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Prediction of Efficiency Factor of Natural Pozzolan by the Use of an Artificial Neural Network

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Abstract. Because of the abundance of the mineral additives and the great variations on their physical and chemical characteristics, the development of a general concept for their use out of concrete is required. In this study, the concept of the efficiency factor is applied like a measurement of the relative performance of these materials compared with Portland cement. The rapid growth of the artificial intelligence had a very important impact on the concrete technology. It makes it possible to solve complex prediction problems of the properties of the concretes with cementitous materials (slag, fly-ashes, silica fume and natural pozzolan). The main aim of this study is to test the validity of the approach of Artificial Neural Networks (ANN) in developing a model for the prediction of the natural pozzolan efficiency factor. The most suitable model is the feed-forward multi-layer network. It is produced to implement the complexity of the nonlinear relation between the data network (the Water/Binder ratio "", the percentage of pozzolan and the age of testing) and the produced result (the efficiency factor). It is also established by an incorporation of a large experimental database and by a suitable choice of architecture and the training process. The model was validated by experimental tests. The ANN Model developed provided effective means for the formulation of the concretes containing natural pozzolan for a given water binder ratio (W/B), an age of testing (t) and a rate of substitution of natural pozzolan (P).

1 Introduction

Cementitous materials have represented an important research subject since 1970 [1], are now recognized and accepted like desirable components, even essential to the concrete for technical-economic and ecological reasons. It is estimated that the production of each ton of Portland cement releases approximately a ton of CO_2. The worldwide production of the clinker is responsible for approximately 7% of the total CO_2 emissions.

The use of the additives as constituent of cement decreases the necessary quantity of clinker per ton, which reduces CO_2 emissions [2]. Cements with additives not only make it possible to reduce the production costs but also to regulate certain environmental problems in addition to offering better concrete performance (low heat of hydration, better durability, etc…).

Several formulas were developed by using various means (experimental, data-processing… etc) in order to determine the efficiency of these additives to estimate their quantity which will be used to reach the same characteristics of replaced cement.

Artificial neural networks inspired by the biological networks of neurons have recently became a very interesting subject, thanks to their high capacity to resolve the most complex problems with very satisfactory material costs and in a less time.

The principal goal of this work consists of the evaluation of the efficiency factor of the cementitous additives when they are introduced into the mortars or the concretes. For this purpose, the artificial neural networks approach will be used in predicting the efficiency factor of natural pozzolan.

2 Data base formation

Before the execution of the ANN program, an important stage e important must be realized and well checked, which is the database preparation..
In this part of work we must take into account various criteria in the choice of the data, which can directly influence the model design.

Generally, considering the sensitivity of this part of work, the selection of the data is done manually and not automatically by a specified software, each research project must be investigated in order to extract the values wished for the various entry's variables, in this case they are: the age, the natural pozzolan percentage and the W/B ratio required for the mortar or the concrete. This procedure was carried out respecting the following criteria:
- An ambient and ordinary curing temperature (between 20C° and 23C°);
- Such a percentage of super-plasticizer (lower than 2%) for low W/B ratios;
- Only the ordinary mixtures (concretes or mortars) were taken into account.

Fourteen (14) research projects for the mortars and twelve (12) for the concretes were chosen, since the shape of the specimens does not influence the efficiency factor, it wasn't standardized.

Table 1. Data of mortars with natural pozzolan

Ref.	Natural Pozzolan		W/B (%)	Strength (MPa)
	Origin	P (%)		
[3]	Algeria	10÷30	0.5	8.46÷41.3
[4]	Turkey	05÷40	0.5	5.4÷48.3
[5]	Turkey	20-30	0.48÷0.52	12.6÷56.7
[6]	Algeria	10÷40	0.47	3.5÷40.2
[7]	Mexico	10-20	0.65	34.5÷42
[8]	Algeria	10÷40	0.5	20÷47.9
[9]	Algeria	10÷30	0.5	11.2÷51.4
[10]	Slovakia	15÷50	0.6	16.9÷36.6
[11]	Algeria	10÷40	0.45÷0.65	18.56÷50.34
[12]	Turkey	35÷55	0.44÷0.5	7.6÷60.8
[13]	Greece	10÷30	0.46÷0.52	10÷50.5
[14]	Turkey	10÷30	0.5	5.3÷60.8
[15]	Turkey	05-30	0.5	10.67÷55.53
[16]	Greece	15	0.4	10.51÷55.34

