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AN EXPERIMENTAL STUDY ON CHLORIDE THRESHOLD VALUE OF STAINLESS STEEL BAR

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ABSTRACT:
Laboratory experiments of corrosion-induced damage of stainless steel bars due to chloride attack in concrete were carried out to evaluate corrosion-resistant property of stainless steel bars. In those experiments, three types of stainless steel bars (SUS304, SUS316, SUS410L) and conventional carbon steel bars were tested by immersing each steel bar in simulated pore solution of concrete. The experimental result shows that stainless steel bars have very high corrosion-resistant property. The chloride threshold value of SUS410L, which has lower corrosion-resistant property compared to SUS304 or SUS316, is more than 23.7kg/m^3.
Keywords: stainless steel bar, chloride threshold value, accelerated corrosion test, corrosion-resistant property

1. INTRODUCTION

Stainless steel is defined as a steel alloy with a minimum of 10.5% chromium content by mass. The passive film of chromium oxide formed on the surface of alloy gives remarkable resistance to corrosion. Stainless steel bars have been studied [1, 2, 3], standardized [4, 5] and applied to reinforced concrete structures under corrosive environment in all over the world. Recently, stainless steel bars have been applied to the construction of major towers of Stonecutters Bridge in Hong Kong, one of the longest stayed-cable bridges in the world with a main span of 1018 meters [6].
In Japan, experimental studies on the behaviors of stainless steel bars [7,8,9] have been performed. Following chloride threshold values for various types of stainless steel bars are obtained through recent studies [10,11].
a) More than 17.7kg/m^3 for SUS304, which is the standard type of stainless steel bars [10].
b) More than 22.9kg/m^3 for SUS316, which has high corrosion-resistant property [11].
c) More than 16.5kg/m^3 for SUS410L [11].
Also, stainless steel bars have been standardized in Japanese Industrial Standards (JIS) in 2008.
Main objective of using stainless steel bars is to improve the durability of reinforced concrete structures under severely corrosive environment. It is very important to evaluate chloride threshold value. So, high corrosion-resistant property of stainless steel bars through experimental studies on the evaluation of chloride threshold value for stainless steel bars in concrete, the behavior of crevice corrosion at rapped joint and galvanic corrosion were examined.
This paper describes the method and the results of corrosion test for stainless steel bars performed in the solution that simulates pore solution in concrete. It also describes the estimation of chloride threshold value of stainless steel bars in concrete obtained from the corrosion test mentioned above.

2. CORROSION TEST IN SOLUTION

Corrosion tests were performed in the solutions that simulate pore solutions in concrete to evaluate corrosion criteria of stainless steel bars in concrete.

2.1 SPECIMENS

(1) Components and dimension

The chemical components of test specimens are shown in Table 1. SUS304 and SUS316 are austenitic stainless steels, and SUS410L is a ferritic stainless steel.
Conventional carbon steel was also used as a reference specimen for the comparison of corrosion-resistant property. Three specimens were arranged for each steel type. Dimensions of specimens are shown in Fig. 1. Width, length and thickness of a specimen are 15mm, 25mm and 5mm, respectively. Specimens were trimmed from a reinforcing bar of which diameter is 25mm.

(2) SOLUTION

Specifications of solutions used are shown in Table 2. Solutions No.1, 2 and 3 simulate the condition of carbonation of pore solution in concrete that of pore

Table 1 Chemical components

Type	C	Si	Mn	P	S	Ni	Cr	Mo
SUS304	0.05	0.39	1.64	0.034	0.025	8.06	18.75	-
SUS316	0.07	0.54	1.71	0.032	0.02	10.09	16.18	2.04
SUS410	0.008	0.36	0.33	0.023	0.004	-	12.67	-
Carbon steel	0.017	0.18	0.7	0.028	0.032	-	-	-

