PREDICTION OF MECHANICAL PROPERTIES OF ALCCOFINE ACTIVATED LOW CALCIUM FLY ASH BASED GEOPOLYMER CONCRETE

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ABSTRACT

Geopolymer concrete was developed with the intention to protect the environment from the carbon dioxide which liberates to the environment, as well as nature is harmed. However, geopolymer concrete had a severe limitation that silica of fly ash, which was activated through thealkalinesolution, could achieve required compressive strength only at high temperature. In the present investigation alccofine which is richer in silica and finer than fly ash has been added up to 10% of fly ash and geopolymer concrete with different fly ash content has been produced. The results are encouraging, as required compressive strength even 40MPa could be achieved at ambient temperature. Compressive and tensile strength have increased with increase in fly ash and alccofine content. The strength further increased significantly up to 90% in the presence of alccofine. Attempts were further made to relate the compressive and tensile strengthin the presence of alccofine. A relationship has been suggested which holds good for geopolymer concrete with and without alccofine at ambiently, and heat cured specimens.

Keywords: geopolymer, fly ash, alccofine, splitting tensile strength, compressive strength.

INTRODUCTION

Globally, researchers are showing high concern about reducing the CO_2 emission, claimed as one of the prominent reasons for global warming. The global concrete consumption as a construction material is second only to water, resulting in huge cement production. Estimated energy needs each ton of cement production is nearly 94.76×10^6 Joules [1], leading into estimated 5 to 7% of the total output of carbon dioxide [2]. Therefore, it is the need of the hour to develop concrete without cement as a greener alternative construction material with desirable properties. Joseph Davidovits in 1978[1] proposed the idea of geopolymer concrete (GPC), based on geopolymerisation, a primary reaction mechanism, comprising of chemical reaction of alkaline liquid activator-like NaOH or KOH with a suitable material rich in silicon and aluminium, such as fly ash [3-6], metakaolin [7-10] , silica [11], rice husk ash [12], slag [13, 14] etc., to produce geopolymer mortar as an alternate construction material. Geopolymer concrete is emerging as a new concrete, which can become a significant contributor towards environmentally sustainable development. Geopolymer is alkali-activated aluminosilicates, lowering CO_2 emission than ordinary Portland cement[15].

Researchers have reported that geopolymer concrete owns the excellent strength and its appearance is similar to that of the conventional Portland cement concrete. Rangan et al. [16-22] proposed a mix design to secure the wished compressive strength of alkali-activated concrete using fly ash.

Palomo *et al.*[16] studied different fly ash samples activated with NaOH having different molarity and heat cured at 85^0 C for 24 hr achieved a compressive strength between 35 and 40 MPa [17-19]. In an earlierstudy, geopolymer concrete for general construction has been obtained at ambient temperature [20]. Dusxon*et al*. [15], inferred in their study that geopolymer concrete showing high compressive strength, low shrinkage, fast or slow setting, acid resistance, fire resistance and low thermal conductivity can be produced by selecting the suitable raw materials and the processing conditions.

Compressive and splitting tensile strengths are two significant features in the design of the concrete structures. Although commonly concrete structures are not intended to take tensile stresses yet the knowledge of estimated tensile strength becomes necessary as it is desirable that permissible tensile stresses are not exceeded to avoid cracking. Tensile strength is important for non-reinforced concrete structures such as dams under earthquake excitation. Pavement slabs and airfield runways are designed based on bending strength, are subjected to tensile stresses[21]. Various test methods adapted to measure tensile strength are direct-tension, flexure and splitting tensile test. However, different types of tests yield different results of tensile strength. Besides its high variability, the complexity, cost and time-consuming nature of the tensile tests, many studies havesuggested assessing tensile strength through compressive strength [21] Therefore, in the design of such structures, tensile strength is equally significant as compressive strength is. Ideally, the splitting tensile strength is measured directly on the concrete samples under normalstresses. However, this is not always easy from an experimental point of view. To avoid the time-consuming direct measurements of the splitting tensile strength, the authors have tried to predict the splitting tensile strength using theoretical and empirical approaches based on compressive strength.