Table 2. Data of concretes with natural pozzolan

Ref.	Natural Pozzolan		W/B (%)	Strength (MPa)
	Origin	P (%)		
[17]	Jordan	13-20-26	0.45÷0.6	14.1÷40.7
[18]	Mexico	28-32	0.45-0.60	8.5÷27.8
[12]	Turkey	20-25-30	0.45	7.1÷34.6
[19]	N/America	10-19	0.32÷0.40	20.3÷55.7
[20]	Turkey	35÷55	0.44÷0.5	7.6÷60.8
[21]	England	2÷75	0.40-0.58	1 ÷52.5
[22]	Turkey	0-50	0.45-0.61	11.8÷45.4
[23]	Algeria	10-20	0.31-0.44	23.3÷64.1
[24]	Nigeria	10-20-30	0.65	4.3 ÷19.6

2.1 Data normalization

The whole data accounts for a total of 64 formulas for the mortars and 120 for the concretes. A total of 425 efficiency factor values for mortars, and 410 for concretes. These results were employed to check the reliability of the mixture predictions (concrete and mortar) with natural pozzolan. The majority of the values have been removed during the evaluation of the data because of their influence on the efficiency factor prediction.

Table 3. Dividing database

Number of data used in Training	187
Number of data used in Test	41
Number of data used in Validation	41

The components which form the entry vector of the ANN have various quantitative limits, thus a normalization of the data is necessary. There exist several linear translations which can be employed to standardize the components of the entry vector so that it takes values ranging between -1 and 1. That among the most used and that has been employed in this work appears in following equation:

$$Xn = \frac{(ymax - ymin) * (X - Xmin)}{(Xmax - Xmin)} + ymin \qquad (1)$$

Where: X_n is the normalized data vector , X is the real input data vector, X_{min} and X_{max} is the minimum and the maximum of the input data vector X respectively, y_{max} and y_{min} are the values of normalizations equal to 1 and -1 respectively

After training the network, the output vector components Y must be de-normalized by using the following equation (2):

$$y = \frac{(Yn - ytmin) * (Xtmax - Xtmin)}{(ytmax - ytmin)} + Xtmin \qquad (2)$$

Where: Y_n is the output vector of the normalized data and Y is the output vector of the real data. X_{tmin} and X_{tmax} are the minimum and the maximum target output vector.

3 Design of the efficiency factor model

An ANN was developed to investgate the efficiency factor of natural pozzolans founded on the numerical database which was formed before. It used computation formulas which are developed based on Ferret calculation resistance models, after having tested the resistance models of Bolomey and Abrams.

3.1 Selecting the programming language

The computer programming languages are numerous, in this case, Matlab 2010b was chosen thanks to its strong mathematical relations instructions especially the possibility to access the ANN's program script, which makes it possible to well control the course of the program and to extract the weights and the bias found for architecture allowing for better judgement, depending on the state of satisfaction of the conditions of an acceptable performance. In addition, the user can choose any computer programming language which he finds more practical according to his knowledge and capacities.

3.2 ANN models development methodology

Executing the program in this version of MATLAB is summarized on one interface, the ANN architecture which was developed for modelling and the various calculation parameters.

Table 4 shows the architecture of this model with the training parameters and performances. This model was involved and tested with the whole training data, tested and validated by using the Feed-forward Propagation algorithm.

Table 4. Architecture and parameters of ANN model.

Age (day)	Architecture			Performance				Output
	N.H.L.	N.N.H.L	N.ITR	E.V	RA	RT	RV	
P (%) W/B	2	2	101	0.02	0.81	0.76	0.80	χ

Note: N. H.L.: Number of Hidden Layer; N.N.H.L.: Number of Neurons by Hidden Layer, N. ITR: Number of Iterations, R2:

coefficient of determination, A: Training, T: Test, V: Validation, EV : Validation Error.

