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Cracking corrosion ratio with respect to cracking of concrete cover

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ABSTRACT: Corrosion of a steel bar may cause serious cracking in concrete cover due to expansion of corroded steel. This affects greatly the serviceability as well as durability of concrete structures. It is therefore necessary to determine realistically the amount of corrosion which causes the initiation of cracking in concrete cover. The purpose of the present paper is to examine the amount of corrosion which causes the surface cracking of concrete cover. For this purpose, a series of experiments have been executed. The corrosion tests of a steel bar in concrete have been conducted and the strains on the surface of concrete cover have been measured according to various amounts of steel corrosion. From these tests, the amount of corrosion which causes the initiation of cracking on the surface of concrete cover was determined. The present paper proposes the appropriate cracking corrosion ratios which cause cover cracking of reinforced concrete structures, which are important for accurate assessment of safety for concrete structures.

1 INTRODUCTION

During the last several decades, many concrete structures have been built in severe environments like sea and marine environments. Those structures are vulnerable to chloride attacks and may suffer seriously from corrosion of reinforcing bars. Accumulation of chlorides around a reinforcing bar will cause corrosion of the steel bar in concrete when the chloride content reaches the threshold value.

The cracking of concrete cover due to steel corrosion is an important and essential problem in concrete structures because it directly affects the durability as well as the safety of structures. Corrosion of a reinforcing bar in concrete induces pressure to the surrounding concrete due to the expansion of corroded steel. This expansion pressure induces tensile stresses in concrete around the reinforcing bar and eventually causes cracking through the concrete cover.

It is therefore necessary to examine the amount of corrosion or corrosion ratio for a reinforcing bar which causes the initiation of cracking on concrete cover. This may be dependent upon several factors such as cover depth and concrete strength.

The main objective of the present research is therefore to examine the corrosion ratio which causes the cracking on the surface of concrete cover. A series of experimental program has been set up and main test variables are concrete strength and cover thickness. Corrosion tests for a steel bar in concrete have been conducted and the strains on the surface of concrete cover have been measured for various test series according to the different amount of steel corrosion. The cracking corrosion ratios of steel bars which cause the initiation of surface cracking were then determined from the present test results for various cover thicknesses and concrete strengths. Reasonable determination of cracking corrosion ratio is very important for the realistic prediction of service life of concrete structures under corrosion environments because it is used to calculate the cracking time of concrete cover.

2 DEFORMATION AROUND REBAR DUE TO CORROSION

The corrosion-induced expansion in concrete generally induces tensile stresses and strains in the surrounding concrete. These tensile strains in concrete increase as the corrosion of steel bar progresses. Further increase of tensile strain will cause cracking in the surrounding concrete including the surface of concrete cover during the expansion process.

The tensile strains on the surface of concrete cover due to corrosion expansion are related to the corrosion ratio w_{corr} of a steel bar in concrete, in which w_{corr} represents the ratio of weight loss due to corrosion to initial weight of a steel bar. The present study determines the corrosion ratios w_{corr} for various cases from the comprehensive experimental study. Therefore, the tensile strains on the surface of concrete cover were measured for various corrosion ratios w_{corr} in the present study, and diagrams of strain versus corrosion ratio have been obtained from those tests. These diagrams of strain versus corrosion ratio enable to determine the cracking corrosion ratio which causes the initiation of cracking on concrete cover.

3 CORROSION TESTS FOR SURFACE STRAIN MEASUREMENTS

3.1 *Variables of tests*

The surface concrete strains were measured as the corrosion of steel bar in concrete progresses in order to determine the corrosion ratio which induces the cracking on the surface of concrete cover. For this purpose, a comprehensive experimental program has been set up to execute the corrosion tests of steel bar in concrete.

Table 1. Measured material properties of concretes.

Test Series	W/C (%)	Compressive Strength MPa	Tensile Strength MPa	Elastic Modulus MPa	Cracking Strain ($x10^{-3}$)
N	0.55	27.5	3.10	24,821	0.125
H	0.45	40.3	3.93	30,019	0.131

The major test variables are the cover thickness and compressive strength of concrete. The concrete cover thicknesses varied from 20 mm to 50 mm. The water-cement ratios of concrete considered here were 0.55 and 0.45 in order to see the effects of compressive strength (see Table 1). The test series were designated here as the test series N for W/C = 0.55 (compressive strength f_c' = 27.5 MPa) and the test series H for W/C = 0.45 (f_c'= 40.3 MPa), respectively. The test specimen identification H-4 represents the specimen with compressive strength f_c' = 40.3 MPa and cover thickness c = 40mm.