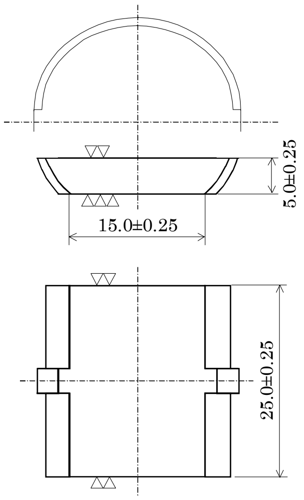


Fig. 1. Dimensions of specimen (mm)

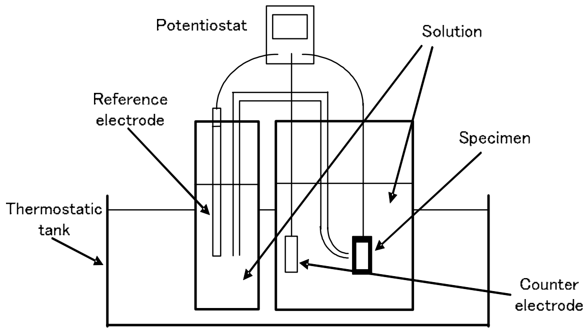


Fig. 2. Outline of test device

solution in normal concrete and that of high-alkali pore solution in concrete, respectively.

2.2 METHOD

Outline of test device is shown in Fig. 2. Tests were conducted in increasing concentration of solution while maintaining electric potential of test face in +200mV (vs. saturated calomel electrode) using potentiostat. The threshold of current density for judging the corrosion occurrence was $0.5 mA/cm^2$. Duration time of test was 48 hours. Temperature of solution was kept 40℃ and test solution without degassing was herein used. Concentrations of chloride solution were incremented by 0.005% for SUS410L and conventional carbon steel in pH 11.9-12.6, and 0.5% for other cases.

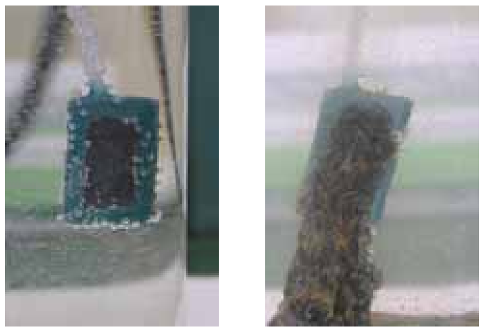
2.3 RESULT

Appearance of tested specimens in the solution No.2 are shown in Fig. 3. Concentration of corrosion occurred are 4.0% , 8.5% and 0.5% for SUS304, SUS316 and SUS410L, respectively.

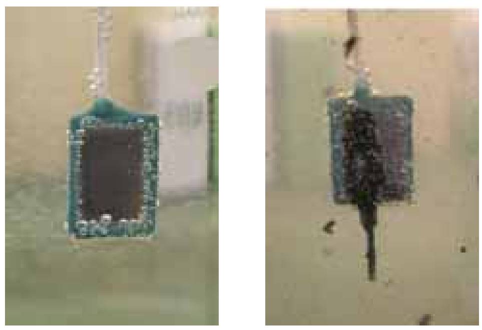
Relationship between corrosion criterion and pH is shown in Fig.4. In all specimens, corrosion criteria are sorted as SUS410L, SUS304 and SUS316, in ascending order. Especially, austenitic stainless steel has very high corrosion-resistant property. Actually SUS316 shows very high corrosion criterion. In addition, the test result for solution No.3 shows the highest corrosion-resistant property of all tests. Test results for SUS410L and conventional carbon steel in solution No.2 are shown in

Table 2 Specifications of solutions

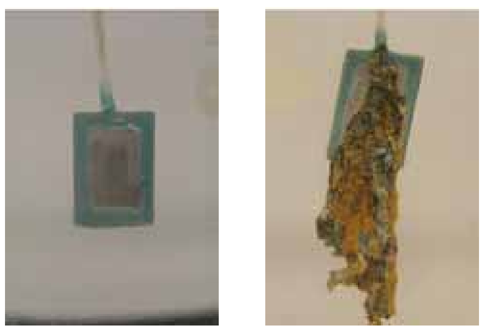
No	Compositions	pH
1	0.015M $NaHCO_3$+0.005M Na_2CO_3	9.1-9.7
2	Saturated $Ca(OH)_2$	11.9-12.6
3	0.9M NaOH	13.2-13.4



