EVALUATION OF CHLORIDE DIFFUSION IN CARBONATED CONCRETE INCLUDING SILICA FUME

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The purpose of this paper is to provide a model for predicting the corrosion process in concrete. This model is defined based on the simultaneous infiltration of chloride ions and the phenomenon of carbonation of concrete under certain environmental conditions. For this purpose, the simultaneous effect of chloride ion diffusion and carbonation phenomenon was studied using experiments on the fabricated samples. For this reason, in the first case, the samples are exposed to carbon dioxide once and then to chloride ions. In the latter case, only samples under the influence of chloride infiltration are examined. To make the samples, which include 9 mixing designs, three water-to-cement ratios of 0.35, 0.4 and 0.5 and three percent of 0%, 7% and 10% silica fume have been used. In this study, accelerated chloride ion (RCPT) penetration, capillary adsorption, pressurized water penetration and compressive strength tests of concrete were performed on the samples. Also in control and carbonate samples, the results of long-term experiments including chloride ion penetration and determination of chloride ion profile and determination of chloride ion diffusion coefficient have been investigated. The results of permeability tests show that carbonation has a direct effect on reducing the flow rate in the chloride ion permeation test and also reducing the capillary adsorption coefficient in the water capillary adsorption test. While increasing the ratio of water to cementations materials, the effect of carbonation on reducing the flow rate and also the capillary absorption coefficient of water increases, it should be noted that increasing the percentage of soot silica reduces this effect. Using linear fitting models on the results of long-term experiments, the amount of changes in chloride ion diffusion coefficient due to carbonation of concrete and determination of chloride ion concentration in concrete is presented.

Keywords: *Carbonation, Chloride diffusion coefficient, Concrete, Porosity, Silica fume*

1. Introduction

Although the fact that concrete and reinforced concrete are very durable compared to steel, but severely corrosive environments such as beaches and ports and islands of the Persian Gulf and the Sea of Oman are highly vulnerable to damage. Therefore, their useful life is significantly reduced. One of the major failures of this type of structure is the corrosion of reinforcement in reinforced concrete because of the penetration of chloride ions and carbonation of concrete. This damage is the most considerable damage to reinforced concrete structures in the world. The damage caused by it has been compared to the damage caused by the war in terms of size and scale.

The coasts and islands of the Persian Gulf have a particular climate and climatic situation in the world. These areas have many unfavorable conditions for the destruction of reinforced concrete structures. It be said that it has the most destructive and unfavorable conditions for reinforced concrete structures in the world. On the other hand, many projects are currently underway in the Persian Gulf region, especially in areas such as Assaluyeh. Significant amounts of concrete are used to build different types of structures. In addition, due to the industrialization of the region, changes in the concentration of pollutants, including CO_2 gas in the region, can be predicted.

Steel buried in concrete is safed against corrosion by a very thin oxide layer placed on the outer surface of the reinforcement. This layer is formed in a highly alkaline environment (pH about 13) of concrete around the reinforcements, and remains stable. If the pH of the environment around this layer reaches about 9, this layer is destroyed and corrosion of the reinforcements begins [1].

The pH of concrete changes with the penetration and release of gases in the environment and the formation of acids. The main effective gases are air CO_2 and SO_3 in rainwater [2].

Carbon dioxide in the air is more important. Its penetration the concrete causes the phenomenon of carbonation. Concrete carbonation is a chemical reaction between carbon dioxide penetrating into concrete with alkaline products Arising from the hydration of cement in concrete. This reaction is one of the exchange reactions between the attacking fluid ,and the cement paste, which leads to the formation of soluble calcium salts.

Page and Vennesland investigated the possibility of increasing the solubility of Friedel salt in microsilica-containing cements. In their study, this group made concrete samples with 10%, 20% and 30% microsilica instead of cement and

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observed changes in pore alkalinity and chloride entrapment [3].

Swami and Suryavanshi investigated the effect of carbonation on the stability of Friedel salt. Some of different concrete slabs were constructed with water to cement ratios (w / b) and the use of mineral additives such as microsilica, steel furnace slag, and fly ash. The slabs were subjected to wet and dry cycles. The results showed that the solubility of Friedel salt increased in carbonate regions [4].

Ishida and Maekawa Using thermodynamic equations and mass transfer governing concrete, proposed a finite element model to forecast the useful life of reinforced concrete structures. This computational model was presented in software called DuCOM, which can model failure phenomena in concrete and thermal analysis [5-7].

Lin and Liang investigated the simultaneous effect of chemicals on reinforced concrete structures using one-dimensional diffusion equations. They proposed an analytical solution of the diffusion equation using the Laplace transform way and the Convolution theorem. Also, the simultaneous effect of Cl^- and CO_2 as well as Cl^- and SO_4^{2-} as well as CO_2 and SO_4^{2-} was included in the equations. To consider the simultaneous effect of the above compounds, this group used a delay coefficient R in their equations to investigate the effect of each ion on the other [8].

