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EXPERIMENTAL STUDY ON BLENDED CONCRETE WITH METAKAOLIN AND GLASS FIBER AND THEIR PREDICTION USING MACHINE LEARNING TECHNIQUES

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ABSTRACT :

Blended concrete incorporating metakaolin and glass fiber is increasingly recognized for its superior mechanical and durability properties compared to conventional concrete. Metakaolin, as a highly reactive pozzolanic material, enhances the microstructure of concrete by forming additional calcium-silicate-hydrate (C-S-H) gel, which reduces porosity and improves strength characteristics. Glass fibers provide reinforcement that bridges microcracks, improving tensile and flexural performance and enhancing post-cracking behavior. This theoretical paper aims to provide an extensive review of the mechanical properties of blended concrete with metakaolin and glass fiber, highlighting compressive, flexural, and split tensile strengths. Additionally, it discusses the potential of machine learning techniques, specifically Gradient Boosting and Random Forest, to predict these mechanical properties accurately, enabling optimization of mix design and reducing the need for extensive experimental testing. A framework is proposed for integrating literature data into predictive models, including preprocessing, training, evaluation, and comparison of performance metrics. This study emphasizes the synergy between metakaolin and glass fiber in enhancing the structural performance of concrete and demonstrates how ML techniques can facilitate data-driven design and decision-making. The paper serves as a comprehensive resource for researchers, engineers, and practitioners interested in advanced blended concrete design and predictive modeling using modern computational techniques, ultimately supporting the development of sustainable and high-performance concrete structures.

Keywords : Metakaolin , Glass Fiber , Compresive Strength , Flexural Strength , split Tensile Strength , Gradient Boosting , Random Forest.

Introduction

Concrete is the most widely used construction material in the world due to its versatility, strength, and durability. However, conventional concrete faces challenges including low tensile strength, susceptibility to cracking, and environmental concerns related to high cement usage. To address these limitations, researchers have explored blended concrete, where part of the cement is replaced with supplementary cementitious materials (SCMs) such as metakaolin, and reinforcement is provided using fibers such as glass fiber. Metakaolin enhances the concrete matrix by reacting with calcium hydroxide to form additional C-S-H gel, resulting in a denser and more durable microstructure. Glass fibers, being alkali-resistant and mechanically strong, improve the tensile and flexural performance of concrete by bridging microcracks and increasing post-cracking toughness. Combining these materials offers a synergistic effect, improving compressive, tensile, and flexural strengths while enhancing durability against chemical attacks and shrinkage. Despite experimental studies confirming these improvements, conducting extensive laboratory testing is time-consuming and costly. Machine learning (ML) techniques provide a promising alternative for predicting the mechanical properties of blended concrete using input parameters such as mix proportions, material properties, and curing conditions. Ensemble ML models, particularly Gradient Boosting and Random Forest, have been effectively applied in literature to predict compressive, tensile, and flexural strengths of various concrete types, achieving high accuracy and reliability. This paper presents a detailed theoretical review of blended concrete components, mechanical properties, and predictive ML techniques, along with a proposed framework for implementing data-driven prediction models, aiming to guide researchers in designing optimized concrete mixtures with reduced experimental effort.

Literature Review on Blended Concrete Components

Blended concrete incorporates materials that partially replace cement or enhance the concrete matrix to improve performance and sustainability. Metakaolin, obtained by calcining kaolinite clay at temperatures of 700–800°C, is a highly reactive pozzolanic material. When added to concrete, it reacts with calcium hydroxide generated during cement hydration to form additional C-S-H gel. This reaction refines the pore structure, reduces permeability, and increases both early-age and long-term compressive strength. Typical replacement levels range from 5% to 20% by weight of cement, depending on the desired mechanical and durability properties. Glass fibers are discrete, alkali-resistant fibers added to the mix to improve tensile and flexural performance. These fibers bridge microcracks, enhance post-cracking toughness, and reduce shrinkage-induced cracking. The addition of fibers must be carefully controlled to maintain workability; common volume fractions range from 0.5% to 1.5%. The combined effect of metakaolin and glass fiber results in synergistic improvements. Metakaolin strengthens the matrix and enhances fiber-matrix bonding, while fibers provide ductility and resistance to crack propagation. Literature indicates that this combination enhances compressive, tensile, and flexural strengths, as well as durability properties such as resistance to chloride penetration, chemical attacks, and shrinkage cracking. The review highlights the importance of optimizing both metakaolin replacement levels and fiber content to achieve maximum performance in blended concrete.

