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Influence of Crack Width on Percentage of Chloride Absorption in Concrete

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Abstract

An experimental study was carried out to investigate the effect of crack widths on chloride content due to the penetration of salty water through the crack by using an immersion test that consists of salty water with a concentration of 5%. Eighteen reinforced concrete beams with dimensions (10cm *10cm * 90cm) were made and reinforced with a mild steel bar of 6mm in diameter at the top and the bottom. These specimens were cracked in the bottom due to a pure bending moment in the middle of their span. The results show that chloride content for the cracked specimens increased and overcame the allowable accepted ratio at the Egyptian Code.

Keywords: *Chloride attack, Cracks Widths, Chloride absorption, Corrosion.*

1. Introduction

Corrosion of steel reinforcement in concrete is the most common problem affecting the durability of reinforced concrete structures. Chloride-induced corrosion is one of the main mechanisms of deterioration affecting the long-term performance of such structures. This may lead to early repair or replacement of the structure. The ability of chloride ions to penetrate the concrete must be known for design and quality control purposes.

Cracks in concrete accelerate the deterioration of reinforced concrete structures since they facilitate the ingress of chloride ions carried by water and oxygen into concrete. Consequently, chloride ions content increases, leading to reinforcing steel corrosion.

R. Sato, T. Shimomura, I. Maruyama, and K. Nakarai (2008), paper gives a summary of the activities of the Working Group on Durability Mechanics (WG3) within the Japan Concrete Institute (JCI). Technical Committee on Time-Dependent Behavior of Cement-Based Materials (JCI-TC061A).

Diffusion is a transfer of mass of free molecules or ions in the pore solution resulting in a net flow from regions of higher concentration to regions of lower concentration of the diffusing substance. This mode of transport operates in fully saturated media such as fully submerged concrete structures. For porous material like concrete, the diffusion coefficient, D, is the material characteristic property describing the transfer of a given substance driven by a concentration gradient. [2]

Hassan Akram Ghanem, B.E., M.E. (2009), His research focuses on the effect of curing on the chloride ion permeability of different mix designs. It is expected that the knowledge gained through his work can be used to optimize the number of curing days and ages required before full traffic can be allowed on bridge decks in Texas. From the ponding results of the mixtures, it was observed that chloride permeability decreased with increased curing duration. This is attributed to the fact that curing improves the hydration process resulting in dense pore structures that lead to a decrease in concrete permeability. From his study, it was shown that

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steel reinforcement could be put at a distance of 1.25 in. below the top surface as chloride concentration there falls below the threshold chloride content.

Y. Lu, E. Garboczi, D. Bentz, and J. Davis, their paper present a preliminary strategy for examining the influence of transverse cracking on chloride ions penetration into concrete that includes a graphical approach for adjusting the predicted service life provided by current models by COMSOL Multi-physics package to reflect this influence. This software contains specific modules for diffusion and absorption/reaction in multiple dimensions then compared with experimental data. Also, NIST (National Institute of Standards and Technology)-simulated total chloride profiles.

Sri Murti Adiyastuti (2**008),** the experimental study investigated the influence of multiple flexural cracks on the chloride diffusivity of reinforced concrete beams; to obtain data that could be considered reliable, reinforced concrete beams, 200 x 250 x 2200 mm in dimensions with 20 mm concrete cover, were used for the experimentation. The measured chloride profiles of the beams with multiple cracks are compared to those obtained from the uncracked (control) beam. An observation was also made on the effect of cracks on the corrosion development of steel bars after two years of immersion in a salt solution.

Song Mu, Geert De Schutter, and Bao-guo Ma (2012), Their study investigated non-steady state chloride diffusion in concrete samples with different crack densities prepared by a non-destructive notch method. The relationship between diffusion coefficient and crack density was discussed. Water and acid-soluble chloride contents increase significantly with increasing crack density up to a certain value. A linear function was found for the relationship between the diffusion coefficient determined by acid-soluble chloride and crack density. A piecewise function including linear and exponential functions was proposed to describe the relationship between the diffusion coefficient determined by water-soluble chloride and the crack density.

