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Life Cycle Assessment of Concrete Using Adaptive Neuro-Fuzzy Inference Systems

İlker Bekir Topçu [1], Turhan Bilir [1], Hakan Kuşan[2],

[1]*Eskişehir Osmangazi University, Department of Civil Engineering, 26480, Eskişehir, Turkey. E-mail: <ilkerbt@ogu.edu.tr>,<tbilir@ogu.edu.tr>..*

[2]*Dumlupınar University, Department of Civil Engineering, 48100, Kütahya, Turkey, E-mail: <hkusan@dumlupinar.edu.tr>.*

ABSTRACT

The aim of this work is to investigate how ANFIS modelling of the chloride permeability of concrete can contribute to the sustainable development. Therefore, to have an opinion about service lives of concrete structures, especially the reinforced ones. Thus, some mixture properties and the rapid chloride permeability test results of different types of concretes obtained from a previous study are used for constructing and developing an ANFIS model. Besides, a linguistic life cycle approach is proposed depending on ASTM C 1202. The performance of model and the linguistic life cycle assessment approach may make it possible to discuss the service live of structures. Additionally, it is available to gain economical and environmental advantages for sustainable development by predicting the chloride permeability of concrete and comparing them with ASTM C 1202 considerations.

INTRODUCTION

Chloride ions are generally known as the most harmful materials for embedded steel in concrete (Baradan et al., 2002). Road bridges, marine structures, tunnels, buildings car parks and precast structures can be deteriorated by the corrosion of reinforcement due to chloride ingress. Chloride ions have many negative effects on corrosion such as dissolving the passive layer that prevents development of corrosion.

According to Polden and Peelen (2002) concretes made with blast furnace cements or slag and fly ash cements show lower chloride penetration so these concrete types have higher electrical resistivity. Oh et. al. (2002) defines high performance concrete as the concrete having high resistance to chloride penetration as well as high strength. They have proved the positive effects of silica fume, fly ash (FA) or slag cement concretes on the property of chloride resistance. It is reported that water-binder ratio, maximum size aggregates, aggregate particle distribution and aggregate- paste volume ratio also affects the chloride ingress [Oh et al., 2002].

Before constructing the model, the properties of ANFIS should generally be discussed. First of all, ANFIS is capable of approximating any real continuous function on a compact set to any degree of accuracy [Jang et al., 1997; İphar et al., 2008]. In other words, there are almost no restraints on the node functions of an adaptive network except piece-wise differentiability. The only limitation of network configuration is of feed-forward type. Thus, the adaptive network applications are commonly used in various areas. The proposed architecture is referred to as ANFIS, standing for adaptive-network-based fuzzy inference system (Jang, 1993). When the data are the measurable system variables with an internal system parameter, a functional mapping may be constructed by ANFIS that approximates the process of estimation of the internal system parameter. ANFIS is a soft computing technique which incorporates the concept of fuzzy logic into the neural networks. ANFIS can simulate and analyze the mapping relation between the input and output data through a hybrid learning to determine the optimal distribution of membership function (İphar et al., 2008). It is mainly based on the fuzzy ‘‘if-then’’ rules from the Takagi and Sugeno fuzzy model (Jang et al., 1997). It involves a premise part and a consequent part.. It has five layers in this inference system and each layer involves several nodes, called as the node function (İphar et al., 2008).

In this study, the data obtained from the study of Güneyisi et al. (2009) is used as input to predict chloride permeability values by developing an ANFIS model. In this way, it is attempted to estimate the life cycle of concrete by the means of rapid chloride permeability using the factors mentioned in the model without conducting any experimental study. Therefore, the producers would decide the chosen cement, water to cement ratios, curing conditions and age to provide approximate life cycle.

METHOD

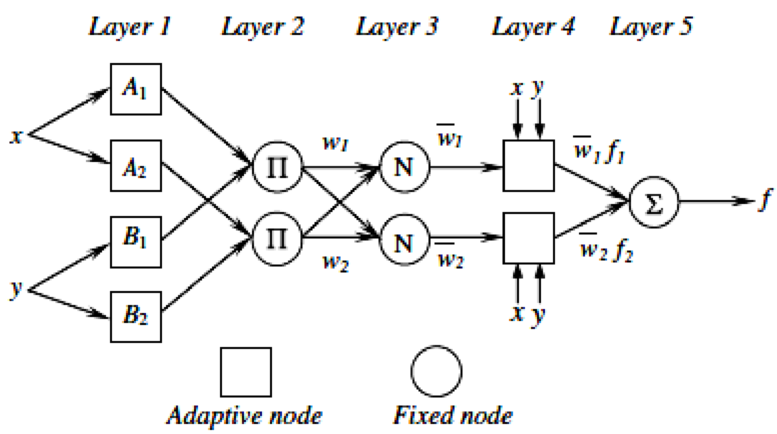

Fig. 1. The Architecture of ANFIS (Jang, 1997)

