Strength and Durability of Fibre Reinforced Geopolymer Concrete

Rekha K P, Hazeena R
Dept. of Civil Engineering
TKM College of Engineering
Kollam ,India.
rekhakallen@gmail.com,
hazeenarrasheed@gmail.com

***Abstract— D*emand for concrete as construction material is on the increase and so is the production of cement. The production of one tonne of cement liberates about one tonne of CO_2 to atmosphere. In order to address environmental effects associated with Portland cement, there is need to develop alternative binders to make concrete. Recent years have seen a great development in new types of inorganic cementitious binders called ''geopolymeric cement'' around the world. This prompted its use in concrete, which improves the greenness of ordinary concrete. Efforts have been made to replace the cement based binder in the current fibre reinforced cement concrete with ''geopolymeric'' binder resulting in Fibre Reinforced Geopolymer Composites (FRGCs). The present work deals with study of fresh properties, strength and durability of flyash based fibre reinforced geopolymer concrete. The study is limited to geopolymer concrete with 0.25%, 0.5%, 0.75% and 1% volume fraction of steel fibres. The observations were analysed and the different attributes of the various mixes were correlated with the fibre content in the mix.**

Keywords— Geopolymer concrete; Fly Ash; Fibre reinforced Geopolymer concrete; strength; durability

I. INTRODUCTION

The climate change due to global warming is one of the greatest environmental issues during the last decade. The global warming is caused by the emission of greenhouse gases, such as CO_2, to the atmosphere by human activities. Among the greenhouse gases, CO_2 contributes about 65% of global warming .The cement industry is responsible for about 6% of all CO_2 emissions, because the production of one ton of Portland cement emits approximately one ton of CO_2 into the atmosphere[1].In order to reduce the usage of Ordinary Portland Cement(OPC) in concrete, recent environmental awareness in construction industries promote the use of supplementary cementitious materials(SCM) such as fly ash, silica fume, granulated blast furnace slag(GGBS), rice-husk ash(RHA) and metakaolin (MK)[2].

Geopolymer consist of silicon and aluminium atoms bonded via oxygen into a polymer network. Unlike ordinary Portland/pozzolanic cements, geopolymer do not form calcium-silicate-hydrates (CSHs) for matrix formation and strength, but utilize the poly condensation of silica and alumina precursors to attain structural strength. Two main constituents of geopolymer are: source materials and alkaline liquids. Any material that is rich in Si and Al in amorphous form such as fly ash, RHA, GGBS, Silica fume etc. can be a possible source material for geopolymer binder. Fly ash is considered to be advantageous due to its high reactivity that comes from its finer particle size than slag. Moreover, low-calcium fly ash is more desirable than slag for geopolymer source material [3].

Geopolymerisation involves the chemical reaction of aluminosilicate oxides with alkali polysilicates yielding polymeric Si – O – Al bonds. Water is expelled from the mixture during the curing process. A critical feature is that water is present only to facilitate workability and does not become a part of the resulting geopolymer structure.

Concrete exhibits brittle behaviour due to its low tensile strength. The addition of fibres, either short or continuous, changes its brittle behaviour to ductile with significant improvement in tensile strength, tensile strain, toughness and energy absorption capacities. Earlier studies show that addition of different types of fibres improves the mechanical properties of geopolymer concrete [4-9]. Efforts have been made to replace the cement based binder in the current fibre reinforced cement concrete with ''geopolymeric'' binder resulting in Fibre Reinforced Geopolymer Composites (FRGCs), which is greener than the former one.

Durability is another important aspect of concrete. Earlier studies revealed that geopolymer concrete composites have performed better than Portland cement composites in durability related tests such as Sulphate, acid and corrosion resistance. This is mainly due to polymeric nature of geopolymer matrix without presence of free lime. [10]

Present study investigates the strength and durability aspects of fibre reinforced geopolymer concrete based on compressive strength, flexural strength, sulphate resistance test, sulphuric acid test and bulk diffusion test.

II. EXPERIMENTAL

A. Materials

Detailed tests were conducted in the laboratory to evaluate the required properties of the individual materials. Properties of the constituent materials were tested as per the methods prescribed by the relevant IS codes.

Fly Ash: Low-calcium, Class F, dry fly ash with specific gravity 2.08, obtained from the silos of Tuticorin Thermal Power Plant in Tamil Nadu is to be used as binder. 70% of flyash was passing through the 45µm sieve. Wet sieve analysis was conducted as per IS 3812(part1):2003[11].

***Alkaline Liquid*:** A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions was used as the alkaline liquid to activate fly ash. NaOH pellets of 98% purity were used to make NaOH solution of 10 molar. The Na_2SiO_3 solution had 34.64% SiO_2, 16.27% Na_2O, and 49.09% water.