Chuanqing Fu, Xianyu Jin, and Nanguo Jin (2010), their researched, the whole chloride diffusion process was divided into two parts: chloride diffusion in sound concrete and crack. The solution concentration gradient existed in the crack obviously, and it changed the chloride concentration along the crack surface continually. In addition, a finite element modeling (FEM) analysis on chloride diffusion in cracked concrete was performed with the new model in ANSYS. A good agreement can be found in comparing the numerical solution with test results. It proves that the new mathematic model is within good accuracy in predicting the chloride diffusion depth in cracked concrete.

Hailong Ye, Nanguo Jin, Xianyu Jin, and Chuanqing Fu (2010), To clarify the mechanism of deterioration subjected to cyclic drying–wetting conditions, an innovative model describing the transport of chloride ions in cracked concrete is elaborated, the results of experimental investigation were also reported. In addition, it is modeled as a flux based on Poiseuille law considering crack width, crack surface roughness, tortuosity, and capillary pores at the crack surface. In addition, the drag coefficient is first applied to calculate the influence of roughness on crack in this work.

Markku Sillanpää (2010), research was focused on investigating non-steady-state chloride migration in cracked and uncracked concrete. Another aim was to compare the non-steady-state migration results in cracked and uncracked concrete and check if the test method described in the NT BUILD 492 method can be used for cracked concrete.

Dienstags and B. Jan (2008), research included the effect of cracks on transport properties in mortar. He used an expansive core to produce cracks. An experimental procedure was used to control the cracking of brick disks. The samples were subjected to control tensile cracking using a mechanical expansive core and external steel confinement rings.

Mustafa Sahmaran, Mo Li, and Victor C. Li (2008), their paper present the results of an experimental investigation on the chloride transport properties of engineered cementations composites (ECC) under combined mechanical and environmental loads.

An experimental study was performed by Ippei, Kazuyuki, and Ryoichi (2006) to investigate the effect of crack on chloride content due to penetration of salty water through the crack under exposure test that consists of cycles of rain of salty water and dry (40% in temperature and 60% in relative humidity).

A. BLAGOJEVIĆ (2016), An experimental set-up was designed to generate knowledge and contribute to existing codes and practice. 32 reinforced concrete beams (1500×100×150 mm^3) were exposed to alternately wetting and drying cycles to simulate an aggressive chloride environment. After two years of exposure, all concrete beams were split into two parts to visualize the achieved chloride penetration and the development of steel corrosion.

2. Outline of Experiment

In this study, ordinary Portland cement was used to cast a concrete mix of 0.50 water-cement ratio. Proportions of concrete mixes are illustrated in Table 1. The coarse aggregate was a crushed stone with a maximum nominal size of 10 mm, density of 2.72 g/cm^3, and fineness of 7.20. Steel bar D6 of 6 mm in nominal diameter and 2400 N/mm^2 in nominal yield strength was used as reinforcement.

Table (1): Details of Concrete Mixes (per $1m^3$)

Mix	Coarse aggregate	Fine aggregate	Cement	Water
1	1150 Kg	575 Kg	460 Kg	230 Liter

The experimental program was chosen to present a guide percentage of chloride absorbed into concrete with a cracked surface. The specimens were immersed in saline water with concentrations of 5%NaCl by weight. The specimens are divided into three groups to achieve the variable time (4 months, 8 months, and 12 months). Every group contains 6 beams to have different crack widths so the number of specimens is equal to18.

All specimens have a square cross-section of 10 cm x 10 cm and 90 cm in length. The longitudinal reinforced was 2Φ6 (grade 24/35) at the top and bottom of the specimens. The stirrups are Ø6/20cm (grade 24/35) in a transverse direction for all specimens.

To introduce cracks from permanent bending moment every two beams are connected by anchor bolts at the end of the specimens and two steel pipes at the center of the specimens as shown in Figure (1). The steps of casting the specimens are shown from Figure (2) to Figure (5).

The pieces of wood with plastic pipes were extracted from the formwork after one hour of flattening leaving holes at the required position. After one day, the beams are extracted from the formwork. Also, cubes are extracted and cured by immersion in clean tap water for 28 days. The results of testing cubes have shown that the concrete compressive strength for all cubes was above 250 kg\cm^2, ranging up to 312 kg\cm^2.