The representation of this model can be realized as follows (Figure 1):

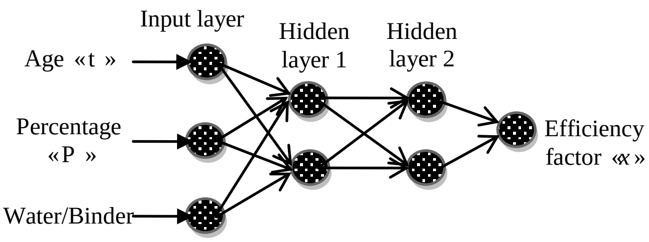


Fig. 1. Architecture o the proposed chosen ANN model

4 Comparison of results and experimental validation of the model

A sensitivity analysis was carried out with this model by the comparison of the results predicted with results of other researchers. Table 5 presents the predicted values of this factor according to the concrete age for various rates of natural pozzolan substitution. According to this table, the evaluation proved that, the efficiency factor decreases as a function of the substitution rate for all ages.

Table 5. Predicted efficiency factor for different W/B ratios.

W/B Ratio	Predicted Efficiency factor			
	2 days	7 days	28 days	90 days
0.4	0.42 - 0.13	0.44 - 0.19	1.33 - 0.58	2.00 - 0.81
0.5	0.30 - 0.08	0.40 - 0.12	1.05 - 0.43	1.58 - 0.59
0.6	0.22 - 0.03	0.29 - 0.07	0.69 - 0.32	1.21 - 0.41

Figure 2 represents the comparison between the efficiency factor variation by age of specimens predicted by the ANN model and the results found by Boukhatem [26] for a two similar input variables {Age(day), P(%)}, these results represent the only data found in the literature.

Unfortunately, there are no other studies on the evaluation of the natural pozzolan efficiency factor in a reasonable way. Knowing that the model suggested by Papadakis et al [27] is valid only for the artificial cementitous materials (slag and fly-ashes) and largely over-estimates the natural pozzolan efficiency factor.

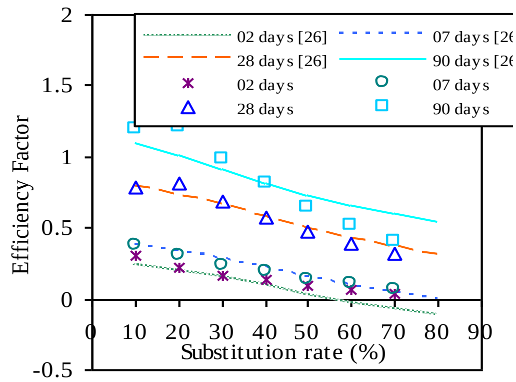
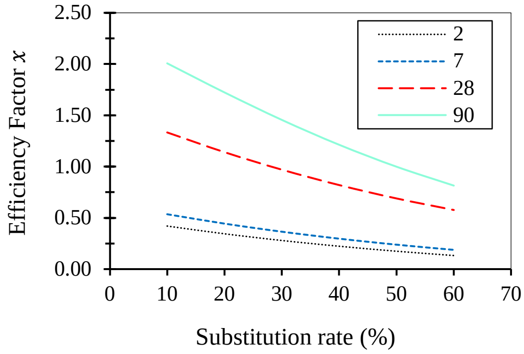
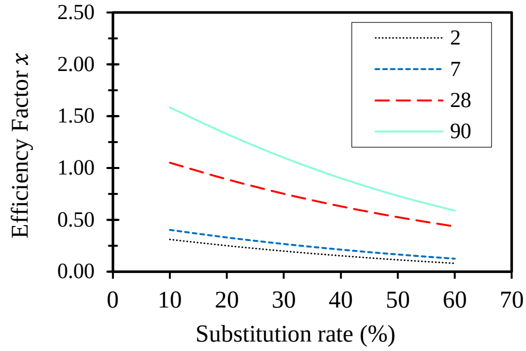


Fig. 2. Comparison of efficiency factor values.

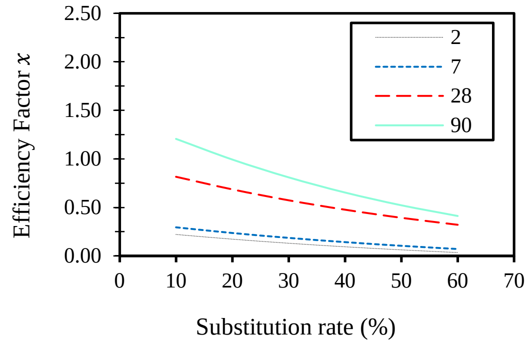
Figure 2 shows clearly that the natural pozzolan efficiency factor depends on the rate of substitution. It was observed that for all the ages, the efficiency factor *x* decreases for percentages of substitution ranging from 10 to 60%. These results are comparable with those obtained by Boukhatem [26] for a W/B=0.6.



