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# Enhanced artificial intelligence for ensemble approach to predicting high performance concrete compressive strength

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## HIGHLIGHTS

- High-performance concrete (HPC) compressive strength is a highly nonlinear function of concrete ingredients.
- To predict HPC compressive strength, an ensemble artificial intelligence approach is proposed.
- This ensemble technique has superior prediction accuracy to individual models.
- The approach automates mix design for HPC compressive strength.
- The proposed approach markedly reduces the amount of laboratory work required.

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## ABSTRACT

The compressive strength of high performance concrete (HPC) is a highly nonlinear function of the proportions of its ingredients. The validity of relationships between concrete ingredients and supplementary cementing materials is questionable. This work evaluates the efficacy of ensemble models by comparing individual numerical models in terms of their performance in predicting the compressive strength of HPC. The performance of support vector machines, artificial neural networks, classification and regression trees, chi-squared automatic interaction detector, linear regression, and generalized linear were applied to construct individual and ensemble models. Analytical results show that the ensemble technique combining two or more models obtained the highest prediction performance. For five experimental datasets, the ensemble models achieved 4.2–69.7% better error rates than those of prediction models in previous studies. This work confirmed the efficiency and effectiveness of the proposed ensemble approach in improving the accuracy of predicted compressive strength for HPC.



## 1. Introduction

In recent years, the use of high performance concrete (HPC) has increased markedly in various structural applications (*i.e.*, high-rise buildings, bridges, masonry applications, parking lots, residential buildings, and pavement construction) [1,2]. Supplementary cement materials, such as fly ash, blast furnace slag, and silica fume, are often added to HPC to increase its compressive strength [3,4]. Notably, HPC is used widely because of its high compressive strength and other beneficial qualities such as high abrasion resistance, low permeability and diffusion, high resistance to chemical attack, and high modulus of elasticity. In concrete mix design and quality control, compressive strength is the most important indication of HPC quality. However, it is affected by many factors, including mix proportions, material characteristics, curing and environmental conditions, and concrete age [5].

Particularly, because it is highly complex, modeling the compressive strength of HPC is problematic. The highly nonlinear relationship between components and concrete properties complicates the mathematical modeling of compressive strength when using available data [3,6]. Early prediction of concrete strength is essential for scheduling concrete form removal and re-shoring to a slab. A prediction model can help reduce the time and cost of post-tensioning by providing essential data to designers and structural engineers. Thus, accurate and early prediction of concrete strength is a critical issue in concrete construction.

Conventional methods to predict concrete compressive strength uses linear or non-linear regression methods [7,8]. These approaches apply a limited amount of experimental data to determine an unknown coefficient. However, many regression models have shown that obtaining an accurate regression equation is difficult. Moreover, several factors that affect the compressive strength of HPC differ from those of conventional concrete. Therefore, to predict compressive strength, regression analysis may be unsuitable [9]. Since conventional models are inadequate for analyzing complex non-linear and uncertain materials, many studies

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have utilized artificial intelligence (AI) in evolutionary or hybrid systems to develop accurate and effective models that can predict concrete compressive strength [5,9–13]. Nevertheless, no model has proven consistently to be superior.

The growing tendency to use combined methods suggests that ensemble approaches enhance applications of individual AI techniques. Although hybrid methods are now very common [14–17], an ensemble approach is rarely used to predict the compressive strength of HPC. Thus, robust models for predicting HPC compressive strength need to enhance their prediction accuracy. To improve prediction accuracy, the ensemble method combines two or more models to obtain predictions that are more accurate than those by any single model. Clearly, while meeting modeling requirements, such a model must also be sufficiently robust to model involved uncertainties and must be easily to manipulate.

In this work, numerical predictor nodes, artificial neural networks (ANNs), support vector machines (SVMs), the classification and regression tree (CART), linear regression (LR), generalized linear regression (GENLIN), and the chi-squared automatic interaction detector (CHAID) were used in the IBM SPSS modeler [18]. The analytical results obtained by the best individual models were then applied to construct ensemble models. For validation, this ensemble modeling system uses a k-fold cross-validation algorithm and five experimental datasets from previous studies [3,19–23]. Performance measures for current and previous models were compared by hypothesis testing.

The remainder of this paper is organized as follows. The Literature Review briefly introduces the study context by reviewing related literature, including studies of concrete compressive strength prediction and some well-known predictive techniques. The Section 3 then describes research methodology, evaluation methods, and set-up procedure of the proposed models. The Section 4 discusses prediction results and compares model performance while the Conclusion section gives a summary of findings and conclusions.

