

CONDENSATION AND BINDING OF INTRUDED CHLORIDE ION IN HARDENED CEMENT MATRIX MATERIALS

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This paper shows that condensation of the water-soluble Cl^- in concrete is surprisingly significant in concrete structures submerged in sea water. That is, the Cl^- concentration of the pore solution in the concrete structures can be very much higher than that of the surrounding sea water. In addition, the formation of Friedel's salt is confirmed to be closely related to the binding of intruded Cl^- in materials with cement matrix. The maximum amount of intruded Cl^- bound in the cement matrix materials is also examined. This research therefore provides better understanding of the intrusion mechanism of intruded Cl^- and the induced corrosion of steel in concrete.

Keywords: chloride condensation, chloride binding, intruded chloride, Friedel's salt

1. INTRODUCTION

The chloride ion (Cl^-) is considered as one of the most common culprits in the corrosion of steel in concrete. It breaks down the passive film and allows the steel to actively corrode at a high rate¹⁾. The "Internal Cl^- " in concrete, that is, Cl^- which is introduced at the mixing stage, can be easily avoided by not using marine aggregates or sea water, etc. However, for the "Intruded Cl^- " in concrete, that is, Cl^- which intrudes into concrete from the surrounding environment, there is still no economical and effective counter measure to prevent it. Therefore, from the point of view of controlling the corrosion of reinforcement in concrete, it is very important and necessary to first understand the mechanism of Cl^- intrusion into concrete, so as to provide guidelines for the prediction of Cl^- penetration and the establishment of measures against the penetration.

At present, the mechanism for the intruded Cl^- penetration into concrete submerged in sea water is generally considered as consisting of only two phenomena. These are diffusion and binding of Cl^- in concrete. For the prediction of the Cl^- intrusion into concrete, the bound Cl^- has to be considered in the diffusion process.

On the other hand, the existence of an electrical double layer at the solid-liquid interface within the cement pastes is well known in the field of Inorganic Materials' research^{2),3)}. Babushkin *et al.*⁴⁾ has even reported that the zeta potentials for the calcium aluminate hydrates, ettringite, calcium hydroxide and dihydrous gypsum are in the range of +10 to +20 mV. This may therefore result in "condensation of water

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soluble Cl^- within the pore structure of the cement paste, as a certain amount of Cl^- will be physically adsorbed onto the pore surface even though it is not chemically bound by the cement hydrates.

In this paper, experiments are performed to quantitatively study the condensation and the binding of the intruded Cl^- in hardened cement paste, mortar and concrete. The effects of the replacement of cement with fly ash and blast furnace slag powder on these characteristics are also investigated. Experimental results are then compared with the reported long-term exposure data. In addition, the mechanism of the binding of the intruded Cl^- is also discussed.

2. LITERATURE REVIEW

To date, there have been very few reports on the study of binding of intruded Cl^- in hardened cementitious matrix, especially, when the whole matrix is immersed in sea water. By exposing rectangular concrete specimens ($10 \times 10 \times 110$ cm) at the splash zone as well as immersing sliced concrete specimens ($10 \times 10 \times 0.5$ cm) into the sodium chloride solution and then using the extraction method⁹⁾ to assess the amount of soluble Cl^- in the specimens, Takewaka *et al.*^{6),7)} qualitatively showed that at least 25 to 30 % of the total amount of Cl^- intruded into concrete are bound in the concrete. It was therefore suggested that the binding of intruded Cl^- may have a significant effect on the Cl^- intrusion into concrete.

On the other hand, a quantitative study carried out by Blunk *et al.*⁸⁾ shows that within the total Cl^- content of 2.5 % by cement weight, the bound Cl^- is about 50 % of the total Cl^- content, that is, about 1.25 % by cement weight when the specimen is immersed in sodium chloride solution. Whereas, when the specimen is immersed in calcium chloride solution, about 68 % of the total Cl^- content is bound. In this study, the hardened cement paste is first cured for 28 days and then crushed into a grain size of 0.5 to 1 mm before being immersed in a salt solution. The amount of bound Cl^- is then assessed by measuring the decrease in the Cl^- concentration of the immersion solution. This is no doubt a very convenient method and an excellent idea if the condensation effect does not exist or is negligible. However, from the report of Goto *et al.*³⁾, the effect of the electrical double layer in cement paste seems to be quite significant. If this is the case, Blunk's results may not reflect the accurate amount of Cl^- chemically bound in the specimen.