(a) W/B=0.4



(b) W/B=0.5



(c) W/B=0.6

Fig. 3. Influence of age and substitution rate on the efficiency factor for: (a) W/B=0.4; (b) W/B=0.5 and (c) W/B=0.6

4.1 Influence of the rate of substitution

Figure 3 illustrates the variation of the efficiency factor x to 2,7,28 and 90 days of the concretes containing ratios from 10% to 60% of natural pozzolan. For these types of concretes, the efficiency factor increases with time of 2 days up to 3 months.

The evaluation of x at 28 days proved that this factor varies from 1,33 to 0,58 for the replacements from 10% to 60% of a mixture prepared with W/B of 0.4. Table 5 shows the variation intervals of x for all the mixtures which are (0.4, 0.5 and 0.6). However, it’s affirmed that the efficiency factor decreases when the quantity of Natural Pozzolan increases. In addition, for all the substitution rate of the natural pozzolan, x increases with time.

4.2 Mathematical model development

By introducing the predicted values of the efficiency factor with their suitable inputs into a statistical tool, a mathematical model in a form of equation of such a degree and such a field of definition can be calculated. A formula is chosen to be used according to the problem to deal with, therefore the complexity of this last requires a more complex equation. In this case the following exponential function (3) was chosen:

$$x\left(t,\frac{W}{B},p\right) = (a_0t^2 + a_1t + a_2)e^{(a_3p + a_4\frac{W}{B})} \qquad (3)$$

Where: x is the efficiency factor, W/B: the Water/Binder ratio, p: percentage of substitution, t: age. The coefficients of regression a0, a1, a2, a3 and a4 are represented in table 6.

Using the same method, Boukhatem [26] has determined the mathematical model containing two variables (age «t » and substitution rate «P »), equation 4 shows the model :

$$\chi(t,p) = (a_0 + a_1t + a_2t^2)\exp^{(a_3p)} \qquad (4)$$

Table 6. Mathematical model parameters.

	a_0	a_1	a_2	a_3	a_4	Coefficient of determination
Eq.3	-0.0012	0.1829	0.8644	-0.01849	-2.7681	0.95
Eq.4	0,098	0,036	-0,00025	-0,012	/	0.98

5 Experimental validation of the models

An experimental program was initially carried out with an aim of determining the compressive strength of twelve (12) concretes mixtures as shown in table 7. To validate the model, the mathematical model results obtained by Boukhatem are compared with the results of the developed mathematical model (eq.3) as shown in table 8.

Table 7. Concrete mixtures.

Designation	W/B	Rate P(%)	Cement (Kg/m³)	Water (W)	Additive (%)	Coarse Aggregates	Fine Aggregates
B1P0	0.6	0	350	210	0	1130	720
B1P10		10	305	210	0	1130	720
B1P20		20	280	210	0	1130	720
B1P30		30	245	210	0	1130	720
B2P0	0.5	0	400	200	1	1100	720
B2P10		10	360	200	1,2	1100	720
B2P20		20	320	200	1,5	1100	720
B2P30		30	280	200	1,9	1100	720
B21P0	0.4	0	450	180	1,8	1050	720
B3P10		10	405	180	2,1	1050	720
B3P20		20	360	180	2,5	1050	720
B3P30		30	315	180	2,8	1050	720

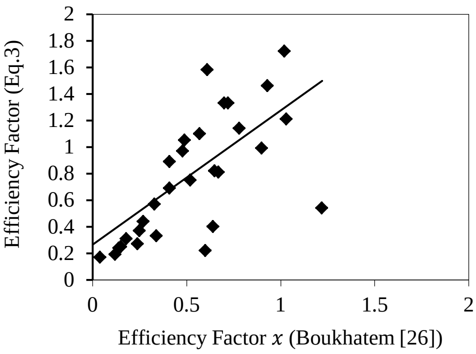
5.1 Experimental program

The experimental program consisted of the compressive strength measurements to 3,7,28 and 90 days on various concrete mixtures using various “water/binder” ratios. Mainly, four types of ordinary concretes in which cement was substituted partially by optimized quantities of natural pozzolan additives: 0%,10%,20% and 30%. After removal from the moulds, at 24 h of age, concrete specimens were immersed in lime saturated water at 20°C until the age of testing. Compression tests were conducted at 2, 7, 28 and 90 days. The results reported are the average of three compression tests.

