Prediction of 28-day compressive strength of concrete on the third day using artificial neural networks

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Abstract

In recent decades, artificial neural networks are known as intelligent methods for modeling of behavior of physical phenomena. In this paper, implementation of an artificial neural network has been developed for prediction of compressive strength of concrete. A MISO (Multi Input Single Output) adaptive system has been introduced which can model the proposed phenomenon. The data has been collected by experimenting on concrete samples and then the neural network has been trained using these data. From among 432 specimens, 300 data sample has been used for train, 66 data sample for validation and 66 data sample for the final test of the network. The 3-day strength parameter of concrete in the introduced structure also has been used as an important index for predicting the 28-day strength of the concrete. The simulations in this paper are based on real data obtained from concrete samples which indicate the validity of the proposed tool.

Keywords: Concrete, Strength, Prediction, Artificial, Neural Networks.

1. INTRODUCTION

Different sciences are developing fast in today's world. In recent decades, man has seen increased relationship of sciences in different fields and the more relationship has led to the appearance of the more new knowledge and technology. Nowadays, one of the most important problems of man are technical and engineering problems. The complexity of the most of the problems in this field has made the experts of this field use the new mathematical and modeling methods for solving this type of problems. Intelligent systems can be used as suitable tools for identifying complex systems, due to their ability of learning and adaptation.

One of the complex problems in our world is the problem of the concrete. The main criterion for evaluating the compressive strength of concrete is the strength of the concrete on 28^{th} day. The concrete sample is tested after 28 days and the result of this test is considered as a criterion for quality and rigidity of that concrete.

Concrete is the most widely used structural material in constructions in the world. Massive concreting in huge civil projects like dams, power plants, bridges and etc… usually is not practicable and it is necessary to be performed in several layers and the compressive strength of each layer should not be less than the specified compressive strength. Therefore one should wait 28 days to achieve 28-day strength of each layer of concrete. Thereupon if we have n layers of concrete we need $28 \times n$ days to complete the total project. [1]

2. CONCRETE

Concrete is the only major building material that can be delivered to the job site in a plastic state. This unique quality makes concrete desirable as a building material because it can be molded to virtually any form or shape. Concrete provides a wide latitude in surface textures and colors and can be used to construct a wide variety of structures, such as highways and streets, bridges, dams, large buildings, airport runways, irrigation structures, breakwaters, piers and docks, sidewalks, silos and farm buildings, homes, and even barges and ships.

The two major components of concrete are a cement paste and inert materials. The cement paste consists of Portland cement, water, and some air either in the form of naturally entrapped air voids or minute, intentionally entrained air bubbles. The inert materials are usually composed of fine aggregate, which is a material such as sand, and coarse aggregate, which is a material such as gravel, crushed stone, or slag.

When Portland cement is mixed with water, the compounds of the cement react to form a cementing medium. In properly mixed concrete, each particle of sand and coarse aggregate is completely surrounded and coated by this paste, and all spaces between the particles are filled with it. As the cement paste sets and hardens, it binds the aggregates into a solid mass.

Under normal conditions, concrete grows stronger as it grows older. The chemical reactions between cement and water that cause the paste to harden and bind the aggregates together require time. The reactions take place very rapidly at first and then more slowly over a long period of time. [2]

3. CEMENT

Cement is a material that has adhesive and cohesive properties enabling it to bond mineral fragments into a solid mass. Cement consists of silicates and aluminates of lime made from limestone and clay (or shale) which is ground, blended, fused in a kiln and crushed to a powder. Cement chemically combines with water (hydration) to form a hardened mass. The usual hydraulic cement is known as Portland cement because of its resemblance when hardened to Portland stone found near Dorset, England. The name was originated in a patent obtained by Joseph Aspdin of Leeds, England in 1824.

Typical Portland cements are mixtures of tricalcium silicate ($3CaO \cdot SiO2$), tricalcium aluminate ($3CaO \cdot Al2O3$), and dicalcium silicate ($2CaO \cdot SiO2$), in varying proportions, together with small amounts of magnesium and iron compounds. Gypsum is often added to slow the hardening process. [2,3]

4. WATER

The water has two roles in concrete mixture: First is the chemical composition with cement and perform cement hydration and second is to make the concrete composition fluent and workable. The water which is used to make the concrete is drink water. The impurity of water can have undesirable effect on concrete strength. [4]

5. AGGREGATES

Since aggregate usually occupies about 75% of the total volume of concrete, its properties have a definite influence on behavior of hardened concrete. Not only does the strength of the aggregate affect the strength of the concrete, its properties also greatly affect durability (resistance to deterioration under freeze-thaw cycles). Since aggregate is less expensive than cement it is logical to try to use the largest percentage feasible. Hence aggregates are usually graded by size and a proper mix has specified percentages of both fine and coarse aggregates. Fine aggregate (sand) is any material passing through a No. 4 sieve. Coarse aggregate (gravel) is any material of larger size.

