MECHANICAL PROPERTIES PREDICTION OF HEAVYWEIGHT CONCRETE USING GENERALIZED REGRESSION NEURAL NETWORK (GRNN)

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In this research, from zero to 100% every 10%, normal aggregates were replaced with heavy aggregate (a mixture of iron ore and barite) in the concrete. A total of 110 cylindrical specimens (15x30cm) and cubic specimens (15x15cm) were used to examine the specific gravity, compressive strength, and tensile strength of Heavyweight Concrete (HWC). The test results confirmed that by substituting Heavyweight Aggregate (HWA) iron ore and barite mixture for 10% (or higher) of regular aggregates, a specific weight greater than 2600 kg/m³ might achieve, and the resulting product classified as HWC. In the second phase of the research, to develop the Generalized Regression Neural Network (GRNN) for estimating compressive and tensile strength, 48 data records from the specimen tests were selected randomly to find the best network with minimum mean square error (MSE) and correlation coefficient. The results confirmed that the proposed informational model could adequately estimate the mechanical properties and simplify the design processes in computational intelligence structural design platforms in the future.

Keywords: *Material Science, Material Property, Material Structure*

1. Introduction

Heavyweight concrete is a type of concrete with specific gravities of higher than 2600 kg/m^3 [1,2], yet the specific weight may be over 6400 kg/m^3 depending on the type and size of its aggregate content and the compaction and discharge methods used. ACI 304 [3] acknowledge that heavyweight concrete has a specific gravity greater than normal concrete. An increase in density and workability [4], decrease in the thickness of structural elements [5,6], acceptance results in mechanical strength [7], freeze-thaw durability [8], and concrete radiation shielding [9,10], are the major issues in producing a heavyweight mixture. There are many ways to produce a heavyweight mixture using heavyweight aggregate:

1. Using natural heavyweight aggregates such as Barite [11-16], Magnetite [17,18], Limonite [19,20], Hematite [21,22], Iron ore [23], Goethite [21], Serpentine [21], Slag [24,25] and Siderite [26].
2. Using artificial heavyweight aggregates like steel punching and iron shot [27], Granulated Ferrous waste [28,29], waste glass [30], and lead mine waste [31] as a replacement for the portion of either fine aggregate or coarse aggregate.
3. Using recycled material such as recycled concrete aggregate [32] and steel treatment waste [33,34].

Some researchers used a combination of two or more natural heavyweight aggregates to make heavyweight concrete [35-37]. Basyigit et al. made heavyweight concrete by different mineral origins (limonite and siderite) as aggregate in order to organize different series of concrete mixtures and studied the radiation shielding of these concrete specimens [19]. They found that the concrete prepared with heavyweight aggregates of different mineral origins improves some of heavyweight concrete's properties like radiation absorbents. Taban Shams et al. make a heavyweight concrete shield for gamma rays using a combination of barite and hematite gradation [6]. They showed that increasing the barite and hematite aggregates increases the linear attenuation coefficient and 28-day compressive strength. Süleyman Özen et al. produced a mixture containing iron ore, steel mill scale, barite, magnetite, and steel slag to make heavyweight concrete [38]. They obtained the best performance in terms of the main mechanical when iron ore was used, while the highest fracture energy values were reached in concretes with steel mill scale, magnetite, or with the combination of steel slag, iron ore, and crushed sand.

Typically, it is not permanently easy to do experimental work to achieve the mechanical properties of concrete. In the past two decades, many scientists have investigated different modeling methods based on artificial neural networks (ANN) for a variety of researchers' studies [39-44]. Previous studies found that considerable data is required to generate the optimum ANN for prediction. Specht introduced the Generalized Regression Neural Network (GRNN), which can be applied as a skilled technique for obtaining reliable outputs with minimum or limited data for network generation [45]. GRNNs have been proved to be a capable method for many scientific and engineering problems prediction, such as sigma processing by

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Kendrick [46], and chemical processing by Mukesh [47]. But, the technique has not been widely applied in the field of Civil Engineering. Razavi et al. applied GRNN for mechanical strength prediction of lightweight mortar made with a different percentage of scoria instead of sand [48].

