© 2019 IJSRSET | Volume 6 | Issue 6 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099
Themed Section : Engineering and Technology
DOI : https://doi.org/10.32628/IJSRSET

Development and Property Evaluation of Fly Ash-Based Geopolymer Concrete

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ABSTRACT

Fly ash-based geopolymer concrete proved to be an ideal alternative to conventional Portland cement concretes with improved mechanical properties as well as superior durability, reducing carbon emissions by over half. The study discusses the impact of variations in fly ash content, ranging from 70% to 85%, on the performance of geopolymer concrete. Experimental methods involved optimising the mix design with the use of activators sodium hydroxide and sodium silicate, and the curing at increased temperatures to accelerate geopolymerization. The major tests conducted for testing durability included compressive strength in accordance with ASTM C39, water absorption ASTM C642, chloride permeability ASTM C1202, sulfate expansion ASTM C1012, and freeze-thaw resistance according to ASTM C666. The results indicate improvement of 23% in compressive strength that ranged from 39 MPa at 70% fly ash to 48 MPa at 85% fly ash. Water absorption improved by 34%, while the chlorides permeability reduced by 44% and the sulfate expansion decreased by 62.5%. The freeze-thaw resistance is enhanced by 3.5% as indicated by the performances under cyclic variations in temperature.

Keywords : Fly Ash-Based Geopolymer Concrete, Mechanical Properties, Durability, Compressive Strength, Carbon Emissions Reduction

1.0 Introduction

Concrete is the most widely used construction material globally, but the production of this material is the main source of carbon dioxide emission in the environment, as it requires a high proportion of Portland cement. Thus, geopolymer concrete is a promising sustainable alternative to respond to the urgent needs of sustainability. The industrial waste of fly ash and others are used in the making of geopolymer concrete. An alkaline solution of sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) activates this. The method of geopolymerization provides the three-dimensional network of aluminosilicate, giving superior durability and mechanical qualities to the material [1-4].

Geopolymers with fly ash from coal combustion at thermal power plants are highly aluminous, rich in silicon and alumina, and appropriate precursors to geopolymer concrete. Furthermore, fly ash utilization minimizes industrial waste, which would have otherwise contributed to environmental footprint because of cement manufacturing. Moreover, geopolymer concrete offers an excellent resistance capacity to aggressive environments such as sulfate attack, chloride penetration, and freeze-thaw cycles, for infrastructure that often experiences extreme exposures.

Although a significant amount of work has been carried out on geopolymer concrete development, much remains to be explored. There are still concerns about variability in fly ash composition, optimization

Received : 25 Nov 2019 | Accepted : 05 Dec 2019 | November-December-2019 [6 (6) : 293-298]

of activator ratios, and curing conditions that have an impact on long-term performance. The objective of this research work is to systematically evaluate the mechanical and durability properties of fly ash-based geopolymer concrete in order to address these gaps. The outcome of this research would contribute toward furthering the use of sustainable construction materials and to encourage geopolymer technology usage in industry [5-9].

Despite the notable beneficial properties exhibited by geopolymer concrete, only a relatively small number of investigations have been conducted to optimize fly ash-based formulations for structural applications and unveil the influence of various curing regimes and alkaline activator compositions on the durability. This study was conducted with the view to fill in these gaps, exploring mechanical and durability characteristics of geopolymer concrete under different curing conditions and activator ratios. The study attempts to compare the compressive strength and workability of fly ash-based geopolymer concrete, as well as analyze durability performance in terms of water absorption, chloride penetration, and sulfate resistance. The study looks forward to establishing an optimal mix design that yields maximum strength and durability while considering sustainability. An understanding of these combined parameters will help to develop a more reliable and environmentally friendly geopolymer concrete formulation for structural applications, such as large-scale constructions. This work will facilitate significant progress in the sustainable development of construction materials and offer direction for subsequent research works and practical implementations of geopolymer technology.

2.0 Experimental Methods

Materials used in the study comprise Class F fly ash from thermal power plants, pellets of sodium hydroxide, sodium silicate solution, fine aggregates like river sand, coarse aggregates which include crushed granite, and potable water. The solution for the alkaline activator was formulated by mixing NaOH with Na2SiO3 in different proportions to achieve the required molarity. The fly ash to activator ratio, aggregate proportion, and water content were all optimized to come up with a well-balanced composition of concrete mix. Preparing the activator solution was done 24 hours before mixing so that complete dissolution of NaOH could occur. Dry blending of fly ash, fine and coarse aggregates initiated the mixing process. Gradual incorporation of activator solution brought about a uniform mix. The fresh geopolymer concrete was then poured into molds and compacted using a vibrating table to minimize air voids and enhance the material's density. Curing was carried out in an oven at elevated temperatures ranging from 60°C to 80°C for a period of 24 hours to accelerate the geopolymerization process, after which the specimens were stored at ambient conditions before testing.