In this study, the chloride permeability values of concrete having different cement types in its composition, different water to cement and aggregate to cement ratios, different curing conditions and ages are attempted to be predicted by using ANFIS method. The required data is obtained from an experimental study conducted by Güneyisi et al. (Güneyisi et al., 2009). In this manner, the experimental values and the predicted values are compared to each other. The typical architecture of ANFIS can be seen in Fig. 1.

In the construction of ANFIS model, cement type (CT), water to cement ratios (W), aggregate content to cement ratios (A), superplasticizer admixture content to cement ratios (SP), curing conditions (CC) and testing age (TA) were used as inputs and chloride permeability (CP) was used as output to train and test the model and hence totally 90 data were obtained from a experimental study developing a neural-network model (Güneyisi et al., 2009). For this way, CEM I, CEM II/A-M, CEM II/B-M, CEM V/A, and CEM III/A type cements were expressed as 1, 2, 3, 4 and 5, respectively. The W, A and SP ratios of different types of mixtures uses as data for constructing the model did not have a wide range. Therefore, it could decrease the performance of the model. However, using these factors could make it possible to demonstrate the properties of the mixture in the developed model in a general way. Similarly, the curing conditions, namely uncontrolled curing (UC), controlled curing (CC), and wet curing (WC) were assigned as 1, 2, and 3, respectively. Uncontrolled curing conditions are the air curing conditions without controlling the temperature and relative humidity until the testing age. Controlled curing conditions were the conditions of 20 °C water immersing for 7 days and then air curing in a room at 20 ºC and 50 % relative humidity until the testing age. The wet curing conditions were the standard water curing conditions. Among all the data only 60 of them are used for training the model and 30 of them are reserved for testing. The training data is given in Table 1 and the testing data is presented in Table 2. Six inputs and one output were used to construct the ANFIS model. Besides, Takagi-Sugeno type ANFIS model and sub-clustering method were used to generate FIS. In the next process, hybrid method and ten epochs were applied. Two Gaussian membership functions were chosen for inputs during the training process. The reason for these choices is to obtain the best solution by using them. Different model types with different parameters were attempted and this model was chosen because of the best performance obtained compared with the other models. Totally 46 rules were obtained.

Table 1. Training Data

Inputs						Output
CT	**W**	**A**	**AP**	**CC**	**TA**	**CP**
2	0.65	6.17	0.0025	1	28	8610
3	0.65	6.14	0.0025	1	28	7694
5	0.65	6.12	0.0025	1	28	6249
1	0.45	4.51	0.0075	1	28	5801
3	0.45	4.47	0.0075	1	28	4286
4	0.45	4.48	0.0100	1	28	4186
1	0.65	6.18	0.0025	2	28	7118
2	0.65	6.17	0.0025	2	28	6933
4	0.65	6.15	0.0025	2	28	4382
5	0.65	6.12	0.0025	2	28	2395
2	0.45	4.50	0.0075	2	28	5230

Table 1. Training Data (Continues)

3	0.45	4.47	0.0075	2	28	3475
5	0.45	4.44	0.0100	2	28	1922
1	0.65	6.18	0.0025	3	28	6828
3	0.65	6.14	0.0025	3	28	4922