There was no detailed study on the mechanical properties of heavyweight concrete using a mixture of iron ore and barite as heavyweight aggregate in the literature. In this research, a mixture of barite and iron ore was used as coarse aggregate to measure the mechanical properties of heavyweight concrete. The main objective of the current research is to investigate the percentage of heavyweight aggregate instead of normal aggregate that can be classified as heavy-weight concrete. For this purpose, normal-weight aggregate content was decreased from zero to 100% every 10% by volume of the concrete mixture prepared, and mixtures were prepared by its substitution with barite and iron ore aggregate at the same rates.

2.Materials and Methods

Material. In this experimental work, to prepare heavyweight concrete, materials with the following properties were used:

Cement. Portland cement type II with a specific gravity of 3.15.

Water. The drinking water in this study was used in the mix design. According to the ACI 304.3R [3], water used in heavyweight concrete mix should be free of any contamination and external materials and should be as in ASTM C94 [49]. Effective water in the mixture of concrete is the water in addition to that absorbed by the coarse and fine aggregates that also help reach the desired workability [50].

Coarse aggregate. According to the ASTM C637 standard [51], the grading of heavyweight aggregates (coarse and fine aggregates) is similar to that of ordinary aggregates and matches the ASTM C33 standard [52]. Considering these facts and limitation of dimensions of casts, coarse aggregates were of size 4.75–19 mm and consisted of ordinary gravel with a specific gravity of 2.80, iron or coarse aggregate with a specific gravity of 3.8, and barite coarse aggregate with a specific gravity of 4.

Fine aggregate. Concrete fine aggregates are materials that can pass through sieve No. 4 [52]. Fine aggregates in this study were ordinary sand with a specific gravity of 2.60, iron ore fine aggregates with a specific gravity of 3.8, and barite fine aggregates with a specific gravity of 4. The sizes of fine aggregates were less than 4.75 mm.

Heavyweight Concrete Production. Ten concrete mix designs were used to build the final specimens (Table 1). Moreover, 15-cm cubic specimens were used to determine the compressive strength of concrete, and the tensile strength was determined using cylindrical specimens with a diameter of 15cm and a height of 30 cm. The tensile strength of the cylindrical specimen is extracted using the Brazilian test. To this end, a total of 66 cubic specimens and 44 cylindrical specimens were built to examine compressive and tensile strength, respectively. It is worth mentioning that the mix design was performed to achieve a specific resistance of at least 40 MPa. Mechanical properties tests, including concrete specific weight test, hardened concrete 28-day compressive strength and hardened concrete 28-day tensile strength test were performed according to ASTM C138 [53], ASTM C39 [54], and ASTM C496 [55], respectively.

Table 1

The final mix design of plain and heavy-weight concrete [kg/m^3]

No.	Heavy-weight aggregates (%)	Cement	Water	Gravel	Sand	Micro silica gel	Super plasticizer	Theoretical density
1	0	364.4	164.5	760	577.6	---	---	2357
2	10	350	157	861	771	25	2.5	2605
3	20	350	157	889	812	25	2.5	2791
4	30	350	157	901	870	25	2.5	2878
5	40	350	157	988	901	25	2.5	2991
6	50	355	160	1112	975	25	2.5	3285
7	60	355	160	1225	1051	25	2.5	3523
8	70	355	160	1295	1121	25	2.5	3698
9	80	360	165	1358	1199	25	2.5	3887
10	90	360	165	1400	1225	25	2.5	3972
11	100	360	165	1437	1263	25	2.5	4064