A significant share of research in the past has been devoted to analyzing the mechanical properties of geopolymer concrete, but a few researchers have also tried to establish the relationship between tensile and compressive strength. Indian Standard code IS 456-2000 represents a relation between the flexural tensile strength (ft) and the compressive strength (fck) of concrete by $f_t = 0.7 \times f_{ck}^{0.5}$ [22].The Canadian code gives the relationshipforconcrete strength up to 80 MPa, $f_r = 0.7 \times f_c^{0.5}$ [23]. ACI 318-95 provides the relationship between modulus of rupture (fr) and the compressive strength (fc) by $f_r = 0.56 \times f_c^{0.5}$ and recommends $f_r = 0.62 \times f_c^{0.5}$ [24]. Raphael *et al.* proposed the relationship between splitting tensile strength of concrete i.e. $f_{sp} = 0.2 \times f_c^{0.7}$ [25].

A few researchers have proposed an empirical relationship between the compressive and splitting tensile strengths of geopolymer concrete that have been discussed in (Eq. (1) - (4)) in the form of an equation $f_{sp} = k \times f_c^n$ where, f_{sp} and f_c are splitting tensile and compressive strengths in MPa, respectively. Constants k and n can be obtained from regression line analysis of the results [26-29].

Ryu *et al.* : $f_{sp} = 0.17 \times f_c^{3/4}$ (1)

Anuradha *et al.* : $f_{sp} = 0.892 \times f_c^{0.422}$ (2)

Lee *et al.* : $f_{sp} = 0.45 \times f_c^{0.5}$ (3)

Sofi *etal.* : $f_{sp} = 0.48 \times f_c^{0.5}$ (4)

This study examines the applicability of the above relationship between compressive strength and splitting tensile on alccofine activated geopolymer concrete with different mix proportions with various curing methods at different ages.

EXPERIMENTAL PROGRAMME

METHODOLOGY

In this study, nine geopolymer concrete mixes (M1 to M9) are prepared with material composition as discussed in Table-1.

Table-1. Mix proportion of geopolymer concrete.

Material (kg/m^3)	M1	M2	M3	M4	M5	M6	M7	M8	M9
Fly ash	350	350	350	370	370	370	400	400	400
FA	575	575	575	565	565	565	540	540	540
CA;7mm	269	269	269	260	260	260	255	255	255
10 mm	460	460	460	450	450	450	445	445	445
14 mm	614	614	614	600	600	600	565	565	565
NaOH	38	38	38	44.4	44.4	44.4	52.58	52.58	52.58
Na_2SiO_3	95	95	95	111	111	111	131.45	131.45	131.45
Water	36.02	36.02	36.02	31.58	31.58	31.58	27.07	27.07	27.07
AF	0.0	5.0	10.0	0.0	5.0	10.0	0.0	5.0	10.0

FA: Fine aggregates; CA: Coarse aggregates; AF: Alccofine

The mix design method adopted isin the light of that proposed by Junaid *et al*[6]. Similar to conventional concrete, coarse and fine aggregates are taken approximately 75-77% by mass of the entire mixture. The molarity of NaOH solution is selected as 16 M to achieve better compressive strength [29]. A 2% Naphthalene Sulphonate based superplasticizer is taken to improve the workability of the fresh geopolymer mix. Water to Geopolymer solids W-GPS ratio of 0.27 is used to achieve higher compressive strength. Alkaline liquid to fly ash (AL-FA) ratio is taken 0.38, 0.42 and 0.46, respectively, for GPC mixture designated M1-M3, M4-M6, and M7-M9. Alccofine 1203 content varied as 0%, 5% and 10% of fly ash content to enhance the mechanical properties.

MATERIALS

Fly ash

Low calcium fly-ash (Class F) confirming to IS: 3812 -2003 [30] is used in this investigation. The chemical compositions and physical properties of fly ash are given in Table-2.

Table-2. Chemical composition and physical properties of fly ash.

