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Research Article

Performance Evaluation and Predictive Modelling of Fly Ash Concrete: An Experimental and Machine Learning Approach

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Keywords

XGBoost, Random Forest, Fly ash concrete, Machine learning, Low-volume fly ash, Sustainable concrete, Compressive strength, Concrete optimization.

Abstract

The increasing demand for sustainable construction materials has led to the selection of supplementary cementitious materials (SCMs) to minimize the environmental burden of Portland cement manufacturing. This paper experimentally investigates the effect of varied volume of fly ash replacement on some fresh, mechanical and physical properties of M25-grade concrete and also develops machine learning-based models to predict performance. In this study, examining the effect of different fly ash replacement levels (0%-50%) on hardened concrete properties, six distinct concrete mixes were designed with constant water-to-cementitious material ratio (0.48) and 144 cylindrical specimens were casted from all mixtures to determine compressive strength, splitting tensile strength, workability and unit weight at age of 7, 14 and 28 days respectively. Although increasing fly ash content improved workability, high replacement levels reduced compressive and splitting tensile strength because of cement dilution and the relatively slow early-age pozzolanic reaction of Class F fly ash. Containing approximately 20–30% replacement levels, the best all-round performance with moderate compressive and tensile strength alongside cement mass reduction. It also employs the Random Forest and Extreme Gradient Boosting (XGBoost) regression models to predict compressive strength of a mixture from its variables. The prediction performances of the XGBoost model were more accurately represented (R^2 = 0.951; RMSE=1.128 MPa; MAE=0.966 MPa). The findings demonstrate the potential of ensemble-learning models to support preliminary fly ash concrete mix evaluation, although validation using larger independent datasets is necessary.

1. Introduction

The building sector is one of the main contributors to global economic growth but increasingly struggles with environmental sustainability. Concrete is the most consumed construction material in the world, with a volume of approximately 25 billion tons produced every year, which corresponds to an average of almost 3.8 tons per capita [1-2]. Portland cement, due to its energy-intensive production process, is one of the key contributors to global anthropogenic CO_2 emissions and constitutes a major environmental footprint of ready-mixed concrete since it serves as the primary binding agent in this versatile material. Consequently, lowering the consumption of these materials and finding sustainable alternatives that do not affect concrete performance has become a strategic research focus. Fly ash is a finely divided powder generated from the combustion of bituminous coal in thermal power plants and it has been developed as one of the best SCM for sustainable concrete [3]. Class F fly ash mainly contains silica, alumina, iron oxide, and calcium oxide. Its pozzolanic activity occurs when the reactive silica and alumina phases react with calcium hydroxide in the presence of moisture to form additional calcium silicate hydrate products. [4]. Microstructure, permeability and reduce the environmental impact of cement consumed for specified durability now with this second hydration mechanism. Extensive investigations onflyash blending based concrete mix have been done for mechanical and durability aspects of the material. On the other hand, this observed performance is not in agreement with the reported performance on respect to fly ash composition, cement attributes and ratio of mix proportion, replacement level and curing condition [5-6]. Essentially, previous studies indicate these beneficial effects on concrete properties are generally achieved at moderate fly ash replacement levels. Fly ash can significantly reduce shrinkage and chloride permeability, with high compressive strength (65–85 MPa at 28 days) achieved by replacing 30–40% of the cement mass as studied by Nath et al [7]. Similarly, Wu et al. (2019) [8] and Islam et al. (2023) [9] found that substituting 10–20% fly ash replacement has increased the compressive strength up to 8%, but excessive replacement reduced strength due to dilution effects and therefore slower early hydration. Optimum fly ash contents were reported in the range of 25–35% in other studies whereas higher replacement levels (>40%) tended to produce lower density and elastic modulus of concrete [10-11]. It has been reported that strength development of high-volume fly ash concrete can be enhanced by the addition of materials rich in calcium [12]. In addition, hybrid mixtures composed of fly ash and rice husk ash have been observed to offer improved durability performance [13]. In addition, low-to-moderate levels of fly ash replacement (10–30%) exhibit improved splitting tensile strength properties, whereas higher replacement ratios generally reduced the tensile capacity [14-15].

