Neural model of projecting flexural strength of cement concrete intended for airfield pavements

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Abstract. This work presents the mathematical model in the form of Artificial Neural Network (ANN), intended for projecting concrete flexural strength. Input data was classified according to the type of component material and its content in concrete mix (cement contents, coarse aggregate, fine aggregate, water and admixtures). In order to determine the mathematical model, a multilayer, one-way perceptron network was used, recursion network with sigmoidal neurons. The model assumes that neurons are gathered in some layers (one input layer, hidden layers and one output layer). The conducted cross-section of the impact of variable parameters values (learning constant $\alpha$ and momentum values $\eta$) on the accuracy of representation of flexural strength was analyses. Assessment criterion was assumed as consideration the lowest mistake level and 100% compliance. According to the obtained results ANN was assumed to be the best representing network for constant value of momentum 0.3, learning constant of 0.04 and 9 neurons in a hidden layer. Very good coincidence of component models with experiment results was achieved. At testing stage, the coincidence was achieved at the level of 99.25%, in case of the assumed network structure. During model verification by means of experimental results, the average coincidence was 99.68%.

1. Introduction
ANN were proved, among others, in the following works [1-3]. This research paper concerns the issue of projecting the flexural strength of concrete intended for airfield pavements as far as structure durability is concerned. One of the basic parameters of hardened concrete, which has the direct impact on the durability thereof in case of airfield pavement, is flexural strength [4, 5]. Using own collected database containing strength, laboratory and field test results, the mathematical model in the form of ANN, intended for projecting concrete strength, was presented.

2. Experimental studies
The testing base used for the purposes of ANN modelling included cement concretes intended for airfield pavements. Aggregate compositions of mixes in case of the analysed concretes were diversified in regard to the content of individual components of concrete mix. In case of each out of 6500 mixes, coarse aggregate was the base element. Fine aggregate in the form of washed sand was also included as aggregate composition of mixes. Due to the diversification of individual mix components, aggregate content was taken into consideration with the change every 1kg/m$^3$. The designed aggregate compositions each time complied with PN-EN 206-1 [6], NO 17A-204 [7]. Mix composition included clean-clinker Portland cement in various amounts CEM I 42.5 (which fulfilled the requirements of PN-
EN 197-1 [8]) and water (complied with PN-EN 1008 [9]), designing diversified water-content ratio with reference to cement amount (w/c), according to the requirements of PN-EN 206-1 [6]. Water-cement ratio significantly impacts concrete durability [7]. Due to the fact that limiting the value of w/c coefficient impacts the reduction of hardened concrete permeability, at the same time increasing durability thereof, in case of pavement concretes, especially concretes intended for airfield pavement application, the value of w/c ratio is reduced to maximum level of 0.4 [5, 7]. Limit content of individual mix components have been presented in the table 1.

### Table 1. Limit component contents of the analysed concrete mixes.

| Elements     | Content | Cement kg/m³ | Coarse aggregate kg/m³ | Fine aggregate kg/m³ | Water kg/m³ | Admixtures kg/m³ |
|--------------|---------|--------------|------------------------|----------------------|-------------|------------------|
| Minimum      |         | 335          | 1149                   | 358                  | 120         | 0                |
| Maximum      |         | 380          | 1401                   | 604                  | 150         | 6.4              |

Concretes curing in standard conditions, (according to the requirements of PN-EN 12390-2[10]) were considered for the purposes of this research paper. On the 28th day since concreting, each sample, prepared and cured in accordance with the requirements of [10], was subject to destructive tests by means of hydraulic press in compliance with PN-EN 12390-4:2009 [11]. Maximum force destroying the sample, obtained according to the measurements, taking into consideration the assumed constant loading speed of 0.05MPa/s, was the basis for defining flexural strength of individual samples. Samples of bar shape and dimensions of 150×150×700 mm were used in the course of the research. Dimensions of samples and load diagram were in compliance with the requirements of [7] (figure 1).

Figure 1. Dimensions of samples and load diagram.

In case of each sample, in compliance with the requirements of [12], the flexural strength $f_{cf}$ was determined, according to the formula (1), where $F$ refers to maximum load registered in the course of sample destruction, $l$ – spacing between supports ($l = 150$ mm), $b$ – width of the sample ($b = 150$ mm), $h$ – height of the sample ($h = 150$ mm).

$$f_{cf} = \frac{F}{bh^2}$$

The strength values obtained in this way were the input base to assess flexural strength of cement concrete intended for airfield pavements using ANN. All obtained test results concerning individual research series corresponded the criterion of minimum strength according to the [7] standard and they were statistically essential. Therefore, they were the reliable source of input data for ANN identification, reflecting concrete strength in case of various compositions thereof.
3. Results

3.1. Network learning

The essence of ANN is the selection of network structure (the number of layers and the number of neurons in particular layers) and defining the parameters thereof (constant values and weights). According to the analyses using the artificial neural networks were created regressive model, where it was expected to provide a specific numerical value being the solution to the problem. In case of the analysed case this value was identified with the assumed flexural strength value. In order to conduct cross-section analysis of the influence of variables parameters values (α and η) on the accuracy of representation of flexural strength, analyses including matrix of 90×90 elements. Values of learning constant α ranged from α\text{min} = 0.01 to α\text{max} = 0.09 every 0.01. Momentum values η were assumed from η\text{min} = 0.01 to η\text{max} = 0.09 every 0.01. In the case of each combination α and η the constant value was assumed to be ε = 0.01.