Fine aggregate provides the fineness and cohesion of concrete. It is important that fine aggregate should not contain clay or any chemical pollution. Also, fine aggregate has the role of space filling between coarse aggregates. Coarse aggregate includes: fine gravel, gravel and coarse gravel

In fact coarse aggregate comprises the strongest part of the concrete. It also has reverse effect on the concrete fineness. The more coarse aggregate, the higher is the density and the lower is the fineness. [3,5]

6. COMPRESSIVE STRENGTH OF CONCRETE

The strength of concrete is controlled by the proportioning of cement, coarse and fine aggregates, water, and various admixtures. The ratio of the water to cement is the chief factor for determining concrete strength as shown in figure1. The lower the water-cement ratio, the higher is the compressive strength. A certain minimum amount of water is necessary for the proper chemical action in the hardening of concrete; extra water increases the workability (how easily the concrete will flow) but reduces strength. A measure of the workability is obtained by a slump test.

Actual strength of concrete in place in the structure is also greatly affected by quality control procedures for placement and inspection. The strength of concrete is denoted in the United States by f'_c which is the compressive strength of test cylinder 6 in. in diameter by 12 in. high measured on the 28th day after they are made. [3]

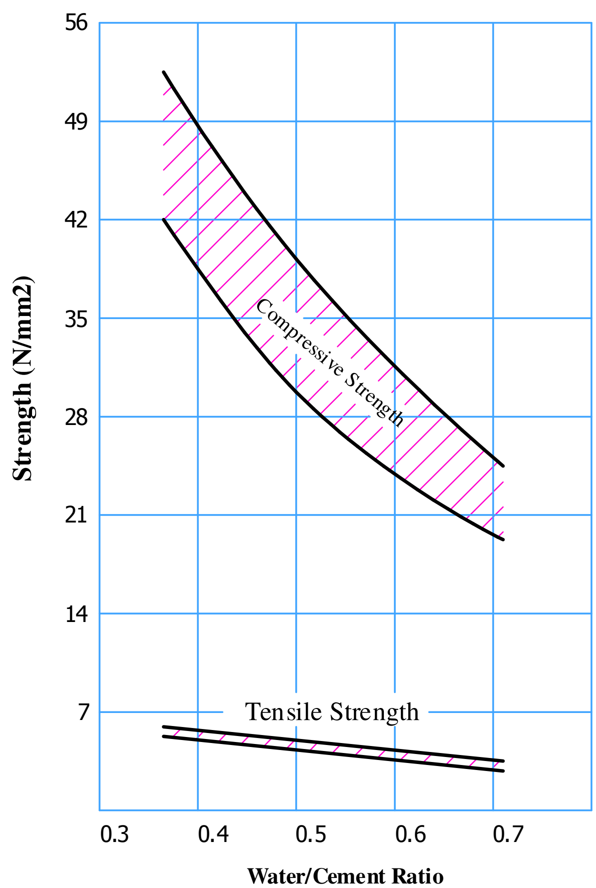

FIGURE 1: illustration of the effect of water/cement ratio in concrete strength [1]

7. CONCRETE SAMPLING

Acceptance of the concrete in the site is performed based on the results of the compressive tests of concrete samples. The concrete samples must be taken from the final consumption place.
The purpose of the concrete sampling is to prepare two specimens of concrete which their compressive tests will be performed after 28 days or in any predetermined day. To predict the 28-day compressive strength of concrete we can also have another sample to be tested earlier than 28 days. [1]

8. CONCRETE MIX DESIGN

The concrete mix design is a process of selecting the suitable ingredients of concrete and determining their most optimum proportion which would produce, as economically as possible, concrete that satisfies a certain compressive strength and desired workability. [6]
The concrete mix design is based on the principles of

- Workability
- Desired strength and durability of hardened concrete
- Conditions in site, which helps in deciding workability, strength and durability requirements

9. ADAPTIVE SYSTEMS

Adaptability, in essence, is the ability to react in sympathy with disturbances to the environment. A system that exhibits adaptability is said to be adaptive. Biological systems are adaptive systems; animals, for example, can adapt to changes in their environment through a learning process [7]. A generic adaptive system employed in engineering is shown in Figure 2. It consists of

- set of adjustable parameters (weights) within some filter structure;
- An error calculation block (the difference between the desired response and the output of the filter structure);
- A control (learning) algorithm for the adaptation of the weights.

