



Properties of low-calcium fly ash based geopolymer concrete incorporating OPC as partial replacement of fly ash



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HIGHLIGHTS

- Effect of adding OPC on compressive strength of low-calcium fly ash based geopolymer concrete.
- Effect of adding OPC on water absorption, porosity, and sorptivity of low-calcium fly ash based geopolymer concrete.
- Effect of adding OPC on chloride permeability of low-calcium fly ash based geopolymer concrete.
- SEM, EDS and XRD analysis of low-calcium fly ash based geopolymer concrete with OPC inclusion as fly ash replacement.

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ABSTRACT

Results of an experimental investigation on the compressive strength and permeation properties of fly ash based geopolymer concrete are presented in this paper. Fly ash was partially replaced with 0, 10, 20 & 30% of ordinary Portland cement (OPC). Tests were conducted for compressive strength and permeation properties such as water absorption, porosity, sorptivity and rapid chloride permeability up to the age of 365 days. Findings from this investigation indicate that compressive strength increased with the increase in OPC content at all ages, with optimum being at 20%. The inclusion of OPC resulted in the reduction in water absorption, porosity, sorptivity, and chloride permeability of geopolymer concrete due to the improvement in microstructure caused by co-existence of hydrated products along with geo-polymeric alumina-silicate polymer structure. The results were also verified by the microstructural analysis, SEM, EDS, and XRD, which indicate better compacted and dense microstructure of geopolymer concrete with the addition of OPC.

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1. Introduction

Portland cement production releases a lot of harmful gasses which lead to the problems like greenhouse effect and global warming [1]. Various studies are focussing on the utilization of industrial by-products as an alternative to the high energy-intensive ordinary Portland cement (OPC). Results of such studies are alkali-activated binders which yields comparable or better mechanical properties than conventional cement concrete. Rapid development of initial mechanical strength, low dry shrinkage and excellent bond strength with reinforcing steel are some characteristics of alkali-activated concrete [2]. They have a broad range of materials such as industrial by-products based geopolymers, that generally require temperature curing to achieve high mechanical properties or commercially available self cured alkali-activated materials such as Zeobonds. Gunasekara et al. [3] also reported

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high compressive strength of 28–88 MPa for various geopolymer concretes at 365 days. These are similar to those of conventional OPC based products in terms of strength, appearance as well as texture [4,5]. Diaz-Loya et al. [6] reported the mechanical properties of fly ash based geopolymer concrete similar to that of conventional OPC concrete and concluded that equations mentioned in ACI 318-08 could also be applied for geopolymer concrete to evaluate its flexural strength and static elastic modulus. The materials rich in alumina (Al) and silica (Si) such as kaolin, fly ash, rice husk ash, etc. can be used as raw materials [7] which in presence of alkaline solutions such as hydroxides and silicates of alkalis, undergo polymerization reactions. Fly ash can be considered as commonly used raw material [8–10] due to its favorable chemical composition, fine size and easy availability whereas hydroxides and silicates of sodium or potassium are used as alkali-activating solutions. The mechanism involves the reaction of silica and alumina with the alkali-activating solution which results in the formation of polymeric chains of Si-O-Al-O three-dimensional ring structure [11–13].

The only limitation of fly ash based geopolymer concrete that is resisting its use in actual field applications is the requirement of high-temperature curing [7]. Various studies reported the requirement of high-temperature curing of around 60–80 °C for geopolymers to have better or comparable mechanical properties to that of conventional concrete, which is not feasible for cast-in-situ applications. To overcome this basic limitation, various studies are emphasized on the synthesis of geopolymers using such materials which can liberate extra heat to the geopolymer system. The addition of calcium in the geopolymer system (in the form of OPC) found to have a positive influence on its properties not only when specimens are temperature cured [14] but also at ambient temperature curing. Previous studies [15–18] also reported the improvement in mechanical properties with other sources of calcium as well such as calcium chloride, blast furnace slag, etc. The results obtained in these studies correspond to the additional calcium based products which enhanced the overall strength of geopolymer system as well as improved its microstructure by making it less permeable and more durable.

This study is confined to low-calcium fly ash based geopolymer concrete in which fly ash was partially replaced by OPC at 0, 10, 20 and 30% in a temperature cured system and its effect on compressive strength and permeation properties such as water absorption, porosity, sorptivity and chloride permeability were studied at ages up to 365 days. In addition, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) analysis were also conducted on the specimens at all ages.