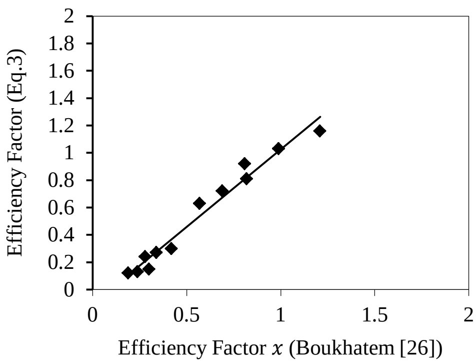
Table 8. Comparison of results.

W/B ratio	P (%)	Boukhatem model [26]				Mathematical model (Eq. 3)			
		2days	7days	28days	90days	2days	7days	28days	90days
0.6	10	0.15	0.30	0.81	1.16	0.19	0.33	0.80	1.19
	20	0.13	0.27	0.72	1.03	0.16	0.27	0.66	0.99
	30	0.12	0.24	0.63	0.92	0.13	0.23	0.55	0.82
0.5	10	0.15	0.30	0.81	1.16	0.26	0.43	1.05	1.56
	20	0.13	0.27	0.72	1.03	0.21	0.36	0.87	1.30
	30	0.12	0.24	0.63	0.92	0.18	0.30	0.72	1.08
0.4	10	0.15	0.30	0.81	1.16	0.34	0.57	1.38	2.06
	20	0.13	0.27	0.72	1.03	0.28	0.48	1.15	1.72
	30	0.12	0.24	0.63	0.92	0.23	0.40	0.96	1.43

Finally, in figure 4, the results of the mathematical model of Boukhatem [26] [2011] were compared with the results of the mathematical model expressed by equation (3). Figure 4 (a) shows a comparison between the efficiency factor obtained by using equation (3) for three W/B ratios (0.4, 0.5 and 0.6) and by using mathematical model of Boukhatem [26], whereas on figure 4 (b) one ratio (W/B = 0.6) was used in calculating efficiency factor by equation (3). In general, it is noted that these efficiency factors increase with age because of the increase in the resistance brought by the pozzolanic reaction of natural pozzolan.



(a)



(b)

Fig. 4. Comparison of results: a) Mathematical model (eq.3) / Boukhatem model, b) Mathematical model (eq.3) / Boukhatem model for W/B=0.6

It is shown on figure 4 that the model of Boukhatem was calculated by using a database containing a high percentage of the ratio W/B=0.6. This model does not vary with the variation of W/B ratio.

6 Conclusion

This prediction required three stages of work. Initially, a methodology was followed for the selection and the organization of the data of existing research on the proportions and the properties of the concretes with additives.

In the second place, the application of the approach of artificial neural networks to investigate the efficiency factor made it possible to develop a model with a satisfactory precision. In order to improve the prediction capacity of this model, the tracing of this factor according to the substitution rate and W/B ratio were carried out each time after training. This model was compared by comparison of the predicted results with the multiple regression model results as well as the mathematical model of Boukhatem [26]. The results prove that the ANN models are better supported by experimental data than the regression analysis in particular with the reduced and not correlated data (input and output data).

In the third part, an experimental program was carried out at the laboratory with an aim of validating developed ANN model. To cover the range of materials used in the model, four types of ordinary concretes were considered, in which cement weight was partially replaced by: 0%, 10%, 20% and 30% natural pozzolan. Moreover, three water-binder ratio: 0.4, 0.5 and 0.6 were used. A total of 12 concrete mixtures were carried out and tested by measuring workability and compressive strength. The experimental results were injected into the model for the numerical simulation of the efficiency factor. The validation tests provided good performance. Precise details were also obtained in the efficiency factor of natural pozzolan in comparison with the mathematical model of Boukhatem [26] at W/B=0.6.

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