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Chloride diffusivity of concrete cracked in flexure

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Abstract

It has been recognized that corrosion of steel in cracked concrete is affected by both the surface crack width and the concrete cover thickness. The crack width/cover ratio (W_{cr}/C) can be a suitable parameter to consider in relation to the durability performance of a cracked reinforced concrete. A linear relationship was observed when plotting the chloride threshold level against C/W_{cr}. It appears that the threshold level can be related to W_{cr}/C by a hyperbolic relationship. The effect of W_{cr}/C on the chloride threshold level appears to be more pronounced as this ratio is decreased. The Australian Standard, AS 3600, does not give any guidance on the allowable crack width at serviceability for reinforced concrete structures, except for the 'deemed to comply' rules. From the viewpoint of durability, a crack width limitation in AS 3600 is necessary in addition to the cover thickness, to minimize W_{cr}/C. Using $W_{cr}/C = 0.01$, in this study, the effect of tensile steel area on the chloride diffusivity in the tension and compression zones of concrete cracked in flexure was investigated. The apparent chloride diffusion coefficient (D_a) in the tension zone was found to be higher than in the compression zone. When the tensile steel area was doubled, a significant decrease in the D_a of the compression zone was observed. This could be attributed to the reduction in the porosity of the concrete in compression, which impedes diffusion process. In contrast, a marginal increase in the D_a of the tension zone was observed.

Keywords: Chloride diffusivity; Chloride threshold level; Crack width; Concrete cover; Durability

1. Introduction

Concrete is essentially watertight in an uncracked state, though not waterproof, when properly placed, compacted, and adequately cured. However, as a result of overstress, environmental effects, and other reasons, cracks do occur. Concrete, thus, becomes vulnerable to the processes of deterioration by corrosion of reinforcement as it gradually loses its watertightness in the course of its service life. In extreme cases, cracks may affect the structural integrity of the concrete member. However, in most instances, cracks do not affect the load-carrying capacity of the concrete structure, but may adversely affect its durability by providing easy access to aggressive agents [1] especially chloride ions in marine environments.

Cracked concrete allows corrosion process to initiate much faster than uncracked concrete [2]. The initiation of steel corrosion in cracked concrete is dependent on the surface crack width [3]. Wider surface crack widths have been found to induce corrosion much faster than relatively smaller ones [4–6]. Other researchers [7,8] reported a slower initiation of steel corrosion in cracked concrete when the cover was increased. This is because corrosion of steel depends on the availability of oxygen, not at the crack, but in the sound concrete on the cathodic end of the steel and hence, on the rate at which oxygen can diffuse through the cover [9]. Thus, it is recognized that both crack width and cover thickness do affect the initiation of steel corrosion in concrete. From the literature review, and comparing only these two variables, the initiation of steel corrosion can be generally summarized as follows:

(a) It occurs faster with increasing surface crack width when the cover is maintained, and
(b) It occurs slower with increasing cover thickness when the surface crack width is maintained.

For a given stress level in the steel bar, other variables being constant, the surface crack width increases with the cover thickness. Hence, the initiation of steel corrosion in

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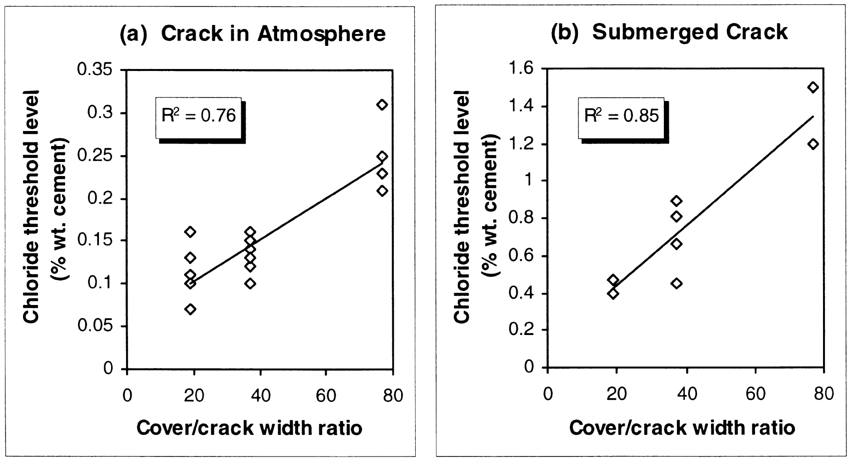

