International Journal of Researches on Civil Engineering with Artificial Intelligence

www.ceai.reapress.com

Int. J. Res. Civ. Eng. AI. Vol. 3, No. 3 (2026) 167–176.

Paper Type: Original Article

Artificial Neural Network-Based Prediction of the Compressive Strength of Lightweight Concrete Reinforced with Industrial and Recycled Steel Fibers

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Citation:

Received: 10 November 2025 *Revised: 15 February 2026* *Accepted: 22 April 2026*	Mansourkia, A., & Moslemi, M. (2026). Artificial neural network-based prediction of the compressive strength of lightweight concrete reinforced with industrial and recycled steel fibers. *International journal of researches on civil engineering with artificial intelligence, 3*(3), 167-176.

Abstract

The incorporation of industrial waste into concrete has emerged as an effective strategy for improving sustainability while reducing the environmental impacts associated with construction materials. Among these recycled materials, waste steel fibers have shown considerable potential as concrete reinforcement. To ensure their efficient utilization, however, reliable prediction of concrete performance is essential. Since direct measurement of compressive strength is often expensive, time-consuming, or impractical for existing structures, the development of accurate predictive models offers an attractive alternative. This research proposes an artificial intelligence-based approach for estimating the compressive strength of concrete reinforced with recycled steel fibers. An Artificial Neural Network (ANN) trained using the Levenberg–Marquardt algorithm was developed from an experimental database consisting of 45 different concrete mix designs. The input variables included steel fiber content, cement content, water content, water-to-cement ratio, and superplasticizer dosage, while the output parameter was the compressive strength measured at curing ages of 7, 28, and 60 days. For model development, the dataset was divided into training (75%), testing (15%), and validation (15%) subsets. Experimental observations demonstrated that incorporating recycled steel fibers enhanced the compressive strength of concrete, which can be attributed to the effective dispersion of fibers within the cementitious matrix and the use of an appropriate fiber dosage. The developed ANN successfully captured the relationship between mixture proportions and compressive strength, producing highly accurate predictions. The validation results yielded a correlation coefficient exceeding 99%, confirming the robustness, reliability, and predictive capability of the proposed neural network model for estimating the compressive strength of steel fiber-reinforced concrete.

Keywords: Compressive strength, Synthetic neural network, Steel fibers, Concrete.

1 | Introduction

Concrete refers to any material with a product that consists of a sticky substance with the property of cementation. This sticky substance is generally the result of the interaction of hydraulic cements and water.

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https://doi.org/10.48314/ijrceai.v3i3.61

Today, the use of concrete in the field of structural issues is very widely used and one of the important materials in the construction of structures [1]. Among the materials used in the construction of structures, concrete is considered more than other materials because of its suitable applications. Among the advantages of concrete, the use of which is increasing in structures, it can be mentioned its lower price, suitable hardness compared to steel, fire resistance and ease of implementation [2].

Today, the use of concrete with higher strength that can withstand many deformations without failure is being considered. Extensive research is being done on increasing the strength of concrete with different fibers and even removing the reinforcement, so with the results obtained, it can be understood that adding steel fibers to smooth concrete increases its compressive strength and this increase in strength gradually. It is done gradually by adding different volume percentages and types of fibers. Also, by adding steel fibers in concrete, we can achieve a concrete with higher compressive strength, which is more economical, by increasing the number and size of rebars, or special considerations in the field of concrete mixing design [3].

Predicting the mechanical properties of concrete reinforced with steel fibers based on Artificial Neural Network (ANN) models without the need to carry out any laboratory studies will save a lot of money in projects. Unlike classical methods in statistical theories, neural networks do not require any specific model or function along with limiting assumptions to linearize problems [4].