Composition (%)	**Fly Ash**	**IS 3812-2003 requirement[30]**
Silica + alumina + iron oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$): wt%	95.91	70.0 (*Min)*
Silica (SiO_2) : wt%	62.55	35.0 (*Min)*
Calcium Oxide (CaO) : wt%	0.87	*Not specified*
Magnesia (MgO) : wt%	0.39	5.0 (*Max)*
Sulphur trioxide (SO_3) : wt%	1.32	3.0 (*Max)*
Sodium oxide (Na_2O) : wt%	0.46	1.5 (*Max)*
Total chlorides : wt%	0.05	0.05 (*Max)*
Loss on ignition : wt% Fineness-specific surface, m^2/kg	0.52 321.7	5.0 (*Max)* *320 (Min)*

Aggregates

Coarse aggregates used in this study comprised of 14 mm, 10 mm and 7 mm downgraded in the saturated surface-dry (SSD) condition of specific gravity 2.60 and fineness modulus 7.10.

Water absorption value was calculated as 0.8%. Both coarse and fine aggregates confirm to of IS 383-1970[31] while fine aggregate used are crushed sand and graded as conforming to IS 2386 (Part I)-1963 [32]. Fineness modulus of fine aggregates is 2.92 with a specific gravity of 2.32 with water absorption 1.5%.

Preparation of Alkaline Solution

The alkaline solution used in this study for geo polymerization is a combination of sodium hydroxide (NaOH) and sodium silicate.

The sodium hydroxide solution of 16M (Molarity) was prepared by dissolving the pellets of NaOH with 98% purity in water. Sodium hydroxide of 16M molarity provides higher compressive strength as compared to 8M and 12 M [33]. Sodium silicate solution in gel form obtained from a local supplier is used. 16M NaOH solution is prepared and given a rest period of 24 h before mixing with sodium silicate solution because on mixing together the both solution polymerization takes place which liberates significant amounts of heat. The mixture of sodium hydroxide and sodium silicate was again given a mixing period of 24 h before using in preparation of geopolymer concrete. The mass of Sodium silicate used is 2.5 times that of the NaOH which is considered as the optimum ratio [34].

Alccofine

Alccofine 1203 (AF) is a specially processed slag based high glass content. AF control high reactivity gained because of controlled granulation. Alccofine improves the workability by reducing water demand. Strength properties of concrete get improved because of alccofine'sunique chemistry and ultra-fine particle size. Alccofine 1203 produces high-performance concrete either as a cement replacement or as an additive to improve the concreteproperties in both fresh and hardened states [35, 36]. Chemical compositions and physical properties of Alccofine 1203 used are given in Table-3 and Table-4.

Table-3. Chemical composition of Alccofine 1203.

Chemical composition	
Constituents	**Composition** (wt.%)
Iron oxide (Fe_2O_3)	1.20
Sulphur trioxide (SO_3)	0.13
Silica (SiO_2)	35.30
Magnesia (MgO)	8.20
Alumina (Al_2O_3)	21.40
Calcium oxide(CaO)	32.20

Table-4. Chemical composition of alccofine 1203.

Physical properties		
Physical property		**Result**
Buk Density(kg/m^3)		680
Specific Gravity		2.70
Particle Size Distribution (in micro metre)	d10	1.8
	d50	4.4
	d90	8.9
Specific Surface Area (cm^2/gm)		12000

A Naphthalene Sulphonate based water reducing superplasticizer confirming to IS 9103:1999 [36]is used to improve the workability of the fresh geopolymer mix.

CASTING OF GEOPOLYMER CONCRETE

Geopolymer Concrete (GPC) specimens prepared as per mix proportion in Table-1 were cured at ambient temperature for 3 days, 7days and 28 days and heat cured also. For heat curing, specimens were given a rest period of 24 hours after casting, followed by heat curing at 90^0C in an electric oven for 24 hours along with moulds. Sharma and Jindal [37] in their study suggested that

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ambient curing of geopolymer concrete results into the development of lower early compressive strength, therefore, heat and ambient curing methods were adopted to investigate the effect of higher temperature. Alccofine was used to increase the compressive as well as splitting tensile strengths [38].

