Effect of steel fibres on the mechanical strengths of fly ash/GGBS based geopolymer concrete under ambient curing condition

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Abstract. The production of concrete involves the use of huge quantity of cement which is the main binder material. However, cement production involves the use of high amount of embodied energy and reduce of embodied CO_2 emission. Hence one of the alternatives is the use of concrete with zero cement called geopolymer. However, the main shortcoming of geopolymer is its higher brittleness and low modulus of elasticity compared to conventional cement concrete. This led to the addition of fibres to geopolymer. In this study, the effect of steel fibres addition on the mechanical strengths of ambient cured geopolymer concrete was investigated. 60% Fly ash class F and 40% GGBFS are used as binder materials to produce ambient geopolymer concrete of grade 30 MPa, which was activated by alkaline solution (mixture of sodium Hydroxide and sodium silicate) with a constant Molarity of Sodium Hydroxide as 10M without any cement. End hooked steel fibres of aspect ratio 35, were added to the geopolymer at 0%, 0.25% and 0.5% by volume fraction. The results findings showed that the workability of the geopolymer decreased with increase in addition of steel fibres. Ambient cured specimens yield good results and higher strength is observed due to high polymerization process. Furthermore, the compressive, split tensile and flexural strengths all improved significantly with increase in percentage of volume of steel fibres at any ambient curing period.

Introduction

Due to easy preparation, availability and fabrication, concrete is very widely used construction material. To produce one tonne Ordinary Portland Cement (OPC) concrete requires 150 to 250 kWh Embodied Energy (EE), produces 75–175 kg embodied carbon dioxide (ECO_2) [1, 2]. Concrete could not be replaced with other materials due to its effectiveness, performance and cost. An alternative solution is required to reduce or replace OPC as its manufacturing process is highly energy intensive and also should be eco-friendly. Use of SCM's appears to be most promising sources to manufacture Geo Polymer Concrete (GPC) because of its lower water demand, alkaline solutions and reliable rheological properties.

In above context, for a complete replacement of cement with a new binder material "Geopolymer" was introduced and it had Geopolymeric alumina silicate gel performing as binder. Geopolymer is an inorganic polymer and was developed by Davidovits in the year 1978 [3, 4]. An alkaline liquid is added to react with the silicon, aluminium present in the source materials. Geopolymer concrete mainly consists of alkaline liquid and source materials. Alkali activation of alumina and silica including blast furnace slag powder, known as GGBFS, has been found out

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since long back. Due to the activation of FA and GGBFS, alkali hydroxides and silicates were observed. Processing conditions for Geopolymer cement concretes (GPCC) are almost similar to cement concretes, except that during mixing operation of concrete, a premixed alkaline solution is added instead of water [3, 4]. The major shortcomings of geopolymer concrete in comparison to conventional cement concrete is its higher brittleness and lower modulus of elasticity [5]. To address this shortcoming of geopolymer concrete, fibres are mostly added. The fibres play a role of reducing the brittleness and increasing the ductility and elastic modulus of the geopolymer. Many types of fibres such as polyvinyl alcohol, polypropylene, glass and carbon fibres, natural fibres etc have been added to geopolymer to enhance its ductility and modulus of elasticity. Steel fibre have been reported to have give more improvement to the ductility and elasticity of geopolymer due to its high tensile strength, modulus of elasticity and fracture toughness

Therefore, the main objective of this study was to investigate the influence of steel fibres on the mechanical strengths of geopolymer concrete produced using hybrid of fly ash and GGBS as the main binder materials under ambient curing condition.

Materials and Methods

Materials

Class F fly ash was used as one of the binder materials. The properties of the fly ash are presented in Table 1. GGBFS is glassy, granular, nonmetallic material with silicates and aluminates of calcium and other bases that are used in geopolymer typically. In the present investigation GGBFS was used as another source binder material. The properties of the GGBS are also presented in Table 2.

Manufactured sand (M-sand) was used as fine aggregates instead of natural sand for sustainable development and as per available conditions. The M-sand has a specific gravity of 2.9, loose and bulk densities of 1664 kg/m^3 and 1894 kg/m^3 respectively, and water absorption of 1.2%. Crushed gravel with maximum size of 20 mm was used as coarse aggregate. The aggregate has a specific gravity value of 2.87, bulk density of 1614 kg/m^3 and water absorption of 1.96%. Hooked end type steel fibres were used in this study. The fiber has an aspect ratio (L/D) of 35, tensile strength of 1123 MPa.

