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Enhancing mechanical and durability properties of geopolymer concrete with mineral admixture

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Abstract. This paper approaches to improve the mechanical and durability properties of low calcium fly ash geopolymer concrete with the addition of Alccofine as a mineral admixture. The mechanical and durability performance of GPC was assessed by means of compressive strength, flexural strength, permeability, water absorption and permeable voids tests. The correlation between compressive strength and flexural strength, depth of water penetration and percentage permeable voids are also reported. Test results show that addition of Alccofine significantly improves the mechanical as well as permeation properties of low calcium fly ash geopolymer concrete. Very good correlations were noted between the depth of water penetration and compressive strength, percentage permeable voids and compressive strength as well as between compressive strength and flexural strength.

Keywords: geopolymer concrete; microstructure; permeability; water absorption; flexural strength; compressive strength; permeable voids

1. Introduction

Geopolymer concrete is a special type of concrete which does not utilize Portland cement as a binder in its production process. Davidovits in 1978 coined the term ‘geopolymer’ as an inorganic polymer resulting from geopolymerisation i.e., polycondensation reaction of alumina–silicate source materials such as fly ash, rice husk ash, and metakaolin, yielding three-dimensional tecto-aluminosilicate frameworks (Davidovits 2005). Geopolymers have the potential to address the issues of the storage and disposal of industrial wastes which are rich in silica such as fly ash, rice husk ash, ground granulated blast furnace slag etc. Geopolymer is energy efficient having energy need of 30% in comparison to OPC (Li *et al.* 2004).

Researchers have shown that elevated temperature cured geopolymer concrete can achieve mechanical properties comparable to conventional concrete (Bakharev 2005a, Guo *et al.* 2010, Noushini *et al.* 2016, Jindal *et al.* 2016, Jindal *et al.* 2018). Several studied has reported in past investigating the mechanical properties of fly ash based geopolymer concrete such as compressive strength (Adam 2009, Rajini 2014, Alanazi *et al.* 2017, Jindal *et al.* 2017a), split tensile strength (Anuradha *et al.* 2011, Arıoglu *et al.* 2006, Lavanya and Jegan 2015, Jindal *et al.* 2017b), flexure strength (Vijai *et al.* 2012, Manjunatha *et al.* 2014, Mehta and Siddique 2017), stress-strain relationship (Manjunatha *et al.* 2014) etc.

Pradip *et al.* (2015) suggested blending of OPC in fly ash based GPC to improve mechanical properties at ambient curing (Nath *et al.* 2015). Mineral admixtures generally proved to be very effective in reducing permeability. Silica fume and fly ash combination resulted in significantly improving the permeability of concrete (Deilami *et al.* 2017). Alccofine 1203 can also be used as an additive to enhance the mechanical properties of GPC at early ages (Jindal *et al.* 2016, Jindal *et al.* 2017a). It is established from the earlier studies that geopolymer concrete possesses acceptable mechanical properties. Geopolymer concrete can be promoted in commercial applications, but prior to that, the durability characteristics of GPC need to be investigated and ascertained.

Several studies have investigated the factors affecting the durability of geopolymer concrete such as effects of corrosion (Kupwade-Patil *et al.* 2011, Shaikh and Afshang 2014), acid resistance (Ariffin *et al.* 2013, Bakharev 2005b, Hewayde *et al.* 2006), permeability (Mehta and Siddique 2017, Rajamane *et al.* 2011, Shane *et al.* 1999, Yang and Cho 2014). It needs to mention here that in most of the investigations of permeability characteristics, rapid chloride permeability test (RCPT) was adopted (Adam *et al.* 2009, Rajamane *et al.* 2011, Ramana *et al.* 2016, Zannerni 2016, Venkatesan and Pazhani 2016, Bondar *et al.* 2012).

RCPT is not the direct permeability measuring test as its name indicates. It does not measure permeability but the ionic movement. Also, the flow of all ions, not just chloride ions, affects the test result (the total charge passed) (Stanish *et al.* 2000).

The RCPT to assess the ability of concrete to resist the

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penetration of chloride ions has been in practice for many years. Many scientists and researchers globally have criticized the rapid chloride permeability test (RCPT) - ASTM C1202 because of its lacking in the scientific base and tough testing conditions (Andrade 1993, Arup *et al.* 1993, Feldman *et al.* 1994, Pfeifer *et al.* 1994, Streicher and Alexander 1994, Scanton and Sherman 1996, Cao and Meck 1996, Shi *et al.* 1998). The conductivity of the free pore fluid increases with increased temperature, and in RCPT the applied electrical potential heats the concrete specimen, thus affecting the flow speed (McCarter *et al.*, 2000). Shi (2004) observed that the transport of ions in concrete get influenced by the pore structure of the concrete, but RCPT results depend on both the pore structure characteristics and electrical conductivity of the pore solution (Shi 2004). ASTM C1202 specify the rating of chloride permeability of concrete based on the charge passed (coulombs) through the concrete specimen in six hours of the testing period. RCPT tests conducted on concrete with fly ash have shown a reduced charge passed value, but its chloride penetration depth indicates that it does not have low permeability. Thus, it can be concluded that RCPT is inappropriate to assess the permeability of geopolymer concrete which contains materials such as fly ash or rice husk ash or ggbfs along with Alccofine.