Sodium hydroxide solution was prepared as mentioned above. Sodium hydroxide, sodium silicate and the required dose of superplasticizer are mixed carefully one hour advance before mixing with ingredients of concrete. Aggregates were mixed in a dry state for 5 minutes, followed by wet mixing for 10 minutes to achieve uniform mixing which considerably influences the structural properties of concrete. The concrete mixture so prepared was poured into 150 mm × 150 mm × 150 mm size steel cube moulds confirming to IS 516-1959 [39]. Six concrete cubes for each mix were cast to evaluate the average compressive and splitting tensile strength.

TEST METHODS

Compressive strength

The concrete cube moulds after a rest period of 24 hours were cured in an electric oven at 90^0C temperature for 24 hours. Compressive strength test in compliance to IS: 516-1959 [39] was performed on 3rd, 7th and 28th days of casting. Concrete cubes are also cured at ambient room temperature. Compressive strength tests were conducted on a set of 81 cube samples. All cubes were tested at room temperature (25 ± 10^0C).

Splitting tensile strength

Splitting tensile strength test confirming to IS: 5816-1999 [40]were performed on the GPC samples on 28th days of casting. Previous researchers in their study conducted a split tensile stress test on cylindrical samples of concrete[21, 26, 27,41]. However, in this study diagonal split testing was carried out as shown in Figure-1. Splitting tensile strength was evaluated as per expression $\sigma_{sp} = 0.5187 \times \frac{P}{S^2}$[41].

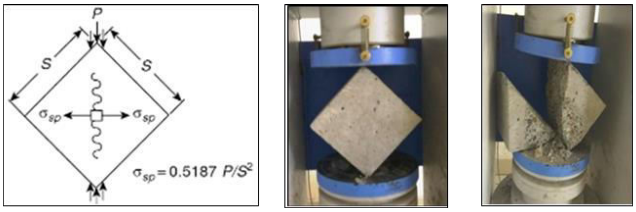

Figure-1. Split tensile strength testing of geopolymer concrete cubes.

RESULTS AND DISCUSSIONS

Compressive strength

Influence of varying fly ash and alccofine contents on compressive strength of GPC at heat and ambient curing has been explained in Figure-2 and Figure-3.

The compressive strength increased with the increase in fly ash content when the specimens were ambient as well as heat cured (Figure-2 and Figure-3). It was further observed that the compressive strength reached to 42MPa from 21MPa (M1 and M7, Figure-2) at the age of 28 days when flyash content increased from 350 kg/m^3 to 400 kg/m^3.However, it was observed in both curing methods that increase in strength was less in the case of a GPC mix with the lower fly ash content than at higher fly ash content.

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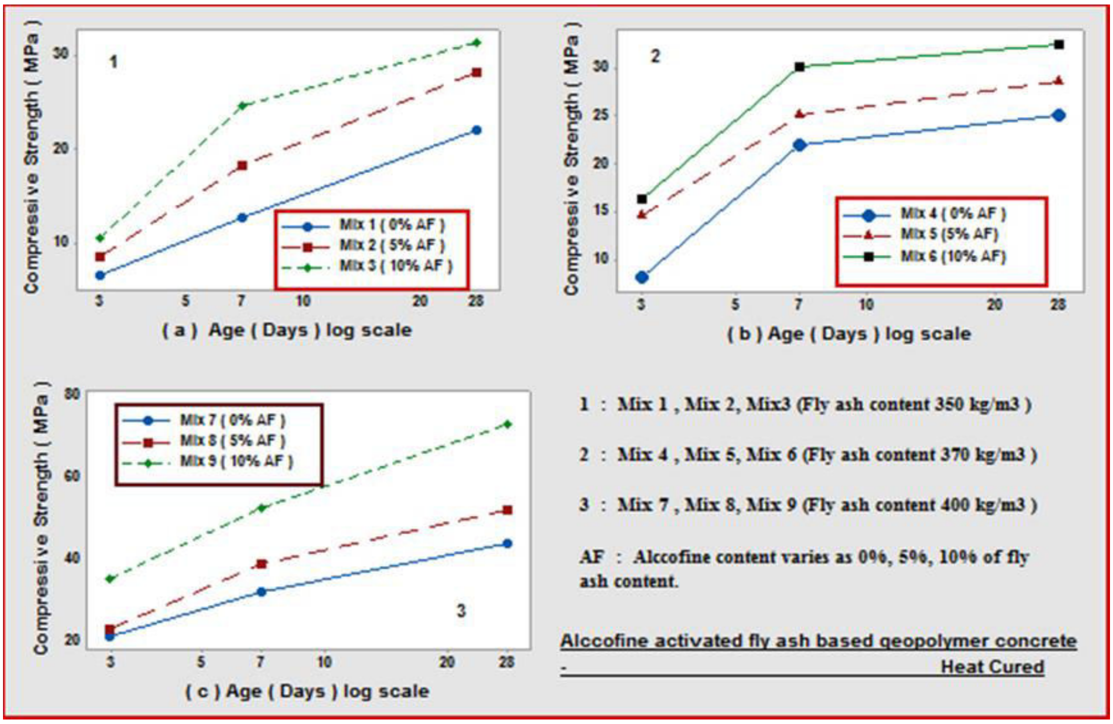