The mechanism of the internal Cl^- bound in cementitious paste has been generally considered as mainly due to the formation of Friedel's salt and adsorption by calcium silicate hydrates⁹⁾⁻¹⁰⁾. By studying the trapping of Cl^- in cement paste containing fly ash, adsorption of Cl^- by fly ash is also found by Roy *et al.*¹¹⁾ to play a significant role in Cl^- removal from pore solution. In contrast, the binding mechanism of the intruded Cl^- in cement paste is hardly discussed. However, Matsuoka *et al.*¹²⁾ have reported that formation of Friedel's salt is also observed in a cement-mortar specimen immersed in saturated sodium chloride solution after 28 days of pre-curing in water. Nagataki *et al.*¹⁰⁾ have also shown that the binding of both the internal Cl^- and the intruded Cl^- in cementitious material are closely related to the formation of Friedel's salt.

3. EXPERIMENTAL PROGRAM

Two series of experiments are performed in this study.

Series I is to study the condensation and binding phenomena quantitatively by using thin plate cementitious paste specimens ($4 \times 4 \times 0.3$ cm) homogeneously distributed with the intruded Cl^- and in which Cl^- is prevented from diffusing away from the specimen.

Series II is to confirm and to compare the "ideal" results obtained in series I with that of the cement paste and mortar specimens ($4 \times 4 \times 16$ cm) as well as concrete specimens ($10 \times 10 \times 13$ cm) submerged in a sodium chloride solution with Cl^- concentration equivalent to that of the sea water, that is, 19 380 ppm. It is considered that with the specimen of these dimensions and the NaCl solution of this Cl^- concentration, the experiment should be able to simulate the actual concrete structure submerged in sea water. However, how closely do these conditions simulate the actual conditions is pending for further study.

(1) Mix details

Details of the sample mixture for both series I and II are shown in Table 1 and the characteristics of the cementitious materials used are in Table 2. Table 3 shows the physical properties of the aggregates used. All the materials used in this study are free of chloride.

(2) Preparation of specimen

a) Series I

In this study, specimens are first cast into special moulds having a thickness of only 3 mm, and then demoulded after 24 hours. These specimens are then cured in water at temperature of 20°C for a scheduled period before immersion in the NaCl solution with Cl⁻ concentration equivalent to that of sea water. The immersion solution is freshly replaced at one week intervals so as to ensure a constant Cl⁻ concentration. After a scheduled period of immersion, a suitable number of the specimens are then put together for pore solution expression¹³⁾. At present, this expression method is considered as the only reliable method for determining water-soluble Cl⁻ content in cement paste¹⁴⁾. In this study, this method is adopted by applying pressure through the piston at an increasing rate of 0.15 tf/cm² per minute until reaching a maximum level of 4.58 tf/cm². It is confirmed that the Cl⁻ concentration of the pore solution collected by this method is not affected by the applied pressure within this maximum limit. In addition, the 3 mm thickness of the plate specimens is believed to be able to provide early saturation of Cl⁻ in the pore solution of the paste so as to minimize the problem of Cl⁻ concentration gradient in the specimen and thus result in a relatively homogeneous distribution of Cl⁻ in the specimen. Therefore, it is believed that the experimental procedure adopted in this study enables the binding as well as the condensation of intruded Cl⁻ in cementitious paste

Table 1 Mix Details.

Cementitious Paste		0.4,	0.5,	0.6
W/C Ratio				
Mineral	Type	Fly Ash(PFA), Blast Furnace Slag Powder(BFS)		
Admixture	Replacement Ratio (wt %)	0, 30		

Mortar

Flow Value	W/C Ratio	S/C Ratio
205	0.4	1.6
210	0.5	2.3

Concrete

Max. Size of Coarse Aggregate (mm)	Slump (cm)	Air Content (%)	W/C Ratio	s/a Ratio (vol.%)	Unit Weight (kg/m ³)			
					Water	Cement	Fine Aggregate	Coarse Aggregate
20	8 + 1	2.0	0.4	46.0	192	480	774	906
20	8 + 1	2.0	0.5	48.0	187	374	856	924

Table 2 Material Characteristics.

Material	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Spec. Surface (cm ² /g)
OPC	63.9	21.8	5.0	2.9	2.3	1.7	3380
PFA	9.6	51.1	29.3	2.8	0.4	2.1	2710
BFS	41.8	33.1	15.0	0.6	-	6.8	3980

Table 3 Physical Properties of Aggregates.

