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ORIGINAL PAPER

The effect of crack width on chloride threshold reaching time in reinforced concrete members

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Abstract

In this study, the effects of changes in the surface chloride concentration and crack width have been simultaneously investigated. To estimate the corrosion occurrence in cracked reinforced concrete members, various samples with different crack widths were modelled and the finite element method was used to model chloride ingress into the concrete. The results of modelling showed that the effect of crack on the corrosion initiation (time that chloride content reach to threshold values) is dependent on surface chloride concentration, chloride threshold, and distance from the crack. In cases of cracks with higher thickness and higher surface chloride concentration, the effect of concrete cover thickness is the most important factor on increases durability of the cracked RC members.

Keywords Reinforced concrete structures · Corrosion of reinforcements · Concrete crack · Chloride diffusion · Surface chloride concentration · Chloride threshold

Introduction

Rebar corrosion caused by chloride ingress in RC structures is one of the most important reasons of durability problems in reinforced concrete structures. Concrete structures, due to the characteristics of their materials, are vulnerable against cracking (Spiegel and Limbrunner 2003). Some important factors that led to crack occurrence in early reinforced concrete structures are as follows: 1. cracks caused by the plastic shrinkage due to excessive sweating or settlement of heavier aggregate inside the concrete mixture. 2. Cracks caused by shrinkage due to cement hydration and producing excessive heat, changes in temperature and thickness of cold seams. 3. Cracks caused by shrinkage due to long-term drying (Ghanooni-bagha et al. 2018). These cracks lead to the rapid chloride and water ingress into concrete matrix; therefore, the service life of reinforced concrete structure will be decreased under the attacks of chloride ions. Corrosion, due to the severity and incident scenario, causes changes in the level of performance of the structures. (Ghanooni-Bagha et al. 2019). The amount of chloride on the concrete surface (C_s) is basically the result of environmental conditions in which the concrete presents; however, the structure geometry and concrete quality affects the accumulation and increase of surface chloride density (Gjørv 2014).The C_s value itself mainly depends on height above sea level and on the side of structural element as well as the location which RC structure exists.(Oslakovic et al. 2010) The minimum density of the required chloride for destroying the passive layer and corrosion initiation is called chloride threshold (Tuutti 1982). Chloride concentration threshold value for corrosion initiation is controversial and depends on many factors such as kind of reinforcement, electrochemical environment of the concrete, PH level of the concrete, water-to-cement ratio, moisture, additives (Angst et al. 2009; Schiessl 1987; Taffese and Sistonen 2017; Šavija 2014). For various types of concretes and conditions, different values have been presented in references (Angst et al. 2009; Schiessl 1987; Taffese and Sistonen 2017). Awareness of process occurrence to estimate the durability of service life

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is necessary (Šavija 2014). Corrosion leads to rust formation that increased occupied space compared to the initial state of fittings and the created tensile stresses cause cracks and finally led to spalling (Kang and Shim 2011; Ghanooni-Bagha et al. 2016). Concrete cover cracks at least produce three important effects: 1. These cracks decrease the time for corrosion emergence through simplifying the way for chloride or carbonate to access reinforcements to start removing protective oxide layer significantly. 2. The minimum corrosion near these cracks increases to provide suitable condition for the diffusion of oxygen inside the concrete matrix 3. These cracks create significant lack of uniformity in chemical and physical environment near the rebar that provides suitable condition for corrosion to start (Bentur et al. 1997; Sangoju et al. 2011). Many of researchers studied the effect of chloride diffusion in sound concrete samples (Andrade et al. 1993; Alonso et al. 2017; Suryavashi et al. 2002; Shayanfar et al. 2015; Ghanooni-Bagha et al. 2017). However, in reinforced concrete structures, the importance of cracking is vital, because in concrete structures, design of the conventional reinforced concrete structures, cracks in concrete samples occur in the Tension (Ghanooni-bagha et al. 2018). Experimental and numerical study on crack-induced diffusivity in concrete is performed by some researchers (Benkemoun et al. 2017; Wang and Ueda 2011; Ismail et al. 2008). In an experimental study, Aldea el al. (1999) identified that the rapid diffusion of chloride on concrete disks under the load with tensile cracks, with the thickness of 0.4–0.5 mm, has lower sensitivity for concrete samples with normal strength of chloride ingress compared to high-strength concrete samples. In a study, Conciatori et al., proposed a numerical model based on Fick's second law of diffusion using TransChor program to simulate chloride movement in concrete (Conciatori et al. 2008). In another study, Djerbi et al., by conducting splitting test on the cracked samples, investigated the effect of single cracks on chloride ingress. The results of experiments showed that the diffusion rate of the cracked area (D_{cr}) is simply dependent on the size of crack (Djerbi et al. 2008); therefore, by increasing the crack (both length and weight), its amount increases. However, for cracks with the width larger than 80 micron, it stays constant. Also, Marsavina et al., studies concrete samples with artificial crack that was created by inserting thin copper sheets inside the samples and removing these sheets and found that the diffusion rate increased by increasing in crack depth (Marsavina et al. 2009). The effects of crack width in this study was undetermined and needs more investigation. Therefore, this study aimed to investigate the effect of surface chloride concentration in various environments and concrete cracking thickness on reaching time of chloride concentration to threshold limit and consequent corrosion initiation time. For this purpose, the finite element model for sound and cracked concrete samples were prepared and put under different values of surface chloride loads. The diffused chloride in different parts with different distances from the cracks in models were estimated using Fick's law.

Mathematical modelling for chloride ingress

The chloride ingress mechanism into the concrete, based on fundamental concepts of diffusion by Fick's law, the validity of the first law, the independency of diffusion coefficient compared to time and one dimensionality of the diffusion are stated as the second law (Crank 1979):

$$\frac{\partial C}{\partial t} = D \times \frac{\partial^2 C}{\partial x^2}\,, \tag{1}$$

where C or C (x, t) is the concentrated chloride on each cross-section of the longitudinal axis in the depth of x and time of t based on [mol/m^3]. D is the chloride diffusion coefficient based on [m^2/s] and x is the spatial coordinates. In software modelling, time-dependent effect diffusion coefficient was ignored. If the chloride diffusion coefficient is a fixed number, the above equation is solved considering the following conditions:

$$C(x,0) = 0, \quad x > 0, \tag{2a}$$

$$C(0,t) = C_0, \quad t \geq 0, \tag{2b}$$

$$C(\infty,t) = 0, \quad t \geq 0. \tag{2c}$$

By solving Eq. (1) (the second diffusion law) for the above boundary conditions, the chloride ingress equation based on the depth of x and time of t will be written as follows:

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

where C_0 is the initial chloride on concrete surface and D_c is the diffusion coefficient. In the above relationship, erf is the error function of the possibilities that are estimated by the following relationship:

$$erf(x) = 2\Phi\left(x\sqrt{2}\right) - 1. \tag{4}$$

For surface chloride concentration, as said before this parameter varies on different marine locations and the depth which RC structure is inside the water. Sodium chloride solutions of 3, 6, and 9% were used in modelling corresponds to chloride concentrations of 523.5, 1026.8, and 1570.2 mol/m^3, respectively. The reason for considering these values is because according to many references C_s value in some marine environments and sea itself is some where around 3% and it has been reported up to 11% in some references, In order to evaluate the effect of C_s Value on chloride induced diffusion in cracked concrete we consider three different values of 3, 6 and 9% which are in the mentioned range in references. Since the most important parameter regarding chloride ingress is diffusion rate and this parameter has different values in different conditions, the used values in each condition were implemented according to Table 1.

