COMPRESSIVE STRENGTH PREDICTION METHOD FOR RECYCLED AGGREGATE CONCRETE BASED ON ARTIFICIAL NEURAL NETWORK

Monika

Research Scholar, Department of Civil Engineering, Bhai Gurdas Institute of Engineering and technology, Sangrur, Punjab, India

Mohit Sharma

Assistant professor, Department of Civil Engineering, Bhai Gurdas Institute of Engineering and technology, Sangrur, Punjab, India

Neeru Singla,

Assistant Professor, IKGPTU, Punjab, India

Ravi Gaba

Assistant Environmental Engineer, Punjab Pollution Control Board, Punjab, India

ABSTRACT:

This paper presents a compressive strength prediction method for Recycled Aggregate Concrete (RAC) using the Artificial Neural Network (ANN). Further, in this research, prediction of the proposed method is enhanced by hyper-tuning the parameters of the ANN algorithm. To accomplish this goal, the metaheuristic Group Learning (GL) algorithm is used. This algorithm searches the best parameter values based on the objective function (OF). In this research, we have designed a multi-objective function by considering the two-error metrics, namely, Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). The simulation evaluation is performed on the standard dataset. The proposed method is tested by splitting the dataset into a 70:30 ratio. Next, the parameters are determined to evaluate the proposed method: RMSE, MAE, Relative Absolute Error (RAE), and coefficient of determination (R^2). The result indicates the proposed method achieves a lower value of MSE and MAE and a higher value of R^2.

Keywords: ANN, Concrete, GLA, Hyper-Tuning, Metaheuristic, Optimization, Prediction, Recycled, Strength.

1. INTRODUCTION

Rapid urbanization has prompted the renewal, repair, and construction of urban public and civil structures, along with municipal structures (Liu et al., 2024). The demolition of buildings generates large amounts of construction waste, with concrete waste comprising a major portion (Munir et al. 2020). Construction and demolition waste are traditionally disposed of in landfills. This covers valuable land resources and has major negative effects on the environment and society. In addition, there is a lack of natural sand and gravel due to the excessive use of concrete brought on by its rapid rate of development. In civil engineering, recycled aggregate concrete (RAC) has become a viable solution to the issues of waste concrete management and the depletion of natural sand and gravel (Yang et al., 2024). RAC is created by crushing, screening, and cleaning the remaining concrete. These aggregates are then substituted for natural aggregates. Additionally, RAC is a combination of several components in appropriate ratios that were obtained via experimental batches. However, recycled aggregate's composition differs significantly from that of regular aggregate, which would impact both the design and production processes (Mai et al. 2023). In case, the batch results are not met, the mix design procedure must be repeated until the desired compressive strength (CS) is reached. Therefore, it is significant to understand the CS of RAC and its procedure. Therefore, in this research, Machine Learning (ML) algorithm is employed for design the compressive strength prediction method for RAC. The main contribution of this research is summarized as follows.

1. The hyperparameter of the ANN algorithm is fine-tuned using the metaheuristic GL algorithm to enhance the prediction of the proposed method.

2. We have designed a multi-objective function by considering the two-error metrics, namely, MSE and MAE.

3. We have achieved a lower error value and a high correlation between the actual and predicted values with the proposed method.

The rest of the paper is as follows. Section 2 shows the related work done in the compressive strength prediction method for recycled aggregate concrete. Section 3 defines the preliminaries required to design the proposed method. Section 4 gives a detailed description of the proposed method for predicting the compressive strength of recycled aggregated concrete. Section 5 shows the simulation results and discussion. Section 6 defines the conclusion.

2. Related Work

Yang et al. (2024) developed an ensemble learning approach based on a compressive strength prediction method for RAC by considering the ANN, Random Forest (RF), Random Tree (RT), and bagging method. Their result shows that the RF outperforms other algorithms and achieves an R^2 value of 0.969, an MAE value of 3.523, an RMSE value of 4.516, and an RAE value of 25.35. Ji et al. (2024) presented BP neural, GA-BPP, and CNN-based compressive strength prediction methods for recycled brick aggregate. The result shows that the CNN outperforms others, achieving an accuracy of 0.969 and 0.927 for the training and testing phases. The authors, Mai et al. (2023), designed an ensemble learning-based approach by considering the various models, namely, AdaBoost, Gradient Boosting (GB), Light GB, Extreme GB, voting, and stacking. The result indicates that they have achieved a 0.95 value of R^2, 2.74 MPa of RMSE, a 2.09 MPa value of MAE, and a 0.10 value of MAPE. Wang et al. (2023) fine-tune the eight ML algorithms using the two swarm intelligence algorithms, namely, Particle Swarm Optimization (PSO) and Grey-Wolf Optimization (GWO), to predict the compressive strength of recycled brick aggregate concrete. The results reveal that GWO-BP outperforms other ML algorithms. Zhou et al. (2024) presented a CS prediction method by considering the three metaheuristic algorithms (GA, PSO, and ABC) and Cascade Forward Neural Network (CSNN). The GA-CSNN approach performs superior to other approaches.