Fig. 1. Relationship between chloride threshold level and C/W_{cr}.

reinforced concrete may be influenced by the combined effect of the crack width and cover thickness, i.e., it is 'directly proportional' to the crack width while at the same time 'inversely proportional' to the cover thickness. From this point of view, it is more appropriate to consider the influence of both parameters, crack width (W_{cr}) and cover thickness (C), simultaneously. The crack width/cover ratio, W_{cr}/C, appears to be a suitable parameter to consider in relation to the durability performance of a cracked reinforced concrete.

2. Chloride threshold level vs. W_{cr}/C

From Ref. [10], the chloride threshold level when plotted against the inverse of W_{cr}/C appears to be linear. This is shown in Fig. 1(a) and (b). These data were collected from five different high performance concrete mixes containing silica fume between 5% and 15% replacement. The water/binder ratio of four of those mixes was 0.3 while the remaining mix was 0.4. The regression coefficient, R^2 of the plot in Fig. 1(a) is comparatively low due to a larger variability in the results. Based on these data on cracked concretes, it appears that the chloride threshold level can be related to W_{cr}/C by a hyperbolic relationship. This is shown in Fig. 2(a) and (b).

Many factors affect the threshold level including concrete grade, type, and curing regime [25]. Steel corrosion sometimes occurred at a relatively low chloride level while sometimes being absent at higher levels [21]. Reinforcement corrosion had been reported to occur in the splash zone concrete at a relatively lower chloride content than concrete in the submerged zone [22]. For uncracked normal strength concrete, the chloride threshold level permitted in many specifications varies between 0.2% and 0.5% by weight of cement. Sandberg et al. [26] have reported that the threshold level can be increased as the water/binder ratio is reduced. In submerged conditions, the threshold level can be as high

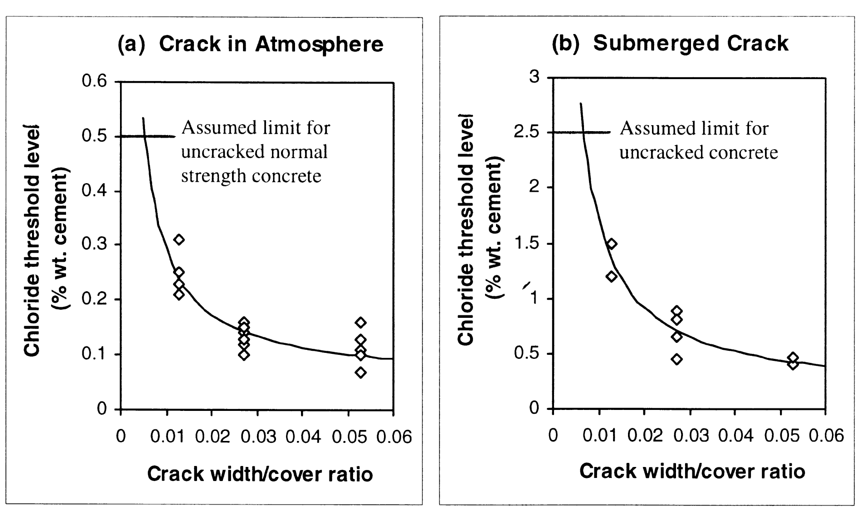

Fig. 2. Relationship between chloride threshold level and W_{cr}/C.

Table 1
W_{cr}/C ratio from various codes
NA-not available.