Razzaqpour et al. presented a numerical model to consider the simultaneous effect of temperature transfer, humidity, chloride penetration, and carbonation phenomenon in concrete. The proposed model includes a numerical solution of two-dimensional equations governing infiltration. In this study, the finite element method was used to solve the equations. The effect of carbonation on the change of concrete pore structure and its interaction with moisture and chloride transfer is considered in this model. The result of carbonation on chloride release is not included in this group. The model of this group is presented in software called CONDOUR [9].

Putatsannan and Soma presented a nonlinear numerical model for the simultaneous penetration of chloride and carbonation into concrete. The model of this group was very similar to the model presented by Razzaqpour. The difference was that this group used the finite difference method to solve the equations. Heat, relative humidity, chloride penetration, and carbonation are the phenomena that were studied in this group as finite difference models. The effect of simultaneous diffusion of chloride and carbonation in two models of homogeneous and heterogeneous concrete has been investigated [10].

Song et al. presented a numerical model to forecast the useful life of reinforced concrete structures under the simultaneous influence of chloride and carbonation. The model presented by this group is somewhat similar to Ishida, which includes models of thermal hydration of concrete components, model of microstructure formation, mass transfer model, chloride penetration, and carbonation and corrosion model of steel. In the model presented by this group, the finite element method was used to solve the equations governing the infiltration phenomenon. This model can also model the failure due to the simultaneous effects of moisture penetration, chloride and structural changes of concrete under the effect of carbonation. The model of this group considers the effect of carbonation on the release of chloride through experimental equations. The results of the proposed model for chloride infiltration were validated with the results of sampling of a river bridge [11].

Ameli et al. They developed an eco-friendly compacted concrete. The following variables were used in their research; high volume fly ash (HVFA) at 50%, 60%, and 70% replacement by volume; crumb rubber at 10%, 20%, and 30% replacement by volume of fine aggregate; nano silica at 0%, 1%, and 2% addition by weight of cementitious materials. The amount the Vebe time, fresh density, compressive strength, flexural strength, splitting and tensile strength of HVFA RCC increased by adding nano [12].

Ghahari et al. investigated the effects of carbonation and simultaneous attack of chloride ions on the mechanical properties and durability of concrete containing silica fume. By comparing the baking of plain cement in the tidal area with the sample containing silica fume in the same baking conditions, it was seen that the sample containing silica fume has 1.5% less porosity than the cement sample [13].

Ramezanianpour et al. Ramzanpour et al. evaluated the durability properties of mortar that has been exposed to carbonation and accelerated chlorination by adding micro silica and slag to the mortar. Based on the obtained results, durability properties are improved by adding slag. It should be noted that one of the good options for increasing mechanical properties and durability is adding micro silica to mortar.

Wang et al. By studying the effect of combined carbonation and chloride ingress regimes on the behavior of chlorides, Wang and his colleagues found that during corrosion caused by chloride, combined carbonation and chloride ingress regimes significantly reduces the useful life of the structure [14].

Fattouh et al stated based on their research that the samples with steel fibers and steel fibers with silica fume have higher compressive strength than the control samples [15].

Bai et al. obtained full strain stress curves by performing uniaxial compression tests on recycled aggregate concrete containing silica fume.

Using this method, the mechanical properties of this type of concrete were evaluated [16].

Wei et al presented an intelligent algorithm for a prediction model of the carbonation depth of concrete containing mineral additives. Based on the results obtained, air ash content and carbonation time are the most important factors affecting the carbonation depth of concrete containing mineral additives. [17].

Bernard et al. The effect of aluminates and carbonates on the stability of hydrates of magnesium silicate phases was discussed on the governing factors of the composition of hydrated phases, the phase set and the degree of reaction with compressive strength by the method of thermodynamic calculations. [18].

In this paper, the physical effects of carbonation on chloride penetration and changes in the physical trait of concrete like changes in concrete porosity are investigated. This research is based on laboratory methods. For this purpose, concrete samples are exposed to chloride ions in two forms of fully carbonated and ordinary non-carbonated concrete. At a certain time, the samples are profiled, and based on this, the change of chloride concentration is obtained. As a result, a relationship between chloride concentration in carbonated concretes and ordinary concretes is obtained. The penetration of chloride into the concrete is considered to be based on the diffusion mechanism, which follows Fick's law. The depth of influence is obtained from the relation resulting from the same law, the relation of the root of time

2. Experimental program

2.1 Materials

ASTM Type I-425 Portland cement with a specific gravity of 3.15 and silica-fume with a specific gravity of 2.90 was used. Nine mix designs, each with a cementitious material content of 400 kg/m3, were used. The W/CM ratios were 0.35, 0.4 and 0.5. The silica fume replacements for cement on a dry mass basis were 0, 7% and 10%. Table 1 shows the properties of various mixture designs in this investigation.

Coarse aggregate with a size range of 6,20 mm was used. The fine aggregate was river sand with a maximum size of 4 mm and a fineness modulus of 3.

2.2 Mixing and preparation of specimens

Nine mix designs, each with a cementitious material content of 400 kg/m3, were used. The water-to-cement (w/c) ratios were 0.35, 0.4, and 0.5. The SF replacements for cement on a dry mass Basis were 0, 7% ,and 10%. Table 2 shows the properties of various mixture designs in this investigation. In this table, C represents the amount of cement and Csf indicates the amount of microsilica. Specimens were cast in moulds of 100 * 100 * 100 mm cubes, and 100 * 200 mm cylinders. The specimens were exposed to chloride in three different conditions for more than 270 days at38ºc.

