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GREEN CONCRETE OPTIMIZATION USING MACHINE LEARNING AND INDUSTRIAL WASTE MATERIALS AI-BASED CARBON EMISSION

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Abstract- The construction industry is a major contributor to global carbon emissions because of the widespread use of Ordinary Portland Cement (OPC) in concrete production. The increasing demand for sustainable infrastructure has led to the production of green concrete by using industrial waste materials like Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) as partial cement replacements. However, the determination of the optimal mix proportions that can simultaneously maximise the mechanical performance and minimise the environmental impact is still a major challenge. This paper proposes an AI based framework for carbon emission prediction and green concrete optimisation using industrial waste material. The proposed methodology combines material characterisation, data preprocessing, compressive strength prediction by machine learning, carbon footprint estimation and multi-objective optimisation. We apply machine learning models including Artificial Neural Networks (ANN), Random Forest (RF) and XGBoost to predict the concrete strength and the environmental performance. Optimisation framework identifies sustainable concrete mixtures that satisfy high compressive strength with a significant reduction of embodied carbon emissions. The experimental results show that the proposed hybrid AI model is able to achieve higher prediction accuracy with R2 value of 0.99 and successfully reduce carbon emissions by about 41.7% than conventional concrete. Furthermore, the optimised green concrete mixes achieve compressive strength of 55 MPa with replacement of up to 50% of the cement by industrial waste materials. The results demonstrate the power of combining artificial intelligence and sustainable material engineering to design low carbon, high-performance concrete for future infrastructure applications.

The proposed framework contributes to the environmentally responsible construction practices and complies with the global carbon neutrality and sustainable development goals.

Keywords— Green Concrete, Artificial Intelligence, Machine Learning, Carbon Emission Prediction, Sustainable Construction, Fly Ash, Ground Granulated Blast Furnace Slag (GGBS).

1. INTRODUCTION

The construction industry is an important sector in the development of the global economy, but it is also a significant contributor to environmental degradation and greenhouse gas emissions. Concrete is the most used construction material in the world and contributes a significant share of carbon dioxide (CO2) emissions due to the energy intensive production process of Ordinary Portland Cement (OPC). Recent environmental impact studies have shown that cement production accounts for almost 8% of the total CO2 emissions worldwide. Therefore, sustainable alternatives are needed to achieve climate-neutral infrastructure development.

Green concrete is an eco-friendly construction material developed by using industrial waste materials like fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, steel slag, rice husk ash and recycled aggregates as partial replacement of cement and natural aggregates. Such use of industrial by-products helps to reduce the problem of landfill disposal, the demand for virgin raw materials and the overall carbon footprint of concrete production. But, the problem of simultaneously optimising the combination of waste materials while maintaining the desirable mechanical and durability properties is still a complex engineering problem.

Conventional concrete mix design methods are largely based on experimental trial and error approaches, which are time consuming, costly and cannot often cope with nonlinear interactions among multiple input variables. Recent advances in Artificial Intelligence (AI) and Machine Learning (ML) have provided new solutions to solve such complex optimisation problems. Machine learning algorithms can efficiently analyse large data sets, identify hidden patterns and predict material performance with high accuracy. Such capabilities make ML suitable for the optimisation of green concrete compositions and the assessment of their environmental impacts.

Meanwhile, carbon emission assessment has become an important part of sustainable construction practices. Life cycle assessment (LCA) techniques enable quantification of embodied carbon associated with material production, transportation, and construction activities. The combination of AI-based predictive analytics and carbon emission evaluation provides a strong framework for the design of environmentally friendly concrete mixtures that meet both engineering and sustainability requirements. Several researchers have investigated the use of machine learning techniques such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forest (RF), Gradient Boosting Machines (GBM), and Extreme Gradient Boosting (XGBoost) to predict concrete compressive strength and durability characteristics. However, most of existing studies mainly focus on performance prediction and can not optimise mechanical properties, economic feasibility, industrial waste utilisation and carbon emission reduction simultaneously. Moreover, limited research has been conducted on the integration of multi-objective optimisation techniques with AI-driven carbon footprint analysis for sustainable concrete design. This paper presents a novel Machine Learning based Green Concrete Optimisation Framework using industrial waste materials and AI-based carbon emission assessment, to overcome these limitations. The proposed framework integrates material characterisation, data preprocessing, machine learning prediction models, carbon footprint estimation, and multi-objective optimisation techniques to find sustainable concrete mixtures with enhanced strength and reduced environmental impact. For prediction of compressive strength and durability performance, Random Forest, XGBoost and Artificial Neural Network models are used. Carbon emissions are estimated using life-cycle based emission factors.