Due to the ever-increasing developments in the construction industry, there is always a need to present new methods. On the other hand, determining concrete resistance parameters in a short time and with acceptable accuracy is one of the challenges facing the construction industry. Advances in computer science in recent years have introduced very practical and fast methods into the field of civil engineering and especially the estimation of concrete resistance parameters. In this research, by studying and examining existing algorithms such as Levenberg algorithm and ANNs, it is possible to train an optimal network that can predict the resistance properties of concrete with minimal error.

2 | Background Research

In 2018 Alton et al. [5] used neural network to estimate lightweight concrete containing steel fibers. For this purpose, cement grade of 35, 400 and 450 kg/m3 was used in the mixing designes. In this research, the effect of different amounts of fibers on lightweight concrete was tested. In their experiment, they used fibers at the rate of 10, 20, 30,40,50,60 kg/m3. 127 cylindrical samples with dimensions of 300*150 mm were made in the laboratory. Their input parameters to the neural network included steel fibers, water, water-cement ratio, sand, gravel and super lubricant. The compressive strength of concrete could be measured in the laboratory by adjusting the laboratory materials. The specific dry weight of sand and gravel was measured in the laboratory as 1.15 and 0.92 kg/cm3, respectively. The fibers used in this experiment had a diameter of 0.75 mm and a length of 60 mm and a tensile strength of 1050 N/mm2. The results show that the neural network provides a suitable estimate of the data. Neural network can provide more appropriate estimation of data even in case of better training. In this research, due to the high correlation coefficient and the variety in the selection of different parameters, it can be expected that the neural network has more variety in solving different problems than the complex statistical methods [5].

To estimate the compressive strength of concrete containing steel fibers used the ANN method in 2015 was another research that was done in this field. Based on the information they had, they designed their neural network based on the lowest error rate or MSE and the highest correlation coefficient or R. The results of their research show that the use of the neural network with the Gauss-Newton algorithm has performed well in this research with a slight difference, and the obtained predictions have a very good correlation with the real data [6].

In another research in 2019, Hameed and AlOmar [7] studied “Prediction of compressive strength of high-performance concrete: hybrid artificial intelligence technique”. In the last decade, various methods were used to predict the behavior of concrete. Meanwhile, the use of neural network has the lowest cost and the most efficiency. It was shown that the use of neural network has a small error. And after many tests, it was found that the results of the laboratory are in good agreement with the results of the neural network [7].

The sensitivity of constituent materials and density of concrete as network inputs and the compressive strength of concrete as the test target or output is study by Erdel [8]. The neural network predicts and measures the 28-day compressive strength of concrete. In his research, Erdal [8] made the mean square of the error as the evaluation criterion of the network in such a way that the least amount of error indicates the proper performance of the network. In this research, the results show that the ANN measures the data with high accuracy and low error [8].

In 2020 Nagarajan et al. [9] study on a comparative prediction models for strength properties of LWA concrete using ANN. In this study, ANN model is constructed to predict the compressive strength, split tensile strength and flexural strength of lightweight aggregate concrete made of sintered fly ash aggregate. An empirical relationship between the compressive strength, split tensile strength, and flexural strength was developed and compared with that of experimental results. The models were formulated based on results obtained from laboratory experiments. The variables considered in the study are the quantity of cement and water-cement ratio. Feed forward neural network and Levenberg-Marquardt back propagation algorithm were used for training algorithm in ANN. Amongst the total data, approximately 70% of the data was considered for training, 15% for testing and the remaining 15% has been considered for validation. The developed models had more accuracy with minimum error and had a higher correlation with the correlation coefficients of 0.916 and 0.955 were obtained for the training and testing data of compressive strength prediction, 0.949 and 0.937 respectively for split tensile strength prediction, 0.926 and 0.928 respectively for prediction of flexural strength. The models were compared with the experimental data's, and the results were discussed [9].

According to the research of others, the use of neural network regarding the estimation of compressive strength of concrete containing waste steel fibers has not been done so far. For this purpose, in this research, the construction of concrete with waste steel fibers and the estimation of compressive strength were investigated by using neural network.