The type of learning represented in Figure 2 is so-called supervised learning, since the learning is directed by the desired response of the system. Here, the goal is to adjust iteratively the free parameters (weights) of the adaptive system so as to minimize a prescribed cost function in some predetermined sense. [8]

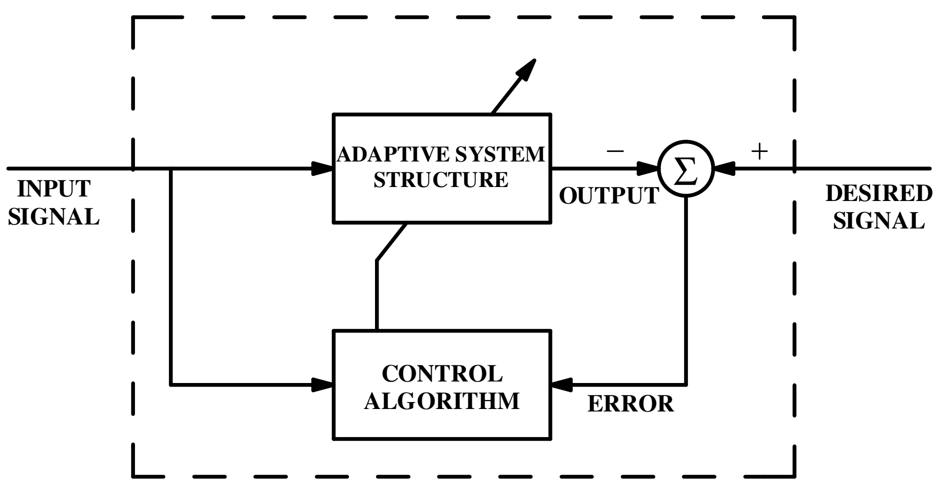

FIGURE 2: Block diagram of an adaptive system

10. ARTIFICIAL NEURAL NETWORKS

Artificial Neural Network (ANN) models have been extensively studied with the aim of achieving human-like performance, especially in the field of pattern recognition and system identification. These networks are composed of a number of nonlinear computational elements which operate in parallel and are arranged in a manner reminiscent of biological neural inter-connections.
The property that is of primary significance for a neural network is the ability of the network to learn from its environment, and to improve its performance through learning. The improvement in performance takes place over time in accordance with some prescribed measure. A neural network learns about its environment through an interactive process of adjustments applied its synaptic weights and bias levels. Ideally, the network becomes more knowledgeable about its environment after each iteration of the learning process. [7]

11. CONCRETE STRENGTH PREDICTION

To predict 28-day strength of concrete, It should identify the effective parameters of the concrete strength. The more accurately identified the parameters, the better is the result.
The studies in this paper were performed in two phases:

1. Phase one, includes the studies about the concrete and effective factors of the concrete compressive strength and also performing the experiments in the real environment and collecting data.
2. Phase two, include studies about how to use artificial neural networks to identify the presented system and to achieve accurate prediction of concrete 28-day compressive strength. [1]

12. PERFORMING EXPERIMENTS

In this study the ACI method is used to perform experiments. Experiments were performed in Aghchay dam in west Azerbaijan in IRAN. The cement used in the experiments was provided from Sofiyan cement plant and the aggregates were provided from the natural materials of the Aghchay dam site. [1]

13. COLLECTING DATA

There are lots of Parameters affect on compressive strength of concrete. But the most important parameters were collected in table 1. It is important that the range of each parameter is limited due to regarding ACI standard.

TABLE 1: Effective parameters of the compressive strength of the concrete

Row	Parameter	Unit	Range
1	Mix Design	-	A-L
2	Water/Cement Ratio	%	35.0 - 75.0
3	Density	ton/m3	2.30 - 2.60
4	Slump	mm	70 - 150
5	Air	%	1.0 - 7.0
6	Silica fumes	gr	0 - 400
7	Super-Plasticizer	kg	0.0 - 3.5
8	Age	day	3, 7, 14, 28, 42
9	Compressive Strength	kg/cm2	70.00 - 420.00

The concrete mix design is affected by these factors:
Cement, Fine aggregate, Fine gravel, gravel, coarse gravel, air

The 1st to 7th parameters are determined in the first day. There is a salient point about 8th parameter (age). As previously mentioned, the concrete age has a direct arithmetic relation with the concrete strength. The more aged the concrete the higher is the compressive strength. [1]

Here is an interesting point so that the 3-day compressive strength of concrete has a mathematical relation with the compressive strength of the same concrete in 7th, 14th, 28th and 42th day. Therefore it can be used as an important parameter for prediction of this system. In other words, the 3-day compressive strength of concrete is a very good criterion to achieve the 28-day compressive strength.

It is conceived from figure.3 that the higher the 3-day compressive strength the higher is the 28-day compressive strength of the concrete. Figure.4 shows the relationship between 3-day compressive strength and 28-day compressive strength for 4 types of concrete with variable w/c ratios, this relation is linear relatively.