Mechanical Properties of Blended Concrete

Compressive Strength

Compressive strength is one of the most critical properties of concrete, representing its ability to resist axial loads. In blended concrete with metakaolin and glass fiber, compressive strength is significantly influenced by the pozzolanic reaction of metakaolin, which forms additional C-S-H gel and densifies the matrix. Studies indicate that moderate replacement levels of metakaolin (10–15%) enhance compressive strength, while excessive replacement (>20%) can reduce workability and slightly lower strength due to dilution effects. Glass fibers have a minor direct effect on compressive strength but improve post-cracking behavior and ductility.

For experimental studies, **cube specimens of size 150 mm × 150 mm × 150 mm** are generally used. The specimens are commonly tested after **7, 14, and 28 days of water curing**, as per standard procedures (IS 516 or ASTM C39). Proper curing ensures complete hydration and maximum strength development of the blended concrete.

Flexural Strength

Flexural strength represents the ability of concrete to resist bending and cracking under tensile stresses. Glass fibers significantly improve flexural strength by bridging cracks and providing post-cracking load capacity. Metakaolin contributes indirectly by improving the matrix-fiber interface and enhancing stiffness. Literature shows that blended concrete with optimal metakaolin and fiber content demonstrates higher flexural toughness, improved ductility, and better energy absorption.

Flexural strength is typically tested using **beam specimens of size 100 mm × 100 mm × 500 mm** after **28 days of water curing**. Standard testing methods such as IS 516 or ASTM C78 are followed to determine the modulus of rupture and assess the flexural behavior of blended concrete.

Split Tensile Strength

Split tensile strength indicates concrete's resistance to tension-induced cracking. Glass fibers directly enhance tensile performance by arresting microcrack propagation, while metakaolin increases the bond strength between fibers and the matrix. Combined, these materials improve tensile strength substantially compared to conventional concrete, making it suitable for structural elements subject to tensile stresses.

For split tensile tests, **cylindrical specimens of 150 mm diameter and 300 mm height** are used. The specimens are tested after **7, 14, and 28 days of curing**, as per IS 5816 or ASTM C496. Proper curing maintains moisture in the matrix, ensuring effective fiber bonding and improved tensile performance.

Compressive Strength

Split Tensile Strength

Flexural Strength

Machine Learning Models

Machine learning (ML) techniques are increasingly being used in civil engineering research to predict the mechanical properties of concrete, such as compressive, flexural, and tensile strengths. These models help minimize the need for extensive laboratory testing by learning patterns from existing experimental data. By analyzing input parameters such as mix proportions, material types, curing periods, and test conditions, ML models can predict outcomes with high accuracy.

Commonly used models in concrete strength prediction include " **Linear Regression (LR)**, **Support Vector Machines (SVM)**, **Decision Trees (DT)**, **Random Forests (RF)**, **Gradient Boosting (GB)**, and **Artificial Neural Networks (ANN)** ". Among these, **Random Forest** and **Gradient Boosting** methods are widely preferred due to their ability to handle nonlinear relationships and complex interactions between mix parameters.

Random Forest method

The **Random Forest** algorithm is an ensemble-based machine learning model that operates by creating multiple decision trees and combining their results to improve prediction accuracy. Each tree is trained on a random subset of the dataset and input features, ensuring diversity and reducing overfitting. In concrete strength prediction, Random Forest helps in capturing complex relationships between parameters like cement content, metakaolin percentage, fiber dosage, and curing age.

The main advantages of this method include its ability to handle nonlinear data effectively, provide the importance of each input feature, and offer strong resistance to overfitting, making it highly reliable for predicting mechanical properties of blended concrete.