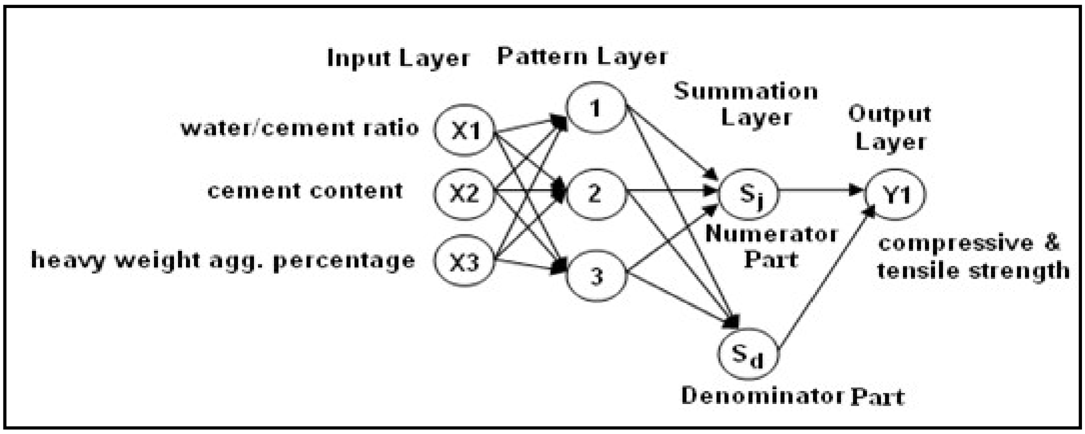

Fig. 1 - The GRNN architecture for the heavyweight concrete made with different percentage of heavyweight aggregate instead of normal aggregate

3.Generalized Regression Neural Network (GRNN)

The GRNN architecture for estimating the compressive and tensile strength of heavyweight concrete involves four layers, as shown in Fig.1:

(1) Input layer: Comprises three neurons for the water-cement ratio, cement content, and heavyweight aggregate percentage instead of normal aggregate.

(2) Pattern neurons: Contains three neurons for individually training case

(3) Summation neurons: Includes two neurons equal to neurons in the output layer

(4) Output layer: Comprises two neurons for the compressive and tensile strength.

The input layer of processing units is responsible for receiving the information from the test results. A unique input neuron is defined in the model for each input variable. No data processing for water-cement ratio, cement content, and heavyweight aggregate was conducted at the input neurons. Then, the input neurons provide the data to the pattern neurons. The data from the input layer are merged in the pattern layer, and then the output parameters are computed using the transfer function. The quantity of the smoothing parameter plays a vital role in the calculated output from the pattern layer. The smoothing parameter indicates how closely the function applied by the GRNN fits the training data. A trial and error approach was considered to find the optimum smoothing parameter. Afterward, the output from the pattern layer was forwarded to the summation layer. The summation layer consists of the numerator and denominator neurons, which compute the weighted and simple arithmetic sum, respectively. The denominator, S_d, and numerator, S_j, are defined by the following equations (Eq.1 and Eq.2).

1. $$S_d = \sum_i \theta_i$$

2. $$S_j = \sum_i w_i \theta_i$$

Subsequently, the calculated summation neurons are sent to the output neuron (Eq.3). In this last phase, the output neuron performs the following division to calculate heavyweight concrete's output parameters (compressive and tensile strength).

3. $$Y_1 = {S_j}/{S_d}$$

4.Results and Discussion

Analysis and Comparison of the Results of Heavyweight Concrete Testing. To study the mechanical and physical properties of the final concrete specimens (including the normal and heavyweight concrete samples), some physical properties tests, including tests to determine the specific weight, compressive and tensile strength, were conducted. The saturated-surface-dry density of the specimens are shown in Table 2 and Fig. 2. As shown, the produced heavyweight concrete is defined in three categories; low heavyweight concrete (LHWC), normal heavyweight concrete (NHWC), and super heavyweight concrete (SHWC) with specific weight in the range of 2400~3000 (kg/m3), (3000~4000) (kg/m3), and greater than 4000 kg/m3, respectively. The specific gravity ratio of LHWC, NHWC, and SHWC to normal concrete is 1.127~1.255, 1.305~1.669, and greater than 1.669 correspondingly.

