Service Life Prediction of Silica Fume Concretes

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Abstract:Deterioration of concrete structures in the Gulf region is a serious problem. Penetration of Chloride ion into concrete is responsible for such early deterioration. Determination of chloride diffusion coefficient is an effective way to predict the service life of concrete structures.
In order to investigate the performance of concrete mixtures in such environments, ordinary and silica fume concrete mixtures containing various water to cementitious materials ratios were used. Rapid chloride permeability test and determination of diffusion coefficient of chloride ion penetration in accordance with bulk diffusion test under laboratory conditons simulated to Persian Gulf climate, and site investigation were performed. Concentration of chloride ions in various depths of concrete specimens was measured using acid soluble chloride test method.
Test results show that silica fume reduces the chloride penetration and the diffusion coefficient in concrete mixtures. Different models were made for rapid chloride test results, and diffusion coefficient, of concretes maintained in the hot and corrosive environments of the Persian Gulf. The models which were calibrated with real data obtained from the concrete structures are capable to predict the penetration and service life of concrete structures in such corrosive environments.

Keywords: *Service life, Silica fume, Severe environments, Diffusion model, Chloride ions , durability.*

1.Introduction

The most important concrete deterioration cases are related to corrosion of reinforcement due to carbonation- or chloride-induced depassivation of steel bars [1]. Chloride may be added to the concrete as impurities of the constituent materials or added to the concrete by means of admixtures. However , the chloride content of any concrete admixture is limited today. In former times calcium chloride used as an accelerator to concrete has caused so many defects that calcium chloride is no longer accepted in concrete. Thus, left as predominant chloride sources are seawater, de-icing salts and industrial processes. Numerous surveys have indicated that chloride ions, originating from deicing salts or seawater, are the primary cause of reinforcing steel corrosion in highways and marine or coastal structures [2]. The chlorides that are transported through the concrete pore network and microcracks depassivate the oxide film covering the reinforcing steel and accelerate the reaction of corrosion. Even high-performance concrete may not necessarily ensure long-term durability in a severe environment unless it is designed for dimensional stability and soundness [3].

On the other hand, it has been well established [4] that sustainable development of the cement and concrete industries can be achieved by complete utilization of cementitious and pozzolanic by-products, such as fly ash, slag, and silica fume. In addition to the effect of these materials on usual structural properties, such as strength and volume stability, the durability of concrete incorporating these supplementary cementing materials (SCM) should be taken into account.

Fick's law of diffusion can represent the rate of chloride penetration into concrete as a function of depth from the concrete surface and time[9]:

$$\frac{dC(x,t)}{dt} = D\frac{d^2C(x,t)}{dx^2} \tag{1-a}$$

$$t = \frac{x^2}{4D_a}\left(erfc^{-1}\left[\frac{C_t(x,t)}{C_s}\right]\right) \tag{1-b}$$

Where *C(x,t)* is the chloride ion concentration, as % by weight of cement, at a distance of x(m) from the concrete surface after t seconds of exposure to the chloride source. D is the chloride diffusion coefficient expressed in m^2/s.

Recently, large-scale structures were actively being built in the Persian Gulf area. The Persian Gulf region is one of the most severe environments in the world due to the combined effects of: 1) high concentrations of chloride and sulphate salts which attack the reinforcement and concrete matrix respectively, 2) elevated ambient temperatures together with strong drying winds which accelerate the rate of corrosion and deterioration as well as compromising the quality during its early exposure, 3) large daily fluctuations in temperature and humidity which produce progressive microcracking in the concrete during service [5] and finally 4) occasional poor workmanship combined with low quality aggregates and binder materials.

In the present work, an experimental investigation of the effect of silica fume on the resistance of Portland cement systems to chloride penetration under simulated Persian Gulf conditions was carried out. For these purposes two test procedures were used: 1) ASTM C1202 Rapid Chloride Permeability test (RCPT) and 2) bulk diffusion test under simulated Persian Gulf conditions. Two neural network models were used to predict the RCPT result and chloride diffusion coefficient (D) using experimental results. Correlation was made between the results of these two models.

It is assumed that the diffiusion coefficient D>0 is either a constant or a function of t alone. When D(t) only depends on time, we can define a new time varriable, for which the diffusion coefficient is constant, so it suffices to assume that D is a constant.

We notice that almost every process in nature is nonlinear, so an application of Fick's seconds law is in principle "only" the first linear approximation of the description of chloride ingress into concrete. It is, however, a very important part of the solution, and in some sense the real behavior can be viewed as perturbations from this linear model. For that reasion Fick's second law is central for the theory, though not the whole answer.
In principle, Fick's second law defines a mixed initial/boundary value problem for a parabolic partial differential equation.

2. Marine environments

It is convenient to define the following three environmental zones of marine exposure,

- Marine atmosphere, ATM. Concrete placed 3 m or more above the highest maximum water level incl. waves. Concrete exposed to marine atmosphere can, if relevant, be subdivided into leeward and windward marine atmospheres.

- Marine splash, SPL. Concrete placed between 3 m above the highest maximum water level incl. waves and 3 m below the lowest minimum water level inclusive of waves.

- Submerged in seawater, SUB. Concrete placed 3 m or more below the lowest minimum water level inclusive of waves.