Type	Max. Size (mm)	F.M.	Spec.Gravity	Absorption
Fine	5	2.74	2.64	1.94
Coarse	20	6.81	2.64	0.68

to be investigated quantitatively.

b) Series II

Cement paste specimens and mortar specimens with the dimensions of 4×4×16 cm are cast, while, for the concrete specimens, the dimensions are 10×10×13 cm. All these specimens are cured in water at 20°C for 3 days after demoulding. Four sides of each of these specimens are then sealed with epoxy coating followed by curing in water for another 4 days before immersion in sodium chloride solution with Cl⁻ concentration of 19 380 ppm. After a scheduled period of immersion, the total Cl⁻ and water-soluble Cl⁻ distribution curves are then obtained by splitting the specimens into a few thin plate layers across the Cl⁻ intrusion direction.

(3) Analysis of test results

a) Cl⁻ condensation index, Cl⁻ binding capacity and Cl⁻ binding percentage

In this study, the Cl⁻ condensation index is used to assess the magnitude of the Cl⁻ condensation phenomenon, and the Cl⁻ binding capacity and the Cl⁻ binding percentage are used to assess the binding phenomenon in the specimens. The Cl⁻ condensation index is defined as the Cl⁻ concentration of the pore solution in the specimen divided by the Cl⁻ concentration of the surrounding solution in which the specimen is immersed. The Cl⁻ binding capacity is defined as the amount of Cl⁻ bound in the specimen by weight of cement. Whereas, for the Cl⁻ binding percentage, it is defined as the percentage of the amount of bound Cl⁻ with respect to the corresponding total Cl⁻ content. They are computed according to the following equations.

$$\text{Cl}^- \text{ condensation index} = B/E \dots\dots\dots (1)$$

$$\text{Cl}^- \text{ binding capacity (wt \%)} = [(D - B \times (W_w - W_a)) \times (C + W) \times 100 / C(W_w - D)] \dots\dots\dots (2)$$

$$\text{Cl}^- \text{ binding percentage (wt \%)} = [(D - B \times (W_w - W_a)) \times 100 / D] \dots\dots\dots (3)$$

where W_w = weight of cementitious sample (g);

W_a = weight of the above sample heated to constant weight at 105°C (g);

D = total Cl⁻ in the above sample (g);

C = cement content (g);

B = Cl⁻ concentration of pore solution (g/g);

E = Cl⁻ concentration of the immersion solution (g/g);

W = water content (g).

In eq. (2), it is assumed that the supply of water from the immersion solution to cementitious pastes is negligible. In addition, prior to the over-dry at 105°C, all the sample are first immersed in the acetone solution for 24 hours so as to stop the hydration reaction.

b) Assessment of total Cl⁻ content

For the analysis of the total Cl⁻ content in the cementitious pastes, specimens are first dried to a constant weight at 105°C and then crushed into powder before fluorescent X-ray spectroscopy analysis.

c) Assessment of water soluble Cl⁻

For the result obtained in Series I, the concentration of the water soluble Cl⁻ can be assessed directly by using the Ion Chromatograph to analyze the expressed pore solution. However, in Series II, the amount of each thin layer specimen after splitting is insufficient for expressing its solution. Therefore, the extraction method⁵⁾ is adopted by first crushing the specimen into powder particles smaller than 149 μm and then mixing 10.0 g of the powder particles with the distilled water at 20°C for an hour. The amount of Cl⁻ passing into the distilled water is then measured by using Ion Chromatograph and is considered as the water soluble Cl⁻ in the powder specimen. However, these results cannot be compared directly with those obtained by the pore expression method. As the results obtained by this method can be affected by a lot of factors, such as, fineness of particle size, extraction time, agitation and temperature of solvent, etc.⁵⁾, it is therefore necessary to correlate the result obtained by the extraction method under the present conditions with that of the corresponding results obtained by using the pore expression method. Fig. 1

shows the correlation between the corresponding results obtained by the present extraction method and that by the pore expression method with the same specimens. The specimens used in this figure are the thin specimens used in Series I. That is, the intruded Cl^- is believed to be homogeneously distributed in the specimens.

d) Assessment of the amount of Friedel's salt

In order to trace the Friedel's salt in cementitious paste, Powder X-ray Diffraction (XRD) analysis is performed. A definite peak at 7.9 \AA position is clearly traced for the corresponding cementitious pastes containing intruded Cl^- . It is therefore assumed in the present study that the peak at this particular position denotes only the formation of Friedel's salt, $\text{C}_3\text{A}\cdot\text{CaCl}_2\cdot 10\text{H}_2\text{O}$.