Figure-2. Compressive Strength of Geopolymer concrete with varying fly ash, age and alccofine content at Heat curing.

Similar patterns of increased compressive strength had been observed for the alccofine activated GPC when the specimens were heat and ambient cured. Figure-2 and Figure-3 show increase of early-age compressive strength of alccofine added GPC (M2 and M3) in the range of 20% to 45% when the alccofine content was increased from 5% to 10%. However, the increase in compressive strength was significantly higher up to 62% and 90% at the age of 28 days on heat curing and ambient curing, respectively, at 10% alccofine when compared to M1 (without alccofine).

It can, therefore, be seen that using alccofine target strength for M25 grade concrete can be achieved using ambient curing (M3, M6, and M9). There remains no doubt that heat curing makes alccofine more efficient at higher fly ash content and the same specimens could achieve 73 MPa (M9). This indicates that geopolymer concrete with alccofine can be well used for general purpose and for precast industries.

SPLITTING TENSILE STRENGTH

Splitting tensile strength test confirming to IS 5816-1999[40] was conducted at the age of 3 days, 7 days and 28 days with varying fly ash as well as alccofine content. Influence of variation in fly ash content, alccofine content, and curing type on splitting tensile strength at the age of 3 days, 7 days and 28 days is shown in Figure-4 and Figure-5.

Effect of alccofine

Figure-4 demonstrates the increase in splitting tensile strength at 5% alccofine content in the range of 10%-22 % and 10%-50 % at heat curing and ambient curing respectively. An increase of 10%-25% and 7 %-25% in splitting tensile strength was observed on addition of 10% alccofine in the case of heat cured, and ambient cured respectively. All the results were in comparison to geopolymer concrete without alccofine. So a significant increase in splitting tensile strength is observed on addition of alccofine.

Effect of fly ash content

Figure-5 shows a nominal increase in the splitting tensile strength of 2.5 % and 10.75 % on increasing fly ash content from 350 kg/m^3 to 370 kg/m^{3}at ambient cured and heat cured respectively. A significant increment of 56% and 71% was observed on increasing fly ash content from 350 kg/m^3 to 400 kg/m^3 at ambient and heat cured conditions, respectively. Above results correspond to geopolymer concrete mix design of grade M15 (M1), M20 (M4) and M35 (M7) as per Table-1. It is concluded from the results that splitting tensile strength increases significantly with increase in compressive strength of geopolymer concrete in the case of heat curing.