3. Experimental Program

3.1. Laboratory Tests

There are several laboratory test methods and in-situ test methods for chloride ingress into concrete. It is characteristic for a majority of the metods on diffusion in concrete that the observations obtained have to be evaluated before applied in practice. Therefore, these test methods are mainly for making comparision between various types of concrete.

3.1.1. Materials and mixture proportions

ASTM Type II Portland cement was used throughout this study. Silica fume was obtained from a local factory and used in a slurry form. The chemical admixture used in all mixtures was Melcrete 2000 superplasticizer (SP). The coarse aggregate was crushed limestone (absorption = 3.12% and specific gravity = 2.54 g/cm^3) and the fine aggregate was a river sand (absorption = 2.43%, and specific gravity = 2.50 g/cm^3). Eight mix designs, each with a cementitious material content of 360 kg/m^3, were used. The W/CM ratios were 0.35, 0.4, 0.45 and 0.5. The silica fume replacements for cement on a dry mass basis were 0 and 7%. Table 1 shows the properties of various mixture designs in this investigation.

Prior to mixing, the silica fume slurry was stirred thoroughly inside a pail with a small automatic mixer to ensure uniformity. Concretes were mixed by hand in a 40 l flat pan. The SP was added to the mix right after the silica fume slurry, in order to reduce the stiffness and enable thorough mixing of the slurry. Specimens were cast in moulds of 100 × 100 × 100 mm cubes, and 100 × 100 mm cylinders. All concrete specimens were cured in a moist condition for 28 days.

3.1.2. Compressive Strength

The compressive strength test was carried out on 100 × 100 × 100 mm specimens at 28 days.

3.1.3. Rapid chloride permeability tests (ASTM C1202)

Due to scheduling of the research program, cylindrical disks of 100 mm diameter and 100 mm height were cut into two 50 mm thick ones and used for RCPT. The samples were vacuum-saturated before being tested. The charges passed after 6 hours were recorded. Three specimens were used for each test. It is the fact that RCPT measures mainly concrete resistivity, and not permeability or diffusivity directly.

3.1.4. Bulk diffusion test under simulated conditions

Climatic conditions of the Persian Gulf region and laboratory conditions exerted on the bulk diffusion test procedure are shown in Table 2. Specimens were tested after 2.5 and 5 months. Two 100 × 100 × 100 mm cubes were used for each test. Cores were immersed in chloride solution inside plastic containers 28 days after casting and powders were collected from the samples after grinding. Chloride content in concrete mass at various depths was determined according to ASTM C114.

3.2. Test Results and Discussion

3.2.1. Compressive Strength

The results of compressive strength test are presented in Table 1. It is clearly seen that the replacement of silica fume and reduction in W/C increase the compressive strength of all concrete mixtures.

Table 1 Properties of concrete mixes

MIX ID	W/CM	WATER (KG)	CEMENT (KG)	SAND (KG)	GRAVEL (KG)	SILICA FUME (KG)	28D STRENGTH (MPA)
C.50	0.50	180	360.0	1000	800	0.0	34.0
SC.50	0.50	180	334.8	1000	800	25.2	36.8
C.45	0.45	162	360.0	1000	800	0.0	35.9
SC.45	0.45	162	334.8	1000	800	25.2	39.1
C.40	0.40	144	360.0	1000	800	0.0	45.5
SC.40	0.40	144	334.8	1000	800	25.2	58.7
C.35	0.35	126	360.0	1000	800	0.0	56.0
SC.35	0.35	126	334.8	1000	800	25.2	61.2

Table 2 Climatic conditions of Persian Gulf region and laboratory conditions exerted on bulk diffusion test

PARAMETER	PERSIAN GULF CONDITIONS	LABORATORY CONDITIONS
Chloride Ions Concentration (g/l)	21.4	54.0
Other Ions Concentration (g/l)	17.6	48.0
Temperature (^oC)	13.0 to 38.4	35.0
Relative Humidity (%)	49.0 to 81.5	80.0

Table 3 Rapid Chloride Permeability Test Results (by Coulombs)

MIX	C.50	SC.50	C.45	SC.45	C.40	SC.40	C.35	SC.35
Coulombs	3791	2884	3461	2440	2608	1820	1748	1169

3.2.2. Rapid chloride permeability tests (ASTM C1202)

The average RCPT results, shown in Table 3, are normalized to a standard diameter of 95 mm as recommended in ASTM C1202. The results clearly indicate that silica fume was effective in reducing the RCPT values. Figure 1 illustrates the effect of silica fume on RCPT results.

3.2.3. Bulk diffusion test under simulated conditions

Figures 2 and 3 present chloride profiles after 2.5 and 5 months of exposure times for different mixture designs. Table 4 shows calculated diffusion coefficient at different exposure times for various mix designs. It is considered that the diffusion coefficient decreases by decreasing W/CM ratio and increasing silica fume. Figure 4 depicts the effect of 7% microsilica on decreasing the diffusion coefficients of concretes containing various W/CM after 2.5 and 5 months of exposure times.