According to the obtained results it was proved that the selection of α and η has significant impact on the extent of the obtained representation. Tables 2, 3 and 4 present exemplary summary of a given internal layers structure, selected in the course of experiment. Table 2 presents the impact of learning constant values, ranging from 0.03 to 0.07, on the accuracy of flexural strength representation for the previously assumed constant values η = 0.3 and ε = 0.01. Table 3 presents the impact of momentum value, ranging from 0.3 to 0.7, on the accuracy of flexural strength representation for the previously assumed constant values α = 0.04 and ε = 0.01.

Analysing the data presented in table 2, the initial tolerance of learning constant was assumed at 0.04 for further analyses. With such assumed tolerance, the least value of the generated mistake (Δ\text{ysr}) and the highest compliance of results was obtained. The assessment of representation accuracy of values from the experiment (\text{yrz}_i) and coefficients generated by neural network (\text{y}_{ANN,i}) was defined on the basis the sum of squares of differences which was determined according to the relationship (2).

\[
\Delta \text{ysr} = \frac{\sum_{i=1}^{N}(\text{y}_{ANN,i} - \text{yrz}_i)^2}{N}
\]

Table 2. Impact of learning constant value α on the accuracy of flexural strength representation (assuming constant value of momentum η = 0.4 and ε = 0.01).

| No ANN | α   | η   | Number of inputs | Number of neurons in the hidden layer | Number of outputs | Percentage of positive events | Δ\text{ysr} |
|--------|-----|-----|----------------|--------------------------------------|------------------|-----------------------------|------------|
| Z/1-1  | 0.03| 0.40| 5              | 3                                    | 1                | 100                         | 0.0051724  |
| Z/1-2  | 0.04| 0.40| 5              | 3                                    | 1                | 100                         | 0.0050352  |
| Z/1-3  | 0.05| 0.40| 5              | 3                                    | 1                | 100                         | 0.0055646  |
| Z/1-4  | 0.06| 0.40| 5              | 3                                    | 1                | 100                         | 0.0066406  |
| Z/1-5  | 0.07| 0.40| 5              | 3                                    | 1                | 100                         | 0.0084439  |

Table 3. Impact of momentum value η (from 0.3 to 0.7) on the accuracy of flexural strength representation (assuming value of learning constant α = 0.04 and ε = 0.01).

| No ANN | α   | η   | Number of inputs | Number of neurons in the hidden layer | Number of outputs | Percentage of positive events | Δ\text{ysr} |
|--------|-----|-----|----------------|--------------------------------------|------------------|-----------------------------|------------|
| Z/2-1  | 0.04| 0.30| 5              | 4                                    | 1                | 100                         | 0.0036493  |
| Z/2-2  | 0.04| 0.40| 5              | 4                                    | 1                | 100                         | 0.0036632  |
| Z/2-3  | 0.04| 0.50| 5              | 4                                    | 1                | 100                         | 0.0037701  |
| Z/2-4  | 0.04| 0.60| 5              | 4                                    | 1                | 100                         | 0.0041493  |
| Z/2-5  | 0.04| 0.70| 5              | 4                                    | 1                | 100                         | 0.0057739  |

Analysing the data presented in table 3 the initial tolerance of momentum was assumed at 0.3 for further analyses. In case of such assumed tolerance, the least value of the generated mistake (Δ\text{ysr}) and the highest compliance of results was obtained.
Analysing the data presented in table 4 the initial number of neurons equalling to 9 was assumed in a hidden layer. In case of such tolerance, the least value of the generated mistake and the highest compliance of results was obtained. Table 5 presents exemplary summary of the selected network structures in case of the diversified number of hidden layers, selected experimentally.