3.2 *Properties of materials*

The measured material properties of concretes are summarized in Table 1. The compressive strength of concrete for each test series was obtained from the mean value of three test cylinder specimens. The yield strength and tensile strength of steel bar were 392 MPa and 480 MPa, respectively. All the tests for material properties were performed according to the ASTM standards. The Type 1 ordinary Portland cement and the river sand with specific gravity of 2.55 were used. The specific gravity of crushed coarse aggregates was 2.6. The maximum aggregate size of concrete was 20 mm. The slump value of fresh concrete was controlled to be 150mm by using superplasticizer in the mixture and air content was 4.5 percent.

3.3 *Specimen configuration*

The size of test specimens was 200 mm×200 mm× 200 mm cube and the cover thicknesses were 20 mm, 30 mm, 40 mm, and 50 mm, respectively. A steel bar of 20mm diameter was put in concrete specimen at the location of designated cover thickness. Therefore, the ratios of cover thickness to rebar diameter (c/d) are 1.0, 1.5, 2.0, and 2.5, respectively.

3.4 *Accelerated corrosion tests*

Figure 1 shows the photo for the test setup for the present corrosion tests. The test specimens were immersed in *NaCl* 3% solution and corrosion circuit was connected using direct-current power supply. The rebar in the specimen plays as an anode and the stainless steel plate as a cathode. An electric resistance was installed in the corrosion circuit to measure the electric potential. The electrical potential difference between anode and cathode accelerates the penetration of chloride ions into concrete and thus accelerates the corrosion of steel bar. The potential used in the acceleration test for corrosion was 30 volts.

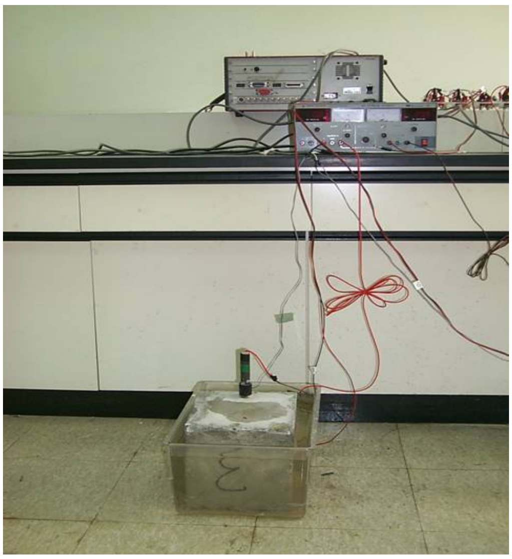


Figure 1. Photo for accelerated corrosion tests.

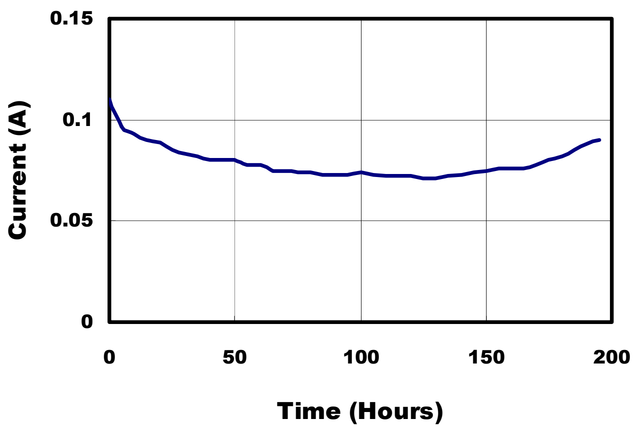
The concrete surface strains and electric potentials were measured every 30 minutes by a data logging system and these measurements were continued until the surface strain increases rapidly and reaches sufficient values. The electric current can be obtained from the resistance value and is used to determine the corrosion amount of the rebar.

3.5 *Evaluation of corrosion ratio*

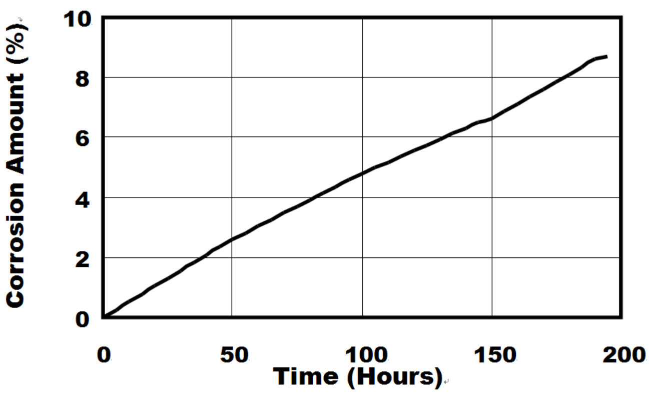
The amount of corrosion of a steel bar may be calculated by Faraday's law. The Faraday's law states that the amount of substance produced or consumed by the electrical quantity of one Faraday (F) is equal to the extracted substance of one chemical equivalent moved by one mol of electron. Equation (1) represents the amount of mol, X, extracted by electrolysis of substance with n electrons.

$$X = \frac{It}{nF} \tag{1}$$

in which I = electric current in ampere(A), n = number of mole participating in production reaction (n = 2 was used here because the initial corrosion products are assumed mostly as n = 2, before surface cracking), t = time (hr), and 1 F = electric quantity of one mole of electron = 96,500 C.



