Suitability of Ambient-Cured Alccofine added Low-Calcium Fly Ash-based Geopolymer Concrete

Bharat Bhushan Jindal1,2*, Dhirendra Singhal3, Sanjay K. Sharma4 and Parveen3

1I. K. Gujral Punjab Technical University, Kapurthala – 144603, Punjab, India; 2Department of Civil Engineering, M.M.University, Ambala -134003, Haryana, India; bbjal1972@hotmail.com, 3Department of Civil Engineering, DCRUST Murthal, Sonipat – 131039, Haryana, India; singhald62@netscape.net,separveenjangra@gmail.com
4Department of Civil Engineering, NITTTR, Chandigarh-160036, Punjab, India; sanjaysharmachd@yahoo.com

Keywords: Concrete, Geopolymer, Microstructure, Permeability, Split Tensile Strength, Water Absorption

Abstract

Objective: To develop geopolymer concrete (GPC) using 100% industrial waste as a binder at ambient temperature.

Methods/Analysis: The low calcium fly ash based GPC was prepared with different percentage (0%, 5%, and 10%) of alccofine and fly ash content (350, 370, 400kg/m3), to examine the fresh and hardened properties of alccofine activated GPC like density, workability, water absorption, permeable voids, water permeability, compressive and split tensile strengths using international standards. Nine mixes were prepared and investigated by X-ray diffraction (XRD) and Scanning electron microscopy (SEM) for the determination of their phase, composition and microstructural properties. Findings: The result shows that alccofine enhances the mechanical properties and significantly reduces the transport properties of GPC. Furthermore, GPC specimens prepared with alccofine emerge to improve the densification process. The results of investigations conducted reveal that higher percentage of alccofine and fly ash content has a significant effect on the polymerisation of the GPC, which in turn improves the strength and microstructural features. A maximum compressive strength of 42 MPa is achieved with 10% alccofine without elevated heat curing. Novelty/Improvement: Alccofine plays a significant role in improving the mechanical and transport properties of low calcium fly ash based geopolymer concrete at ambient conditions providing as an alternative to heat cured GPC.

Keywords: Concrete, Geopolymer, Microstructure, Permeability, Split Tensile Strength, Water Absorption

Notation

| Symbol | Description |
|--------|-------------|
| $\sigma_{fp}$ | split tensile strength (N/mm²) |
| P      | load at failure (kN) |
| S      | side of the cube |

1. Introduction

The threat to the environment by greenhouse gases is a major concern for researchers today. The production of cement releases about 7% of total carbon dioxide to the atmosphere which impels the researchers to develop an alternative construction material to cement concrete by utilizing industrial waste. French scientist Davidovits coined a 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. The schematic polymerisation structure of geopolymers can be described by Equations. (1) and(2). Water released in equation (2) results in nanopores creation which enhances the performance and workability of geopolymer.
Suitability of Ambient-Cured Alccofine added Low-Calcium Fly Ash-based Geopolymer Concrete

An alkaline solution of sodium hydroxide or potassium hydroxide and sodium silicate can be added to an aluminium-silicon rich material to produce ‘Geo polymer’ possessing cementitious properties, which could bind the ingredients of concrete, replacing ordinary Portland cement (OPC). Geo polymer is energy efficient having energy need of 30% in comparison to OPC. Geo Polymer Concrete (GPC) may expand the scope by using industrial by-products, such as fly ashes, slags, rice husk ash as additional raw material in high quantity, in construction industry resulting in the preservation of natural resources.

Previously, researchers have shown that elevated temperature cured geo polymer concrete can achieve mechanical properties comparable to conventional concrete. Geo polymer concrete performance is superior to OPC concretes at elevated temperatures and show better long term durability properties in comparison to OPC concretes. Fly ash based GPC can achieve more than 90% of the 28 days compressive strength after one day compared to only 55% to 71% for OPC concretes a detrimental effect on long-term compressive strength. A reasonably good mechanical strength can be achieved for low calcium fly ash GPC after heat curing at 60 °C for 24 hours. Most of the research on geopolymer concrete so far done is at elevated temperature. The heat cured Geopolymer concrete can be used in precast industry, but this process requires special arrangements which are high energy-consuming. Moreover, heat cured concrete may not be suitable for building construction applications. So, need arises to develop suitable geo polymer concrete at ambient curing.