3 | Design of Neural Network

The use of neural networks to model the mechanical properties of each type of concrete can produce very appropriate and accurate results, and by using neural networks to predict concrete strength only once using the modeled laboratory results and achieve instant and accurate resistance prediction [10–12]. It is done properly and reduces many concrete sampling costs. It is very beneficial to use these models to further investigate the effective parameters on all types of concrete. The use of more characteristics of aggregates, the type of cement used and the conditions of making the samples, among other input parameters, makes the prediction of resistance more accurate. In this research, to predict the compressive strength of concrete made with polymer fibers, perceptron model ANNs and its combination with particle mass algorithm (to optimize the percentage of fiber consumption) have been used [13], [14]. Particle swarm optimization algorithm has been introduced with other names such as particle swarm algorithm and bird algorithm. The schematic diagram of how to use the neural network is shown in *Fig. 1*.

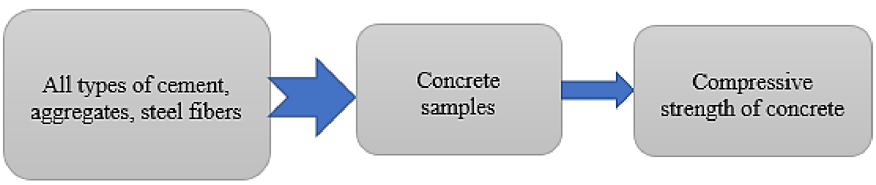

Fig. 1. The scheme of using ANN in mixing designes.

4 | The Method of Using Artificial Neural Network of Multilayer Perceptron

The number of neurons in the input layer is 11 neurons, after which 11 inputs will be induced into the network, and the output includes one neuron, which is the compressive strength of reinforced concrete with steel fibers and waste fiber. The *Fig. 2* shows the method of working with a Multilayer Perceptron (MLP) ANN.

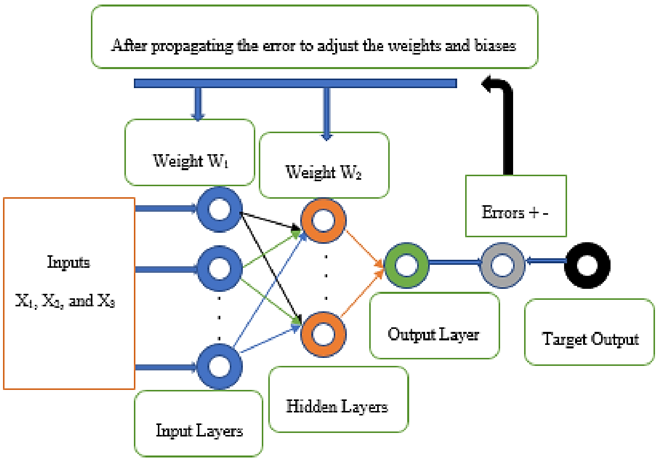

Fig. 2. The method of working with a MLP ANN.

To separate test data and training data randomly by the program, so that 75% of the data is used for the training process, 15% of the data is used for testing, and 15% is used for validation. Was taken the input layer receives the input data and sends it to the hidden layer neurons (10 neurons).

5 | Data Used in Neural Network

In order to predict the compressive strength of concrete mixed with different amounts of water, the amount of steel fibers, water, the amount of coarse grain, the amount of fine grain, the amount of cement and also the age of concrete were considered in *Table 1* and the compressive strength of their concrete was also estimated.

Table 1. Data used in neural network.

