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Evaluation of Fly Ash as a Partial Replacement for Cement in Concrete: Effects on Strength and Durability

Vikram M K[1], Aparna B P[2], Roopakala C G[3]
[1]Senior Lecturer, Department of Civil Engineering, Government Polytechnic, Channapatna, Karnataka, India
[2]Senior Lecturer (senior scale), Department of Civil Engineering, Government Polytechnic Ramanagara, Karnataka, India
[3]Senior Lecturer, Department of Civil Engineering, Government Polytechnic, Sira, Karnataka, India

Abstract: This article details a study that looked at the effects of 10%, 20%, and 30% fly ash substitution on the mechanical and durability qualities of concrete. Compressive, tensile, flexural, workability, heat of hydration, and water absorption tests were performed on the resulting mixtures after OPC was partially replaced with fly ash. The best compressive, tensile, and flexural strengths along with durability characteristics were found at the 20 % replacement. The workability increases with an increase in fly ash due to its lubricating effect, which decreased the heat of hydration up to 20 % replacement and then started to rise slightly at 30 % replacement. Water absorption is significantly reduced at 20% fly ash whereas increased at 30% as a result of excess porosity and voids. These observations indicate that 20% fly ash represents the optimum level of substitution in order to strike the balance between the performance under mechanical stress as well as durability, thus would be a sustainable replacement for the conventional cement.
Keywords: Fly Ash, Mechanical Properties, Durability, Sustainable Concrete, Supplementary Cementitious Materials.

I. INTRODUCTION

This common construction material, much used, proves to be a significant contributor to global carbon dioxide emissions because it consumes a lot of energy. Thus, the high carbon footprint created by cement manufacture has led to interest in sustainable alternatives and optimization of concrete mix designs to reduce environmental impact without a compromise on performance. Among the different strategies explored, supplementary cementitious materials like fly ash, slag, and silica fume have been considered worthwhile. Fly ash is one of the popular industrial by-products readily available due to industrial combustion of coal in thermal power plants, hence increasing its great potential as partial replacement for cement in concrete mixtures.

Due to the fact that fly ash is known to possess pozzolanic qualities, it is able to react with calcium hydroxide, which is created as a by-product during the cement hydration process. This results in the formation of more C-S-H gel, which results in an overall improvement in the strength and durability of concrete. The use of fly ash as a partial substitute for cement not only lowers the quantity of cement that is used, which in turn reduces the amount of carbon dioxide emissions, but it also enhances some particular features of the concrete, such as its workability, lowered heat of hydration, and long-term strengths. In addition to this, it is a component of waste management in terms of sustainability since it makes use of industrial by-products that would otherwise be disposed of in landfill space [1-3].

Researchers F. Baeza and colleagues [4] investigated the idea of employing a mixture of industrial waste from a variety of sources as a partial alternative for Portland cement in mortars and pastes when it comes to the production of these materials. SSA, marble dust, fly ash, and rice husk ash were among the additions that were evaluated in the pastries that were prepared using Portland cement and a variety of other additives. Numerous curing durations have been explored, and some of the factors that have been taken into consideration include density, mechanical strengths, ultrasonic pulse velocity, thermogravimetry, and water absorption. The studied mineral admixtures, when combined with waste materials, exhibit better absorptions, densities that are comparable to those of the control sample, and they also exhibit pozzolanic activities. The cement strength class is often exceeded or not met by the compressive strength of the composite material. When SSA, F.A., and RHA were coupled with 30% cement replacement, the strength of the material rose by 9% in comparison to the one that served as the control. The Chan W.W.J. and his colleagues [5] conducted research to determine the durability of concrete manufactured from a variety of non-reactive waste materials, including carbon black, silts, and clays, as well as the influence of varying water concentrations on the performance of the concrete.