In this study, an effort has been made to investigate and improve the mechanical and durability properties of low calcium fly ash based geopolymer with alccofines. Alccofine was added up to 10% percent by weight of fly ash into class F fly ash-based geopolymer. Water permeability test was conducted on GPC cube specimen of size 150 mm, after 28 days according to the German code DIN-1048 (Part5) which gives the water permeability in terms of depth of water penetration. DIN -1048 (Part 5) test didn't provide any relationship of water permeability in terms of quantity of flow of water, therefore, water absorption and percentage permeable voids tests were also performed on GPC specimen at the age of 28 days to evaluate relative porosity in accordance to ASTM C 642-82 (ASTM 1997).

2. Research significance

The durability of geopolymer concrete is one of the prominent aspects which needs to be investigated. Concrete need to perform satisfactorily in the working environment when subjected to the anticipated exposure conditions during service life. The porosity of concrete influences the migration of alkali ions into geopolymer concrete, the moisture and then have an effect on the mechanical strength and durability (Okoye *et al.* 2017). Water permeability directly influences the durability of concrete. In the current study, geopolymer concrete specimens were tested for water permeability in terms of depth of water penetration along with investigating the water absorption and percentage permeable voids which validates the depth of water penetration test of permeability. A correlation has also been developed between the compressive strength and depth of water penetration. The effect of the addition of Alccofine has also been studied.

Table 1 Chemical composition and physical properties of fly ash

Composition (%)	Fly ash	IS 3812-2003 requirement
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%	0.52	5.0 (Max)
Fineness-specific surface, m^2/kg	321.7	320 (Min)

Table 2 Chemical composition & physical properties of Alccofine 1203

Chemical Composition		Physical Properties	
Constituents	Composition (wt.%)	Physical Property	Results
Iron oxide (Fe_2O_3)	1.20	Bulk Density (kg/m^3)	680
Sulphur trioxide (SO_3)	0.13	Specific Gravity	2.70
Silica (SiO_2)	35.30	Particle Size Distribution (in micro metre) d10 d50 d90	1.8 4.4 8.9
Magnesia (MgO)	8.20		
Alumina (Al_2O_3)	21.40		
Calcium oxide (CaO)	32.20	Specific Surface Area (cm^2/gm)	12000

3. Experimental design

Since the compressive strength, porosity, permeability, and durability are interdependent parameters. of geopolymer concrete. The compressive strength of GPC specimens prepared by varying fly ash and Alccofine content at the age of 3 days, 7 days and 28 days were investigated. The curing regime of ambient temperature and heat curing at 90 degrees were adopted. Water permeability depth of GPC was investigated at the age of 28 days of curing as per German standards DIN–1048 (Part 5). The water absorption and permeable voids test for conducted in accordance with ASTM C 642-82 (ASTM 1997).

3.1 Materials and experimental methods

3.1.1 Materials

The chemical compositions and physical properties of the fly ash and Alccofine obtained from the suppliers' data sheets are presented in Tables 1-2. Low calcium (Class F) fly ash, sourced by Ultra Tech RMC Plant, Panchkula Haryana, used as a source of aluminosilicate with specific gravity 1.95 and 96% passing through 45-micron sieve, confirming to IS 3812 -2003 (BIS 2013). Alccofine 1203 (AF), a low calcium silicate microfine material based on blast furnace slag with high reactivity through controlled granulation sourced from Ambuja Cements Ltd, Andheri