Mixing Number	Cement (kg/m3)	Steel fibers (kg/m3)	Water (kg/m3)	Gravel (kg/m3)	Sand (kg/m3)	Super Lubricant (kg/m3)
1	350	0	105	1180	850	1.24
2	332.5	17.5	105	1150	850	1.95
3	315	35	105	1150	850	2.52
4	297.5	52.5	105	1150	850	2.87
5	280	70	105	1150	850	3.1
6	350	0	140	1100	820	1.05
7	332.5	17.5	140	1100	820	1.17
8	315	35	140	1100	820	1.75
9	297.5	52.5	140	1100	820	2.34
10	280	70	140	1100	820	2.8
11	350	0	175	1015	810	0
12	332.5	17.5	175	1015	810	0.24
13	315	35	175	1015	810	0.48
14	297.5	52.5	175	1015	810	0.84

Table 1. Continued.

Mixing Number	Cement (kg/m3)	Steel fibers (kg/m3)	Water (kg/m3)	Gravel (kg/m3)	Sand (kg/m3)	Super Lubricant (kg/m3)
15	280	70	175	1015	810	2.04
16	400	0	120	1100	850	1.82
17	380	20	120	1080	850	2.64
18	360	40	120	1080	850	3.68
19	340	60	120	1080	850	4.02
20	320	80	120	1080	850	5.29
21	400	0	160	1000	830	0.7
22	380	20	160	1000	820	0.88
23	360	40	160	1000	820	1.06
24	340	60	160	1000	820	1.89
25	320	80	160	1000	820	2.25
26	340	80	0	980	750	2.25
27	320	0	20	980	750	0.24
28	400	20	20	980	750	0.24
29	380	40	40	980	750	0.6
30	360	60	60	980	750	0.96
31	340	80	80	980	750	1.33
32	320	0	0	1050	800	2.54
33	450	22	22.5	1050	800	6.36
34	427.5	45	45	1050	800	13.89
35	405	67.5	67.5	1050	800	16.21
36	382.5	90	90	1050	800	23.74
37	360	0	0	950	800	0.71
38	428.5	22.5	22.5	920	800	1.2
39	405	45	45	920	800	1.2
40	385	67	67.5	920	800	1.8
41	362	90	0	900	800	2.4
42	452	0	22.5	900	700	00
43	425	22.5	45	900	700	00
44	410	45	67.5	900	700	0.06
45	352	67	90	900	700	0.55

The input information for training the neural network is the data of each of the mixing designs and the target data of compressive strength of concrete samples at the ages of 7, 28 and 60 days are considered, in total 135 data are considered as targets.

6 | The Structure of the Neural Network

The training of this neural network has been done with the help of Levenberg algorithm and using MATLAB software. In the structure of this network, 75% of the data is randomly considered as training data, 15% as target data and 15% of data as validation. As shown in the *Fig. 3*, the constructed neural network is stopped after 5 times of training and this point is considered as the best point to stop the training. The *Fig. 3* shows the degree of correlation in each of the stages of training, evaluation and testing for the selected neural network.

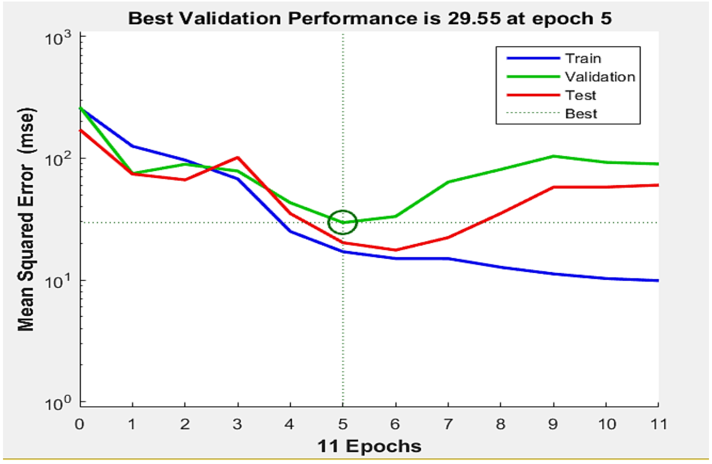

Fig. 3. The stopping point of the training in the desired neural network.

