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Characteristics of Developed High-Strength Prestressing Strand

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ABSTRACT

High-strength prestressing strand (HPS) has been developed that the tensile load is 20% higher at 7-wire strand and 15% higher at 19-wire strand than the conventional prestressing strand (CPS) specified in JIS G 3536. Then, HPS obtains the same level of a fracture elongation compared to CPS. Furthermore, HPS has the same relaxation loss as CPS and the same mechanical properties of tensile fatigue and deflected tensile compared with those of CPS. Especially there is a concern that the sensitivity of hydrogen embrittlement was increased by strengthening strand. A sensitivity of hydrogen embrittlement for HPS was researched.

Keywords. High-strength prestressing strand, Prestressed concrete, hydrogen embrittlement, delayed fracture, tensile fatigue property

INTRODUCTION

Recently, high-strength concrete has been used for structural weight saving and downscale of concrete members. Their high strength is expected to reduce the materials of concrete members and the energy for their production and transportation, and to shorten the construction period. However, when high strength concrete is used for prestressed concrete members, there is a problem in the lack of setup-space for prestressing strand to remain the design strength of concrete members. To solve this problem, HPS is needed. In this paper the characteristics of developed HPS, especially a sensitivity of hydrogen embrittlement, are provided.

MECHANICAL CHARACTERISTICS OF DEVELOPED HIGH-STRENGTH PRESTRESSING STRAND

Tensile Test. Prestressing strand is produced through stranding and hot-stretching processes with high carbon steel wires that are drawn after the heat treatment known as patenting. Typically, for strengthening the wire, carbon, silicon and chromium concentration are added in the conventional material and a total reduction of area in drawing is increased. To achieve both strengthening and ductility, material component and manufacturing conditions of heat-treatment, wire drawing and hot-stretch are optimised. The tensile test results of HPS were listed in Table 1. Table 1 show that the tensile load of HPS is 20% higher at 7-wire strand and 15% higher at 19-wire strand than CPS and fracture elongation of HPS is equivalent to CPS.

Table 1. Results of Tensile Test

Sample	Diameter (mm)	Maximum-load (kN)	Yield-load (size)	Elongation (%)
High-strength prestressing strand	15.2	321 (≥ 314)	301 (≥ 267)	6.0 (≥ 3.5)
	15.7	344 (≥ 335)	336 (≥ 285)	7.0 (≥ 3.5)
	21.8	682 (≥ 659)	648 (≥ 570)	6.3 (≥ 3.5)
Conventional prestressing strand	15.2	276 (≥ 261)	263 (≥ 222)	7.6 (≥ 3.5)
	21.8	592 (≥ 573)	565 (≥ 495)	5.6 (≥ 3.5)

The value in parenthesis indicates the specification.

Stress Relaxation Test. At first, HPS 15.2mm was loaded at 70% of characteristic maximum load specified in table 1. Then, at a constant strain, the reduction in load was verified as relaxation loss. Figure 1 shows the results Relaxation loss of HPS 15.2mm was 1.04% after 1,000 hour and less or equivalent to CPS. This was satisfied with a low relaxation grade specified in JIS G 3536, i.e., less than 2.5% at 1,000 hour.

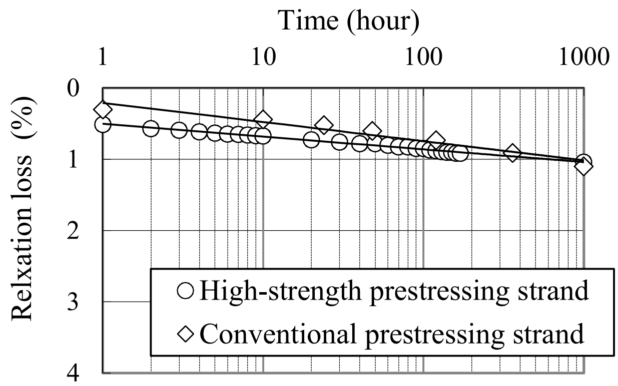

Figure 1. Results of Stress Relaxation Test

Tensile Fatigue Test. Tensile fatigue test is prescribed in ISO 6934-4 that prestressing strand must not be fractured till two million cycles at the condition that maximum stress is 70% of nominal tensile strength and stress range is 195N/mm^2. HPS and CPS were examined at the condition of the above maximum stress and other stress range. The results are shown in Figure 2. It shows that HPS meets the ISO 6934-4 and has the same characteristic of tensile fatigue compared with CPS.