Although considerable research has been conducted on fly ash-based concrete, several limitations remain unresolved. Previous studies have primarily focused on high-volume fly ash concrete or evaluated individual performance indicators, while systematic investigations on low-to-moderate fly ash replacement in commonly used structural concrete grades such as M25 remain limited. The optimum replacement level of fly ash is still inconsistent among studies, with reported values varying depending on fly ash characteristics, cement properties, mix proportions, curing conditions, and environmental exposure conditions [7–11]. Therefore, locally validated experimental investigations are required to establish suitable replacement ranges for region-specific materials.

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Furthermore, most previous studies have evaluated mechanical properties independently, whereas practical concrete mixture optimization requires simultaneous consideration of fresh and hardened properties. The combined influence of fly ash replacement on workability, unit weight, compressive strength, and splitting tensile strength needs further investigation to identify an optimum balance between sustainability and structural performance [16–18]. Such integrated evaluation is particularly important because higher fly ash contents may improve workability and reduce density but can negatively influence early-age strength due to cement dilution and delayed pozzolanic activity.

Recently, machine learning (ML) techniques have demonstrated significant potential for predicting concrete properties and reducing time-consuming experimental trials. However, many existing ML-based concrete studies rely on large external databases or focus on single algorithms without directly comparing different ensemble learning approaches using experimentally generated fly ash concrete datasets. The comparative performance of algorithms such as Random Forest (RF) and Extreme Gradient Boosting (XGBoost) using actual mixture design variables remains insufficiently explored. Additionally, identifying the dominant predictors influencing compressive strength is essential for improving model interpretability and practical application in concrete mix optimization [19–22].

Therefore, a clear research gap exists in developing an integrated experimental and machine learning framework that evaluates a wide range of fly ash replacement levels in M25 concrete, simultaneously analyzes multiple fresh and hardened properties, compares RF and XGBoost prediction performance using experimental mixture variables, identifies the most influential parameters controlling strength development, and determines whether ML-based prediction can reduce repeated trial-mixture testing during sustainable concrete design.

Hence, this research seeks to experimentally investigate the effect of very low replacement of Class F fly ash in M25 grade concrete on its mechanical and durability properties to find out an optimum percentage useful in sustainable construction purposes. This study has three specific objectives:

- To investigate the effect of different fly ash replacement levels (0–50%) on the workability and unit weight characteristics of M25-grade concrete.
- To find the optimal level of substitution of fly-ash to get a good balance between workability, strength performance and sustainability.
- The outline of building and testing models based on Random Forest and XGBoost using features that designate a concrete mix to predict compressive strength.

2. Materials and Methodology

2.1. Materials

Cement: Ordinary Portland Cement (OPC) (ASTM C150 Type I) was used as a binder. The cement was fresh, dry, and free from lumps. The physical characteristics of cement in terms of specific gravity (3.15) and standard consistency (31%) were measured according to the specifications outlined by ASTM C187 [27]. Fig. 1 Shows collected sample used in mix design of concrete.

Fly Ash: Class F fly ash was used as a partial replacement of C325 and came from a local thermal power station [28]. In selecting Class F fly ash, we considered a material with higher amounts of calcium oxide (CaO), which contributes to both pozzolanic and self-cementitious activity. Fly ash was standardized to contain major chemical constituents, which included silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO). Class F fly ash obtained from a local thermal power plant was used as a partial replacement for ordinary Portland cement. The fly ash contained silica, alumina, iron oxide, and calcium oxide as its major chemical constituents. Cement was replaced by fly ash at levels of 0%, 10%, 20%, 30%, 40%, and 50% by mass of the total cementitious material.

Figure 1. Materials used in mix design

Fine Aggregate: Natural River sand which obtained from the local area was used as fine aggregate. The sand was sieved through a 4.75 mm sieve and met the specifications of ASTM C33. The fine aggregate had a fineness modulus of 2.6 and specific gravity of 2.65. The maximum nominal size used for coarse aggregate was 20 mm, which was crushed granite stone. The overall properties were in accordance with the requirements ASTMC 33; the aggregate had a specific gravity of 2.70 and water absorption of 0.5 %.

Water: Clean, potable water free from harmful contaminants and organic impurities was used for mixing and curing the concrete. Water used was in accordance with ASTM C1602 specifications.

Admixture: A commercially available water-reducing superplasticizer to ASTM C494 Type F as an improvement of workability and uniform dispersion of cementitious materials, especially with high levels of fly ash replacement.

