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Feasibility study of ambient cured geopolymer concrete –A review

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Abstract. Geopolymer concrete is a fastest developing field of research for utilizing industrial and agro waste materials as an alternative for Portland cement based concrete. Geopolymers are formed by the alkaline activation of aluminosilicates rich materials termed as geopolymerization. The process of geopolymerization requires elevated temperature curing which restricts its application to precast industry. This review summarizes the work carried out on developing the geopolymer concrete with the addition of various mineral admixtures at ambient curing temperature conditions. An overview of studies promoting the geopolymer concrete in general building construction is presented. Literature study revealed that geopolymer concrete with the addition of admixtures can exhibit desirable properties at ambient temperature conditions.

Keywords: geopolymer concrete; ambient curing; admixtures; compressive strength; durability

1. Introduction

Worldwide concrete consumption as a construction material owing to its wide-ranging mechanical properties, better performance, suitability, easy application, and cost-effectiveness encourages the manufacturing of cement on a gigantic scale. The global cement demand is estimated at over 4.216 billion metric tons in 2018 as per International Cement Review Research Report (2017). The estimated approximately 94.76×10^6 Joules/ton of energy is spent in cement production process per year (Davidovits 1994), resulting into estimated 5 to 7% of the total output of carbon dioxide (Mehta 2001) which is considered as a prominent reason to accelerate global warming.

Growing industrialization further leads to the release of waste by-products such as fly ash, rice husk ash, ground granulated blast furnace slags, which are pozzolanic in nature. Further, environmentally compatible dumping of waste materials by suitable techniques is of serious concern imposing thought-provoking technical challenges.

The world earth summits also expressed their concern about the increased emission of greenhouse gases to the atmosphere (Malhotra 1999), which warn cement industry to switch over from Portland cement to a greener alternative binder with desirable structural properties.

Davidovits in 1978 coined the term ‘geopolymer’ to represent a broad range of materials

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characterized by chains or networks of inorganic molecules and also pointed out the possibility of geopoymers being used by Egyptians in the construction of pyramids (Davidovits 1984). The special features of the geopolymer such as the development of high early strength and better resistance to chemical attacks attracted the interest of scientists in cement and concrete research area. Geopolymers so used were environmentally friendly materials which did not emit greenhouse gases during the polymerization process. Unlike Ordinary Portland cement, geopolymer did not require calcium-silicate-hydrate (C-S-H) gel for matrix formation and developing strength but utilized the polycondensation of silica and alumina precursors to achieve required mechanical strength properties.

The main constituents of Geopolymer are source material rich in silicon (Si) and aluminum (Al) and alkaline activator solutions. The source materials for Geopolymer could be natural minerals such as kaolinite, clays, and industrial by-products such as rice husk ash, GGBFS, fly ash, silica fume, and red mud. The alkaline liquids used as an activator for the geopolymerisation process may be a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na_2SiO_3) solution. Water in a geopolymer mixture plays no significant role in the chemical reaction taking place and aids in producing a workable mixture (Sreevidya 2014).

Palomo *et al.* (1999), Xu and Van Deventer (2000) reported that the waste materials such as slag, fly ash and metakaolin which are calcined in nature are mostly the amorphous types which accelerate the geopolymerisation process (Xu and Van Deventer 2000, Bakharev 2004). Fly ash-based geopolymer concrete attains better compressive strength by the formation of aluminosilicate gel which is rich in alumina content during the initial stage of alkaline activation of fly ash particles and further increased due to the formation of silica enrich material (Fernandez-Jimenez *et al.* 2006).

The curing process of geopolymer concrete (GPC) differentiates it from conventional concrete. Unlike conventional concrete, water curing is not used in GPC. Heat curing i.e. steam curing and dry curing is generally used to activate the chemical reaction that takes place in geopolymer matrix. Research conducted so far has suggested that low calcium fly ash based geopolymer shown better mechanical properties at heat cured regime (Lloyd and Rangan 2010, Sujatha *et al.* 2012, Patil *et al.* 2014, Shekhovtsova *et al.* 2015, Neupane *et al.* 2016) but not at ambient temperature curing conditions (Sharma and Jindal 2015). Curing in which GPC is left exposed to air under ambient temperature termed as ambient curing could also be employed to cure the Geopolymer concrete.

Geopolymer concrete cured at ambient temperature has shown poor compressive strength (Nath *et al.* 2015, Sharma and Jindal 2015, Xie and Ozbakkaloglu 2015, Jindal *et al.* 2017a). Several researchers focused their study on improving the mechanical strength and durability properties of geopolymer concrete with the blending of ordinary Portland cement (Nath and Sarker 2015), ground granulated blast furnace slag (Supraja and Rao 2012, Inti *et al*. 2016, Venkatesan and Pazhani 2016), nano-silica (Zhang *et al*. 2012, Adak *et al*. 2014, Deb *et al*. 2015, Adak *et al*. 2017) and Alccofine (Limited 2014, Jindal *et al*. 2016, Jindal *et al*. 2017a, Jindal *et al*. 2017b) at ambient temperature curing.

In India, the ambient temperature varies mostly in the range of 15-48°C. The acceptability of ambient temperature curing is high but the main drawbacks of adopting ambient temperature curing are that the geopolymerization reaction needs higher temperature curing. The rate of geopolymerization reaction necessary influences the rate of gain of strength. Moreover, the heat curing mechanism itself is highly cumbersome and costly which necessitated the development of geopolymer concrete at ambient curing conditions.

Table 1 The composition of fly ash

Composition %	SiO_2	Al_2O_3	CaO	MgO	SO_3	Na_2O	Total Chlorides	Loss on Ignition	Fineness
Fly Ash (Jindal *et al.* 2017**a**)	62.55	27.78	0.87	0.39	1.32	0.46	0.05	0.52	321.7
Fly Ash (Adak *et al.* 2014)	64.97	26.64	0.33	0.85	0.33	0.49	---	0.45	---
Fly Ash (Nath and Sarker 2015)	53.71	27.20	1.90	--	0.30	0.36	---	0.68	--

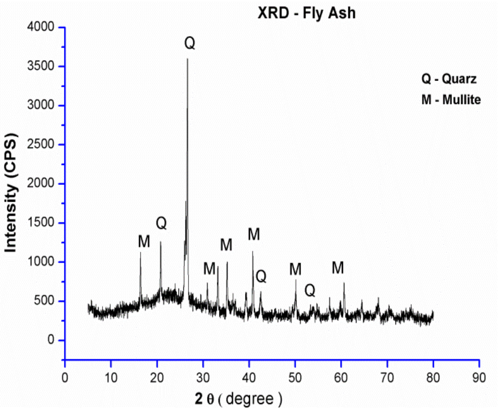


Fig. 1(a) XRD graphs for fly ash (Jindal *et al.* 2017a)

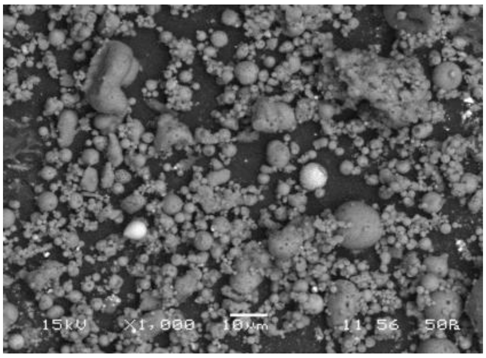


Fig. 1(b) SEM graphs for fly ash (Behera 2010)

This paper presents a comprehensive review of various types of geopolymer concrete prepared with mineral admixtures to enhance the mechanical as well as durability properties.