Fig. 4 shows the correlation between laboratory data and neural network regarding the data of training, evaluation and compressive resistance test in neural network.

The neural network built in this research has 10 hidden layers, 6 input layers, and 3 output layers, and the training results of this network are the final output layer. The desired neural network is trained with Levenberg algorithm.

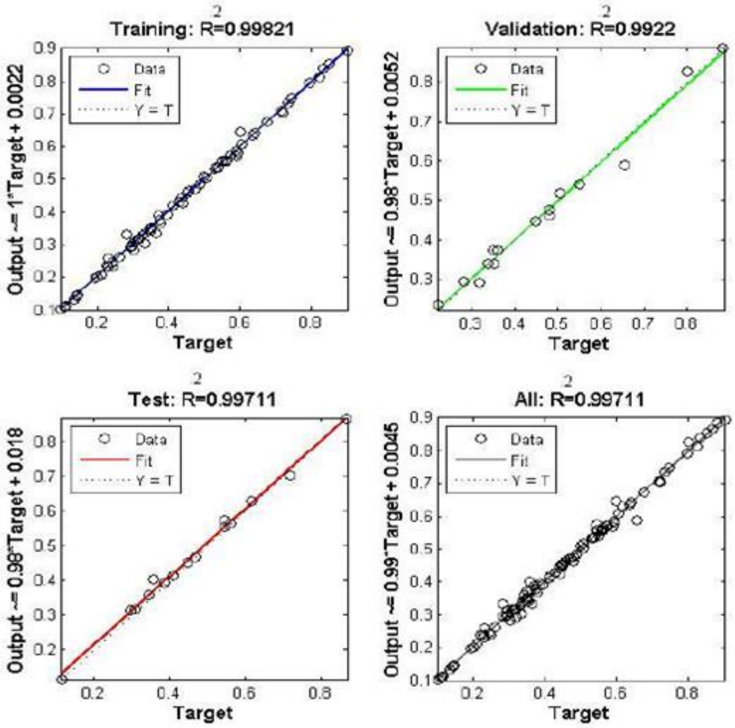

Fig. 4. Linear relationship between measured and estimated values of compressive strength using Lorenberg's algorithm.

Correlation of training, testing and validation data shows that these data are correlated with each other with correlation coefficients of 0.99, 0.99 and 0.99%, respectively, and it shows that the well-designed neural network has the ability to predict the desired outputs.

7 | Comparison of Designed Neural Network Results and Laboratory Results in Predicting Compressive Strength

The results of the 7-day compressive strength estimated with the help of the neural network constructed with the results of the laboratory compressive strength are shown in *Fig. 5*.

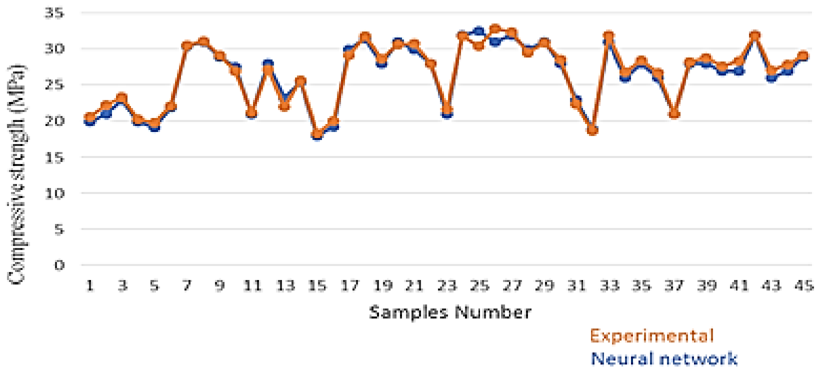

Fig. 5. Comparison of predicted values and experimental values 7-day compressive strength.