Concentration:3.0%   Concentration:4.0%
(a)SUS304



Concentration:8.0%   Concentration:8.5%
(b)SUS316



Concentration:0.0%   Concentration:0.5%
(c)SUS410L

Fig.3. Appearance of tested specimen

Fig. 5.Corrosion criterion of SUS410L was 0.5-0.9 % and that of conventional carbon steel was 0.005-0.05%. Corrosion criterion of SUS410L is lower than that of austenitic stainless steel, but more than 10 times higher than that of conventional carbon steel.

2.4 DISCUSSION

Corrosion criterion in solution No.2 is shown in Table 3. It was 3.5-5.5% for SUS304, 8.5-10.5% for SUS316, 0.0-0.9% for SUS410L and 0.005-0.05% for conventional carbon steel. However, this test was conducted by maintaining electric potential of test face in +200mV (vs. saturated calomel electrode), so corrosion criterion should be lower than the result obtained from the test without maintaining electric potential.

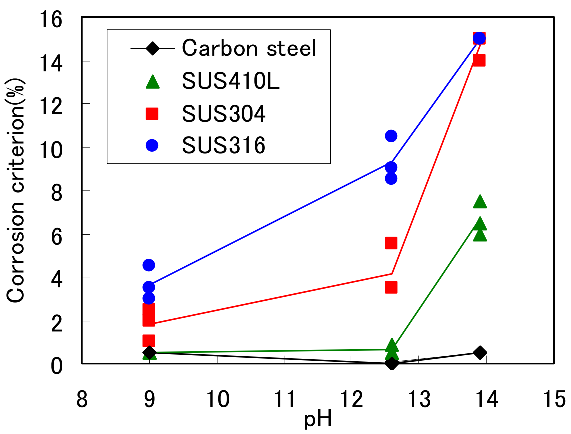


Fig.4 Result of solution test

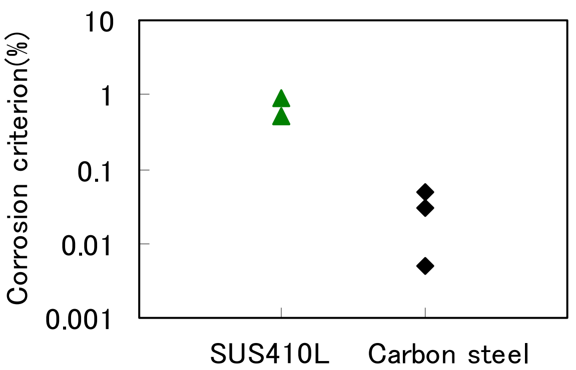


Fig. 5. Result of solution test(pH11.9～12.6)

Table 3. Corrosion criterion (pH11.9-12.6)

	Corrosion criterion (% by mass of solution)	
	Minimum	Maximum
SUS304	3.5	5.5
SUS316	8.5	10.5
SUS410L	0.5	0.9
Carbon steel	0.005	0.05

3. ACCELERATED CORROSION TEST

3.1 TEST METHOD

Outline of test method is shown in Fig. 6. Test was conducted by immersing specimens 5-10mm in 10% NaCl solution in a tank settled in thermo-hygrostat. In order to accelerate infiltration rate of chloride and corrosion of bars, the temperature in thermo-hygrostat was kept to be 40℃.

3.2 SPECIMEN

Outline of specimens is shown in Fig. 7. Mix proportions of concrete is shown in Table 4. The both ends of a specimen were coated by silicon. Parameters of specimens are shown as below.