Table 1. Properties of Fly Ash

Property	Requirements As Per IS 3812 Part 1 [6]	Observed Value
Fineness (m^2/Kg)	320	355
Soundness Auto Clave Expansion (%)	0.8 Max	0.06
Specific Gravity	------	2.19
Particle Retained On 45μ IS Sieve, % By Mass	34 Max	30
SiO_2+Al_2O_3+Fe_2O_3	70.0min	92.33
SiO_2	35.0min	61.24
Reactive Silica	20.0min	31.11
MgO	5.0max	1.01
SO_3	3.0max	0.1
Cl	0.05max	≤.01
Loss on Ignition (LOI)	5.0max	0.63

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Table 2. Properties of GGBS

Property	Requirement as per IS 16714 [7]	Test Result
Fineness(m^2/Kg)	320 (Min)	381
Specific Gravity	–	2.89
Residue by wet basis on 45μ (%)	–	5.00
Manganese oxide	5.50(Max)	0.21
Magnesium oxide	17.00(Max)	8.02
Sulphur Sulphide	2.00(Max)	0.52
Sulphate	3.00(Max)	0.16
Insoluble residue	3.00(Max)	0.14
Chloride content	0.10(Max)	0.005
Loss on ignition	3.00(Max)	0.39
Moisture	1.00 (Max)	0.022
Glass	85 (Min)	97.75
Initial Setting Time	more than OPC	180min
Slag Activity Index		
7 days	Not less than 60 % of control OPC 43 Grade cement mortar cube	69.78
28 days	Not less than 75 % of control OPC 43 Grade cement mortar cube	89.74
Chemical Moduli		
$(CaO+MgO+ 1/3Al_2O_3)$ / $SiO_2+2/3Al_2O_3$	1.00 (Min)	1.11
$CaO + MgO + Al_2O_3 / SiO_2$	1.00 (Min)	1.84
$(CaO + MgO + SiO_2)$	66.66 (Min)	79.96
$(CaO + MgO/SiO_2)$	>1.0	1.26
(CaO/SiO_2)	<1.40	1.03

Alkaline Solutions

10M Sodium hydroxide (NaOH) solution was prepared by dissolving pellets in the water. Sodium hydroxide (NaOH) solution must be prepared before 24 hours prior to casting and also strongly recommended that the prepared solution should not be exceeding 36 hours because it terminates to semi solid-liquid state. 10M NaOH solution consists of 400grams of solid NaOH per liter solution

The sodium silicate (Na_2SiO_3) (water glass or liquid glass) which is liquid or gel was used. In the present investigation the ratio of sodium silicate to sodium hydroxide is kept to be 1.23. Alkaline liquid was prepared by mixing of Na_2SiO_3 and NaOH at room temperature according to mix ratio considered for design. When both the solutions are mixed together they start reacting, it means polymerization starts taking place. It is to be noted that, as it liberates large amount of heat, it should be kept for about 24 hours before using it for mixing. The alkaline liquid to solid binder ratio was chosen to be 0.36.

Mix Design
Grade M30 (30 MPa compressive strength) geopolymer mix was designed based on trial and error methods. 60% Fly ash class F and 40% GGBFS were used as binder materials to produce ambient geopolymer concrete of grade 30 MPa, which is activated by alkaline solution (mixture of sodium Hydroxide and sodium silicate) with a constant Molarity of Sodium Hydroxide as 10M without any cement. The mix proportions of the conventional geopolymer is given in Table 3. The proportion of steel fibres added were 0.25% and 0.5% by volume of the geopolymer. Each mix was assigned a unique ID. Mix G-S-0, G-S-0.25 and G-S-0.5 are the geopolymer mixes with 0%, 0.25% and 0.5% steel fibres respectively.

Table 3. Mix Proportions

Mix id	Steel fibre	Fly ash	GGBFS	Sodium silicate solution	Sodium hydroxide solution	CA	FA	Water
	(%)	(kg/m^3)						
G-S-0	0.00	239	159	96	77	1111	721	52
G-S-0.25	0.25							
G-S-0.5	0.50							

Manufacturing of Fresh Geopolymer Concrete
Geopolymer concrete specimens were prepared based on the methods adopted by Rafeet, et al. [8]. As per mix proportions the Alkaline Activator Solution (AAS) was prepared one day before to the casting of fresh geopolymer concrete. The coarse aggregate and M-sand were in saturated surface dry condition. The fly ash, ground granulated blast furnace slag and the aggregates were first mixed together in pan mixer with rotation for about 3 minutes. The liquid component Alkaline Activator Solution (AAS) was then added to the dry materials gradually with addition of steel fibres and calculated free water to the mix and the mixing continued by rotating pan mixer for further about 4 minutes to manufacture the fresh geopolymer concrete. The fresh Geopolymer concrete is tested for workability tests. After the tests are performed the concrete is cast into the specimen moulds. The demoulding is done carefully to take out specimens without damaging from moulds. The weight of all specimens along with specific names was noted. After demoulding specimens were kept for ambient curing that is at room temperature till they are tested.