Concrete Compressive Strength Test Results. A concrete compressive strength test was carried out using 15x15cm cubic specimens, and the results are presented in Fig.3. The figure indicates the changes in compressive strength values of the concrete specimens according to the change of heavyweight aggregate with a ten exponential growth. The experiment results showed that by increasing the amount of the heavyweight aggregates from 10% to 30%, the compressive strength of the cubic specimen increased from 421 kg/cm^2 to 489 kg/cm^2. In other words, for the specimen containing 30%

Table 2

The results of the concrete density test

No.	Heavyweight aggregates (%)	SSD specific weight (kg/m3)	Heavyweight concrete (HWC)	The ratio of specific weight of concrete specimens to the specific weight of normal concrete
1	0	2391	Normal Concrete	1
2	10	2696	Low Heavyweight Concrete	1.127
3	20	2992	(LHWC)	1.251
4	30	3001	2400~3000 (kg/m^3)	1.255
5	40	3121		1.305
6	50	3295	Normal	1.379
7	60	3615	Heavyweight	1.512
8	70	3699	Concrete (NHWC)	1.547
9	80	3950	(3000~4000) (kg/m^3)	1.652
10	90	3991		1.669
11	100	4102	Super HWC (> 4000 kg/m^3)	1.716

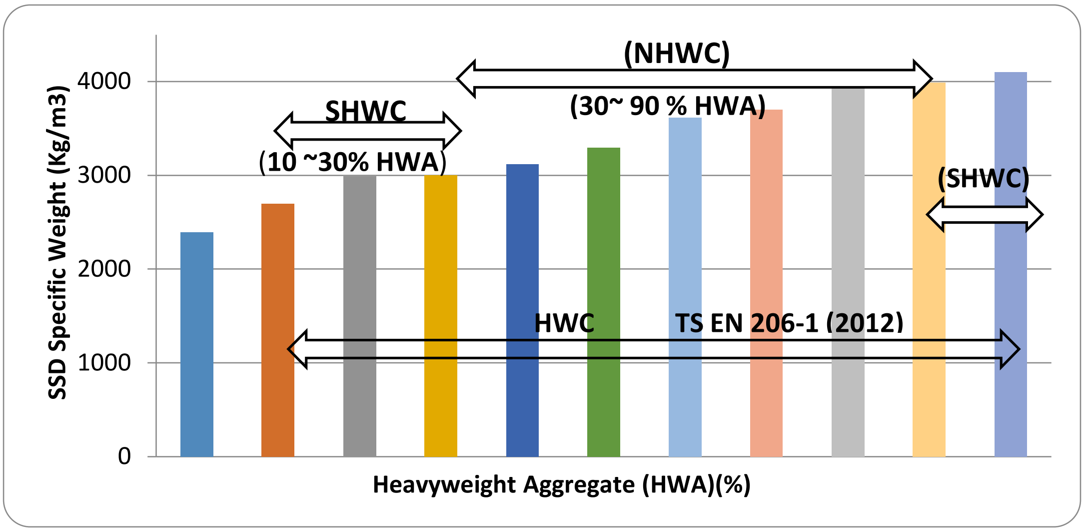

Fig. 2 - The density of concrete made of heavyweight aggregate (with a 10 exponential growth) instead of normal aggregates

