression of a cylinder specimen along its length with the increase in strain the length of the cylinder decreases.

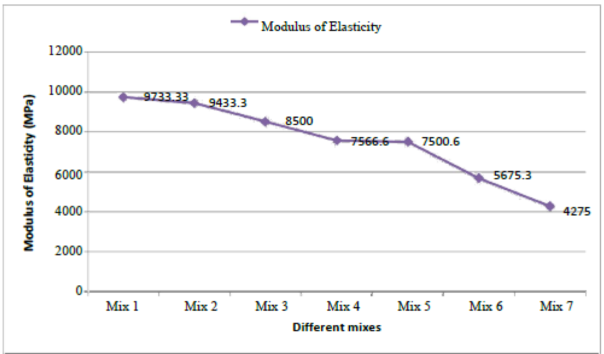

Fig.4.8 Variation in the modulus of elasticity of GPC

Figure 4.8 shows the variation of modulus of elasticity for different mixes of GPC. From the graph it is observed that for 0% replacement with silica fume the value of Young's modulus is 9733.33 MPa and with 100% the value is 4275 MPa. There is a significant decrease in the value of modulus of elasticity up to 50% replacement which is 7566.6 MPa. The value decreased gradually from 60% replacement, 7500.6MPa. However the final value at 100% is low when compared with other replacements.

Carbonation

Table 3.15 shows the results of carbonation of GPC. The phenolphthalein indicator was used in the test for carbonation. The indicator was used on the broken surfaces of cube specimens after they were tested for compression. The results show that there is no carbonation effect on the GPC at 28 days of ambient curing. However there is a slight reaction of carbon dioxide on the surface of the cube specimens. But there is no carbonation effect inside the surface of GPC.

Density

4.7 Density

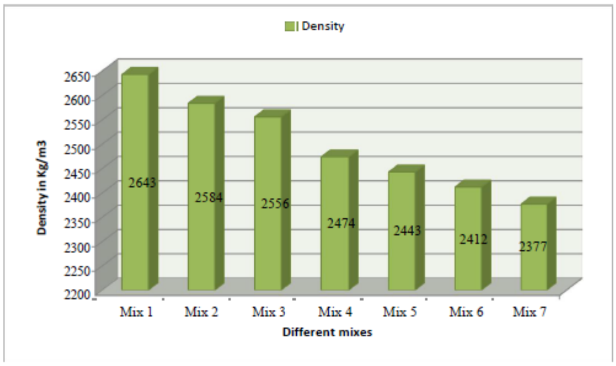

Fig.4.9 Variation in the density of GPC

Figure 4.9 shows the density of concrete with silica fume as replacement to GGBS. The densities decreased with the increase in the replacement percentage of silica fume from 0% to 100%. The densities varied from 2643 kg/m3 to 2377 kg/m3 at 28days of ambient curing. This decrease in the densities is due to low specific gravity of silica fume compared to GGBS.

Cost Analysis

Figure 4.10 gives the cost per unit weight of materials. It can be observed that sodium hydroxide (NaOH) is having the maximum cost per unit quantity and GGBS is having the minimum cost per quantity.

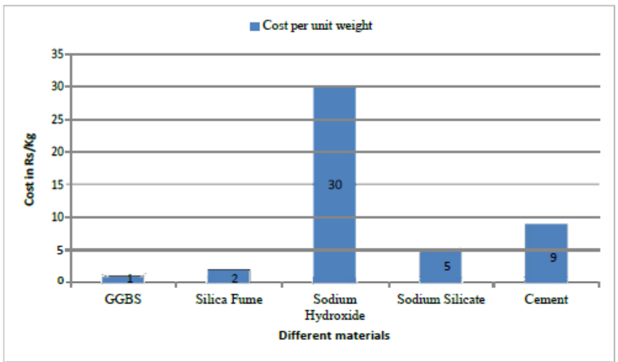

Fig.4.10 Cost per unit weight of materials used in GPC

Cost analysis for geopolymer based concrete

Cost of each material per unit quantity is already discussed. The cost incurred in producing the GPC is calculated here. Table 5.1 gives the cost details for geopolymer concrete made using GGBS and Silica Fume. Figure 5.11 shows percentage contribution of each material to the cost. Sodium silicate is the highest contributor with 44% of cost of the concrete. Sodium hydroxide is second largest contributor with 35%. Silica fume and GGBS are next with 14% and 7% respectively.