## 2. Literature review

Predicting the mechanical properties of construction materials is an important research task in materials science [12]. Since conventional material models, such those used to model the compressive strength of HPC, perform poorly in complex non-linear systems, scholars are constantly seeking to enhance prediction tools. For many years, researchers have investigated various approaches for predicting the compressive strength of concrete of various ages. Empirical or computational modeling, statistical techniques and AI approaches have acceptable accuracy. Several algorithms for predicting concrete compressive strength based on conventional regression analysis and statistical models have been proposed [7,19]. Further in 1998, Yeh showed that the ANN was superior to regression methods in predicting HPC compressive strength [3].

Meanwhile, Boukhatem et al. comprehensively reviewed recent developments in information technology and their applications in concrete mix design [11]. Their research showed that simulation models, decision support systems, and AI techniques are useful and powerful tools for solving complex problems in concrete technology. Baykasoğlu et al. applied a multi-objective model to optimize and predict the properties of high-strength concrete *via* regression analysis, neural networks and Gene Expression Programming (GEP) [24]. The best results obtained by the ANN were superior to the best results obtained by regression analysis and by the GEP algorithm developed by Ferreira [25].

More researchers have applied or evaluated the ability of ANNs to predict strength and other concrete behaviors [5,22,23,26–30]. Ni and Wang, for instance, used multi-layer feed-forward neural networks to predict 28-day concrete compressive strength based on various factors [5]. The use of an ANN for evaluating the impact of fly ash and silica fume replacement content on the long-term strength of concrete was studied by Pala et al. [22]. Yeh also used an ANN to successfully predict the slump of concrete with fly ash and blast furnace slag [28].

Similarly, evolutionary algorithm-based methodologies, such as genetic programming (GP), have been applied to automatically generate equations for inputs and outputs. Chen approximated HPC compressive strength by combining a macro-evolutionary algorithm and GP [31]. A novel method of GP is being weighted using coefficients assigned to each GP linkage in a tree improved GP in terms of its weight coefficients, and acquired accurate analytical results and formula outputs [32]. Mousavi et al. applied gene expression programming (GEP), a subset of GP, to approximate the compressive strength of HPC mixes [33]. Prediction performance of the optimal GEP model was superior to that of regression-based models.

As the need for prediction accuracy increases, complexity approaches that of combined models. Yeh and Lien proposed a Genetic Operation Tree (GOT). By combining an operation tree and genetic algorithm, the GOT automatically obtained self-organized formulas for predicting accuracy of HPC compressive strength [9]. Comparisons show that GOT is more accurate than nonlinear regression formulas but less accurate again than neural network models. Additionally, Chou and Tsai improved prediction accuracy for HPC compressive strength using a novel hierarchical approach that applied a combined classification and regression technique [34].

Moreover, an innovative model developed by Videla and Gaedicke estimated the general compressive strength of HPC with Portland blast furnace slag cement by combining a compressive time function with a strength-dosage function [21]. Similarly, by

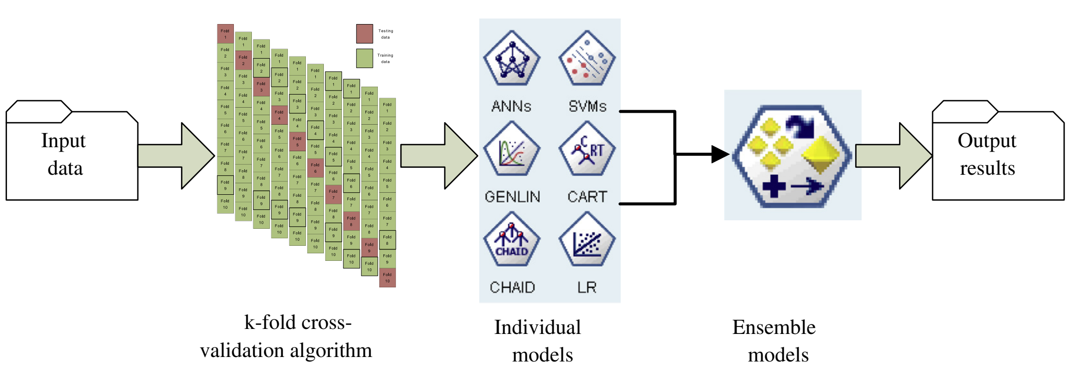


**Fig. 1.** Cross-validation and ensemble modeling procedure.