The superplasticizer used in making the samples was also selected from the neutral type without chloride ions. The construction of the samples was done according to the Aba

Table 1

Physical and chemical properties of ordinary Portland cement and SF

	Chemical composition %									Specific gravity	Blaine cm^2/g
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O		K_2O	Ig.loss		
Ordinary Portland cement	21.50	3.68	2.76	61.50	4.80	0.12		0.95	1.35	3.15	3.0
SF	96	0.6	0.6	0.3	0.5	0.1		0.2	1.7	2.90	3.83

Table 2

Mix proportions of concretes

Mix ID	W/(c+csf)	Csf/(c+csf)	Water kg/m^3	Cement kg/m^3	Gravel kg/m^3	Sand kg/m^3	SF kg/m^3
M-35-0	0.35	0	140	400	1050	800	-
M-35-7	0.35	7%	140	372	1050	800	28
M-35-10	0.35	10%	140	360	1050	800	40
M-40-0	0.4	0	160	400	1050	800	-
M-40-7	0.4	7%	160	372	1050	800	28
M-40-10	0.4	10%	160	360	1050	800	40
M-50-0	0.5	0	200	400	1050	800	-
M-50-7	0.5	7%	200	372	1050	800	28
M-50-10	0.5	10%	200	360	1050	800	40

regulations. In making samples, a slump between 5 and 7 cm is considered a slump. The samples were processed in containers containing saturated lime water solution at a temperature of 21 ± 2 ° C.

It should be noted that because the penetration depth in the samples was about 2.5 cm in the maximum case, so the selection of the sample size did not effect on the results. Also, according to the dimensions of the experimental samples, the maximum aggregate dimension was limited to 2.5 cm. However, according to previous studies, the maximum aggregate has been little considered in the diffusion models, and its effect on the chloride ion diffusion coefficient is not very significant.

2.3 Carbonate the samples

Since the goal of this study is to study the effect of carbonation on changing the properties of concrete, the samples were tested in both carbonate and non-carbonate states. In order to carbonate the concrete, samples, after 28 days of curing, several samples were subjected to CO2 gas for one month to perform the carbonation process in the carbonation machine at 60% humidity. Control samples were also placed in the tank to control the carbonation of the samples. The amount of incoming gas was determined to occupy at least half of the space inside the tank with carbon dioxide gas. For this purpose, the amount of exhaust gas was determined according to the exhaust gas flow rate (observed from the regulator degree) and time measurement. However, due to the possibility of gas leakage, the gas injection was performed several times. Phenolphthalein solution was used to control the carbonation depth of the control samples. Carbonated samples along with control samples were subjected to chloride ions for 270 days in three submerged environmental conditions, tides, and above water level (atmosphere). The fixate of chloride ion in the medium was considered to be 30 gr/lit.

3. Analysis of test results

3.1 Compressive strength of samples

Compressive strength test was carried out on 10 cm cubic specimens at 28, 90, and 270 days according to ASTM C39 standard.

Figure 1 to 3 shows the strength of carbonated and non-carbonated samples based on the mixing design and the age of the samples. As can be seen, the resistance changes in the samples do not have a specific trend based on whether the samples are carbonate or not, and practically carbonation does not cause a important variation change in the strength of the samples. This can be considered in the low carbonation depth compared to the sample dimensions. In other words, although it is expected that the strength of this layer will increase with surface carbonation, because the strength of the cubic sample is more affected by the middle layers of concrete, the effect of carbonation on changing the strength is not obvious. A similar result of this research is mentioned in reference [19-20].