From the previous studies, we found that several machine learning algorithms are employed for concrete strength prediction of RAC. Out of these, Neural Network (NN) is the most preferred algorithm. The performance of the NN algorithm is dependent on the parameter values. As a result, hyper-tuning parameters help prevent overfitting and underfitting by determining the setup. This maximizes the model's prediction performance on unseen data (Payal et al. 2024). By determining the best values, fine-tuning hyperparameters may increase training efficiency as well as speed up convergence.

3. Preliminaries

This section defines the machine learning ANN and metaheuristic GL algorithm employed to design the proposed compressive strength prediction method.

3.1 Artificial Neural Network

ANN is a different type of machine learning algorithm that was developed by drawing inspiration from the nervous system and the human brain. This allowed the learning model to develop exceptional capabilities like distributed networks and parallel processing. The artificial neural network (ANN) is made up of many interconnected neurons that carry out computations at the same time, similar to the biological nervous system. In a neural network, each neuron takes in signals from its neighbors or outside sources, processes them mathematically, and then sends out the result to another neuron. During training, the network acquires the weights, which are the strength of the links between neurons (Ashwathi et al. 2024). By modifying these weights during training, the network will be able to predict outputs with accuracy on the input set. In this research, a metaheuristic GL algorithm is employed to find the best parameter values of weights of the ANN. Metaheuristics are smart optimization methods that guide the search process by using both exploitation and exploration (Salleh et al. 2018). In exploration, the whole search area is explored to find secret places, whereas in exploitation, the search is expanded to include possible neighbourhoods that have previously been visited.

3.2 Group Learning Algorithm (GLA)

As the name suggests, the GLA mimics how managers and group leaders influence the skills of group members (Rahman, C.M., 2023). This algorithm differs from others in that it separates the population into several equal groups. After that, it chooses a few people to lead each group based on their fitness and then determines the manager. The manager is the person with the highest fitness level among all the people. The following are the proposed algorithm's key features:

- The initial population is generated at random.

- The best person is the one who has the greatest level of fitness among all people. This person becomes the manager of all people.

- Several groups are represented by the whole population (four groups were considered in this study).

- The leader of each group is the superior member or the one who is the most suited inside the group.

- Each group leader has an impact on the other members of the group.

- The manager influences other people as well as the group leaders.

- The process of mutation is used to randomly change an individual's structure.

4. Proposed Compressive Strength Prediction Method for Recycled Aggregate Concrete

This section presents the compressive strength prediction method for RAC. The main novelty of the proposed method is that the parameter values of the ANN algorithm are hyper-tuned using the metaheuristic GL algorithm for better prediction. Besides that, we have proposed a multi-objective function by considering the multiple error metrics in the proposed method. The block diagram of the proposed method is shown in Figure 1.
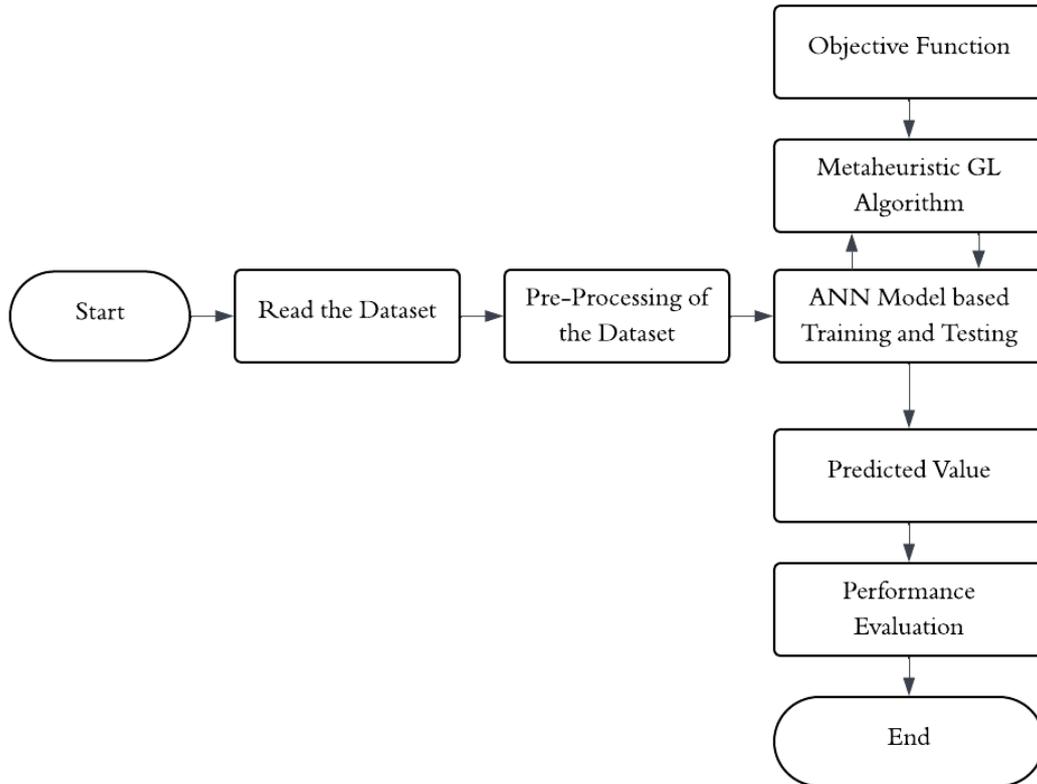