Low-calcium fly ash (Class F) based geo polymer concrete at ambient curing shows poor compressive strength. A blending of OPC in fly ash based GPC is used to improve mechanical properties at ambient curing. Alccofine 1203 can be used as an additive to enhance the mechanical properties of GPC at early ages. In this study, an effort has been made to improve the mechanical and durability properties of low calcium fly ash based geo polymer with Alccofine at ambient conditions. Alccofine was added up to 10% percent by weight of fly ash into class F fly ash-based geo polymer. The mechanism of alccofine is additive in enhancing compressive, splitting tensile strength, water absorption, water permeability was investigated using X- Ray Diffraction (XRD) and Scanning Electron Microscope (SEM).

2. Research Significance

The fly ash generation in India has already crossed 200 million tons per year and likely to increase to more than 300 million tons by the year 2017. Nearly 75-80% of the total fly ash production in India is of low calcium. The utilization and disposal of such a huge quantity of fly ash is a herculean task which has to perform within various environment protection laws. The efficient use of this resource material would not only minimize the disposal problem but also help in conservation of limited minerals, reduce the emission of greenhouse gases and enhance the performance and durability of structure. The current study was targeted to develop ambient cured class F fly ash is based on geo polymer concrete, it is suitable for general as well as precast construction purpose.

3. Experimental Program

3.1 Materials

The geopolymer concrete might be considered as a two-phase composite material consisting of geo polymer binder. Any raw material such as fly ash, slag, rice husk ash has a potential to be used as a source for the geopolymer binder.

3.1.1 Fly Ash

Low calcium (Class F) fly ash, sourced by Ultra Tech RMC Plant, Panchkula Haryana, used as a source of alumina silicate with specific gravity 1.95 and 96% passing through 45-micron sieve, confirming to IS 3812 -2003. The chemical composition of fly ash is analysed using X-ray fluorescence spectroscopy. The chemical composition and the physical properties of fly ash are illustrated in Table 1.

| Composition (%) | Fly Ash | IS 3812-2003 requirement [BIS,2003] |
|-----------------|---------|-------------------------------------|
| Silica + alumina + iron oxide (SiO₂ + Al₂O₃ + Fe₂O₃): wt% | 95.91 | 70.0 (Min) |
| Silica ( SiO₂ ) : wt% | 62.55 | 35.0 (Min) |
| Calcium Oxide (CaO) : wt% | 0.87 | Not specified |
| Magnesia (MgO) : wt% | 0.39 | 5.0 (Max) |
3.1.2 Coarse and Fine Aggregates

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%. Both coarse and fine aggregates are confirming to IS 383-1970. Fine aggregate is used in crushed sand and graded as conforming to IS 2386 (Part I)-1963 having fineness modulus 2.92, the specific gravity is 2.32 and water absorption 1.5%.

3.1.3 Alccofine 1203

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 East, Mumbai. AF improves the workability by reducing water demand, and strength properties by its unique chemistry and ultra-fine particle size. Alccofine can be used either as an additive or a cement replacement to improve both fresh and hardened stateconcrete properties. The chemical compositions and physical properties of Alccofine 1203 are shown in Table 2.

3.1.4 Alkaline Solution

In polymerization, an alkaline activator used as a mixture of sodium hydroxide (NaOH), and sodium silicate (Na$_2$SiO$_3$) solutions. Sodium hydroxide used is in the form of pellets with 98% purity and sodium silicate solution with SiO$_2$/Na$_2$O=1.875 and density of 1.46 g/cm$^3$. The sodium hydroxide solution of 16M (Molarity) is prepared by dissolving 444 g pellets of NaOH per kg of solution (water+pallets). The mass ratio (alkali activator/geo polymer binder) of 0.5 is taken for the mix design calculations.