2. Materials and methods

2.1. Materials

Fly ash obtained from Rajiv Gandhi thermal power plant, India with specific gravity 2.33 and specific surface area 270 m²/kg was used as alkali source in this study. OPC was used as a calcium source which was added as fly ash replacement with physical and chemical properties as shown in Tables 1 and 2 respectively. The results showed the presence of low calcium, high silica and alumina content in fly ash whereas high calcium content was observed in OPC. Fig. 1 shows the XRD analysis of fly ash and OPC particles used in the present study. For fly ash; quartz, mullite, and albite, whereas for OPC; hatrurite, alite, calcium silicate, and quartz were identified as major phases. Quartz refers to the silica; albite refers to alumina, whereas alite and hatrurite refer to tricalcium and dicalcium silicates. Similar phases were also reported in the previous studies [19,20] as well. The total amorphous content in fly ash was observed to be 88.5% and crystalline content was found to be 11.5%. River sand with a specific gravity as 2.54, water absorption as 0.20% and fineness modulus as 2.54, was used as fine aggregates and crushed stone aggregates with a specific gravity as 2.70 and water absorption as 1%, were used as coarse aggregates. Alkali-activating solution was prepared by mixing sodium hydroxide (NaOH) and sodium silicate solution 24 h before casting to eliminate the effect of large heat that was liberated at the time of mixing [21,22]. NaOH solution of molarity 10 M was prepared by mixing NaOH pellets with distilled water whereas sodium silicate solution (Na₂SiO₃) was prepared by mixing 16.20% Na₂O, 34.72% SiO₂ and 49.08% water. Also, naphthalene based superplasticizer was used to achieve adequate workability.

2.2. Methods

2.2.1. Synthesis

The dry mixture was obtained by mixing together alkalis and aggregates in the pan mixture for 5 min. The previously prepared alkali-activating solution with superplasticizer at 2% (by weight of total alkalis) was added to the dry mixture. After performing the trial mixtures, the final mixture proportions were adopted as shown in Table 3. The constituents were mixed for almost 15 min till a

Table 1
Physical properties of OPC.

Physical properties	Value
Normal consistency (%)	30
Initial setting time (minutes)	79
Final setting time (minutes)	412
Specific gravity	3.12

Table 2
Chemical properties of OPC and fly ash.

Oxides	OPC (%)	Fly ash (%)
Calcium oxide (CaO)	64.46	4.23
Aluminium oxide (Al ₂ O ₃)	4.69	27.89
Silica oxide (SiO ₂)	21.87	53.01
Iron oxide (Fe ₂ O ₃)	4.27	8.71
Magnesium oxide (MgO)	0.98	1.84
Potassium oxide (K ₂ O)	0.76	1.63
Sodium oxide (Na ₂ O)	0.28	0.58
Sulphur trioxide (SO ₃)	2.69	0.96
LOI	–	1.15

homogenous mixture was obtained. The concrete was filled in the specimens followed by compaction on the vibrating table to reduce the voids. After the rest period of an hour, the specimens, covered with steel plate, were subjected to oven curing at 80 °C for 24 h. The specimens were de-moulded after curing, wrapped by cling film to avoid the moisture loss and kept at room temperature until the testing age.

2.2.2. Compressive strength

Compressive strength tests were performed on the mixtures at 3, 7, 28, 90 and 365 days in accordance with BIS: 516 [23]. Cubical specimens of size 150 × 150 × 150 mm were cast and tested in a compression testing machine (CTM) of 2000 kN capacity where the load was applied without any jerk. Also, to study the microstructural characteristics, the powder residues were subjected to SEM (JEOL JSM 6510 LV), EDS and XRD analysis. The peaks were obtained as scanned spectrum and phase identification was done by using High Score Plus software.

2.2.3. Water absorption and porosity

Water absorption and porosity tests were conducted in accordance with ASTM C642 [24] on geopolymer concrete specimens at 28, 90 and 365 days. The discs of size 100 × 50 mm were cut from parent cylindrical specimens of size 100 × 200 mm. The values were calculated as:

$$\text{Porosity (\%)} = \frac{(W_a - W_d)}{(W_a - W_w)} \times 100 \quad (1)$$

$$\text{Water Absorption (\%)} = \frac{(W_a - W_d)}{W_d} \times 100 \quad (2)$$

where,

w_a = weight of the saturated sample in air (g),
 w_d = weight of dried sample (g) and
 w_w = weight of the saturated sample in water.

This method of testing water absorption and porosity were also adopted in other studies [14,25,26] as well.

2.2.4. Sorptivity

The rate of sorptivity was calculated in accordance with ASTM C1585 [27] at 28, 90 and 365 days. The specimens were placed upright with the sides curved surface sealed properly so that water was able to penetrate only through the bottom. Above the bottom of the specimen, a constant head of 5 mm and the sufficient gap of around 100 mm between the samples were maintained in the tray for its easy absorption by the capillary action. The weight of specimens before the immersion and at 1, 5, 10, 20, and 30 min and further at 1, 2, 3, 4, 5 and 6 h of immersion were observed and rate of sorptivity was calculated in terms of $\mu\text{m/s}^{1/2}$ by performing regression analysis.

2.2.5. Rapid chloride permeability testing (RCPT)

Rapid chloride permeability tests were conducted on the geopolymer concrete specimens as per ASTM C1202 [28] at 28, 90 and 365 days. From the parent cylindrical 100 × 200 mm specimens, discs of size 100 × 50 mm were cut and placed in between the testing assembly whose one end was immersed in sodium hydroxide and the other in sodium chloride solution. A constant potential difference of 60 V DC was maintained throughout the test. Total electric charge passing through the specimens was measured up to 6 h. The resistance to the chloride ions was measured in terms of the total charge passed which was related to the range of permeability specified in Table 4 [28] as high, moderate, low, very low and negligible.

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