Predicting Concrete Carbonation Depth and Investigating the Influencing Factors through Machine Learning Approaches and Optimization

Shoaib Mansouri, Alireza Rahai, Seyed Hadi Rashedi, Fereydoun Moghaddas Nejad*

Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran

ABSTRACT

Accurate prediction of concrete carbonation depth is crucial for mitigating detrimental effects such as cracking and corrosion. However, due to the complexity of the process and the multitude of variables involved, identifying the most significant parameters for modeling carbonation depth poses a considerable challenge. This paper introduces a hybrid feature selection method known as MOEA/D-ANN. The primary aim of this method is to identify the most critical variables that contribute to achieving the highest prediction accuracy. The proposed approach combines a multi-objective evolutionary optimization algorithm based on decomposition with artificial neural networks to effectively address the feature selection problem using the strengths of optimization and machine learning techniques. To evaluate the performance of the introduced method, the conventional feature ranking algorithm RReliefF was also employed. ANN was used for predicting carbonation depth, while the combined methods of MOEA/D-ANN and RReliefF were utilized to identify influential variables. The results indicate that the model developed using the MOEA/D-ANN approach significantly reduced the error rate and increased accuracy by combining the selected variables. This model achieves a notable coefficient of determination (R^2 = 0.99), highlighting its excellent accuracy in predicting concrete carbonation depth and confirming the precise selection of influential variables. Additionally, the results demonstrate that an increase in the water-to-cement ratio by 10% leads to a 15% increase in carbonation depth.

KEYWORDS

Carbonation depth; prediction; machine learning; artificial neural network; MOEA/D; optimization.

* Corresponding Author: Email: moghadas@aut.ac.ir

1. Introduction

Concrete is the most commonly used material in various construction, industrial, and civil projects, such as building construction, transportation infrastructure, water protection, and port structures. One critical factor in evaluating concrete performance is its durability, essential for maintaining the integrity and safety of reinforced concrete structures throughout their lifespan [1-3]. Several factors influence concrete durability, with carbonation as a significant issue due to CO_2 diffusion into concrete pores [4-6].

Several studies have utilized ANN models for carbonation depth prediction. These models have been trained on diverse variables, including cement type, water-to-binder ratio, fly ash content, aggregate size, and environmental conditions. Studies demonstrate that optimizing ANN hidden neuron counts can enhance accuracy [7-9].

Feature selection methods, like the MOEA/D-ANN hybrid algorithm, improve ML model performance by identifying relevant features, reducing overfitting, and enhancing interpretability, especially with large datasets [10]. The MOEA/D-ANN model used in this study combines heuristic optimization with ANN to predict carbonation depth by analyzing significant factors like time, relative humidity, and CO_2 concentration, achieving high accuracy in prediction.

2. Methodology

The study collected 198 data samples from previous research [11-17], covering various material weight ratios like water-to-binder, fine aggregate, and superplasticizer, which are key for concrete property prediction. Selected ratios include water-to-cement, coarse aggregate-to-binder [18], and fly ash-to-cement ratios, which aid in estimating carbonation depth [19].

In this study, 37 input variables from 9 main factors, like water-to-cement and aggregate ratios, were used to predict carbonation depth, with feature selection improving model accuracy. Table 1 shows descriptive statistics for material weights, covering mean, standard deviation, minimum, and maximum values for key variables.

A new feature selection method, MOEA/D-ANN, was developed in this study. It involves two objectives: the first measures the number of selected input variables, and the second evaluates the ANN model's prediction error. A random population is created, and input variables are selected for each vector. The first objective is calculated based on the selected variables, and the second objective is determined using the mean squared error (R^2) of the ANN. MOEA/D iterates to achieve Pareto efficiency in solving the feature selection problem.