Steel type: 4 cases (SUS304, SUS316, SUS410L and conventional carbon steel)
Diameters of bar: 13mm(primary bar), 8mm(secondary bar)
Concrete cover(c): 20mm
Water-cement ratio: 50%
Content of cement: 327kg/m^3

Table 4. Mix proportions of concrete

Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit content (kg/m^3) W	C	S	G	Admixture (kg/m^3)
10.5	4.8	50	43.5	162	327	780	1053	3.564

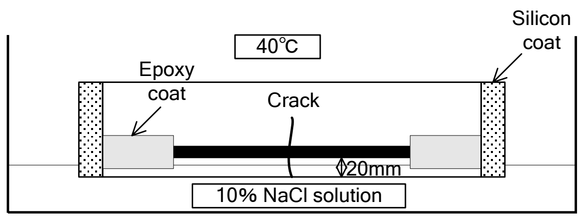


Fig. 6. Outline of test method

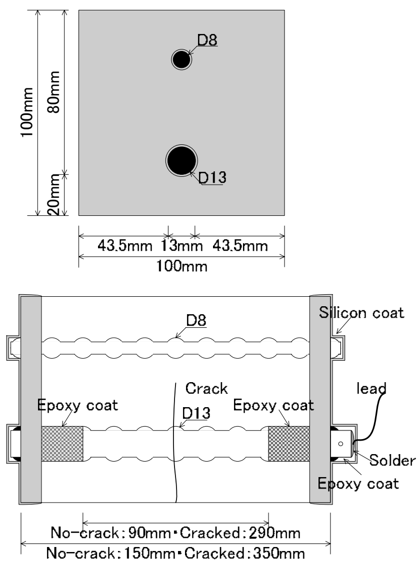


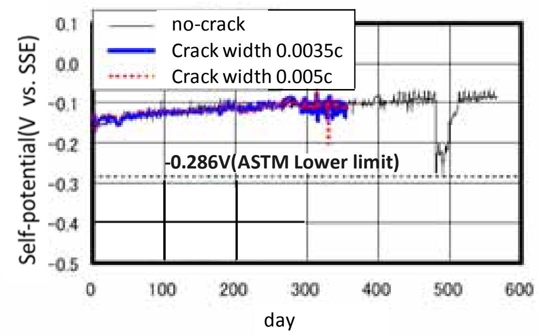
Fig. 7. Outline of specimens

Dimensions:
no-crack specimens(100mm width × 100mm high × 150mm length)
Crack-induced specimens(100mm width × 100mm high × 350mm length)
Crack width : 2 cases(around 0.0035c(0.07mm), and above 0.005c(0.16-0.2mm))

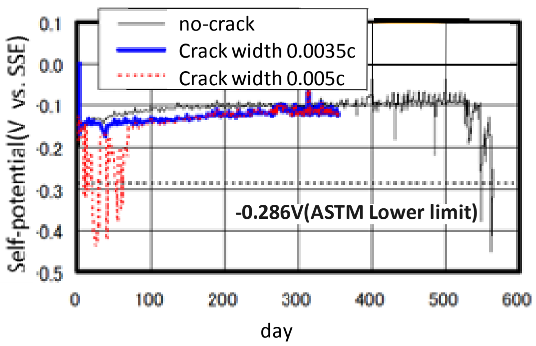
3.3 RESULT

The self-potential curve of specimens with stainless steel bars is shown in Fig. 8. Dashed line shows the electric potential converted from -0.35V(vs. CSE) which is the corrosion criterion evaluated as "Corrosion occurred 90% of the time" in ASTM C 876 to -0.286V(vs. SSE).

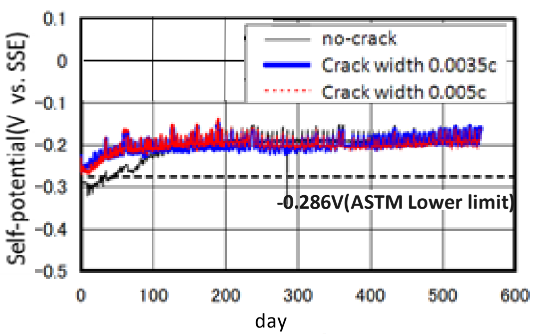
The self-potential curve showed the stable value in all specimens. All the specimens showed more positive self-potential value than ASTM corrosion criterion that is presumed to be no corrosion occurred on the stainless steel bars. Also no occurrence of corrosion was detected through the observation of stainless steel bars after the accelerated corrosion test.