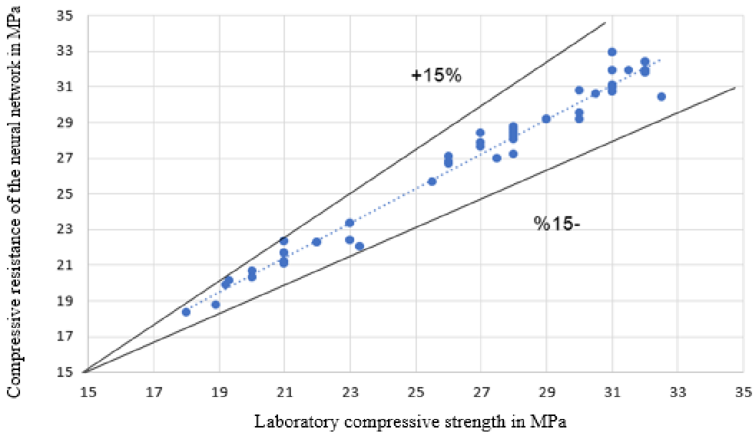

Fig. 6. Comparison between predicted values and experimental values of 7-day compressive strength.

As shown in *Figs. 5* and *6*, the 7-day compressive strength estimated by ANN is very close to the compressive strength obtained in the laboratory.

The results of the 28-day compressive strength estimated with the help of the neural network built with the results of the laboratory compressive strength are given in *Fig. 7*.

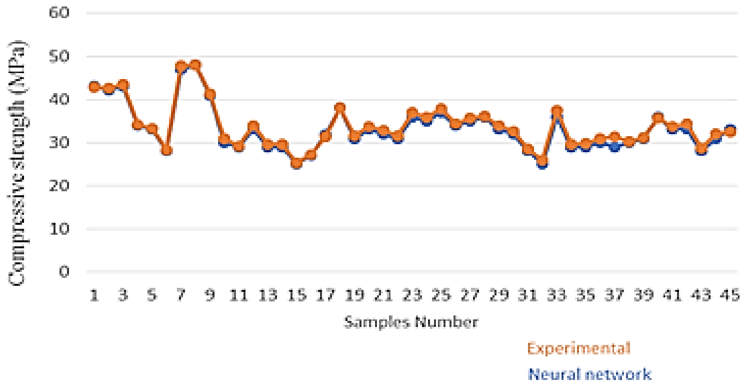

Fig. 7. Comparison of predicted values and experimental values 28- day compressive strength.

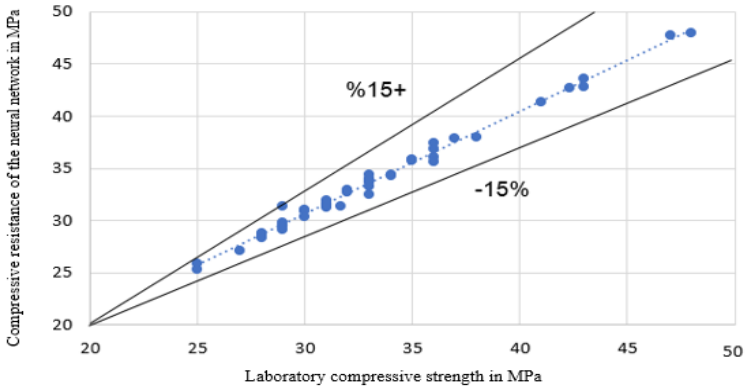

Fig. 8. Comparison between predicted values and experimental values of 28-day compressive strength.

As shown in *Figs. 7* and *8*, the 28- day compressive strength estimated with the ANN is very close to the compressive strength obtained in the laboratory.

The results of the 60- day compressive strength estimated with the neural network built with the results of the laboratory compressive strength are given in *Fig. 9*.

