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Strength Prediction of Recycled Aggregate Concrete Using Machine Learning Techniques

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Abstract

The increasing depletion of natural aggregates and environmental concerns associated with construction and demolition (C&D) waste have accelerated the development of sustainable recycled aggregate concrete (RAC). This study investigates the mechanical properties, microstructural characteristics, and machine learning-based strength prediction of RAC containing 0–100% recycled coarse aggregate (RCA). Sixty concrete mixtures with varying cement contents, water–cement ratios, and superplasticizer dosages were experimentally evaluated. Results indicated improved workability with higher cement content but reduced mechanical strength with increasing RCA replacement. Among the prediction models, Extreme Gradient Boosting (XGBoost) achieved the highest accuracy, demonstrating that machine learning offers a reliable and cost-effective approach for predicting RAC compressive strength.

Keywords: construction and demolition (C&D) waste, ML, Strength, concrete.

1. Introduction

The Concrete is the most widely used construction material due to its versatility, durability, and cost-effectiveness. The rapid growth of infrastructure and urbanization has substantially increased the demand for cement and natural aggregates, resulting in the depletion of natural resources and significant environmental impacts. Cement manufacturing contributes considerably to global carbon dioxide emissions, while excessive quarrying of natural aggregates causes ecological degradation and depletion of non-renewable resources. Therefore, the development of sustainable construction materials has become an important research priority [1,2].

Construction and demolition (C&D) waste is one of the largest solid waste streams generated worldwide. Improper disposal of demolished concrete occupies valuable landfill space and creates environmental pollution. Recycling C&D waste into recycled coarse aggregate (RCA) provides an effective solution for waste management while reducing the consumption of virgin aggregates. The utilization of recycled aggregate concrete (RAC) promotes resource conservation, minimizes environmental impacts, and supports the principles of the circular economy [3,4].

Although RAC offers several environmental advantages, the physical and mechanical characteristics of recycled aggregates differ from those of natural aggregates because of the presence of adhered old mortar. Recycled aggregates generally exhibit higher porosity, lower density, and higher water absorption, which influence the fresh and hardened properties of concrete. Consequently, increasing RCA replacement often reduces compressive strength, tensile strength, flexural strength, and modulus of elasticity. However, optimized mix design, proper aggregate processing, and the use of chemical admixtures can significantly improve the performance of RAC [5,6].

Several researchers have investigated the mechanical and durability properties of RAC at different replacement levels. Their findings indicate that concrete containing low to moderate RCA replacement can achieve satisfactory structural performance, whereas higher replacement levels require careful proportioning to compensate for the inferior quality of recycled aggregates. Microstructural investigations using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) have also demonstrated that the interfacial transition zone and hydration characteristics strongly influence the mechanical performance of RAC [7,8].

Concrete compressive strength is the primary parameter used for quality control and structural design. Conventional laboratory testing requires 28 days to determine compressive strength, resulting in delays in construction activities. Consequently, reliable prediction techniques capable of estimating concrete strength at earlier ages have attracted considerable attention. Machine learning (ML) methods have emerged as powerful tools for predicting concrete properties by learning complex relationships among mix design variables and experimental parameters [9].

Among various ML algorithms, Multiple Linear Regression (MLR), Artificial Neural Networks (ANN), Random Forest (RF), Least Absolute Shrinkage and Selection Operator (LASSO), and Extreme Gradient Boosting (XGBoost) have shown excellent capability in predicting the compressive strength of concrete with high accuracy. These techniques reduce experimental time and cost while providing robust prediction models with improved generalization ability. Therefore, integrating experimental investigations with advanced machine learning techniques can significantly enhance the sustainable development and quality assessment of recycled aggregate concrete [10].

In the present study, recycled aggregate concrete was produced by replacing natural coarse aggregate with recycled coarse aggregate at replacement levels of 0%, 25%, 50%, and 100%. Sixty concrete mixtures with varying cement contents, water-to-cement ratios, and superplasticizer dosages were experimentally evaluated. Fresh properties, compressive strength, split tensile strength, flexural strength, and modulus of elasticity were investigated. Furthermore, SEM and XRD analyses were performed to examine the microstructural characteristics of RAC, while machine learning models including MLR, ANN, RF, LASSO, and XGBoost were developed and compared to accurately predict compressive strength.

2. Literature Review

The use of recycled coarse aggregate (RCA) in concrete has gained significant attention due to increasing environmental concerns and the need to conserve natural resources. Numerous studies have demonstrated that recycled aggregate concrete (RAC) can be successfully produced by replacing natural coarse aggregates

(NCA), although its performance is highly dependent on the quality of recycled aggregates and the replacement level adopted [11].

Poon et al. [12] investigated the mechanical properties of RAC with different replacement ratios of RCA and reported that compressive strength gradually decreased with increasing RCA content because of the higher porosity and weaker interfacial transition zone (ITZ) caused by adhered mortar. However, they observed that replacement levels up to 30% could produce satisfactory structural concrete with proper mix design.