As mentioned above, there is not any theoretical agreement upon threshold chloride. This is due to the lack of standard and comprehensive experiment; therefore, a vast spectrum of the proposed numbers by the researchers are available (Adiyastuti 2005). Meanwhile, another factors such as temperature, moisture, and surface hardness of rebars inside the concrete influence the threshold chloride (Japan Society of Civil Engineers (JSCE) 2007). According to the JSCE standard, the threshold chloride concentration in rebar surface is proposed as 1.2 kg/m^3 that equals 34 mol/m^3 (Japan Society of Civil Engineers (JSCE) 2007), but this amount is an optimistic and non-theoretical value (Otsuki et al. 2007). A study by Otsuki et al. (2007), showed that the amount of real threshold chloride in some of the existing constructs is more than 10 kg/m^2 (Otsuki et al. 2007).

Modelling in the software

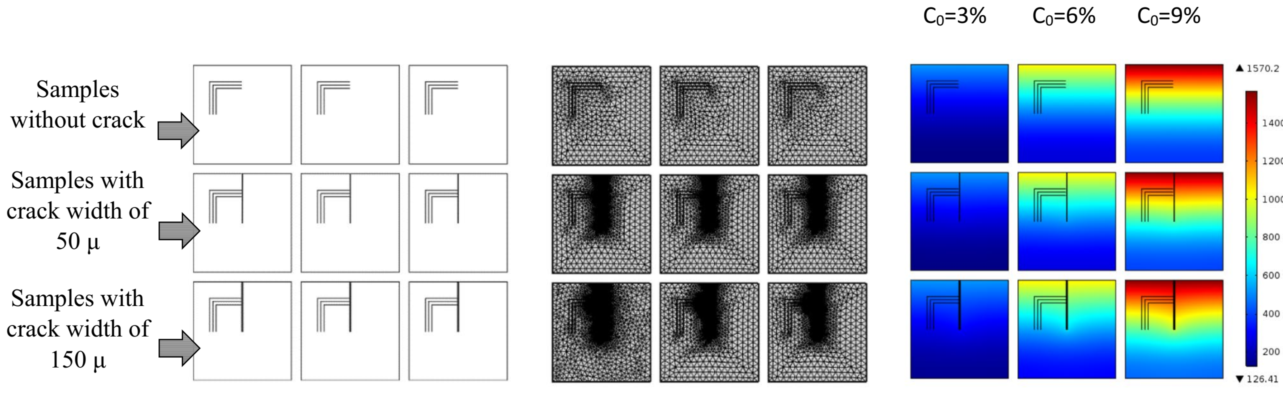
In this study, to investigate the effect of surface chloride concentration (different environmental conditions) and thickness of cracks created on the concrete on the durability of construct, nine concrete samples (300 × 300 mm) were prepared in COMSOL finite element software environment. In this regard, three samples without any crack were selected as the reference samples, three samples with the crack width of 50 micron and length of 150 mm and finally three samples with the crack width of 150 micron and length of 150 mm were modelled. Meanwhile, all cracks were considered at the center of the samples. For each sample, three surface chloride concentrations were considered to take into account the effect of environmental conditions regarding the sound and cracked samples with different crack widths. For all samples, the concrete density was 2500 kg/m^3 and young's modulus and Poisson coefficient entered the model as 25×10^9 Pascal and 0.33, respectively. In Fig. 1, the modelling in the software, meshing, and finally, the chloride ingress into the modelled samples after 3650 days (10 years) can be observed (Fig. 2).

In brief, all assumptions that we take into account are:

1. C_s value differs from time to time and location to location, due to its very variable nature it is hard to model it in both numerical and experimental studies. To deal with this shortcoming, we consider three different values from 3 to 9% as mentioned earlier.
2. There is still no global agreement on the diffusion coefficient value. We use Bentz et al. values as they are relatively famous for being used in many references.
3. We do not model the rebars their selves. Since corrosion starts after rebar's passive layer reaches minimum necessary density of required chloride and in this study we discuss effect of cracks on reaching chloride threshold value for RC structure members.
4. The time period using for this study is set to 10 years. Graphs have shown that most marine structures when crack occurs couldn't maintain their serviceability more than 10 years even in lowest diffusion coefficient rates.
5. Geometric specifications of the model considered as below:

Table 1 Values for the required parameters for modelling (Bentz et al. 2013)

Parameter	Calibrated value	Unit
Diffusion coefficient of chloride in concrete	6 * 10^(− 11)	m^2/s
Diffusion coefficient of chloride damaged areas (between crack and concrete)	1.2 * 10^(− 9)	m^2/s
Diffusion coefficient of chloride in small cracks (width lower than 100 micron)	2 * 10^(− 9)	m^2/s
Diffusion coefficient of chloride in large cracks (width larger than 100 micron)	4 * 10^(− 9)	m^2/s
The size of damaged zone for small cracks (width lower than 100 micron)	1	mm
The size of damaged zone for large cracks (width larger than 100 micron)	4	mm
Coefficient of thermal expansion	10e − 6	1/K
Density for reinforced concrete	2500	Kg/m^3
Thermal Conductivity	1.8	W/(m K)
Heat capacity at constant pressure	880	J/(kg K)
Porosity	0.1828	1
Young's modulus	25e9	Pa
Poisson's ratio	0.33	1



a Models created in the software **b** meshing based on crack zones **c** chloride ingress contour after 10 years

Fig. 1 Modelling in the software

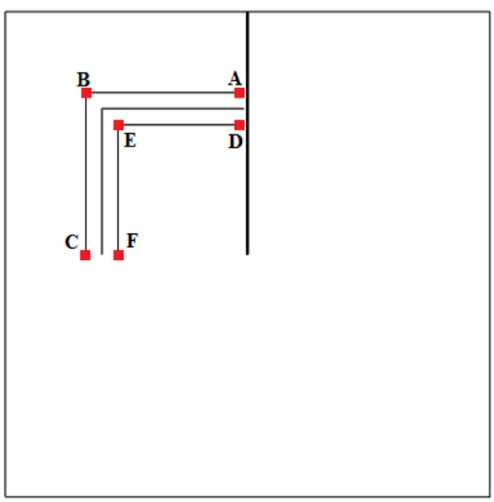


Fig. 2 Geometry details of modelling with reference points and reference lines

a. COMSOL used its presumptions for meshing model. It is set to super fine meshing which are even finer near reference and crack lines.
b. The reference lines located where the existence of rebars in RC structure in marine sites are most probable. We model them with a distance of 50, 60 and 70 mm from upper left edges of the samples. Upper right edges are totally similar to upper left since we model cracks exactly in centre of samples and lower edges are not important as well since they are more far from the cracks.