Codes	Allowable crack width, W_{cr} (mm)	Minimum cover, C (mm)	W_{cr}/C
CEB/FIP Model Code [16]	0.3	40	0.0075
ACI Manual [17]	0.15	50–60	0.0025–0.003
ENV 1991 [18]	0.3	40	0.0075
BS 8110 [19]	0.3	50	0.006
AS 3600 [20]	NA	40–50	–

as 2.1–2.5% by weight of cement [10,27]. In spite of the hyperbolic trend observed, a cut-off level can thus be assumed as W_{cr}/C tends to zero.

The trend observed in Fig. 2(a) and (b) implies that the corrosion initiation of steel in concrete becomes more rapid as the W_{cr}/C is increased. Similar trends are observed for both the cracked specimen exposed to the atmosphere and the cracked specimen fully submerged, even though the threshold levels are different for the same W_{cr}/C. This trend indicates the suitability of W_{cr}/C as a parameter for durability performance of a cracked concrete. From Fig. 2(a) and (b), it is observed that the effect of W_{cr}/C on the chloride threshold level becomes more pronounced as the ratio decreases, i.e., the slope of the curve becomes steeper as W_{cr}/C is reduced. It appears that to enhance the durability of a cracked concrete, it is desirable to minimize W_{cr}/C.

A survey of the permissible crack width and the minimum concrete cover given in various Codes for design of reinforced concrete structures in seawater exposure is shown in Table 1. The corresponding W_{cr}/C varies from 0.0025 to 0.0075. Among these Codes and from the viewpoint of W_{cr}/C, ACI Manual [17] appears to be more stringent on its durability requirement while AS 3600 [20] does not give any guidance on the allowable crack width at serviceability, except for the 'deemed to comply' rules. In AS 3600, flexural cracking in reinforced concrete beams (at serviceability) shall be deemed to be controlled when the center-to-center spacing of bars near the tension face of the beam does not exceed 200 mm. In addition, the distance from the side or soffit of a beam to the center of the nearest longitudinal bar shall not exceed 100 mm. Even if these 'deemed to comply' rules are satisfied, cracks may develop especially when there is a tendency now to use higher yield strength steel bars (f_y = 500 MPa) as reinforcements for concrete structures in Australia. Therefore, from the viewpoint of durability, a crack width limitation in AS 3600 is necessary in addition to the cover thickness, to minimize the W_{cr}/C of a cracked reinforced concrete.

For a given W_{cr}/C, it may be of interest to determine the effect of tensile steel area on the chloride diffusivity of concrete in flexure. In the present study, a W_{cr}/C of 0.01 is chosen while the only variable considered is the area of steel (same diameter and type) in the tension zone. A comparison between the chloride diffusion coefficient in the tension and compression zones of the reinforced concrete prisms was made.

3. Experimental procedure

3.1. Preparation of specimens

A grade 20 concrete mix was designed using locally available Nepean crushed gravel (20 mm maximum size) and Nepean sand as coarse and fine aggregates, respectively. The concrete mix was prepared in accordance with Australian Standard, AS1012. Both aggregates were pre-soaked in water before batching. All batched aggregates were stored in airtight containers to ensure no moisture loss before mixing. At the same time, moisture contents of the aggregates were determined and adjustments were then made to the mix proportions. General Purpose cement (similar to ASTM Type I) complying with AS3972 was used. A water reducing admixture was added at a dosage of 400 ml/100 kg of cement to achieve a slump of about 120 mm. Details of the mix proportions are given in Table 2.

Reinforced concrete prisms, 90 × 100 × 650 mm, were cast in two layers. Each layer was compacted using a vibrating table. After casting, the specimens were covered with plastic sheets. All mixing and casting were carried out in a standard laboratory condition at 23 ± 2°C and 50 ± 5% RH. The prisms were demoulded the following day and moist-cured in lime-saturated water up to 28 days of age.

3.2. Cracking of the prisms

Each concrete prism was reinforced with one or two round mild steel bars of diameter 8 mm. Both ends of the steel bars, which projected beyond the concrete, were threaded over a short length so that nuts can be installed. This was to provide anchorage to the bar when subjected to bending. A uniform concrete cover of 30 mm was maintained for all concrete prisms containing either one or two mild steel bars.