Among the concrete tests that he has explored are the compressive strength, workability, water permeability, and sorptivity of the material. His next step was to go further into the issue by using image microscopy, energy dispersive X-ray spectroscopy, and scanning electron microscopy to investigate the microstructure and cement hydration change in these concretes. He did this in order to get a better understanding of the situation. Increasing the specific surface area or making use of a superplasticizer are two methods that may be used to attain desired levels of workability. In light of this, he investigated a number of different silt and clay ratios in the current research. In addition to this, he observed that silts and clay had the potential to replace up to 25 percent of the volume of cement when combined with a water-to-cement ratio of 0.5, therefore producing concrete. It has a lower amount of cement and water compared to OPC. Additional to that, there will be a decrease in the cost of concrete. Before making the decision to use reservoir sludges in the manufacturing of 20% blended cement, O. Rodriguez and colleagues [6] conducted an analysis of the chemical, physical, morphological, mineralological, and pozzolanic characteristics of a number of different reservoir sludge combinations.

The sludges being studied have good pozzolanic activity, with sample 5 showing especially high levels of SiO_2, Al_2O_3, and Fe_2O_3. Mixtures of cement pastes containing 20% sludge meet the European standard for compressive strength exceeding 32.5 MPa after 28 days of curing, with the exception of sample 5, which exhibited compressive strength values that were comparable to the reference cement and up to 2% higher with longer curing times. In order to find a partial cement substitute for mortars, Khmiri et al. [7] studied the pozzolanic activity of finely ground waste glass. Two sets of experiments were utilized to assess its behavior: one to examine and clarify the pozzolanic processes using a lime-glass test, and the other to follow the growth of strength using a compressive strength test.

Testing with DSC, XRD, and SEM on samples with 25% $Ca(OH)_2$ and 75% powdered glass confirmed that this mixture initiates the synthesis of calcium silicate while reducing the amounts of lime and hydrate sodium carbonate. Because the reaction mentioned earlier produces the subsequent step in hydrated sodium silicate synthesis, we were able to quantify the size stability of mortars made using this method. The compressive strength of mortars with ground glass particle sizes ranging from 80 to 40 lm, 20 lm fineness, and 100 to 80 lm showed strong pozzolanic activity in the 20 lm class. The corresponding strength activity indices were 82% at 7 days, 95% at 28 days, and 102% at 90 days. There has been a lot of study on using fly ash in place of cement in concrete, but most of it has concentrated on how it affects workability and compressive strength, rather than how it holds up to long-term factors like water absorption, chloride penetration, and resistance to harsh environmental conditions. The ideal fly ash content to impart mechanical strengths is far more important than the percentage that strikes a balance between strength and durability under different curing conditions; the former has yet to be determined.

Filling up the aforementioned information gaps is necessary for developing a more balanced understanding of the performance of fly ash-based concrete for different structural applications. The current research set out to systematically examine how various fly ash weight percentages (ranging from 10% to 30% of cement) affected the mechanical and durability properties of concrete. In this light, the purpose of this research is to investigate the effects of fly ash on the compressive and tensile strengths, resistance to water absorption and chloride ion penetration, and environmental viability of fly ash as a cement alternative.

In this context, recommendations are given based on the findings in enhancing concrete mix designs with regard to structural applications, hence leveraging the recourse to greener construction materials.

II. MATERIALS AND METHODS

To investigate the mechanical and durability properties of concrete, an experimental investigation was carried out to investigate the partial replacement of cement with fly ash. Experiment materials were prepared in accordance with IS 383 standards and consisted of Ordinary Portland Cement of grade 53, river sand for fine aggregates, and crushed granite for coarse aggregates. The fly ash came from a thermal power plant that was close by. As per ASTM C618 for Class F fly ash, it is a cementitious additive with a fineness of 320 m^2/kg. The water-to-cement ratio was 0.45 when the mixtures were made. There were four different mix designs created: one without fly ash, one with 10%, one with 20%, and one with 30% fly ash by weight of cement. With a target compressive strength of 40 MPa in mind, the mix proportions stayed the same. The concrete was mixed, mixed, and cast in compliance with ASTM C192 to ensure that the fly ash was distributed evenly throughout the mixture. Curing and casting of cube specimens of 150 mm × 150 mm × 150 mm were carried out in compliance with ASTM C39 in order to conduct compressive strength testing. Cylindrical specimens meeting the requirements for tensile testing were manufactured according to ASTM C496 and had dimensions of 150 mm diameter and 300 mm height. The dimensions of the beam specimen used for the flexural strength test were 100 mm × 100 mm × 500 mm, as per ASTM C78. One day later, each specimen was removed from the molds and allowed to cure in water at a temperature of 23°C ± 2°C for a duration of 28 days.