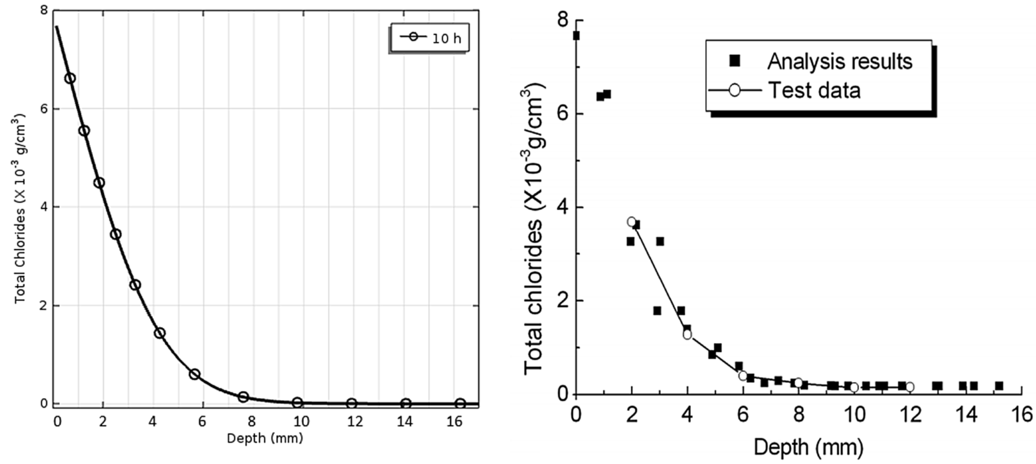
To validate and ensure the accuracy of the results obtained from COMSOL software, Wang and Ueda (Bentz et al. 2013) drew some diagrams for showing the amount of chloride concentration by increasing the depth of crack based on the studies of Mesoscale and the results of Ismail et al. (Adiyastuti 2005) experiments considering diffusion time of 10 h and crack width of 60 microm and diffusion rate in normal concrete and cracked one, respectively, equal to $1.1 \times 10^{-10}\ (m^2/s)$ and $2.76 \times 10^{-6}(m^2/s)$ and finally the amount of surface chloride load $7.68 \times 10^{-3}(g/cm^3)$ (Fig. 3b). Considering the assumptions above, modeling was done in COMSOL software and the obtained results showed good agreement with the results of Wang and Ueda. This comparison has been shown in Fig. 3.

Interpreting the results

According to the modelling and the results of analyses, the effects of crack change effects and surface chloride concentration on various parts of cracked concrete samples are investigated using drawn graphs. In these graphs, the horizontal axis indicates time (based on day) and the vertical axis indicates chloride diffusion based in mol/m^3. The investigated points simply indicate the hypothetical place of rebars in concrete samples. As mentioned, the main purpose of this study is investigating the effect of crack thickness and changes of surface chloride concentration on reaching the threshold chloride based on JSCE as the lower bound (34 mol/m^3) and studies by Otsuki et al. as the upper bound (283 mol/m^3). Therefore, most of the graphs are drawn between to diffusion bounds.

Chloride concentration in the points far from cracks and close to concrete surface

Figure 4a and b shows chloride concentration in different times in 50 and 70 mm distances from two sides of the



a modeling results in Comsol – present study **b** modeling results in Wang and Ueda [21]

Fig. 3 The amount of chloride ion ingress due to crack after 10 h

sample (points B and E) that is practically equal to hypothetical rebars beside the concrete samples considering concrete cover in different areas.

According to the results in Fig. 4, the distance between the curves in the cracks with the widths of 50 and 150 micron, in surface chloride concentration, 3% is lower from this distance between 50 and 150 micron cracks in 9% diffusion mode. In other words, as can be seen in Fig. 4, by increasing the surface chloride concentration in the concrete, the importance of cracks thickness increases and concrete samples with the cracks with higher thickness, show more difference in chloride ion in similar times compared to lower thicknesses. Also, comparing Figs. 4a and 3.4, it is concluded that by increasing the concrete cover, the effect of cracking in long-term period increases. Therefore, it is observed that the difference between concrete samples with the cracks of 150 and 50 micron in Fig. 4b is larger than Fig. 4a that is due to approaching to the crack (expanding the cover from *x* and *y* sides—point B and E).

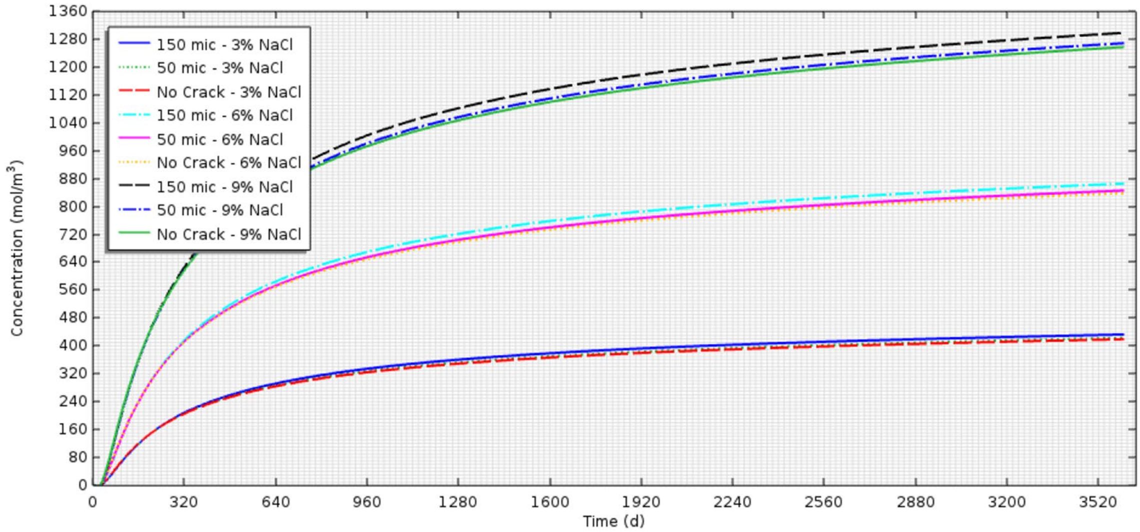
Figure 5 shows limiting the chloride diffusion between two stated bounds (based on JSCE and Otsuki et al.). Unlike the overall results observed in Fig. 4, in Fig. 5, the threshold chloride is much lower than the applied surface chloride concentration and in the areas with higher surface chloride concentrations, the effect of cracking on diffusion is lower. Here, since the initial parts of the Fig. 4 are of interest, in surface chloride concentrations of 6% and 9%, the cracked and sound concrete graphs are overlapped. It means that cracks in the points of interest will be unimportant. Of course, for 70 mm cover that is closer to the crack (despite increased depth), the crack has increased diffusion rate. In 4–3, we will see that as we move toward the crack, its effect will be tangible in high surface chloride concentrations. In not too extreme environmental conditions (surface chloride concentration of 3%), the existence of crack affects the time of chloride concentration reaching to threshold chloride value and as the crack width increases, the changes increase between the Sound and cracked concretes.