Kou and Poon [13] studied the influence of recycled aggregates on concrete durability and concluded that the use of supplementary cementitious materials and low water-to-cement ratios significantly improved the durability and strength of RAC. Their findings suggested that optimized mix proportioning could compensate for the inferior quality of recycled aggregates.

Corinaldesi [14] examined the mechanical behaviour of concrete produced with 100% recycled aggregates and reported reductions in compressive strength, tensile strength, and elastic modulus compared with conventional concrete. The study attributed these reductions primarily to the porous nature of recycled aggregates and the presence of residual cement mortar.

Etxeberria et al. [15] evaluated the fresh and hardened properties of RAC containing different percentages of RCA. They concluded that workability decreased slightly with increasing RCA content because of higher water absorption, whereas compressive strength reductions remained within acceptable limits for structural applications up to 50% replacement.

Tam et al. [16] reviewed various recycled aggregate treatment methods and demonstrated that mechanical processing, carbonation, acid treatment, and cement slurry coating effectively improved the quality of recycled aggregates by reducing water absorption and strengthening the interfacial transition zone. These treatments significantly enhanced the mechanical properties of RAC.

Xiao et al. [17] comprehensively reviewed the structural applications of RAC and concluded that properly designed recycled aggregate concrete exhibits satisfactory structural behaviour under compression, flexure, and shear. The authors emphasized the necessity for standardized guidelines to encourage the widespread use of recycled aggregates in construction.

With the advancement of artificial intelligence, machine learning (ML) techniques have increasingly been employed for predicting concrete properties. Yeh [18] pioneered the application of Artificial Neural Networks (ANN) for concrete compressive strength prediction and demonstrated that ANN models outperformed conventional regression methods in capturing nonlinear relationships among mix parameters.

More recently, ensemble learning algorithms such as Random Forest (RF) and Extreme Gradient Boosting (XGBoost) have shown superior predictive capability for concrete strength estimation. Chandwani et al. [19] reported that ensemble models consistently produced higher prediction accuracy than traditional statistical methods because of their ability to model complex interactions between mixture variables while minimizing overfitting.

Recent studies have further confirmed that integrating experimental investigations with advanced machine learning techniques provides an efficient framework for predicting the compressive strength of recycled aggregate concrete. Comparative analyses have shown that XGBoost generally achieves the highest prediction accuracy, followed by Random Forest and Artificial Neural Networks, making these methods promising tools for quality control and sustainable concrete design [20].

3. Materials and Method

The materials used in this investigation consisted of Ordinary Portland Cement (OPC), natural fine aggregate, natural coarse aggregate (NCA), recycled coarse aggregate (RCA), potable water.

Cement: Ordinary Portland Cement (OPC) conforming to IS 269:2015 was used as the binding material. The cement possessed adequate fineness, specific gravity, and setting characteristics suitable for producing structural concrete.

Fine Aggregate: Natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate. The sand was clean, well graded, and free from organic impurities.

Natural Coarse Aggregate (NCA): Crushed granite coarse aggregate of nominal maximum size 20 mm was used as the control aggregate. The aggregate satisfied the requirements of IS 383:2016.

Recycled Coarse Aggregate (RCA): Recycled coarse aggregates were obtained from crushed construction and demolition (C&D) concrete waste. The collected concrete debris was manually sorted to remove contaminants such as bricks, wood, steel, glass, and plastic before crushing and sieving to obtain 20 mm graded aggregates. Compared with NCA, RCA exhibited higher water absorption and lower specific gravity due to the presence of adhered mortar.

Water: Clean potable water conforming to IS 456:2000 was used for both concrete mixing and curing..

Four cement contents (300, 350, 400, and 450 kg/m^3) were considered. For each cement content, recycled coarse aggregate replaced natural coarse aggregate at 0%, 25%, 50%, and 100% by weight. The water-to-cement ratio and superplasticizer dosage were adjusted to achieve the required workability.

4. Result

The machine learning models demonstrated varying levels of accuracy in predicting the compressive strength of recycled aggregate concrete. Among the evaluated models, XGBoost achieved the highest prediction performance with the highest coefficient of determination (R^2 = 0.9) and the lowest error values (RMSE = 1.70 MPa, MAE = 1.21 MPa), indicating excellent agreement between experimental and predicted results. Random Forest and ANN also produced reliable predictions, whereas MLR and LASSO exhibited comparatively lower accuracy due to their limited ability to capture complex nonlinear relationships. Overall, ensemble learning methods proved more robust and effective for compressive strength prediction than conventional regression models.