***Steel Fibre*:** Round Crimped steel fibres having diameter 0.45mm and length 25mm were used for the present study. The aspect ratio of the fibre was 55 and has a density of 7.2g/cc. Fibre was purchased from STEWOLS INDIA (P) LTD.

***Fine aggregate*:** Manufactured sand having fineness modulus 3.06 and specific gravity 2.50 was used as fine aggregate. Tests are conformed to IS: 383-1970[12].

***Coarse aggregate*:** Crushed stone aggregate of size between 20mm and 4.75mm and specific gravity 2.80 and fineness modulus 7.09 was used as coarse aggregate. Tests are conformed to IS: 383-1970[12].

***Water*:** Clean drinking water available in the college water supply system was used for mixing and preparing alkaline liquid.

Superplasticizer: The superplasticizer used was Conplast SP430 supplied by M/s Fosroc Chemical (India) Pvt. Ltd.

B. Mix Proportion

So far no standard mix design approaches are available for GPCs, since they are a new class of construction materials. So trial and error method is adopted. To obtain the mix proportion of present study, the optimum values of different parameters were adopted from previous literature [16]. In the design of geopolymer concrete mix, coarse and fine aggregates together were taken as 70% of entire mixture by mass. From the past literatures it is clear that the average density of fly ash-based geopolymer concrete is similar to that of OPC concrete (2400 kg/m^3). Knowing the density of concrete, the combined mass of alkaline liquid and fly ash can be arrived at. By assuming the ratios of alkaline liquid to fly ash as 0.55, mass of fly ash and mass of alkaline liquid was found out. To obtain mass of sodium hydroxide and sodium silicate solutions, the ratio of sodium silicate solution to sodium hydroxide solution was fixed as 2.5. For the present investigation, concentration of NaOH solution is taken as 10molar. Extra water (other than the water used for the preparation of alkaline solutions) and dosage of super plasticizer was added to the mix according to the workability desired. Five different mixes were prepared. The various mix designation is shown in Table 1**.** For all mixes other than conventional concrete, only fibre content will change and the quantity of fine aggregate, coarse aggregate, fly ash, alkaline liquid and water to binder ratio remains constant. (Fine aggregate – 588 kg/m^3, Coarse aggregate – 1092 kg/m^3, Fly Ash – 464.51kg/ m^3, Alkaline Liquid – 206.36kg/m^3,Water – 49.129 kg/m^3).

The manufacture of geopolymer concrete is carried out using the usual concrete technology methods. For present study, heat curing was adopted. Curing time and curing temperature adopted for the study was 24hrs and 80ºC respectively.

Table 1. Mix Designation

Mix No	Designation	Fly ash (%)	Fibre (%)
1	GPC	100	0
2	FRGPC 1	100	0.25
3	FRGPC 2	100	0.5
4	FRGPC 3	100	0.75
5	FRGPC 4	100	1

C. Methods

Workability: The workability was assessed by determining the compacting factor as per the **IS 1199:1959** [13] specification.

***Compressive strength*:** In the present study, compression tests were carried out on 100mm cube specimens at ages of 3, 7, 28, 56 and 90 day as per **IS:516-1959** [14]**.** The reported strength values are average of three test results.

***Flexural Strength Test*:** Flexural strength test was conducted as per **IS: 516-1959**.The standard beam specimens of size 500 x 100 x 100 mm were used for this investigation. Two-point loading was applied and breaking load was noted at 28th day.

***Sulphate Resistance Test*:** The test was conducted based on ASTM C 452-02[15] test method. After 56 days and 90 days of 20000ppm magnesium sulphate exposure, 100mm cube specimens were tested for compressive strength.

Sulphuric Acid Attack Test: To check the durability of GPC mixes against sulphuric acid, 100mm concrete cube specimens were tested based on modified ASTM C 267-01 test method. After 7 days of curing, the concrete specimens were exposed to 3% sulphuric acid solution for 56 days and 90 days, and the surface colour change and surface deterioration were studied.

Bulk Diffusion Test: The test proposes to assess the chloride attack on concrete specimen by measuring the depth of chloride penetration into the concrete specimen. This test method was based on Italian Standard (UNI) in which a chemical manifests a colour change boundary in response to the quantity of chloride ions present.

II. RESULTS AND DISCUSSIONS

This session provides a summary of the experimental results and endeavours to draw some conclusions. The test result covers the workability, mechanical properties and durability properties geopolymer concrete with and without steel fibres.