2. Types of geopolymer materials

2.1 Fly ash

Fly ash is a by-product of burning pulverized coal in electric power generating plants which is widely available worldwide and lead to the anthropogenic pollution. Fly ash is rich in silicate and alumina, hence it reacts with an alkaline solution to produce aluminosilicate gel that binds the aggregate to produce good geopolymer concrete. The major elementary constituents of fly ash are Si, Al, Fe, Ca, C, Mg, K, Na, S, Ti, P, and Mn. The properties of fly ash may vary according to several factors such as the geographical origin of the source coal, ambient conditions during combustion and sampling position within the power plant. A typical composition of fly ash from various sources is shown in Table 1. Fly ash is quite complicated in its chemical and phase compositions. It consists of complex combinations of crystalline and glassy phases. Fig. 1(a) and (b) illustrates the XRD and SEM graph of fly ash. SEM graph shows that the fly ash particles are almost entirely spherical in shape, allowing them to flow and blend freely in mixtures.

2.2 Rice husk ash

Table 2 The chemical composition of rice husk ash

Composition %	SiO_2	Al_2O_3	CaO	MgO	SO_3	Na_2O	Loss on Ignition
Rice husk ash (Kishore and Gayathri 2017)	90.7	0.4	0.4	0.5	0.1	0.1	4.80
Rice husk ash (Kim *et al.* 2014)	90.79	2.22	0.92	0.47	--	0.50	4.00

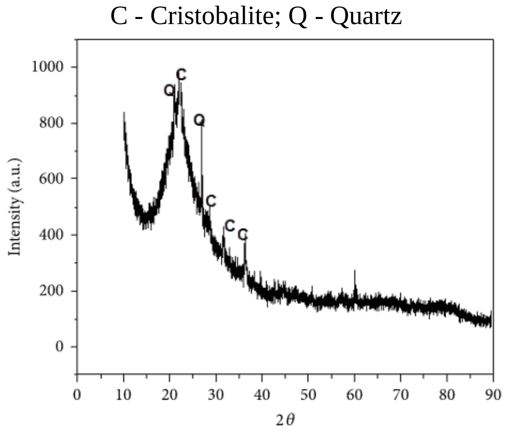


Fig. 2(a) XRD graphs for RHA (Kim *et al.* 2014)

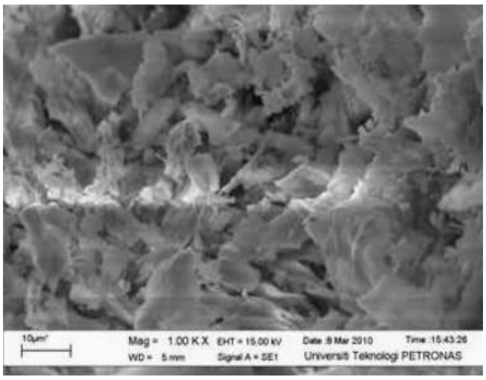


Fig. 2(b) SEM graphs for RHA (Daffalla *et al.* 2010)

Rice husk ash (RHA) is also an industrial waste product obtained from burning of rice husk mainly used for the generation of electricity. The primary component of the rice husk ash is silica (>90–95 wt.%), existing predominantly in amorphous and partly in crystalline phases which is further influenced by the temperature and duration of burning (He *et al.* 2013, Srinivasreddy *et al.* 2013). The amorphous silica contained in RHA react with an alkaline solution to produce binders. The average size of RHA particles is nearly three times smaller than fly ash particle and are irregular in shape as compare to the spherical shape of fly ash particles, which may negatively influence the workability of concrete (Srinivasreddy *et al.* 2013). A typical chemical composition of rice husk ash from various sources is shown in Table 2. It can be observed from Table 2 that rice husk ash contains high content of silica which further supports the formation of geopolymer gel.

X-Ray diffraction and SEM graphs of RHA are shown in Fig. 2(a) and (b). The diffraction peaks correspond to quartz and cristobalite are seen. Mostly, RHA is found to be amorphous in nature. The amorphous or crystalline phase of silica depends upon the burning temperature as well as the method of ash production (Foletto *et al.* 2009).

2.3 Alkaline activators

The alkaline activators commonly used to activate aluminosilicate materials are sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3) and potassium silicate (K_2SiO_3). Potassium hydroxide (KOH) provide more alkalinity in the mix in comparison to NaOH. But in practice, NaOH is more preferred because it possesses the higher capacity to liberate silicate and aluminate monomers (Duxson *et al.* 2007).

The mass ratio of sodium silicate to that of hydroxide solution significantly affects the compressive strength of geopolymer concrete. It has been reported that a value between 2.3 and

2.8 is very much appropriate for development of good compressive strength (Wallah *et al*. 2006). A ratio of 2.5 is very much appropriate in the development of low calcium fly ash based geopolymer concrete to achieve desired strength and durability properties (Jindal *et al*. 2017a).

The properties of geopolymers can be optimized by proper selection of raw materials, correct mix, and processing design to suit a particular application (Malhotra 1999). Alkaline activator of higher molarity provides better workability, higher strengths, and shorter demolding time (Hardjito *et al*. 2004). The compressive strength increases with increasing molarity of the activator (10-16 M) probably due to the formation of stable aluminosilicate networks during geopolymerization (Singh *et al*. 2015, Jindal *et al*. 2017c).

3. An overview of additives use in geopolymer concrete

3.1 Ordinary Portland Cement (OPC)

Ordinary Portland cement (OPC) due to its exothermal reaction mechanism can increase the temperature which can enhance the rate of geopolymerisation reaction of geopolymer. OPC along with increasing the temperature of geopolymer gel which supports the geopolymerization reaction also forms calcium-silicate-hydrate (CSH) gel. This CSH gel which coexists with NASH/CASH (Sodium/Calcium Alumino Silicate: the product obtained from geopolymerisation of geopolymer compounds) result into the increased concentration of binder material. Therefore, OPC can be an effectively used as an admixture to improve the properties of geopolymer at ambient temperature (Nath and Sarker 2015, Mehta and Siddique 2017).