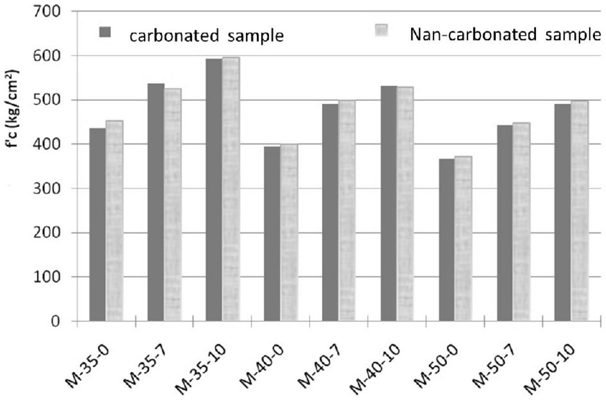

Fig1-Results of compressive strength testing at 28 days age

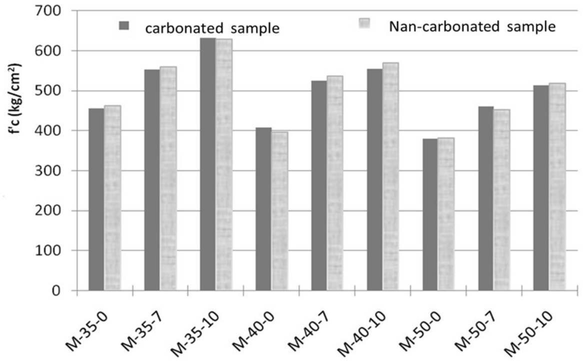

Fig2-Results of compressive strength testing at 90 days age

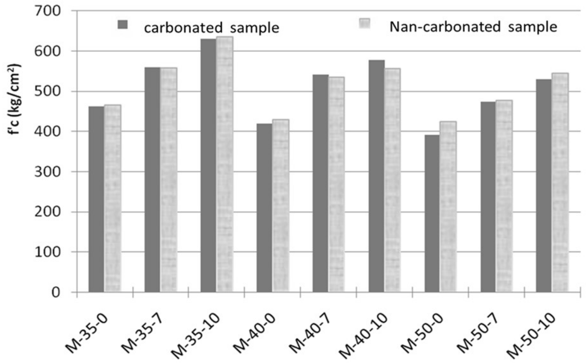

Fig3-Results of compressive strength testing at 270 days age

Table3

Results of the RCPT test

Mix ID	Non-carbonated concrete		carbonated concrete	
	Age(days)		Age(days)	
	28	90	28	90
M-35-0	1104	952	730	732
M-35-7	481	367.5	324	240.5
M-35-10	299	284.5	236	175
M-40-0	1323	940	899	643.5
M-40-7	785	661.5	615	470
M-40-10	661	586.5	576	438.5
M-50-0	2445	2260	1368	1610
M-50-7	2127	1877	1012	848
M-50-10	1046	992	831	751.5

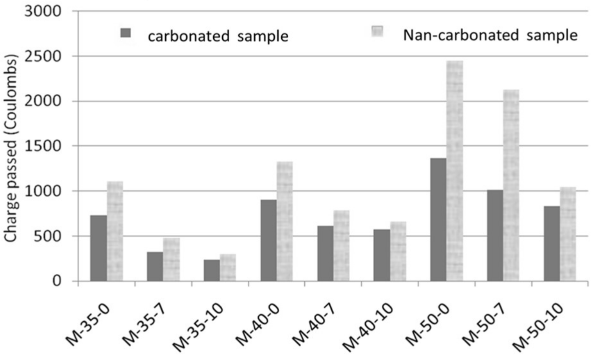

Fig4 - Results of RCPT test at 28 days in carbonate and control samples

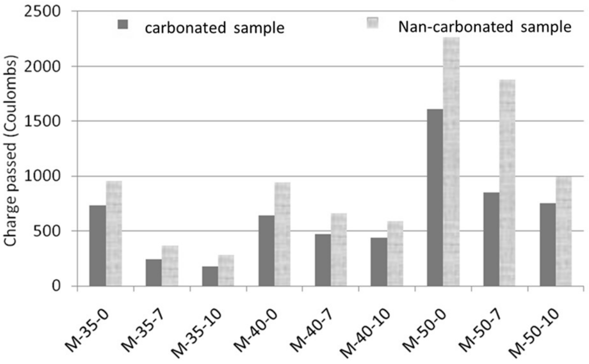

Fig5 - Results of RCPT test at 90 days in carbonate and control samples

3.2 The rapid chloride ion permeability test (RCPT)

In the RCPT test, the passing load of the concrete sample is measured according to ASTM C1202 or AASHTO T277 standard, and it is used to grade concrete according to standard. To perform this test, cylindrical samples with a diameter of 10.2 cm (4 inches) should be used. And a height of 51± 3 cm (2 ± 1.8 inches). Table 3 demonestrate the results of the RCPT test for nine mixing designs at 28 and 90 days of age. The presented results are the average results for three samples.

Figures 4 and 5 show the flux changes in the RCPT test for different samples. Due to the placement of the samples in a cell of the experimental device and the same conditions for making the samples, the flux changes in this experiment can be attributed to the carbonation effect. In other words, due to the reality that carbonation has reduced the porosity of the surface adjacent to sodium chloride, the flux has also decreased. Comparison of the graphs also shows that with increasing the percentage of silica fume, the result of carbonation in reducing the flow rate is reduced. The reason for this can be seen in the reduction of calcium hydroxide in samples with silica fume and thus reducing the effect of CO_2 gas on porosity changes.

The effect of silica fume in reducing the porosity of concrete and the predominance of this effect on the reduction of porosity due to carbonation is another reason for reducing the effect of carbonation on flux changes in samples with silica fume. Similar results in reference [16] also show that at carbonation depths of more than 1 cm, changes in the flux rate are pretty evident in the RCPT experiment. Considering that in the existing samples, the carbonation depth is more than 1 cm, the obtained results show a similar trend with the reference [19].

3.3Absorption test

The test is performed after the processing age the samples are dried in the oven (at a temperature of 50 ° C for three days) and weighed. Then, the samples are placed inside the water side so that 0.5 cm of their bottom is placed in the water, and water can penetrate from the bottom of the sample. By determining the change in weight of the sample at specific times up to 72 hours, the amount of capillary water absorption of the samples is determined. Table 4 shows the results of capillary uptake test for nine mixing designs at 28 and 90 days of age. The presented results are the average results for three samples.