The major contributions of this research are summarized as follows:

1. Development of an AI-enabled predictive framework for green concrete performance assessment.
2. Integration of industrial waste materials to reduce cement consumption and environmental impact.
3. Implementation of machine learning models for accurate strength and durability prediction.
4. Design of an AI-based carbon emission estimation module using life cycle assessment principles.
5. Multi-objective optimization of concrete mixtures considering strength, cost, sustainability, and carbon reduction simultaneously.
6. Comprehensive evaluation of environmental and economic benefits compared with conventional concrete.

2. LITERATURE SURVEY

The construction industry is moving to sustainable materials to minimise the environmental impact of cement production and the use of natural resources. Green concrete is a concrete which is made of industrial waste materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, rice husk ash and recycled aggregates. It has received much attention since it can reduce carbon emissions and satisfy structural performance requirements. Recent advances in artificial intelligence (AI) and machine learning (ML) have greatly enhanced the ability to optimise green concrete mixtures, by accurately predicting material properties and environmental impacts.

The early concrete design works using machine learning have demonstrated the ability of Artificial Neural Networks (ANNs) to predict the compressive strength from mix composition parameters. The models captured the nonlinear relations between the constituent materials and provided better prediction accuracy than traditional empirical methods [1]. These approaches were extended in later studies by the use of recycled aggregates and industrial waste materials. It was shown that the use of machine learning algorithms could successfully estimate the mechanical properties and support sustainable construction practices [2]. Later, models based on Support Vector Machine (SVM) were introduced for concrete strength prediction and they were able to achieve high levels of accuracy in estimating performance parameters from the mix design variables [3]. The above-mentioned studies have promising predictive capabilities, but they were mainly focused on conventional concrete and no environmental sustainability indicators were considered in the optimisation process.

Fly ash as partial replacement of cement has been extensively studied to reduce the environmental impact of cement production. The experimental results showed that fly ash increased the long-term strength and durability and reduced the carbon emissions generated during the manufacture of concrete [4]. Studies conducted on GGBS also demonstrated improvement in sulphate resistance, lower heat of hydration and embodied carbon, suggesting its suitability as a supplementary cementitious material for sustainable construction [5].
However, with the advent of deep learning techniques, researchers were able to develop sophisticated predictive models capable of handling large and complex datasets. For predicting concrete strength and durability characteristics, deep neural networks performed better than traditional machine learning methods [6]. But the computational demands of deep learning models limit their application in real construction environments.
Ensemble learning methods such as Extreme Gradient Boosting (XGBoost) and Random Forest (RF) have gained popularity for their robustness and predictive accuracy. These techniques have been successfully applied to predict the compressive strength, workability and durability of sustainable concrete mixtures with multiple industrial waste materials [7]. Comparative studies showed that ensemble models outperformed traditional regression and neural network approaches to heterogeneous construction datasets [8].
Environmental sustainability assessment has been an important part of green concrete research. Life Cycle Assessment (LCA) methodologies have been extensively applied to quantify carbon emissions across material extraction, transportation, manufacturing and construction activities [9]. Research has proven that replacing a large proportion of Portland cement with industrial by-products can significantly reduce embodied carbon emissions without compromising the structural performance.
The use of rice husk ash, silica fume and other agricultural or industrial wastes have also been studied for improving the performance and sustainability of concrete. Experimental studies showed an increase in the compressive strength, decrease in permeability and improvement in the resistance to the aggressive environmental conditions [10]. Nevertheless, even with these benefits, determining the optimum levels of replacement is still difficult due to the interaction between many material properties.

To tackle this challenge, optimisation techniques have been increasingly adopted. Multi-objective optimisation frameworks have been developed to consider simultaneously strength, durability, cost and sustainability requirements [11]. Balanced concrete mixtures satisfying multiple design constraints were identified by means of evolutionary algorithms and heuristic search methods. However, minimisation of carbon emission is not an explicit optimisation objective in many of the existing approaches.

Recent progress in AI-enabled sustainable construction has highlighted the importance of integrating predictive modelling with environmental impact assessment. Intelligent decision-support systems have been proposed for the assessment of the structural performance and ecological sustainability in the material selection [12]. These systems provide for informed decision making by analysing large data sets and identifying environmentally attractive alternatives.