At 28 days of age, the prisms were pre-cracked at midspan using three-point loading. It was to generate a fine crack line at the midspan of the prism. Two prisms were then loaded back-to-back and the crack width was opened up to 0.3 mm by tightening the two ϕ12 mm bolts at both ends of the paired prisms. A typical schematic diagram of the prisms in pair is shown in Fig. 3.

It shall be noted that the tension and compression zones of the prism, in flexure, constitute the two vertical sides of

Table 2
Concrete mix proportions

Grade	Mix proportions (kg/m^3) Cement	Water	Sand	C/Agg	w/c	f_c at 28-day(MPa)
20	300	180	847	1035	0.60	29.5

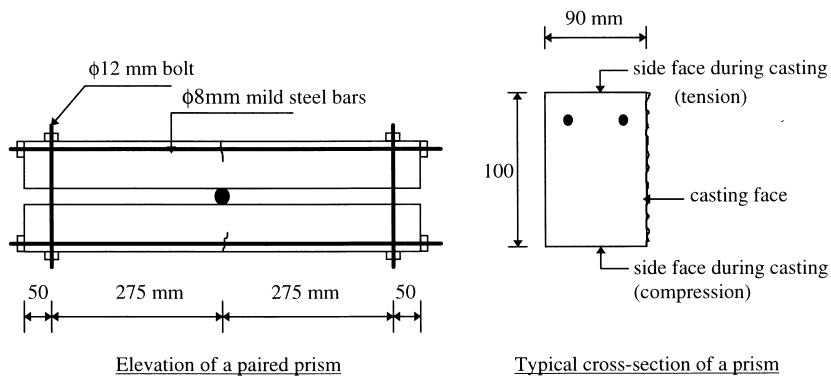

Fig. 3. A typical schematic diagram of the prisms loaded back-to-back.

the forms during casting. It was intentionally orientated this way so that an unbiased comparison between the chloride ion diffusion in the tension and compression zones can be made. For unstressed concrete prism, Mangat and Gurusamy [11] found a significant difference between the diffusion rates of chloride through the casting face and the bottom face (during casting) of the prism. However, they reported similar chloride diffusivity through the two vertical faces (during casting) of the prism. One of the reasons could be the wall effect during casting, which causes more paste or mortar to accumulate at the surface of the concrete specimens [12]. In the present test, all the faces of the prisms were coated with epoxy leaving only the two faces in tension and compression (90 × 650 mm) uncoated. The paired prisms were immersed in 3% NaCl solution for 300 days in a controlled room at 23 ± 2°C and 50 ± 5% RH.

3.3. Chloride determination

The positions of sampling for chloride profiling on the prism are shown in Fig. 4. At each location, two sample holes were dry drilled using a 20-mm diameter rotary impact drill. Powdered samples from locations, for example, (b) were combined to give a test sample representing the average chloride diffusivity in the tension zone 100 mm away from the crack. Similarly, samples from (g) were combined to give a test sample representing the average chloride diffusivity in the compression zone 100 mm away from the midspan. Samples were also obtained at the location of cracks marked as (d). Samples from (a) and (e), and (j) and (f) were combined to give two test samples, respectively, each representing the unstressed control. Here, two test samples are required as a check if there is any significant difference in their results.

The powdered concrete samples obtained were used to extract acid-soluble chloride contents [23]. Mohr titration was used to determine the chloride concentration in the solution. The chloride ion transport into concrete is assumed to be one-dimensional in a semi-infinite medium complying with Fick's 2nd Law of Pure Diffusion [13] given as:

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \tag{1}$$

An analytical solution to Eq. (1) is given by:

$$C_x = C_s \left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_a t}}\right)\right] \tag{2}$$

where C_x is the chloride concentration at distance, x, from the exposed surface, C_s is the surface chloride concentration, D_a is the apparent chloride diffusion coefficient, t is the exposure time and erf is the error function [13]. The value of D_a was determined from the best fit curve represented by Eq. (2) for the measured chloride profile.

