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Strength, permeability and micro-structural characteristics of low-calcium fly ash based geopolymers

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HIGHLIGHTS

- Effect of OPC replacement on workability properties.
- Effect of OPC replacement on compressive and split tensile strength.
- Effect of OPC replacement on chloride permeability.
- SEM, EDS and XRD analysis of fly ash based geopolymer concrete.

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ABSTRACT

The paper presents the properties of low-calcium fly ash based geopolymer concrete in which fly ash was partially replaced (0, 10, 20 and 30%) with ordinary Portland cement (OPC). Tests were conducted for workability, compressive strength, split tensile strength and rapid chloride permeability (RCPT) up to the age 28 days. SEM, EDS and XRD analysis were also carried out.

Test results indicate that workability of low-calcium fly ash based geopolymer concrete decreased with increase in OPC content. Further, inclusion of OPC enhanced the compressive strength and reduced the permeability at all ages (3, 7 and 28 days). However optimum results were obtained for geopolymers with 20% OPC. SEM, EDS and XRD analysis confirmed the modifications in matrix making it denser, compact and less permeable.

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1. Introduction

With the ever increasing growth in the infrastructure sector, the demand for concrete and its binder material such as ordinary Portland cement (OPC) is increasing exponentially. But from last few years, questions are being raised regarding its environmental hazards caused by clinker production [1,2]. This major issue has prompted the researchers to develop supplementary cementitious materials (SCMs) as a replacement and or as addition to cement to develop a whole new range of cement-less binder known as geopolymers [3–6]. Geopolymers are formed by the combination of materials rich in silica and alumina like bottom ash, fly ash, metakaolin, etc and alkali solutions like potassium hydroxides of sodium and potassium, etc with soluble silicates of sodium and potassium. The resultant aluminium oxides and silica oxides further undergo the polymeric reactions resulting in formation of aluminosilicate three-dimensional networks whose strength can be even higher to that of conventional concrete. For curing purpose, heat is generally applied ranging from 60° C to 100° C to the geopolymer specimens for about 24–48 h and then can be left at room temperature for use. Based on above mechanism all the materials that can dissolute silica and alumina in the system can be used which in the presence of strong alkalis and high temperature forms geopolymers. For instance, GGBS, which is a waste product of iron industry, have been found satisfactory in various studies when used as raw material for geopolymer concrete [7,8]. Similarly other waste products such as pulverized fuel ash [9], fly ash [10], oil fuel ash [3,11], rice husk ash [6,12] are also being used. These waste products from various industries, when used as a raw material in geopolymer technology, not only reduce the disposal problems but also lower the cement usage for concrete applications. Also apart from excellent strength properties, due to its dense microstructure, they exhibit good durability properties as well such as acid resistance, sulphate resistance, etc. For instance geopolymer synthesized with fly ash has better sulphuric acid

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resistance than conventional OPC concrete [13]. Similar conclusions were made by Tho-in et al. [14] which showed excellent durability characteristics for fly ash based geopolymers. Apart from all the advantages of geopolymers the only thing that resists its use in the field applications is its curing method. As already mentioned it requires heat curing period of 24–48 h at 60–100° C which becomes very difficult in actual field applications. Researchers are more focussed to develop geopolymers using various additives such as GGBS, metakaolin, Portland cement, etc [15–17].

The addition of OPC to the geopolymers can be an effective measure to improve the properties as at normal temperature as it has exothermal reaction mechanism which can increase the temperature and help in strength development of the resultant geopolymer. Also OPC is the most common commodity that is being used in construction industry and so there can be no issue regarding the availability as compared to other materials. The aim of this research is to study the effect of replacing fly ash with OPC at different percentages (0%, 10%, 20% and 30%). Kong and Sanjayan [18] tested compressive strength of geopolymer specimens up to 3 days only which was reported as equivalent to 28 days strength development of conventional OPC concrete [19]. It is also observed from other studies [20,21] that after the completion of temperature curing period, as the mechanism is related to polymerization reactions, there is no significant increase in strength after that. Joseph and Mathew [9] also reported no significant development in strength beyond 7 days. Based on this, as no significant effect of age after temperature curing period is reported, the properties in this paper are studied up to 28 days only. The main objective of this study is to develop the geopolymer concrete with high strength characteristics and to observe the effect of adding calcium content (in the form of OPC) at different proportions on its strength and permeability properties. As this concrete aims at very high early age strength, it can overcome the use of conventional cement in various industrial applications. The properties such as workability are studied for fresh concrete, strength parameters are studied for up to 28 days and chloride permeability is studied at 28 days. In addition scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) & X-ray diffraction (XRD) analysis are also performed on 28 days specimens. Also, the relationship between workability, strength parameters and chloride permeability are also discussed.