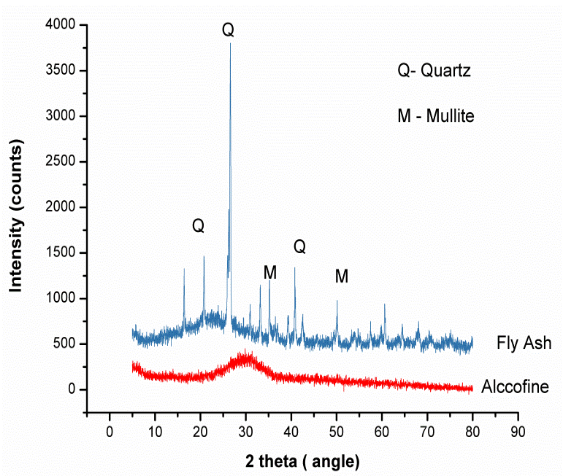

Fig. 1 XRD of fly ash and alccofine 1203

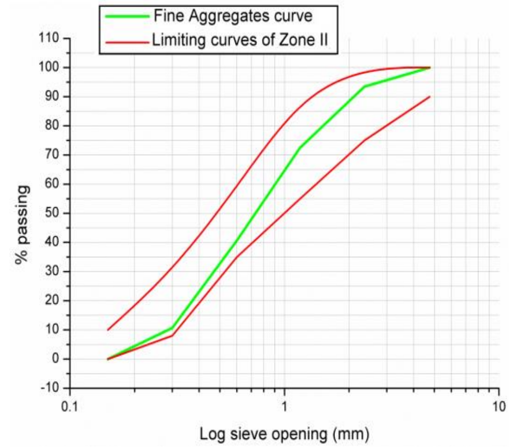

Fig. 2 Particle size distribution of fine aggregates

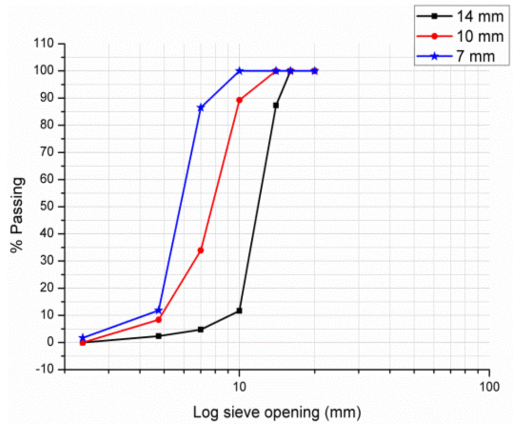

Fig. 3 Particle size distribution of coarse aggregates

East, Mumbai. Alccofine is used to improve the workability and porosity of geopolymer concrete. Alccofine due to its high calcium oxide content also results in accelerated polymerization process thus enhancing the mechanical strength properties of GPC. The XRD analysis of fly ash and Alccofine is shown in Fig. 1.

XRD pattern of fly ash shows clear sharp peaks mainly the crystalline phases in fly ash sample are mullite (JCPDS card no. 15-776) and quartz (JCPDS card no. 5-490) together with the amorphous component by X-ray diffraction (XRD) analysis. Mullite (Alumina silicate) shows peaks at 16.520, 35.59°, 42.61° of 2θ values (d spacing of 5.36, 2.52, 2.12 Å). The quartz exhibits peaks at 20.835°, 26.66°, 42.61°, 54.93° of 2θ values (d-spacing of 5.36, 2.52, 2.12 Å). The fly ash also constituents in amorphous phases is identified as a broad diffraction hump in the region between 12 to 30 degrees (2θ). The amorphous phase consists of amorphous silica and alumina. The XRD pattern of Alccofine shows a broad hump between 220 and 350 indicates its amorphous nature. Further, it can be seen that Alccofine shows a low number of peaks meaning no crystalline phase are detectable in the Alccofine. Due to no crystalline phase and having small ultrafine particle size indicate that the Alccofine may have a high degree of reactivity (Jindal *et al.* 2017a).

The most commonly used alkaline solution comprising a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) is used as an activator in preparing geopolymer. Sodium hydroxide pellets with 98% purity and sodium silicate solution with SiO_2/Na_2O=1.2.144 and density of 1.46 g/cm^3 was used in this study. The sodium hydroxide solution of 16M (Molarity) was prepared by dissolving 444 g pellets of NaOH per kg of solution (water+pallets). The mass ratio (alkali activator/geopolymer binder) of 0.5 taken for the mix design calculations as per the mix design methodology suggested by Junaid *et al.* (2015) and previously adopted by author (Jindal *et al.* 2017a).

Coarse aggregates used in this study comprised of 14 mm, 10 mm and 7 mm downgraded in size in saturated surface-dry (SSD) condition, of specific gravity 2.60, fineness modulus 7.10 and water absorption value is 0.8%. Particle size distribution of fine and coarse aggregates is shown in Figs. 2 and 3, respectively. Both coarse and fine aggregates are confirming to IS 383-1970 (BIS 1970). Fine aggregates used are crushed sand and graded as conforming to IS 2386 (Part I)-1963 (BIS 1963) having fineness modulus 2.92, the specific gravity of 2.32 and water absorption 1.5%.