3.2 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is formed in blast furnace during the manufacturing process of iron from its ore. GGBFS in addition to the high silica and alumina contents also possesses high CaO content (~40%) in comparison to fly ash. The XRD patterns show that GGBFS is more amorphous and finer particle size generally 95% finer than 30 μm, which enhances reactivity (Ravikumar *et al.* 2010, Singhal *et al.* 2017). Generally, the particle shape of the GGBFS is the crystalline and

Table 3 The chemical composition of GGBFS, Nanosilica, and Alccofine

Composition (%)	GGBFS (% by mass) (Goriparthi and Rao 2017)	Nano-Silica (Haruehansapong *et al.* 2014)	Alccofine (Jindal *et al.* 2017a)
SiO_2	34.06	99.8	35.30
Al_2O_3	20.00	-	21.40
Fe_2O_3	0.80	-	1.20
SO_3	0.90	-	0.13
CaO	32.60	-	32.20
MgO	7.89	-	8.20
Na_2O	Nil	-	-
LOI	NIL	0.2	-
Specific surface area (m^2/kg)	375	90000	1200

angular form which also varies according to grinding techniques (Siddique and Khan 2011). The higher amounts of glass content in GGBFS helps in increasing the hydraulic activity thus accelerates polymerization process (Goriparthi and Rao 2017). Table 3 shows the typical chemical composition of GGBFS.

3.3 Nano silica

The nano-silica is the most widely used nanomaterial in the cement and concrete to enhance the properties of concrete due to its pozzolanic reactivity along with the pore-filling effect (Zhang *et al.* 2012, Aggarwal *et al.* 2015). Nano-particles of SiO_2 increases the densification of the concrete matrix, thus improving the strength and durability of the material. There are various methods of producing nano-silica. Nano-silica produced by vaporization of silica between 1500 to 2000°C by reducing quartz (SiO_2) in an electric arc furnace provides a higher fineness consisting of spherical particles or microspheres with a main diameter of 150 nm with the high specific surface area (15 to 25 m^2/g) (Quercia and Brouwers 2010). Table 3 shows the typical chemical composition of nano-silica.

3.4 Alccofine

Alccofine is a low calcium silicate microfine material based on blast furnace slag with high reactivity through controlled granulation. Alccofine is a microfine material of particle size much finer than other hydraulic materials like cement, fly ash, silica etc. Addition of Alccofine improves the packing density of paste component, workability by lowering water demand, compressive strength and durability parameter of concrete by refined pore structure, reduced permeability by its unique chemistry and ultra-fine particle size (Limited 2014, Jindal *et al*. 2016, Jindal *et al*. 2017a, Jindal *et al.* 2017b). Alccofine can be used either as an additive or a cement replacement to improve both fresh and hardened state concrete properties. Alccofine conforms to ASTM C989-05 (ASTM 2005). Table 3 shows the typical chemical composition of Alccofine.

4. Geopolymer concrete

Geopolymer concrete is prepared by the geopolymerization of aluminosilicate materials and alkaline solutions. For curing purpose, both air curing and heat curing methods are adopted. Heat curing is generally applied in heat curing regime ranging from 60^oC to 100^oC to the geopolymer specimens for about 24-72 hr and then left at room temperature.

4.1 Geopolymer concrete at ambient and heat curing

Geopolymer concrete cured at ambient temperature do not undergo exothermic processes to the extent that are experienced by conventional OPCs. The ambient temperature cured coal ash-based GPCs exhibit a higher drying shrinkage compared to that of OPC due to a large amount of unreacted coal ash particles in the hardened GPC structure that results from a lower degree of geopolymerisation when coal ash-based GPC is cured at ambient temperature (Xie and Ozbakkaloglu 2015).

Vijai *et al.* (2010) reported that the fly ash based geopolymer paste reacts slowly at ambient temperature as compared to heat cured samples. Geopolymer concrete could achieve 28 days compressive strength below 20 MPa while ambient curing is adopted but it increased to 33 MPa on heat curing. Fly ash-based Geopolymer paste cured at ambient temperature (25-33°C) took more than 24 h for initial setting due to the slow rate of chemical reaction at a low ambient temperature (Shinde and Kadam 2016).

Low-calcium fly ash (Class F) based geopolymer concrete cured at ambient temperature has shown poor compressive strength (Adam 2009, Sharma and Jindal 2015). Jindal *et al.* (2017c) predicted that in case of ambient curing the processed fly ash geopolymer concrete could achieve the maximum compressive strength of 20 MPa on 28 days of ambient curing. A higher compressive strength of 42 MPa was achieved on heat curing at 90°C.

Due to the demerit of attaining higher compressive strength at ambient curing, researchers adopted heat curing methods in their investigations to obtain higher compressive strength in comparison to ambient curing. The curing temperatures were reported in the range between 40°C and 90°C for complete geopolymerization reactions (Palomo *et al.* 1999, Van Deventer *et al.* 2002, Perera *et al.* 2007, Kani and Allahverdi 2009, Jindal *et al.* 2017e).

The heat-cured geopolymer concrete possesses the high compressive strength, low drying shrinkage and creep, and good resistance to sulfate and acid attack (Rangan *et al.* 2005, Rangan 2008, Lloyd and Rangan 2009). Earlier studies reported that Geopolymer concrete possesses higher bond strength with reinforcing steel as well as better splitting tensile strength in comparison to OPC concrete (Sofi *et al.* 2007, Alanazi *et al.* 2016, Kathirvel *et al.* 2017).

Palomo *et al.* (1999) reported that the compressive strength of geopolymers (8-12 M) cured at 85°C for 24 h was much higher than those cured at 65°C, curing time more than 24 h didn't provide any significant change.

The heat curing of metakaolin-based geopolymers for a longer period of time failed the samples at a later age due to the thermolysis of –Si–O–Al–O– bond (Heah *et al.* 2011). Further, the metakaolin based geopolymer at elevated temperature (40-80°C) enhances the strength but a deterioration in the mechanical properties noticed in comparison to ambient temperature cured specimens (Rovnaník 2010).

Noushini *et al.* (2016) reported the optimum heat-curing temperature to be 75°C for 18 h for obtaining best performance and energy efficiency for fly ash based geopolymer concrete. Heat curing does not impose any detrimental effect on the strength of GPC in comparison to conventional concrete. The compressive strengths of properly heat-cured GPCs (cured at 75°C and 90°C) are always superior to those of ambient-cured samples.

