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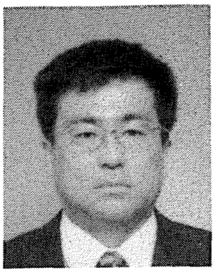
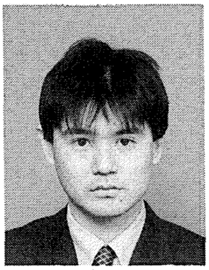
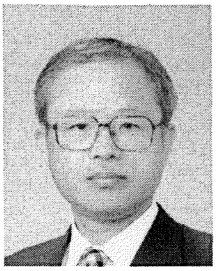
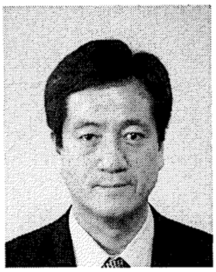
BASIC STUDY OF HYDROGEN STORED IN PRESTRESSING STEEL BARS DURING DESALINATION

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On the assumption that diffusible hydrogen is the main cause of hydrogen embrittlement of prestressing steel bars, the amount stored in prestressing steel bars during and after desalination is investigated by means of thermal analysis and scanning electron microscopy. Behavior of diffusible hydrogen storage in notched and highly tensioned prestressing steel bars is investigated as desalination is continuously and intermittently applied to prestressed concrete. The analysis reveals that the intermittent application of desalination to prestressed concrete contaminated with chloride ions is a better recovery method than either continuous desalination or no desalination at all.

Key Words: *desalination, electrochemical technique, hydrogen embrittlement, prestressed concrete, intermittent desalination*

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1. INTRODUCTION

The premature deterioration of concrete caused by chloride attack has recently become a serious concern. An important repair method for this kind of deterioration is desalination, an electrochemical technique for extracting chloride ions from concrete[1]. The application of this technique to reinforced concrete has been increasing yearly. The mechanism of the desalination technique is shown in Figure 1. The electrochemical removal of Cl^- is accomplished by placing a temporary iron anode with an alkaline electrolyte on the concrete surface and passing direct current between the anode and the reinforcing steel bars (which form the cathode). Since anions migrate toward the anode, Cl^- is removed from the concrete as contaminating chloride ions. As noted, the steel bars embedded in the concrete act as a cathodic electrode for the desalination process, since their potential is lower than the hydrogen potential. Through this desalination process, hydrogen gas is generated at the reinforcing bars and hydrogen embrittlement of the reinforcing bars may arise, especially in high tensile strength steels as used for prestressing tendons. For this reason, the use of desalination has been restricted to reinforced concrete and it has not yet been used with prestressed concrete.

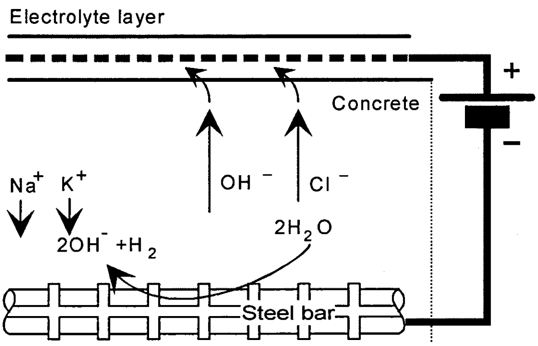


Fig.1 Mechanism of desalination

The authors[2][3] have already demonstrated that desalination has no significant influence on prestressing steel bars when the prestressing force is 50% or 60% of their tensile strength. They have also shown that all diffusible hydrogen stored in the tendons during desalination dissipates within one month of desalination. In this study, to take into account extra prestressing force applied to prestressing steel bars as a result of cross-sectional defects caused by heavy corrosion, notched and highly tensioned prestressing bars are examined. Furthermore, various methods of continuous and intermittent desalination are also investigated.

2. EXPERIMENTAL PROGRAM

2.1 Experimental Specimens

The experimental program described here consists of three stages. The first and second stages use notched prestressing

Table 1 Notched PC bar [1st stage]

Prestressing ratio (%)	Current density (A/m^2)	Period of treatment (week)	Period to be kept after treatment	Depth of notch (mm)
60%	0.0	0	0	0.5
				1.0
				1.5
				2.0
	5.0	1	0	1.0
		2	0	1.0
		4	0 day, 14 days	0.5
				1.0
				1.5
				2.0
		6	0	1.0
		8	0 day 14 days	0.0
				0.5
				1.0
				1.5
				2.0

(Note) Electrolytic solution = $Ca(OH)_2$ saturated solution

Table 2 Highly tensioned PC bar [2nd stage]

Prestressing ratio(%)	Kind of electrolytic solution	Period of treatment (week)
60%	NH_4SCN solution	1
		2
		4
		8
70%		8
80%		8
88%		8
	$Ca(OH)_2$ saturated solution	2
		3
		4
		8

steel bars and highly tensioned prestressing steel bars, respectively, to take into account the cross-sectional defects caused by heavy corrosion. In the third stage, intermittent desalination is applied to prestressed concrete. Details of each stage are shown in Tables 1 through 3.