Workability: It was observed that the workability values are decreasing gradually from GPC to FRGPC. Addition of steel fibres causes decrease in workability. It might be due to viscous nature of geopolymer concrete and uneven distribution of fibres in the mix. An attempt has been made to correlate the decrease in workability of Geopolymer concrete due to the addition of fibres. Fig.1 represents this variation compacting factor with fibre content.

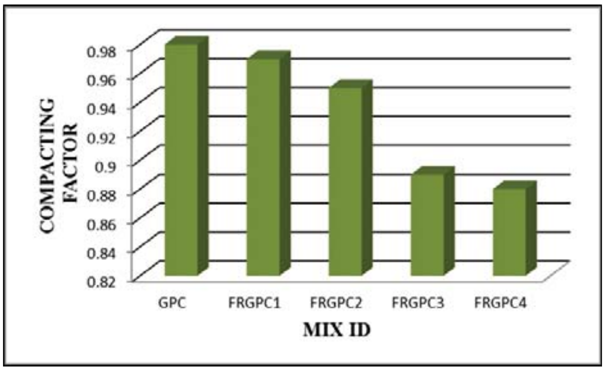

Fig. 1 Compacting factor variation

Compressive Strength test: It was noted that as the fibre content increased, the compressive strength also increased. Maximum compressive strength was obtained for FRGPC4 mix, i.e. the mix with 1% steel fibre. In GPC, as an average about 93% of strength development was observed within 3 days and 98% of strength development was observed within 7 days. FRGPC mixes are also shows the same trend. Fig.2 shows the variation for compressive strength for all the five mixes. As the volume fraction increases from 0.25 to 1%, compressive strength increases with respect to the control mix. So, unlike ordinary concrete, the rate of strength development of geopolymer concrete beyond 28th day is not significant. Because the chemical reaction of the geopolymer gel is due to substantially fast polymerisation process, the compressive strength does not vary with the age of concrete. This observation is in contrast to the well-known behaviour of OPC concrete, which undergoes hydration process and hence gains strength over the time.Fig.3 shows the variation of compressive strength with age.

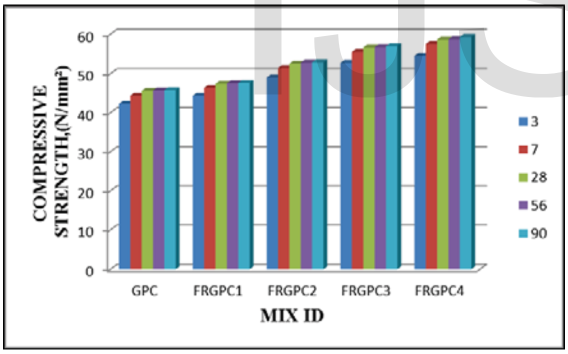

Fig. 2 Compressive strength variation for different mixes

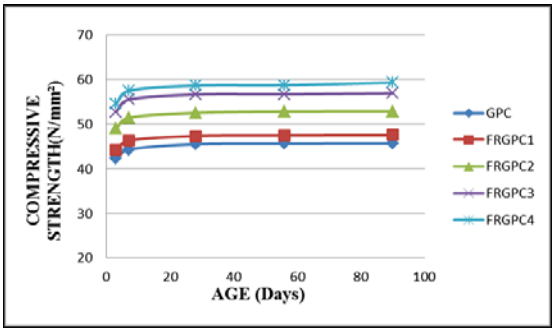

Fig.3. Variation of compressive strength Vs. Age

Flexural strength Test: As the volume fraction increases from 0.25 to 1%, flexural strength increases with respect to the control mix. The increase in modulus of rupture was about 15.01%, 23.65%, 32.76% and 42.45% for FRGPC1, FRGPC2, FRGPC3 and FRGPC4 respectively with reference to GPC mix. The increase in flexural strength is due to the effectiveness of the steel fibre in taking up the tension developed in the specimens. The maximum flexural strength was obtained as 5N/mm^2 for FRGPC4. Fig.4 shows the variation of modulus of rupture of various mixes at 28th day.