It can be noted that most of the geopolymer concrete tested so far was shifted from ambient cured to heat cured at a higher temperature to gain better strength properties. The ambiently cured geopolymer concrete didn't provide satisfactory strength properties. While heat cured GPC can be used in precast industry, but this process restricts the applications of GPC for general construction purpose.

Therefore, the need to develop Geopolymer concrete which can be used for general construction purposes at normal temperature propelled the researchers to explore a new methodology which can address the issue of poor compressive strength and durability.

Geopolymer concrete will have a broader sphere of applications in situ construction as well as in precast construction if ambient curing condition can be adopted. Ambient curing conditions will provide a more economical as well as energy efficient product in comparison to heat curing process.

In the inquisition of improving geopolymerisation process at room temperature, various studies

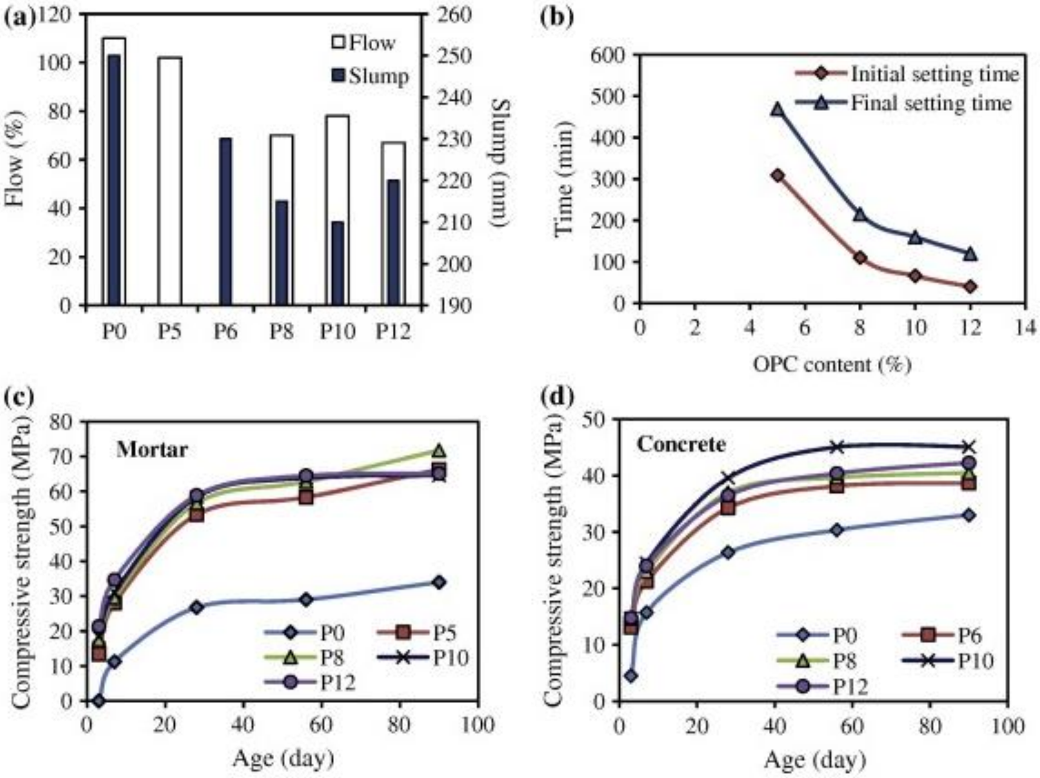


Fig. 3 Effect of different percentages of OPC on the (a) workability of mortars and concretes, (b) setting time of pastes, (c) compressive strength of mortars and (d) compressive strength of concretes (Nath and Sarker 2015)

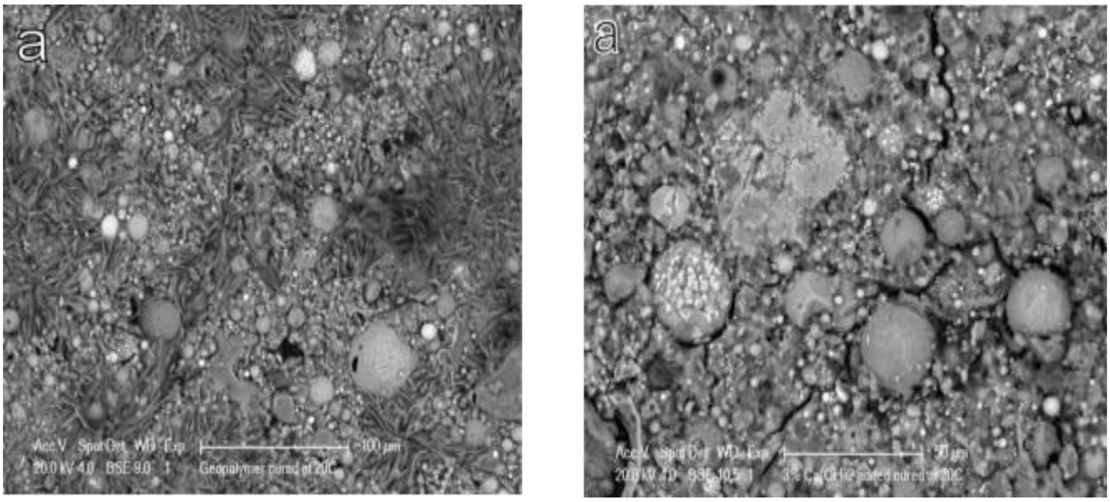
aimed to boost the reactivity of aluminosilicate source material in the alkaline environment by incorporating some supplementary materials such as OPC, nano silica, rice husk ash, metakaolin, GGBFS, and Alccofine (Rashad 2014, Jindal *et al.* 2016, Jangra *et al*. 2018).

4.2 An overview of geopolymer mortar and concrete with admixtures at ambient curing

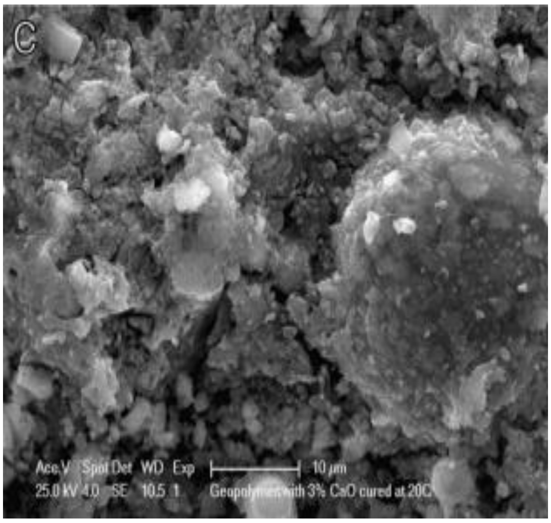
Nath and Sarker (2015) added OPC up to 12%, mix designated as P0, P5, P8, P10 and P12 containing 0,5,8,10 and 12%OPC, respectively, of the total binder in Fly ash based geopolymer paste, mortar and concrete mixtures in ambient curing condition. They reported the presence of OPC accelerated the geopolymerisation reaction as well as affected the workability and setting time as shown in Fig. 3. Geopolymer concrete with 5% OPC achieved compressive strength of about 40 MPa at 28 days. A cost and energy effective Fly ash based GPC with the replacement of binder by 5% OPC at ambient curing condition can be prepared with a setting time comparable to that of OPC concrete.