3.3. Neural Network Models

Neural network (NN) approach, as a sub-field of Artificial Intelligence, is used to

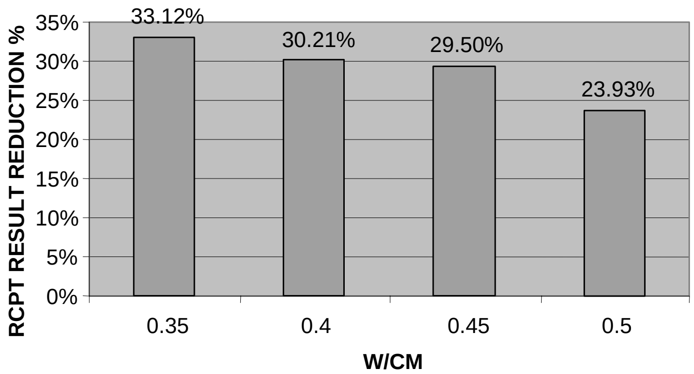


Fig.1 The effect of using silica fume (by cement mass) on decreasing RCPT results

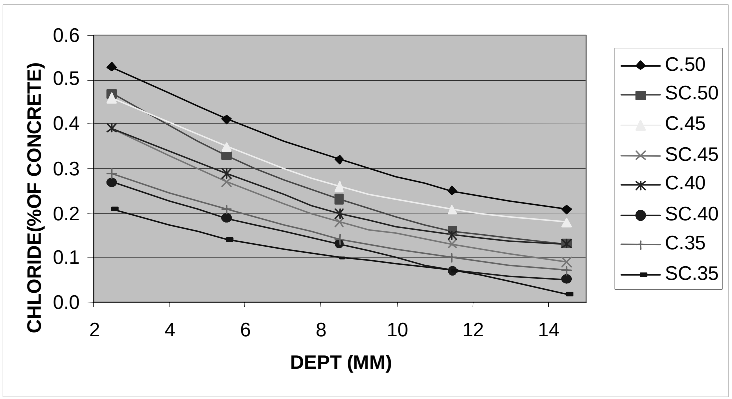


Fig. 2 Chloride profiles after 2.5 months exposure time, for different mix designs

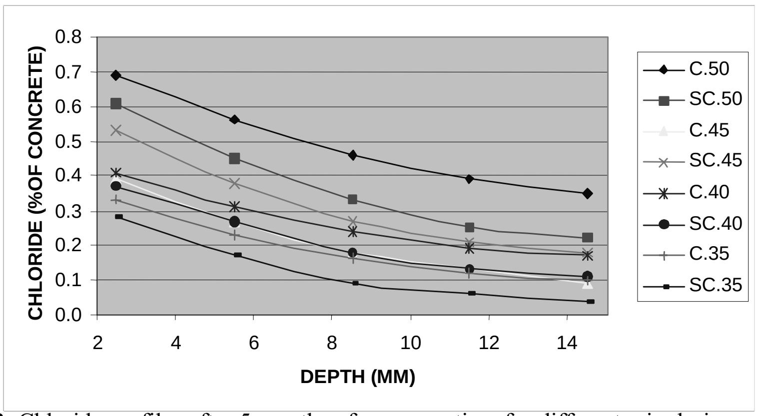


Fig.3 Chloride profiles after 5 months of exposure time for different mix designs

Table 4 Calculated diffusion coefficient (D_B [mm^2/year]) at different exposure times

MIX ID	C.50	SC.50	C.45	SC.45	C.40	SC.40	C.35	SC.35
2.5 months exposure time	402.0	241.9	381.1	207.0	287.9	155.4	208.8	100.9
5 months exposure time	331.5	169.5	295.1	156.0	205.8	123.2	127.0	63.7

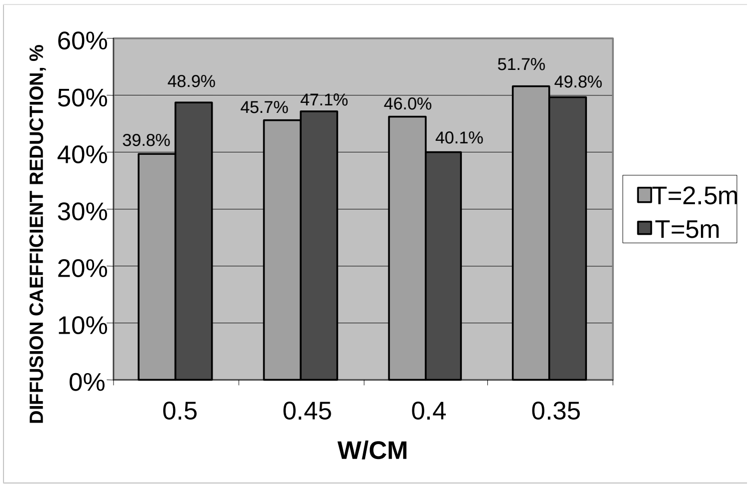


Fig. 4 Diffusion coefficients reduction for various W/CM ratios after 4 and 8 months of exposure times

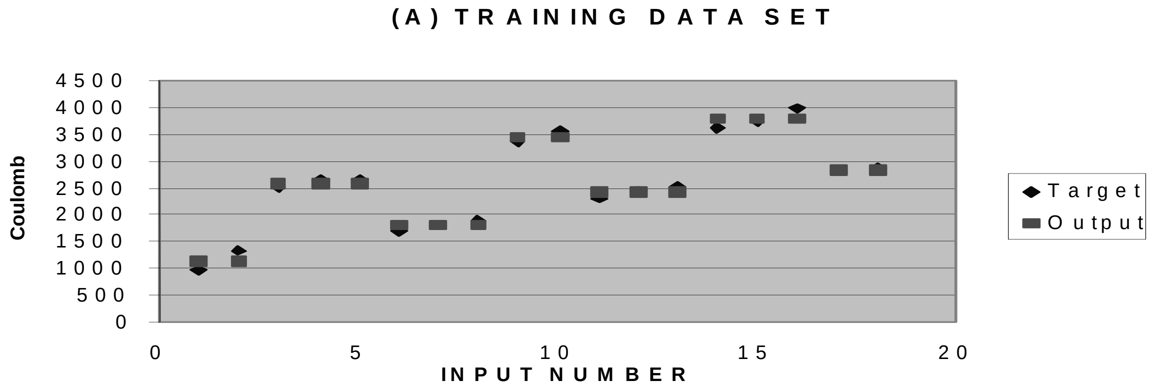
Table 5 Evaluation of neural network models