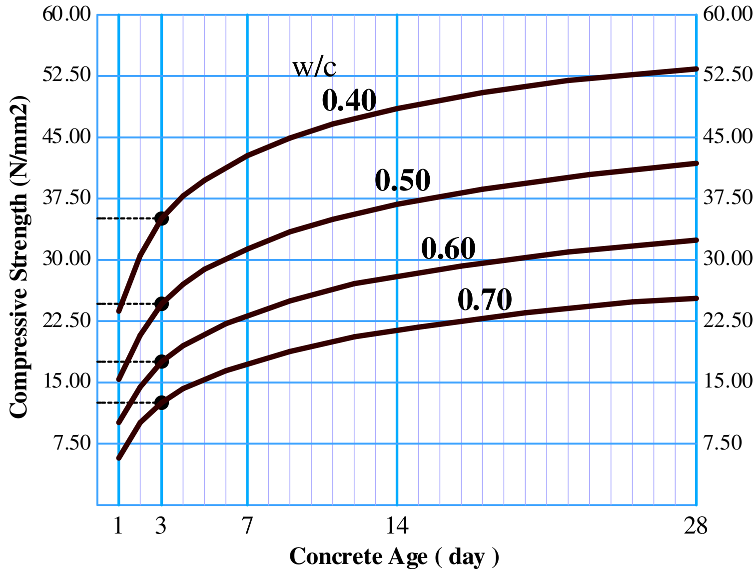

FIGURE 3: illustration of relationship between age and compressive strength of concrete [1]

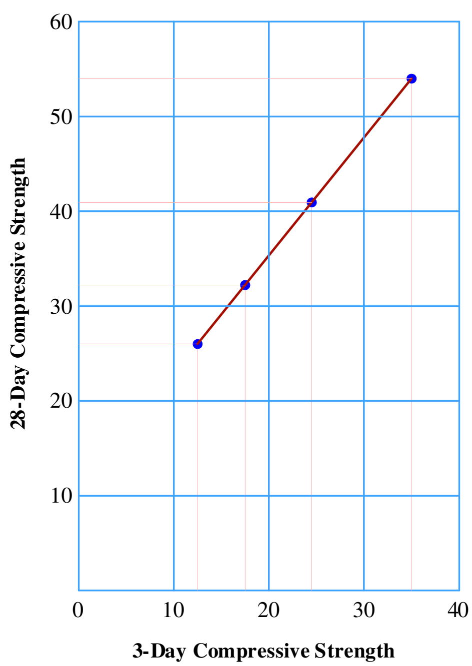

FIGURE 4: illustration of relationship between 3-day and 28-day strength of concrete [1]

14. METHODOLOGY OF CONCRETE STRENGTH NEURAL IDENTIFICATION

A methodology for concrete strength neural identification was developed. It is shown schematically in Figure 5. Three blocks can be distinguished in the scheme. Experimental results, forming a set of data on concrete, used for training and testing the neural network are an integral part of block1.

The experimental results as a set of patterns were saved in a computer file which was then used as the input data for the network in block 2. The data were divided into data for training and testing the neural network. The training patterns were randomly input into the network as following:

1. 70% of total data for training of the neural network
2. 15% of total data for validation of the neural network
3. 15% of total data for testing of the neural network,

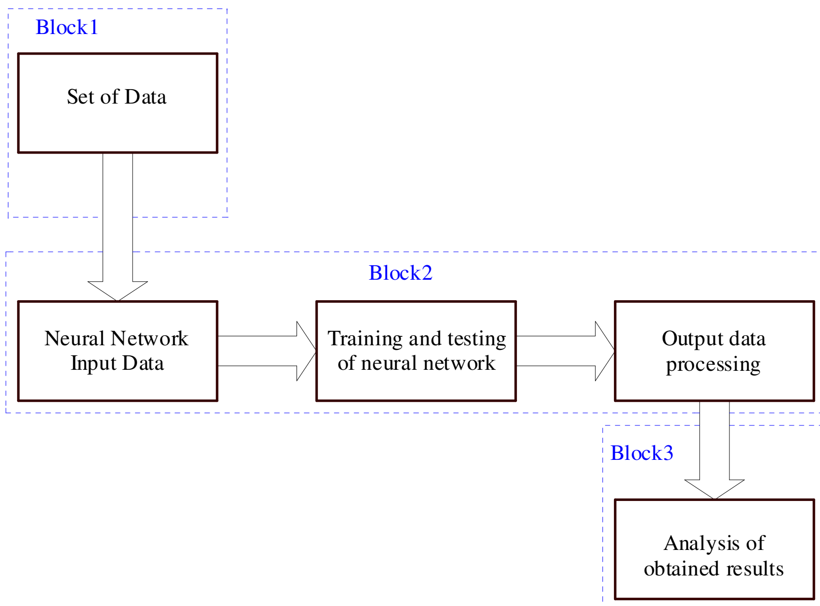

FIGURE 5: Block diagram of concrete compressive strength identification by means of neural networks [9]

If the neural network correctly mapped the training data and correctly identified the testing data, it was considered trained. The obtained results were analyzed in block 3 whose output was identified concrete compressive strength f'_c. [9]

15. FEED-FORWARD NEURAL NETWORK

The Feed-forward neural network structure for prediction of concrete compressive strength is shown in Figure 6. Feed-forward networks often have one or more hidden layers of sigmoid neurons followed by an output layer of linear neurons. Multiple layers of neurons with nonlinear transfer function allow the network to learn nonlinear and linear relationships between inputs and outputs. [10]