2. Experimental details

2.1. Materials

Fly ash (FA) was procured from Rajiv Gandhi thermal power plant in Khedar, India and 43 grade ordinary Portland cement (OPC) was obtained from the local vendors. The physical tests on OPC [22] as shown in Table 1 and chemical tests on OPC and fly ash as shown in Table 2 were performed. The specific gravity of fly ash was observed to be 2.31 and its specific surface area was found to be 270 m^2/kg. SEM and EDS analysis of OPC and fly ash were performed as shown in Figs. 1 and 2 respectively. As expected the fly ash particles found to be spherical in shape with a high content of silica and alumina whereas OPC found to have high calcium content in addition to silica. Natural river sand obtained from the local sources of fineness modulus 2.56 as fine aggregates and 12.5 mm diameter crushed stone aggregates as coarse aggregates were used. The aggregates were tested as per Indian standards [23]. The specific gravity of fine and coarse aggregates was 2.57 and 2.74 whereas water absorption was 0.21% and 1.04% respectively. In addition, the alkali solution consisting of hydroxides and silicates of sodium or potassium was required to liberate silica and aluminas from the source materials i.e. fly ash and OPC which undergo polymerization to form NASH, CASH and CSH. In this study, sodium hydroxide (NaOH) solution of molarity 10 M was prepared from NaOH pellets, which were obtained from Fisher Scientific Company, and sodium silicate solution (Na_2SiO_3) with 16.20% Na_2O, 34.72% SiO_2 and 49.08% water was used.

Table 1
Physical properties of OPC and fly ash.

Physical properties	OPC	Standard values
Standard consistency	31%	–
Initial setting time	89 min	Not less than 30 min
Final setting time	373 min	Not greater than 600 min
Specific gravity	3.04	–
Fineness (m^2/kg)	318	–

Table 2
Chemical properties of OPC and fly ash.

Oxides	OPC (%)	Fly ash (%)
Silica Oxide (SiO_2)	21.68	37.6
Aluminium oxide (Al_2O_3)	4.69	14.79
Iron oxide (Fe_2O_3)	4.37	18.56
Calcium oxide (CaO)	64.27	19.61
Magnesium oxide (MgO)	0.98	2.7
Potassium oxide (K_2O)	0.76	0.98
Sodium oxide (Na_2O)	0.28	0.73
Sulphur trioxide (SO_3)	2.69	4.81

2.2. Mixing, casting, and curing

As observed from the previous studies [24,25] that the mixing of alkali solutions releases a large amount of heat, before mixing to the dry mixture it should be left at room temperature for about 24 h to bring down the temperature. On the other hand, few studies suggested that the alkali solutions should directly be mixed to the dry mixture [26,27]. However, in this study, the alkali solutions were mixed together 24 h prior to use to bring down its temperature to ambient temperature. Naphthalene based admixture at 2% dosage by total weight of fly ash and OPC was added to the alkali solution before mixing them to the dry mixture. The mixture proportion of geopolymer specimens with the addition of OPC at different levels is shown in Table 3. The dry mixture was obtained by mixing fly ash, OPC and aggregates in addition to previously mixed alkali solution with plasticizer in the pan mixture for about 15 min. The mixes were denoted as G100C0, G90C10, G80C20 and G70C30 as OPC was added as fly ash replacement at 0%, 10%, 20% and 30% respectively. After mixing the concrete specimens were cast in different moulds for example 150 mm cubical moulds for compressive strength test, 150 × 300 mm cylindrical moulds for split tensile strength and 100 × 200 mm cylindrical moulds for rapid chloride permeability test (RCPT) which were further cut in the size 100 × 50 mm. Table vibrator was used for the compaction of specimens. They were covered with steel plates at room temperature for an hour followed by temperature curing at 80° C for 24 h in an oven. The moulded specimens were de-moulded and covered by cling film to avoid moisture loss at room temperature till their testing age.

2.3. Testing procedures

Due to the high viscosity of geopolymer concrete specimens, compacting factor test was also performed in addition to slump test. For strength testing, the specimens were placed inside the compression testing machine (CTM) where the load was applied without the jerk till it breaks down and no further load was sustained. The tests were conducted as per ASTM C109 and the results

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