MODEL	DATA	R	AVG. ABS.	MAX. ABS.	RMS	RECORDS
M1	Train	0.992	84.031	199.300	101.958	19
	Test	0.991	92.200	138.500	112.359	5
M2	Train	0.999	2.180	6.750	3.023	13
	Test	1.000	5.200	6.580	5.331	3
M3	Train	0.999	3.200	11.900	4.520	19
	Test	0.994	8.150	18.540	10.860	5
M4	Train	0.993	4.270	7.530	5.780	19
	Test	0.994	6.750	10.480	7.440	5

solve a wide variety of problems in civil and structural engineering [6-8]. It facilitates economic considerations (due to reducing experimentations) by learning complex cause and effect relationship from historical experimental data. This paper presents NNs application for predicting of chloride penetration resistance of concrete. For this purpose and concerning test results, four models are proposed: 1) Model 1 (M1) predicts RCPT results in coulombs, 2) Model 2 (M2) predicts bulk diffusion coefficient (D_B) under simulated conditons, 3 and 4) Models 3 and 4 (M3 and M4) represent correlation between RCPT results and D_B in ordinary and silica fume concrete (0 and 7% silica fume by cement mass). The input parameters for the neural network are mix proportion and test condition. The backpropagation algorithm and Levenberg-Marquardt are used for training neural networks. The work demonstrates that using NNs for predicting concrete resistance to chloride penetration is practical and beneficial.

3.3.1. M1: Neural Network Model for RCPT results

Water to cementitious material ratio (W/CM), and silica fume content (by mass of concrete) were selected as the two input parameters, because they are the two most important factors affecting chloride



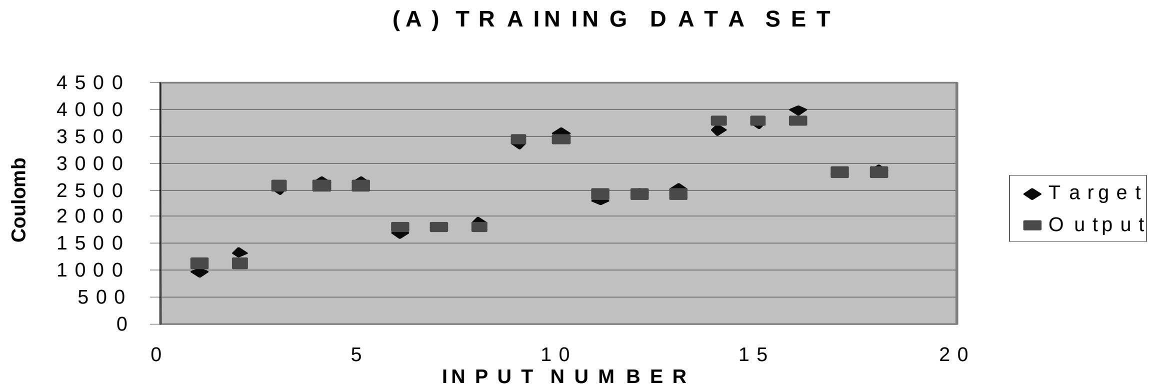


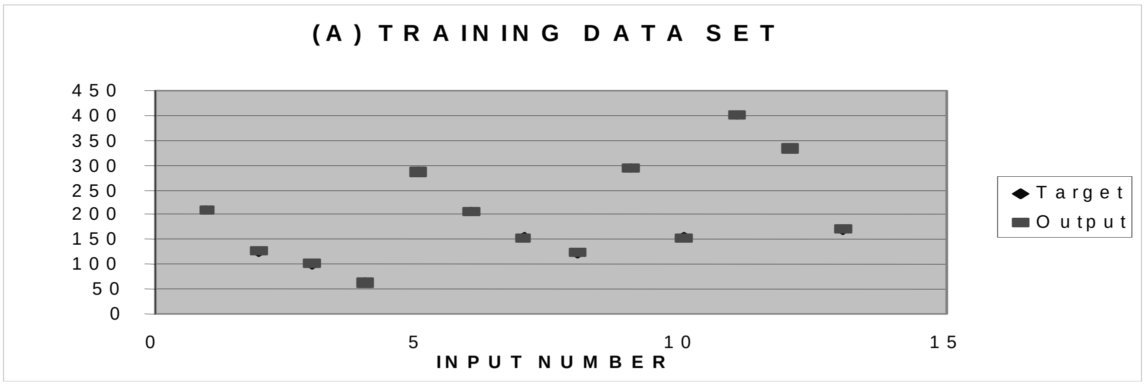
Fig.5 Comparison of predicted and real values of RCPT results (by coulomb) using neural network M1

penetration.