a) Mix Proportion of Concrete
The mix proportion of the concrete used in the experiments is shown in Table 4. Ordinary Portland cement was used. A certain quantity of Cl^- was mixed into the concrete specimens by dissolving sodium chloride (NaCl) into the mixing water at a rate of 8.0 kg/m^3. This represents a quantity equivalent to severe chloride corrosion of the steel. The compressive strength of the concrete after curing in water at 20℃ was 45N/mm^2 at the age of 28 days.

b) Specimens
All specimens were 150x150x400(mm) concrete prisms with a prestressing steel bar (ϕ13mm) through the center of the square section. The bars were prestressed by the pretensioning method shown in Figure 2. The prestressing force was not applied directly to the concrete itself so as to prevent loss of prestress due to creep and drying shrinkage of the concrete; rather, the reaction force was taken by the steel frame. The prestressing force on the bars varied from 60% to 88% of the steel tensile strength.

The prestressing steel bars themselves were quenched and tempered by the high-frequency heating method. The properties and chemical composition of the steel are given in Tables 5 and 6, respectively. To take into account cross-sectional defects of the steel bars caused by heavy corrosion, some of the prestressing steel bars were provided with a notch measuring 0.5 to 2.0 mm in depth and 0.1 mm in width at their mid-point. These notches were cut with a wire sawed and left to corrode.

c) Electrochemical Treatment
Concrete was cast around the pretensioned prestressing bars. After curing in wet conditions for 4 weeks, a direct current of 5.0 A/m^2 was applied to the surface. Desalination was carried out in this way for the periods shown in Tables 1 through 3. The current was applied through two sides of the specimens;

Table 3 Intermittent treatment [3rd stage]
Intermittent treatment =2 weeks on and 1 week off

Prestressing ratio		60%
Kind of solution		$Ca(OH)_2$ saturated solution
Total treatment period (weeks)	2	"2"
		"2" + ①
	4	"2" + ① + "2"
		"2" + ① + "2" + ①
	6	"2" + ① + "2" + ① + "2"
		"2" + ① + "2" + ① + "2" + ①
	8	"2" + ① + "2" + ① + "2" + ① + "2"

(Note) "2" = desalination is on for 2 weeks.
①= desalination is off for 1 week.

Table 4 Mix proportion of concrete

W/C (%)	S/a (%)	Gmax (mm)	Unit mass (kg/m^3)					
			W	C	S	G	WRA	Cl
39	43	25	169	434	731	982	4.67	8.0

Table 5 Mechanical properties of PC bar

Type of Bar	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
C-type (SBPR1080/1230)	1228	1273	8

Table 6 Chemical compositions of PC bar (%)

Type of Bar	C	Si	Mn	P	S	Cu
C-type (SBPR1080/1230)	0.35	1.74	0.74	0.016	0.006	0.01

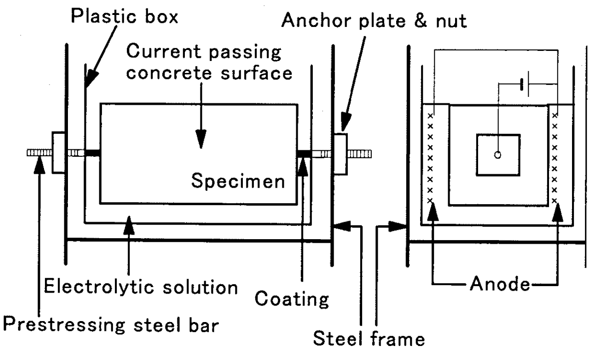


Fig.2 Specimen and experimental set-up for desalination

the other four sides were insulated with epoxy resin. The specimens were immersed in a saturated solution of $Ca(OH)_2$ or a solution of 5 wt% NH_4SCN as the electrolyte. Specimens not subjected to the current treatment were held in saturated solution of $Ca(OH)_2$ until testing.

After finishing desalination treatment, the prestressing bars were removed from the specimens and held below 243K (–30℃) in a freezer until thermal analysis could be carried out. Some of the specimens with pretensioned prestressing steel bars intact were held at 20℃ and 60%RH in a chamber during the period after treatment, as shown in Table 1.