Figure 1. Block Diagram of the Proposed Compressive Strength Prediction Method for RAC

The detailed description of the different steps utilized in the proposed method is given below.

- **Read the Dataset:** In this research, we have collected the secondary database from the literature and employed it in our research (Yang et al. 2024). The database contains 19 attributes of RAC. The first 18 attributes are input types (such as age, cement type, fly ash, slags, silica fume, water/binder, natural and recycled coarse aggregate, and so on), and the 19th attribute is output type, which represents the compressive strength of RAC.

- **Pre-Processing of the Dataset:** In this step, the input and output attributes are determined to train the ANN model. Followed by, the dataset is split into training and testing ratios. In this research, a 70:30 ratio is considered. 70% of the dataset is considered for training purposes, whereas 30% of the dataset is for testing purposes.

- **ANN Model-Based Training and Testing:** In this step, the feed-forward ANN algorithm is employed to train and test the dataset. However, the performance of the ANN algorithm is dependent on the weight parameter that connects the nodes. Therefore, the optimal weight value is determined by utilizing the metaheuristic GL algorithm. The GL algorithm searches for the best weight value by exploring the solution space in the lower and upper bound values of the weight parameter based on the objective function. In this paper, we have developed a multi-objective function by considering the RMSE and MAE, and the value of the objective function is minimized while exploring the best solution. Table 1 shows the steps of the GL algorithm for finding the best weight value of the ANN algorithm.

Table 1. Steps of the GL Algorithm

Input:	Lower and Upper Bound of Weight, GL_{Pop}, $GL_{Iteration}$, Objective Function, $GL_{Manager}$, GL_{Groups}, GL_{Leader},
Output:	Best value of Weight

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1.	Initialize the GL_{Pop} randomly in the LB and UB of the weight.
2.	Evaluate the population and determine the best population which works as $GL_{Manager}$ in the GL algorithm.
3.	Divide the population into groups and find the GL_{Leader}
4.	Explore the solution space population by calculating the impact of managers on leaders, leaders impact on group members, and managers impact on group members.
5.	Step 4 is iterated for fixed number of iterations based on $GL_{Iteration}$ value.
6.	The manager population defines the best value of the weight.

- **Performance Evaluation:** The prediction of the proposed method is compared with respect to the actual value based on the various performance parameters. Table 1 gives the detailed description of these parameters (Yang et al. 2024; Wang, Q., 2024).

Table 1. Performance Parameter

Parameter	Equation	
RMSE	$RMSE = \sqrt{MSE}$	(1)
	$MSE = \frac{\sum_{i=1}^{N}(P_i - A_i)^2}{N}$	(2)
R^2	$R^2 = 1 - \left(\frac{\sum_{i=1}^{N}(P_i - A_i)^2}{\sum_{i=1}^{N}(P_i - \bar{A})^2}\right)$	(3)
RAE	$RAE = \frac{\sum_{i=1}^{N}|P_i - A_i|}{\sum_{i=1}^{N}|A_i - \bar{A}|}$	(4)
MAE	$MAE = \frac{\sum_{i=1}^{N}|P_i - A_i|}{N}$	(5)

In above table, AP denotes the actual and predicted value whereas N represents the total number of samples.