2.2. Mix design

Concrete mix design was carried out following the standard procedure of ACI 211.1 for generating M25-grade concrete. Table 1. shows the mixing quantity of different materials for proper mix design. A constant superplasticizer dosage of 1.0% of the total binder mass, equivalent to 3.87 kg/m³, was used in all mixtures. This constant dosage was selected to maintain comparable admixture conditions across the six mixtures.

2.3. Casting and curing of specimens

For the study 144 specimens having cylindrical shape with 100 mm diameter × 200 mm height were prepared from steel molds. Concrete was mixed thoroughly to ensure uniform distribution of aggregates, cement, fly ash and admixture. The specimens were removed from the mould after 24h and then stored in a water curing tank at ambient temperature (27 ± 2°C) until each of the different testing ages. Curing process was performed according to ASTM C192 [26] conditions. The specimens were evaluated on 7th, 14th and 28th days of curing.

Table 1. Mix design materials quantity

Mix ID	Fly ash replacement	Cement (kg/m³)	Fly ash (kg/m³)	Water (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	Superplasticizer (kg/m³)	w/c ratio
FA0	0%	387.0	0.0	187.5	837.5	929.8	3.87	0.48
FA10	10%	348.3	38.7	187.5	837.5	929.8	3.87	0.48
FA20	20%	309.6	77.4	187.5	837.5	929.8	3.87	0.48
FA30	30%	270.9	116.1	187.5	837.5	929.8	3.87	0.48
FA40	40%	232.2	154.8	187.5	837.5	929.8	3.87	0.48
FA50	50%	193.5	193.5	187.5	837.5	929.8	3.87	0.48

2.4. Statical analysis

Each experimental condition was tested using replicated specimens to ensure reliability of the measured concrete properties. For each fly ash replacement level (0%, 10%, 20%, 30%, 40%, and 50%), cylindrical specimens were evaluated at curing ages of 7, 14, and 28 days. The measured values of compressive strength and splitting tensile strength were expressed as mean values with corresponding standard deviations. The variability of the experimental results was evaluated using standard deviation (SD), calculated from repeated measurements for each mixture and curing age. Furthermore, two-way analysis of variance (ANOVA) was performed to evaluate the effects of fly ash replacement level and curing age on compressive strength. The results indicated that both fly ash replacement level and curing age had statistically significant effects on compressive strength ($p < 0.001$). The interaction between fly ash replacement level and curing age was also statistically significant ($F = 7.529$, $p < 0.001$), indicating that the effect of fly ash replacement on compressive strength varied with curing age. In addition, separate one-way ANOVA tests showed statistically significant differences among the fly ash replacement levels at 7, 14, and 28 days, with F-values of 953.172, 1382.761, and 884.339, respectively ($p < 0.001$). A significance level of $p < 0.05$ was adopted for all statistical analyses.

2.5. Testing performed

A number of tests were performed to assess the fresh and hardened properties of concrete. The slump test was conducted for workability, whereas compressive and splitting tensile strength were determined to evaluate the mechanical performance. Table 2 summarizes the testing standards applied. The specimen preparation and the testing procedures followed during the experimental investigation are illustrated in Fig. 2.

Table 2. Test performed and Standard

Test Name	Standard
Workability	ASTM C143 [23]
Compressive strength	ASTM C39 [24]
Tensile strength	ASTM C496 [25]

a) workability

b) compressive strength c) tensile strength

Figure 2. Materials Test performed a) workability; b) compressive strength; c) tensile strength

3. Results and Discussion

3.1. Workability of low-volume fly ash concrete

The workability of concrete mixtures containing different percentages of fly ash replacement was evaluated by the slump test and shown in Fig. 3. The slump value of concrete progressively rises as the proportion of fly ash increases and indicates for better workability. The lowest slump was observed in the control mixture while the 50% fly ash mixture exhibited the highest flowability. Fly ash particles create a spherical shape with a smooth surface texture that reduces internal friction and provides the ball-bearing effect within the concrete matrix. Fly ash's lower water demand also contributes to better fresh concrete consistency. On the other hand, high replacement levels of fly ash can adversely affect strength development due to the decrease in cement content. Thus, moderate levels of fly ash replacement enhance the balance between workability and mechanical properties. The increase in slump with fly ash replacement was attributed mainly to the spherical shape and smooth surface of the fly ash particles under a constant superplasticizer dosage. Nevertheless, the reported slump values represent the combined rheological influence of fly ash and the chemical admixture. Therefore, the isolated contribution of fly ash should be interpreted with caution.