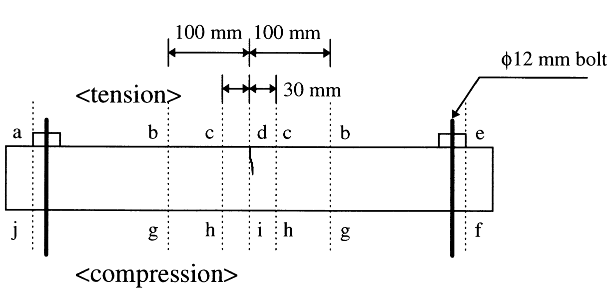

Fig. 4. Locations of the chloride profiling.

4. Results and discussion

The chloride concentration profiles in the tension and compression zones of the reinforced concrete prisms in flexure are shown in Figs. 5 and 6. The chloride concentration profile of the control is also plotted together for comparison. There is no significant difference between the D_a obtained from the two test samples (a) and (e), and (j) and (f). Thus, the average result of the two test samples is

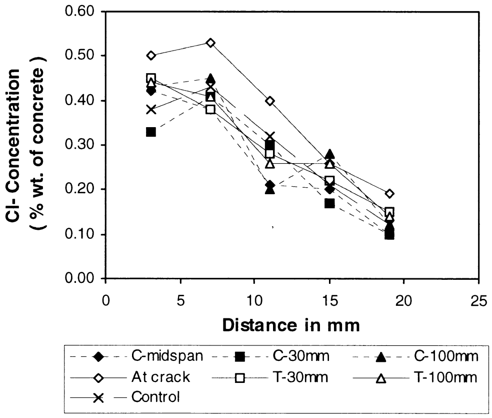

Fig. 5. Chloride profiles of concrete prisms containing 1R8 bar after 300 days in salt solution.

used as a control to be more representative of the two sides of the prism. Table 3 shows the calculated D_a while the values of the normalized D_a (against the control) are given in Table 4.

Tables 3 and 4 clearly show that the chloride diffusivity in the tension zone is greater than that in the compression zone. The chloride diffusivity in the compression zone was observed to decrease as the steel quantity is increased. Comparing Figs. 5 and 6, a wider difference between the chloride concentration profiles in the tension and compression zones is observed from the prism containing two bars. This could be attributed to the increase in stress levels in the tension and compression zones of the concrete.

For the same W_{cr}/C, higher stress levels can be expected to develop in both the compression and tension zones of the concrete in flexure when the quantity of the tensile steel area is doubled. In the compression zone, the increase in flexural stress appears to be an advantage as the chloride diffusivity was found to decrease. This is evident by comparing the D_a in the compression zone at midspan and at 100 mm away. There is a progressive reduction in the D_a towards the midspan of the prism in which maximum stress is expected.

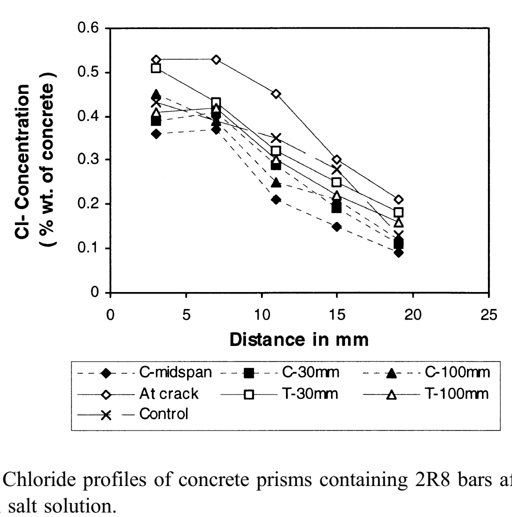

Fig. 6. Chloride profiles of concrete prisms containing 2R8 bars after 300 days in salt solution.

Table 3
Apparent chloride diffusion coefficient (D_a)
C30 = compression 30 mm away from midspan; T30 = tension 30 mm away from crack.