By comparing and investigating the results from Figs. 4 and 5, it is concluded that the threshold chloride has a determining role in cracking, its width, and its beginning. For better comparison and quantifying the results, achieving time to threshold chloride content values (corrosion initiation time) in reinforced concrete samples has been presented in Table 2.

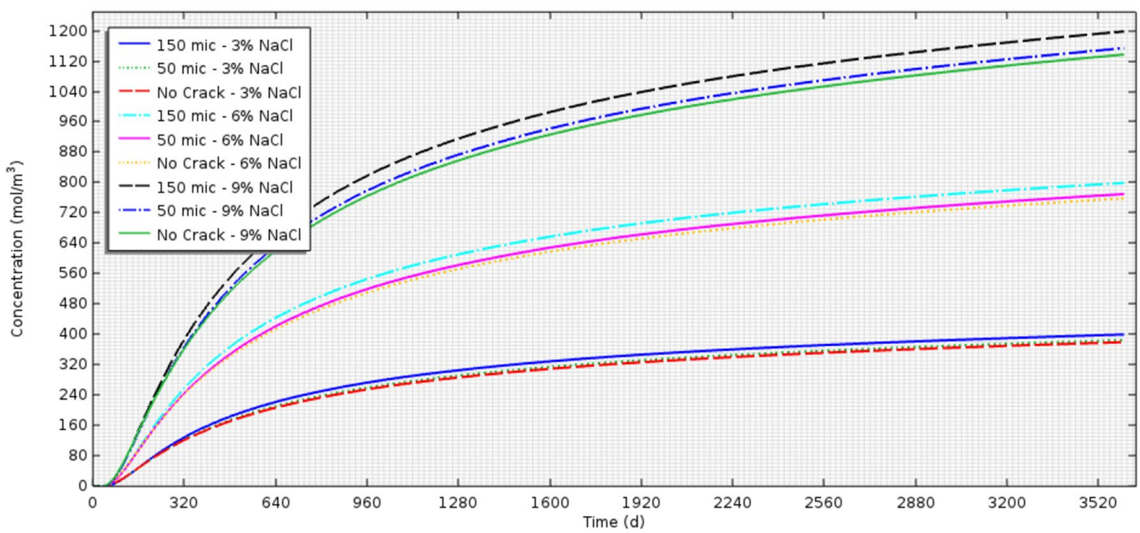
As can be seen in Table 2, change in cover thickness by 20 mm in all conditions increases the time to achieve threshold concentration from 1.8 to 2 times that shows the importance of cover in attacking conditions. The crack width effect on the corrosion is dependent on the threshold chloride and surface chloride concentration (indeed, the ration of these two that is surface chloride concentration to threshold chloride is a very important factor and the larger number, the smaller cracking effect would be). In lower threshold chloride values (JSCE), the beginning time for corrosion is not dependent on the crack's width. In high surface chloride concentrations (9%), the corrosion initiation is almost steady and independent from the crack width. The reason for this condition is high difference between the available chloride concentrations with threshold chloride for the corrosion initiation.

Chloride concentration in deeper points and relatively far from cracks

By selecting a point with the depth of 150 mm and distance of 80 mm from the crack that simultaneously has a distance from both crack and the sample surface, the results of Fig. 6



a 50 mm concrete cover from two sides of the sample (point B)



b 70 mm concrete cover from two sides of the sample (point E)

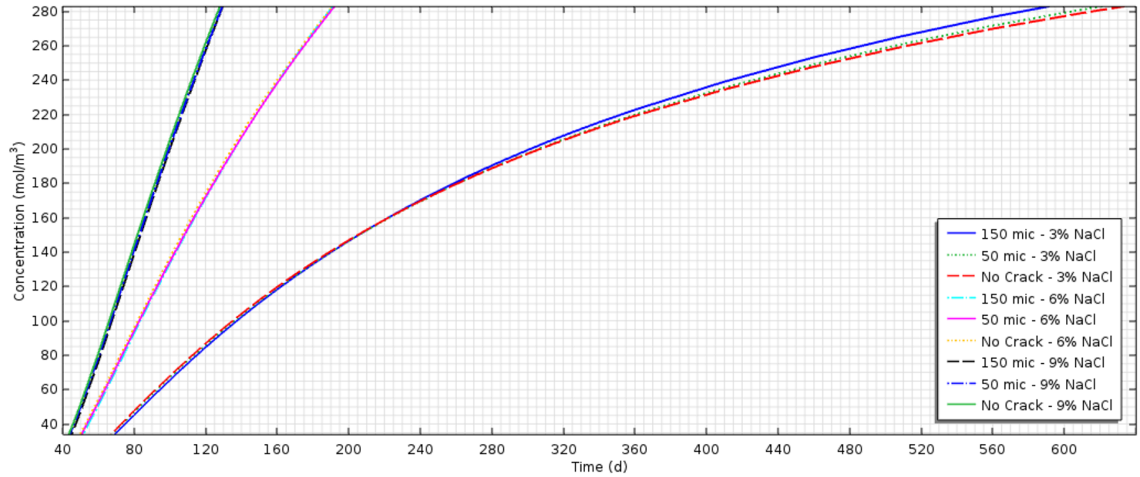
Fig. 4 Chloride concentration based on time (day) in the distance of 50 and 70 mm from the left side and top of the sample (Fig. 3a) and (Fig. 3b)

and Table 4 for threshold chloride will be resulted. From Fig. 6-a, it is observed that the point of interest getting away from the concrete surface and crack, the chloride concentration graph in different times gets more uniform mode and increases by gentle concentration slope and this slope keeps its trend until the end of the 10th year with small changes relative to close modes to the surface and crack. In these points that are far from the concrete surface and have a relatively large distance from the crack, the crack effects on the onset of corrosion, like the previous part, is dependent on the threshold chloride level.