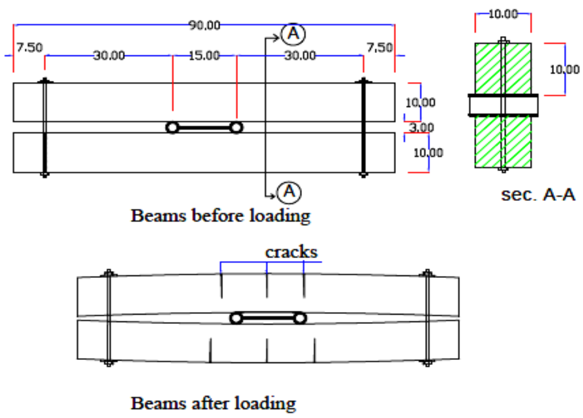

Figure (6): the system followed for introducing cracks

Figure (2): Formwork shape

Figure (3): wooden pieces were fixed at formwork.

Figure (4): Compacting second layer.

Figure (5): flattening the surface.

Every two beams in the same group are connected by bolts and nuts after putting the steel pipes in between them as shown in Fig. 6. The beams are loaded by rotating the nuts at the two ends of the beams until the required crack widths are reached. The targeting crack widths are between 0.1 and 0.30 mm. The crack widths are shown in Table (2). This system of loading aims to introduce cracks from the bending moment constant with the time. The crack widths were measured using a microscope as shown in Figure (7). His accuracy equals (0.02 mm). Every crack is measured at two positions and has the average of them.

Figure (6): Preparing the beams for loading

Figure (7): Crack width measurement.

Table (2): The accurate cracks in the beams for category 2 (5% NaCl).

Group No.	Beam No.	Cracks width (mm)
1 (4 months)	1	0.14 , 0.1 , 0.3
	2	0.14, 0.22, 0.1, 0.2
	3	0.05, 0.1, 0.2, 0.14
	4	0.05 , 0.05
	5	0.06 , 0.28 , 0.12
	6	0.24 , 0.32 , 0.05

2 (8 months)	7	0.08 , 0.18 , 0.12 , 0.1
	8	0.3 , 0.08
	9	0.12 , 0.1
	10	0.05 , 0.05
	11	0.06 , 0.28
	12	0.12 , 0.2 , .08
3 (12 months)	13	0.1 , 0.1 , 0.05
	14	0.18 , 0.2
	15	0.1 , 0.2 , 0.12
	16	0.05, 0.1
	17	0.05 , 0.05
	18	0.2 , 0.32

The specimens of every group were extracted from the pelvis after it`s time had passed and then left in the air to dry for one week. The specimens are taken by drilling using a drill with a diameter of 8 mm as shown in Fig. (8) then the extracted powder is kept in a small bottle. These specimens were taken from crack widths of 0.1 mm, 0.2mm, and 0.3mm at a depth of 2.5 cm.

Figure (8): Taking specimens from the sample at a depth of 2.5 cm.

After the drilling phase is completed, the sample collection bottles are moved to a partially controlled environmental lab (e.g. temp 65" ± 10") where the samples are tested to determine the chloride ion in the concrete. At the beginning of this research project, we followed the Volhard's method guidelines explicitly. This method covers procedures for the determination of the acid-soluble chloride ion content of aggregates, Portland cement, mortar, and concrete. The total amount of chloride is usually equal to the acid-soluble chloride. However, organic additives or minerals that contain acid-insoluble chloride may be present in concrete and concrete raw materials. These constituents may become acid soluble during long-term exposure to the alkaline environment in concrete or mortar.

This procedure is described as follows:

1. The sample to the nearest milligram of a 2 g powdered sample representative of the material under test is determined. All material must pass a 0.300 mm (NQ. 50) sieve. AU pulverizing tools and sieve are washed with alcohol or distilled water and dried before use with each separate sample.
2. The sample is transferred quantitively to a beaker of capacity 250 mL. 75 mL of distilled water and 10 ml of concentrated nitric acid is added.
3. The beaker was covered with a watch glass and brought to a boil on a hot plate magnetic stirrer using a small magnet. The sample is boiled for 5 minutes.