To quantify the amount of Friedel's salt ($d=7.9 \text{ \AA}$), zinc oxide ($d=2.48 \text{ \AA}$) is thoroughly mixed with the specimen powder with a weight ratio of 1 to 20. The peak at 7.9 \AA position of each trace is then divided by the peak of ZnO . This resultant peak ratio (R) is considered as proportional to the actual amount of Friedel's salt in each trace¹⁰

4. CONDENSATION OF INTRUDED CHLORIDE ION IN CONCRETE

(1) Condensation of intruded Cl^- in thin plate specimen (Series I)

The soluble Cl^- concentration of the pore solution in the specimen, having W/C ratio of 0.5 by weight, with respect to the immersion period in the sodium chloride solution is shown in Fig. 2. It can be seen that irrespective of the period of pre-curing in water, the Cl^- concentration of the pore solution increases with the immersion period. In addition, it goes beyond the level of Cl^- concentration of the immersion solution within a immersion period of 4 weeks. At the immersion period of 13 weeks, the Cl^- concentration of the pore solution is almost twice as high as that of the immersion solution, that is, with a condensation index of about 2.0. Furthermore, at this stage, the Cl^- concentration of the pore solutions are still in an increasing trend.

Fig. 3 shows the effect of W/C ratio and the replacement ratio of cement with fly ash or blast furnace slag powder on the condensation phenomenon after the specimens were immersed for 13 weeks in the sodium chloride solution. It should be noted that the condensation index used in this paper serves as an indicator whether the "average" Cl^- concentration of the pore solution in the specimen at a macro-scale level is higher or lower than that of the immersion solution. It also used as a macro-scale indicator for assessing the magnitude of the phenomenon. It can be seen that the condensation phenomenon is significant in all the specimens with W/C ratio of 0.4 to 0.6 and with or without mineral admixtures. However, the relationship between the W/C ratio and condensation index cannot be identified. For the specimen with W/C ratio of 0.5 containing blast furnace slag powder, results generally show that the shorter the pre-curing period, the higher is the condensation index. Whereas, for the specimen containing fly ash, there is no clear relationship between the pre-curing period and the condensation index.

The results in these figures therefore clearly show that the condensation phenomenon does exist, that is, the soluble Cl^- concentration of the pore solution will become denser than that of the immersion solution when the cementitious paste is immersed in the chloride solution. And this phenomenon may become significant within a short period as indicated in Fig. 2.

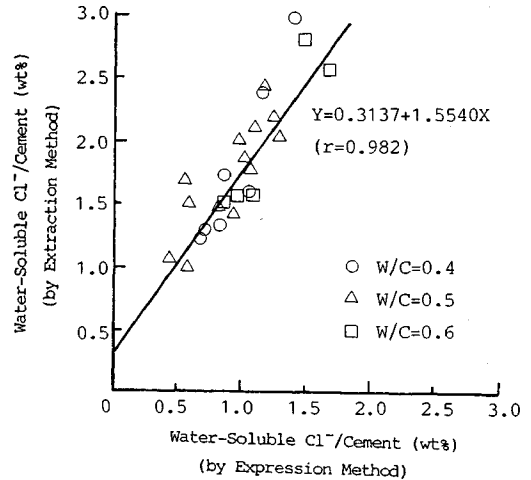


Fig.1 Extraction Method versus Expression Method.

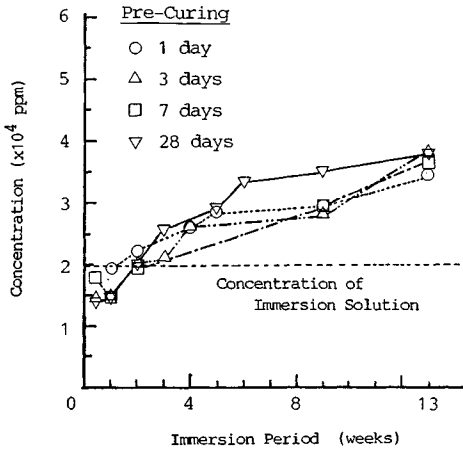


Fig. 2 Immersion Period and Cl^- Concentration of Pore Solution (Series I).

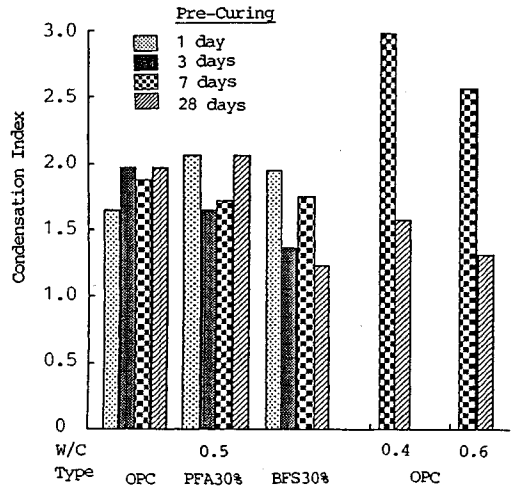


Fig. 3 Effect of W/C ratio and Mineral Admixtures on Condensation (Series I).