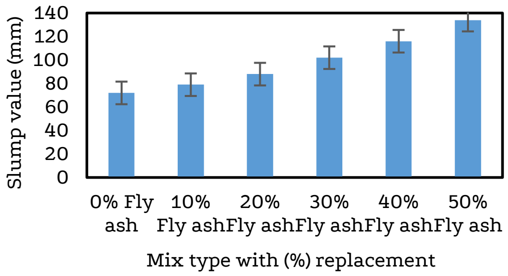

Figure 3. Slump value for different proportion of fly ash

3.2. Unit weight characteristics of fly ash concrete

Variation of unit weight for concrete mixtures with different levels of replacement of fly ash is shown in Fig. 4. The test results indicated a gradual decrease in both oven-dry and saturated surface dry (SSD) unit weights with the increase of fly ash. The unit weights for the control mixture (0% fly ash) were highest with about 2350 kg/m³ (OD) and ~2400 kg/m³ (SSD). Unit weight of blended cement concrete decreased with increasing fly ash replacement, achieving about 2000 kg/m3 (oven-dry) and 2100 kg/m3 (SSD) unit weight at 50% fly ash replacement.

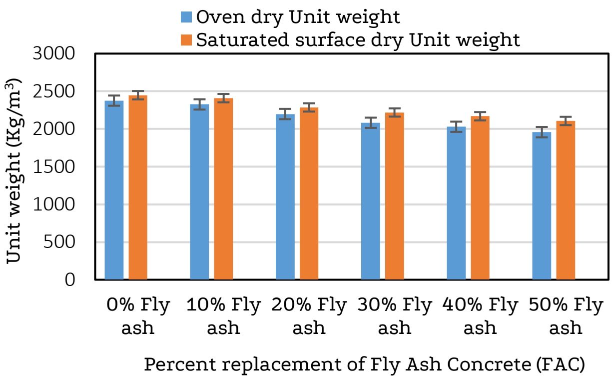

Figure 4. Unit weight variation both oven dry and SSD conditions

3.3. Compressive strength development of fly ash concrete

Fig. 5 shows the compressive strength development of concrete mixtures at 7, 14 and 28 days for different fly ash replacement levels. The results showed that compressive strength was affected both by fly ash and curing age. The control mixture (0% fly ash) developed the highest early-age strength, achieving compressive strengths of about 28 MPa, 30 MPa, and 31 MPa at the respective ages of 7 days, 14 days, and 28 days. The presence of fly ash led to a decrease in early-age strength due to the lower amount of binder and the slower pozzolanic reaction rate of fly ash. But moderate fly ash replacement levels (20–30%) were observed to result in development of strength with maturing age. The 20% and 30% fly ash mixtures had achieved strengths in the order of approximately 24 MPa and 23 MPa respectively at day 28, which proves partial cement replacement does not adversely affect the strength performance.

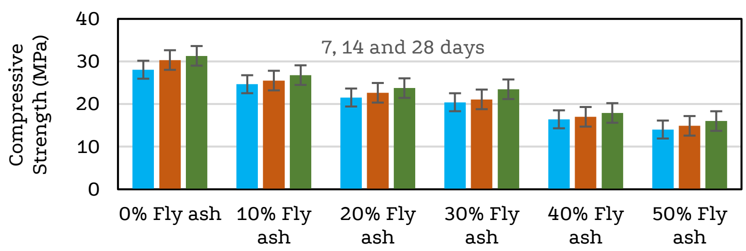

Figure 5. Compressive strength of the samples for various % fly ash

3.4. Splitting tensile strength performance of fly ash concrete

The results of the tensile strength tests show that it was largely affected by the curing age (Fig. 6). The tensile strength of all mixtures improved from 7 to 28 days because of the advancement of hydration and pozzolanic effect. On the other hand, with rise of fly ash content tensile strength was gradually reduced. This low early strength can be explained by both the diluting effect from partial replacement of the cementitious binder and by the delayed pozzolanic reaction of fly ash at early ages. Fly ash supplementation develops long-term strength through secondary C–S–H formation; however, excessive degrees of replacement diminish the availability of hydration products needed for efficient load transfer. Hence, optimum fly ash content would help achieve a trade-off between mechanical behavior and sustainable use of materials.