Experimental Methods
Workability tests namely slump cone and compaction factor tests are conducted on freshly prepared geopolymer concrete mixes before casting the specimens. Compressive strength test is carried out on cubes of size 150mm*150mm*150mm after 28 days, 56 days and 90 days of ambient curing. Following are the results for different mixes of geopolymer concrete. Split tensile strength test is conducted on cylinders of diameter 150mm and Length 300mm after 28 days, 56 days and 90 days of ambient curing. Following are the results for different mixes of geopolymer concrete. Flexural strength test was conducted on beams of size 100mm*100mm*500mm after 28 days, 56 days and 90 days of ambient curing. Following are the results for different mixes of geopolymer concrete.

Results and Discussion

Workability
Slump cone and compaction factor test results for different steel fibre reinforced geopolymer concrete (SFRGC) mixes are given in Table 4. It can be observed that that as steel fiber content in

geopolymer mix increases the slump and compaction factor values decreases. The slump and compaction factor values are higher for G-S-0 compared to G-S-0.25 and G-S-0.5. Even though the slump and compaction factor values decrease due to addition of steel fibres to concrete mixes, all mixes are in good workable stage. Due to high viscosity of geopolymer it is necessary to perform workability of fresh geopolymer. From the results it is seen that there is no balling effect of steel fibres in concrete and fibres are dispersed uniformly throughout the mix. It is also seen that for all geopolymer concrete mixes compaction factor value is less than unity. An increase in percentage of steel fiber content decreases workability of GPC due to more stiffness of steel fiber compared to 0% SFRGPC.

Table 4. Workability results of SFRGPC

Mix ID	Slump (mm)	Compaction Factor
G-S-0	198	0.90
G-S-0.25	187	0.87
G-S-0.5	178	0.84

Compressive Strength

The results of the compressive strength of SFRGPC mixes is presented in Fig. 1. It is noticed that as the age of concrete increases the compressive strength also gets increased due to continuous polymerization reaction. The addition of steel fiber resulted to enhancement of the compressive strength of the geopolymer concrete. The compressive strength of G-S-0.25 and G-S-0.5 is observed to be higher than G-S-0 at all ages. At 28 days, the compressive strength of mixes G-S-0.25 and G-S-0.5 improved by 5.8% and 8.2% respectively compared to mix G-S-0. Similarly, at 90 days the compressive strength of mixes G-S-0.25 and G-S-0.5 were superior by 7.6% and 15.6% respectively compared to mix G-S-0. The improvement in strength of the geopolymer was more pronounced at higher age of curing. This is due to the fact that the continuous polymerization led to stronger bonding between the fiber and binder matrix, hence higher strength. The improvement in compressive strength with addition of steel fiber can be ascribed to the binder mechanism as well as bond mechanism of geopolymer. As hooked end steel fiber is used, the bonding between the fiber and binder matrix is very strong which contributed to the strength improvement. Steel fibre enhanced the structural integrity of the cement matrix, delay the beginning, growth and spread of macro and micro crack, which led to significant rise in post-cracking load resistance and consequently improvement in compressive strength [9, 10].