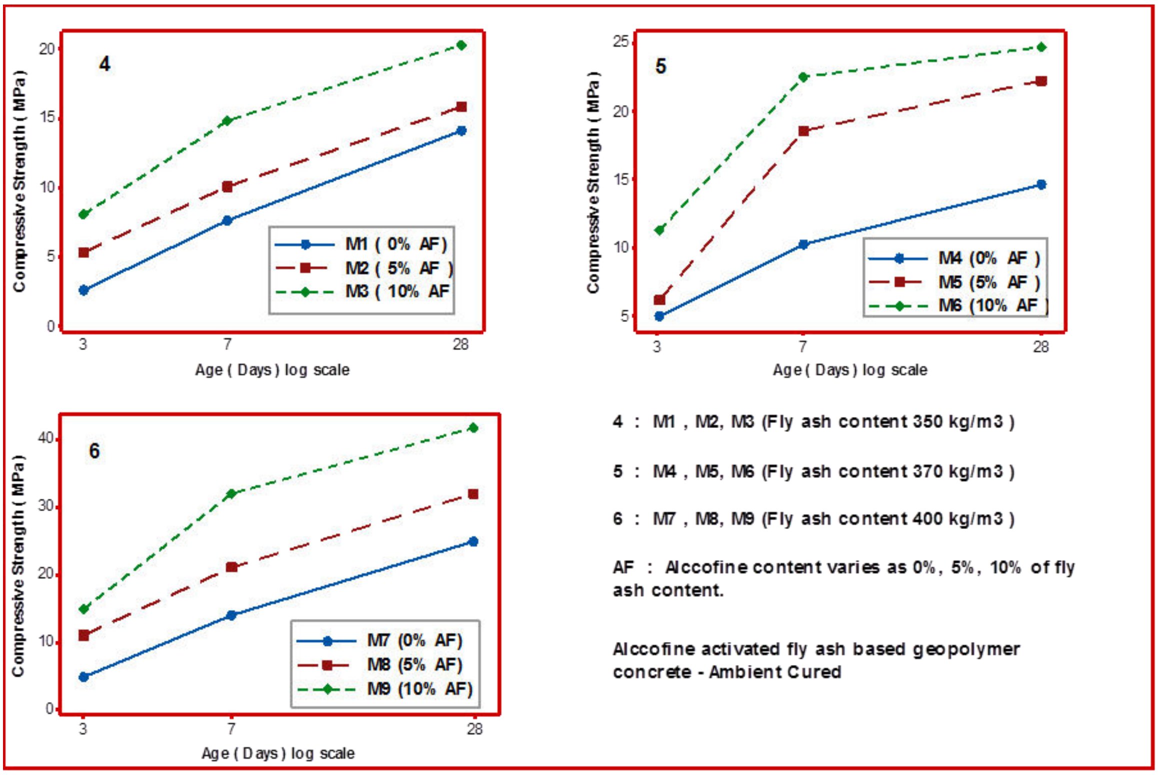

Figure-3. Compressive strength of geopolymer concrete with varying fly ash, age and alccofine content at ambient curing.

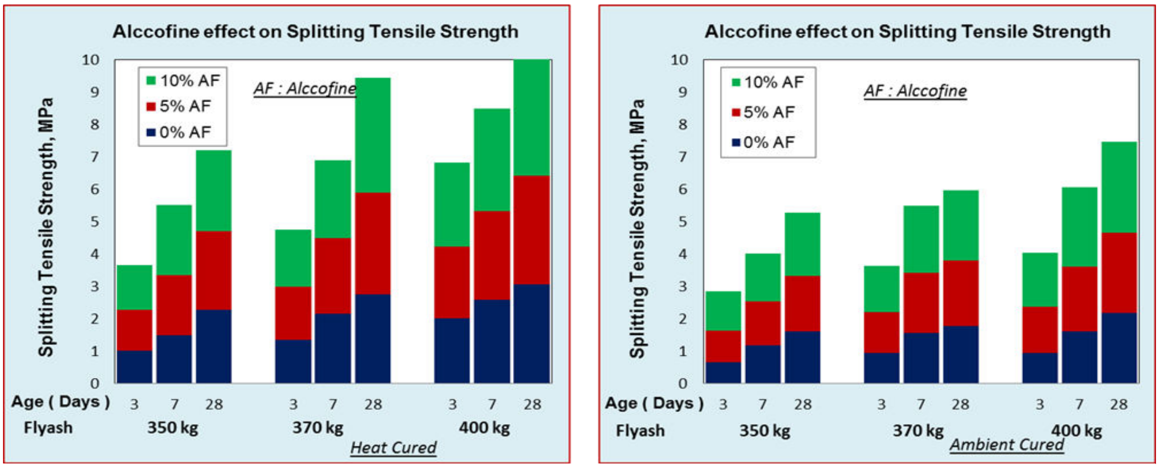

Figure-4. Effect of alccofine on splitting tensile strength.