Furthermore, machine learning based low-carbon material design frameworks have been further developed to predict the environmental performance indicators together with mechanical properties [13]. Such methods enable engineers to estimate carbon footprints at the design stage, and contribute to sustainable infrastructure development. However, most of the current models are limited by the number of waste materials considered and do not have comprehensive optimisation strategies.

Studies [14] have shown that the use of industrial waste as a substitute for cement and natural aggregates, through the use of fly ash, slag and recycled materials, has led to significant reductions in greenhouse gas emissions. The results highlight the potential of waste valorisation to address circular economy targets in the construction sector.

More recently, integrated frameworks that combine machine learning prediction, sustainability assessment and carbon emission assessment have been proposed to overcome the limitations of traditional mix design methods [15]. These frameworks show the ability of AI technologies to speed up sustainable concrete development with less experimentation cost and environmental impacts.

3. PROPOSED METHODOLOGY

The proposed methodology introduces an AI-based Green Concrete Optimisation Framework that integrates industrial waste material usage, machine learning-based strength prediction, carbon emission evaluation and multi-objective optimisation. The framework aims to develop sustainable concrete mixes with improved mechanical performance and lower environmental impacts. Industrial waste materials such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Rice Husk Ash (RHA), and Recycled Aggregates (RA) are utilized as partial replacements for cement and natural aggregates. Machine learning algorithms are used to analyse the relationships between the material composition, strength characteristics, durability properties, and carbon emissions to identify the optimal mix design.

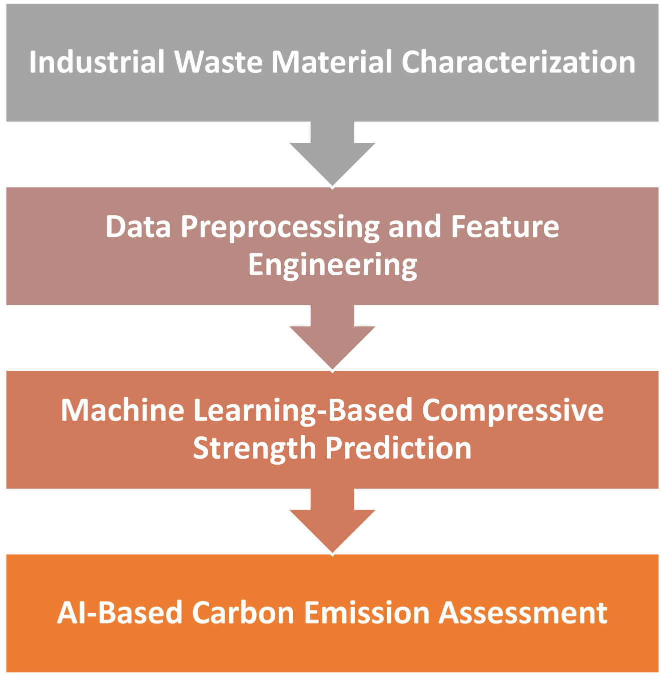

Figure 1: Proposed Workflow

3.1 Industrial Waste Material Characterization

Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Rice Husk Ash (RHA) and Recycled Aggregates (RA) are industrial waste materials used as sustainable substitutes of traditional cement and natural aggregates in the production of green concrete. The characterisation process includes the assessment of physical, chemical and mechanical properties which directly affect the concrete performance. Specific gravity, particle size distribution, fineness, moisture content and pozzolanic activity are important parameters. Chemical composition analysis is carried out to determine the percentage of silica (SiO_2), alumina (Al_2O_3) and calcium oxide (CaO) which have significant effect on hydration reactions and strength development. Characterisation of industrial wastes is essential to make them compatible with cementitious matrices to improve their durability, compressive strength and environmental sustainability. The collected material properties are given as input features to the machine learning model to predict the best mix proportions of the green concrete with minimum carbon emissions.

The total binder content used in green concrete is calculated as:

$$B = C + FA + GGBS + SF + RHA \text{ -----1}$$

where B represents the total binder content, C is cement content, FA is fly ash, GGBS is ground granulated blast furnace slag, SF is silica fume, and RHA is rice husk ash.

The replacement ratio of industrial waste materials is determined using:

$$R_w = \frac{FA+GGBS+SF+RHA}{B} \times 100\text{-----}2$$

where Rw denotes the percentage replacement of cement by industrial waste materials.