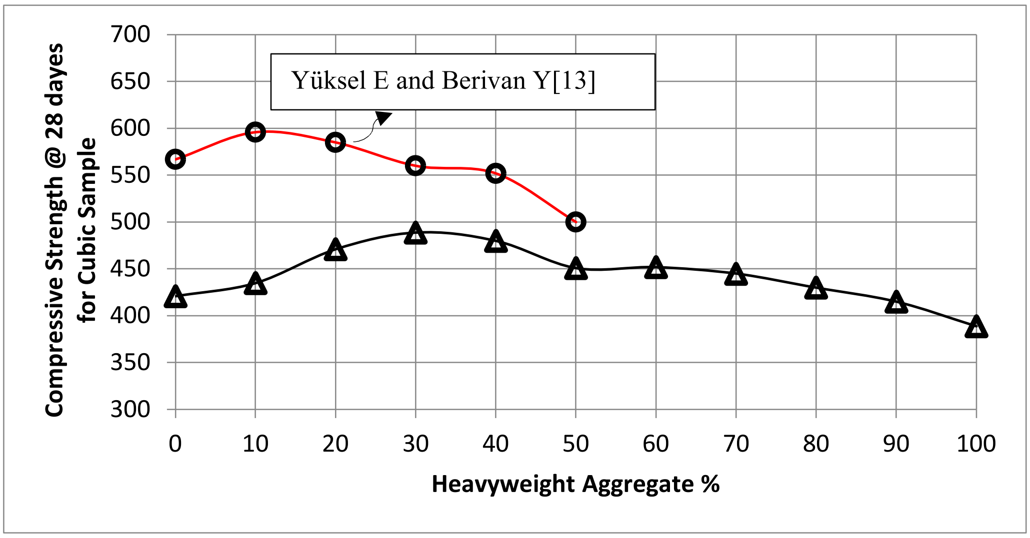

Fig. 3 - The variations of the compressive strength of the cubic concrete specimen made of heavy materials (with a 10% exponential growth) instead of normal aggregates

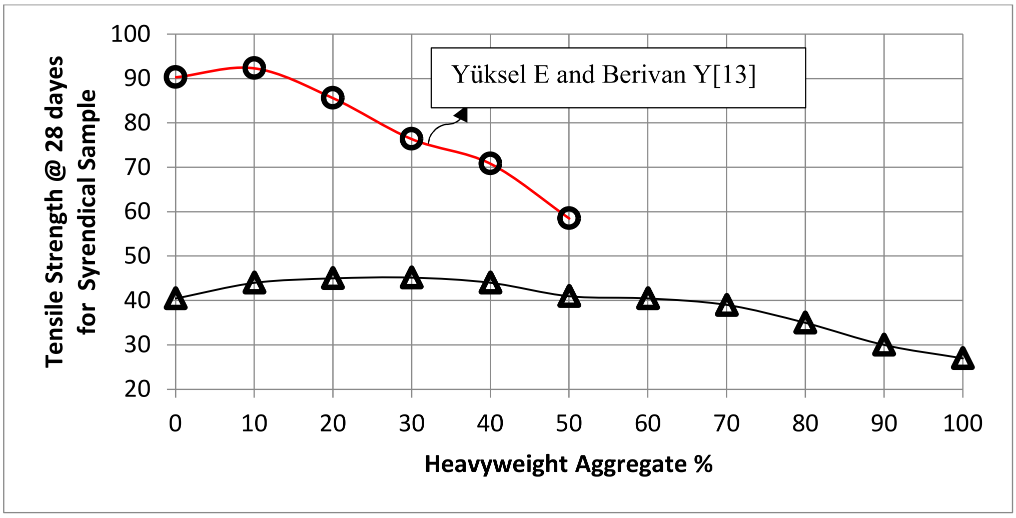

Fig. 4 - Variations of the tensile strength of the cylindrical specimen made of heavy aggregates (with 10% exponential growth) instead of normal aggregates