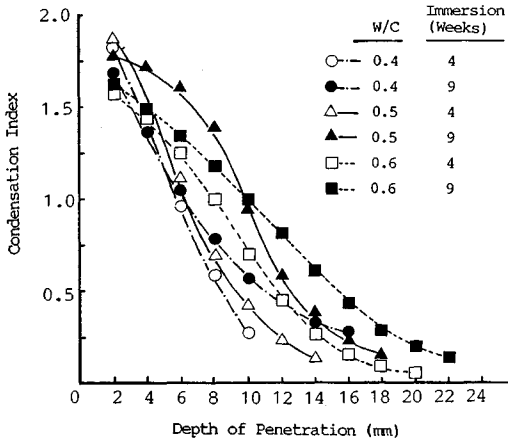


Fig. 4 Cl^- Condensation in Cement Paste Specimens. (Series II)

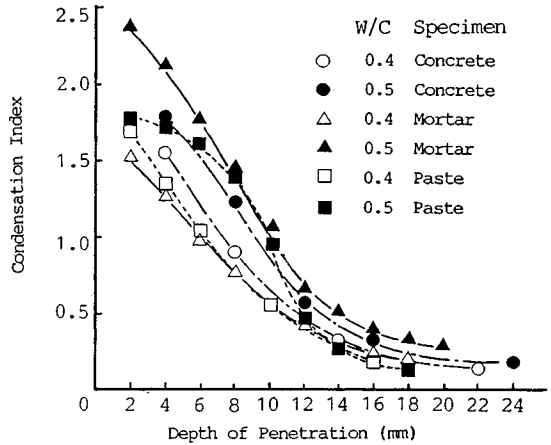


Fig. 5 Effect of Aggregates on Cl^- Condensation (Series II).

(2) Condensation of intruded Cl^- in specimen which simulates the actual concrete structures immersed in sea water (Series II)

Fig. 4 shows the variation of the Cl^- condensation index along the penetration direction in the cement paste specimens having W/C ratio of 0.4, 0.5 or 0.6 after immersion in the sodium chloride solution for a period of 4 to 9 weeks. It can be clearly seen that for all the specimens, irrespective of the W/C ratio and immersion period, the portions closer to the exposure surface have a condensation index above 1.0, that is, the Cl^- concentration of the pore solution in these portions are all greater than that of the immersion solution. This condensation index decreases with the depth of intrusion. In addition, the condensation index for the same portion generally increases with the immersion period.

The comparison between the Cl^- condensation index throughout the Cl^- penetration route in the cement paste, the mortar and the concrete specimens which have been immersed in the sodium chloride solution for a period of 9 weeks is shown in Fig. 5. It can be observed that for the same W/C ratio, there is almost no difference between the condensation index of the specimens with or without the aggregates.

The results in these figures therefore clearly suggest that the condensation phenomenon is also

significant in the actual concrete structures immersed in sea water, especially, at those portions near the exposure surface.

5. BINDING OF INTRUDED CHLORIDE ION IN CONCRETE

(1) Mechanism of Cl^- binding

As mentioned in Section 3, in the XRD analysis, the resultant peak ratio (R) of the peak at 7.9 \AA with respect to that of the ZnO is considered as proportional to the amount of Friedel's salt. It can be seen from Fig. 6 that the resultant peak ratio (R) increases proportionally with an increase in the corresponding Cl^- binding capacity. The result obtained is similar to the case of the binding of internal Cl^- in cement paste¹⁰ These results therefore suggest that the formation of Friedel's salt is closely related to the mechanism of Cl^- binding in the cement matrix with or without mineral admixtures. If formation of Friedel's salt is the only mechanism for Cl^- binding and all the C_3A content of the cement is used up in the formation of the salt, then the maximum amount of Cl^- that can be bound by using the cement employed in this study should be 2.2 % by cement weight.

(2) Maximum Cl^- binding capacity and maximum Cl^- binding percentage

a) Binding capacity

Fig. 7 shows the Cl^- binding capacity of the thin plate specimen (Series I) containing 100 % cement paste, with W/C ratio of 0.5 by weight, with respect to the period of immersion in the sodium chloride solution. It can be seen that after the immersion period of about 4 weeks, the binding capacity is not much affected by the pre-curing period in water. The maximum binding capacity is about 2.5 % by weight of cement.