Shinde and Kadam (2016) investigated the properties of Geopolymer concrete prepared with the addition of Ordinary Portland cement up to 12% of binder content at ambient curing regime. A significant increase in compressive strength in the range of 94.25% was achieved at 28 days.

Temuujin *et al.* (2009) conducted an extensive study of fly ash based geopolymer with the addition of calcium compounds. The addition of the calcium compounds such as CaO and $Ca(OH)_2$ enhances the mechanical properties of the fly ash based geopolymers cured at ambient temperature. Calcium compound addition results in the formation of CSH/CASH phases and improves the geopolymerisation reaction. The addition of $Ca(OH)_2$ is more beneficial than CaO in terms of compressive strength. Fig. 4(a) shows the incomplete dissolution of the fly ash spheres indicating that GPC at low temperature is not the structurally sound product. Fig. 4(b) and (c) indicates that the addition of calcium more homogeneous microstructure is obtained. The possibility of formation of CSH/CASH gel has increased the homogeneity of product which may have enhanced the mechanical properties. Efflorescence is also observed in ambient temperature cured samples because of the presence of the excess alkaline solution caused by incomplete dissolution of the fly ash spheres and low dissolution rate.



(a) only fly ash based (b) with 3% $Ca(OH)_2$



(c) with 3% CaO

Fig. 4 SEM micrograph of fly ash based geopolymer cured at ambient temperature (Temuujin *et al.* 2009)

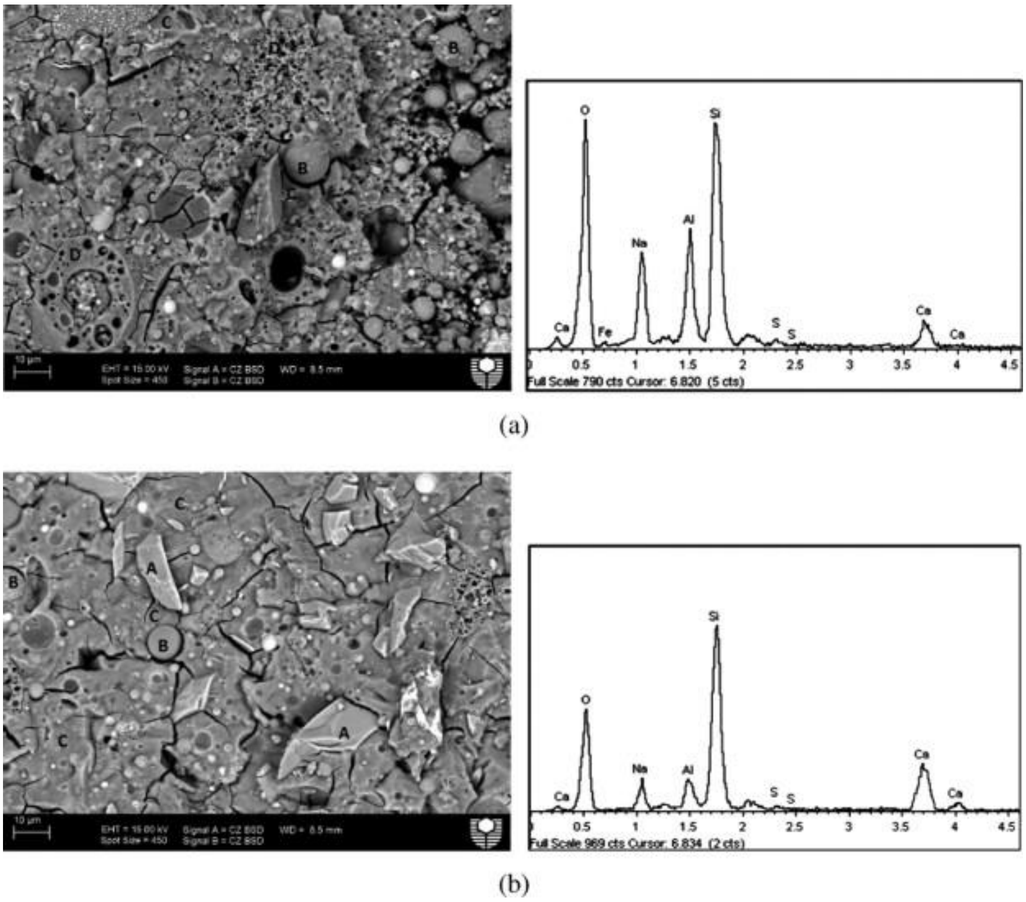


Fig. 5 Scanning electron microscope image of paste having (a) 10% GGBFS and (b) 50% GGBFS; where *A*=un-reacted or partially reacted slag particles, *B*=un-reacted or partially reacted fly ash particles, *C*=aluminosilicate geopolymer gel containing calcium as indicated in EDX spectrum and *D*=pure aluminosilicate geopolymer gel (Nath and Sarker 2014)

The increase in the denseness of geopolymer matrix and fibrous structure as shown in Fig. 4, indicates the presence of CSH, NASH, and CASH. EDS images can be used to differentiate and quantify the C-S-H gel from geopolymer gels (CASH/NASH).

However, the optimum content of OPC or CaO based additives depends upon the quality of aluminosilicate source materials, targeted compressive strength and durability properties which still need to be investigated.

Al-Majidi *et al.* (2016) prepared to fly ash based geopolymer concrete mixes with GGBFS (10-50%) of fly ash and cured under ambient temperature conditions. Test results revealed a considerable effect on setting time by the GGBFS content in the mix. The compressive strength was significantly increased in the ranges of 65-162% on addition of GGBFS. It is reported that pores of the microstructure of the geopolymer were packed with additional hydration products from GGBFS.