The data for model M1 were obtained from standard RCPT results. Two independent neural networks were trained for this model. Each of the networks had two inputs (W/CM ratio and silica fume content) and one output (RCPT results in coulomb). The optimal number of nodes in the hidden layers was determined empirically (There is no mathematically oriented way of determining the optimal number of nodes in the hidden structure). However, there is a heuristics number - for example, the number of nodes in the hidden layer should be equal to the sum of the nodes in the input and output layer – but this tends to be a specific problem.

It is often possible to obtain good performance on a training set. One of the best methods of measuring the success is to evaluate model performance with new data (independent test set). Thus the data files were divided into a training set and a test set, which concluded 80 and 20% of the data in each, respectively. The model was constructed using the appropriate training set, and was validated by using the corresponding test set.

Statistical evaluation of the model for training set and test set are presented in Table 5. The factor R is the linear correlation between the real world target output and the real world target model output. In Table 5 all of the values of R are greater than 0.99. This shows that more than 99% of the variations are accounted for by the model. Since the



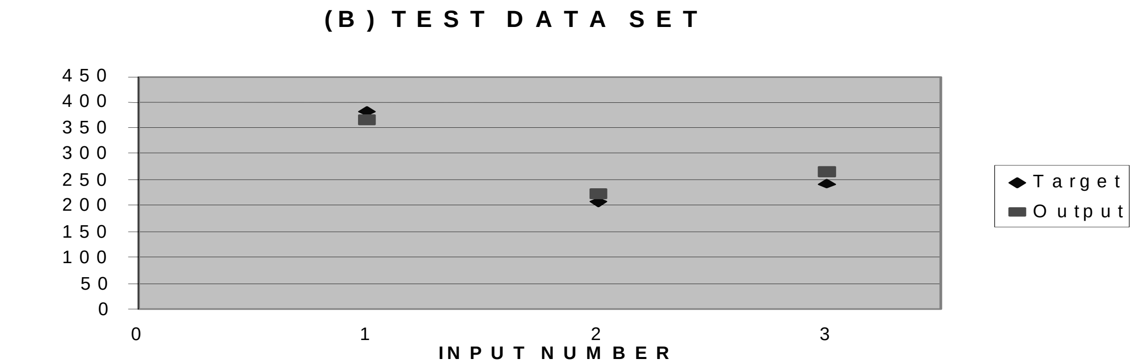


Fig.6 Comparison of predicted and real values of bulk diffusion coefficients (D_B) under simulated conditons using neural network M2

maximum value of R is 1, the values in Table 5 confirm the appropriate fitnesses between the target and output values. Average absolute (Avg. abs.) is the average difference between the real world target output and the real world prediction. Maximum absolute (Max. abs.) is the maximum difference between the real world target output and the real world prediction. RMS is the root mean square error between the real world target output and the real world prediction.

Charges passed the concrete in coulomb for different W/CM ratios and silica fume contents are produced separately for training and test sets using the trained models, and compared with actual experimental data (see Fig. 5). It shows that the NN models give a good prediction of the actual coulomb values from experimental results. The models are reliable and accurate, thus they can be used to predict the RCPT results with two contents of silica fume, and different W/CM ratios between 0.35 and 0.5.

3.3.2. M2: Neural Network Model for Bulk diffusion coefficient (D_B)

Water to cementitious material ratios (W/CM), silica fume content and exposure time were selected as the three input parameters, because they are the three most important factors affecting chloride penetration.

The data for model M2 were obtained from bulk diffusion tests under simulated conditions which gave diffusion coefficient (D_B). Two independent neural networks were trained for this model. Each of the networks had three inputs (W/CM ratios, silica fume contents and exposure times) and one output