4	0.65	6.15	0.0025	3	28	3279
1	0.45	4.51	0.0075	3	28	4575
2	0.45	4.50	0.0075	3	28	4786
4	0.45	4.48	0.0100	3	28	1911
5	0.45	4.44	0.0100	3	28	1231
2	0.65	6.17	0.0025	1	90	8176
3	0.65	6.14	0.0025	1	90	7284
5	0.65	6.12	0.0025	1	90	5857
1	0.45	4.51	0.0075	1	90	4744
3	0.45	4.47	0.0075	1	90	3301
4	0.45	4.48	0.0100	1	90	2356
1	0.65	6.18	0.0025	2	90	6554
2	0.65	6.17	0.0025	2	90	6742
4	0.65	6.15	0.0025	2	90	4026
5	0.65	6.12	0.0025	2	90	1951
2	0.45	4.50	0.0075	2	90	4060
3	0.45	4.47	0.0075	2	90	2371
5	0.45	4.44	0.0100	2	90	811
1	0.65	6.18	0.0025	3	90	5799
3	0.65	6.14	0.0025	3	90	3938
4	0.65	6.15	0.0025	3	90	2087
1	0.45	4.51	0.0075	3	90	3152
2	0.45	4.50	0.0075	3	90	3760
4	0.45	4.48	0.0100	3	90	1353
5	0.45	4.44	0.0100	3	90	566
1	0.65	6.18	0.0025	1	180	6871
2	0.65	6.17	0.0025	1	180	7934
3	0.65	6.14	0.0025	1	180	6945
5	0.65	6.12	0.0025	1	180	5481
1	0.45	4.51	0.0075	1	180	4538
3	0.45	4.47	0.0075	1	180	3412
4	0.45	4.48	0.0100	1	180	2277
1	0.65	6.18	0.0025	2	180	6259
2	0.65	6.17	0.0025	2	180	6055
4	0.65	6.15	0.0025	2	180	3370
5	0.65	6.12	0.0025	2	180	1767
2	0.45	4.50	0.0075	2	180	3654
3	0.45	4.47	0.0075	2	180	2127
5	0.45	4.44	0.0100	2	180	679
1	0.65	6.18	0.0025	3	180	5470

Table 1. Training Data (Continues)

3	0.65	6.14	0.0025	3	180	3093
4	0.65	6.15	0.0025	3	180	1227
1	0.45	4.51	0.0075	3	180	2937
2	0.45	4.50	0.0075	3	180	3099
4	0.45	4.48	0.0100	3	180	900

5	0.45	4.44	0.0100	3	180	457

Table 2. Testing Data

Inputs						Output
CT	**W**	**A**	**AP**	**CC**	**TA**	**CP**
1	0.65	6.18	0.0025	1	28	7441
4	0.65	6.15	0.0025	1	28	8883
2	0.45	4.50	0.0075	1	28	5427
5	0.45	4.44	0.0100	1	28	5067
3	0.65	6.14	0.0025	2	28	5608
1	0.45	4.51	0.0075	2	28	4869
4	0.45	4.48	0.0100	2	28	3083
2	0.65	6.17	0.0025	3	28	6425
5	0.65	6.12	0.0025	3	28	1384
3	0.45	4.47	0.0075	3	28	2998
1	0.65	6.18	0.0025	1	90	6948
4	0.65	6.15	0.0025	1	90	7149
2	0.45	4.50	0.0075	1	90	4169
5	0.45	4.44	0.0100	1	90	3599
3	0.65	6.14	0.0025	2	90	5201
1	0.45	4.51	0.0075	2	90	3431
4	0.45	4.48	0.0100	2	90	1575
2	0.65	6.17	0.0025	3	90	6322
5	0.65	6.12	0.0025	3	90	768
3	0.45	4.47	0.0075	3	90	2178
1	0.65	6.18	0.0025	1	180	6871
4	0.65	6.15	0.0025	1	180	6839
2	0.45	4.50	0.0075	1	180	4191
5	0.45	4.44	0.0100	1	180	3001
3	0.65	6.14	0.0025	2	180	4814
1	0.45	4.51	0.0075	2	180	3050
4	0.45	4.48	0.0100	2	180	1485
2	0.65	6.17	0.0025	3	180	4675
5	0.65	6.12	0.0025	3	180	582
3	0.45	4.47	0.0075	3	180	1886

RESULTS AND DISCUSSION

Fig. 2. presents the comparison between the experimental and prediction results after training and testing the model. It is seen that the prediction and experimental results for the data are rather close to each other. On the other hand, the differences between these results can be relatively higher for some of data in both training and testing phases. Additionally, the maximum difference between the prediction and experimental results is 18.67 %. These differences can occur because of the narrow range of some experimental distribution of W, A and SP parameters. The experimental values of these parameters are limited to certain values

and have narrow ranges. This situation affects the performance of the ANFIS model. However, the experimental and predicted values are close and the differences are in acceptable range. On the other hand, this ANFIS model has been proposed for life cycle assessment in the means of chloride permeability which can demonstrate the quality and the durability of concrete. Additionally, high chloride permeability may lead to corrosion in reinforced concrete, thus corrosion can also reduce the service life of the reinforced concrete structures (Poupard, 2004; Richardson, 2002). The experimental results, the prediction results and the error percentages between them are given in Table 3.