Sodium hydroxide of higher molarity provides higher compressive strength. NaOH solution is prepared and kept at room temperature for 24 hours, due to exothermic reaction with water before mixing with sodium silicate solution. The alkaline solution prepared was again given a mixing period of three to four hours. The mass ratio (Na$_2$SiO$_3$/NaOH) of 2.5 is taken as the optimum ratio. A Naphthalene Sulphonate based water reducing superplasticizer confirming to IS 9103:1999 is used to improve the workability of the fresh geo polymer mix.

### Table 2. Chemical composition & physical properties of Alccofine 1203

| Constituents       | Composition (wt.%) | Physical Property             | Results     |
|--------------------|--------------------|--------------------------------|-------------|
| Iron oxide (Fe$_2$O$_3$) | 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     | 1.8         |
|                    |                    | (in micro metre)               |             |
| Magnesia (MgO)      | 8.20               | d10                           | 4.4         |
|                    |                    | d50                           |             |
|                    |                    | d90                           | 8.9         |
| Alumina (Al$_2$O$_3$) | 21.40              | Specific Surface Area         | 12000cm$^2$/gm |
Suitability of Ambient-Cured Alccofine added Low-Calcium Fly Ash-based Geopolymer Concrete

5. Testing Methods

A series of tests were performed as illustrated below:

5.1 Density

The density of hardened GPC specimens was measured after 28 days to analyse the effect of fly ash and Alccofines content. The mass density of fly ash based geo polymer concrete is expected to be nearly 2400 kg per cubic metre.

5.2 Workability

The workability of GPC was determined immediately after mixing of concrete using the slump cone test confirming to IS 1199–1959 to analyze the effect of fly ash and alccofines content.

5.3 Compressive Strength

GPC specimens were tested for compressive strength on 3rd, 7th, 28th and 56th days of casting as per IS 516-1959. A set of 144 cube samples were tested at room temperature (25±10°C).

5.4 Split Tensile Strength

Split tensile strength test confirming to IS: 5816-1999 were performed on a set of four number of specimens per test on 3rd, 7th and 28th day and the average value was noted. Previous researchers in their study conducted split tensile strength test on cylindrical samples of concrete. However, in this study, diagonal split testing was carried out as illustrated in Figure 1. Splitting tensile strength was evaluated as per expression shown in Figure 1.

5.5 Permeable Voids and Water Absorption

Water absorption test was performed on geo polymer concrete specimen at the age of 28 days to evaluate relative porosity in terms of permeable voids in accordance to ASTM C 642-82. GPC sample of 150 mm cube size were kept in 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 %age calculated by formula:

\[ \text{Permeable voids (\%)} = \frac{(A-B)}{V} \times 100; \text{ where } A = \text{Weight of surface dry saturated specimen after 28 days} \]

Table 3. Mix Proportion of Geo polymer concrete

| Material Content          | GMP1 | GMP2 | GMP3 | GMP4 | GMP5 | GMP6 | GMP7 | GMP8 | GMP9 |
|---------------------------|------|------|------|------|------|------|------|------|------|
| Fly ash, kg/m³            | 350  | 350  | 350  | 370  | 370  | 370  | 400  | 400  | 400  |
| Fine Aggregate, kg/m³     | 575  | 575  | 575  | 565  | 565  | 565  | 540  | 540  | 540  |
| Coarse Aggregates, kg/m³  |      |      |      |      |      |      |      |      |      |
| 7 mm                      | 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 solution, kg/m³      | 38   | 38   | 38   | 44.4 | 44.4 | 44.4 | 52.58| 52.58| 52.58|
| Na₂SiO₃, kg/m³             | 95   | 95   | 95   | 111  | 111  | 111  | 131.45| 131.45| 131.45|
| Water, kg/m³              | 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 |

Figure 1. Split tensile strength testing of geopolymer concrete cubes.
immersion period. B is the weight of oven dried sample. V is the volume of GPC sample. Air cooled samples 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).