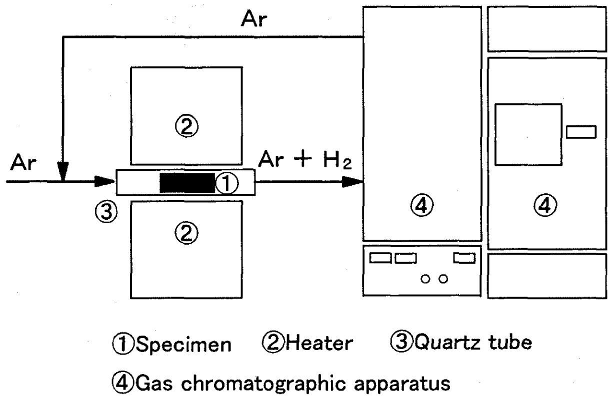


Fig.3 Schematic diagram of hydrogen thermal analysis

2.2 Thermal Analysis

Prestressing steel tendons, which are usually of high-tensile steel and maintained under high tension in the concrete, undergo metallographic embrittlement as they absorb and store diffusible hydrogen within their atomic structure. Ultimately, they may crack as a result of this hydrogen embrittlement. The amount of diffusible hydrogen can be measured by recovering evolved hydrogen at temperatures of 300K through 500K in a thermal analysis test [5]. Figure 3 shows a schematic diagram of the test method used, in which the prestressing bars were heated at a rate of 100K/Hr in an argon(Ar) environment. The hydrogen evolved between 300K and 700K was measured by gas chromatography.

3. AMOUNT OF DIFFUSIBLE HYDROGEN

3.1 Notched PC bar (1st stage)

a) Notch and stored hydrogen

Figure 4 shows the amount of hydrogen collected from prestressing bars immediately after eight weeks of current treatment. The legend in Figure 4 indicates the notch depth, with "0 mm" representing a non-notched bar. Taking the diffusible hydrogen evolved between 300K and 500K as the main factor in hydrogen embrittlement, the cumulative amounts of diffusible hydrogen were calculated from Figure 4. Table 7 shows these cumulative amounts and the temperatures corresponding to peaks between 300K and 500K. There is no significant difference in the cumulative amounts and peak temperatures, demonstrating that diffusible hydrogen, the main factor in hydrogen embrittlement, is not affected by the presence of notches in the prestressing steel bars. However, a further experiment is required to clarify whether the same amount of hydrogen may have a greater effect on bars with a larger notch.

In Figure 4, the non-notched bar (notch size=0 mm) exhibits a peak of non-diffusible hydrogen at 570K,

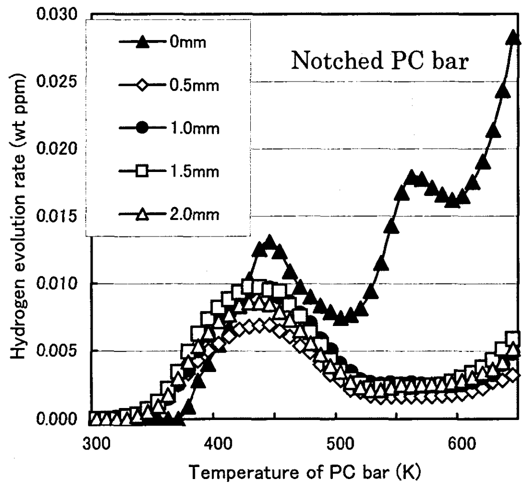


Fig.4 Hydrogen evolution curves just after desalination

Table 7 The cumulative amount of diffusible hydrogen

Depth of notch (mm)	0	0.5	1.0	1.5	2.0
Diffusible hydrogen (wt ppm)	0.13	0.09	0.12	0.13	0.11
Temperature of peak (K)	440	440	430	430	430

whereas no notched bar has a peak above 500K. The tensile stress at the bottom of a notch is far greater than the nominal stress calculated over the full cross section of the bar, and this introduces a new plastic strain as an effective trap-site around the bottom of the notch. Non-diffusible hydrogen is absorbed in this very effective trap-site, and the evolution peak is considered to shift above 700K.

b) Duration of current and stored hydrogen

Figure 5 shows results thermal analysis carried out immediately after current treatment on prestressing bars with a notch depth of 1.0 mm. In this case, treatment was carried out for 1 week, 2 weeks, 4 weeks, 6 weeks and 8 weeks. It is clear that with a treatment duration of 4 to 8 weeks, diffusible hydrogen is generated and absorbed into the prestressing steel bars. On the other hand, little diffusible hydrogen is absorbed during the first 1 to 2 weeks of treatment. This indicates that prestressing steel bars are at no risk of hydrogen embrittlement if current treatment is limited to no more than 2 weeks, even if the bars have cross-sectional defects caused by corrosion.

Similarly, Figure 6 shows the results for similar bars after 4 weeks and 8 weeks of treatment alongside those where two weeks elapsed before the analysis. In Here, it is obvious that diffusible hydrogen stored in corroded prestressing bars is dissipated quickly within the two weeks following current treatment. This reflects the results presented by the authors in an earlier paper [2] for the hydrogen embrittlement of prestressing steel bars without corrosion.

Figure 7 shows the relationship between current duration and cumulative diffusible hydrogen in notched bars. The amount of diffusible hydrogen stored in prestressing bars, as measured immediately after current treatment, rises with treatment duration. The rate of increase in the first 2 weeks, and also when treatment lasts more than 4 weeks, is very low. In contrast, the rise is rapid between 2 and 4 weeks. Once treatment stops, the diffusible hydrogen in prestressing bars dissipates within 2 weeks, as is plotted by □, as in Figure 6.