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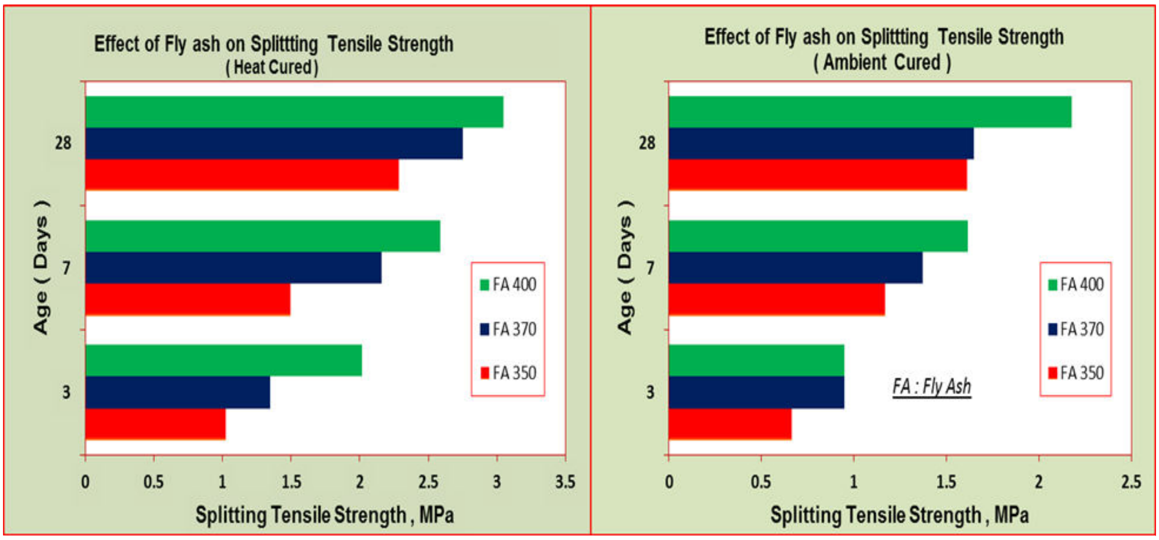

Figure-5. Effect of fly ash content on splitting tensile strength.

Relation between compressive and splitting tensile strengths of geopolymer concrete

Previous researchers depicted a close relationship between splitting tensile and compressive strengths of concrete. Nonlinear equations proposed were based on regression analysis of thetensile and compressive strength of concrete. Literature revealed that when compressive strength increases, the rate of increase of the tensile strength decreased [25] and the same results had also been observed in this investigation.

In this study, the relationship between compressive and
Splitting tensile strengths is developed considering the properties of ingredients of geopolymer concrete and the effects of curing temperature. Figure-6 shows that the development of splitting tensile strength and the compressive strength of alccofine activated fly ash based geopolymer concrete at heat cured condition, as well as ambient curing, is significantly higher than the geopolymer concrete with no alccofine.

The relationship between the compressive strength and tensile strength for alccofine activated fly ash based geopolymer concrete is proposed by equations (5) and (6) for ambient cured and heat cured respectively.

$$f_{spt} = 0.4146 \times f_c^{0.515} \quad (5)$$

$$f_{spt} = 0.355 \times f_c^{0.58} \quad (6)$$

It can be concluded from the Figure-6 that the regression line for geopolymer concrete does not depend on the variables like the alkaline solution, fly ash and other parameters. It has a direct relationship with the compressive strength similar to ordinary concrete. It can also be noted that the change in the mechanical strength observed was less than 15% for all the cases.