A. Testing and Characterization

A Universal Testing Machine was used to measure compressive strength in compliance with ASTM C39. A load of 0.5 MPa/sec was applied. The split tensile test, as per ASTM C496 standards, was used to measure the tensile strength. The four-point bending test, as described in ASTM C78, is used to determine flexural strength. Slump cone tests were conducted in compliance with ASTM C143 to determine the workability. Slump cone dimensions were 300 mm in height, 200 mm in base diameter, and 100 mm in top diameter. There were three layers of freshly poured concrete, and 25 tamping rod applications were made to each layer. The amount of slump is proportional to the vertical distance from the cone's apex to the concrete's highest point. Following the guidelines laid forth by ASTM C1702, the heat of hydration was determined using an isothermal calorimeter. To measure the total heat emitted, the concrete mixture was placed in the calorimeter and the temperature variations were tracked continuously for 72 hours. The procedure for the water absorption test followed the guidelines laid forth by ASTM C642. The concrete specimens were baked in the oven and then weighed after a certain curing time. After 48 hours in water, they were reweighed to find the percentage of mass gain, which indicates that the specimens had absorbed water.

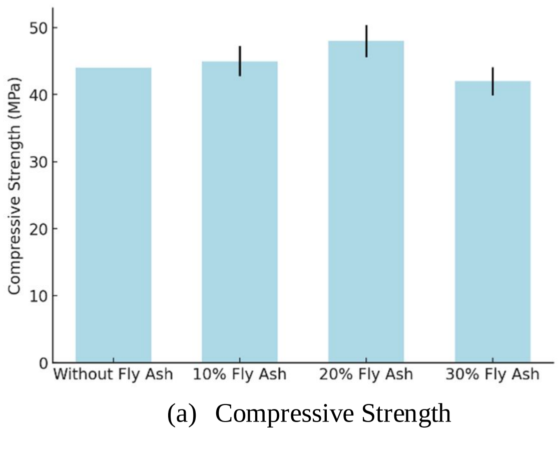
III. RESULTS AND DISCUSSION

A. Compressive Strength

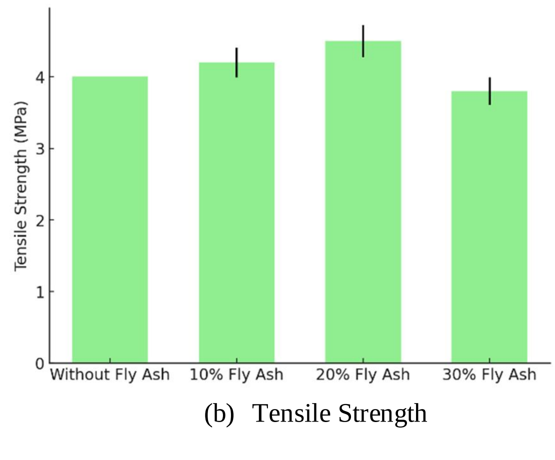
As shown in Figure 1a, the compressive strength rises from 44 MPa to 48 MPa at a fly ash concentration of 20% before starting to fall again, this time to 42 MPa at a 30% concentration. The addition of C-S-H gel to the fly ash causes a pozzolanic reaction, which improves the interfacial transition zone and overall strength. This is the only cause of the maximum increase at 20%. In terms of the diluting impact, however, the extra fly ash is to blame for the 30% strength drop. The strength was reduced since there was less cement available for the matrix. The strength increased about 9 percent compared to the control mix at 20 percent fly ash content and then decreased by 12.5 percent at 30 percent. It implies that fly ash beyond 20 percent would have a detrimental effect on compressive strength. The trend in compressive strength indicates an initial rise to 20% fly ash and then diminishes at 30%. The rise at 20% is attributed to the pozzolanic reaction between fly ash and calcium hydroxide (CH), which is a by-product of cement hydration, forming supplementary C-S-H gel, thus increasing both strength and density of the concrete matrix. However, at 30% fly ash, there is a dilution effect. The counterpart to this is reduced availability of CH for pozzolanic reactions that favor the poorer quality C-S-H gel formation responsible for lower compressive strength.