Another result that can be obtained from capillary absorption test is capillary absorption coefficient. In general, the curve of changes in sample weight versus time is a nonlinear curve. However, if the sample weight changes against the time square are plotted, a line can be easily fitted between the relevant points. The slope of this line is known according to Equation 1 as the capillary absorption coefficient

$$K = S \times t^{0.5} \qquad (1)$$

Figure 6 shows an example of the results for one of the mixing schemes. The amount of capillary absorption coefficient is presented in Table 5

Table4

Experimental results of absorption test (weight change percentage of samples)

Mix ID	Non-carbonated concrete		carbonated concrete	
	Age(days)		Age(days)	
	28	90	28	90
M-35-0	1.66	2.31	1.58	1.59
M-35-7	1.17	1.05	0.88	0.94
M-35-10	1.97	1.36	1.96	1.17
M-40-0	2.68	1.91	2.25	1.06
M-40-7	2.1	1.88	1.88	1.91
M-40-10	1.98	2.1	1.63	1.82
M-50-0	3.73	4.27	3.4	4.3
M-50-7	4.95	3.38	2.4	3.6
M-50-10	1.33	3.7	3	3.1

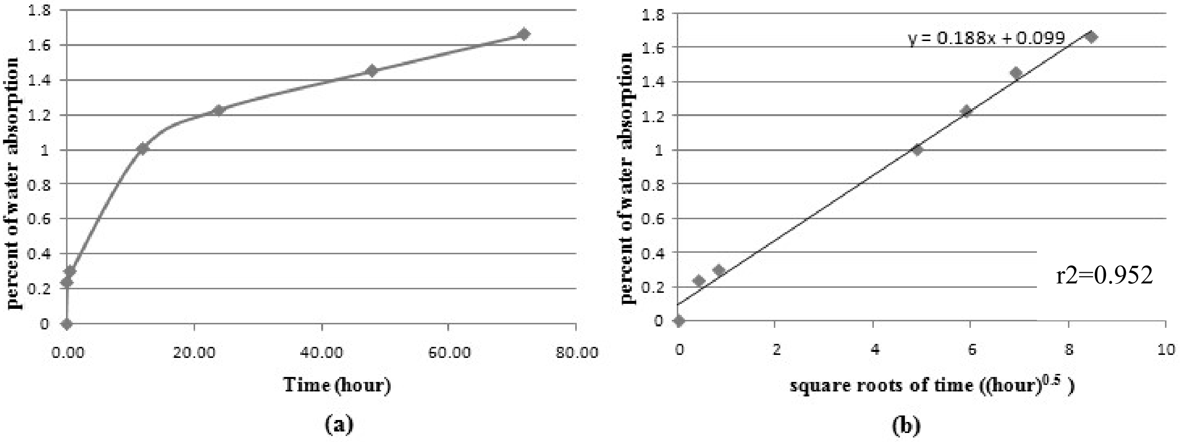

Fig.6 - Comparison of weight variation curve in absorption test

Table 5

Experimental results of absorption test (1/hour 0.5)

Mix ID	Non-carbonated concrete		carbonated concrete	
	Age(days)		Age(days)	
	28	90	28	90
M-35-0	0.23	0.20	0.183	0.17
M-35-7	0.156	0.18	0.141	0.153
M-35-10	0.123	0.152	0.105	0.12
M-40-0	0.285	0.251	0.266	0.21
M-40-7	0.225	0.184	0.212	0.16
M-40-10	0.214	0.165	0.211	0.15
M-50-0	0.50	0.532	0.39	0.33
M-50-7	0.428	0.41	0.32	0.28
M-50-10	0.389	0.325	0.275	0.26

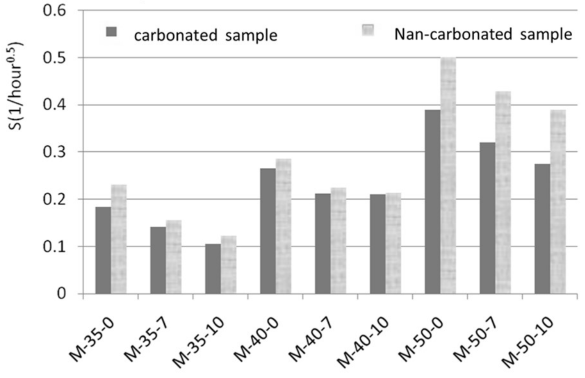

Fig.7 - Experimental results of absorption test at 28 days of age in carbonate and control samples

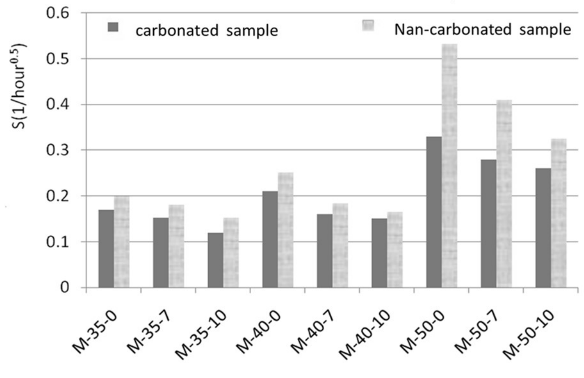

Fig.8 - Experimental results of absorption test at 90 days of age in carbonate and control samples

Figures 7 and 8 shows the changes in capillary absorption coefficient (S) versus the mixing scheme for carbonate and non-carbonate samples. changing the S coefficient is very similar to the RCPT test. In other words, in samples with high water to cement ratio and less silica fume, the effect of carbonation is more significant in decreasing the S coefficient and decreasing with decreasing water to cement ratio and increasing silica fume.