The process of learning with teacher in this network is executed through a back-propagation algorithm so that the network output converges to the desired output. The key distinguishing characteristic of this feed-forward neural network with the back-propagation learning algorithm is that it forms a nonlinear mapping from a set of input stimuli to a set of output using features extracted from the input patterns. The network can be designed and trained to accomplish a wide variety of nonlinear mappings, some of which are very complex. This is because the neural units in the neural network learn to respond to features found in the input. [11]

The number of input and output units is determined by dimensions of the data set whereas the number of hidden layer (M) is a free parameter which is adjusted to achieve the maximum performance. Note that, M determines the degree of freedom of the system. Therefore we expect that there was an optimum value for M. The criterion to achieve the optimum M is defined as: "The smallest M which causes minimum mse while the maximum error is small"

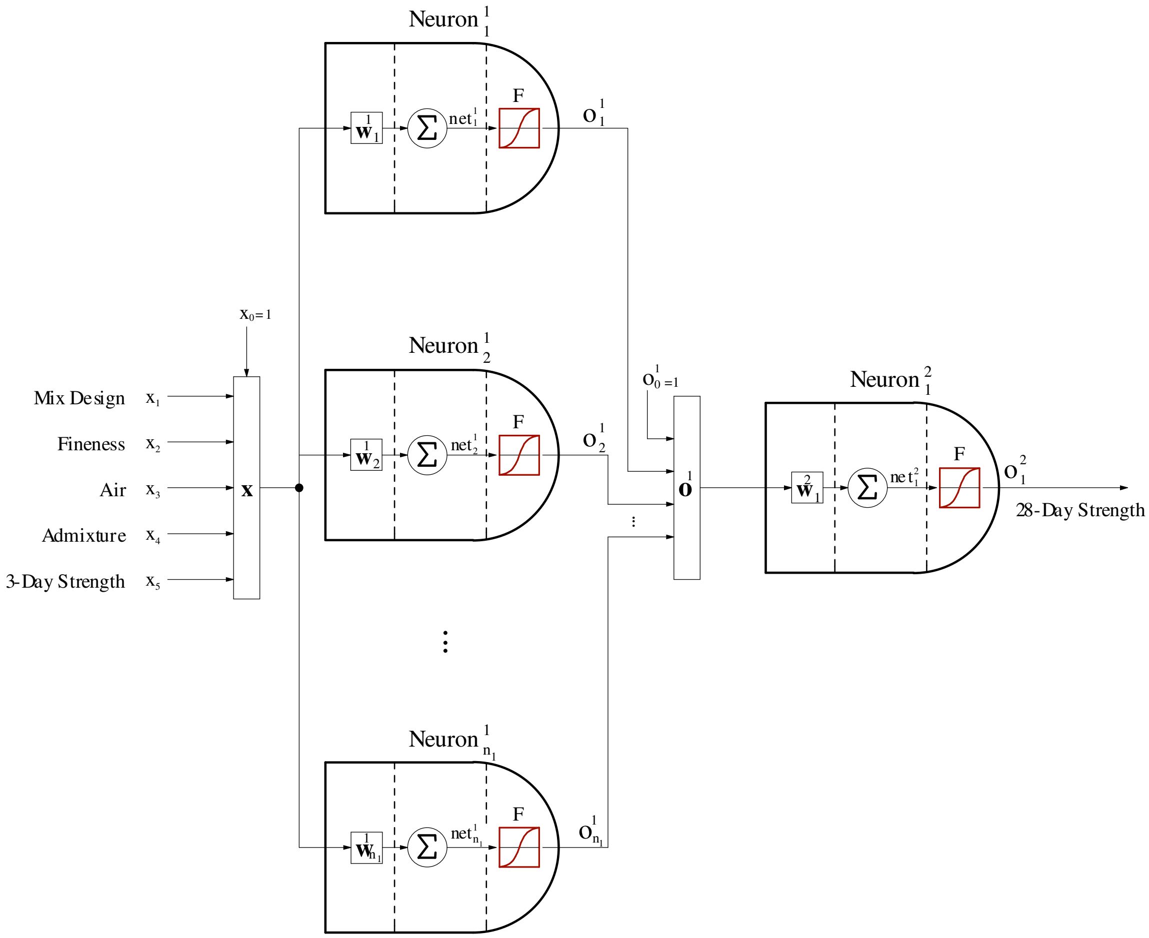

FIGURE 6: Diagram of the feed-forward neural network used for concrete compressive strength prediction

Figure.7 shows the mean squared error of the network output for validation and test data with 10 iterations for each number of hidden neurons. Figure.8 shows the maximum error between desired outputs and the network outputs with 10 iterations for each number of hidden neurons.
The optimum value in this structure is to choose *M=11* for the number of hidden neurons.
In order to backpropagage the error and update the network weights, Gradient-Descent, Quasi-Newton, Conjugate-Gradient and Levenberg-Marquardt Algorithms were used.