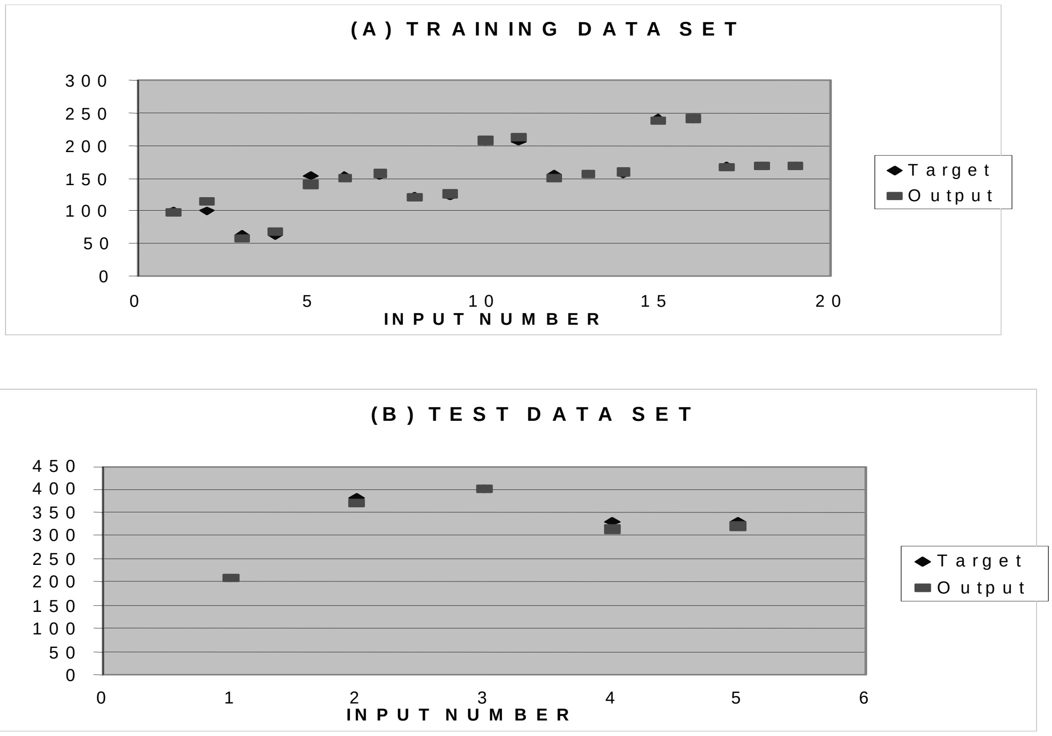


Fig. 7 Comparison of predicted and real values of bulk diffusion coefficients (D_B) under simulated conditons using neural network M3

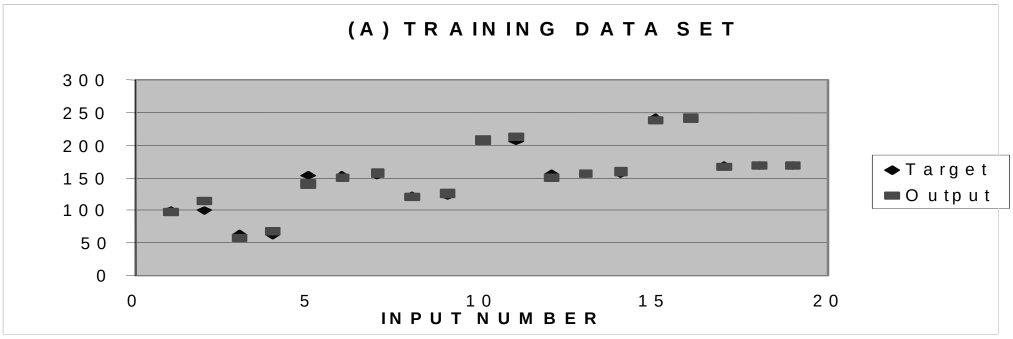
(D_B). Other neural network topology conditions of this model are similar to model M1. Performance and selecting training and test data sets for this model are also similar to model M1.

Statistical evaluation of the model for training set and test set are presented in Table 5. All of the parameters in this table have been explained in previous sections. Since the maximum value of R is 1, the values in Table 5 confirm the appropriate fitnesses between the target and output values.

Bulk diffusion coefficient (D_B) of concrete with different W/CM ratios, silica fume contents and exposure times are produced separately for training and test sets using the trained models and compared with actual experimental data (see Fig. 6). It shows that the NN models give a good prediction of the actual bulk diffusion coefficient (D_B) from the experimental results. The model is reliable and accurate thus it can be used to predict the bulk diffusion coefficient (D_B) with two silica fume contents (0 and 7 percent), two exposure times (2.5 and 5 months) and different Coulomb values.

3.3.3. M3 & M4: correlation between RCPT results and D_B

RCPT results and exposure time under simulated conditions were selected as the two input parameters for M3 & M4 models.
The data for M3 & M4 models were obtained from RCPT and bulk diffusion test under simulated conditons. Two independent neural networks were trained for these models. Each of the networks had three inputs (RCPT results and exposure times) and one output (bulk diffusion coefficient, D_B). Other neural network topology conditions of these models are similar to model M1. Performance and selecting training and test data sets for these models are also similar to model M1.



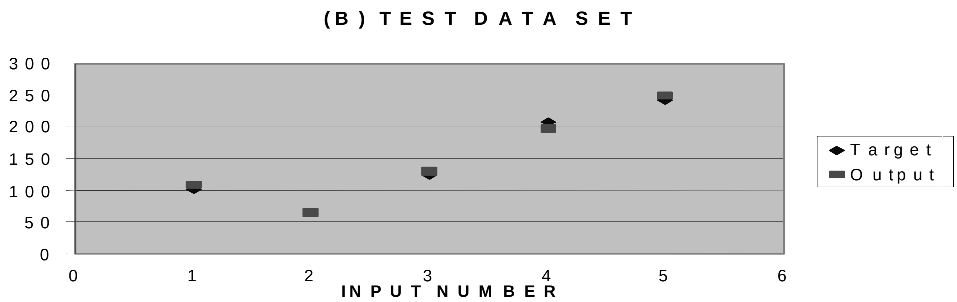


Fig. 8 Comparison of predicted and real values of bulk diffusion coefficients (D_B) under simulated conditons using neural network M4

Table 6 Mean Values of Permeability Depth (DIN 1048) (mm)

w/c \ Mix Type		Type 1	Type 1+%7MS	Type 1+%10MS
0.45	28d	11	9	8
	180d	8	8	5
0.40	28d	9	8	6
	180d	8	6	5
0.35	28d	8	7	6
	180d	7	7	5

Statistical evaluation of the model for training set and test set are presented in Table 5. All of the parameters in this table have been explained in previous sections. Since the maximum value of R is 1, the values in Table 5 confirm the appropriate fitnesses between the target and output values.

Bulk diffusion coefficient (D_B) of concrete with different Coulomb values (RCPT results) and exposure times are produced separately for training and test sets using the trained models and compared with actual experimental data (see Fig. 7 & 8). It shows that the NN models give a good prediction of the actual bulk diffusion coefficient (D_B) from the experimental results. The model is reliable and accurate thus it can be used to predict the bulk diffusion coefficient (D_B) with two exposure times (2.5 and 5 months) and different Coulomb values.