4. The filter paper was weighed and recorded then the hot solution was filtered.
5. The beaker was washed with hot distilled water until the beaker had been clean from the sediment.
6. The filter paper was dried in the oven for 24 hours.
7. After the drying step the filter paper was weighed and the difference in the weight was recorded (weight of sand).
8. 5 mL from calibrated silver nitrate (16.969 grams of silver nitrate in one liter of distilled water), two drops from the reagent Ferric Alum (100 ml cold solution of ferric sulfate Alamonyumih with 10 ml of concentrated nitric acid), and 1 mL from Natrubnzen solution were added to the filter at the beakers.
9. The glass tube was filled with 0.2-mm ammonium thiocyanate then the tube was opened to fall drops at the beakers with revolution until the solution color was changed from white color to red brown color.

Analytical of results:
W1 (Weight of sand at the mortar) = weight of filter paper after filtering and drying method – weight of empty filter paper.
W2 (weight of solved cement) = weight of the sample (2 gm) - W1

$$CL = \frac{(\text{size of ammonium thiocyanate} - \text{size silver nitrate}) * 0.355}{\text{W2}}$$

3. Results

3.1 Chloride content for Beams has a crack width (W_k) of 0.1 mm.

To study the effect of immersion time on chloride absorption, constant crack width, and constant depth are used for taking the samples at different immersion times. The samples were taken at a depth of 2.5 cm through the crack width which equals nearly 0.1 mm. Sample numbers, immersion times, beam numbers, and chloride content as a percentage of cement weight are shown in Table (3).

Table (6): Chloride content in the required samples

	Mix (1)	
Immersion time (months)	**Sample No.**	**CL % of cement weight**
0	9	0.16
4	10	0.82
8	11	1.817
12	12	2.27

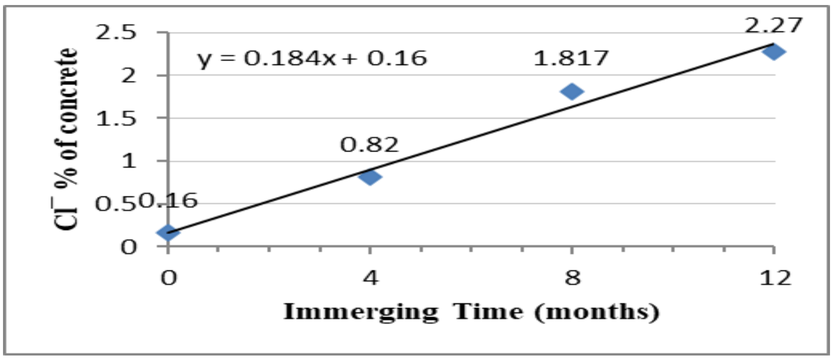

Figure (9): Effect of the immerging time in chloride absorption (Wk =0.1mm).

3.2 Chlorides Content for Beams have crack width (W_k) 0.2 mm.

In this part studying the coarse aggregate type on chloride absorption was done for beams that had been immersed in saline water having 5% NaCl by weight. The samples were taken at a depth of 2.5cm at a crack width equal to about 0.2mm**.** Sample numbers, immersion times, beam numbers, and chloride content as a percentage of cement weight are shown in Table (7).

Table (7): Chloride content in the required samples (W_k=0.2mm).

	Mix (1)		Mix (2)	
Immersion time (months)	**Sample No.**	**CL % of cement weight**	**Sample No.**	**CL % of cement weight**
0	17	0.27	21	0.20
4	18	1.94	22	0.91
8	19	2.375	23	1.7
12	20	2.77	24	1.89

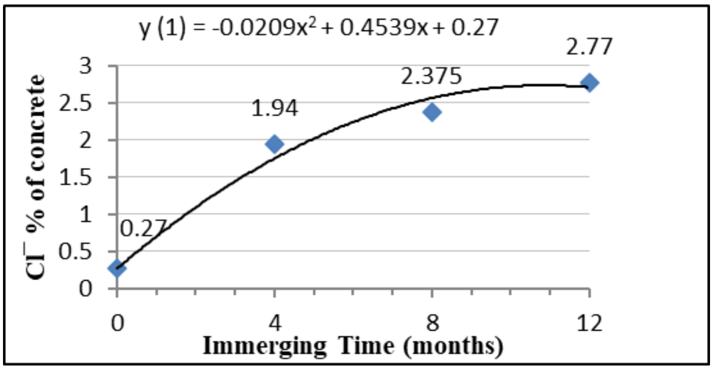

Figure (19): Effect of the immerging time in chloride absorption (Wk =0.2mm).