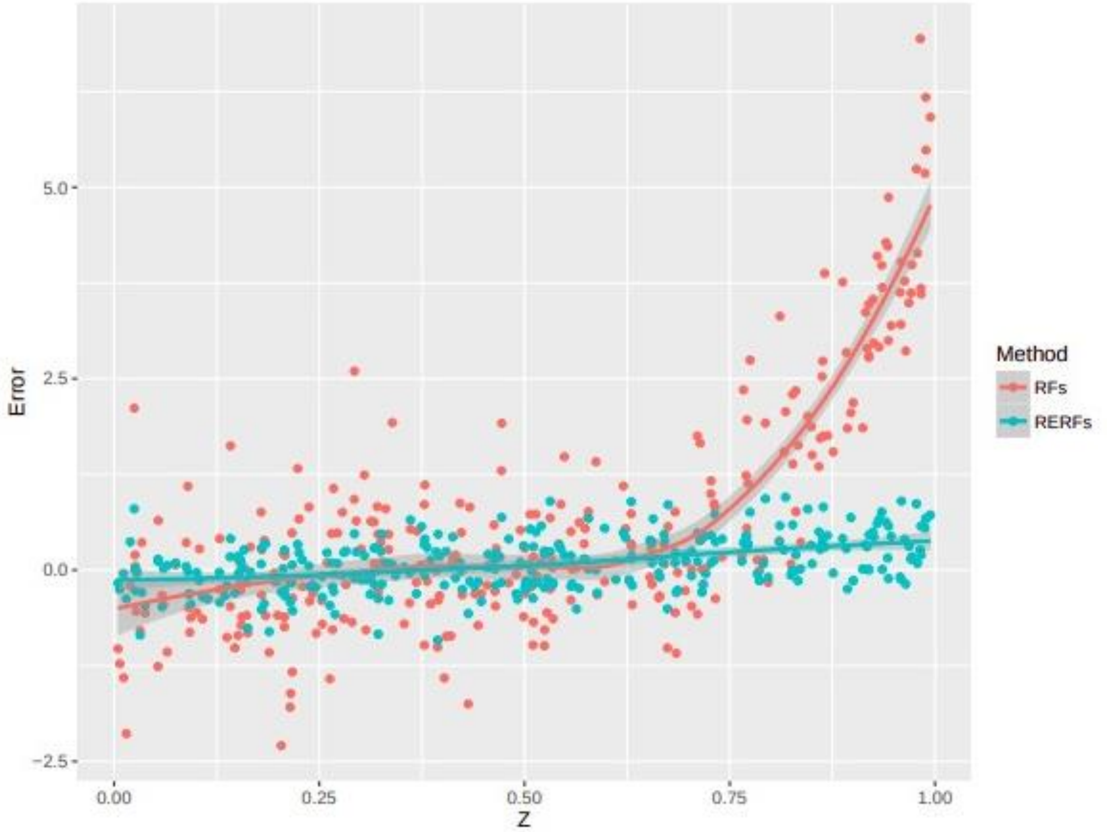
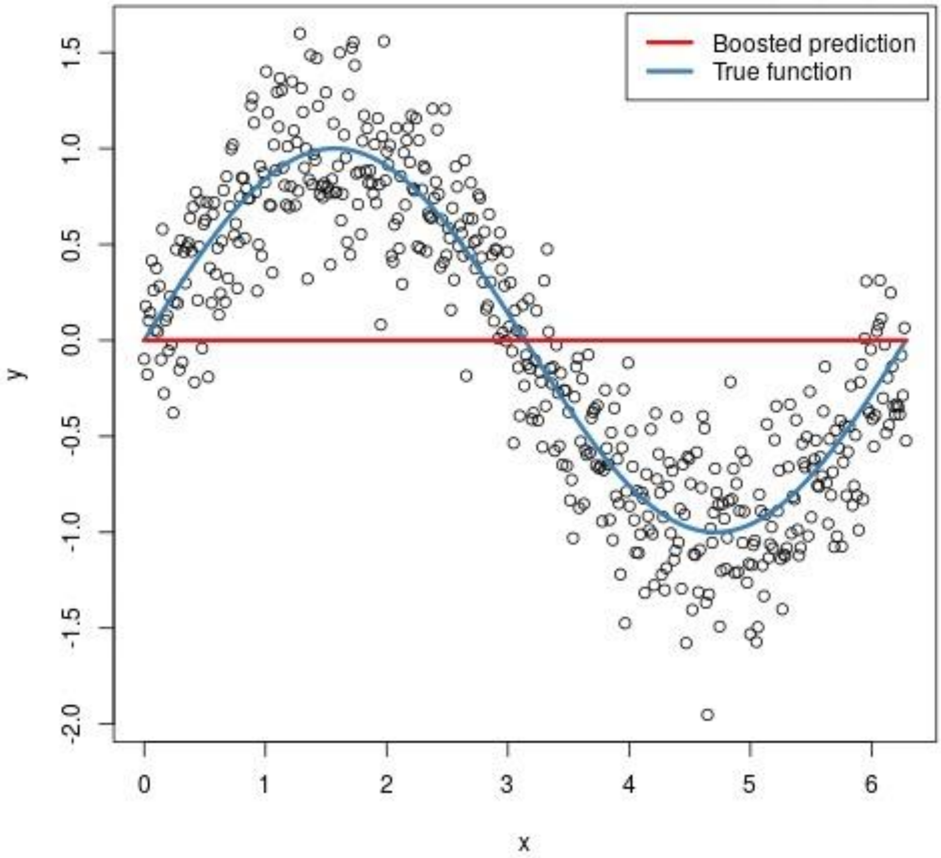


Figure 1: The pointwise prediction errors $Y - \widehat{Y}$ given by a random forest (red) and a regression-enhanced random forest (blue) against the predictor Z and the corresponding Loess smooth curves of $Y - \widehat{Y}$ against Z.

Gradient Boosting Method

The **Gradient Boosting** algorithm is another ensemble technique that builds multiple trees sequentially, where each new tree focuses on correcting the errors made by the previous ones. This step-by-step improvement process increases the overall model accuracy. In predicting the mechanical behavior of concrete, Gradient Boosting can effectively model complex relationships between various mix parameters and strength outcomes.