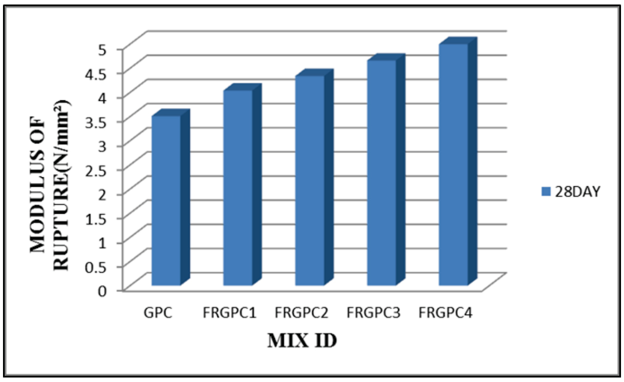

Fig. 4 Modulus of rupture for various mixes

Sulphate Resistance Test: It was observed that the visual appearance of the test specimens after soaking in magnesium sulphate solution up to 90 days revealed that there was no change in the appearance of the specimens compared to the condition before they were exposed. There was no sign of surface erosion, cracking or spalling on the specimens. It can also be seen that there was no reduction in the mass of the specimens, as confirmed by the visual appearance of the specimens. There was a slight increase in the mass of specimens due to the absorption of the exposed liquid. Figure 6 shows the compressive strength of various mixes after exposure of sulphate solution. From Fig.6 it was clear that reductions in compressive strength of mixes are very less. When comparing the each mix with 28th day compressive strength, percentage reduction in compressive strength at 56th day was 0.55%, 0.42%, 0.3%, 0.22% and 0.19% and that of 90th day was 0.93%, 0.71%, 0.59%, 0.48% and 0.29% for GPC, FRGPC1, FRGPC2,FRGPC3 and FRGPC4 respectively.

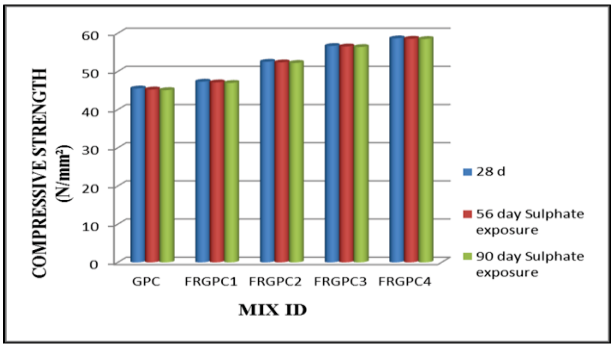

Fig.6. Compressive strength of various mixes after sulphate solution exposure

So it was observed that FRGPCs are not susceptible to sulphate attack. Because there is generally no gypsum or ettringite formation in the main products of geopolymerisation, there is no mechanism of sulphate attack in fly ash-based geopolymer concrete.

Sulphuric Acid Attack Test: The visual appearance of the geopolymer concrete specimens after soaking in sulphuric acid solution shows that GPCs undergoes erosion of the surface. Surface of the specimens get damaged due to the high concentration of acid. But the severity of damage and distortion of specimen was less. From visual appearance it was see that there was slight reduction in mass of specimen exposed to sulphuric acid. Maximum percentage of mass loss was shown by GPC mix and the value was 1.4% after 90 days of exposure. It was observed that percentage mass loss decreases with increase in fibre content. Overall percentage of mass loss after 56 days of exposure was 1% and 90 days of exposure was 1.2%. This mass loss is considerably small. When comparing different mixes percentage mass loss of FRGPC4 mix was less than that of GPC.

Figure 7 presented the variation of compressive strength of specimens exposed to sulphuric acid solution. It was observed that compressive strength of different mixes decrease with exposure period. It can also see that percentage loss of compressive strength decreases with increase in fibre content. The degradation in strength is related to depolymerisation of aluminosilicate polymers in acidic media and the formation of zeolites. From the results it was concluded that FRGPC4 mix have better acid resistance than GPC mix. It's both mass loss and strength loss were lower compared with GPC mix.

Generally geopolymer concrete exhibit excellent acid resistance because it does not produce lime (CaO) during chemical reaction. Thus it does not dissolve in acid solution.

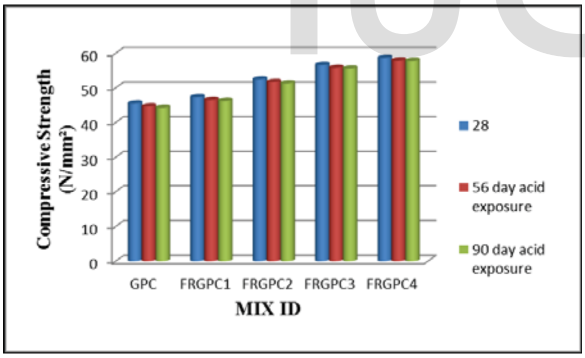

Fig.7 Variation of compressive strength of specimens exposed to sulphuric acid solution

Bulk Diffusion: No corrosion products could be found on the surface of the geopolymer materials while they were kept in the NaCl solution. The diffusion characteristics of the specimens studied to determine their resistance to chloride penetration. Variation in the depth of penetration of chloride ions in GPC mix was shown in Fig.8.