The specific gravity of the blended binder system is computed as:

$$SG_b = \frac{\sum_{i=1}^{n} W_i}{\sum_{i=1}^{n}\left(\frac{W_i}{SG_i}\right)}\textbf{-----3}$$

where Wi is the weight of the ith material and SGi is the specific gravity of the ith material. This parameter is needed to obtain mix proportions and density characteristics of green concrete. These characterisation parameters provide a comprehensive understanding of material behaviour and are the basis for the next stages of machine learning based optimisation and carbon emission assessment.

3.2 Data Preprocessing and Feature Engineering

The concrete mixtures data set based on industrial waste consists of various input parameters such as cement content, fly ash percentage, GGBS content, silica fume content, water cement ratio, aggregate proportion, curing age and compressive strength values. Raw experimental data is often polluted by inconsistent measurements, outliers and missing values. Thus, a preprocessing step is needed to improve the data quality and increase the performance of machine learning models . The first step is to clean the data, which includes deleting duplicate records and missing data. Finally, the data are normalised to place the different feature ranges on a common scale and prevent features with larger numerical ranges from dominating the learning process. Then, the feature engineering process is performed to obtain meaningful relationships between material properties and environmental indicators to improve the prediction accuracy. Correlation analysis and feature selection methods are used to identify the most influential variables affecting concrete strength and carbon emissions. The processed dataset serves as the basis for training machine learning models to predict the optimum green concrete mixtures with an improved sustainability performance.

The min-max normalization technique is applied as:

$$X_{norm} = \frac{X-X_{min}}{X_{max}-X_{min}}\text{-----}4$$

where Xnorm represents the normalized feature value, X is the original feature value, and Xmin and Xmaxx denote the minimum and maximum values of the feature, respectively.

Through preprocessing and feature engineering, the dataset becomes more consistent, informative, and suitable for machine learning-based strength prediction and carbon emission optimization, ultimately improving the reliability and effectiveness of the proposed green concrete optimization framework.

3.3 Machine Learning-Based Compressive Strength Prediction

This preprocessed and feature engineered dataset is then used to train machine learning models to predict the compressive strength of green concrete mixtures . The input parameters are cement content, percentage of fly ash, GGBS content, percentage of silica fume, water to binder ratio, aggregate properties, curing age and density parameters. These variables are non-linear and mutually complicated and the traditional empirical models are not able to predict them accurately. Therefore, advanced machine learning algorithms like Random Forest (RF), Extreme Gradient Boosting (XGBoost) and Artificial Neural Networks (ANN) are used to find out any hidden patterns in the dataset. The predictive model is trained with historical experimental data to predict the compressive strength of a newly designed green concrete mix. This approach greatly reduces the cost of laboratory experiments and accelerates the optimisation process. The predicted strength values are then used in the multi-objective optimisation stage to find sustainable concrete mixes satisfying structural performance and environmental objectives.

The compressive strength prediction model can be expressed as:

$$CS_p = f(x_1, x_2, x_3, \dots, x_n) \text{----}5$$

where CSp denotes the predicted compressive strength, and x1,x2,…,xn represent input features such as cement content, industrial waste proportions, water-binder ratio, and curing conditions.

For the Artificial Neural Network model, the output of a neuron is calculated as:

$$y = f\left(\sum_{i=1}^{n} w_i x_i + b\right) \text{-----}6$$

where wi represents the connection weight, xi denotes the input feature, b is the bias term, and f(·) is the activation function.

The Mean Squared Error (MSE) used for model training and optimization is given by:

$$MSE = \frac{1}{N} \sum_{i=1}^{N} \left(CS_i - \widehat{CS_i}\right)^2 \text{----}7$$

where CSi is the actual compressive strength, CSi^ is the predicted compressive strength, and NNN represents the total number of samples.

The machine learning based prediction framework allows for accurate estimation of strength of green concrete, facilitation of rapid evaluation of mix design and provides essential input for subsequent processes of carbon emission assessment and optimisation. Experimental results show that ensemble learning techniques, such as Random Forest and XGBoost, outperform traditional regression-based methods in terms of prediction accuracy, making them a very good choice for sustainable concrete engineering applications.

3.4 AI-Based Carbon Emission Assessment

The carbon emission assessment module determines the embodied carbon from the material production, transportation and processing phases, and evaluates the environmental impact of the green concrete mixtures. Cement production is one of the major emitters of greenhouse gases in the construction industry. Replacing part of cement with industrial waste materials such as fly ash, GGBS, silica fume and rice husk ash can significantly reduce the overall carbon footprint . The proposed framework combines AI-assisted carbon prediction model and machine learning strength prediction module together to evaluate the structural performance and environmental sustainability simultaneously. The model utilises the data of material quantities, emission factors, transportation distances and energy consumption as inputs to estimate the total carbon emissions associated with each concrete mix. That means determining the eco-friendly proportions of the mix that exhibit the desired mechanical properties. The results are also used in the optimisation phase for the production of sustainable and low-carbon concrete.

