Analysis of Mathematical Models for Predicting the Mechanical Resistance of Concrete Reinforced with Steel Fibers Using Experimental and Machine Learning Methods

Mohammad Hossein Taghavi Parsa [1], Morteza Esmaeili [2], Mohammad Reza Adlparvar [3*]

1 - Faculty of Engineering, Department of Civil Engineering, University of Qom, Qom, Iran, mh.taghavi@stu.qom.ac.ir

2 - Faculty of Railway Engineering, University of Science and Technology, Tehran, Iran, m_esmaeili@iust.ac.ir

3- Faculty of Engineering, Department of Civil Engineering, University of Qom, Qom, Iran, adlparvar@qom.ac.ir

Abstract

In this study, the mechanical properties of steel fiber-reinforced concrete, including compressive, tensile, and flexural strengths, were investigated using experimental data and machine learning techniques. Laboratory tests were conducted on concrete specimens reinforced with different types and volume fractions of steel fibers. After data preparation and elimination of non-reinforced concrete samples, an overfitting-based feature selection strategy was applied to identify the most effective parameters influencing the mechanical behavior of steel fiber-reinforced concrete. Symbolic regression models were then developed to predict the strength properties. The results show that the proposed predictive relationships provide higher accuracy compared to existing empirical models, indicating the capability of the adopted approach for reliable prediction of the mechanical strengths of steel fiber-reinforced concrete.

Introduction

Steel fiber-reinforced concrete has been extensively investigated due to its enhanced mechanical properties compared to conventional concrete. Experimental studies have demonstrated that the compressive, tensile, and flexural strengths of steel fiber-reinforced concrete are significantly influenced by fiber volume fraction, geometry, and aspect ratio [1-7]. Although several empirical relationships have been proposed to estimate these strength properties, their applicability is generally limited to specific experimental conditions and datasets.

To address these limitations, recent studies have increasingly employed artificial intelligence and machine learning techniques to model the nonlinear behavior of steel fiber-reinforced concrete [8-11]. These data-driven approaches have shown improved prediction accuracy compared to traditional empirical models; however, challenges related to overfitting and model generalization have been reported. Consequently, feature selection strategies and overfitting-based approaches have been introduced to improve model robustness and predictive performance [12-14]. In this context, the present study applies a machine learning-based symbolic regression framework to predict the mechanical strength properties of steel fiber-reinforced concrete.

Methodology

The overall workflow of the proposed approach, including data preparation, feature selection, and model development, is illustrated in Figure (1). After data preprocessing and grouping the dataset based on fiber type, an overfitting-based feature selection strategy was applied. Five-fold cross-validation (k = 5) and regularization techniques were used to control overfitting and improve model generalization.

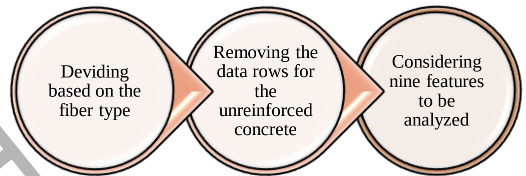

Figure (1): The process illustration for the data preparation and feature selection.

The generation of predictive equations was carried out using symbolic regression, as illustrated in Figure (2). This approach enables the derivation of explicit mathematical expressions that relate the selected input variables to the compressive, tensile, and flexural strengths of steel fiber-reinforced concrete.

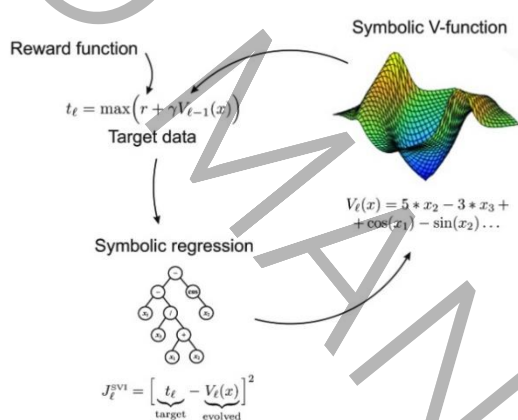

Figure (2): Equation generation process using the symbolic regression model

Results and Discussion

A representative comparison between experimental and predicted compressive strength values is presented in Figure (3), demonstrating a strong agreement between the proposed model outputs and laboratory test results. The error analysis of different predictive relationships for compressive strength, shown in Figure (4), indicates that the proposed symbolic regression model achieves lower prediction errors compared to conventional empirical equations. Similar trends were observed for tensile and flexural strengths, where the developed models exhibited improved prediction accuracy and consistent agreement with experimental results. These findings confirm that the proposed approach is effective in predicting various mechanical strength properties of steel fiber-reinforced concrete.

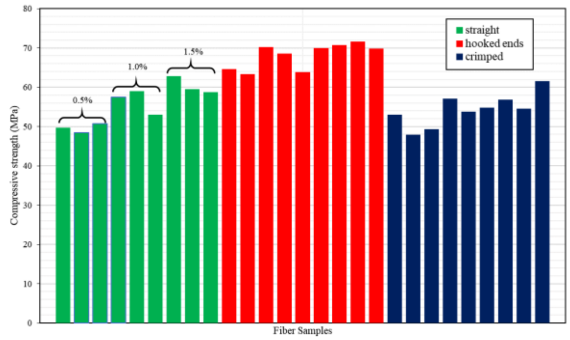

Figure (3): Diagram of compressive strength results of steel fiber-reinforced concrete specimens with the investigated volume fractions

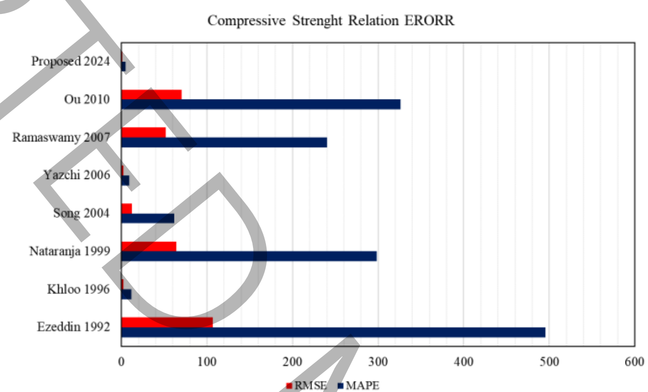

Figure (4): Diagram of error results of different equations for predicting compressive strength

Conclusion

Based on the experimental results and predictive modeling, this study demonstrates that the proposed symbolic regression models can accurately estimate the compressive, tensile, and flexural strengths of steel fiber-reinforced concrete. The comparison between predicted and experimental results indicates that the developed models improve the prediction accuracy by up to 34% compared to conventional empirical relationships. This improvement confirms the effectiveness of the overfitting-based feature selection strategy combined with machine learning techniques. The results of this study show that the proposed equations can be used as reliable tools for predicting the mechanical behavior of steel fiber-reinforced concrete within the investigated range of parameters.

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