Nath and Sarker (2014) investigated the properties of fly ash based geopolymer concrete and mortar mixtures adding GGBFS up to 30% of the total binder at ambient curing. Sodium silicate and sodium hydroxide solution mixture was used as an activator. The compressive strength of geopolymer concrete up to 55 MPa and of mortar up to 63 MPa at 28 days on the addition of GGBFS up to 30% of the total binder was achieved. Microscopic images of slag (10% and 50%) blended fly ash geopolymer cured at ambient temperature (20-23°C) are shown in Fig. 5. The SEM and EDX graphs reveal the geopolymer pastes are mostly of the amorphous phase.

The paste having 50% GGBFS is more compact and less porous than that having 10% GGBFS. The partially reacted and un-reacted fly ash particles visible. The geopolymer gel consists of sodium alumino-silicate hydrate (N–A–S–H). and calcium alumino-silicate hydrate (C–A–S–H). Therefore it is very much clear that addition of GGBFS result in the availability of additional calcium-bearing compound and producing an additional binding product which improves the properties of geopolymeric gel in early age.

Rao and Rao (2015) reported that partial replacement of fly ash by GGBFS in geopolymer accelerates the setting of geopolymer paste. Fly ash-based geopolymer with GGBFS at ambient curing increases the compressive strength of geopolymer mortar. Test results indicate that geopolymer can attain compressive strength even under ambient curing if GGBS and fly ash together are used as source material. The reason for the increase in compressive strength due to GGBFS can be attributed to higher calcium content present in GGBFS.

Most of the studied so far used GGBFS in geopolymer concrete are devoted to analyzing the strength properties but the investigations on durability properties still pose a broad gap. So the impact of the use of GGBFS in geopolymer concrete in terms of permeability, water absorption and drying shrinkage needs to be ascertained.

Phoo-ngernkham *et al.* (2014) investigated the effect of the addition of nano-SiO_2 and nano-Al_2O_3 dosages up to 3% by weight on the properties of high calcium fly ash geopolymer pastes cured at an ambient temperature of 23°C. The sodium hydroxide solution of 10M with

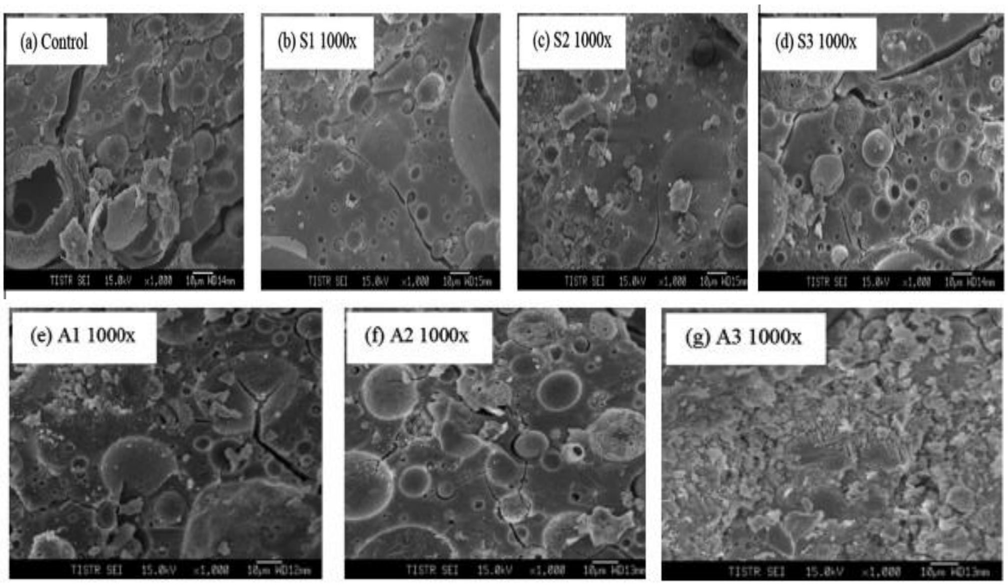


Fig. 6 SEM of geopolymer pastes at 28 days, (a) control mix, (b) 1% nano-SiO_2, (c) 2% nano-SiO_2, (d) 3% nano-SiO_2, (e) 1% nano-Al_2O_3, (f) 2% nano-Al_2O_3, (g) 3% nano-Al_2O_3 (Phoo-ngernkham *et al.* 2014) All SEM graphs are at magnification of 1000x

Na_2SiO_3/NaOH ratio of 2.0, the alkaline liquid/binder ratio of 0.60 was used in the mixture. The test results showed that the use of nano-SiO_2 and nano-Al_2O_3 as an additive to geopolymer results in an accelerated setting. Further adding 1-2% nano-particles improved the compressive strength, flexural strength, and elastic modulus of geopolymer pastes due to the formation of additional calcium silicate hydrate (CSH) or calcium aluminosilicate hydrate (CASH) and sodium aluminosilicate hydrate (NASH) gel in geopolymer matrix. Fig. 6 shows the SEM images for nano-SiO_2 and nano-Al_2O_3 added geopolymer matrix. Fig. 6(a)-(c) indicate the development of denser microstructures of geopolymer pastes containing 1-2% nano-SiO_2 but Fig. 6(d) shows less dense structure, maybe because of 3% nano-SiO_2 result into the presence of excessive amount of nanoparticles. A Similar pattern is observed in the case of nano-Al_2O_3 added geopolymer as shown in Fig. 6(e)-(g).

Adak *et al.* (2014) investigated the properties of low calcium fly ash geopolymer mortar having three molar concentrations (8 M, 10 M and 12 M) of activator liquids along with different percentage of nano silica addition (0%, 4%, 6%, 8% and 10% of fly ash). Mix designated as 12M0 and 12M6 represent the sample with 12 Molarity with 0% and 6% nano silica, respectively. In these studies, authors reported that geopolymer mortar prepared with the addition of 6% nano silica shows significant improvement in compressive, flexural and tensile strengths at 28 days under ambient temperature curing. The improvement in nano-silica added geopolymer is because of formation of new phases such as SiO_2, Ca_3SiO_5, $Na(AlSi_3O_8)$, $Na_2Si_2O_8$ and $CaCO_3$ in comparison to the geopolymer mixture without nano silica as shown in Fig. 7. With the addition of nano silica more number of peaks indicate the increased amount of crystalline compound in the geopolymer matrix. It is reported that due to the more crystalline content in mix 12M6 as compare to mix 12M0, the compressive strength obtained is of higher value with higher nano silica content.