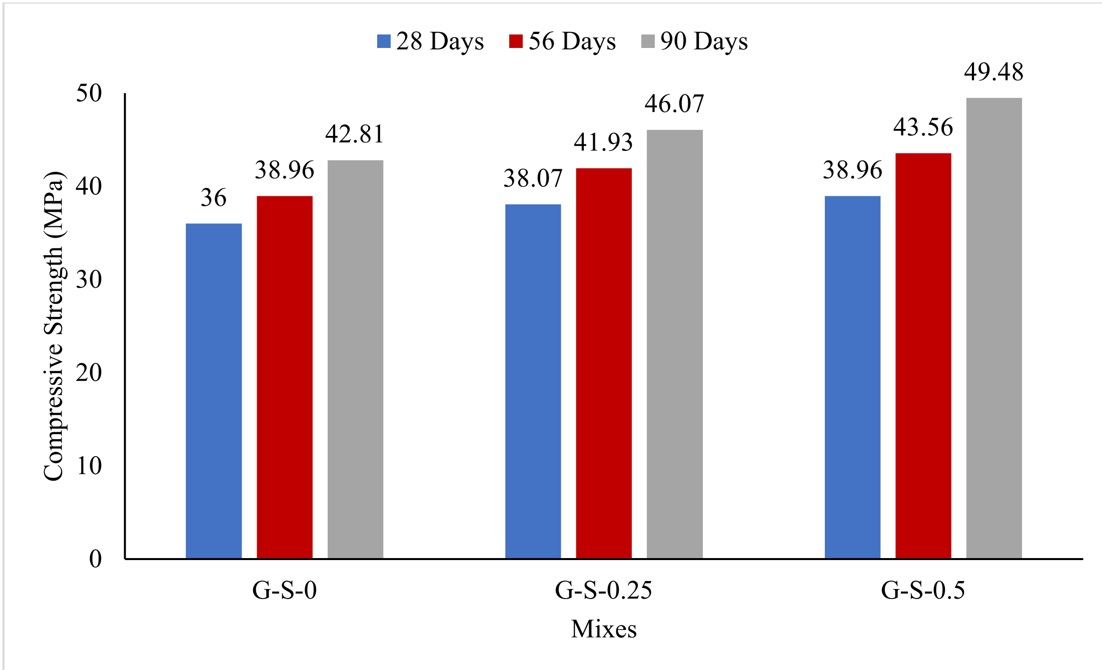

Fig. 1. Compressive Strength of SFRGPC

Split Tensile Test

The results of the splitting tensile strength of the SFRGPC mixes is presented in Fig. 2. The split tensile strength increased with age due to continues polymerization reaction of the geopolymer. The addition of steel fiber to the geopolymer concrete under ambient curing conditions led to improvement in tensile strength. The split tensile strength of G-S-0.25 and G-S-0.5 is observed to be higher than G-S-0 at all ages. At 28 days, the compressive strength of mixes G-S-0.25 and G-S-0.5 were higher by 26.9% and 44.2% respectively compared to mix G-S-0. Similarly, at 90 days the compressive strength of mixes G-S-0.25 and G-S-0.5 were superior by 17.7% and 22.9% respectively compared to mix G-S-0. The increase in split tensile strength with addition of steel fiber to the geopolymer is due to the high tensile strength of the fiber which invariable increased the tensile strength of the concrete. Additionally, the steel fiber due to its ability to prevent the occurrence, growth and propagation of cracks in the geopolymer when subjected to tensile load, enhanced the post-cracking load resistance and ductility of the concrete and hence improvement in tensile strength [11].