3.1.2 Specimen preparation and curing

The mixing of alkali solution of sodium hydroxide with water releases a large amount of heat, therefore, 16 M solution was prepared at room temperature and given a rest period of 24 hours, as mentioned earlier, prior to mixing with sodium silicate solution. The mass ratio (Na_2SiO_3/NaOH) of 2.5 is taken considering the optimum ratio (Pawar and Saoji 2013).

The sodium hydroxide solution then mixed with sodium silicate and was again given a mixing period of three to four hours. A Naphthalene Sulphonate based high-range water reducer at 3% dosage by weight of total fly ash content was added to the alkaline solution before mixing with dry materials to minimize the water requirement and improve the workability of the fresh geopolymer mix.

The geopolymer concrete mixing was done according to specifications given in IS 516-1959 (BIS 1959). The concrete mixture was prepared by mixing fly ash, Alccofine and aggregates in an 80-liter capacity rotating pan mixer and subsequently, the liquid components (i.e., premixed

Table 3 Mix proportion of geopolymer concrete. material content (kg/m^3)

	M1A0FA	M1A5FA	M1A10FA	M2A0FA	M2A5FA	M2A10FA	M3A0FA	M3A5FA	M3A10FA
Fly ash,	350	350	350	370	370	370	400	400	400
Fine Aggregate	575	575	575	565	565	565	540	540	540
Coarse Aggregates 7mm, 10 mm, 14 mm	269	269	269	260	260	260	255	255	255
	460	460	460	450	450	450	445	445	445
	614	614	614	600	600	600	565	565	565
NaOH solution	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
Alccofine, %age of Fly ash	0.0	5.0	10.0	0.0	5.0	10.0	0.0	5.0	10.0

alkaline activator solution along with the dose of superplasticizer and extra water) was added gradually to the pan mixture for about 5 minutes.

The mixture proportion of Geopolymer specimens with different flyash and Alccofine contents is shown in Table 3. Nine number of GPC mixes were prepared with a varying fly ash content as 350,375 and 400 kg/m^3 along with varying Alccofine as 0%, 5% and 10% of fly ash by weight. The water/geopolymer solids ratio was taken 0·27 for all the nine mixes. The total mass of water includes water in the sodium silicate solution and any extra free water, and the mass of geopolymer solids includes the mass of fly ash, alkaline hydroxide solids, and alkaline silicate solids. Since these solids contribute to the 'geopolymerisation process' so they are termed as geopolymer solids.

After mixing the concrete specimens of 150 mm size cubes were prepared to conform to IS 516-1959 (BIS 1959). An electrically operated vibration table was used for compaction of cube moulds. Cube moulds were covered with polythene and kept at ambient temperature before un-moulding. The specimens were un-moulded after 48 hours and then kept wrapped in polythene paper to avoid moisture loss at room temperature till the period of testing for ambient curing testing. For heat curing regime the cube specimens along with steel moulds were kept in electrically operated hot air furnace for a period of 72 hours to accelerate the polymerization reaction. Heat cured specimens were un-moulded and wrapped in polythene sheets to keep at room temperature till their testing period.

3.1.3 Testing

A series of tests were performed on specimens to ascertain their properties as illustrated below.

3.1.3.1 Compression test

A compression strength test on 150 mm size cubes was performed using an electrically operated compression testing machine (Aimil 2000 kN capacity).

The cube specimens were subjected to a compression load at the rate of 5.2 kN/s till the failure of the specimen. The test was performed on 3rd, 7th, 28th days of casting at room temperature as per IS 516-1959 (BIS 1959) and the average results of three cubes were reported.

3.1.3.2 Flexural tensile strength

Flexural strength testing was performed on the beam specimens of size 15 cm×15 cm×70 cm in a flexural testing machine by applying the load to the upper surface along two lines spaced 20 cm apart. The maximum load applied at failure was recorded to calculate the flexural strength as per IS- 516 (BIS 1959).

3.1.3.3 Water permeability as per DIN 1048

The Water permeability of geopolymer concrete was determined through permeability tests on cube specimens of size 150 mm, after 28 days according to the Germann water permeability DIN -1048 (Part 5) (DIN 1991). The resistance against water of GPC with different fly ash and alccofine content was investigated. Three cube specimens were placed in the permeability cell and subjected to a constant water pressure of 0.5 N/mm^2 applied at the bottom surface in a way to force the water to penetrate into the specimens for a period of three days. It was inspected that whether the unexposed faces of specimen show any signs of water penetration if so the specimen was rejected. The pressure was released after three days and the specimens were removed from apparatus. The specimens after drying for five minutes were split down along the tested direction at the center of the face which was exposed to water. The depth of water penetration was measured. The variation in depth of water penetration was recorded to analyze the effect of fly ash and alccofine content. The concrete with the depth of water penetration less than 30 mm is termed as low, 30-60 mm as medium and greater than 60 mm as high permeable as per DIN 1048 (Part 5).