(a) Electric current diagram according to time



(b) Corrosion amount according to time

Figure 2. Electric current diagram and corrosion ratio as function of time for test specimen H4.

An electric resistance was installed in the corrosion circuit to measure the electric potential. The electric current was then obtained from the resistance value. The total electric change was also obtained by integrating the electric current values with respect to time and then the number of mol of corroded rebar was determined by using Faraday's law.

Figure 2(a) shows the current values obtained from the present corrosion tests according to time for the specimen H4, which is the specimen with compressive strength f_c' = 40.3 MPa and concrete cover c=40mm. Figure 2(b) depicts the increase of corrosion amount according to time that is obtained from both the current-time curve of Figure 2(a) and Faraday's law.

3.6 *Measurement of strains on concrete surface*

Strains on the surface of concrete specimen were measured according to time. This is to see the increase of tensile strain due to volume expansion of corroded rebar and to find the time at which the crack occurs on the concrete surface. For this purpose, concrete strain gages were attached on the concrete surface near reinforcing bar. The strain gages were installed in the direction perpendicular to the anticipated crack direction.

The strains were automatically measured and stored by a data logging system. From the measurement of concrete strains, the critical value of corrosion ratio which causes the crack occurrence on the concrete surface has been determined.

The cracking corrosion ratio is the corrosion ratio at which the crack occurs firstly on the surface of concrete cover. The procedure of determination of this value will be addressed in the next section.

4 TEST RESULTS AND DISCUSSION

4.1 *Effect of cover thickness*

The strain values were measured on the surface of concrete specimens. Figure 3 shows the concrete strains as a function of corrosion ratio for test series H with different cover thicknesses. It can be seen from Figure 3 that the development of surface strains is larger and faster as the cover thickness becomes smaller. Namely, much larger strains occur for shallow-thickness specimens at the same corrosion amount. This is because expansive pressure due to same corrosion amount causes much larger surface strains for thin-covered specimens.

The surface strain increases slowly at lower corrosion amount, but increase rapidly after a certain higher corrosion amount. The thin-covered specimens show this rapid increase of strain at relatively lower corrosion amount. The time at surface cracking, which is necessary for the determination of cracking corrosion ratio, was reasonably defined here as the moment at which the cover concrete strain reaches the cracking strain, i.e., the strain at the tensile strength of concrete. The thinner the cover thickness is, the lower the cracking corrosion ratio is.

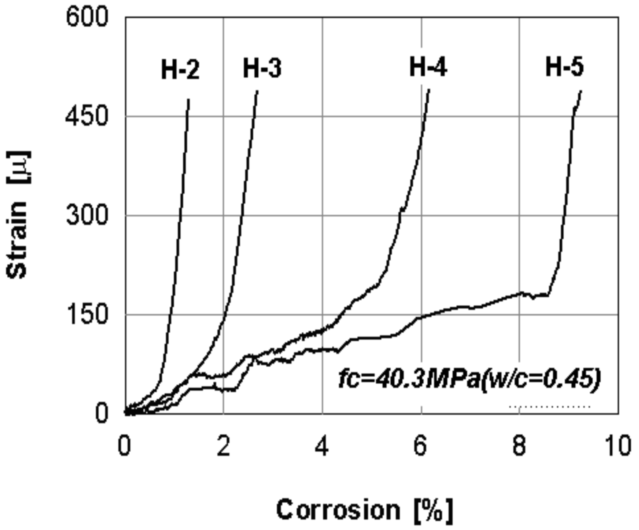


Figure 3. Strain values measured on the surface as function of corrosion ratio for test series H with different cover thicknesses.

4.2 *Effect of concrete strength*

Figure 4 shows the increase of surface strain with an increase of corrosion ratio for various concrete strengths and cover thicknesses. It can be seen that in the case of cover thickness of 20mm, the surface strain versus corrosion ratio curves are almost same irrespective of various concrete strengths.