**Table 4.** Impact of neurons number (3-14) in a hidden layer on the accuracy of representation of flexural strength at constant value of momentum 0.3, learning constant 0.04 and $\varepsilon = 0.01$.

| The number of neurons in the hidden layer | Percentage of positive events | $\Delta y_{sr}$ |
|------------------------------------------|-------------------------------|----------------|
| 3                                       | 100                           | 0.0051505      |
| 4                                       | 100                           | 0.0036632      |
| 5                                       | 100                           | 0.0052850      |
| 6                                       | 100                           | 0.0039173      |
| 7                                       | 100                           | 0.0052694      |
| 8                                       | 100                           | 0.0063905      |

The number of neurons in the hidden layer 9 10 11 12 13 14

Percentage of positive events 100 70,8 70,8 70,8 100 100

$\Delta y_{sr}$ 0.0033323 0.0709030 0.0718920 0.0694870 0.0071414 0.0063639

**Table 5.** Impact of neurons number (1-10) in a hidden layer on the accuracy of representation of flexural strength at constant value of momentum 0.3, learning constant 0.04 and $\varepsilon = 0.01$.

| No. ANN | $\alpha$ | $\eta$ | number of inputs |
|---------|----------|--------|-----------------|
| Z/3-1   | 0.04     | 0.30   | 5               |
| Z/3-2   | 0.04     | 0.30   | 9               |
| Z/3-3   | 0.04     | 0.30   | 5               |
| Z/3-4   | 0.04     | 0.30   | 5               |
| Z/3-5   | 0.04     | 0.30   | 5               |
| Z/3-6   | 0.04     | 0.30   | 5               |
| Z/3-7   | 0.04     | 0.30   | 5               |
| Z/3-8   | 0.04     | 0.30   | 5               |
| Z/3-9   | 0.04     | 0.30   | 5               |
| Z/3-10  | 0.04     | 0.30   | 5               |
| Z/3-11  | 0.04     | 0.30   | 5               |
| Z/3-12  | 0.04     | 0.30   | 5               |
| Z/3-13  | 0.04     | 0.30   | 5               |
| Z/3-14  | 0.04     | 0.30   | 5               |
| Z/3-15  | 0.04     | 0.30   | 5               |
| Z/3-16  | 0.04     | 0.30   | 5               |
| Z/3-17  | 0.04     | 0.30   | 5               |
| Z/3-18  | 0.04     | 0.30   | 5               |
| Z/3-19  | 0.04     | 0.30   | 5               |

According to the obtained analysis results ANN was assumed the best representing network for constant value of momentum 0.3, learning constant of 0.04, 9 neurons in a hidden layer and assumed $\varepsilon = 0.01$. In case of network of 5-9-1 structure, the first digit (5) refers to the number of inputs, next (9) the number of neurons in a hidden layer, and the last one (1) refers to one output identified with the assumed compressive strength value. This structure was adopted as a result of accuracy tests of representing real flexural strength values by the network. As the assessment criterion was assumed the lowest mistake level ($\Delta y_{sr}$) and 100% compliance.
Figure 2 presents the courses of the learning in case of network with neurons in a hidden layer. It can be observed that minimum values $\Delta y_{sr}$ amount to 0.008, and maximum values amount to 0.250 in the case of the assumed number of iterations.

According to the obtained results of ANN analysis it was proved that the determined network can be recognized reliable for 170000 iterations.

**Figure 2.** The course of learning process by artificial neural networks of diversified neurons number in a hidden layer.

### 3.2. Network testing

Out of the collection of 6500 diversified concrete mix compositions intended for airfield pavements, 20% was selected randomly and intended for the educated network testing. Table 6 presents approximate contents of individual mix components intended for network testing.

For the purposes of this research paper, the analysis included concretes curing in standard conditions and examined on 28th day since concreting. The research process, aimed at defining flexural strength, was in compliance with the one presented in section 2. Figure 3 presents graphic summary of data determined at testing stage by the educated network.

**Table 6.** Limit component contents of the analysed concrete mixes.

| Content | Elements | Cement kg/m³ | Coarse aggregate kg/m³ | Fine aggregate kg/m³ | Water kg/m³ | Admixtures kg/m³ |
|---------|----------|---------------|------------------------|----------------------|-------------|------------------|
| Minimum | 300      | 1200          | 400                    | 110                  | 0.1         |                  |
| Maximum | 490      | 1700          | 840                    | 190                  | 3.6         |                  |

**Figure 3.** The course of testing process of the artificial neural network of 5-9-1 structure.
According to the obtained characteristics (Table 7), it was proved that testing the artificial neural network model reflects the values determined by the network. The obtained average coincidence value from 1300 events is very high. Average value of coincidence is 99.26%.