When current treatment begins, the electrolytic solution contains plenty of soluble oxygen. In this situation, formula (1) predominates and prevents the generation of hydrogen. This explains why little diffusible hydrogen is stored in the steel within the first two weeks. Once the soluble oxygen in the electrolytic solution is exhausted, the cathodic reaction is generally dominated by formula (2), and hydrogen gas is generated near

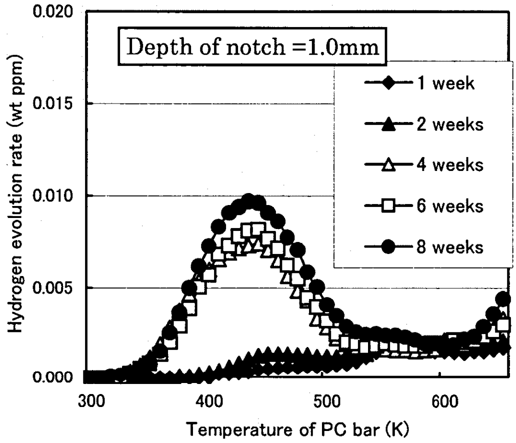


Fig.5 Hydrogen evolution curves for various treatment times

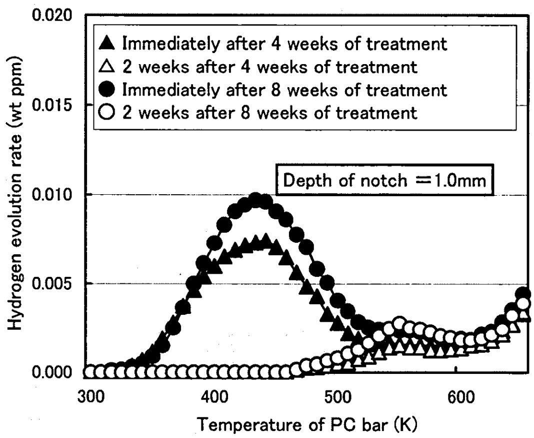


Fig.6 Hydrogen evolution curves after desalination

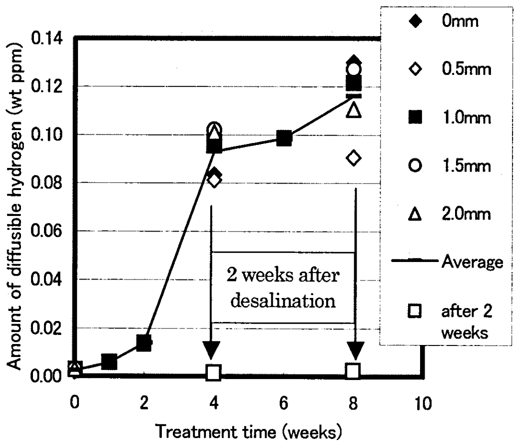


Fig.7 Relationship between diffusible hydrogen and duration of treatment

the cathodic electrode. As a result, an increasing amount of hydrogen is stored in the prestressing bars as time passes. On the other hand, when the level of stored hydrogen reaches a certain level, diffusion out of the prestressing bars to the surroundings begins to take place. Thus, after 4 weeks of current treatment, the amount of hydrogen indicated by formula (2) reaches an equilibrium with the rate of diffusion from the bars.

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \qquad (1)$$
$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad (2)$$

3.2 Highly tensioned PC bar (2nd stage)

a) Highly tensioned PC bar

Figure 8 shows the hydrogen evolution rate in the case of non-notched prestressing steel bars tensioned with a prestressing ratio equivalent to 88% of their tensile strength(or almost equal to their yield strength). Treatment was carried out for 2 weeks, 3 weeks, 4 weeks and 8 weeks at a current density of 5.0 A/m^2 at the surface of the bars. The electrolyte was saturated $Ca(OH)_2$ solution. Figure 9 shows the relationship between treatment duration and cumulative diffusible hydrogen evolved between 300K and 500K; in this case, the prestressing tension was 60% and 88% of the tensile strength of the bars.

The cumulative amount of diffusible hydrogen is far more at a prestressing ratio of 88% than at 60%, regardless of the treatment duration. In fact, 2 weeks of treatment at 88% is almost equivalent to 8 weeks at 60%. This indicates that the amount of diffusible hydrogen stored in prestressing steel bars is affected not only by treatment duration but also by the tensile stress acting on the bars. Since the stress is higher in bars that have cross-sectional defects caused by heavy corrosion, such bars will accumulate higher levels of diffusible hydrogen than those without corrosion for a given treatment duration. However, given that prestressing bars loaded with a prestressing ratio of 88% exhibited no fractures at all in this experiment, the amount of diffusible hydrogen stored in the bars clearly does not reach the critical level under ordinary desalination conditions, which never exceed 8 weeks of treatment or 5.0 A/m^2 with saturated $Ca(OH)_2$ solution.