From Figure (19) the difference between the two mixes at time zero equals a small value of 0.07 %. The chloride content for Mix (1) in immersion time 4 months is more than the chloride content for Mix (2) by percentages 113.2%, 39.7%, and 46.6% respectively. This difference between the two mixes may be because the density of Mix (1) is less than the density of Mix (2). By comparing these percentages, at early times the percentage is small and increases with time until nearly 4 months then the percentage decreases with time or becomes constant. It is noticed that the difference in chloride content between the two mixes in time 4 months is larger than at any time. This may indicate that at a crack width of 0.2 or more, the chlorides are absorption quickly than at a crack width of 0.1mm or less. From the fitting curves, the difference between the two mixes increases with increasing the time by decreasing rate (-0.15x + 0.255) % where x is the immersion time by month unit. If we deport the point at time zero, the difference between the two fitting lines is equal small decreasing value of 0.02% as shown in Figure (20).

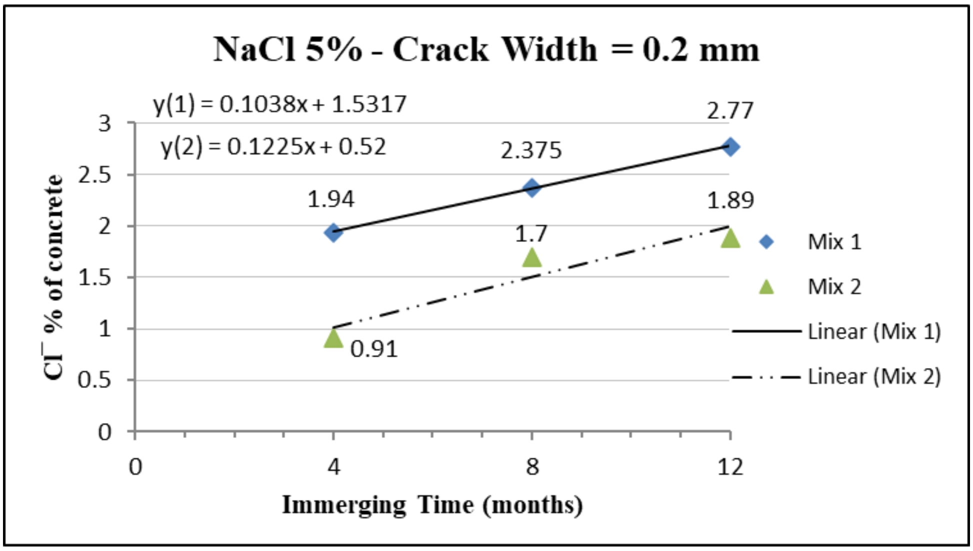

Figure (20): Comparison between Mix (1) and Mix (2) from immersion time 4 months to 12 months.

3.4 Effect of Cracks Widths (0.1, 0.2 and 0.3mm)

In this part studying the effect of the coarse aggregate type on chloride absorption was done for beams that had been immersed in 5% NaCl by weight for an immersion time of 8 months and had different crack widths (0.1, 0.2, and 0.3mm). Also, the samples were taken at a depth of 2.5cm. Sample numbers, immersion times, and chloride content as a percentage of cement weight for the two mixes are shown in Table (8).