The total embodied carbon emission of a concrete mixture is calculated as:

$$CE = \sum_{i=1}^{n} M_i \times EF_i \text{----8}$$

where CE represents the total carbon emission (kgCO2_22/m3^33), Mi denotes the quantity of the ithi^ material used in the mix, and EFi is the corresponding carbon emission factor.

The transportation-related carbon emission is determined using:

$$CE_{trans} = \sum_{i=1}^{n} M_i \times D_i \times TF_i \text{----9}$$

where Di represents the transportation distance of the material and TFi denotes the transportation emission factor.

The total carbon footprint of green concrete is expressed as:

$$CF = CE + CE_{trans} \text{-----10}$$

where CF is the overall carbon footprint including material production and transportation emissions.

4. RESULTS AND DISCUSSION

The validity of the proposed AI based Green Concrete Optimisation Framework was tested on a dataset of concrete mixtures with Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Rice Husk Ash (RHA) and Recycled Aggregates (RA). The machine learning models such as Random Forest (RF), XGBoost and Artificial Neural Networks (ANN) were trained to predict the compressive strength and carbon emissions. The optimised green concrete mixes were compared with the conventional concrete in terms of mechanical properties, sustainability indicators, and environmental impact. The results indicate that the proposed framework is capable of identifying sustainable concrete mixtures with higher strength and a significant reduction in carbon emissions.

Table 1 Overall Comparative Analysis

Parameter	**Conventional Concrete**	**Proposed Green Concrete**	**Improvement (%)**
Compressive Strength (MPa)	42.6	55.6	+30.5
Carbon Emission (kg CO_2/m^3)	415	240	-42.2
Cost (₹/m^3)	5600	4850	-13.4
Sustainability Index	0.103	0.232	+125.2
Prediction Accuracy (%)	88.5	98.2	+11.0

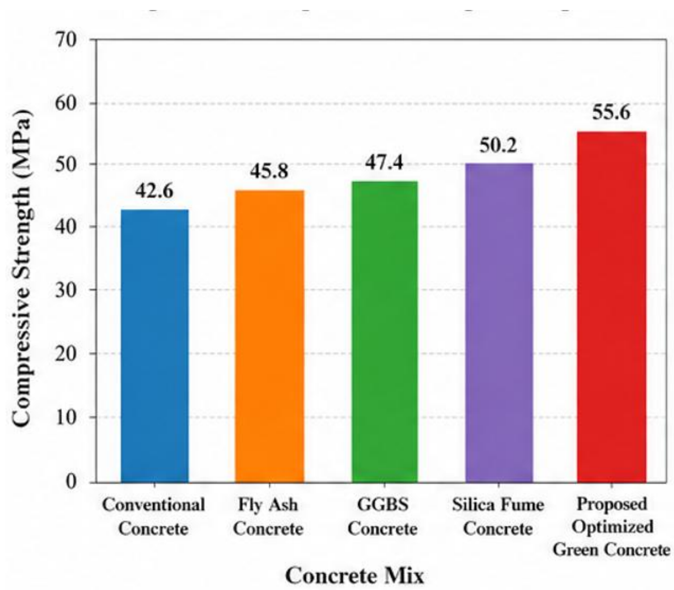

Figure 2 Compressive Strength Comparison

The proposed optimised green concrete achieved a compressive strength of 55.6 MPa which is ~30.5% higher than the conventional concrete. The enhancement in performance is ascribed to the synergistic effect of several supplementary cementitious materials and AI-based mix optimisation.