B. Tensile Strength

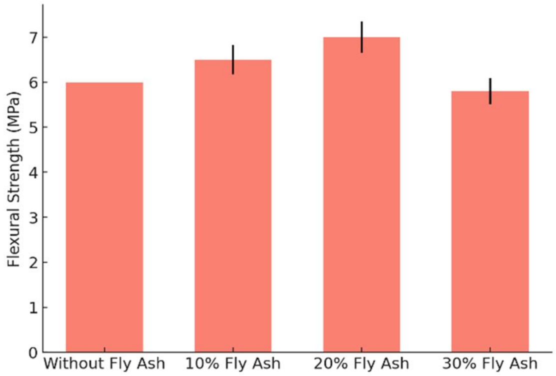
The tensile strength (Fig.1b) increased from 4.0 MPa without fly ash to 4.5 MPa at 20% fly ash and dropped to 3.8 MPa at 30%. The improvement at 20% is because of the increased densification of the microstructure and reduction in micro-cracks created due to the filling effect of fly ash. The 30% one is because of the mere cement hydration products getting unhydrated, leading to bad bonding. Tensile strength increased by 12.5% at 20% fly ash and then decreased by 15.5% at 30%. The fluctuation allows scientists to optimize the content of fly ash for tensile strength growth. The trend with tensile strength also displays a bell shape, as it has increased at a 20% fly ash content and then followed by a decline at 30%. The growth here is basically because of better interfacial transition zones and microstructure refinement due to the filling effect of fly ash. Moreover, the denser cementitious matrix with lower internal micro-cracks is produced due to pozzolanic reaction. For fly ash content at 30%, poor cohesion of particles occurs as a result of too much fly ash, resulting in weakness and lower tensile resistance, as the formation of the matrix is disturbed[8-11].



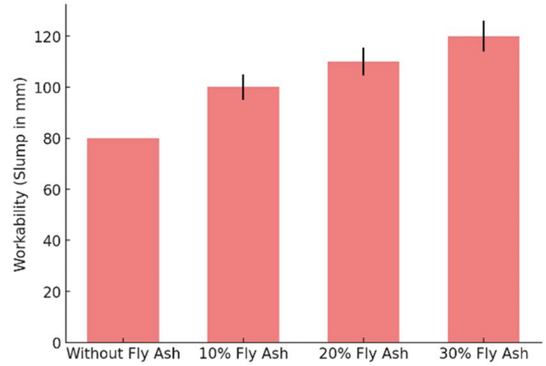
(a) Compressive Strength



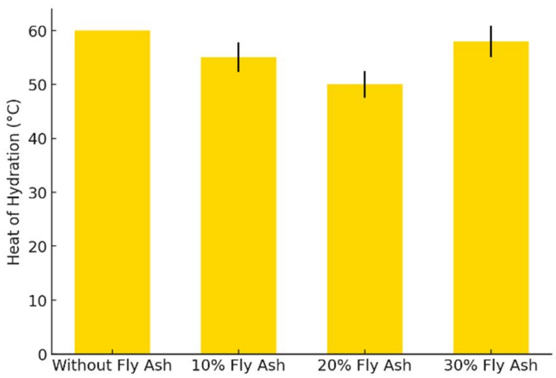
(b) Tensile Strength



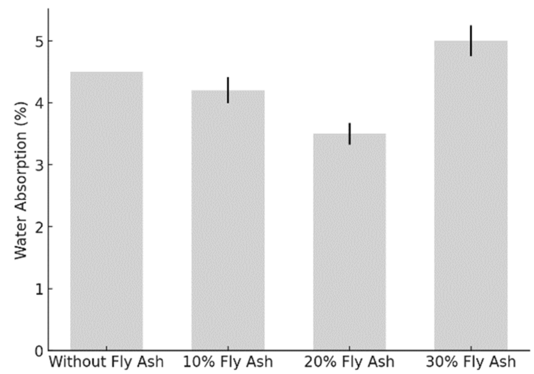
(c) Flexural Strength



(d) Workability



(e) Heat of Hydration



(f) Water absorption

Fig.1(a-f) Variation of mechanical and durability parameters with respect to flyash addition.