Fig. 8 shows the effect of W/C ratio and the replacement of cement with fly ash or blast furnace slag powder on the Cl^- binding capacity in cementitious paste specimens which have been immersed in the sodium chloride solution for a period of 13 weeks. Results in this figure generally show that there is no significant effect of W/C ratio on the Cl^- binding capacity. For the same W/C ratio of 0.5, and irrespective of the pre-curing period, replacement of cement with blast furnace slag powder will result in an increase in the Cl^- binding capacity. In contrast, the replacement of cement with fly ash will result in a lower Cl^- binding capacity as compared to that of 100 % cement paste.

Fig. 9 shows the distribution of the total Cl^- and the binding capacity along the penetration route of the cement paste, mortar and concrete specimens (Series II) with W/C ratio of 0.5, after 9 weeks of immersion in the sodium chloride solution. It clearly shows that there is no significant difference in the distribution of total Cl^- in the mortar and concrete specimens and they are significantly higher than that of the cement paste. This may be due to the fact that mortar and concrete specimens are generally more

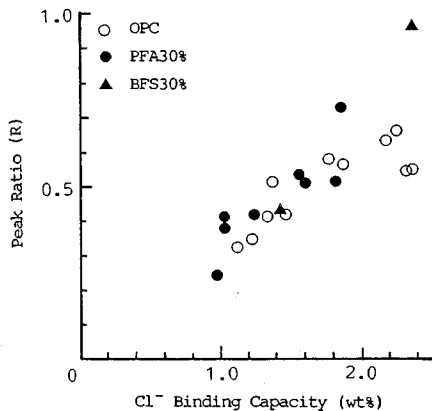


Fig. 6 Friedel's Salt versus Cl^- Binding Capacity.

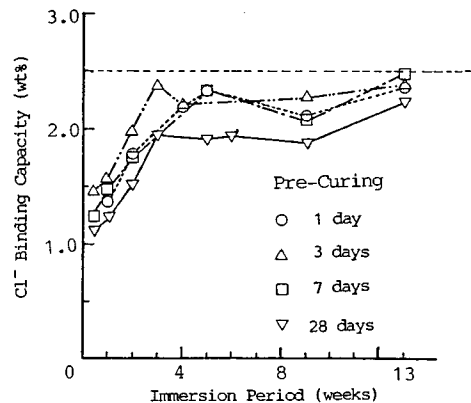


Fig. 7 Cl^- Binding Capacity versus Immersion Period (Series I).

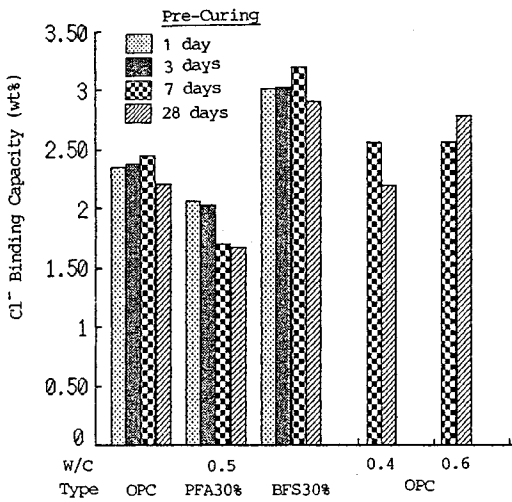


Fig. 8 Effect of W/C ratio and Mineral Admixtures on Cl⁻ Binding Capacity (Series I).

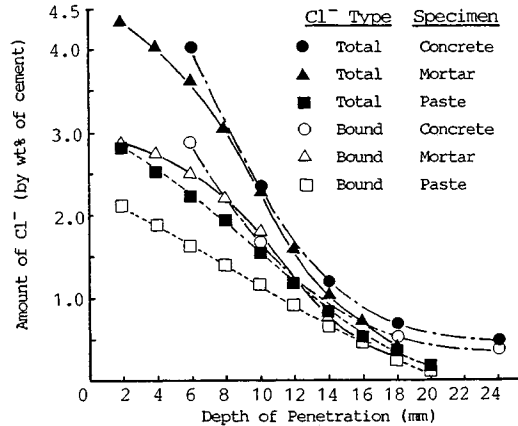


Fig. 9 Distribution of Total Cl⁻ and Bound Cl⁻ (Series II).

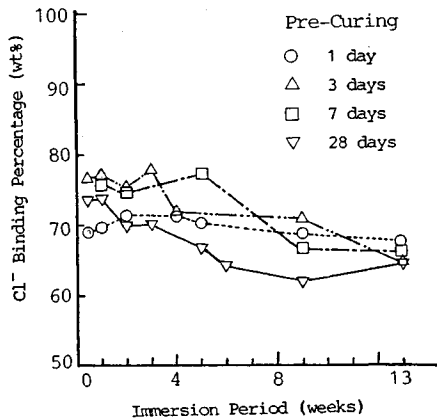


Fig. 10 Cl⁻ Binding Percentage versus Immersion Period (Series I).