(a) SUS304



(b) SUS316



(c)SUS410L

Fig. 8 Self-potential curve

The measurement position of concentration of chloride ion is shown in Fig. 9. Concentration of chloride ion is shown in Table 5. Also no occurrence of corrosion was detected through the observation of stainless steel bars after the accelerated corrosion test. SUS304 contained 12.3-17.2kg/m^3 of chloride in concrete. Also specimens with SUS316 contained 9.6-22.9kg/m^3 of chloride and specimens with SUS410L contained 7.8-23.7kg/m^3 of chloride in concrete. Thus chloride threshold value of each stainless steel bar is more than 17.7kg/m^3 for SUS304, 22.9kg/m^3 for SUS316 and 23.7kg/m^3 for SUS410L.

3.4 DISCUSSION

Corrosion-resitant property of stainless steel bars increases with the amount of contained chromium. The amount of chromium contained in steel bars is sorted as SUS410L, SUS304 and SUS316, in ascending order. The result of solution test shows the same tendency as suggested above. Therefore, it is estimated that SUS304 and SUS316 have higher corrosion-resistant property than SUS410L.

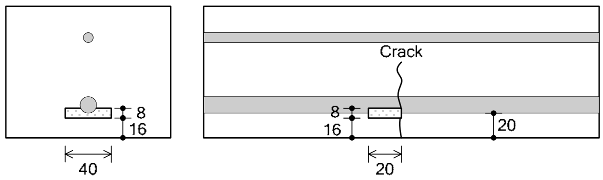


Fig. 9 Measurement positions of concentration of chloride ion

Table 5. Concentrations of chloride ion (kg/m^3)

Type	Max crack width (mm)	Immersing period (months)				
		3	5.5	7.5	12	18.5
SUS 304	0	—	—	—	14.0	14.8
						13.7
	0.1	—	13.4	—	13.4	17.7
	0.18	—	12.3	—	15.4	17.2
SUS 316	0	—	—	—	9.6	13.2
						14.9
	0.08	—	15.7	—	16.5	21.0
	0.18	—	20.2	—	16.4	22.9
SUS 410L	0	7.8	—	14.2	—	19.7
	0.08	10.7	—	16.5	—	23.7
	0.18	10.7	—	15.0	—	19.9

4. CHLORIDE THRESHOLD VALUE

4.1 ESTIMATION

The chloride threshold values can be estimated from the results of solution tests by means of calculating both concentrations of free chloride ion and fixed chloride ion. Results of the solution test of which pH value is ranged from 11.9 to 12.6 were used for estimation.

(1) Pore solution volume in concrete

The pore solution volume in concrete p(% by volume) is calculated by eq. (1) with water content W(kg/m^3), cement content C(kg/m^3) and degree of hydration h(%).

$$p = \frac{W - C \times h/100}{1000} \times 100 \qquad (1)$$

Then, mix proportions of concrete in Table 3 are used as reference for water content and cement content. Degree of hydration is set at 20%.

Thus, pore solution volume in concrete is calculated as 9.66%.

(2) Free chloride

The calculated concentrations of free chloride ion C_v(kg/m^3) are shown in Table 5. Concentration of free chloride ion is calculated by eq. (2) with pore solution volume p(% by volume) and corrosion criteria which are results of solution test.

$$C_v = 1000 \times \frac{a}{100 - a} \times \frac{p}{100} \qquad (2)$$

(3) Fixed chloride

The calculated concentration of fixed chloride a_{fix} (% by mass of binder) is shown in Table 6. Concentration of fixed chloride is calculated by bilinear curved eq. (3) which is derived from approximated relationship between concentration of chloride a_{mob} and concentration of fixed chloride a_{fix}. Above relationship was reported in Ishida's research[13].