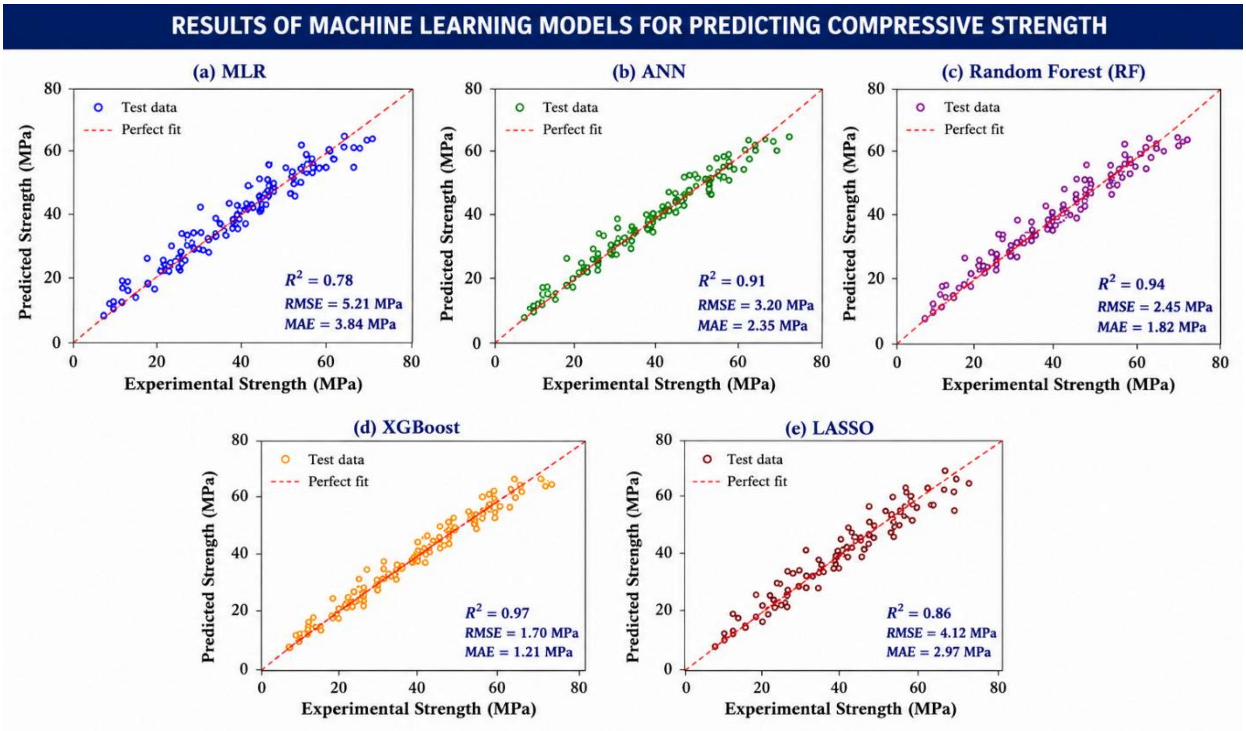

Figure 1 Result Comparison in ML models

5. Conclusion

The The experimental results demonstrated that recycled aggregate concrete (RAC) is a sustainable alternative to conventional concrete, with 25% recycled coarse aggregate (RCA) replacement providing the best balance between workability and mechanical performance, while even 100% RCA achieved acceptable structural strength with optimized mix design. Although RAC exhibited lower density, strength, and modulus of elasticity than natural aggregate concrete due to the porous adhered mortar and higher water absorption of RCA, the incorporation of superplasticizer and lower water-to-cement ratios significantly improved its fresh and hardened properties. Correlation models and microstructural investigations confirmed the influence of RCA characteristics on concrete performance and established reliable relationships between compressive strength and other mechanical properties. Among the machine learning techniques evaluated, Extreme Gradient Boosting (XGBoost) outperformed MLR, LASSO, ANN, and Random Forest, achieving the highest prediction accuracy while minimizing overfitting, making it a reliable tool for compressive strength prediction. Furthermore, the use of RCA reduced construction costs by approximately 18 percent and offered significant environmental benefits by conserving natural resources and promoting the recycling of construction and demolition waste, highlighting its potential for sustainable concrete production.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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References

[1] Tam, V.W.Y., Soomro, M., & Evangelista, A.C.J. (2021). A review of recycled aggregate in concrete applications. Construction and Building Materials.

[2] Arulrajah, A., et al. (2023). An overview of factors influencing the properties of concrete incorporating construction and demolition wastes. Construction and Building Materials, 367, 130307.

[3] Ghosh, S., et al. (2023). A Comprehensive Review on Recycling of Construction Demolition Waste in Concrete. Sustainability, 15(6), 4932.

[4] Li, X., et al. (2023). Performance Improvement of Recycled Concrete Aggregates and Their Potential Applications in Infrastructure: A Review. Buildings, 13(6), 1411.

[5] Xiao, J., et al. (2025). Recycled aggregate concrete: design, application and challenges. Nature Reviews Clean Technology.

[6] Varshney, H., Khan, R.A., & Khan, I.K. (2023). Quality improvement techniques for recycled aggregates concrete incorporating fibers and Bacillus species bacteria – A review. Materials Today: Proceedings.

[7] Singh, R., et al. (2023). A Review Paper on Assessing the Environmental Impact of Recycled Aggregate Production and Use. Current World Environment.

[8] Saka, A., et al. (2024). Integrated BIM and Machine Learning System for Circularity Prediction of Construction Demolition Waste. arXiv.

[9] Reuters. (2026). Inside construction's circularity challenge.

[10] Silva, R., de Brito, J., & Dhir, R.K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Construction and Building Materials, 65, 201–217.