C. Flexural Strength

It can clearly be seen in the figure that flexural strength(Fig.1c) increases from 6.0 MPa with no fly ash content to 7.0 MPa at 20% with a subsequent decrease to 5.8 MPa at 30%. The improvement at 20% is due to the ITZ properties and also due to better packing of particle. The decrease at 30% is due to dilution effect causing improper formation of C-S-H, thus decreasing the flexural performance. Flexural strength improves by 16.7% at 20% fly ash, then decreases at 30% by 17.1%. Flexural strength is found to increase with moderate percentages of fly ash. The increase in flexural strength at 20% fly ash was due to better packing of particles and the resultant increase in compactness of the matrix that improve upon the load-transferring capability and resistance to flexure. It drops at 30% because strength lowers with lesser cement content, which results in less hydrate products, weaker bonding with micro-defects that are stress concentrators when flexed; hence, it fails early during bending tests.

D. Workability

In parallel, workability(Fig.1d) of the concrete mix increased progressively from 80 mm without fly ash to 120 mm at 30% fly ash. Spherical shape and fineness of fly ash particles act as lubricants which reduce internal friction and enhance flowability; thus, the mix becomes easier to work with. The slump increased by 25% at 10%, 37.5% at 20%, and 50% at 30% fly ash compared with the control mix, thus showing steady improvement in workability. The slump readings show a consistent upward trend as the fly ash concentration increases. This is mostly because the fly ash particles are smooth and have a spherical form; they are really ball bearings, which means they lessen friction within the mixture. Fly ash's finer particles improve flowability and reduce internal resistance by filling the spaces between aggregates. So, mixtures with a greater fly ash content have better workability and higher slump values.

E. Heat of Hydration

Fig1e shows the drop from 60°C without replacement to 50°C at 20% replacement or an increase to 58°C at 30% is from the slower pozzolanic reaction rate of fly ash compared with the cement; otherwise, the generated exothermic heat that causes this phenomenon will be decreased. In addition, the slight increase at 30% is due to increased water content, which changes hydration kinetics.

The heat of hydration reduced by 16.7% at 20% fly ash and increased by 13.3% at 30%, which shows threshold values to handle the hydration heat well. The heat of hydration decreased up to 20% content of fly ash in the mixture and then began to increase at 30%. Fly ash gradually retards the initial hydration process because it is less reactive than cement and produces less amount of heat. At 30%, the minor increase in heat is only because of the increasing water-cement ratio for workability, which also facilitates hydration of the remaining cement particles by causing a marginal increase in the total heat generation.

F. Water Absorption

Fig.1f shows the drops from 4.5 percent without the fly ash to 3.5 percent at 20 percent of fly ash addition. It again picks up to 5.0 percent at 30 percent. The drop at 20 percent is due to filling effect and pozzolanic reaction of fly ash, which reduces porosity. An increase at 30 percent is due to large content that forms voids and micro-cracks caused by inadequate hydration. Water absorption decreased to 22.2% at 20% of fly ash, then it increased to 11.1% at 30%. This trend indicates that there has to be an optimal percentage of fly ash that is required in order to balance porosity and permeability, thus regulating the water absorption. The trend is decline till 20% of fly ash, but a rise at 30%. At 20%, porosity is reduced and this makes the matrix denser and lowers water absorption. At 30%, excess fly ash content causes improper hydration, leaving behind voids and micro-cracks. This tends to increase the permeability and absorption because water can easily go through these weak zones of the concrete structure [12-17].

IV. CONCLUSIONS

1) The concrete that included fly ash as a 20% substitute had the greatest compressive, tensile, and flexural strengths.
2) Workability had increased step by step with fly ash content, so the flowability had increased.
3) The heat of hydration considerably decreased at 20% fly ash, thus lowering the risk of thermal cracking.
4) Water absorption was smallest at 20% replacement; this was quite a dense microstructure.
5) More than 20% fly ash resulted in reduced strength and durability because of increased porosity.

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