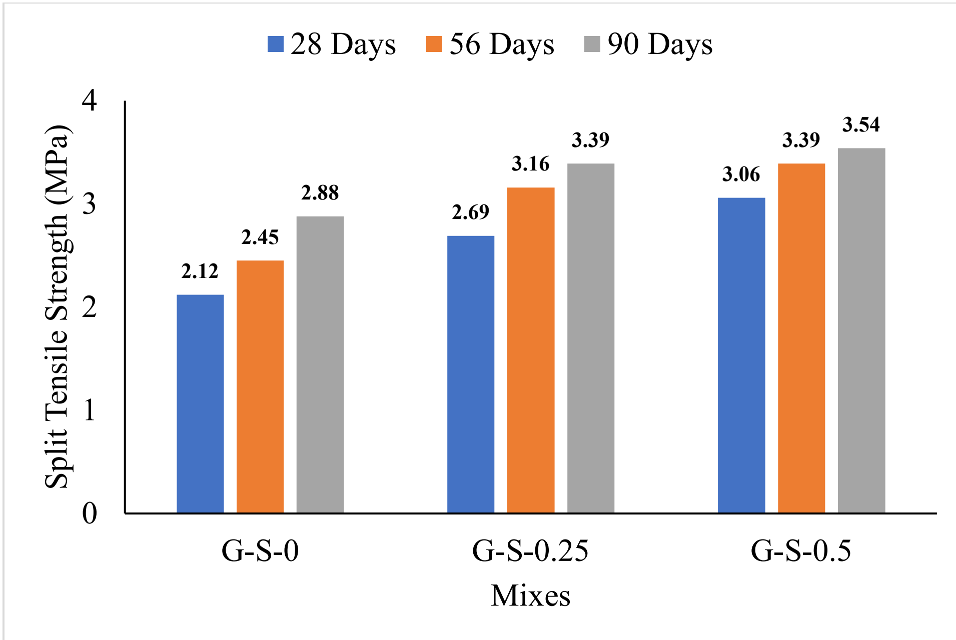

Fig. 2. Split Tensile Strength of SFRGPC

Flexural Strength

The results of the SFRGPC mixes is presented in Fig. 3. It is noticed that as the age of the geopolymer increases the flexural strength also gets increased due to continuous polymerization process. Similar to compressive and split tensile strengths, the flexural strength of the geopolymer concrete increased with increase in streel fiber content at all ages. In comparison to the control mix (G-S-0), the flexural strength of mixes G-S-0.25 and G-S-0.5 were higher by 21.5% and 42.9% respectively at 28 days, and by 19.4% and 42.1% respectively at 56 days, and 14.8% and 35.2% respectively at 90 days. One of the main reason for the enhancement in flexural strength with addition of steel fibers to geopolymer is the strong adhesion between the binder matrix and steel fiber which is better for SFRGPC compared to steel fiber reinforced concrete [12]. Additionally, steel fiber due to its high tensile loads when added to geopolymer concrete significantly improved its bending resistance. Furthermore, steel fiber due to its crack bridging through strong bonding, delay failure of the geopolymer when subjected to bending loads through redistribution and transfer of stresses across the matrix and improving the post cracking failure resistance [11, 13]

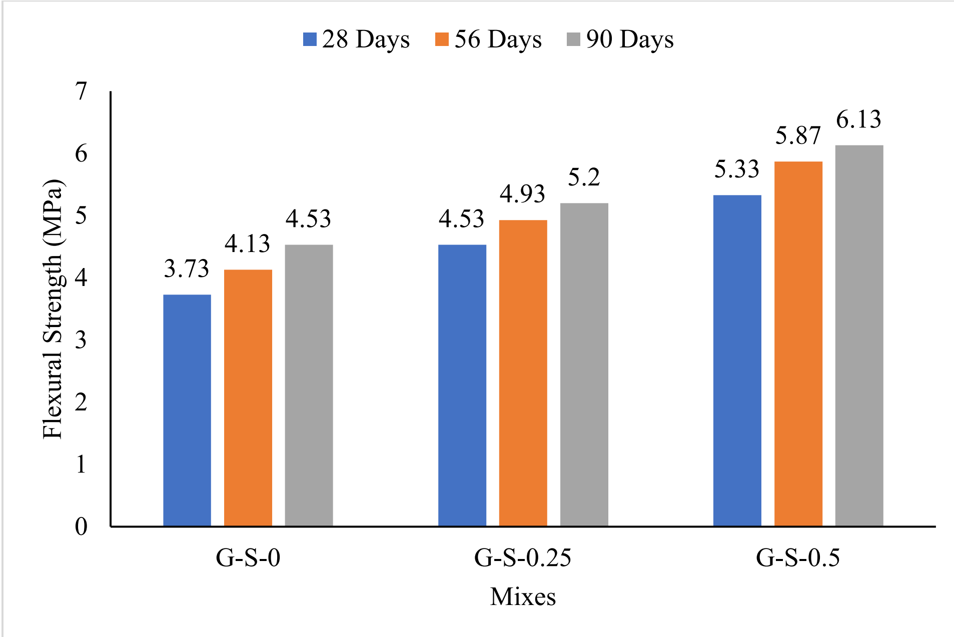

Fig. 3. Flexural Strength of SFRGPC

Microstructural Evaluation

The microstructural morphology of mix G-S-0 as obtained using scanning electron microscopy (SEM) is presented in Fig. 4. It can be observed that pores and formation of geopolymer matrix are present. The aggregate surface, reacted fly ash, reacted GGBFS, partially reacted fly ash and unreacted GGBFS can also be seen on the surface. Crystal needles and N-A-S-H gel matrix and microcracks can also be seen. Fig. 5 presents the microstructural morphology of mix G-S-0.5. In the microstructure pores, cracks, reacted GGBFS, partially GGBFS, N-A-S-H gel matrix, unreacted GGBFS, unreacted fly ash, partially reacted fly ash, reacted fly ash are observed. By comparing the morphology of mixes G-S-0 with G-S-0.5, it can be seen that the latter is more densified with less microcracks and pores compared to the former.