3.4 Chloride ion profile

Chloride ion profile testing was performed in three submerged environmental conditions, atmospheric and dry. For this purpose, carbonate ,and control samples were exposed to 30 g / l chloride ion for one year.

The penetration of chloride ions in terms of depth from the concrete surface at a specified time is expressed by the second law of Fick diffusion [4]:

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \tag{2}$$

After solving, the above differential equation is as follows:

$$C(x,t) = C_0 \left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_c t}} \right) \right] \tag{3}$$

Where x is the distance from the concrete surface in meters, t is the exposure time in seconds, Dc is the concrete diffusion coefficient in square meters per second, C is the weight percentage of chlorine ions in the concrete surface and C (x, t) is the weight percentage of chlorine ions in The depth x is relative to the surface and at time t. erf is also an error function, which is expressed as follows:

$$erf(a) = \frac{2}{\sqrt{\pi}} \int_0^a e^{-\beta^2} d\beta \tag{4}$$

In each profile, there are two series of six percent by weight of chlorine ion and the corresponding depth. Using Matlab software, the curve of Equation 2 is fitted from the test results and the values of Dcl and Cs are obtained. Tables 6 and 7 summarize the results of chloride diffusion coefficient for carbonated and control samples after 1 year.

Figures 9 to 11 show a comparison of the chloride diffusion coefficient in carbonate and control concretes versus the mixing scheme of the samples for the three conditions of environmental, submerged, atmospheric, wet and dry conditions. Although the Dcl coefficients in the three environments are significantly different, the trend of DCL coefficient changes in all three environments is almost the same. The graphs show that carbonation can reduce the DCL coefficient by about 50%. This is almost independent of the amount of microsilica in water to cement ratios of 0.5. Therefore, it can be concluded that in water to cement ratios higher than 0.5, the effect of carbonation will be practically independent of the amount of microsilica. The reason for this can be seen in the enlargement of concrete capillary cavities in high water to cement ratios and the inability of microsilica to fill these cavities. However, in low water to cement ratios, the percentage of microsilica shows its effect and it is observed that with increasing the amount of microsilica, the effect of carbonation in reducing the DCL coefficient also decreases. Comparison of diagrams also shows that in water to cement ratios of 0.35, the effect of water to cement ratio on the percentage of microsilica is somewhat dominant so that the reducing effect of carbonation on chloride penetration is almost constant.

4- Linear fitting model for chloride diffusion modeling

There are several methods to specify the useful life of a reinforced concrete structure against environmental factors. The most common of these methods are as follows:

- Estimation based on experience gained
- Inference from the performance of similar materials
- Accelerated experiments

Table 6

Values of chloride diffusion coefficient in control sample(non-carbonated)

Mix ID	**D_{cl}(mm^2/year)** (submerged)	**D_{cl}(mm^2/year)** (atmospheric)	**D_{cl}(mm^2/year)** (tidal)
M-35-0	105	57	153
M-35-7	101	50	131
M-35-10	89	37	87
M-40-0	311	57	340
M-40-7	119	54	160
M-40-10	104	40	105
M-50-0	451	87	323
M-50-7	343	80	285
M-50-10	228	67	243

Table 7

Values of chloride diffusion coefficient in carbonated sample

Mix ID	**D_{cl}(mm^2/year)** (submerged)	**D_{cl}(mm^2/year)** (atmospheric)	**D_{cl}(mm^2/year)** (tidal)
M-35-0	67	42	104
M-35-7	82	43	111
M-35-10	77	33	79
M-40-0	177	34	204
M-40-7	80	36	112
M-40-10	89	27	93
M-50-0	180	35	129
M-50-7	151	35	125
M-50-10	119	46	141

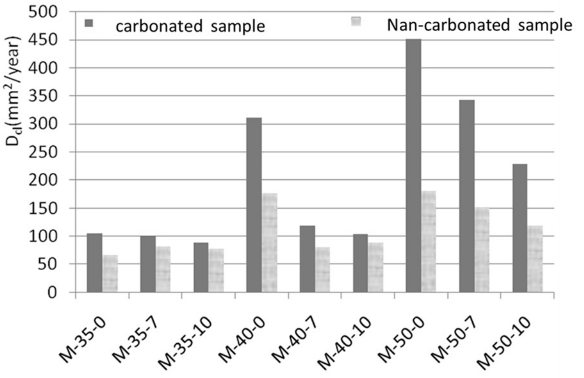

Fig.9- Chloride penetration coefficient in carbonate and control sample in submerged condition

Mathematical modeling based on chemical and physical processes

In the discussion of mathematical modeling, the existing methods include statistical simulation methods, neural network methods, fitting methods and numerical modeling, and numerical modeling such as finite element method.