b) NH_4SCN solution

Figure 10 shows hydrogen evolution results for non-notched prestressing bars tensioned to 60% of their tensile strength. The treatment duration was 1 week, 2 weeks, 4 weeks and 8 weeks at a current density of 5.0 A/m^2 at the surface of the bars, and the electrolyte in this case was a solution of 5 wt%

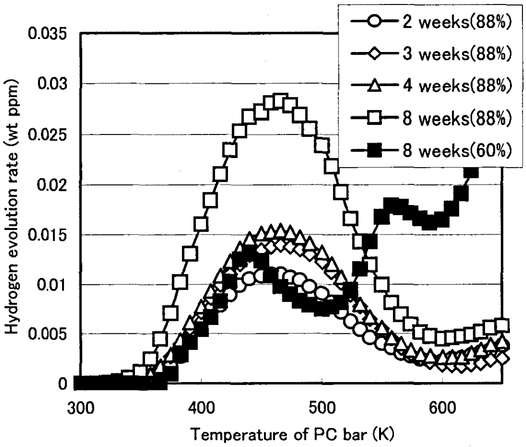


Fig.8 Hydrogen evolution curves of high-tensioned PC bar

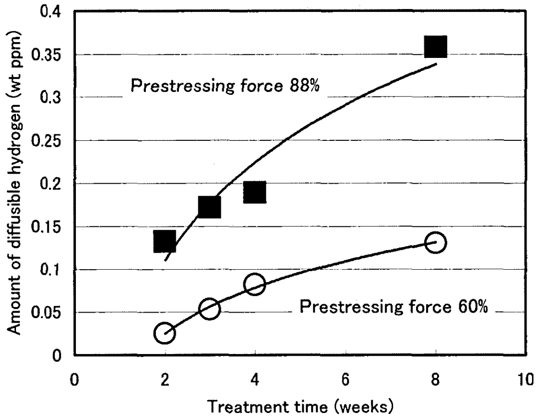


Fig.9 Relationship between diffusible hydrogen and treatment time

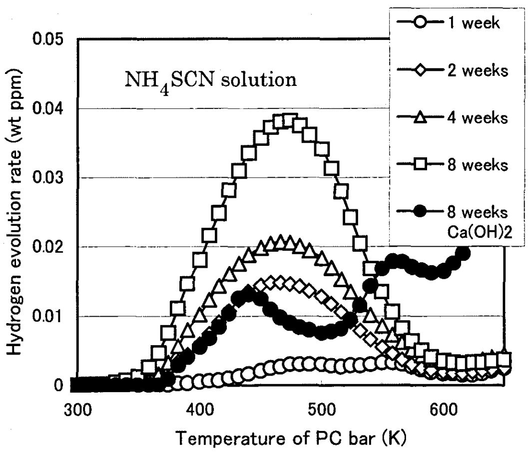


Fig.10 Hydrogen evolution curves (NH_4SCN solution)

NH_4SCN. This is a weak acid that provides more hydrogen for possible accumulation into the prestressing bars. Figure 11 shows the hydrogen evolution results for non-notched bars tensioned with prestressing ratios varying from 60% to 88% of their tensile strengths using the same electrolyte.

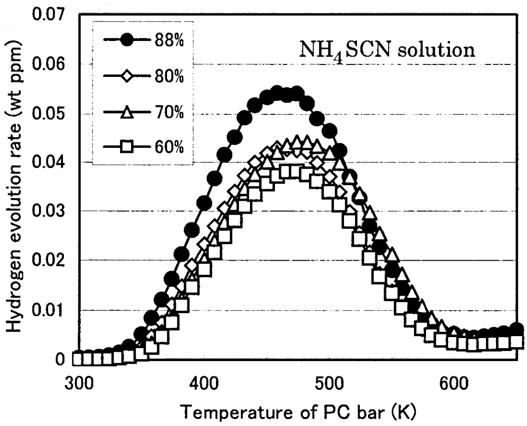


Fig.11 Hydrogen evolution curves of high-tensioned PC bar

In this case, almost all hydrogen stored in the prestressing bars is diffusible, with diffusion peaks at temperatures below 500K. Moreover, the peak after 2 weeks of treatment using NH_4SCN solution is higher than the peak after 8 weeks of treatment using $Ca(OH)_2$ solution. This indicates that a weak acid such as NH_4SCN results in much greater risk of hydrogen embrittlement than an alkali such as $Ca(OH)_2$ solution. Figure 11 shows that the amount of diffusible hydrogen stored in prestressing bars is affected by tensile stress when the electrolyte is NH_4SCN, just as with $Ca(OH)_2$. The cumulative absorption of diffusible hydrogen released between 300K and 500K in Figures 10 and 11 are listed in Table 8. The prestressing bar with a prestressing ratio of 88% in Table 8 failed as a result of hydrogen embrittlement after 56 days of current treatment. This indicates that a cumulative amount of 0.72(wt ppm) of diffusible hydrogen can be considered the critical diffusible hydrogen content.