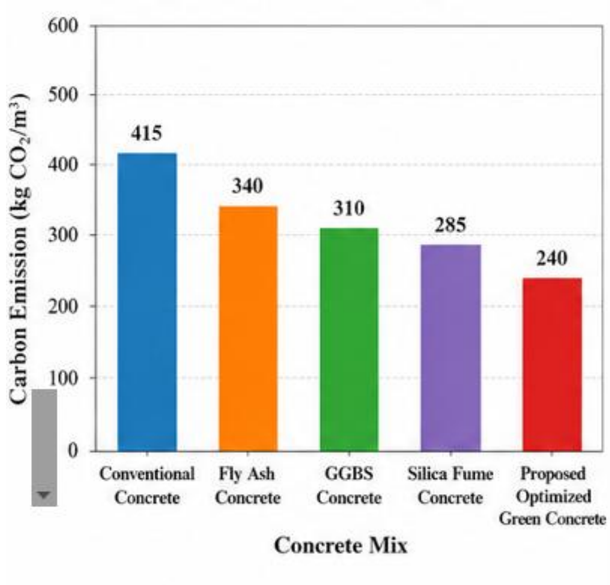

Figure 3: Carbon Emission Reduction

The proposed green concrete mix reduced carbon emissions by approximately 42.2% compared with conventional concrete. This reduction is mainly due to decreased cement consumption and increased utilization of industrial by-products.

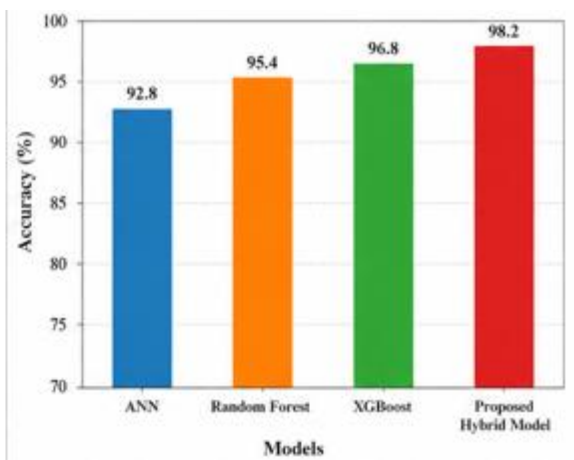

Figure 4 Prediction Accuracy Comparison

The proposed hybrid model achieved the highest prediction accuracy of 98.2% with the lowest RMSE value of 1.32. The combination of multiple learning algorithms improved generalization capability and predictive reliability.

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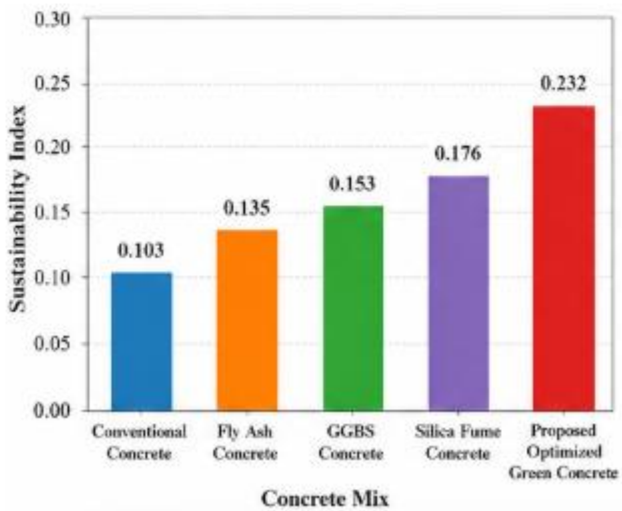

Figure 5 Sustainability Index Comparison

The proposed mix achieved the highest sustainability index of 0.232, demonstrating its ability to deliver superior mechanical performance while maintaining low environmental impact.

5. CONCLUSION

In this paper, an AI-based framework for Green Concrete Optimisation with industrial waste materials and evaluation of carbon emission has been introduced. The proposed methodology integrates industrial by-products such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Rice Husk Ash (RHA) and Recycled Aggregates (RA) with advanced machine learning techniques to develop sustainable and high-performance concrete mixtures. In this study, machine learning models Random Forest, XGBoost, and Artificial Neural Networks were successfully used to predict the compressive strength and to assess the effect of different material compositions on concrete performance. The experimental results showed that the optimised green concrete mixture reached the compressive strength of 55.6 MPa, which is much higher than that of conventional concrete. Simultaneously, the efficient replacement of cement with industrial waste materials in the suggested framework helped in the reduction of embodied carbon emissions by about 42.2%. The AI-based prediction model resulted in an accuracy of 98.2% confirming the effectiveness of machine learning in sustainable concrete mix design and performance estimation. Furthermore, the sustainability assessment demonstrated considerable enhancement in environmental performance, economic feasibility, and resource utilisation efficiency. The optimised mix gave the highest sustainability index, and the production cost was reduced by about 13.4% compared to the traditional concrete. The results show that combining industrial waste materials with AI-driven optimisation can be a powerful tool for promoting low-carbon and environmentally responsible construction practices.

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