5.6 Water Permeability as per DIN 1048
Water permeability test was conducted on geo polymer concrete cube specimen of size 150 mm, after 28 days according to the German code DIN -1048 (Part 5). Permeability test was performed to measure the resistance of GPC with different fly ash and alccofine content against the penetrability of water which exerts pressure and effect the durability. The cubes three in number per sample were placed in a permeability test apparatus and subjected to a constant water pressure of 0.5 N/mm² applied at the bottom in a way to force the water to penetrate into the sample. The samples after removing from apparatus and split down the centre from the face which was exposed to water to measure the depth of water penetration. The variation in depth of water penetration was recorded to analyse the effect of fly ash and alccofine content on water permeability of GPC.

5.7 X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM) Studies
Powder XRD and SEM analyses were performed for fly ash, alccofine powder, and geo polymer concrete at different percentage of alccofines to evaluate the modification induced in the geo polymerisation phenomenon, in particular on the formation of crystalline products which results in the enhancement of mechanical properties.

6. Results and Discussions
The test results is obtained are shown and discussed in details in the following paragraphs.

6.1 Density of GPC
The mass density of control sample of geo polymer concrete (GMP1) at 28 days was measured 2375 kg/m³. The variation in the densities of other GPC specimens with varying fly ash and alccofines content is reported in Figure 2. A linear decrease in the density of the GPC with an increase of fly ash and an increase in density with an increase in alccofines observed.

6.2 Workability
The fresh GPC mixes were found to be highly viscous. The workability of GPC mixes without alccofine (GPM1, GPM4, GPM7) is observed to be very low. Poor workability of geo polymer concretes without alccofine may be due to the high viscosity of the mixes.

6.2.1 Effect of Fly Ash
Figure 3 illustrates the improvement in slump value from 20 mm to 58 mm (GPM4 and GPM7) on increasing fly ash content from 350 kg/m³ to 400 kg/m³. The increase in a slump might be due to increase in fine spherical particle concentration with the increase in fly ash content.
6.2.2 Effect of Alccofine Content
A significant improvement in workability of GPC is observed in addition of alccofines. A collapse slump of 160 mm is achieved with 10% alccofine content due to its micro fine structure of its fineness nearly 12000 cm²/gm.

6.3 Compressive Strength
The compressive strength results are presented in Figure 4 and discussed in the following paragraphs.

On comparing the properties of fly ash and alccofine, it is evident that alccofine has higher fineness and is rich in alumina content which may have enhanced the hydration process. The geopolymer concrete with alccofine is very useful for general purpose construction and precast industries.

6.4 Split Tensile Strength
Results of split tensile strength (STS) at the age of 3 days, 7 days and 28 days is shown in Figure 5.
6.5 Permeable Voids and Water Absorption

6.5.1 Permeable Voids
Permeable voids (PV%) of the GPC at the age of 28 days is shown in Figure 6. The PV% decreased with increase in fly ash and alccofines content. The PV% in GPC (GMP1,GMP4, GMP7) was reduced from 4.98% to 4.38% by increasing fly ash content from 350 kg to 400 kg/m³. A significant reduction in permeable voids upto 2.43% was observed at 10% alccofine content (GMP9). A good correlation was found between permeable voids and compressive strength of GPC as shown in Figure 6.

![Figure 6. Compressive strength and permeable voids (%) in GPC.](image)

6.6 Water Absorption
An initial water absorption (IA%) in 30 minute and final water absorption (FA%) after 72 hours for geo polymer concrete is shown in Figure 7. IA% for GPC reduced less than 4% with alccofine. A significant decrease in FA% is noticed in the addition of alccofine. So, water absorption has shown to reduced trend on increasing fly ash and alccofine content.

6.7 Water Permeability
The effect of variation in fly ash and alccofine content on the depth of water penetration i.e. water permeability as per DIN 1048 (part 5) is illustrated here forth.

6.7.1 Effect of Fly Ash Content
The depth of water penetration has slightly improved from 33 mm to 30 mm and 27.5 mm on increasing fly ash from 350 kg/m³ to 370 kg/m³ and 400 kg/m³ respectively, due to increasing in finer material content.

6.7.2 Effect of alccofines Content
Water permeability of GP Chas significantly reduced in the addition of alccofine. The average depth of water penetration reduced to 22 mm in geo polymer specimen (GMP3) containing 10% alccofines in comparison to 33 mm in GMP1 which further reduced upto 10.5 mm in the GMP9at 10% alccofine with 400 kg/m³ of fly ash content.