		$D_a \times 10^{-12}$ m^2/s						
		Compression zone			Tension zone			
W_{cr}/C	No. of bars	*M*/span	C30	C100	Crack	T30	T100	Control
0.01	1R8	4.26	5.01	5.31	6.68	5.97	6.06	5.60
	2R8	3.78	4.65	4.52	7.48	6.63	6.75	6.12

The relatively lower D_a values in the compression zone of the prism containing 2R8 bars provide further evidence of the compressive stress effect on chloride diffusivity in concrete. A similar reduction in D_a was also observed when concrete specimens were subjected to uniaxial compression [14]. A possible explanation for this would be the reduction in the porosity of the concrete in compression which impedes chloride diffusion. Diffusion is much slower with smaller pore sizes due to the greater tortuosity of the path an ion has to follow [24]. The compressive stresses in concrete may partially close some microcracks or capillaries that exist in the direction of diffusion. Lower chloride contents at the crack location of pre-stressed specimens had been reported when compared with that of the non-pre-stressed specimens [3].

In the tension zone, a relatively higher D_a was observed when compared to the compression zone. This can be attributed to the damage at the aggregate–paste interface in the tension zone which can expedite diffusion [15]. There is no significant difference in the D_a at 30 and 100 mm away from the crack. These locations were chosen to ensure that the D_a in the tension zone is not influenced by the salt water present in the crack. Thus, a fair comparison between the D_a in the tension and compression zones in flexure can be made. Increasing the number of tensile rebars does not appear to affect D_a in the tension zone significantly.

At the crack, salt water may fill the crack and diffusion may occur from the cracked plane. This is evident from the high chloride content measured along the depth of the crack. The mechanism of chloride transport through a crack in concrete is, thus, different from diffusion in a semi-infinite medium assumed in this paper. Therefore, the D_a determined at the crack may not have any significant implication in terms of the assumed diffusion process. Further study is needed to address the chloride transport mechanism through a crack.

Table 4
Values of normalized D_a

	Normalized D_a					
	Compression zone			Tension zone		
No. of bars	*M*/span	C30	C100	Crack	T30	T100
1R8	0.76	0.89	0.95	1.19	1.07	1.08
2R8	0.62	0.76	0.74	1.22	1.08	1.10

For W_{cr}/C = 0.01 considered in this study, when the tensile steel area is doubled, the decrease in the D_a in the compression zone is 14% at midspan while a marginal increase is observed in the tension zone of a prism in flexure.

5. Conclusions

The crack width/cover ratio, W_{cr}/C, can be a suitable parameter to consider in relation to the durability performance of a cracked reinforced concrete.

Based on some published data on cracked reinforced concretes, made from high performance concrete mixes, it appears that the chloride threshold level can be related to W_{cr}/C by a hyperbolic relationship. However, a cut-off level in the relationship can be assumed as W_{cr}/C tends to zero.

AS 3600 does not give any guidance on the allowable crack width for reinforced concrete structures at serviceability, except for the 'deemed to comply' rules. However, cracks may develop even if the 'deemed to comply' rules are satisfied especially when there is a tendency now to use higher yield strength steel bars (f_y = 500 MPa) as reinforcements for concrete structures in Australia. From the viewpoint of durability, a crack width limitation in AS 3600 is necessary in addition to the cover thickness, to minimize the W_{cr}/C of a cracked reinforced concrete.

At W_{cr}/C = 0.01, a significant reduction in the D_a in the compression zones is observed when the tensile steel area is doubled in the prism in flexure. However, a marginal increase in the D_a is observed in the tension zone of the prism.

In both one- and two-bar prisms in flexure, the D_a value in the tension zone was found to be relatively higher than in the compression zone. This may be attributed to the damage at the aggregate–paste interface in the tension zone, which can expedite the diffusion process. In contrast, the compressive stresses in concrete impede chloride diffusion, which can be attributed to the reduction in the porosity of the concrete.

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