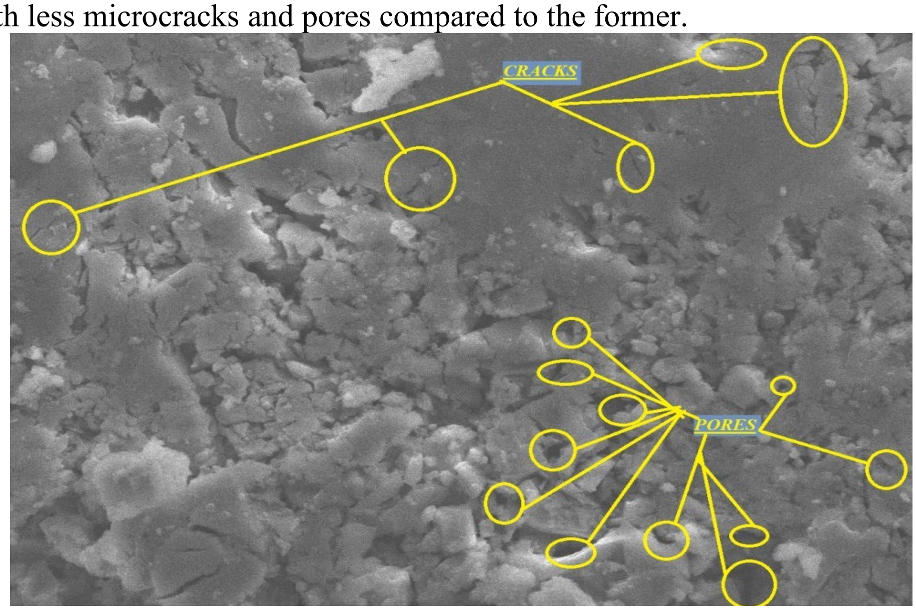

Fig. 4. Microstructural morphology of mix G-S-0.5

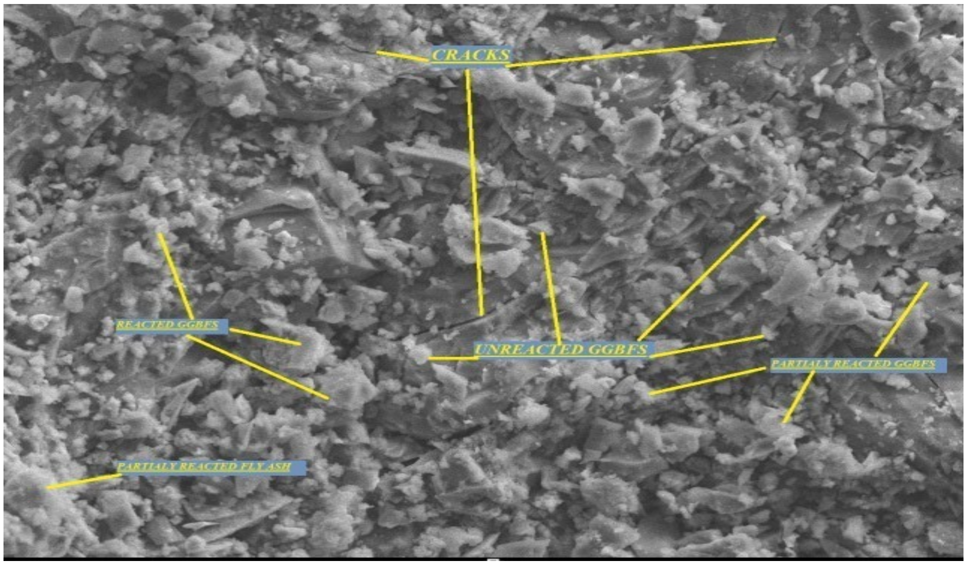

Fig. 5. Microstructural morphology of mix G-S-0.5

Conclusions

The following conclusions were drawn.

1. Workability of GPC decreases with increase in percentage of steel fibres.
2. Ambient cured specimens yield good results and higher strength is observed due to high polymerization process.
3. Compressive, split tensile and Flexure strength increases with increase in percentage of volume of steel fibres.
4. Strength of geopolymer concrete depends on binder mechanism as well as bond mechanism of concrete.
5. The addition of steel fiber densified the microstructure of the geopolymer concrete by preventing the occurrence and growth of microcracks.

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