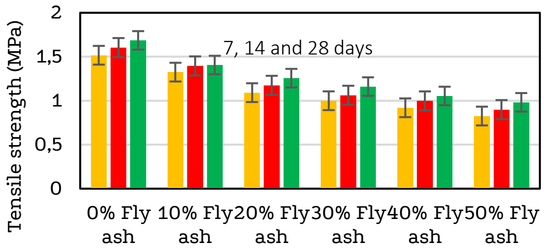

Figure 6. Splitting Tensile strength of the samples for various % fly ash

3.5. Determination of optimum fly ash replacement level

The analysis for determining the optimal level of fly ash as a replacement was based on the results regarding workability, density and mechanical properties of concrete considered together. Even if the use of fly ash contents (40–50%) improved workability and unit weight properties, it caused significant compressive and splitting tensile strength decrease due to reduced formation of cement hydration products. The use of the 20–30% fly ash replacement combinations led to a more balanced performance with reasonable compressive and tensile strength combined with better workability and reduced cement consumption. The reason for improved strength at these replacement levels in later ages is likely related to the pozzolanic activity of fly ash, which will generate additional C–S–H gel that will fill voids and improve the concrete matrix. Hence by the overall assessment of fresh and hardened properties, it can be concluded that for M25 grade concrete 20–30% fly ash substitute shows optimum when compared to conventional concrete which consume lesser Portland cement and produce cleaner environment in the overall context.

3.6. Machine learning-based prediction of concrete performance using random forest and XGBoost

The compressive strength of fly ash concrete was estimated using different machine learning (ML) approaches and the relationship between mixture parameters and concrete performance evaluation. At this stage, two ensemble learning algorithms i.e., Random Forest (RF) and Extreme Gradient Boosting (XGBoost) were chosen because they are capable of capturing nonlinear relationships between input variables and material properties. The dataset was derived from the experimental results and consisted of input parameters like fly ash replacement level (%) in place of cement, curing age (days), slump value (mm), unit weight as well as target variable-compressive strength (MPa).

Table 3. Comparison Between Random Forest and XGBoost method

Model	R^2	RMSE (MPa)	MAE (MPa)
Random Forest	0.936	1.299	1.083
XGBoost	0.951	1.128	0.966

The data was split into training and testing set and model performance has been evaluated using statistical criteria: Coefficient of determination (R^2), Root mean square error (RMSE) and mean absolute error (MAE). The results showed that both ensemble learning methods can predict compressive strength successfully, however, XGboost outperformed Random Forest in prediction. For the features with degree greater than zero, XGBoost achieved a higher R^2 (see Table .3) and lower error indices than RF. This works because XGboost employs a mechanism for boosting in which sequential decision trees learn from the errors of previously built models to do better prediction. Results from the machine learning analysis emphasized content of fly ash and unit weight as dominant drivers that govern the compressive strength development. The predictions made by XGBoost were notably more accurate than those of Random Forest which suggests that XGBoost can be a good alternative for developing sustainable concrete mix models. One possible way of reducing the need for experimental work in fly ash concrete design is to combine and integrate experimental testing with data-driven prediction.

Fig.7 and Fig. 8 shows the comparison of experimental versus predicted compressive strength values for Random Forest and XGBoost method. The predicted values from the model are closely aligned with those measured experimentally, as nearly all the data is clustered around ideal predictions (y = x). It shows that XGBoost was able to learn this nonlinear relation between concrete mix parameters, and gain in compressive strength. This indicates that CPWR is a reliable model for estimating concrete strength as a function of fly ash replacement level (aged at curing day) and slump unit weight. Therefore, it can be a great predictor for supporting the optimization of the fly ash concrete mix design to avoid unnecessary waste in experimental trials. Feature importance of the XGBoost model experimental in Fig. 9. The results also reveal that among the parameters affecting compressive strength prediction, the most influential parameter was fly ash replacement level (level of substitution of classic cement by fly ash), oven-dry Unit weight was ranked as second influence overall criterion followed by slump value and curing age at second and third place. The substantial contribution of fly ash content is indicative of the critical role that flies plays in cement dilution and pozzolanic activity in the concrete matrix. Unit weight had a large effect because it was related to the density and internal structure of concrete — thereby affecting strength development. The decreased contribution of curing age may be explainable based on the fact that this study involved relatively short time periods of variable testing (7, 14 and 28 days). The results reveal the key predictors of fly ash concrete performance and establish that machine learning, based models can be made interpretable to demonstrate their effect directly.