Various tests were conducted under the guidelines of ASTM standards for assessing the strength and durability of fly ash-based geopolymer concrete. For evaluating the axial load-carrying capacity, compressive strength was assessed through ASTM C39. The degree of porosity and permeability of the material were measured with water absorption test in accordance with ASTM C642. The rapid chloride permeability test (ASTM C1202) was conducted to assess the resistance of the concrete to chloride ion ingress, which is critical for structures exposed to marine environments. Sulfate resistance was examined using ASTM C1012 by immersing specimens in sulfate solutions and monitoring expansion over time to determine the concrete's ability to withstand chemical attacks. In addition, freeze-thaw resistance was evaluated through ASTM C666 to establish the durability of the material under cyclic freezing and thawing conditions.

3.0 Results and Discussions

3.1 Compressive Strength

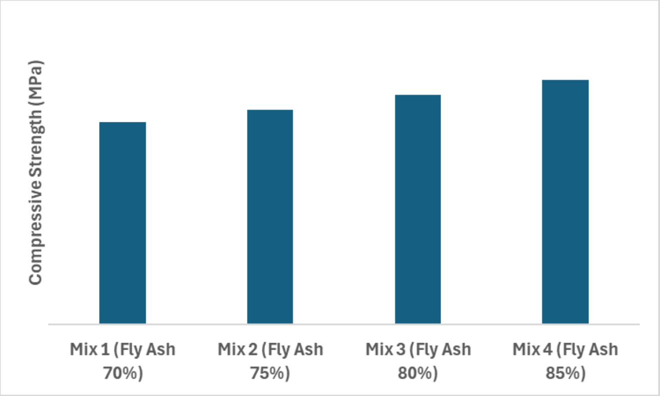

Fig. Effect of flyash on compression strength

The compressive strength graph shows a positive trend where the strength increases with an increase in fly ash content from 70% to 85%. Mix 1, Fly Ash 70%, has a compressive strength of about 39 MPa, while Mix 4, Fly Ash 85%, has the highest strength at about 48 MPa. This is because geopolymerization activity is intensified by the increase in fly ash content, as it offers extra alumina and silica for creating a denser aluminosilicate matrix. Statistically, the mixes have a small standard deviation with consistent improvements in strength. At 85%, the mix increased strength by 23% when compared to that of the 70% mix, which would indicate that increased proportions of fly ash are beneficial in increasing compressive strength [8-12].

3.2 Water Absorption

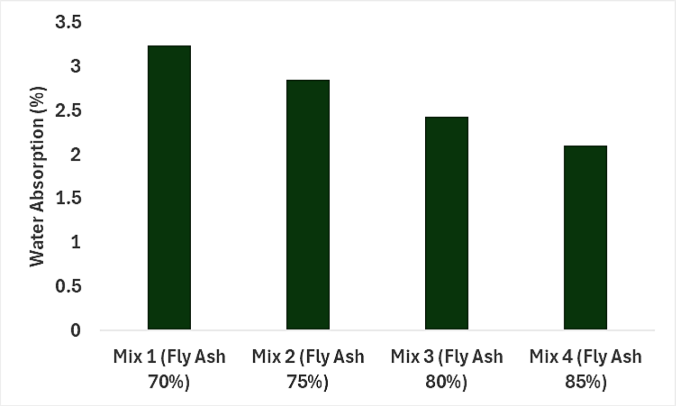

Fig.2 Effect of flyash on water absorption

The influence of flyash on water absorption is given in Fig.2. It is observed from the water absorption curve that it has a downward trend, wherein absorption values reduce from 3.2% in Mix 1 to 2.1% in Mix 4. The reason behind such a decrease is the increment of fly ash percentage, as the microstructure turns denser and porosity gets reduced. The statistical analysis indicated a decrease in water absorption of 34% from Mix 1 to Mix 4. This proved the improved impermeability of the mixes, indicating that with decreased absorption, durability is higher and Mix 4 is thus most resistant to moisture ingress [10-14].

3.3 Chloride Permeability

Fig.3 depicts the impact of flyash on Chloride permeability. The chloride permeability graph indicates that the permeability decreases significantly with an increase in fly ash content. Mix 1 records a permeability of about 850 Coulombs, while Mix 4 has the lowest value at around 480 Coulombs. The decrease is due to the improved pore structure developed as a result of the enhanced geopolymerization. A statistical analysis shows that the chloride permeability has decreased by 44% from Mix 1 to Mix 4, which makes the higher fly ash content suitable for marine and chloride-rich environments [12-16].