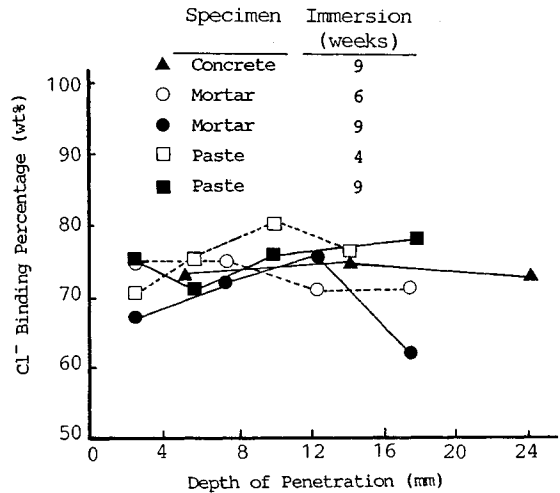


Fig. 11 Cl⁻ Binding Percentage versus Penetration Depth (Series II).

permeable than the corresponding cement paste specimens, due to the presence of "water pockets" beneath the fine and coarse aggregates in the cement matrix materials¹⁵⁾. Similarly, there is no significant difference between the Cl⁻ binding capacity of the mortar and the concrete specimens, and the cement paste specimen has the lowest Cl⁻ binding capacity. These results are attributed to the higher total Cl⁻ content in the mortar and the concrete specimens as compared to that of the corresponding cement paste specimens. The results in these figures seem to suggest that in general the maximum binding capacity in the cement matrix can be around 3.0 % of cement, by weight. This result together with the results shown in Fig. 6 suggest that although the Cl⁻ binding phenomenon is closely related to the formation of Friedel's salt in cementitious matrix, mechanism other than Friedel's salt should also be present. This suggestion is consistent with the results reported by Nagataki *et al*¹⁰⁾, for both the binding of internal Cl⁻ and intruded Cl⁻ in cement paste.

b) Binding percentage

The binding percentage of Cl⁻ in the thin plate cement paste specimens (Series I) having W/C ratio of

0.5 with respect to the immersion period is shown in Fig. 10. It shows that the maximum percentage is about 78 % of the total Cl⁻ content, by weight. However, the longer the immersion period the lower is the Cl⁻ binding percentage. After the immersion period of 13 weeks, the binding percentage is about 64 to 68 % of the total Cl⁻ in cement paste.

Fig. 11 shows the variation of Cl⁻ binding percentage along the penetration direction, in the cement paste, the mortar and the concrete specimens (Series II) with W/C ratio of 0.5 after immersion in the sodium chloride solution for a period of 6 to 9 weeks. It clearly shows that within these immersion periods the maximum Cl⁻ binding percentage varies within the range of 70 to 80 %, with or without aggregates.

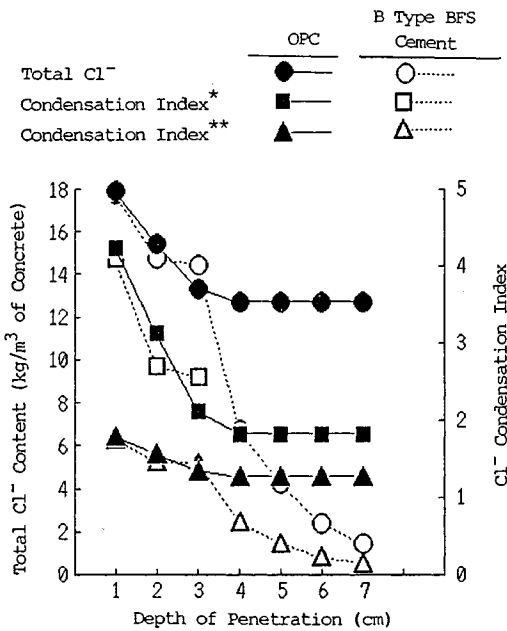
6. CONDENSATION AND PENETRATION OF THE INTRUDED CHLORIDE ION IN CONCRETE AFTER LONG TERM EXPOSURE

The results in Section 4 clearly show that condensation is significant in cement matrix materials. They therefore suggest that in the actual marine concrete structures exposed for a long period, the Cl⁻ concentration of the pore solution may be much greater than that of the sea water. This is very much different from the present general belief and understanding.

The experimental results in Series I show the maximum condensation index within a period of 13 weeks is about two. However, the condensation phenomenon is still on the upward trend after this period.