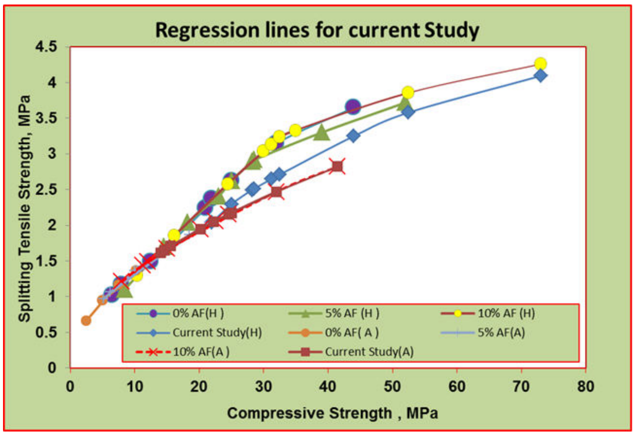

Figure-6. Relationship between compressive strength and splitting tensile strength of geopolymer concrete.

Regression line curves are drawn for geopolymer concrete based upon existing relationships [26, 28,29] and result obtained from the current investigation. Figure-7 compares the regression lines proposed for present study and previous studies by other researchers.

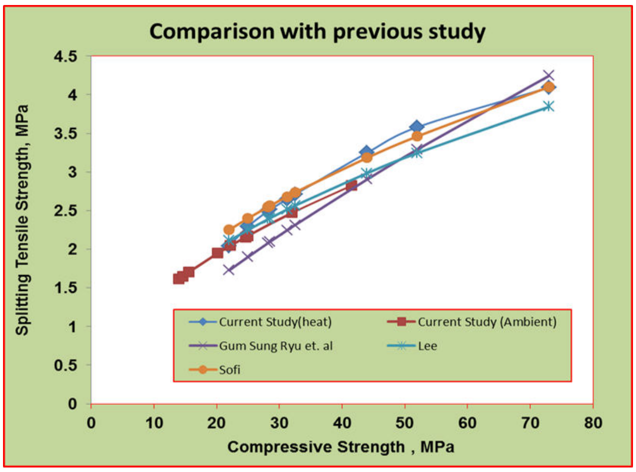

Figure-7. Comparison of current and existing study.

The current investigation is done toexamine the trend of the regression line for alccofine based GPC and efforts are done to explore the applicability of the regression equations obtained between split tensile strength and compressive strength for alccofine activated low calcium fly ash based geopolymer concrete with the existing relationships. The slopes (n) and the intercepts (k) values of equation proposed by other researchers as well as obtained in the current study are tabulated in Table-5.

It can be concluded from Table-5 that the slope of regression line obtained in this study is very similar to that obtained by other researchers.

Table-5. Properties of theregression line.

S. No.	Source	Slope, n	Intercept, k
1.	Gum Sung Ryu et al.[26]	0.75	0.17
2.	Lee *et al*[42]	0.5	0.45
3.	Sofi *et al*[43]	0.5	0.48
4.	Current Study (Ambient Cured)	0.515	0.4146
5.	Current Study (Heat Cured)	0.51	0.422

As the variation in the slopes of the regression line is less than 15% for all the mixes so, it can be concluded that relationship line for the alccofine activated geopolymer concrete at heat and ambient curing is much similar to the GPC prepared without alccofine.

CONCLUSIONS

The present study summarizes the use of alccofine as raw material along with fly ash in GPC and found to exhibit better properties than the GPC without alccofine. Based on the above results and discussions presented following conclusions can be derived upon.

Increased amount of fly ash and presence of alccofine achieves better compressive strength as well as tensile strength.

Heat curing plays an important role while achieving the compressive and split tensile strength. However, theminimum required compressive strength forgeneral construction purpose can be attained with alccofine even at room temperature.

The improvement in compressive and split tensile strength is significant at 90^0C in the presence of alccofine and perhaps provides an opportunity for themost economical and sustainable way to achieve higher strength.

The proposed relationship between compressive and tensile strength applies to geopolymer concrete with and without alccofine.

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