SEM graphs as shown in Fig. 8 indicates of the transformation of more amount of amorphous

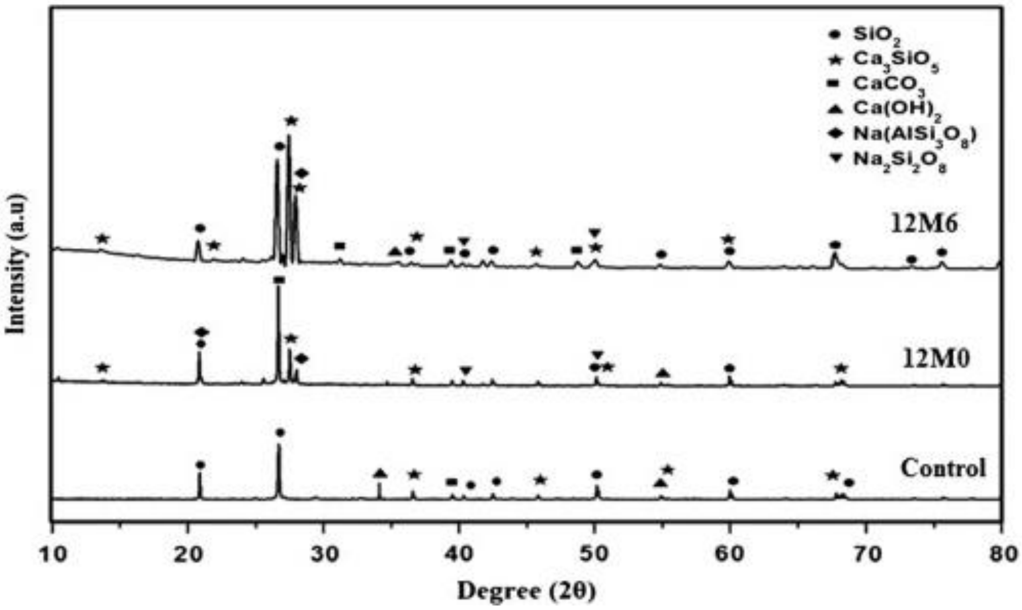


Fig. 7 XRD analysis report of fly ash based geopolymer mortar sample (12M0 and 12M6) and cement mortar samples (control) (Adak *et al.* 2014)

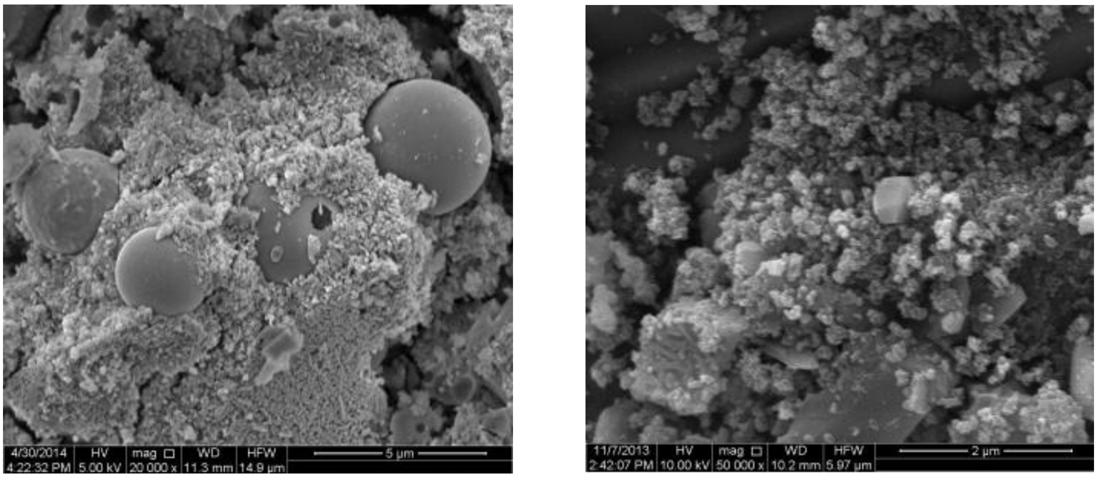
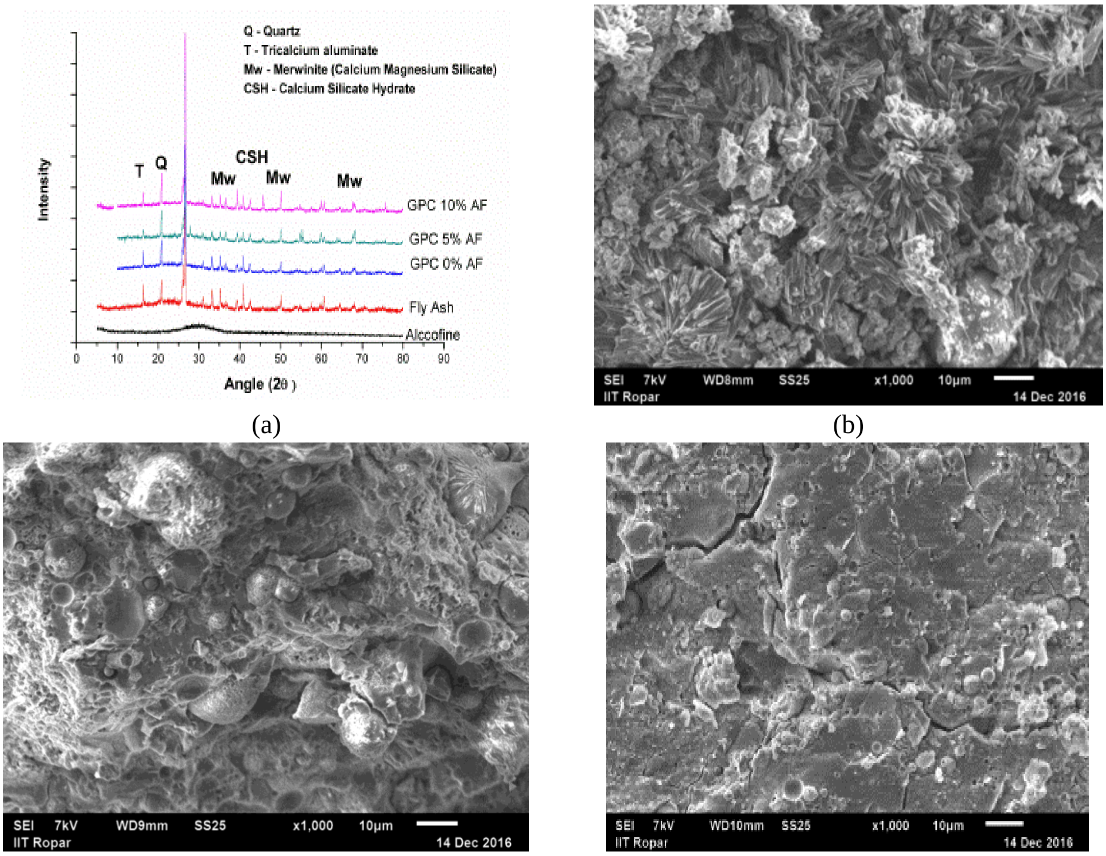