- Gradient Descent $W(k+1) = W(k) - \alpha_\kappa g_k$
- Quasi Newton $W(k+1) = W(k) - H_K^{-1} g_K$
- Conjugate Gradient $W(k+1) = W(k) - g_{k+1} + \alpha_\kappa \Delta W_\kappa$

Where *W* is the weight matrix, *α* is the learning rate, *g* is the gradient of error and *H* is the hessian matrix of the cost function. [12]
The levenberg-marquardt algorithm is like quasi-newton but it doesn't need to calculate hessian matrix where it can be estimated as follows:

$$H = J^T J \quad , \quad \nabla E = J^T e$$

$$W(k+1) = W(k) - [H + \mu I]^{-1} . \nabla E$$

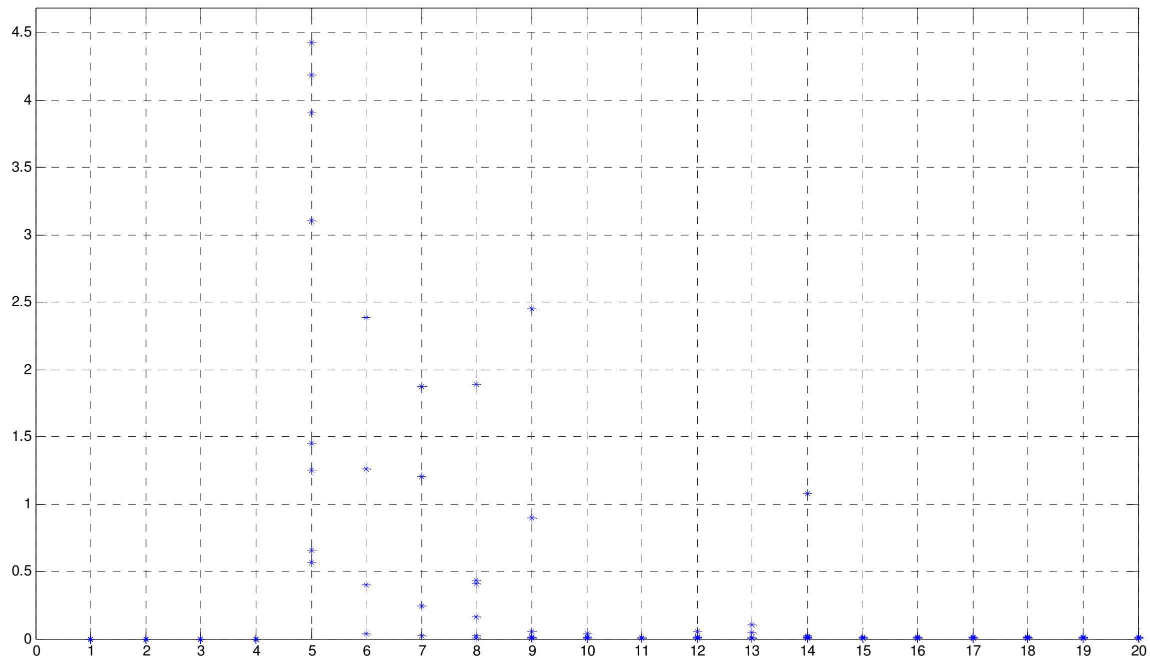

FIGURE 7: Diagram of mean squared error of the network output with 10 iterations for certain number of neurons