In the data fitting method, after obtaining the test results of a function that produces the least error compared to the experimental results, it is obtained that the more parameters this function considers, the higher its accuracy will be. In general, this function is as follows:

$X = f(A, B, C, D, E_1, E_2, CE_1, CE_2, F_1, F_2, CF_1, CF_2, t_1, t_2)$ (5).

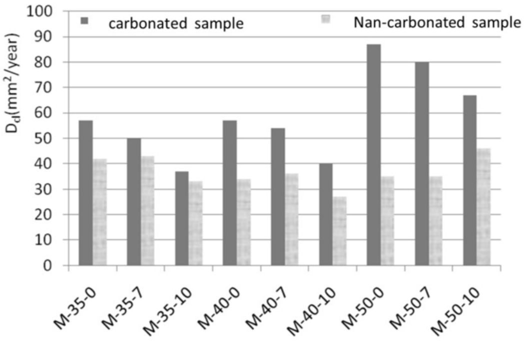

Fig.10 - Chloride penetration coefficient in carbonate and control sample in atmosphere condition

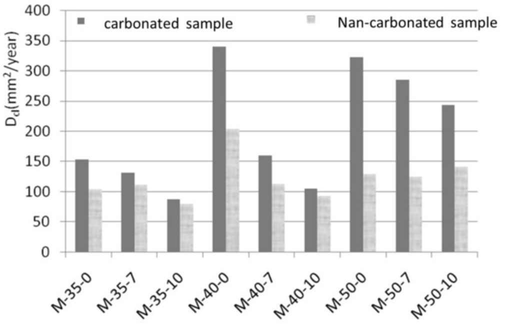

Fig.11 - Chloride penetration coefficient in carbonate and control sample in tidal condition

$$\beta = \frac{(D_{cl})_{non-carbonated} - (D_{cl})_{carbonated}}{(D_{cl})_{non-carbonated}} \quad (6)$$

$$\beta = \sum_{i=0}^{2} \sum_{j=0}^{2} a_{i,j} . \left(\frac{W}{C}\right)^{i} . (S.F)^{j} \quad (7)$$

$$\beta_{submerg} = 0.15 - 0.1 * \left(\frac{W}{C}\right) - 1.35 * (S.F) + 2 * \left(\frac{W}{C}\right)^2 + 0.164 * (S.F)^2 + 6.23 * \left(\frac{W}{C}\right) . (S.f) - 0.78 * \left(\frac{W}{C}\right) . (S.f)^2 - 7.05 * \left(\frac{W}{C}\right)^2 . (S.F) + 0.9 * \left(\frac{W}{C}\right)^2 . (S.F)^2$$

$$\beta_{atmospheric} = -1.82 + 8.5 * \left(\frac{W}{C}\right) + 6.29 * (S.F) - 7.33 * \left(\frac{W}{C}\right)^2 - 0.1 * (S.F)^2 - 3.41 * \left(\frac{W}{C}\right) . (S.f) + 0.52 * \left(\frac{W}{C}\right) . (S.f)^2 + 4.50 * \left(\frac{W}{C}\right)^2 . (S.F) - 0.67 * \left(\frac{W}{C}\right)^2 . (S.F)^2 \quad (8)$$

$$\beta_{tidal} = 0.133 - 0.40 * \left(\frac{W}{C}\right) - 1.22 * (S.F) + 2.67 * \left(\frac{W}{C}\right)^2 + 0.145 * (S.F)^2 + 5.53 * \left(\frac{W}{C}\right) . (S.f) - 0.68 * \left(\frac{W}{C}\right) . (S.f)^2 - 6.12 * \left(\frac{W}{C}\right)^2 . (S.F) + 0.76 * \left(\frac{W}{C}\right)^2 . (S.F)^2$$

In the above relation x penetration depth, a chemical composition of cement, B amount of cement, C mixing ratios, D concrete compaction, E1 relative humidity during processing, E2 ambient temperature, F1 ambient humidity during processing, F2 ambient temperature, F_1, CE_1, CE_2 ,and CE_2 are the interactions between processing and mixing ratios.

In order to determine the effect of carbonation on the penetration of chloride ions in concrete, a dimensionless coefficient was defined as follows and the mixing design was calculated for the main values.

The coefficient β in the above equation represents the number of changes in the diffusion coefficient of chloride due to carbonation. In order to determine the change function β, a linear fitting function similar to the following function was used to determine β. Considering that in obtaining β values, the number of input parameters for the W / C ratio and the percentage of micro silica was 3, so the maximum power of the proposed function was considered to 2.

By minimizing the error function values, the β function for different environmental conditions is obtained as follows [6]:

5. Conclusion

In the present paper, the result of carbonation infiltration on chloride infiltration in concretes containing silica fume was investigated. The study procedure was that the concrete samples were first carbonated and then exposed to chloride ions for one year to study the effect of carbonation on changes in chloride diffusion coefficient. Accelerated experiments such as RCPT, capillary adsorption and compressive strength were also performed on carbonate and non-carbonate samples. In total, the following results were obtained from experiments and modeling:

1- Due to carbonation, the chloride ion profile undergoes changes. As a result of these changes, the concentration of chloride ions in the carbonate areas of the concrete surface will be lower than the values predicted by Fick's law.