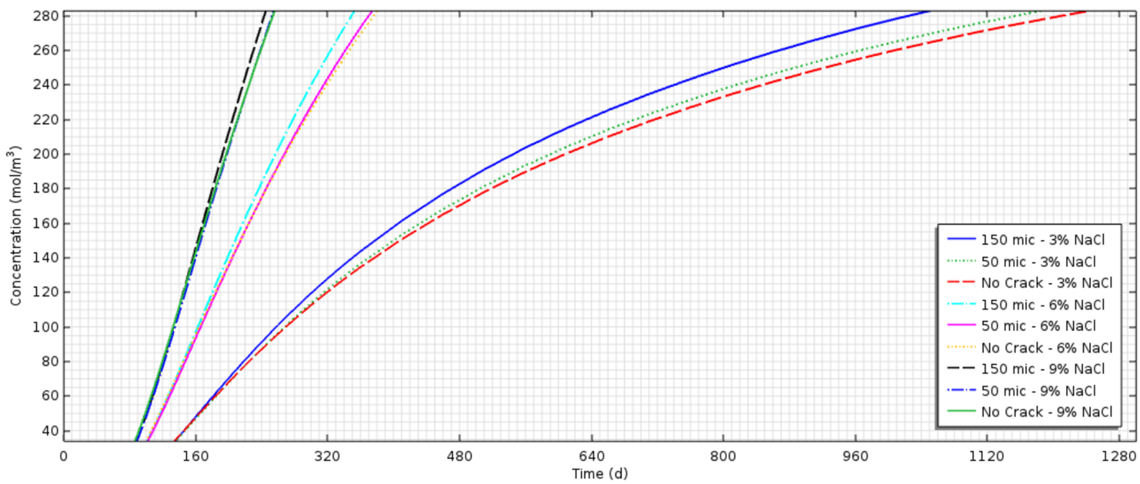
In this part, for better comparison and quantifying the results, the corrosion initiation time due to threshold chloride content value for the identified criteria in part 2 have been presented for different concrete samples in Table 3.

Chloride concentration in the points close to the crack and relatively close to concrete surface

By selecting points close to the crack in distances of 50–70 mm that most of the reinforcements are placed in, the conducted investigations for threshold concentrations are repeated. This point should be mentioned that since the points were far from the crack, by increased surface chloride concentration, the threshold chloride concentration occurs for similar conditions earlier. However, when the point of



a 50 mm concrete cover from two sides of the sample (point B)

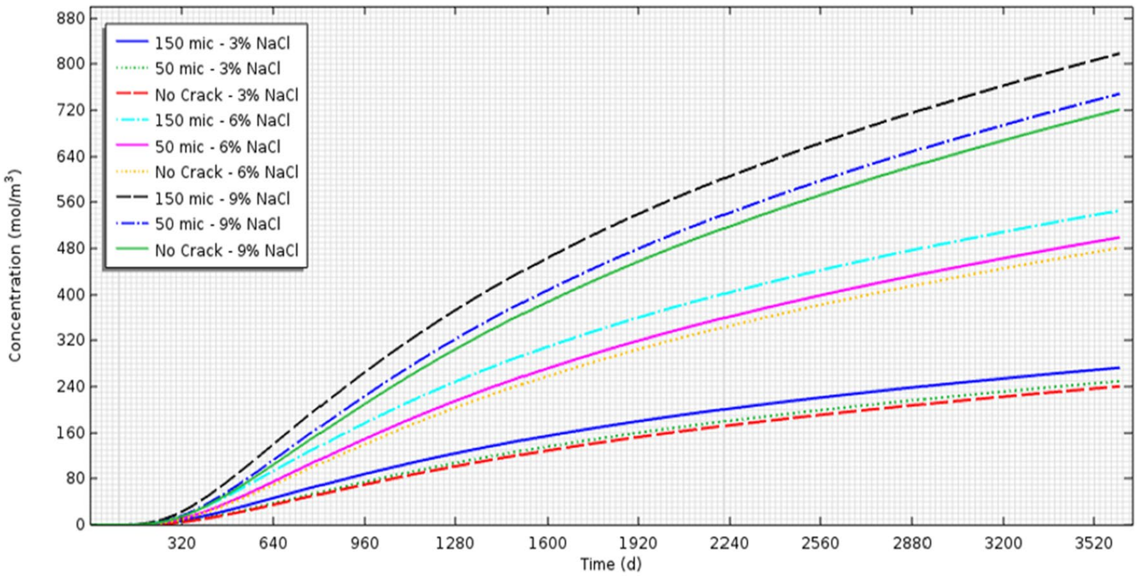


b 70 mm concrete cover from two sides of the sample (point E)

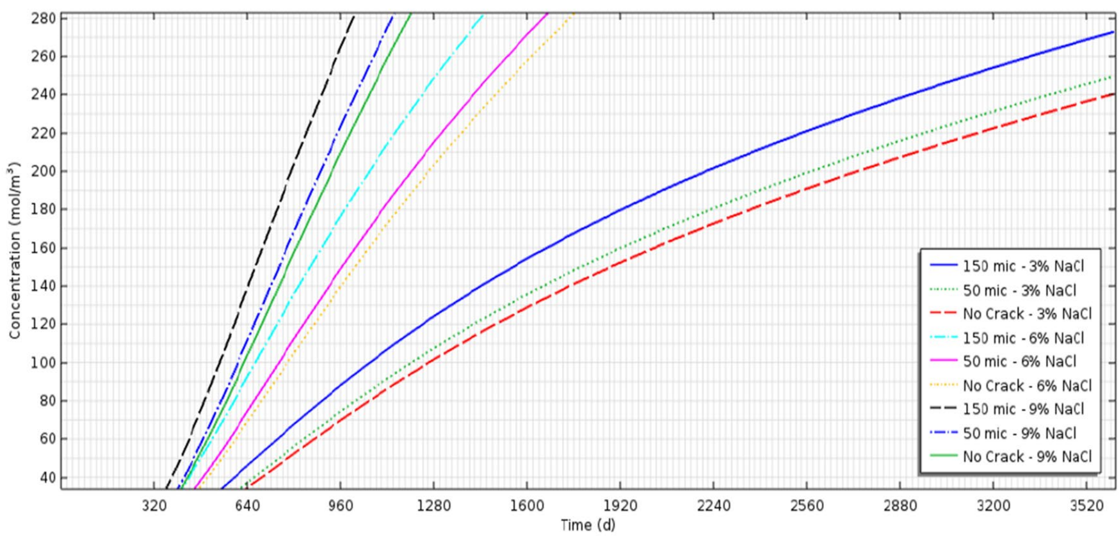
Fig. 5 Zooming chloride diffusion in the depths of 50 and 70 mm from both sides

Table 2 Achieving time the threshold chloride for different conditions of reinforced concrete samples in 50 and 70 mm covers (day)