3.4. Laboratory Results

Mean values of permeability depth and acid soluble chloride contents are given in Tables 6 and 7, respectively.

Table 7 Acid Soluble Chloride Ion Contents (9 months) (%)

MIX Type w/c	Type 1					Type 1+%7MS					Type 1+%10MS				
	Depth (mm)														
	4	8	12	16	20	4	8	12	16	20	4	8	12	16	20
0.45	.28	.17	.15	.11	.12	.16	.15	.06	.00	.00	.17	.14	.10	.01	.00
0.40	.27	.18	.11	.09	.09	.19	.18	.05	.00	.00	.20	.15	.09	.02	.00
0.35	.25	.14	.13	.06	.02	.18	.16	.04	.00	.00	.14	.13	.07	.00	.00

4. Surveying Existing RC Structures in Marine Environments

Concrete is a kind of material which is characterized by an ongoing change of its microstructure, chemically as well as physically. The greatest change takes place immediately after casting when the hydratiom of the binders start. However, the microstructural changes will take place even after years with a notable change in properties and characteristics of the concrete. After the development of the final microstructure an ageing process will take place, also resulting in a change of properties and characteristics of the concrete.

The chloride diffusion coefficient of concrete is one of the properties which will be time-depenent. However, when the concrete has been exposed to a chloride laden environment for more than 20-30 years the change in time per year has slowed down. This means that it is possible to obtain a rough estimate of future ingress and the initiation period by neglecting the time dependency.

There are several sources of uncertainties when determining the chloride content of concrete. Even mistakes can take place as shown by several tests. There are four main sources of uncertainties:

- Exposure conditions, in field as well as in laboratory.

- Preparing samples for analysis, in-situ as well as in laboratory.

- Analysis of chloride content, the test methods chosen in-situ as well as in laboratory.

- Interpretation of observations, when rejecting or accepting observations for curve-fitting.

Also, the chloride content of the exposed concrete surface Cs is time- dependent. However, concrete submerged in seawater or exposed to the marine splash will reach its (nearly) final value after 5-10 years, and it certainly will be a fair estimate to assume that the chloride content of the surface will remain constant after a time- interval of approximately 25 years. On the other hand, concrete which is exposed to a marine atmosphere and traffic splash seems to show a time-dependent chloride surface content for a considerable longer time.

4.1. Studying Two Silica Fume Concrete Structure in Persian Gulf Seashores

In order to study the behavior of concrete structures in actual conditions, two concrete

Table 8 Schmidt hammer results

Place of sampling	Main Water Reservoir				Sulphure Warehouse	
	parallel to shore	normal to shore	Trash Canal	Valve Box	1	2
Compressive strength (Schmidt hammer) (MPa)	52	51	48	34	49	50

Table 9 Chloride profile results

Location \ Depth (mm)	0-3	3-6	6-9	9-12	12-15
Water Reservoir, The wall parallel to sea bank	0.51	0.42	0.35	0.30	0.27
Water Reservoir, The wall perpendicular sea bank	0.48	0.40	0.34	0.29	0.26
Water Reservoir, Trash Canal	0.63	0.54	0.46	0.40	0.36
Water Reservoir, Valve Box	0.71	0.62	0.55	0.48	0.44
Sulphur Warehouse, The wall parallel to sea bank	0.29	0.23	0.18	0.15	0.13
Sulphur Warehouse, The wall perpendicular to sea bank	0.35	0.27	0.22	0.18	0.15

structures, constructed with silica fume concrete in Energy Free Zone of Asaluyeh in Iran were studied. These structures were “Main Water Resevouir” and “Sulphur Warehouse”, aged 4 and 2 years, respectively. Three characteristics of the concretes were studied: Compressive strength, based on Schmidt rebound hammer; chloride profile; and carbonation depth.

4.1.1. Schmidt rebound hammer results

Schmidt hammer results are given in Table 8.

4.1.2. Chloride Profile

Chloride ingress into the near-to-surface layer of a chloride exposed concrete structure or a concrete specimen can, at any time, be determined and described by its chloride profiles. The total information about the environment, the length of the exposure period, and the chloride profile will give a clear but also an inconvenient picture of the chloride exposure and the response of the concrete.

In order to determine chloride profile, first by using profile Grinder apparatus, concrete powder of 3-mm layers were prepared.
Then chloride profile of each layer was determined by using titration method in accordance with ASTM- C114. The results are given in Table 9 .

4.1.3. Carbonation Depth

In order to determine Carbonation depth, the phenolphtalein Solution was used. The results are shown in Table 10 .