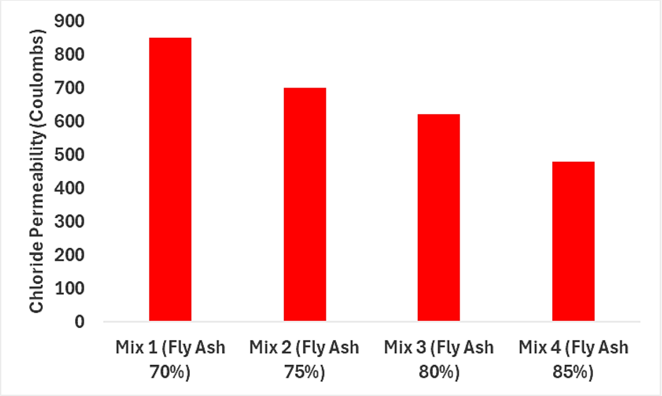

Fig.3 Effect of flyash on Chloride permeability

3.4 Sulfate Expansion

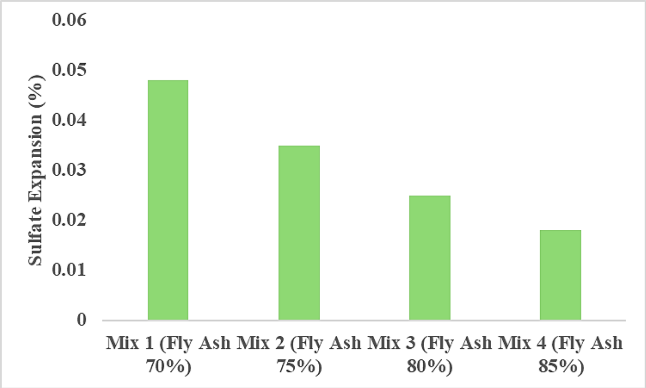

Fig.4 Effect of flyash content on Sulfate expansion

Fig. 4 shows the fly ash content impact on sulphate expansion. The graph of the sulphate expansion shows a decreasing trend and values reduce from 0.048% for Mix 1 down to 0.018% in Mix 4. The reason for this reduction in expansion is due to the improved chemical resistance of the geopolymer matrix, thereby inhibiting the formation of expansive sulphate compounds. The data shows that the expansion from Mix 1 to Mix 4 has been reduced by 62.5%, which means higher fly ash mixtures endure longer when exposed to sulphate [17-21].

3.5 Freeze-Thaw Resistance

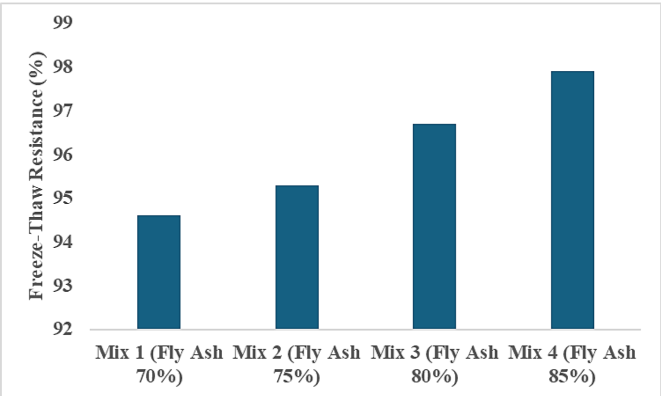

Fig.5 Effect of flyash content on freeze thaw resistance

Fig.5 shows the effect of flyash content on freeze thaw resistance. The freeze-thaw resistance graph shows a trend of enhanced durability with increasing fly ash content. Mix 1 has achieved a resistance value of 94.6% and Mix 4 has shown the highest resistance value of 97.9%. This denser microstructure restricts the entrance of water into the matrix and protects it against damage caused during freeze-thaw cycles. Therefore, it results in higher resistance. A statistical analysis of data shows that an increase in 3.5% of resistance across mixes. It has also proved the justification of having higher fly ash contents for structures undergoing periodic temperature variations.

4.0 Conclusions

- The compressive strength of geopolymer concrete improves with increased content of fly ash. Mix 4, having 85% fly ash content, showed 48 MPa, while that of Mix 1, containing 70% fly ash content, was recorded at 39 MPa, which is 23% stronger. This reveals the effectiveness of increased geopolymerization to strengthen the matrix.
- Water absorption decreased substantially with the increase in fly ash content. Mix 4 had 2.1%, whereas Mix 1 had 3.2%. This indicates a 34% reduction with an increase in fly ash content, thus forming a denser microstructure and increasing impermeability.
- The chloride permeability reduces by 44% from 850 Coulombs in Mix 1 to 480 in Mix 4. It shows that fly ash at higher percentages enhances resistance to chloride ion penetration and hence can be applied along the coastal and marine environments.
- Sulfate expansion decreases from 0.048% in Mix 1 to 0.018% in Mix 4, which means a reduction of 62.5%. This is due to the chemical stability of the geopolymer matrix, which prevents the formation of expansive compounds upon exposure to sulfate.
- Freezing-thawing resistivity enhances from 94.6% in Mix1 to 97.9% in Mix4 and thereby enhancing by 3.5%. The reduced porosity and water penetration ensure that no structural degradation of the concrete will be contributed during the cyclic freezing and thawing.

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