Sample	Surface chloride concentration	50 mm concrete cover		70 mm concrete cover	
		(lower bound) JSCE (Marsavina et al. 2009)	(upper bound) Otsuki (Crank 1979)	(lower bound) JSCE (Marsavina et al. 2009)	(upper bound) Otsuki (Crank 1979)
Samples without crack	3% Sodium chloride	70	635	135	1240
	6% Sodium chloride	50	195	100	380
	9% Sodium chloride	45	130	85	255
Samples with crack width of 50 micron	3% Sodium chloride	70	620	135	1180
	6% Sodium chloride	50	195	100	375
	9% Sodium chloride	45	130	85	255
Samples with the crack width of 150 micron	3% Sodium chloride	70	590	135	1050
	6% Sodium chloride	50	195	100	350
	9% Sodium chloride	45	130	85	245



a Chloride diffusion in 10 years



b Chloride diffusion in upper and lower bounds of threshold chloride concentration

Fig. 6 Chloride diffusion in 10-years period and zooming it in threshold chloride areas for a point with the depth of 150 mm and distance of 80 mm from the crack (point F)

interest is too close to the crack, the crack effects in early times will be higher than the surface chloride concentration. In other words, around the cracks, the crack thickness affects the ingress value and concentration of chloride ions. Finally (high concentrations of chloride), this difference shows the surface chloride concentration on the samples that determines the main difference between samples in terms of chloride concentration in these areas. However, since the achieving time to threshold chloride occurs at the beginning of the period, the effect of cracks' proximity to the concrete surface should be considered. Therefore, although the surface chloride concentration in long-term period implements large effects on the crack, in short-term period, as can be seen from Figs. 7b and 8b, the crack thickness has the most important role.

In this section, for better comparison and quantifying the results, the corrosion initiation time due to threshold chloride content value for the identified criteria in part 2 has been presented for different concrete samples in Table 4.

It is observed that in the points close to the crack (relatively low depths from the concrete surface), the achieving time of threshold chloride significantly decreases and this issue is intensified by increased thickness of the cracks. According to the Table 4, in the depth of 50 mm near to the

Table 3 Achieving time of threshold chloride for different concrete conditions in relative deep points far from the crack (day)

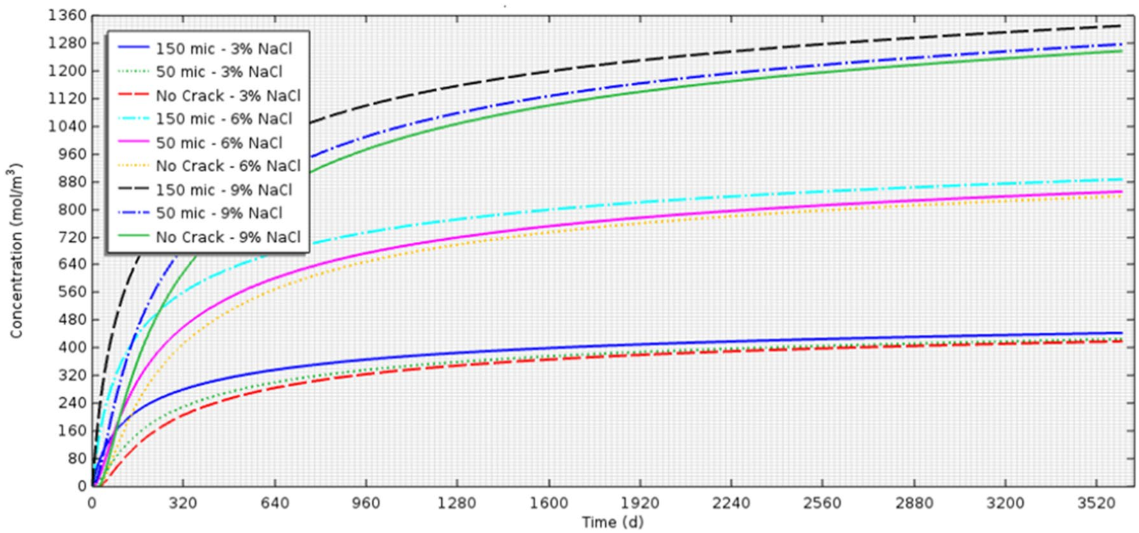
Sample	Surface chloride concentration	A point with the depth of 150 mm and distance of 80 mm from the crack	
		(lower bound) JSCE (Marsavina et al. 2009)	(upper bound) Otsuki (Crank 1979)
Samples without crack	3% Sodium chloride	630	At the end of 10 years does not reach the threshold level
	6% Sodium chloride	480	1780
	9% Sodium chloride	415	1200
Samples with crack width of 50 micron	3% Sodium chloride	620	At the end of 10 years does not reach the threshold level
	6% Sodium chloride	460	1690
	9% Sodium chloride	400	1150
Samples with the crack width of 150 micron	3% Sodium chloride	550	At the end of 10 years does not reach the threshold level
	6% Sodium chloride	415	1450
	9% Sodium chloride	360	1000

crack, according to JSCE criteria, the possibility to occur corrosion decreases to 5 days. Here, we see that although both points are close to the cracks, increased concrete cover by 20 mm has increased the achieving time of threshold chloride (corrosion initiation time) more than two times. This increases by three times in larger crack width. Meanwhile, as can be observed, in each point, the achieving time of threshold chloride in the samples with highest difference has reached to its maximum level. For example, in the point with the depth of 50 mm and distance of 5 mm from the crack, considering JSCE criteria, the latest time of achieving to threshold chloride for the sample with crack with the thickness of 150 micron and surface chloride concentration of 9%, is 13.6 times larger than the earliest time for the sample without crack under the chloride concentration of 3%. This issue again shows the importance of distance from crack in the corrosion initiation time.

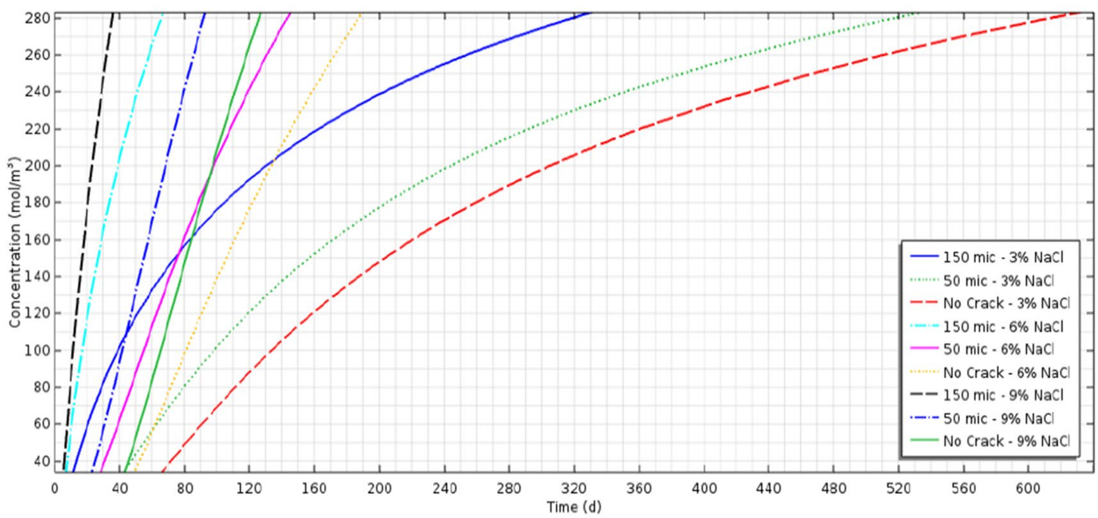
Chloride concentration on a line with the distance of 60 mm from the diffusion place