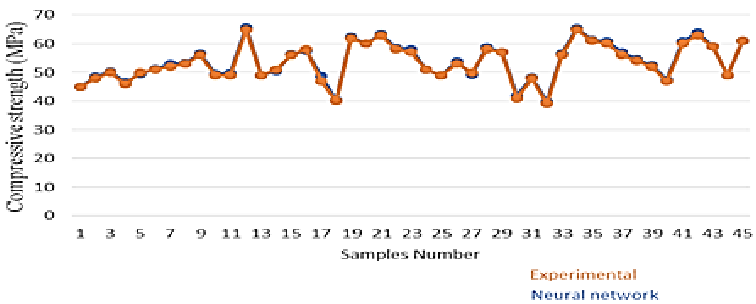

Fig. 9. Comparison of predicted values and experimental values 60-day compressive strength.

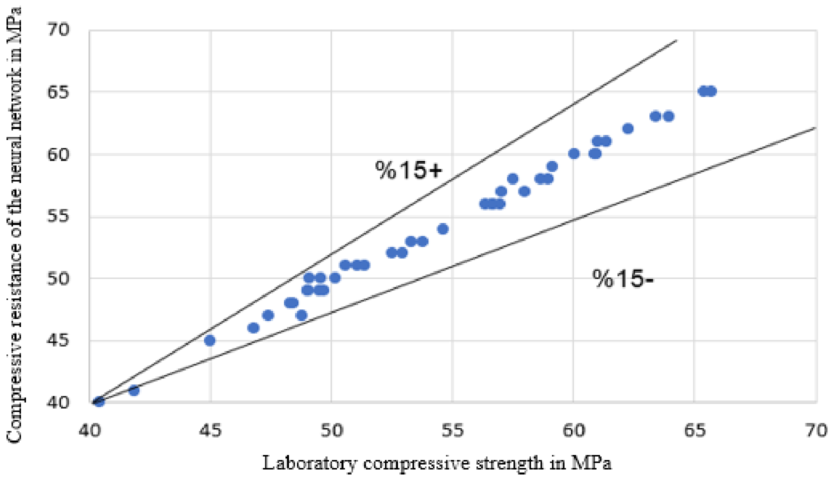

Fig. 10. Comparison between predicted values and experimental values of 60-day compressive strength.

As shown in *Figs. 9* and *10*, the 60-day compressive strength estimated with the ANN is very close to the compressive strength obtained in the laboratory.

8 | Conclusion

The results shows that the ANN has the ability to estimate the compressive strength of concrete at different ages.

The use of steel fibers in reinforced concrete increases the compressive strength of the samples, and this increase in strength has been done gradually. Also, the increase in compressive strength resulting from this increase in the percentage of fibers can be considered due to the proper placement of fibers and their uniform distribution in the cement matrix, or in other words, the optimal amount of desired fibers in the concrete itself.

The compressive strength ANN model was trained by using the Levenberg algorithm, with ten neurons in hidden layers, revealing great prediction performance. The predicted values were fairly close to the experimental results for both the training and testing data sets in the proposed model. The compressive strengths predicted by the neural network have shown a correlation of about 99% for the test data, which indicates the proper performance of the neural network in data analysis.

Predicting the mechanical properties of concrete reinforced with steel fibers based on ANN models without the need to perform any laboratory studies can save a lot of costs in projects.

Unlike the classic methods in statistical theories, neural networks do not need any specific model or function along with limiting assumptions to linearize the problem.

Author Contributaion

F. N.; initiated the idea, designed the study, conducted a brief literature survey, scrutinized the literature, participated in sequence alignment, and prepared a draft copy of the manuscript. A. M.; collected the data, scrutinized the literature, categorized them according to the sequence, participated in sequence alignment, and designed the graphics and illustrations. All authors read and approved the final manuscript.

Funding

This research study was not supported by any external funding sources. All expenses related to the study were covered by the authors.

The authors guarantee that the contribution is original (and has not been published previously), and is not under consideration for publication elsewhere.

Data Availability

Not applicable. However, if any literature data is required, first author would provide them.

Conflicts of Interest

We would like to declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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