To study the magnitude of condensation in the actual marine concrete structures or field specimens after long term exposure to sea water, the Cl⁻ concentration of the pore solution in the specimens from the reported long term exposure data¹⁶⁾ are examined. Unfortunately, the water-soluble Cl⁻ content in these field data are all based on the extraction method without quantitative study. In addition, the total porosity of the specimens are generally not provided. Therefore, the Cl⁻ concentration of the pore solution in the specimens cannot be accurately studied. Nevertheless, critical (upper-limit bound) but reasonable assumptions on the total porosity and the Cl⁻ binding capacity or the Cl⁻ binding percentage can be made to

study the minimum Cl⁻ concentration of the pore solution. From the discussion in the Section 5, the amount of Cl⁻ bound in materials with cement matrix can be critically assumed as 3.0 % by cement weight (Cl⁻ binding capacity) or 80 % by weight of the total Cl⁻ content (Cl⁻ binding percentage). And the total porosity is critically assumed here as 25 % of the weight of cement paste based on the results obtained in this experiment. Fig. 12 shows the variation of the condensation index along the Cl⁻ intrusion direction of the concrete of W/C ratio of 0.5, with or without blast furnace slag powder, after 10 years of immersion in sea water. The mix proportions are shown in Table 4¹⁶⁾. It can be seen that even under such a



* Assuming Cl⁻ binding capacity is 3.0 %.
 ** Assuming Cl⁻ binding percentage is 80 %.

Fig. 12 Total Cl⁻ Content¹⁶⁾ and Estimated Cl⁻ Condensation Index.

Table 4 Mix Proportions¹⁶⁾

Cement Type	W/C Ratio	Air Content (%)	s/a (%)	kg/m ³			
				Cement	Water	Aggregates	
						Fine	Coarse
OPC	0.5	-	37	304	152	715	1242
B Type BFS Cement	0.5	-	37	308	154	706	1230

critical assumptions, the possible minimum condensation index for the concrete can reach the maximum value of about 4, based on the assumption of 3.0 % of Cl^- binding capacity, or 2 based on the assumption of 80 % of Cl^- binding percentage. Therefore, the actual condensation index may be easily more than 4.0 based on the former assumption, and 2.0 on the latter assumption. That is to say, the Cl^- concentration of the pore solution in the actual concrete after 10 years' exposure in sea water can be at least 4 times as high as that of the sea water level. These results therefore clearly show that from the point of view of controlling the Cl^- induced corrosion in concrete, the condensation phenomenon cannot be neglected. However, whether this phenomenon will result in a positive or negative effect on the corrosion of the embedded steel is still yet to be studied.

Fig. 12 also shows that the total Cl^- content in the concrete containing blast furnace slag powder is generally smaller than that of the concrete with only ordinary portland cement. This may be attributed to the lower Cl^- diffusion coefficient in the material containing blast furnace slag due to its densely micro-structure and tortuosity¹⁷⁾. It may also be a result of its higher Cl^- binding capacity, compared to the materials containing only ordinary portland cement, as shown in Fig. 8.

7. CONCLUSION

The following conclusions can be obtained from the present study :

(1) For all the specimens irrespective of the W/C ratio and immersion period, the portions closer to the exposure surface have condensation index above 1.0, that is, the Cl^- concentration of the pore solution in these portions are all greater than that of the immersion solution. This condensation index decreases with the depth of intrusion. In addition, it can also be seen that the condensation index for the same portion generally increases with the immersion period.

(2) The condensation phenomenon is significant in the materials with cement matrix constantly submerged in sea water. For concrete structures submerged in sea water for a period of 10 years, the Cl^- concentration of the pore solution in the concrete may be more than 4 times as high as that of the surrounding sea water. Therefore, from the point of view of controlling the Cl^- induced corrosion of steel in concrete, the condensation phenomenon has to be considered.

(3) For the same W/C ratio, there is almost no difference between the condensation index of the specimens with or without the aggregates.

(4) Formation of Friedel's salt is closely related to the mechanism of intruded Cl^- binding in materials with cement matrix with or without mineral admixtures.

(5) The maximum Cl^- binding percentage is varied within the range of 70 % to 80 %, whereas, the maximum Cl^- binding capacity is about 3.0 % by cement weight. However, the binding percentage decreases with a longer immersion period. After the immersion period of 13 weeks, the binding percentage is about 64 to 68 % of the total Cl^- in the cement paste.

(6) Irrespective of the pre-curing period, replacement of cement with 30 % of blast furnace slag will result in a higher Cl^- binding capacity, whereas, the replacement of cement with fly ash will result in a lower Cl^- binding capacity.

8. ACKNOWLEDGMENT

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