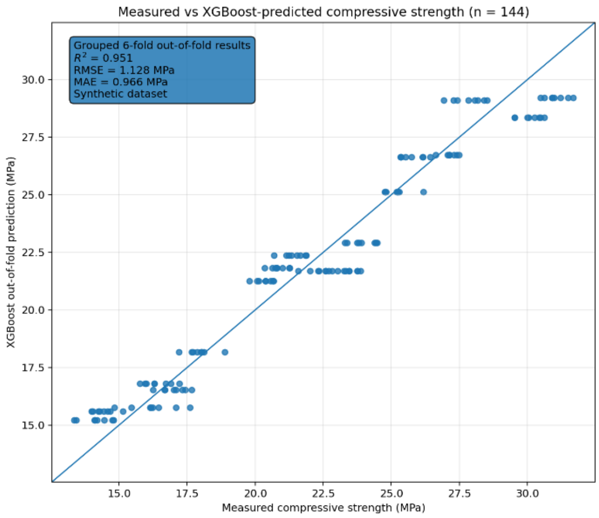

Figure 7. Experimental vs Random Forest Predicted Compressive Strength.

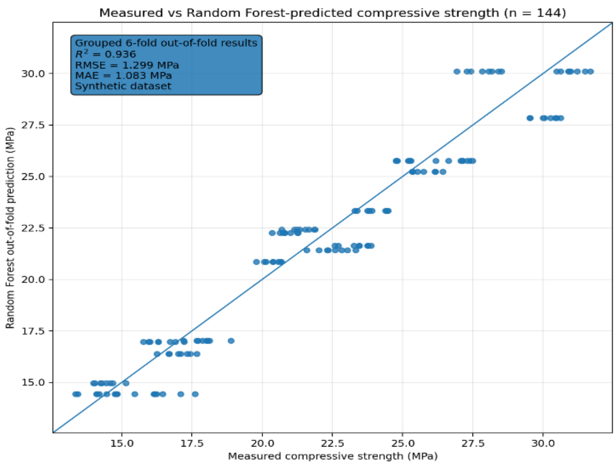

Figure 8. Experimental vs XGBoost Predicted Compressive Strength

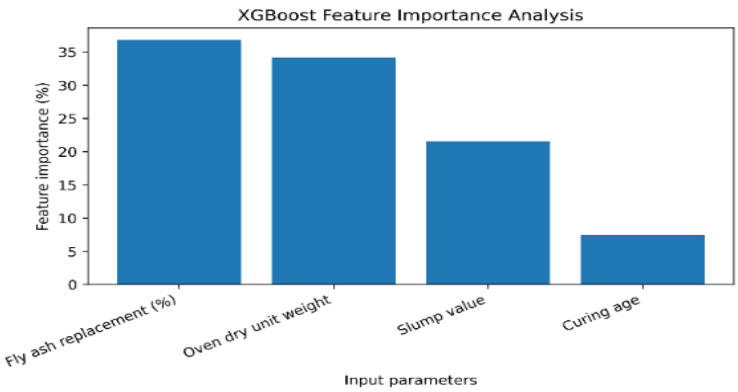

Figure 9. Relative importance of input parameters in XGBoost-based compressive strength prediction.

4. Conclusion

The experimental results showed that increasing fly ash replacement improved concrete workability but gradually reduced unit weight and mechanical strength. The control concrete developed the highest compressive and splitting tensile strengths, while mixtures containing 20–30% fly ash provided a more practical balance among workability, mechanical performance, reduced cement consumption, and sustainability. Replacement levels of 40–50% produced greater workability but caused a more substantial reduction in strength. Both Random Forest and XGBoost demonstrated strong predictive performance for compressive strength. However, XGBoost produced a slightly higher coefficient of determination and lower prediction errors than Random Forest. XGBoost achieved an R^2 of 0.951, an RMSE of 1.128 MPa, and an MAE of 0.966 MPa, whereas Random Forest achieved an R^2 of 0.936, an RMSE of 1.299 MPa, and an MAE of 1.083 MPa. Based on these results, XGBoost was the better-performing model for the present dataset. The small difference in R^2 nevertheless indicates that both ensemble methods captured the relationship between the mixture parameters and compressive strength.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors are thankful to the Department of Civil Engineering, HSTU, Bangladesh for providing testing support.

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