Table 3. The Error Percentages Between Experimental and Prediction Results

Prediction	Experimental	Error Percentage
8831	7441	-18.67
7402	8883	16.67
5317	5427	2.03
4653	5067	8.18
5813	5608	-3.65
5321	4869	-9.28
2895	3083	6.11
6212	6425	3.31
1284	1384	7.22
3470	2998	-15.75
8176	6948	-17.68
7056	7149	1.30
4250	4169	-1.95
2987	3599	17.00
5596	5201	-7.59
3578	3431	-4.30
1777	1575	-12.83
5353	6322	15.33
887	768	-15.48
2159	2178	0.89
8110	6871	-18.04
6799	6839	0.59
4871	4191	-16.23

Table 3. The Error Percentages Between Experimental and Prediction Results (Continues)

Prediction	Experimental	Error Percentage
3165	3001	-5.46
4298	4814	10.71
3096	3050	-1.49
1394	1485	6.13
5247	4675	-12.24

665	582	-14.19
2094	1886	-11.02

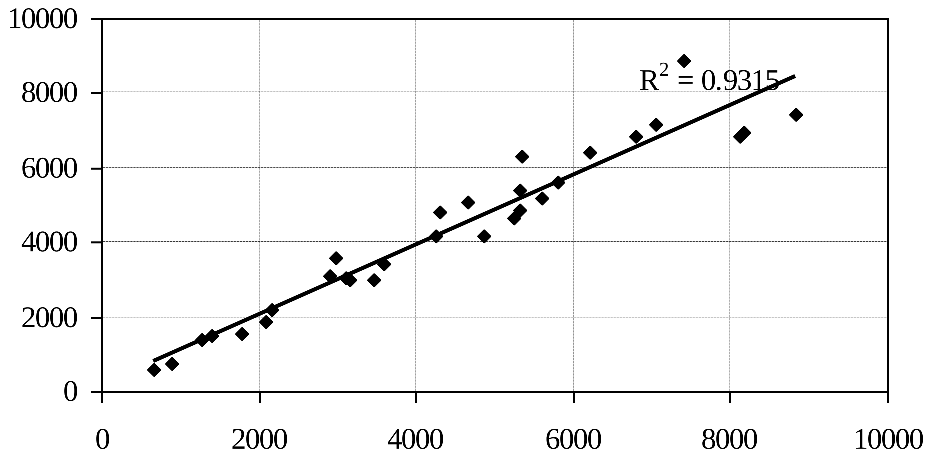

Fig. 2. The Performance of Proposed ANFIS Model

The absolute fraction of variance (R^2) is used to evaluate the performance of the model as their exesions by using the equation 1 given below. Besides, it is given in Fig. 2. It can be pointed out that the model parameters are chosen after trying different parameters such as sub-clustering, other kinds of MFS, different numbers of MFs and iterations. The performance value is checked and it is decided that the best solutions and predictions can be obtained by using this ANFIS model. On the other hand, it should still be indicated that the prediction results are acceptable and close to the experimental chloride permeability results.

$$R^2 = \frac{(n\sum t_i o_i - \sum t_i \sum o_i)^2}{(n\sum t_i{}^2 - (\sum t_i)^2)(n\sum o_i{}^2 - (\sum o_i)^2)} \qquad \text{Eq. 1.}$$

In order to asses the life cycle of concretes, the predicted chloride permeability results can be compared to the considerations of ASTM C 1207 (ASTM, 1997), then the predicted results can give an opinion by using the proposed linguistic approach given in Table 4. As known, there are some life cycle assessment approaches using surface chloride ion concentration. On the other hand, it is difficult to predict the service life of concrete and concrete structures, because there are many mixture designs, environmental and mechanical factors that decrease the durability of concrete. Thus, the service life of concrete can change depending on these factors. On the other hand, if the service life assessment could be simplified using only some parameters such as mixture design and one of the most critical durability properties such as chloride ion ingress, it might be easier to estimate the service life of concrete. Besides, if the service life ranges related to chloride permeability were coded as low or high, the service lives of high chloride permeable concretes would be in the critical service life range and thus, the required preventions could be taken in the mixture design stage in order to improve the quality and the performance of concrete in the means of chloride permeability. In this way, a linguistic approach is thought as given in Table 4.