Table 8 Cumulative amount of diffusible hydrogen (NH_4SCN solution)

Prestressing ratio (%)	60				70	80	88
Treatment time (weeks)	1	2	4	8	8		
Diffusible hydrogen (wt ppm)	0.03	0.17	0.25	0.46	0.53	0.54	0.72

c) Critical value of diffusible hydrogen

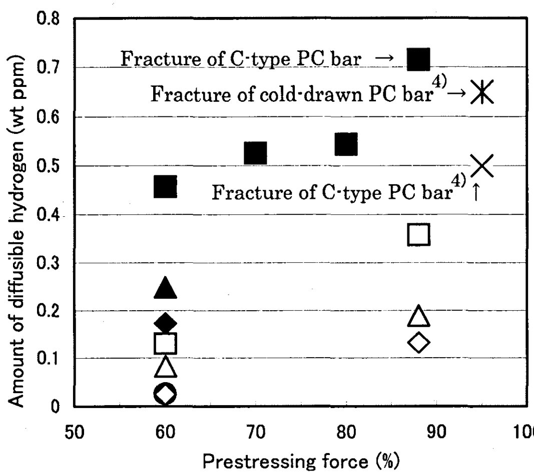
In our experiments, no fracturing of prestressing steel bars was observed under ordinary desalination conditions, which are up to 8 weeks of current treatment at a current density of 5.0 A/m^2 or less at the bar surface. This was true even at a prestressing ratio of 88% of bar tensile strength. When using NH_4SCN solution as the electrolyte, also, bars prestressed to a ratio of 80% or less suffered no fractures at all with up to 8 weeks of treatment at 5.0 A/m^2. Only where the prestressing ratio reached 88% and NH_4SCN solution was used for treatment at a current of 5.0 A/m^2 for 56 days did the bars fracture due to hydrogen embrittlement.

Comparing results for prestressing ratios up to 80% with those for 88%, the amount of hydrogen generated was same because the treatment time was 8 weeks in both cases and the same 5 wt% NH_4SCN electrolyte was used. Nevertheless, the bar prestressed to 88% fractured while bars with prestressing ratios of 80% or less did not fail. That is to say, the amount of diffusible hydrogen stored in prestressing steel bars depends on the prestressing ratio and the critical value of diffusible hydrogen at which the bars fracture due to hydrogen embrittlement also depends on prestressing ratio. The critical value of diffusible hydrogen is 0.72 (wt ppm) for C-type (SBPR1080/1230) prestressing bars with a prestressing ratio of 88%, while the value for prestressing ratios of 80% or less is probably greater than 0.72 (wt ppm).

Yamasaki et al.[4] reported that the critical value of diffusible hydrogen needed to cause failure of prestressing steel tendons was 0.50 (wt ppm) for C-type prestressing bars and 0.65 (wt ppm) for cold-drawn prestressing bars with a prestressing ratio of 95%. These results were obtained using slow strain rate tensile test[6] on specimens plated with cadmium(Cd) after hydrogen stored. Our experimental value of 0.72 (wt ppm) is somewhat higher than Yamasaki's critical values. However, given that the prestressing ratio was 95% in Yamasaki's tests, our results can be considered reasonable.

Figure 12 shows the relationship between prestressing ratio and the amount of diffusible hydrogen obtained in the 1st stage and 2nd stage experiments. Yamasaki's results for 0.50 (wt ppm) hydrogen in C-type and 0.65 (wt ppm) hydrogen in cold-drawn type are also shown in this figure.

It is generally accepted that a lower critical value of diffusible hydrogen leads to fracture due to hydrogen embrittlement as the tensile stress acting on prestressing tendons increases[6][7]. In this experiment, a bar with a prestressing ratio of 88% fractured at 0.72 (wt ppm) of diffusible hydrogen (Figure 11). In Yamasaki's experiment with a prestressing ratio of 95%, bars fractured at 0.50 (wt ppm) and 0.65 (wt ppm). It can be inferred that for prestressing ratios less than 88%, the critical value of diffusible hydrogen will be higher than 0.72 (wt ppm). On the contrary, where prestressing ratios are higher than 95%, the critical value can be expected to be below 0.50 (wt ppm). In the case of actual prestressed concrete structures, the prestressing ratio acting on steel tendons as a result of creep and drying shrinkage is generally estimated at 50% to 60%. The corresponding critical value of diffusible hydrogen can be safely said to be 0.72 (wt ppm) from this experiment and 0.50 to 0.65 (wt ppm) from Yamasaki's experiment.



○● = 1 week of treatment ◇◆ = 2 weeks of treatment
△▲ = 4 weeks of treatment □■ = 8 weeks of treatment
○◇△□ = Results of $Ca(OH)_2$ solution
●◆▲■ = Results of NH_3SCN solution

Fig.12 Relationship between prestressing force and diffusible hydrogen

3.3 Intermittent treatment (3rd stage)

To investigate the effects of intermittent current treatment, a cycle of treatment was defined as 2 weeks with a current flow followed by 1 week with no current. Thus, one cycle is equivalent to 2 weeks of current treatment, two cycles is equivalent to 4 weeks of current treatment, and so on.