2- Due to carbonation, the properties of carbonate concrete (outer and surface layer of concrete) change. These changes will also affect the permeability of concrete to chloride ions. Therefore, in the case of carbonate concretes, the initial form of fic diffusion theory cannot be used to study the chloride ion diffusion parameters and concrete should be considered as a two-layer material (outer layer of carbonated concrete and inner layer of non-carbonated concrete).

3- The results of accelerated experiments show that carbonation reduces the flow rate in the RCPT test and also reduces the penetration depth and capillary adsorption coefficient in the capillary water absorption test. However, in the compressive strength test, no specific procedure is observed.

REFERENCES

[1] S.H. Jung, Y.J. Choi, B.C. Lee, Influence of carbonation on the chloride diffusion in concrete, construction material research center, Korea institute of construction materials, 2007,1465\(4), 1191.

[2] D. Conciatori, F. Laferrier, E.Bruhwiler, Comprehensive modeling of chloride ion and water ingress into concrete considering thermal and carbonation state for real climate, Cement and Concrete Research, 2010, 40, 109.

[3] C.C.Page, O.Vennesland , Effect of Carbonation on Chloride Binding, Materials and Constructions, 1983, 16(19).

[4] A.Suryavanshi, R.Swamy, Stability of Friedels Salt in Carbonated Concrete Structural Elements, Cement And Concrete Research,1996, 26(5), 729

[5] K.Maekawa, T.Ishida, Service Life Evaluation of Reinforced Concrete Under Coupled Forces and Environmental Actions.Proceedings of the JCI, 2002, 20(2), 691.

[6] K.Maekawa, T.Ishida Multi-Scale Modeling of Concrete Performance Integrated Material and Structural Mechanics, Journal of Advanced Concrete Technology, 2003, 1, 91.

[7] K.Maekawa, T.Ishida ,Theoretical Identified Strong Coupling of Carbonation Rate and Thermodynamic Moisture States in Microspores of Concrete,Journal of Advanced Concrete Technology,2004, 2 ,213.

[8] M.Lin, M.Liang, Modeling of Transport of Multiple Chemicals in Concrete Structures: Synergetic Effect Study, Cement and Concrete Research, 2003, .33, 1917.

[9] O.Burkan Isgor, A.Ghani Razaqpur , Advanced Modeling of Concrete Deterioration due to Reinforcement Corrosion, 2005.

[10] W.Puatatsananon, V.E.Saouma, Nonlinear Coupling of Carbonation and Chloride Diffusion in Concrete, Journal of Materials in Civil Engineering, 2005, 17(3), 264.

[11] H.Song, S.Pack, C.Lee , service Life Prediction of Concrete Structures Under Marine Environment Considering Coupled Deterioration, 2006.

[12] A.R. Ameli, E. Parvaresh Karan, SAH. Hashemi, Mechanical Properties and Performance of Roller Compacted Concrete (RCC) Containing High Volume of Fly Ash, Crumb Rubber and Nano Silica using Response Surface Method, Journal of Transportation Research, 2018,15(3), 381.

[13] S. A. Ghahari, A. M. Ramezanianpour, A. A. Ramezanianpour, and M. Esmaeili, An Accelerated Test Method of Simultaneous Carbonation and Chloride Ion Ingress: Durability of Silica Fume Concrete in Severe Environments, advances in material science and engineering, 2016.

[14] A. ramezanian pour, S. sedighi, M. kazemian, A. Ramezanianpour, Effect of Micro Silica and Slag on the Durability Properties of Mortars against Accelerated Carbonation and Chloride Ions Attack, AUT Journal of Civil Engineering, 2020, 4(4).

[15] MS. Fattouh, BA. Tayeh, IS. Agwa, EK. Elsayed, Improvement in the flexural behaviour of road pavement slab concrete containing steel fibre and silica fume, Case Studies in Construction Materials,2023, 18 , e01720.

[16] W. Bai, Z. Song, C. Yuan, J. Guan, C. Xie, H. Huang, Study on mechanical properties and damage mechanism of recycled concrete containing silica fume in freeze–thaw environment, Construction and Building Materials ,2023, 375, 130872.

[17] Y, Wei, P, Chen, S, Cao, H, Wang, Y, Liu, Z, Wang, Prediction of Carbonation Depth for Concrete Containing Mineral Admixtures Based on Machine Learning, Arabian Journal for Science and Engineering, 2023, 1.

[18] E. Bernard, B. Lothenbach, A. German, D. Rentsch, F. Winnefeld. , Effect of aluminate and carbonate in magnesia silicate cement, Cement and Concrete Composites, 2023, 139, 105.

[19] Y. Wanga, S. Nanukuttanb, Y. Baic, P.A.M. Basheerd, Influence of combined carbonation and chloride ingress regimes on rate of ingress and redistribution of chlorides in concretes, Construction and Building Materials, 2017, 140, 173.

[20] I. Yoon, C. Lee, 2004, Prediction of chloride profile of concrete under combined deterioration of carbonation and chloride ions, Consec, 2004, PP.353.

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