Table (8): Chlorides content in the required samples for Mix (1) and Mix (2) in different cracks widths

	Mix (1)		**Mix (2)**	
Crack Width (mm)	Sample No.	CL^- % of cement weight	Sample No.	CL^- % of cement weight
0.1	11	1.817	15	1.41
0.2	19	2.375	23	1.7
0.3	25	2.3	26	1.89

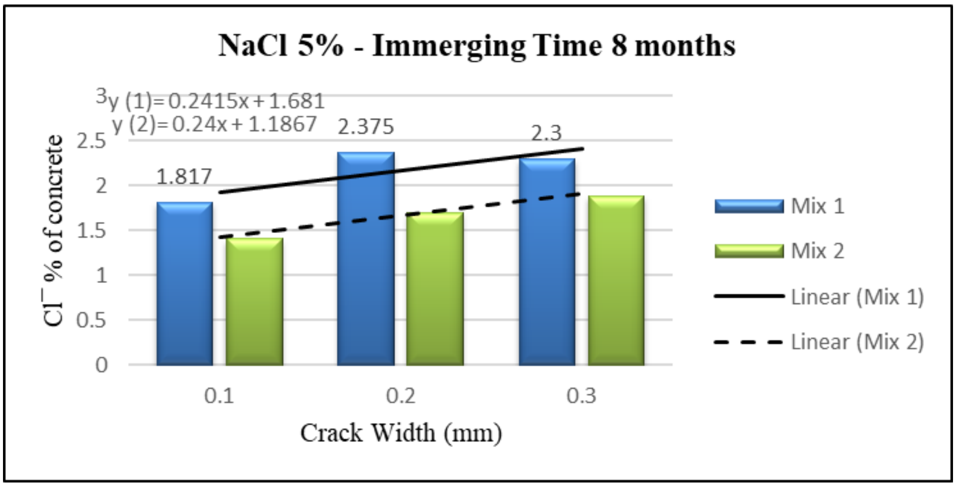

Figure (21): Comparison between Mix (1) and Mix (2) on chloride absorption for samples taken at different crack widths.

From Figure (21) the difference between the two mixes at a crack width of 0.1 mm is equal to 0.4%. This difference is the same difference at a crack width of 0.3 mm (0.4%). This may indicate that the difference in chloride content between the two mixes is constant at different crack widths. The difference between the two mixes at a crack width of 0.2 mm is equal large value of 0.675%. This may be because the position of sample no 19 has a lower density than another sample.

4. Conclusions

- For beams immersed in 5% NaCl and having a crack width of 0.1mm, the chloride content is increased by a value of 0.66% of cement content at the immerging time of 4 months and then increased by a percentage of 284% at the immerging time 12 months. The increasing rate is nearly constant with time and equals 0.184% almost every month.
- For beams immersed in 5% NaCl and having a crack width of 0.2mm, the chloride content is increased by a value of 1.78% of cement content at the immerging time of 4 months and then increased by a percentage of 46.6% at the immerging time of 12 months. The increasing rate equals (-0.164x+0.484) % where (x) is the time by month unit.
- Chloride content at wide crack widths is larger than chloride content at narrow crack widths at a depth of 2.5cm. Also, at large crack widths above 0.1mm are nearly absorbing the same amount of chlorides.
- The difference between the two rates of chlorides increasing for the samples that had been immersed in 5% NaCl and 3%NaCl is equal to 0.036%.
- At the surface of the crack, the chloride ions concentration is decreased by increasing the depth of the concrete.
- For beams immersed in 3% NaCl and having crack width of 0.1mm, the chlorides content for Mix (1) in immerging times 4, 8, and 12 months is more than the chlorides content for Mix (2) by percentages 8.5%, 58.3%, and 17% respectively. The difference in the increasing rate between them is nearly equal 0.04% almost every month.
- For beams immersed at 5% NaCl and having crack width 0.1mm, the chlorides content for Mix (1) at immerging times 4, 8, and 12 months are more than the chlorides content for Mix (2) by percentages 11.6%, 29%, and 13.5% respectively. The difference in the increasing rate between them is equal to 0.037% almost every month.
- For beams immersed at 5% NaCl and having a crack width of 0.2mm, The chlorides content for Mix (1) in an immerging time of 4 months is more than the chloride content for Mix (2) by percentages 113.2%, 39.7%, and 46.6% respectively. The difference of the increasing rate between them is equal (-0.15x + 0.255) % where x is the immerging time by months unit.
- The difference in chloride content between the two mixes is equal (0.4, 0.675, and 0.41% of cement content) at crack width (0.1, 0.2, and 0.3) respectively.
- The mixes having gravel are better than the mixes having dolomite.

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