Figure 13 shows the amount of hydrogen stored in prestressing bars removed from concrete specimens immediately after current treatment. Figure 14 shows the amount of hydrogen stored in prestressing bars remove from concrete specimens and kept in a chamber at 20℃ and 60%RH for a week after current treatment. All specimens in these figures contained non-notched prestressing bars with a prestressing ratio 60%, and the current density was 5.0 A/m^2 using a saturated $Ca(OH)_2$ electrolyte solution.

Figure 15 shows the relationship between treatment duration and amount of diffusible hydrogen, as obtained from Figures 13 and 14. The results of continuous current treatment, or ordinary desalination, are also shown in Figures 13 and 15.

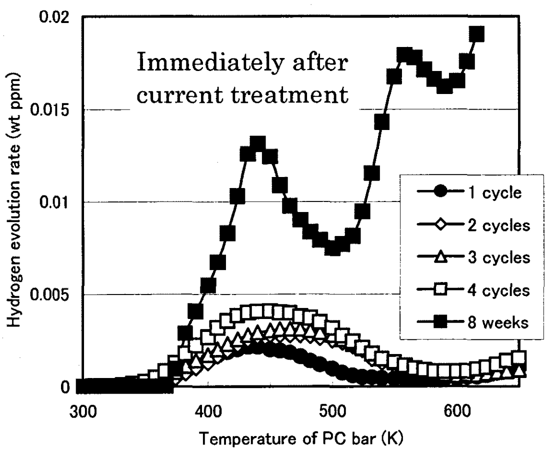


Fig.13 Hydrogen evolution curves immediately after current treatment

In Figure 13, the amount of hydrogen stored in the prestressing bar immediately after current treatment is far less in the case of intermittent treatment than when treatment is continuous for 8 weeks. Even taking four cycles of treatment as equivalent to 8 weeks of continuous treatment, the amount of hydrogen absorbed after 4 cycles is far less. Figure 14 shows that the amount of hydrogen a week after treatment stops is less than that immediately after treatment. Therefore, it can be concluded that intermittent treatment allows diffusible hydrogen stored in prestressing bars to dissipate, as reported in the authors' previous paper [2] as well as in Figures 6 and 7 in this paper.

In Figure 15, continuous treatment by the ordinary desalination is indicated by solid black squares(■) and intermittent treatment by solid black circles(●). With continuous treatment, the cumulative amount of diffusible hydrogen rises up to 0.13 (wt ppm) as time elapses. On the other hand, in the case of intermittent treatment, the cumulative amount of diffusible hydrogen varies between 0.02 and 0.06 (wt ppm), with the higher levels recorded immediately after treatment and lower ones a week later. There does appear to be a tendency for the cumulative total to be slightly higher with each successive cycle, and this is attributed to as the number of repetition of cycle increases. Because it is considered the fact that diffusible hydrogen is easily absorbed into trap-sites in the prestressing bars as repeated absorption and evolution of hydrogen takes place.

Continuous treatment is generally chosen as a method of desalination, since it offers the quickest and most efficient path to restoration. However, Figures 13 to 15 make it clear that intermittent current treatment reduces the amount of diffusible hydrogen to a minimum, so this is a preferable method of desalinating prestressed concrete structures.

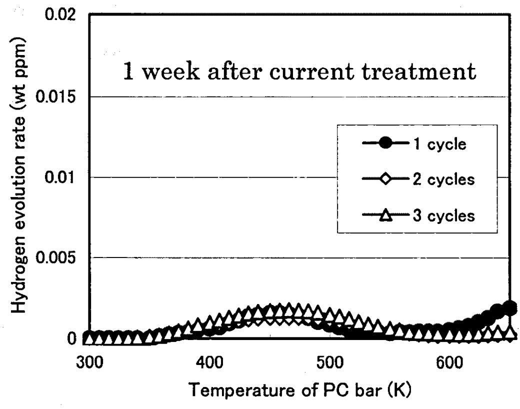


Fig.14 Hydrogen evolution curves 1 week after current treatment

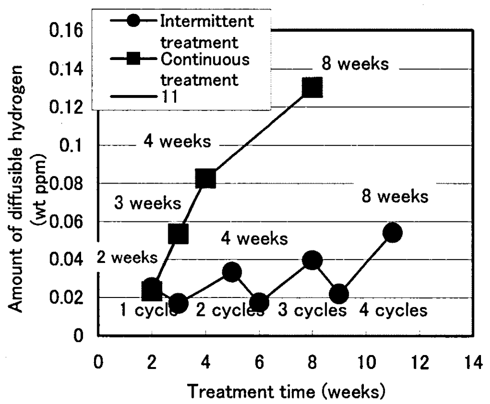


Fig.15 Relationship between treatment method and diffusible hydrogen

4. APPLICATION OF DESALINATION TO PC

This examination of the diffusible hydrogen content of prestressed concrete structures reveals four characteristics of hydrogen storage, as follows:

① Hydrogen is stored in prestressing steel tendons during the desalination process;

② The diffusible portion of the hydrogen dissipates quickly from the tendons with in a few days of current treatment being halted;

③ The critical value of diffusible hydrogen in the prestressing steel tendons is 0.50 through 0.72 (wt ppm) for prestressing ratios of 88% to 95%;

④ Intermittent desalination treatment can be applied to successfully control the amount of diffusible hydrogen stored in tendons to a level far less than the critical value. It has already been shown that intermittent treatment is suitable for application to prestressed concrete structures. This study showed that intermittent current has the same chloride-extracting effect as continuous treatment as long as the total duration of current flow is unchanged[8].

In general, where desalination is planned for a prestressed concrete structure, some deterioration of the concrete has already been caused by chloride attack and the prestressing steel tendons can be assumed to have some corrosion. In applying desalination treatment in such a situation, the degree of corrosion needs to be carefully considered, as follows:

1) Prestressing steel tendons without corrosion or with only slight corrosion

On the basis of results given in papers[2][3], it is clear that up to 8 weeks of desalination treatment may be applied, even if continuous, because the prestressing ratio acting on the tendons is estimated at between 50% and 60%. The cumulative amount of diffusible hydrogen stored in prestressing steel tendons during continuous desalination is only 0.13(wt ppm), which is far less than the critical value for prestressing ratios of 88% to 95%.

2) Prestressing steel tendons with corrosion pitting
The first stage of this experiment indicates that up to 8 weeks of continuous current treatment is possible. However, in order to increase the margin of safety during desalination, intermittent treatment with up to 8 weeks of total current flow is preferable.

Of course, in an actual prestressed concrete structure it is not always easy to make a judgment as to which of the above corrosion conditions apply using non-destructive methods. To ensure safety and act with sensible caution, it would be wise to apply intermittent treatment with up to 8 weeks of total current flow even where continuous treatment might appear suitable.

3) Prestressing steel tendons partially fractured or close to fracture
In this case, observation of the concrete is enough to make judge that corrosion of the prestressing tendons is severe. Large cracks are likely to be visible along the tendons, heavy rust stains emanate from cracks in the concrete, and cover concrete may be missing. When these conditions are found, it is necessary to examine structural safety and add enough reinforcement to support the assumed loading before considering the application of desalination. The application of a desalination process should be considered only once the structural strength has been restored and the prestressing ratio on prestressing steel tendons reduced. In such cases, it is obviously sensible to apply intermittent treatment with up to 8 weeks of total current flow.

5. CONCLUSIONS

This study focused on the hydrogen stored in prestressing steel tendons, and particularly on diffusible hydrogen, which is the main factor causing hydrogen embrittlement. The conclusions of this study are outlined below.

(1) In applying desalination at a current of 5.0 A/m^2 to prestressed concrete, diffusible hydrogen is stored in prestressing steel tendons.
(2) According to thermal analysis testing, the temperature at which diffusible hydrogen is evolved from steel tendons with cross-sectional defects is lower than when there are no cross-sectional defects. On the other hand, the cumulative quantity of diffusible hydrogen is little different whether or not tendons have cross-sectional defects.
(3) When the treatment duration is no more than 2 weeks, prestressing steel tendons absorb very little diffusible hydrogen, even if there are cross-sectional defects, so there is very little risk of hydrogen embrittlement. Moreover, even if the period of treatment exceeds 4 weeks, the stored hydrogen is dissipated quickly once the flow of current stops.
(4) The amount of diffusible hydrogen stored in prestressing steel tendons is influenced not only by the duration of current treatment but also by the prestressing force acting on them. Therefore, the amount of diffusible hydrogen stored in tendons with cross-sectional defects is greater for a given treatment duration.
(5) The critical value of diffusible hydrogen absorption in a steel tendons, defined as the level at which hydrogen embrittlement causes fracturing of the tendon, is 0.72 (wt ppm) for C-type (SBPR1080/1230) prestressing steel bars when the prestressing ratio is 88%. If the prestressing ratio is less than 88%, the critical value can be expected to be above 0.72 (wt ppm), while higher stresses may cause the critical value to fall below 0.72 (wt ppm).
(6) Intermittent desalination treatment, based on a cycle of two weeks of treatment followed by a week with no current, can greatly reduce the cumulative total of diffusible hydrogen in steel tendons. Using this method, the absorbed amount fluctuates between 0.02 and 0.06 (wt ppm) when the total treatment time is 8 weeks or less. This is a lot lower than the 0.13 (wt ppm) accumulated over 8 weeks of continuous current treatment.
(7) Intermittent desalination treatment is a good means of controlling the amount of diffusible hydrogen stored in prestressing tendons to a level far below that measured with continuous treatment. Where desalination is to be applied to prestressed concrete structures that have suffered chloride deterioration, this form of intermittent treatment offers a much larger margin of safety.

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