It was noted that depth of penetration decrease with increase in fibre content. The maximum depth of penetration was shown by GPC mix and minimum was FRGPC4 mix. As the fibre content increases the concrete become more dense and impermeable. So penetration of chloride ions in FRGPC was less.

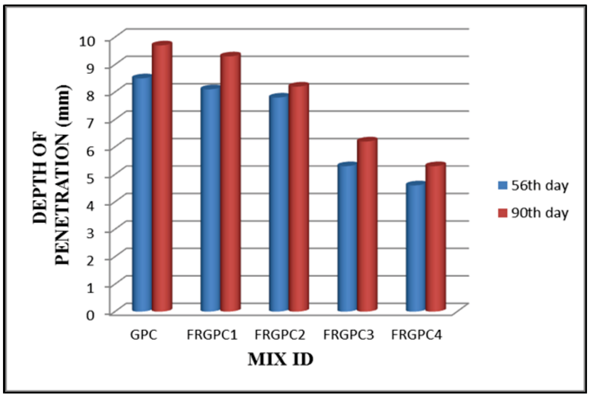

Fig.8 Variation of Depth of penetration of chloride ions

The depths of chloride ion penetration from simple immersion test are used to calculate the chloride ion diffusion coefficient (Basheer, 2001) to get an idea of permeability of concrete. The equation used is as follows:

$$Xd = 4\sqrt{Dt} \quad (1)$$

Where Xd – the chloride penetration depth in m,

t - The time of exposure in s, and

D – Chloride diffusion coefficient in m^2/s.

The calculated diffusion coefficient values are used to classify the concrete in terms of their permeability as per the recommendations of the Concrete Society as given below High permeability concrete: $>5x10^{-12}$ m^2/s

Average permeability concrete: 1 to 5 x 10^{-12} m^2/s

Low permeability concrete: < 1 x 10^{-12} m^2/s

Chloride diffusion coefficient (m^2/s) was found out using depth of penetration of chloride ions. Fig 9 shows the variation of chloride diffusion coefficient in different mixes.

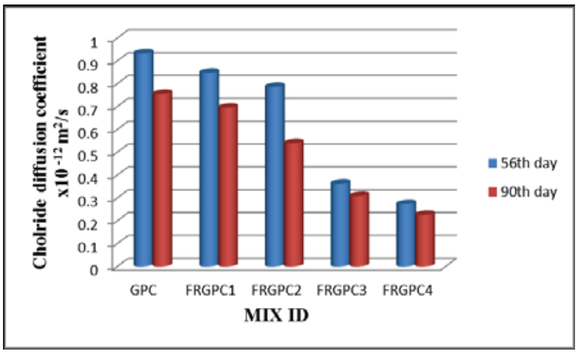

Fig.9 Variation of chloride diffusion coefficient in different mixes

Chloride diffusion coefficients of all mixes are less than

$1\times10^{-12}m^2/s$. It shows that all the mixes shows low permeability.

IV. CONCLUSIONS

From the above experimental works following conclusions could be drawn:

- Workability of the geopolymer concrete is decreased with increase of fibre content. Maximum workability was shown by GPC mix, i.e.; the mix without fibre.
- Compressive strength is increased with increased fibre content. 3rd day compressive strength was found as 93% and 7th day strength was 98% of 28th day strength.
- It was observed that compressive strength did not vary largely with age. It was found that the curing temperature adopted is sufficient for completing the polymerization process and attaining the strength.
- Flexural strength also increased with increase in percentage of fibre. The increase in modulus of rupture was about 15.01%, 23.65%, 32.76% and 42.45% for FRGPC1, FRGPC2, FRGPC3 and FRGPC4 respectively with reference to GPC mix. The maximum flexural strength was obtained as $5N/mm^2$ for FRGPC4
- The test results demonstrate that heat-cured fly ash-based FRGPC has an excellent resistance to sulphate attack. There is no damage to the surface of test specimens after exposure to magnesium sulphate solution up to 90 day. There are no significant changes in the mass and the compressive strength of test specimens after exposure. These test observations indicate that there is no mechanism to form gypsum or ettringite from the main products of polymerisation in heat-cured low-calcium fly ash-based fibre reinforced geopolymer concrete.
- FRGPC4 mix shows more acid resistant than GPC based on visual appearance, change in mass and change in compressive strength.
- It was observed that depth of penetration of chloride ion was decrease with increase in fibre content. The maximum depth of penetration was shown by GPC mix and minimum was FRGPC4 mix. Chloride diffusion coefficient (m^2/s) was found out for each mixes. As per the recommendations of the Concrete Society, all mixes comes under low permeability concrete.

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