$$\begin{aligned} &when \quad a_{mob} < 0.358 \\ &a_{fix} = 4.74 \times a_{mob} \\ &when \quad a_{mob} \geq 0.358 \\ &a_{fix} = 0.240 \times a_{mob} + 1.615 \end{aligned} \qquad (3)$$

$$a_{mob} = a \times \frac{W}{C} \quad \text{(\% by mass of binder)}$$

The calculated concentration of fixed chloride ion C_f(kg/m^3) is shown in Table 7. Concentration of fixed chloride ion is calculated by eq. (4) with concentration of fixed chloride a_{fix} and cement content C.

$$C_{fix} = C \times a_{fix} \qquad (4)$$

(4) Chloride threshold value

The chloride threshold value Cl is the summation of concentration of free chloride ion C_v and concentration of fixed chloride ion C_{fix} . Thus, chloride threshold value is calculated by eq. (5).

$$Cl = C_v + C_{fix} \qquad (5)$$

4.2 DISCUSSION

The estimated chloride threshold value is shown in Table 9. Estimated chloride threshold value of austenitic stainless steel showed high value such as 10.38-13.42kg/m^3 for SUS304 and 18.16-21.46kg/m^3 for SUS316. On the other hand, the chloride threshold value of ferritic stainless steel showed low value such as 4.36-6.57kg/m^3 for SUS410L. The chloride threshold value of conventional carbon steel is 0.043-0.43kg/m^3 , of which value showed lower than the value showed in the Standard Specification for Concrete Structures such as 1.2kg/m^3[14].

Chloride threshold value showed 4.36-6.57kg/m^3 by the estimation from solution test, but it also showed more than 20kg/m^3 as a result of accelerated corrosion test. It is presumable due to the electric potential of test face in solution test and high pH of concrete in accelerated corrosion test. Thus, considering the actual corrosion-resistant property in concrete, it is identified that the stainless steel bars have very high corrosion-resistant property.

Table 6. calculated concentrations of free chloride ion

	Free chloride ion C_v(kg/m^3)	
	Minimum	Maximum
SUS304	3.50	5.62
SUS316	8.97	11.33
SUS410L	0.49	0.88
Carbon steel	0.0048	0.048

Table 7. calculated concentration of fixed chloride ion

	Fixed chloride a_{mob} (%)	
	Minimum	Maximum
SUS304	2.03	2.27
SUS316	2.62	2.86
SUS410L	1.18	1.72
Carbon steel	0.012	0.12

Table 8. Calculated concentration of fixed chloride ion

	Fixed chloride ion C_{fix}(kg/m^3)	
	Minimum	Maximum
SUS304	6.64	7.41
SUS316	8.58	9.36
SUS410L	3.84	5.63
Carbon steel	0.038	0.38

Table 9. Chloride threshold value

	Chloride threshold value(kg/m^3)	
	Minimum	Maximum
SUS304	10.14	13.04
SUS316	17.55	20.69
SUS410L	4.33	6.51
Carbon steel	0.043	0.43

5. CONCLUSIONS

The following conclusions were obtained from the experimental study on the chloride threshold value of stainless steel bars in concrete.

(1) The corrosion-resistant property of stainless steel bars is improved when the pH value is increased.

(2) The chloride threshold value of stainless steel bars is improved with the material grade as in the following order, SUS410L, SUS304, SUS316.

(3) The corrosion criteria of stainless steel bars in solution which simulated concrete pore solution were 0.005-0.05% for conventional carbon steel, 0.5-0.9% for SUS410L, 3.5-5.5% for SUS304 and 8.5-10.5% for SUS316, respectively.

(4) The stainless steel bars above mentioned showed no corrosion in accelerated corrosion test. The accelerated corrosion tests were carried out for 18.5 months in high chloride environment where the content of chloride ion was more than $10kg/m^3$.

(5) It is confirmed that the chloride threshold value of SUS410L, which has lower corrosion-resistant property compared to SUS304 orSUS316, is more than $23.7kg/m^3$.

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