5. SIMULATION RESULTS

This section presents the simulation results of the proposed method and comparative analysis with the previous methods. The proposed method was designed and simulated in MATLAB 2018a software. In the proposed method, the ANN and GL algorithms are initialized for the predict the compressive strength, as shown in Table 2.

Table 2. Initialization of ANN and GL Algorithm

Parameter	Value
ANN	
Network Type	Feed-Forward
Hidden Size	10
GL	
Objective function	(RMSE, MAE)
Population	10
Iteration	40

5.1 Performance Evaluation

This section presents the performance evaluation of the proposed method using the various parameters. Followed by, the evaluation of the metaheuristic GL algorithm using the convergence rate graph.

Table 3 shows the parameters are evaluated for the proposed method which is based on ANN and hybrid combination of ANN and metaheuristic GL algorithm. The result shows that the proposed method achieves lower value of error metrics such as RMSE, MAE, and RAE whereas high value of determination of correlation over ANN algorithm due to finding the best parameter value of the ANN algorithm.

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Table 3. Performance Evaluation of the Proposed method

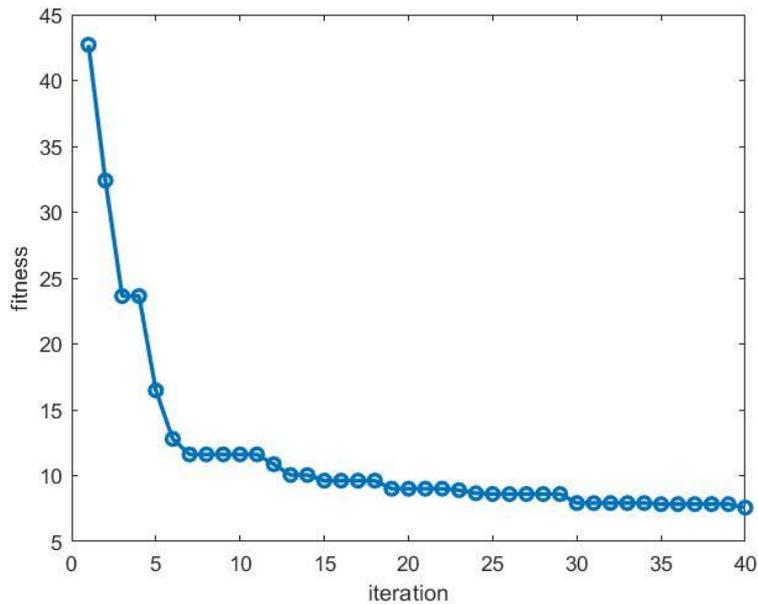| Parameter	RMSE (MPa)	MAE (MPa)	RAE (%)	R^2
ANN	26.384	21.99	1.8432	0.077387
Proposed Method (ANN+GL Algorithm)	2.0978	1.6882	0.14151	0.99155

Figure 2. Convergence Rate Graph for Metaheuristic GL Algorithm

Figure 2 shows the convergence rate graph of the metaheuristic GL algorithm to find the best weight value of the ANN algorithm. The result shows that the GL algorithm achieves the desired objective function in the 30th iteration.

5.2 Comparative Analysis

In this section, the performance of the proposed method is compared with the existing method (Yang et al. 2024). To accomplish this goal, the same dataset is considered and evaluated using four parameters, namely, MAE, RMSE, RAE, and R^2 in Table 4. The result indicates that the proposed method achieves better R^2 and lower values of MAE, RMSE, and RAE. This shows that the proposed method is effective in predicting the strength value of RAC with respect to the actual value due to the fine-tuning of the parameter values.

Table 4. Comparative Analysis

Algorithms	RMSE	MAE	RAE	R^2
ANN (Yang et al. 2024)	5.295	4.028	28.98	0.9568
RF (Yang et al. 2024)	6.879	5.100	36.70	0.9245
Proposed Method	2.0978	1.6882	0.14151	0.99155

6. CONCLUSION

In this research, we have presented a compressive strength prediction method for RAC using the ANN algorithm. Further, the parameter of the ANN algorithm is hyper-tuned using the metaheuristic GL algorithm. Due to this procedure, the simulation results of the proposed method show that the error value between the actual and predicted values is minimal. Further, the comparative analysis indicates that the proposed method outperforms the existing algorithms, namely, ANN and RF (Yang et al. 2024). Despite these encouraging findings, the small number of dataset samples (289) may constrain

the generalizability of our research. Thus, in the future, we will collect a large dataset and explore other algorithms to enhance the performance of the proposed method.

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