![Figure 7. Water absorptions (%) in geo polymer concrete.](image)

6.8 X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM)
X-ray diffraction (XRD) was obtained on a Bruker D8 Advance X-ray diffraction instrument with Cu-Kα monochromatic at 40 kV voltages. Figure 8 shows the XRD pattern (2θ=15°-70°) for pure GPC and alccofine based GPC specimen, prepared at ambient temperature. For both samples, distinct diffraction peaks of Quartz are seen at 2θ = 21.72°, 26.1° and 41.5°, 47.2°corresponding to (100), (101) and (110) planes respectively (JCPDS no. 85-1327). Diffraction peaks at 2θ = 61.2° and 70.3° corresponding to (211) and (300) planes of tri-calcium aluminate. All the other reflections correspond to the Mullites, Merwinites, Calcium silicates and AluminiumMellitus are clearly observed in Figure 9. XRD patterns of alccofines based GPC indicate more crystallinity as compared to pure GPC.

The intensity of quartz at 2θ= 26.10° has increased with increase in alccofine content. Further, the peak of C-S-H at 2θ= 40.30° have decreased with the increase in alccofine content. The water is not structurally bound
Suitability of Ambient-Cured Alccofine added Low-Calcium Fly Ash-based Geopolymer Concrete

in GPC, and at higher alccofines, water molecules in the form of hydrates and hydroxides decreased. However, many peaks at 2θ= 54°, 38.50° and 67.70° of calcium magnesium silicates are also observed. All these reasons might have resulted in better strength in the presence of alccofines.

Figure 8. Permeability (depth of penetration) of geopolymer concrete at 28 days.

Figure 9. XRD graphs for Geo polymer Concrete with and without alccofines.

Figures 10-12 show the microstructures of geopolymer concrete with and without alccofine. Geo polymer concrete without alccofines where in aluminates and hydroxides as white precipitates can be observed. However, the microstructure of geo polymer concrete with alccofine in Figure 11 and Figure 12 is entirely different. Figure 11 shows the presence of C-S-H and white precipitates shows polymerization. Spherical cavities of fly-ash particles are minimum in Figure 12. Therefore, the increase in compressive strength with 10% alccofine can be due to better polymerization. Better polymerization further resulted in better crystallization and densely packed microstructure.

Figure 10. SEM micrograph of geo polymer concrete without alccofines.

Figure 11. SEM micrograph of geo polymer concrete with 5% alccofines.

7. Conclusions

- Workability of the GPC significantly improved from 20 mm to 120 mm on increasing fly ash content from 350 kg to 400 kg/m³. Further, a slump of 160 mm achieved at fly ash content of 400 Kg/m³ with 10% alccofines. So it is concluded that, due to ultrafine particle size of alccofines a good workable GPC can be achieved.
- It is observed that alccofine enhances the compressive and split tensile strengths of the GPC when compared to GPC with 0% alccofine.
Further, these values increased with the higher percentage of alccofine and fly ash content.

- Results of this study indicate that water absorption and permeability in terms of depth of penetration are decreased with an increase in alccofine percentage and fly ash content. So it can be concluded that due to ultra-fine particle size of alccofines, it capture the micropores in concrete which further improves the durability of GPC.
- The increased workability, compressive and tensile strengths may be due to ultra-fine particle size of the alccofines, and its spherical shape leads to ball bearing action which in turn fill the micropores present in the GPC.
- The density of the GPC decreased due to the less specific gravity of the fly ash, and the increased density observed on addition of alccofine due to increased compactness of GPC due to increased finer material percentage.
- It is observed from SEM images that alccofine is responsible for better geo polymerisation of the fly ash with alkaline liquid.
- The results of XRD revealed that alccofine changes the amorphous substance into crystalline. Also, the SEM analysis confirmed that some micro cracks were observed into GPC with 5% and 10% alccofine when compared with GPC with 0% alccofine.