Table 4. Chloride in Penetrability Based on Charge Passed (ASTM, 1997)

Charge passed (coulomb)	Chloride ion penetrability	Service Life (Linguistic Approach)
>4000	High	Very Low
2000-4000	Moderate	Low
1000-2000	Low	Moderate
100-1000	Very Low	High
<100	Negligible	Very high

In this approach, the service lives are thought to be low even if the chloride permeability is moderate. As known, these concrete types may have service lives more than at least 50 years. However, if it is thought like this, the service life can stay below the critical levels. For instance, when the predicted chloride permeability result of ANFIS model is obtained as negligible, the engineer does not have to modify the mixture design. On the other hand, if the chloride permeability is obtained as very high; the engineer can estimate the service life of concrete as very low and needs to modify the mixture design to improve the quality of concrete and the service life of the structure constructed using this concrete. .

The authors think that the consideration of ASTM C 1202 for chloride permeability and modern, empirical or statistical modeling of chloride permeability are very important to have an opinion about the service life of concrete structures. The rapid chloride permeability test are generally conducted at the ages of 28, 90, 180, 360 etc. Therefore, the structure may be constructed when chloride permeability test results are obtained. When the engineer attempts to estimate the chloride permeability at mixture design stage, the service life of the concrete structure can be discussed before the structure is constructed. Therefore, the quality and the durability of concrete can be improved; the required preventions can be taken and it may lengthen the service life of the structure. In this way, time and economic savings can be made. In developing countries, the quality of concrete is determined by conducting standard compressive strength test on specimens taken from fresh concrete while the structure is being constructed at the age of 28. If the quality of concrete is not sufficient, the related part of the concrete structure is demolished. Thus, early estimation of concrete quality may avoid this time and economical losses. Besides, new models can be developed by generalizing the input parameters to demonstrate all kinds of concretes. In this manner, the water content, types of used cement, aggregate (artificial such as rubber, waste concrete, waste glass, slag, fly ash, bottom ash, copper slag, etc. or natural), mineral (industrial by-products or natural pozzolans) and chemical admixtures, the contents of aggregates and admixtures can also be used in model construction in addition to the parameters used in this study. On the other hand, testing ages may also be predicted using chloride permeability as input. It may be possible with the experiences of researchers and the engineers. If the mixture properties of concrete used in the existing structures are known, the ages of existing structures can also be predicted by conducting rapid chloride permeability test on core samples taken from those structures. Such knowledge would make it easy to discuss the life cycle of existing or new constructed structures.

On the other hand, structures with longer service lives are very important for sustainable development. In other words, the situations mentioned above can also be said as important for industrial ecology and sustainable development. The energy and natural sources savings can be provided, the effects of demolished wastes of structures on environment and economy can also be prevented. Therefore, prediction of chloride permeability would also contribute to the sustainable development.

Finally, it can be said the predicted and experimental results are close to each other for most of the testing data and ANFIS can be employed to predict the rapid chloride permeability results without attempting rapid chloride permeability test by determining only mixture proportions and properties such as water to cement , aggregate to cement, super plasticizer to cement ratios. Furthermore, the prediction results give an opinion about the chloride permeability and life cycle performance of such concretes and ANFIS could be adapted for predicting the chloride permeability results of different types of concretes. Consequently, it would be available and possible to provide required precautions in order to improve the chloride permeability performance and thus, the durability and the service life of concrete.

CONCLUSIONS

It is extremely difficult to take into account of all controllable or uncontrollable parameters for the prediction of chloride permeability. Some models have recently been used for chloride permeability prediction. In this study, chloride permeability values obtained from the rapid chloride permeability test could easily be predicted.

Consequently, the ANFIS prediction model developed for GBFS mortars can be a useful tool for engineers as a preliminary guide for evaluating the effects of chloride permeability on service lives of concrete structures considering the mixture properties, curing conditions and ages. Moreover, improvements and modifications for the model may be achieved by constructing a wider database and including additional input variables even if they were expressed linguistically. Besides, this developed model or the improved one can be adapted for different kinds of concretes incorporating different types of materials such as cements, aggregates, mineral and chemical admixtures, bottom ash, fly ash, rubber, crushed tile etc.; as mineral admixture or aggregate, having different water to cement ratios, different sizes of aggregates, water content, cement content, etc. Briefly, it is possible to construct different types of models predicting different properties of concretes having different properties under different circumstances. In this study, this advantage has been used for predicting the chloride permeability. Therefore, the life cycle of concrete structures can be discussed before the construction and the precautions can be taken for the contribution of concrete as a wide used material especially in developing countries to the sustainable development. Consequently, all studies improving the sustainable development can be said as important for the future of humanity and the world.

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