The key advantages of this approach are its high prediction accuracy, strong performance with small or noisy datasets, and its capability to capture intricate variable interactions, making it one of the most efficient algorithms for strength prediction in blended concrete.



Conclusion

Blended concrete incorporating metakaolin and glass fiber demonstrates enhanced mechanical properties, including compressive, flexural, and split tensile strengths, along with improved durability and microstructural performance. The synergistic action of metakaolin's pozzolanic reaction, which refines the pore structure, and the crack-bridging ability of glass fibers, enhances both strength and ductility of the concrete. Machine learning models, particularly Gradient Boosting and Random Forest, have shown high reliability in predicting these mechanical properties, allowing researchers to optimize mix proportions effectively. The proposed framework presents a systematic approach for integrating literature and experimental data into predictive models, encompassing stages such as data preprocessing, model training, evaluation, and feature importance analysis. This data-driven methodology minimizes the requirement for extensive laboratory testing, supports efficient mix design, and contributes to the development of sustainable and high-performance concrete. Future studies can focus on employing deep learning techniques and hybrid ensemble models to further improve predictive accuracy and generalization. Moreover, the integration of machine learning with Building Information Modeling (BIM) and optimization tools can pave the way toward intelligent, automated, and environmentally responsible construction practices.

REFERENCES

1. Afzali, S. A. E., Shayanfar, M. A., Ghanooni-Bagha, M., Golafshani, E., & Ngo, T. (2024). The use of machine learning techniques to investigate the properties of metakaolin-based geopolymer concrete. Journal of Cleaner Production, 446, 141305.
2. Abdellatief, M., Elsafi, M., Murali, G., & ElNemr, A. (2025). Comparative evaluation of hybrid machine learning models for predicting the strength of metakaolin-based geopolymer concrete enhanced with Gaussian noise augmentation. Journal of Building Engineering, 113302.
3. Manhas, A., Mehta, S., & Sharma, S. (2025). Predictive modeling and strength optimization of sustainable concrete incorporating glass fiber and marble dust using machine learning techniques. Asian Journal of Civil Engineering, 1-19.
4. Shah, H. A., Yuan, Q., Akmal, U., Shah, S. A., Salmi, A., Awad, Y. A., ... & Khan, M. I. (2022). Application of machine learning techniques for predicting compressive, splitting tensile, and flexural strengths of concrete with metakaolin. Materials, 15(15), 5435.

5. Sobuz, M. H. R., Rahman, M. M., Aayaz, R., Al-Rashed, W. S., Datta, S. D., Safayet, M. A., ... & Abdullah, M. (2025). Combined influence of modified recycled concrete aggregate and metakaolin on high-strength concrete production: Experimental assessment and machine learning quantifications with advanced SHAP and PDP analyses. Construction and Building Materials, 461, 139897.
6. Moradi, M. J., Khaleghi, M., Salimi, J., Farhangi, V., & Ramezanianpour, A. M. (2021). Predicting the compressive strength of concrete containing metakaolin with different properties using ANN. Measurement, 183, 109790.
7. Nakkeeran, G., Krishnaraj, L., Bahrami, A., Almujibah, H., Panchal, H., & Zahra, M. M. A. (2023). Machine learning application to predict the mechanical properties of glass fiber mortar. Advances in Engineering Software, 180, 103454.
8. Rabie, M., & Shaaban, I. G. (2025). Glass fibre concrete: Experimental investigation and predictive modeling using advanced machine learning with an interactive online interface. Construction and Building Materials, 472, 140951.
9. Alyami, M., Ullah, I., AlAteah, A. H., Alsubeai, A., Alahmari, T. S., Farooq, F., & Alabduljabbar, H. (2025, January). Machine learning models for predicting the compressive strength of cement-based mortar materials: Hyper tuning and optimization. In Structures (Vol. 71, p. 107931). Elsevier.
10. Kumar, S., Kumar, R., Rai, B., & Samui, P. (2024). Prediction of compressive strength of high-volume fly ash self-compacting concrete with silica fume using machine learning techniques. Construction and Building Materials, 438, 136933.
11. **IS 10262: 2019** – *Concrete Mix Proportioning – Guidelines (Second Revision)*, Bureau of Indian Standards, New Delhi.
12. **IS 456: 2000** – *Plain and Reinforced Concrete – Code of Practice*, Bureau of Indian Standards, New Delhi
13. **IS 516: 2018** – *Method of Tests for Strength of Concrete (Compressive, Flexural, and Elastic Properties)*, Bureau of Indian Standards, New Delhi.
14. **IS 5816: 1999** – *Splitting Tensile Strength of Concrete – Method of Test*, Bureau of Indian Standards, New Delhi.