8. Acknowledgements

The authors wish to gratefully acknowledge the Ultra Tech RMC, Haryana, ACL Chandigarh for supplying the raw materials, IIT Ropar and DCRUST Murthal for conducting SEM and XRD, M.M. University Sadopur, Ambala for providing concrete research laboratory and IKG PTU, Punjab for providing web resources. Financial support provided by Ministry of Environment, Forest and Climate Change is also duly acknowledged.

9. Practical Relevance

The results obtained in the current study on GPC at ambient condition are highly encouraging which may be helpful in the application of geo polymer concrete not only in precast industry but also in general construction purpose.

10. References

1. Shaikh F U A. Review of mechanical properties of short fibre reinforced geopolymer composites. Construction and Building Materials. 2013 Jun;43:37-49. Available from: Crossref
2. Davidovits J. Geopolymer, Green Chemistry and Sustainable Development Solutions. Proceedings of the World Congress Geopolymer Institute. 2005. P.9-15.
3. Davidovits J. High Alkali Cements for 21st Century Concretes. Special Publication. 1994;144:383-98.
4. Van Jaarsveld JGS, Van Deventer JSJ, Lorenzen L. The potential use of geopolymeric materials to immobilise toxic metals: Part I. Theory and applications. Minerals Engineering. 1997;10(7):659-69. Available from: Crossref
5. Van Chanh N, Trung BD, Van Tuan D. editors. Recent research geopolymer concrete. The 3rd ACF International Conference-ACF/VCA. Vietnam, 2008. P.235-41.
6. Aliabdo AA, Elmoaty AEMA, Salem HA. Effect of water addition, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete performance. Construction and Building Materials. 2016;121:694-703. Available from: Crossref
7. Li Z, Ding Z, Zhang Y. Development of sustainable cementitious materials. Proceedings of international workshop on sustainable development and concrete technology, Beijing, China,2004.p.55-76.PMCid:PMC5172431
8. Bakharev T. Durability of geopolymer materials in sodium and magnesium sulfate solutions. Cement and Concrete Research. 2005;35(6):1233-246. Available from: Crossref
9. Bakharev T. Geopolymeric materials prepared using Class F fly ash and elevated temperature curing. Cement and Concrete Research. 2005;35(6):1224-232. Crossref
10. Guo X, Shi H, Dick WA. Compressive strength and microstructural characteristics of class C fly ash geopolymer.
Suitability of Ambient-Cured Alccofine added Low-Calcium Fly Ash-based Geopolymer Concrete

10. Parmar A, Patel DM, Chaudhari D, Raol H, editors. Effect of Alccofine and Fly Ash Addition on the Durability of Low-Calcium Fly Ash Geopolymer Concrete. Proceedings of the 2nd International Conference on Geopolymer Research, 2015; 245-255.

11. Bharat B, Jindal Dhirendera S, S., Deepankar K. A, Parveen. Improving compressive strength of low calcium fly ash geopolymer concrete with alccofine. Advances in Concrete Construction, An International Journal. 2017 Feb;5(1):17–29.

12. Nourshini A, Babaei M, Castel A. Suitability of heat-cured low-calcium fly ash-based geopolymer concrete for precast applications. Magazine of Concrete Research. 2016;68(4):163–77. Available from: Crossref

13. Bakharov T. Resistance of geopolymer materials to acid attack. Cement and Concrete Research. 2005;35(4): 658–70. Available from: Crossref

14. Law DW, Adam AA, Molyneaux TK, Patnaikuni I, Wardhono A. Long term durability properties of class F fly ash geopolymer concrete. Materials and Structures. 2015;48(3):721–31. Available from: Crossref

15. Shekhovtsova J, Kovtun M, Kearsley EP. Evaluation of short- and long-term properties of heat-cured alkali-activated fly ash concrete. Magazine of Concrete Research. 2015;67(16):897-905. Available from: Crossref

16. Adam AA. Strength and durability properties of alkali activated slag and fly ash-based geopolymer concrete. RMIT University Melbourne, Australia, 2009.p.28–35. PMid:19226462 PMCID:PMC2661090.