3.1.3.4 Permeable voids and water absorption

Water absorption of concrete is closely related to the permeability. Water absorption testing of concrete measures the absorbed mass of water per unit mass of the pre-dried concrete material, after complete immersion in water until saturation is reached. Water absorption is expressed in terms of the volume percent of permeable pores. The water absorption test was performed on GPC specimen at the age of 28 days in accordance with ASTM C 642-82 (ASTM 1997). GPC specimen of 150 mm cube size was kept in a hot air oven at 105°C for 24 hours, and the same step repeated till the difference in mass obtained with previous value was negligible.

Permeable voids (%)=$((A\text{-}B)/V)\times 100$; where A=Weight of surface dry saturated specimen after 28 days immersion period. B is the weight of oven dried specimen. V is the

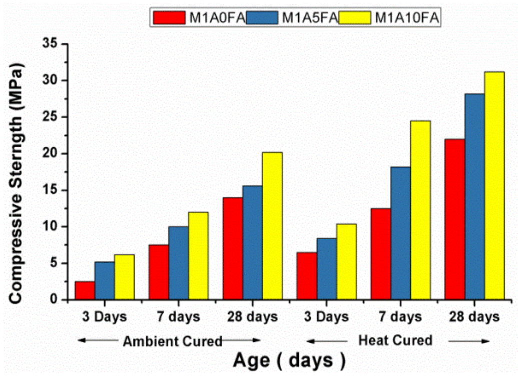

Fig. 4 The compressive strength of GPC (fly ash 350 kg per cubic meter) with varying alccofine

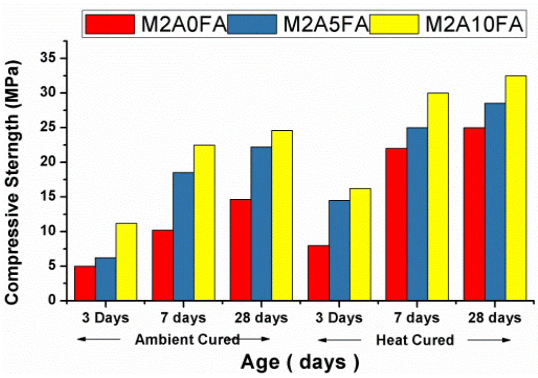

Fig. 5 The compressive strength of GPC (fly ash 370 kg per cubic meter) with varying alccofine

volume of GPC specimen.

Air cooled specimens were then completely immersed in water, and weight gain was measured until a constant weight is achieved. The initial surface absorption (IA%) value after 30 minute and final absorption value were recorded when the difference between two consecutive weights was practically negligible. IA% value was then compared with recommendations of Euro-International Committee for Concrete (CEB) (Concrete *et al.* 1989). The concrete with initial surface absorption percentage less than 3.0 is termed as having low absorption rate indicating good quality concrete as well as having more than 5.0 as poor quality concrete.

3.2 Results and discussions

The test results so obtained are shown and discussed in detail in the following paragraphs.

3.2.1 Compressive strength

The compressive strength results of geopolymer concrete with different fly ash and Alccofine contents at ambient and heat curing conditions are shown in Figs. 4-6.

It was observed that the early age (7 days) compressive strength of GPC increased from 7.5 MPa to 14 MPa on increasing the fly ash content from 350 to 400 kg/m^3 at ambient curing. A significant increase in 28 days compressive strength of 25 MPa from 14 MPa was observed at ambient curing.

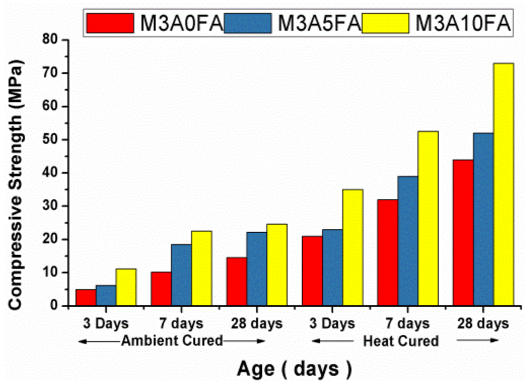

Fig. 6 The compressive strength of GPC (fly ash 400 kg per cubic meter) with varying alccofine

Increased fly ash resulted in an increased quantity of binding material which provides more surface area with increased Si-Al bond for polymerization resulted in the development of more denser concrete which further improved the compressive strength (Jamkar *et al.* 2013, Jindal *et al.* 2017a). A higher increase of 44 MPa from 22 MPa was observed at heat curing conditions at the age of 28 days. Heat curing results in an intensive polymerization reaction which increased the compressive strength (Palomo *et al.* 1999).