Table 1. Descriptive statistics of variables

Variable	Abbrv.	Min	Max	Mean	Std Dev
Cement (kg/m³)	C	120	494	263.2	79.2
Fly Ash (kg/m³)	F	0	280	100.2	80.3
Coarse Aggregate (kg/m³)	CA	501.8	1071	691.9	157.6
Fine Aggregate (kg/m³)	FA	790	1258	1061	114.3
Water (kg/m³)	W	112	220	165	12
Superplasticizer (kg/m³)	S	0	7.7	0.7	1.7
Cycle (days)	CY	3	126	39.6	32.2
Relative Humidity (%)	RH	55	70	64.6	4.7
CO_2 Concentration (%)	CC	1	50	10.3	12.7
Carbonation Depth (mm)	CD	0	57	9.9	10.2

3. Results and discussion

Previous studies often overlooked specific input ratios, such as superplasticizer-to-binder, fly ash-to-water, and water-to-aggregate, which this study includes to potentially impact carbonation depth. MOEA/D-ANN was used to identify optimal variables, while the RReliefF method selected 13 top features based on weight. Both methods highlighted shared and unique variables, with most inputs represented as weight ratios.

ANN using general data achieved 98% accuracy for carbonation depth prediction, outperforming previous models. By selecting relevant features with MOEA/D-ANN and RReliefF, the model improved prediction performance, reaching an R^2 of 0.99 with fewer input variables.

A sensitivity analysis was performed to assess how input variables affect concrete carbonation depth prediction accuracy. Time, relative humidity, and carbon dioxide concentration were found to have the most significant impact. According to the results in Figures 1 to 3, as these variables (cycle days, relative humidity, and CO_2 concentration) increased, carbonation depth also increased. Notably, the depth rises with CO_2 concentration from 1% to 25%, then stabilizes at nearly constant levels.

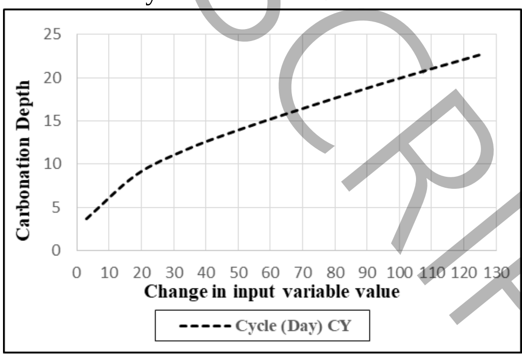

Figure 1. Sensitivity analysis on the input variable cycle (days) (CY)

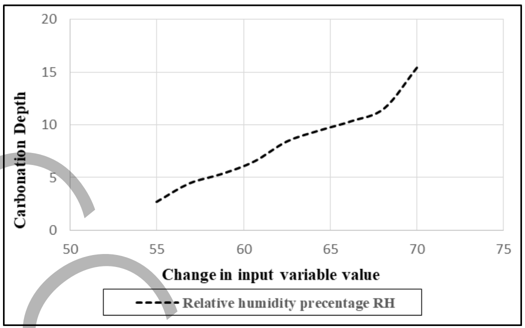

Figure 2. Sensitivity analysis on the input variable relative humidity percentage (RH)

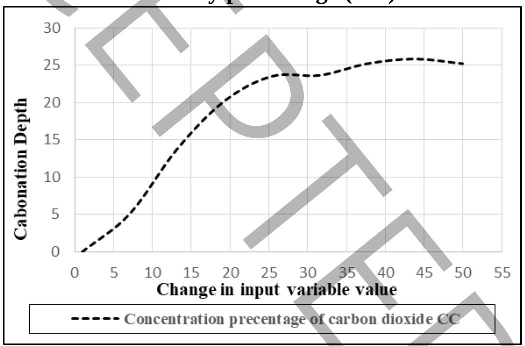

Figure 3. Sensitivity analysis on the input variable carbon dioxide concentration percentage (CC)

4. Conclusions

This study aims to accurately predict concrete carbonation depth, essential for preventing cracks and corrosion. Data from multiple sources led to 198 carbonation depth samples and 37 input variables, with the most significant ones related to concrete mix ratios. A new feature selection method, MOEA/D-ANN, was introduced to improve accuracy and address computational complexity, alongside the conventional RReliefF method. After removing redundant variables, 13 remained, leading to a model with an R^2 value of 0.99, highlighting its high accuracy. The results showed that key variables like cycle, humidity, CO_2 concentration, and mix ratios significantly affect carbonation depth. This model's framework can be extended to other concrete properties and structural failure predictions.

5. References

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