### Table 7. Testing of ANN model.

| L.p. | C[^a] kg/m³ | Kg[^a] kg/m³ | Kd[^a] kg/m³ | W[^a] kg/m³ | D[^a] kg/m³ | from the network MPa | during testing MPa | accuracy % |
|------|-------------|--------------|--------------|-------------|-------------|----------------------|-------------------|------------|
| 1.   | 370         | 1510         | 630          | 144         | 0.1         | 5.9                  | 6.0               | 98.33      |
| 2.   | 320         | 1580         | 590          | 127         | 1.7         | 7.1                  | 7.1               | 100.00     |
| 3.   | 390         | 1150         | 840          | 150         | 1.5         | 6.3                  | 6.3               | 100.00     |
| 4.   | 380         | 1290         | 760          | 152         | 2.2         | 5.2                  | 5.2               | 100.00     |
| 5.   | 310         | 1650         | 430          | 120         | 0.6         | 6.8                  | 6.8               | 100.00     |
| 6.   | 360         | 1430         | 610          | 140         | 2.0         | 5.4                  | 5.5               | 98.18      |
| 7.   | 280         | 1370         | 790          | 115         | 2.9         | 6.9                  | 6.9               | 100.00     |
| 8.   | 410         | 1620         | 580          | 158         | 2.3         | 4.5                  | 4.6               | 97.83      |
| 9.   | 290         | 1430         | 820          | 110         | 2.5         | 6.1                  | 6.1               | 100.00     |
| 10.  | 490         | 1350         | 810          | 195         | 1.5         | 5.8                  | 5.8               | 100.00     |

[^a]: C – Cement; Kg – Coarse aggregate; Kd – Fine aggregate; W – Water; D – Admixtures

### 3.3. Network verification

The educated and tested ANN network of 5-9-1 structure was intended for experimental verification. The collected data, out of 20% of all laboratory tests, were subject to verification - this data were not intended for network learning or testing. Tables 8 and 9 includes the obtained analyses results. Table 8 presents approximate contents of individual mix components intended for network testing.

### Table 8. Limit component contents of the analysed concrete mixes.

| Content | Elements | Cement kg/m³ | Coarse aggregate kg/m³ | Fine aggregate kg/m³ | Water kg/m³ | Admixtures kg/m³ |
|---------|----------|---------------|------------------------|----------------------|-------------|------------------|
| Minimum |          | 260           | 1100                   | 380                  | 100         | 0.0              |
| Maximum |          | 430           | 1670                   | 690                  | 165         | 4.4              |

### Table 9. ANN model verification.

| L.p. | C[^a] kg/m³ | Kg[^a] kg/m³ | Kd[^a] kg/m³ | W[^a] kg/m³ | D[^a] kg/m³ | from the network MPa | during testing MPa | accuracy % |
|------|-------------|--------------|--------------|-------------|-------------|----------------------|-------------------|------------|
| 1.   | 268         | 1310         | 650          | 110         | 0.9         | 6.4                  | 6.5               | 98.46      |
| 2.   | 295         | 1590         | 410          | 125         | 1.2         | 7.3                  | 7.3               | 100.00     |
| 3.   | 315         | 1280         | 720          | 120         | 2.1         | 6.5                  | 6.5               | 100.00     |
| 4.   | 390         | 1420         | 480          | 150         | 0.8         | 5.9                  | 5.9               | 98.31      |
| 5.   | 410         | 1360         | 620          | 156         | 0.0         | 5.2                  | 5.2               | 100.00     |
| 6.   | 365         | 1250         | 680          | 148         | 0.8         | 6.8                  | 6.8               | 100.00     |
| 7.   | 403         | 1530         | 450          | 153         | 3.4         | 7.3                  | 7.3               | 100.00     |
| 8.   | 340         | 1610         | 400          | 130         | 2.1         | 6                    | 6.1               | 98.36      |
| 9.   | 355         | 1330         | 420          | 135         | 3.5         | 7.1                  | 7.1               | 100.00     |
| 10.  | 280         | 1470         | 530          | 114         | 4.0         | 6.9                  | 6.9               | 100.00     |

[^a]: C – Cement; Kg – Coarse aggregate; Kd – Fine aggregate; W – Water; D – Admixtures
According to the obtained characteristics (table 9), it was proved that verification the artificial neural network model reflects the values determined by the network. The obtained average coincidence value from 1300 events is very high. Average value of coincidence is 99.68%.

4. Conclusions
It should be concluded that the assumptions concerning the construction of ANN model and the course of analysis can anticipate with credibility the parameters of composite material – concrete. The results of the conducted analyses prove the purpose of application of the presented method in modelling the composition of concrete mix and projecting the flexural strength of concrete after 28 days of curing in standard conditions.

The analysed structure 5-9-1 make it possible to draw conclusions regarding material parameters even in the case of limited number of elements. The network analysing five neurons in an input layer, diversified in terms of the selection of hidden neurons amount, complies with model assumptions. It was proven that a 5-9-1 network, with learning constant of 0.04, momentum 0.3 and $\varepsilon = 0.01$, is the most favourable structure for the assumed data. Very good coincidence of component models with experiment results was achieved. At testing stage, the coincidence achieved was at the level of 99.25%, in case of the assumed network structure. During model verification by means of experimental results, the average coincidence was 99.68%.

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