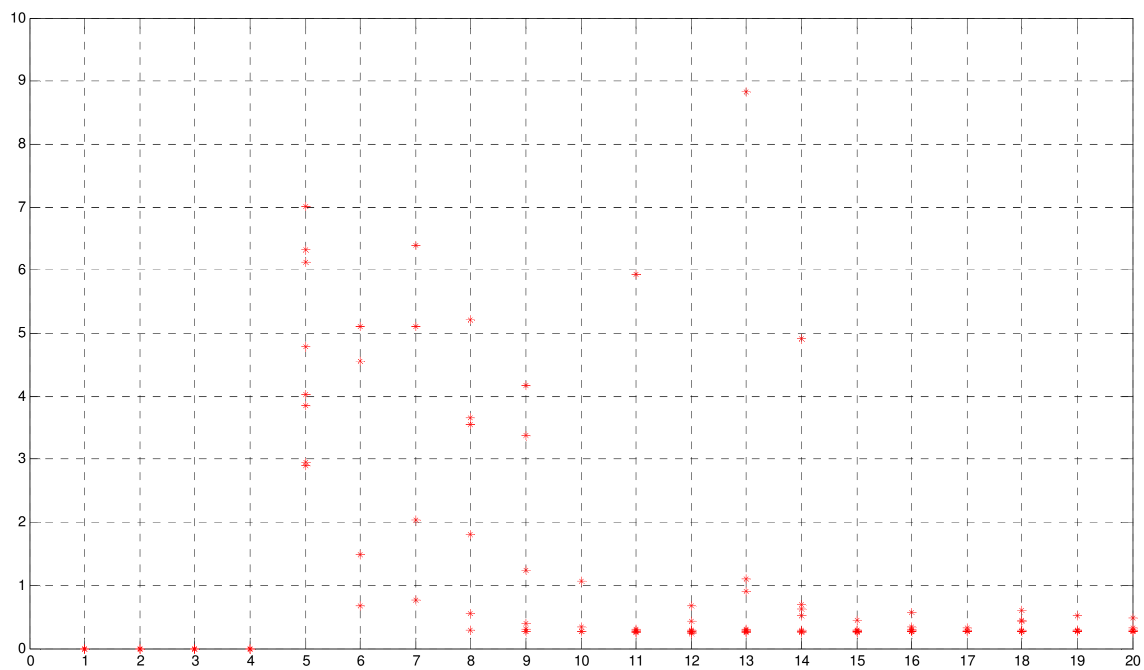

FIGURE 8: Diagram of maximum error of the network output with 10 iterations for certain number of neurons

The results of above algorithms have been collected in Table 2. Each row of the table is the result of average 40 iterations of each method. Evaluation criterion of adaptive systems was defined as following formula:

$$AveragePercentageError : APE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{e_i}{T_i}\right| * 100\%$$

Where T_i is the desired output and e_i is the output error. [13]

TABLE 2: Comparison of different algorithms used for predicting the concrete compressive strength

Row	Algorithm	Accuracy on data (%)				Ave. Time
		Train	Validation	Test	Total	(second)
1	Levenberg-Marquardt	99.436	99.389	99.397	99.407	7.7
2	Polak-Ribiere Conjugate Gradient	98.861	98.836	98.866	98.854	17.3
3	Fletcher-Powell Conjugate Gradient	98.713	98.675	98.695	98.694	12.4
4	Gradient Descent	98.584	98.567	98.606	98.586	24.3
5	Quasi-Newton	98.388	98.341	98.423	98.384	89.2
		Maximum Error (kg/cm2)				epochs
1	Levenberg-Marquardt	5.830	5.056	4.437	5.108	58
2	Polak-Ribiere Conjugate Gradient	9.686	8.536	7.652	8.635	571
3	Fletcher-Powell Conjugate Gradient	10.758	9.457	8.597	9.604	368
4	Gradient Descent	11.897	10.376	9.018	10.430	1833
5	Quasi-Newton	13.825	11.539	10.691	12.018	1999

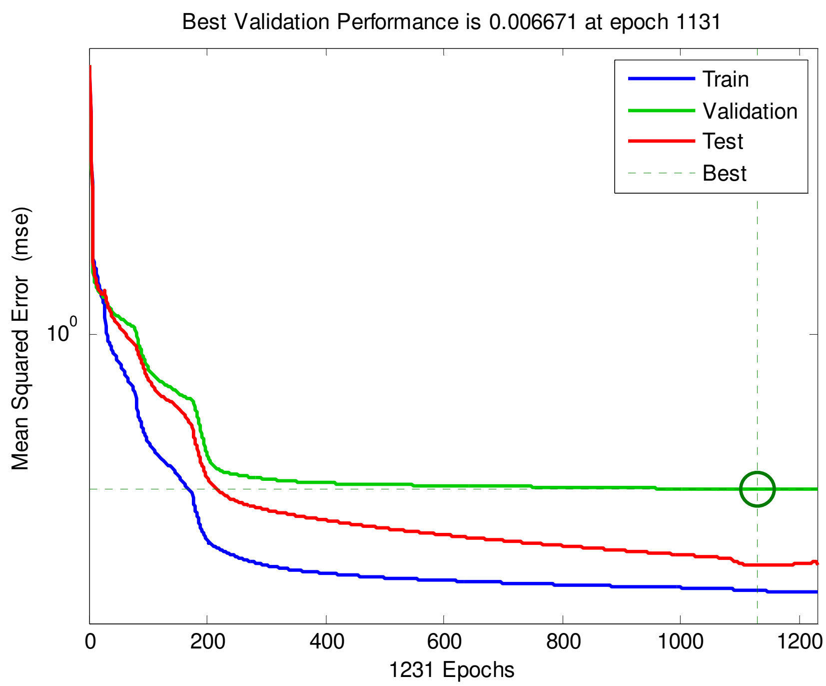

FIGURE 9: Diagram of mean squared error in the feed-forward neural network

It is conceived from table 2, that the best structure for prediction of concrete strength is the first method with levenberg-marquardt algorithm.

Figure 9 shows the mse diagram of the cost function reduction for training, validation and test data. The following results are being conceived from this figure.

1. The final mse is small and admissible
2. The test dataset error and validation dataset error are almost equal.
3. Over fitting was not happened

The diagram of figure.10 also shows the linear regression between network output and desired output for training, validation, test and total data.