These graphs show the concentration of chloride along the time. The main difference between this graph and other graphs is the indication of chloride on the reference line instead of a reference point. Indeed, this line has been selected assuming rebars with the concrete cover of 60 mm. in these graphs, in each time, the maximum and minimum chloride concentrations estimated on the reference line are drawn as vertical bars. In Fig. 9, the results of chloride concentration in the reference line with the distance of 60 mm from the diffusion place until the crack, has been drawn for chloride threshold. Figure 9a shows concentration under surface concentration chloride of 3, 6, and 9% for samples with the crack of 150 micron and Fig. 9b shows chloride concentration in the samples with the crack of 50 micron.

In graph performance, the concentration across the line under each surface chloride concentration in each certain time has been shown with a vertical bar graph. The upper part of each bar graph shows the reference line near the crack and the lower part at the distance of 60 mm shows the sides of the sample. According to Fig. 9, the concentration difference for 50 microns crack is always more than 150 microns that indicates increased chloride concentration difference across the reference line. The reason for increased thickness is the existence of 150 microns crack compared to 50 microns crack that facilitates the formation of chloride diffusion in each horizontal line. Therefore, in each certain time, small difference will be created between maximum and minimum concentration. Also, concentration difference between cracks and farther areas is higher in the areas with more surface chloride concentration. The efficiency of this graph in indicating the earliest time of achieving to threshold chloride for each concrete cover is optional. For example, from Fig. 9a, it is identified that if we have reinforced concrete with cover thickness of 60 mm and crack of 150 microns, despite the place of rebar, the earliest time to achieve threshold chloride content value with the criteria of JSCE is about 10 days and for maximum threshold chloride based on studies by Otsuki is about 65 days.



a Chloride diffusion in 10 years



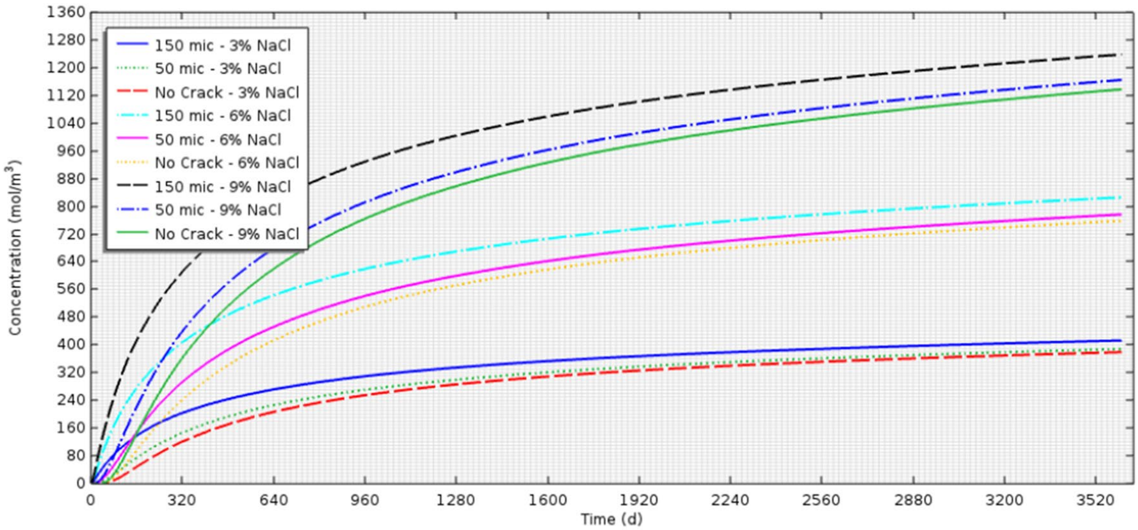
b Chloride diffusion in upper and lower bounds of threshold chloride concentration

Fig. 7 Chloride diffusion in the reference point with the depth of 50 mm and distance of 5 mm from the crack (point A)

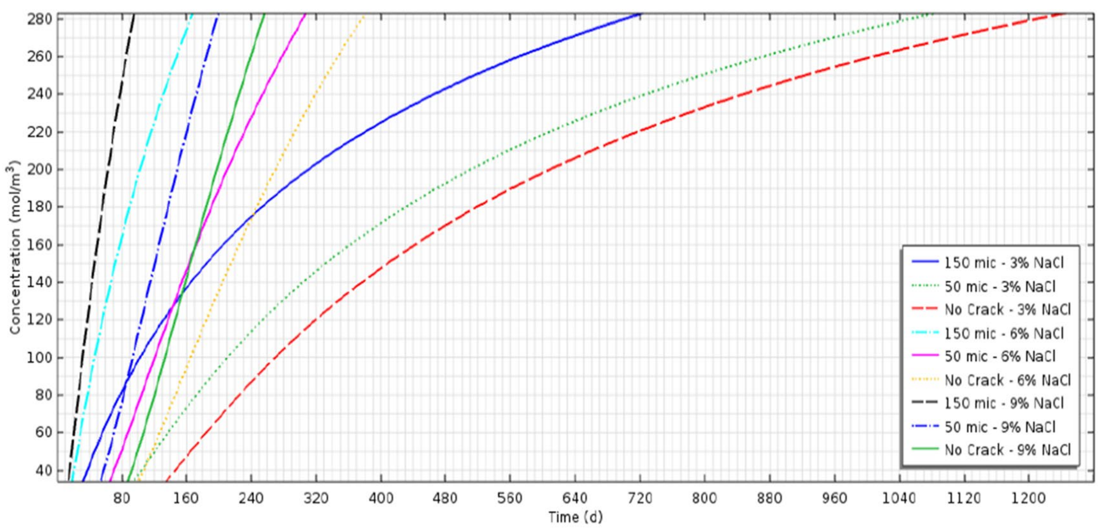
Conclusion

In this study, the effects of crack width changes and surface chloride concentration were investigated using numerical modelling in COMSOL software. The time of achieving to threshold chloride content value for five reference points were investigated and compared. According to the modellings, the following results were obtained:

The penetration depth increasing with an increasing crack depth which is more pronounced for longer test durations as it said before by numerous studies. Concrete cover thickness is effective for increasing the lifetime of structure. So that with increased concrete thickness from 50 to 70 mm, depending on the distance from the concrete surface and crack, the time of achieving to threshold chloride content value increases by 2 or 3 times. Generally, higher surface chloride concentration (C_s) depends on the time of reaching to threshold chloride content value in the concrete sample. In this regard, those points that are relatively close to the crack, will be under the influence of crack thickness and this leads to increased chloride concentration in the first months. However, the higher surface chloride concentration (C_s) effects are shown with the passage of time. There are some studies that determine the effect of crack width on diffusion coefficient. One of the further research suggestions of Djerbi et al. study is to determine how different crack width effect corrosion initiation time so one of our aims was to research this effect. Some of the most important results are: Except locations near the crack, the ratio of surface chloride



a Chloride diffusion in 10 years



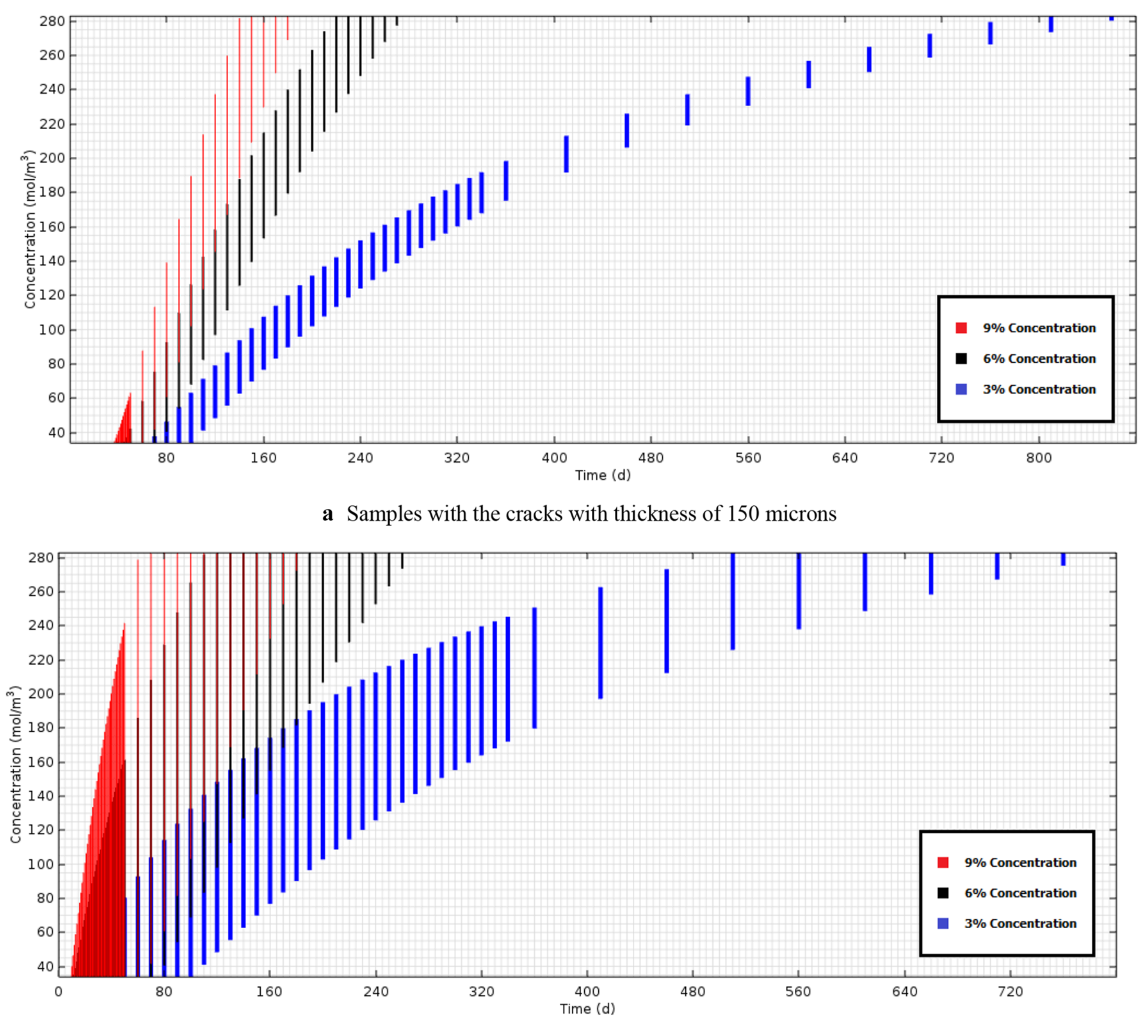
b Chloride diffusion in upper and lower bounds of threshold chloride concentration

Fig. 8 Chloride diffusion in the reference point with the depth of 70 mm and distance of 5 mm from the crack (point D)

concentration to threshold chloride has a reverse relationship with the crack thickness. As the ration increases, the importance of crack ingress into the chloride decreases. Except the initial times and consistent with low chloride concentrations, with increased surface chloride concentration, the difference between chloride concentration between Sound and cracked samples of 50 and 150 microns increases. This trend increases by the passage of time. It is concluded that despite the initial moments that are consistent with chloride ingress concentration, with increased surface chloride concentration and passage of time, the effect of cracks width increases too. Of course, this is more evident near the cracks. This is not correct for the points that are very close to the crack (i.e. points A and D). The reason is the importance of crack existence and width compared to surface chloride concentration near crack area.

Table 4 Achieving time of threshold chloride concentration for different concrete Samples in reference points with the depths of 50 and 70 mm and distance of 5 mm from the crack (day)

Sample	Surface chloride concentration	50 mm concrete cover		70 mm concrete cover	
		(lower bound) JSCE (Marsavina et al. 2009)	(upper bound) Otsuki (Crank 1979)	(lower bound) JSCE (Marsavina et al. 2009)	(upper bound) Otsuki (Crank 1979)
Samples without crack	3% Sodium chloride	70	635	135	1240
	6% Sodium chloride	50	195	100	380
	9% Sodium chloride	45	130	85	255
Samples with crack width of 50 micron	3% Sodium chloride	42	532	95	1082
	6% Sodium chloride	30	145	65	305
	9% Sodium chloride	24	92	55	200
Samples with the crack width of 150 micron	3% Sodium chloride	12	330	32	722
	6% Sodium chloride	8	66	20	170
	9% Sodium chloride	5	35	15	95



a Samples with the cracks with thickness of 150 microns

b Samples with the cracks with thickness of 50 microns

Fig. 9 The bar graph of chloride concentration under different surface chloride concentrations (3, 6 and 9%)

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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