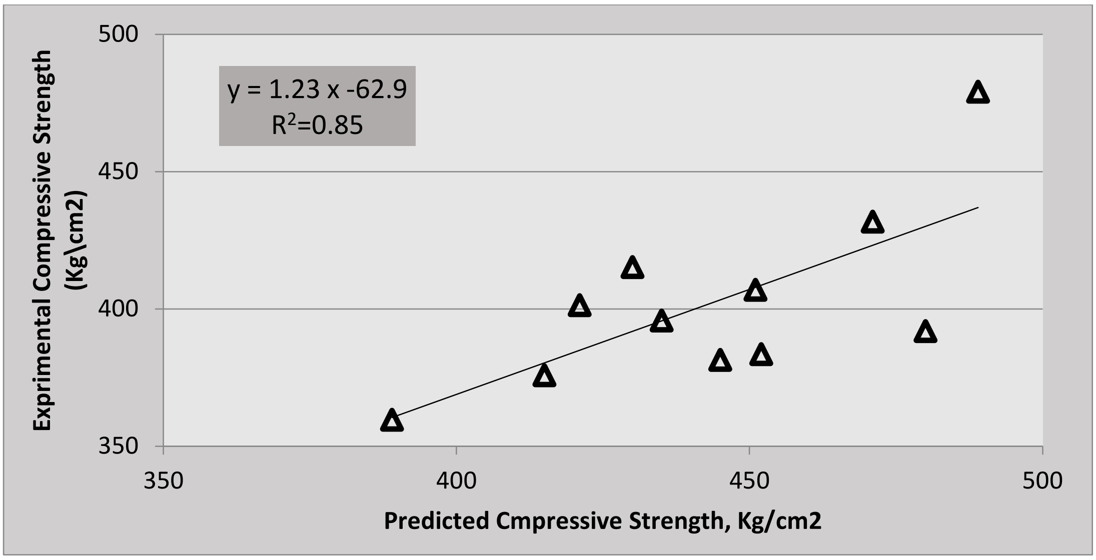

Fig.5 - The correlation of determination between target and predicted compressive strength in testing phase

heavyweight aggregate, the maximum compressive strength was achieved by 489 Kg/cm^2. As the heavyweight aggregate ratio increased, compressive strength tended to decrease. This might be related to the characteristic structure of heavyweight aggregate, which is a mixture of proportional iron ore and barite in this study. A previous study (shown in Fig. 3) reported that compressive strength decreased as the barite percentage increased [13]. This result is consistent with the data obtained in the present study.

Concrete Tensile Strength Test Results. The tensile strength experiments on the specimens were conducted using 15x30cm cylindrical specimens, and the results are presented in Fig. 4.

Fig. 4 indicates the change of tensile strength values depending on the percentage of heavyweight aggregate. In control specimens, tensile strength was calculated as 40.5 Kg/cm^2. In the specimen containing 20% and 30% heavyweight aggregate, tensile strength was calculated as 45 Kg/cm2. In the present study, it was found that compressive strength and tensile strength curves were parallel.

Network results. 48 randomly selected data were applied for network creation by considering the 37 data used for network generation and 11 data for testing. The percentages of heavyweight aggregate instead of normal aggregate, water-cement ratio, and cement content represented the input layers, and compressive and tensile strength were the output layers. The statistical metrics results confirmed that the testing stage's mean squared error (MSE) was 1.04% (Table 3). Overall, a good agreement between experimental compressive strength and predicted by GRNN in the testing phase is exists; with a coefficient of determination of 0.85 is shown in Fig. 5

Table 3

Comparison between experimental and predicted results for normalized compressive strength using GRNN

Neuron(n)	Experimental	Network	Deferent between Experimental and Network (E)	E^2
1	0.86	0.82	0.04	0.0016
2	0.89	0.81	0.08	0.0064
3	0.96	0.88	0.08	0.0064
4	1.00	0.98	0.02	0.004
5	0.98	0.80	0.18	0.0324
6	0.92	0.83	0.09	0.0081
7	0.92	0.78	0.14	0.0196
8	0.91	0.78	0.13	0.0169
9	0.88	0.85	0.03	0.009
10	0.85	0.77	0.08	0.0064
11	0.80	0.74	0.06	0.0036
			$MSE=\Sigma E^2/n=1.04\%$	