The effect of the addition of Alccofine was also studied. The 28 days compressive strength was increased from 14 MPa to 20.2 MPa on the addition of 10% Alccofine with 350 kg/m^3 of fly ash at ambient curing. It was also observed that the 28-day compressive strength increased from 25 MPa to 42 MPa on increasing Alccofine content from 5% to 10% Alccofine with 400 kg/m^3 of fly ash content at ambient curing. A similar pattern was also observed in heat cured specimens. A significantly higher compressive strength of 73 MPa was achieved when 10% Alccofine was added to 400 kg/m^3 at heat curing.

Alccofine due to its average particle size of 4 to 6 microns and having blain fineness of more than 12000 cm^2/gm significantly improves the packing density of paste component and hence improved the compressive strength of geopolymer concrete. Moreover, Alccofine having CaO nearly 30-33% results into accelerated polymerization reaction.

The alccofine due to inherent calcium oxide content results in hydration reaction which produces calcium silicate hydrate (CSH) along with the formation of an alkaline aluminosilicate hydrate gel such as sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H) which is considered as the primary reaction product of polymerization reaction in geopolymer materials (Alonso *et al.* 2001, Granizo *et al.* 2002, Li *et al.* 2013, Alehyen *et al.* 2017). The CSH along with CASH/NASH results in an enhanced cementing material which is responsible for the development of early ages compressive strength (Yip *et al.* 2008, Granizo *et al.* 2002).

3.2.2 Flexural strength

The Flexural strength of low calcium geopolymer

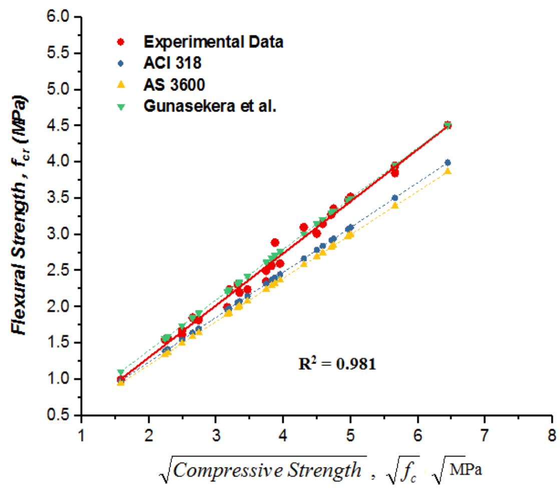

Fig. 7 The relationship between flexural and compressive strength

concrete also followed the pattern similar to compressive strength with and without Alccofines. Fig. 7 shows a scatter graph of flexural versus the compressive strengths. A linear regression line fitting shows the relationship between the two variables. The proposed regression relationship is shown in Eq. (1), where 'f_{cr}' is the mean flexural strength and 'f_c' is the mean compressive strength. The proposed relationship shows the similarity with the relationships recommended by ACI 318, AS 3600 and

Gunasekera *et al.* (2017) and is illustrated in Fig. 7.

$$f_{cr} = 0.718\sqrt{f_c} \tag{1}$$

3.2.3 Water permeability

The effect of binder content and Alccofine on the depth of water penetration of geopolymer concrete at ambient and heat curing are shown in Figs. 8 and 9, respectively. The effect of fly ash and Alccofine content can be seen through the observation of the test results for all type of GPC specimens. It was observed that the depth of water penetration reduced from 33 mm to 27.5 mm and 30 mm to 23 mm on increasing the fly ash content from 350 to 400 kg/m^3 at ambient and heat curing respectively. Further, it was also observed that a minimum depth of water penetration of 10 mm was achieved at fly ash content of 400 kg/m^3 on the addition of 10% Alccofine.

Increased fly ash and Alccofines results in increased glass microspheres of SiO_2, Al_2O_3, and Fe_2O_3. The glass microspheres of silica and alumina in fly ash further react with $Ca(OH)_2$ generated from Alccofine due to the presence of calcium oxide and produce calcium aluminate and hydrated calcium silicate with the higher cementing property, which significantly improves the packing density by minimizing micropores of geopolymer concrete. Therefore, increased flyash and Alccofines results into improving in strength and durability properties (Sinsiri *et al.* 2010, Nath *et al.* 2011, Zhang *et al.* 2013, Jindal *et al.* 2017c).