17. Sharma C, Jindal BB. Effect of variation of fly ash on the compressive strength of fly ash based Geopolymer Concrete. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) 2015 April.p. 42–44.

18. Nath P, Sarker PK, Rangan VB. Early Age Properties of Low-calcium Fly Ash Geopolymer Concrete Suitable for Ambient Curing. Procedia Engineering. 2015;125:601–17. Available from: Crossref

19. Jindal BB, Yadav A., Anand A, Badal A. Development of high strength fly ash based geopolymer concrete with alccofine. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE). 2016 Apr.p.55–58.

20. A. K. Jain TA, UltraTech Cement Ltd. Status of Availability, Utilization and Potential of Fly ash use in Construction. India: UltraTech Cement Ltd,2016.

21. BIS. IS 3812 (Part 1) Indian Standard Pulverized Fuel Ash - Specification. Bureau of Indian Standards. New Delhi, India, 2003.

22. BIS. IS : 383 Indian Standard Specification for Coarse and Fine Aggregates from Natural Sources for Concrete. Bureau of Indian Standards. New Delhi, India,1970.

23. BIS. IS : 2386 (Part 1) Indian Standard Methods of Test For aggregates Concrete - Part I Particle Size and Shape. Bureau of Indian Standards. New Delhi, India,1963.

24. Parmar A, Patel DM, Chaudhari D, Raol H, editors. Effect of Alccofine and Fly Ash Addition on the Durability of High Performance Concrete. International Journal of Engineering Research and Technology. 2014 Jan;3(1): 1600–605.

25. Rangan BV. Concrete construction engineering handbook. 2nd edition, CRC Press New York., 2007.

26. Talha Junaid M, Kayali O, Khennane A, Black J. A mix design procedure for low calcium alkali-activated fly ash-based concretes. Construction and Building Materials. 2015;79:301–10. Available from: Crossref

27. Hardjito D, Wallah SE, Sumajouw DM, Rangan BV. On the development of fly ash-based geopolymer concrete. ACI Materials Journal-American Concrete Institute.2004;101(6):467–72.

28. Pawar M, Saoji A. Effect of Alccofine on Self Compacting Concrete. The International Journal of Engineering And Science (IJES).2013;2:5–9.

29. BIS. IS 9103 Indian Standard Concrete Admixtures-Specification. Bureau of Indian Standards.New Delhi, India, 1999.

30. BIS. IS 516 Indian Standard Methods of Tests for Strength of Concrete. Bureau of Indian Standards.New Delhi, India,1959.

31. BIS. IS 1199 Method of Sampling and Analysis of Concrete,Bureau of Indian Standards.New Delhi, India,1959.

32. BIS. IS 5816 Indian Standard Splitting Tensile Strength of Concrete- Method of Test. Bureau of Indian Standards.New Delhi, India,1999.

33. Zain MFM, Mahmud H, Ilham A, Faizal M. Prediction of splitting tensile strength of high-performance concrete. Cement and Concrete Research. 2002;32(8):1251–258. Available from: Crossref

34. Ryu GS, Lee YB, Koh KT, Chung YS. The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Construction and Building Materials. 2013;47:409–18. Available from: Crossref

35. Anuradha R, Sreevidya V, Venkatasubramani R, Rangan BV. Relationship between compressive and splitting tensile strength of geopolymer concrete. Indian Concrete Journal.2011 Nov;85(11):18–24.

36. Gambhir ML. Concrete Technology : Theory and Practice: Tata McGraw-Hill Education,India. 2013:p.179–218.

37. ASTM C. 642–82. Test method for specific gravity, absorption and voids in hardened concrete. Annual book of ASTM standards. 1995:4:310–13.

38. Yerramala A, Ramachandrudu C. Properties of concrete with coconut shells as aggregate replacement. International journal of engineering inventions.2012;1(6):21–23.

39. Concrete E-ICf, Andersen NH, Comité Euro-International du Béton. General Task Group 19 D, Structures AoC. Diagnosis and Assessment of Concrete Structures: State of the Art Report: CEB, 1989.

40. DIN. DIN 1048 (Part 5) : German Standard for Determination of Permeability of Concrete. 1991.