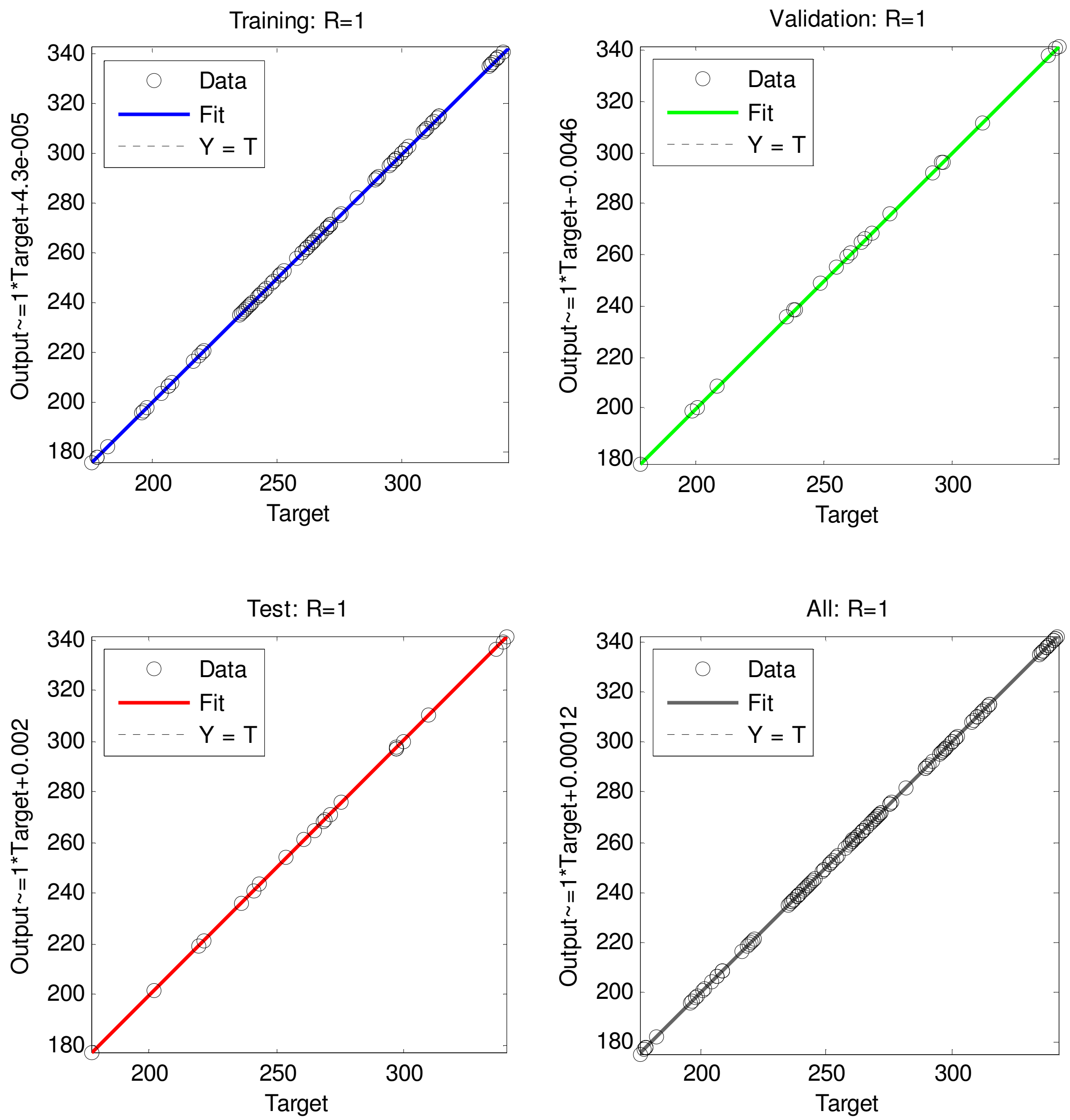

FIGURE 10: Diagram of the network output and desired output for train, validation, test and all data

16. CONCLUSION

In this paper, a practical approach has been presented for prediction of 28-day compressive strength of concrete. Basically, in all of the methods have been resented previously, the 3-day compressive strength of concrete was not considered as an important parameter.

From this point of view we can consider the proposed method as a new method in which the 3-day compressive strength parameter has been introduced as a very important index. [Ref: 13, 14, 15, 16]

The proposed technique can be used as a very useful tool for reducing the duration of the project execution in huge civil projects. For example, imagine if we have a massive concrete structure which requires 10 stages of concreting then we need at least 28×10=280 days to complete the total project regarding to standards. Therefore this project will be finished after about 1 year considering the frigid winter days which concreting is impossible.

Using the proposed tool we can have a precise prediction of the 28-day compressive strength of the concrete on the third day. Thereupon we need $3\times10=30$ days to complete this project and this is an important progress in order to reducing the duration of the civil projects execution.

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