The depth of water penetration provides a qualitative indication of the durability of GPC. Further, the depth of

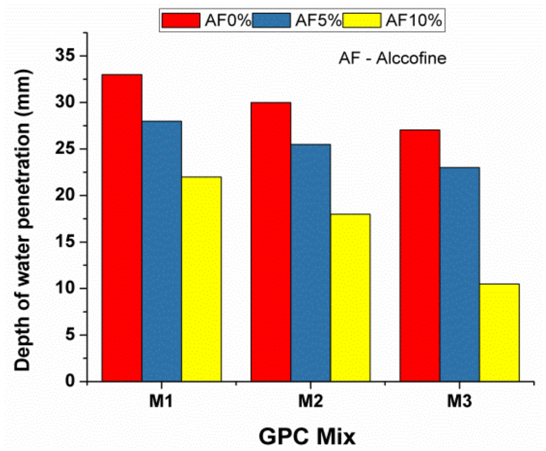

Fig. 8 The permeability of geopolymer concrete with varying alccofine at ambient curing

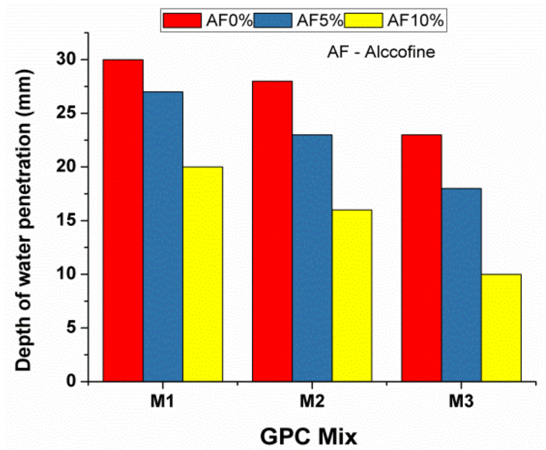

Fig. 9 The permeability of geopolymer concrete with varying alccofine at heat curing

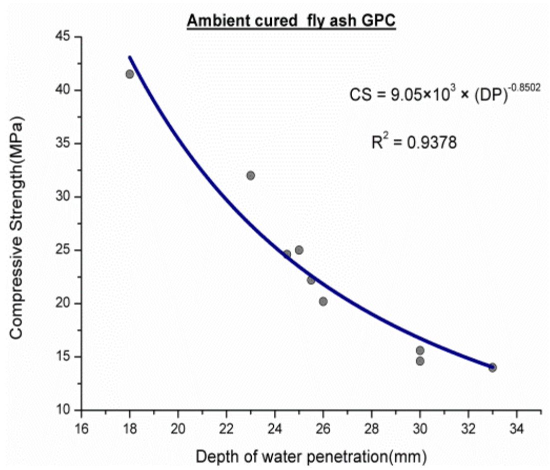

Fig. 10 The relationship between compressive strength (ambient cured) and permeability

penetration, micropore structure of concrete, compressive strength and durability are correlated to each other.

The best-fit equations and the coefficients of correlation (R^2) obtained by statistical analysis of the experimental data are shown in Figs. 10 and 11 for ambient and heat curing, respectively. The correlation coefficients more than 0.80

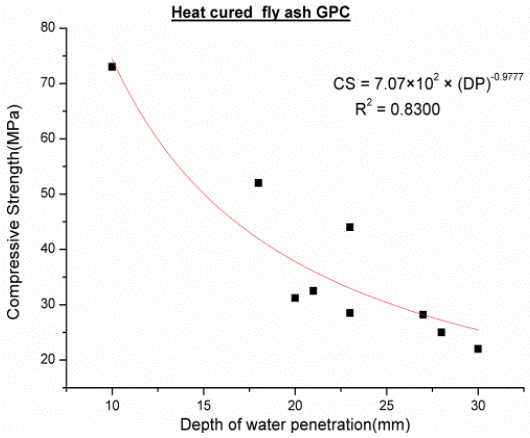

Fig. 11 The relationship between compressive strength (heat cured) and permeability