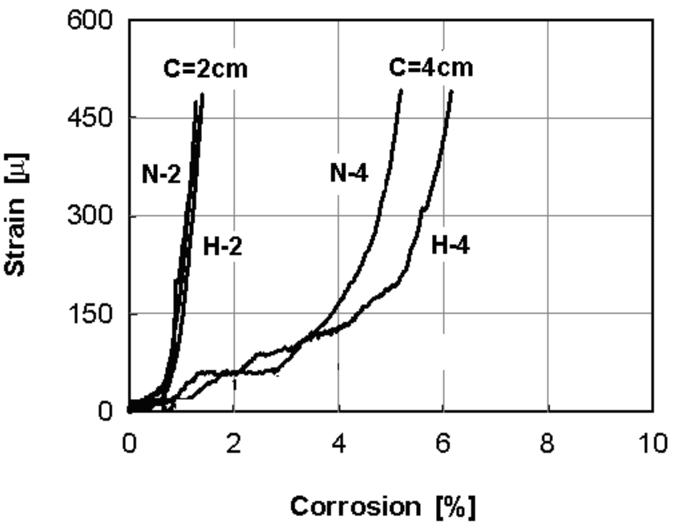


Figure 4. Strain values measured on the surface as function of corrosion ratio for cover thickness c = 2 cm and c = 4 cm for various test series.

However, for thicker concrete cover of 40mm, the surface strain profiles according to corrosion ratio are much different among the different concrete strengths, i.e., among the different test series of N and H, respectively. The compressive strengths of test series N and H are 27.5 MPa and 40.3 MPa, respectively.

Figure 4 indicates that, as the strength of concrete increases, the amount of corrosion that induces the same value of surface strain increases. It is generally true that the concrete of higher strength has higher stiffness (i.e., higher elastic modulus) as shown in Table 1.

This means that higher stiffness of concrete needs higher expansive pressure (and thus higher corrosion ratio) in order to develop the same surface strain. However, the strength of concrete does not affect much the corrosion-induced surface strains for the thin-covered specimens like c = 20 mm as shown in Figure 4.

4.3 *Assessment of cracking corrosion ratio*

It is generally hard to determine the instance of surface cracking by naked eyes. Therefore, the time at surface cracking was reasonably defined here as the moment at which cover concrete strain reached the cracking strain, i.e., the strain at the tensile strength of concrete. This cracking strain can be obtained by dividing the tensile strength by the elastic modulus of concrete (see Table 1).

The critical corrosion ratio which causes the initiation of surface cracking has been determined from the strain versus corrosion-ratio curves (shown in Figs. 3-4) by employing the cracking strains for each test series. The cracking corrosion ratios for various concrete strengths and cover thicknesses may be summarized as follows.

Namely, the cracking corrosion ratios are 0.83 % and 3.60 % for N2 and N4 series, respectively, and 0.88 %, 1.92 %, 4.00 %, 5.59 % for H2, H3, H4, H5 test series, respectively.

It is seen from the test results that the cracking corrosion ratio increases drastically with an increase of cover thickness and also increases with an increase of concrete strength.

The present test results indicate that the cracking corrosion ratio increases approximately proportional to the square of cover thickness as shown in Equation (2). The correlation coefficient of Equation (2) was found to be $R^2 = 0.9941$, which means that Equation (2) correlates very well with the present test data.

$$w_{cr} = 0.0018\, c^2 \qquad (2)$$

in which w_{cr} = cracking corrosion ratio (%) of initial weight of steel bar and c= cover thickness in mm.

The effect of concrete strength on the cracking corrosion ratio becomes larger as the cover thickness increases. It is however interesting to note that the cracking corrosion ratio does not vary much depending upon concrete strength when the cover thickness is rather small such as c = 20mm. This is because, when the cover thickness is small, the cracking occurs under very small corrosion ratio.

5 SUMMARY AND CONCLUSION

The cracking of concrete cover due to steel corrosion is an important and essential problem in concrete structures because it directly affects the durability as well as the safety of structures.

Corrosion of a reinforcing bar in concrete induces pressure to the surrounding concrete due to the expansion of corroded steel. This expansion pressure induces tensile stresses in concrete around the reinforcing bar and eventually causes cracking through the concrete cover.

The purpose of the present study is to explore the cracking corrosion ratio which causes the surface cracking of concrete cover. A comprehensive experimental program has been set up and conducted in the present study. Major test variables include concrete strength and cover thickness of rebar.

It was found from the present study that the cracking corrosion ratios are 0.83 % and 3.60 % for cover thickness c = 2 cm and 4 cm of normal strength concrete (27.5 MPa), respectively.

It was also shown that the cracking corrosion ratios are 0.88 % and 4.00 % for cover thickness c = 2 cm and 4 cm of high strength concrete (40.3 MPa), respectively.

The present study indicates that the cracking corrosion ratio increases greatly with an increase of cover thickness. The concrete strength also affects the cracking corrosion ratio. It was shown that the cracking corrosion ratio does not vary much depending upon concrete strength when the cover thickness is rather small. However, the effect of concrete strength on the cracking corrosion ratio becomes larger as the cover thickness increases.

It is suggested that more data for cracking corrosion ratios for various concretes be accumulated continuously for development of more rational assessment and design codes for durability of concrete structures.

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