Table 10 Carbonation Depth

Location`	Carbonation depth (mm)
Water Reservoir, The wall parallel to sea bank	45
Water Reservoir, The wall perpendicular sea bank	32
Water Reservoir, Trash Canal	48
Water Reservoir, Valve Box	36
Sulphur Warehouse, The wall parallel to sea bank	28
Sulphur Warehouse, The wall perpendicular to sea bank	24

Table 11 C_x values for different concrete mixes (cover thikness=70mm)

Concrete mixes	w/c	x(mm) 2	4	6	8	10	12	14	16	18	20
		C_x									
Type II cement	0.40	0.37	0.36	0.35	0.33	0.30	0.29	0.26	0.24	0.22	0.22
	0.35	0.39	0.34	0.24	0.25	0.24	0.21	0.19	0.17	0.16	0.13
Type II+ 7% SF	0.40	0.37	0.27	0.24	0.20	0.16	0.14	0.12	0.09	0.08	0.04
	0.35	0.20	0.18	0.16	0.11	0.10	0.08	0.06	0.04	0.03	0.04

4.1.4. Determining Surface concentration parameter (C_s) and effective diffusion coefficient for chloride ion (D)

Second Fick's law is assumed to govern the process:

$$C_x - C_b = (C_s - C_b)\left[1 - erf\,\frac{x}{2(Dt)^{\frac{1}{2}}}\right] \qquad (2)$$

To determine the time for initiating corrosion of reinforcements by using this equation, first it is necessary to calculate C_s and D parameters. For this, we shoud apply curve-fitting approach of the equation. The corresponding values for C_x are given in Table 11 .

Since C_s and D are time dependent, so it is necessary to determine their functions varying by time. These functions can be written as:

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m \qquad (3)$$

$$C_s(t) = C_{s(ref)}\left(\frac{t_{ref}}{t}\right)^n \qquad (4)$$

where t_{ref} is the reference time, which is 4 years for Water Resource Structure, and 2 years for Sulphur Warehouse structure. For Determining m and n constants, we need to know D and C_s in two different time.

Thus, because of close similarity between conditions of two structures, only their age, we can consider the C_s and D of Sulphur Warehouse structure as C_s and D for 2 years, and C_s and D of water Resource building as C_s and D for 4 years. Mean while C_s and D is

Table 12 Calculated parameters for different concrete mixes

Concrete type	w/c	Fitted line $\sqrt{C_x} = ax + b$	C_s (% Cl^- by concrete mass)	D_0 ($mm^2/year$)	K_1 ($mm/\sqrt{year}$)	t (years)
type II	0.40	-0.0087x+0.6353	0.404	444	47.3	2.2
	0.35	-0.0128x+0.6153	0.378	192	30.0	5.5
type II+ 7% SF	0.40	-0.0202x+0.6187	0.383	78	19.5	13.0
	0.35	-0.0161x+0.4780	0228	74	15.8	20.0

considered as the mean of two corresponding values for the walls perpendicular and parallel to the sea bank.

t= 2(years) D=44.826 mm²/year, *C_s = 0.335 % mass binder*

t= 4(years) D=37.015 mm²/year, *C_s = 0.514 % mass binder*

Then, m and n are achieved as: m=0.26, n=0.618

By comparing these results with life - 365 relations , presented by ACI, we have:

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m \times e^{-0.165SF} \qquad (5)$$

The basic value of m is consindered equal to 0.2, and the silica fume content equal to 0.07, then:

t= 2(years)

$$\Rightarrow 44.826 = D_{ref}\left(\frac{28}{2\times 365}\right)^{0.2} \times e^{-0.165\times 0.07}$$

t= 4(years)

$$\Rightarrow 37.015 = D_{ref}\left(\frac{28}{4\times 365}\right)^{0.2} \times e^{-0.165\times 0.07}$$

which results:

$$D_{ref} \approx 84\, mm^2/yr$$

4.1.5. Predicting the Time for Initiating Corrosion of Reinforcements

By substituting equations (3) and (4) and values m and n in equation (2), we have:

$$C_x - C_b = \left[0.514\left(\frac{2}{t}\right)^{-0.618} - C_b\right]\left[1 - erf\frac{x}{2\left[44.826\left(\frac{2}{t}\right)^{0.276} - t\right]}\right] \qquad (6)$$

Because of previous experiments, the concentration of chloride ion C_b, and critical concentration of chloride ion are considered equal to 0.02 and 0.05, respectively.

Substituting these values in equation (6), the time for reaching the concentration of chloride ion on the surface of reinforcements to the critical value, i.e. the bar cover, was computed. Then, the predicted times for initiating reinforcement corrosion, t:, depending the bar cover, are computed and presented in Table 12.

4.1.6. Site Results

Chloride penetration results of concretes placed in Persian Gulf conditions are shown in Tables 11 and 12. The maximum chloride concenration at the surface (C_s), the chloride diffusion coefficient (D_0), the first year ingress of the critical chloride concentration (K_1), and the remaining service life of the structure (t) are included in these Table 12.

Results show that the incorporation of silica fume in the mixes reduces the depth of chloride penetration and thus increases the service life design of concrete structures. Longer service life can be achieved by lower w/c.

5. Conclusion

Based on the experimental investigation, and neural network models constructed using test results, the following conclusions are drawn:

- The Rapid Chloride Permeability Test (ASTM C1202) results indicate that using 7% silica fume in concrete decreases the passing charges. This reduction varies between 23.9 to 33.1 percent, depending on different W/CM ratios of concrete mixtures.

- The bulk diffusion test results under simulated conditons show the reduction of diffusion coefficient (D_B) with a reducing W/CM ratio, and an increase with the exposure time.

- The bulk diffusion test under simulated conditions indicates that using 7% silica fume in concrete decreases the measured diffusion coefficient (D_B). This reduction varies between 39.8 to 51.7 percent, depending on different W/CM ratios and different exposure times.

- The work indicates that neural network models which were constructed with the test results, are capable to predict the concrete resistance to chloride penetration.

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