CS-Compressive Strength, DP-Depth of penetration

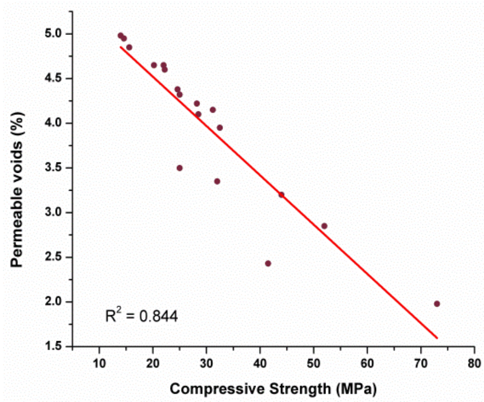

Fig. 12 The relationship between permeable voids and compressive strength

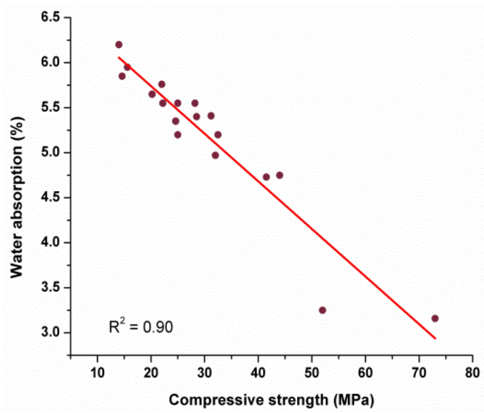

Fig. 13 The relationship between water absorption and compressive strength

indicates a good correlation between the depth of water penetration and compressive strength.

3.2.4 Water absorption and permeable voids

As mentioned earlier the water absorption indicates a number of accessible microcracks and air voids in concrete which is strongly related to the permeability of the concrete is also considered a relevant parameter about the performance of concrete (Kandil *et al*. 2017). An initial water absorption in 30 minute and final water absorption after 72 hours for geopolymer concrete specimens were measured. It was observed that water absorption value was significantly reduced from 6.2% to 5.85 and 5.2% on increasing fly ash content from 350 to 370 and 400 kg/m^3, respectively, during ambient curing. The same decreasing trend was followed by heat curing also. A minimum of 4.73% and 3.16% water absorption value was achieved at higher fly ash content along with 10% Alccofine at ambient and heat curing respectively.

To further ascertain the porosity of geopolymer concrete permeable voids (PV%) testing was also performed. The observed results of PV% also strengthen the observations of water absorption as well as compressive strength results.

The best-fit regression line between permeable voids and compressive strength are shown in Figs. 12 and 13 for ambient and heat curing, respectively. The R^2 value more than 0.80 shows a good correlation between the permeability in terms of permeable voids and compressive strength of geopolymer concrete.

4. Conclusions

The geopolymer concrete produced using three different low calcium fly ash contents with the addition of Alccofine 1203 (a low calcium GGBFS based microfine material) in different percentages of fly ash. The compressive strength, flexural strength, permeability, water absorption and permeable voids volume were studied experimentally. The ambient curing at 27-degree average temperature as well as heat curing at 90-degree Celsius was adopted. The statistical relationships in terms of regression line fitting to predict the correlation between compressive strength with flexural strength, depth of water penetration and permeable voids in geopolymer concrete were also studied.

The prominent conclusion drawn from the study are presented as follows:

• The 28 days compressive strength of geopolymer concrete achieved by low calcium fly ash based geopolymer concrete is in the range between 14.0-25 MPa and 22-44 MPa at ambient and heat curing respectively. A significantly higher compressive strength of 41.5 and 73 MPa is achieved at higher fly ash 400 kg/m^3 with 10% Alccofine content at ambient and heat curing respectively. Alccofine due to its unique microfine structure and higher calcium content results in the formation of CSH gel along with aluminosilicate hydrate gel such as sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H) which significantly improves the compressive strength. It is concluded that a reasonably good compressive strength can be achieved at both curing conditions but in the presence of Alccofine.

• A very good correlation (R^2=0.981) exists between the flexural and compressive strengths of low calcium fly ash-based geopolymer concrete. The flexural strength is 0.718 times the square root of average compressive strength which is very close to the relation suggested by

IS-456 (2000) and Gunasekera *et al.* (2017) in their studies. The relationship between flexural and compressive strengths is independent of the type of curing method.

• There exist a good linear relationship and between compressive strength and depth of water penetration in geopolymer concrete. The coefficient of correlation R^2 is 0.9378 and 0.83 for ambient and heat curing specimens respectively. The value of R^2 more than 0.80 is accepted as a good correlation between two variables. This correlation shows the good refinement of the pore structure of geopolymer concrete with increased compressive strength. With the increase in compressive strength, there would be a decrease in water permeability due to the improvement in micro-structural characteristics. In other words, the more the depth of water penetration, lesser would be its compressive strength.

• A linear relationship (R^2=0.844) between permeable voids percentage and compressive strength also shows that both the parameters are closely related. With the increase in permeable voids in geopolymer concrete, lesser would be its compressive strength which further justifies the depth of water penetration pattern.

• From the above-discussed results, it can be concluded that increase in fly ash content along with Alccofine fairly improves the mechanical strength as well permeability properties which result in the enhanced durability of low calcium fly ash based geopolymer concrete.

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