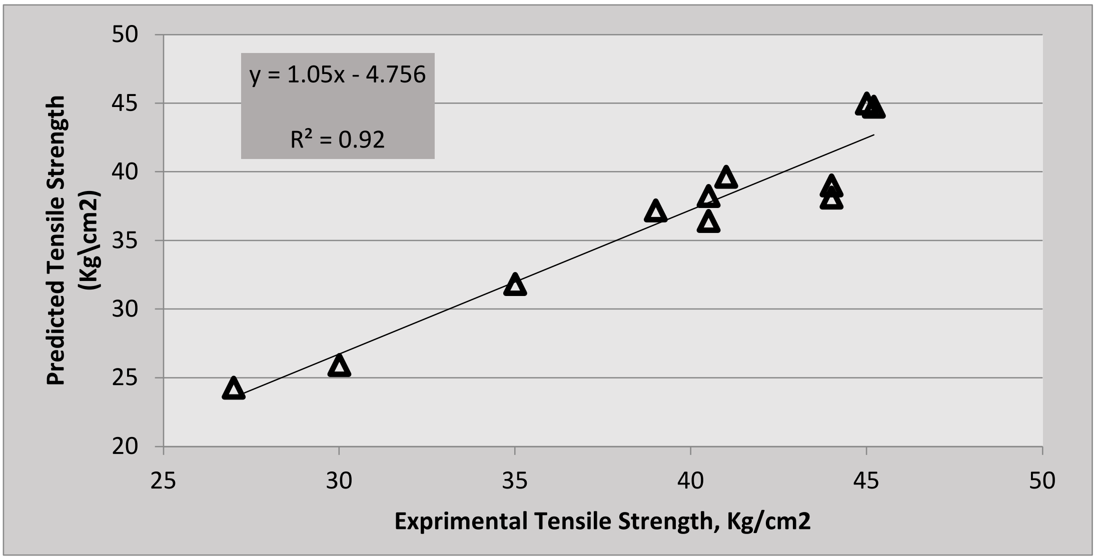

Fig. 6 - The correlation of determination between target and predicted tensile strength in testing phase

The predicted tensile strength from generated GRNN is in good agreement with the experimental Results. The GRNN response for the tensile strength compared with the experimental results is presented in Fig. 6. In network testing, the selected network represented 0.925 for correlation of determination, and the MSE in network testing was 0.6 % (Table 4).

5.Conclusion

In this research, normal aggregates were replaced by a mixture of iron ore and barite to produce heavyweight concrete. The following conclusion was drawn from this study:

1- Replacing 10% or more of the normal aggregates with heavy aggregates in producing concrete was categorized as heavyweight concrete according to TS EN 206-1.

2- The experiment results showed that by increasing the amount of the heavyweight aggregates (that substitute normal aggregates) from 0% to 100%, density increased by 12.7%, 25.1%, 30.5%, 37.9%, 51.2%, 54.7%, 65.2%, 66.9%, and 71.6% with a 10% exponential growth rate.

3- Average compressive strength was calculated as 421 Kg/cm^2 in control specimens. In the specimen containing 30% heavyweight aggregate, compressive strength was calculated as 489 Kg/cm^2. Nevertheless, as the heavyweight aggregate ratio increased, compressive strength tended to decrease.

4- In control specimens, tensile strength was calculated as 40.5 Kg/cm^2. In the specimen containing 20% and 30% heavyweight aggregate, tensile strength was calculated as 45 Kg/cm^2

5- Forty-eight data records were tested and used to train the GRNN, and the mean square errors of the compressive and tensile strength in the testing phase were 1.04 and 0.6%, respectively. The correlation of coefficient in the testing stage for compressive and tensile strength were 0.85 and 0925, respectively, indicating the high potential of the proposed model in industry-oriented applications.

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