Fig. 8 FESEM image of fly ash based geopolymer mortar sample (a) without nano silica (12M0), (b) with 6% of nano silica (12M6) (Adak *et al.* 2014)



(a) (b)

(c) (d)

Fig. 9 (a) XRD pattern of geopolymer concrete with Alccofine, (b) SEM image of GPC without Alccofine, (c) SEM image of GPC with 5% Alccofine, (d) SEM image of GPC with 10% Alccofine (Jindal *et al.* 2017d)

Table 2 Effect of adding different admixtures on geopolymers at ambient curing

Type of study	Additives	Temperature range	Compressive strength range	Primary findings
(Nath and Sarker 2015)	Fly ash and ordinary Portland cement (up to 12%)	20-23℃	20-60 MPa	Fly ash-based geopolymer mortar and concrete showed a higher compressive strength in the presence of ordinary Portland cement at ambient curing.
(Shinde and Kadam 2016)	Fly ash and ordinary Portland cement (up to 12%)	15-32℃	16-32 MPa	Fly ash-based geopolymer concrete with OPC showed improved compressive strength at ambient curing.
(Temuujin *et al.* 2009)	Fly ash and calcium oxide (CaO) or calcium hydroxide $Ca(OH)_2$ compounds	20℃	11-30 MPa	Fly ash with the inclusion of calcium compounds as a fly ash substitute improved mechanical properties for the ambient temperature cured samples
(Al-Majidi *et al.* 2016)	Fly ash and ground granulated blast furnace slag	21-23℃	25-50 MPa	The compressive strength of fly ash based geopolymer concrete significantly improved with the addition of slag at ambient curing.
(Nath and Sarker 2014)	Fly ash and ground granulated blast furnace slag	20-23℃	15-70 MPa	Fly ash-based geopolymer with GGBFS is found to be a suitable for low to moderate strength concrete application at ambient curing condition.
(Rao and Rao 2015)	Fly ash and ground granulated blast furnace slag	35±2℃	41-75 MPa	The compressive strength of geopolymer mortar with the inclusion of GGBFS at ambient curing increases with increase in GGBFS content.
(Phoo-ngernkham *et al.* 2014)	High calcium fly ash, nano-SiO_2, and nano-Al_2O_3	23℃	29-46 MPa	High calcium fly ash geopolymer with the additions of both nano-SiO_2 and nano-Al_2O_3 improve compressive strength, flexural strength, and elastic modulus and shear bond strength.
(Adak *et al.* 2014)	Low calcium fly ash and nano-silica	27±2℃	12-38 MPa	Low calcium fly ash based geopolymer mortar with the addition of 6% nano silica shows significant improvement in compressive, flexural and tensile strength at 28 days under ambient temperature curing.
(Jindal *et al.* 2017c, 2017d, Jindal 2017)	Fly ash and Alccofine	25±10℃	15-42 MPa	Low calcium fly ash geopolymer concrete with the addition of Alccofine shows an appreciable increase in compressive, split tensile strengths as well as decreased water permeability thus enhanced the durability of concrete at ambient curing conditions.

compound to crystalline compound with the addition of 6% nano-silica which results into denser microstructure in comparison to geopolymer without nano-silica.

Literature review establishes that the use of nanomaterials significantly improves the mechanical as well durability properties of geopolymer concrete but earlier research lacks in analysing the cost-effectiveness of these materials as generally, nanomaterials are more costly in comparison to other mineral admixtures.

Jindal *et al.* (2017a, c, e) extensively investigated the fresh and hardened properties of low calcium fly ash based geopolymer concrete prepared with different percentages (0%,5%, and 10%) of alccofine and fly ash content (350,370,400 kg/m^3). The tests results indicate that alccofine significantly enhances the mechanical properties and reduces the transport properties of geopolymer concrete at ambient curing. The XRD and SEM analysis as shown in Fig. 9. further reveal that with an increase in alccofine content the densification of the geopolymer matrix improved which is due to enhanced polymerization. The calcium oxide content in Alccofine has produced CSH gel along with NASH/CASH gel. The higher percentage of alccofine and fly ash content has a significant effect on the polymerization of the GPC, which in turn improves the strength and microstructural features.

Table 2 summarizes the various studies that have used admixtures in geopolymer mortar and concrete technology to improve the properties of geopolymer products at ambient curing conditions to present an alternative idea to elevated temperature curing.

5. Conclusions

The present review summarizes the investigations conducted on geopolymer mortar and concrete to make it feasible for general construction application at ambient temperature curing conditions. The works on the use of various mineral admixtures such as OPC, GGBFS, nanomaterials, and Alccofines to accelerate the geopolymerization reaction and their effects on mechanical and durability properties of geopolymer concrete at ambient curing have been explored. Most of the calcium-based admixtures are found to improve properties of geopolymers at normal room temperature which broaden the scope of utilization of geopolymer concrete in general construction applications in addition to the precast industry.

The following conclusions can be drawn from this study:

1. The inclusion of Ordinary Portland cement in fly ash based geopolymer concrete accelerates the geopolymerisation reaction and produce addition calcium silicate hydrate (CSH) gel in addition to CASH/NASH in the geopolymeric matrix. Enhanced quantity of Geopolymeric gel results into a denser geopolymer product with improved mechanical properties at normal room temperature curing.
2. A small quantity of OPC can significantly affect the setting time of geopolymer mortar and concrete.
3. Ground granulated blast furnace slag as a partial replacement of fly ash in geopolymer shown better properties even at ambient temperature curing.
4. The use of nano-SiO_2 and nano-Al_2O_3 as an additive to geopolymer can significantly accelerate setting process, improved the compressive strength, flexural strength, and elastic modulus of geopolymer pastes due to the formation of additional calcium silicate hydrate (CSH) or calcium aluminosilicate hydrate (CASH) and sodium aluminosilicate hydrate (NASH) gel in geopolymer matrix. Nano silica helps in reducing porosity and thus denser

geopolymer products can be developed at normal temperature curing which promotes the scope of geopolymer concrete in general construction applications.

5. Alccofine which is a specially controlled granulation slag based microfine material can be used as an admixture to achieve a significantly higher compressive strength and enhanced durability at normal room temperature.
6. Broadly, calcium-based minerals admixtures can be used as an additive to accelerate the geopolymerization reaction as an alternative method to heat curing.
7. A broad scope of investigating the durability and cost effectivess as well cost optimization is still available. Further the effect of inclusion of various nano materials in geopolymer products at ambient temperature can be investigated.
8. Most of the studies so far are based on fly ash based geopolymer concrete, therefore other type of aluminosicliate waste materials can be explored for the developing geopolymer products along with mineral admixtures at ambient temperature curing.

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