S.NO	Material	Cost(Rs/Kg)	Mix Quantities	Cost(Rs)
1	GGBS	1	0.5	0.5
2	Silica Fume	2	0.5	1
3	Sodium Hydroxide	30	0.08	2.4
4	Sodium Silicate	5	0.6	3
5	Water	0	0.41	0
6	Total			6.9

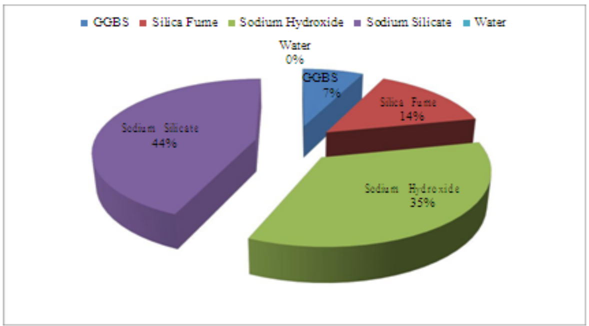

Figure 4.11 Percentage contribution of each material to the total cost of GPC

From the above table 5.1 the cost per 1 m3 of GPC for Mix 4 (50% GGBS & 50% Silica fume) is Rs.1503.2/-.

V. CONCLUSION

- The densities of the GGBS based GPC decreased with increase in the replacement percentage of silica fume. This is due to the low specific gravity of silica fume than GGBS. The density was lowest at 100% replacement (Mix 7) of GGBS with silica fume.
- In case of 100% GGBS (Mix 1) the workability and setting time of the concrete are less. Whereas for 100% replacement of Silica fume (Mix 7) the workability and setting time are more when compared with other mixes.
- Due to the presence of oxides like Al_2O_3, SiO_2, CaO and MgO, GGBS may absorb more water for the reactions with oxides. Whereas Silica fume contains 90% of SiO_2 and the other oxides like Al_2O_3, FeO, and CaO in minute quantities it may not absorb more water for the reactions with oxides.
- The presence of more water in the mix may leave minute pores in the hardened concrete which may cause reduction in the concrete strength.
- Compressive strength of GPC decreases with increase in the replacement of silica fume. Reduction in strength is continuous and significant from 0% to 50% of replacement, which is from 68.33 MPa to 30 MPa. However from 50% to 100% replacement the reduction is gradual from 33 MPa to 13.33 MPa.
- The reduction in split tensile strength is significant between 0% and 40% of replacement, which is from 3.82 MPa to 2.44 MPa. From 40% to 100% the reduction is gradual, which is from 2.44 MPa to 1.04 MPa.
- Flexural strength decreased significantly from 0% to 50% of replacement, which is from 5.12 MPa to 2.4 MPa. However from 50% to 100% replacement the reduction is gradual from 2.4 MPa to 1.6 MPa.
- The stress values for different mixes increased up to certain limit and beyond that stress decreased with the increase in strain in case of axially compressed cylinder specimens. At same strain value the corresponding stress values for different mixes (replacements) also decreased.
- The modulus of elasticity of GPC at 0% replacement is 9433.33 MPa and at 100% replacement it is 5666.6 MPa.
- The carbonation effect on the GPC is restricted to the surface of the specimens. There are no traces of carbonation in inner surfaces of concrete cube specimens at 28 days of ambient curing.
- From the cost analysis it is evident that Sodium Hydroxide (NaOH) has highest cost per individual unit quantity, which is 30 Rs per unit.
- Sodium silicate is the highest contributor with 44% of cost of the concrete. Sodium hydroxide is second highest contributor with 35%. Silica fume and GGBS are next with 14% and 7% respectively.
- The percentage increase in compressive strength from 7 days to 28 days is maximum at 100% replacement of silica fume which is 12.53% and minimum at 50% replacement with 2.04%.
- In split tensile strength the percentage increase from 7 to 28 days is maximum with 18.4% at 50% replacement and at 40% replacement it is minimum with 1.64%.

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