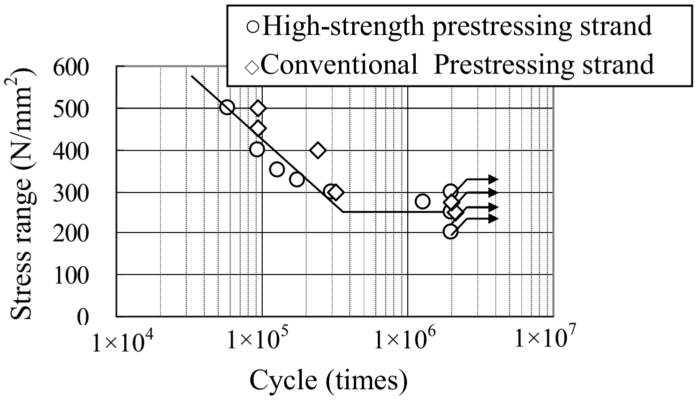

Figure 2. Results of Tensile Fatigue Test

Deflected Tensile Test. It is concerned that a resistance of HPS to a local bending tensile strength is smaller than CPS because of its higher prestress. Therefore, the deflected tensile test based on FIP Recommendations of "Deflected Tensile Test" shown in Figure 3 was conducted. In the result, the reduction rate of deflected tensile strength is 19% at HPS 15.2mm and 13% at CPS. The reduction rate of HPS 15.2mm was greater than CPS. However, it is less than 28% and meets in FIP Recommendations.

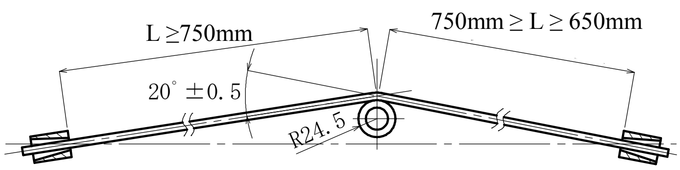

Figure 3. A schematic diagram of deflected tensile test based on FIP recommendations

DELAYED FRACTURE CHARCTERISTICS OF DEVELOPED HIGH-STRENGTH PRESTRESSING STRAND

Delayed Fracture. Delayed fracture takes place probably by hydrogen embrittlement under coexistence of corrosion environment and a tensile stress. One of some theories for hydrogen embrittlement is considered the following. At first, hydrogen atoms that are produced by cathodic reaction on the surface of the base materials with anode dissolution intrude and diffuse into the material, and these hydrogen atoms re-combine and form hydrogen molecules in minuscule voids of the materials. Then they create pressure into the voids and the pressure can increase to the levels where the material has reduced the ductility and tensile strength up to the point of cracking open. Furthermore, it is known that the hydrogen exists as two states of diffusible hydrogen and non-diffusible hydrogen in the hard-drawn steel wire with pearlite structure. Diffusible hydrogen is weakly-trapped in vacancies, and non-diffusible hydrogen is strongly-trapped in dislocation and precipitates. Hydrogen embrittlement is affected by diffusible hydrogen and not by non-diffusible hydrogen. Although hard-drawn pearlite steel wires such as prestressing strand is known as superior to hydrogen embrittlement characteristic, it is a concern that the sensitivity increases with an increase of strengthening. Therefore, hydrogen embrittlement characteristic was evaluated by making relative comparisons between HPS and CPS.

FIP Test. FIP(The international Federation of Prestressed Concrete) test is currently used for ascertaining hydrogen embrittlement susceptibility of the prestressing strand. In FIP test, the fracture time of the wire maintaining 80% of maximum load and immersed in 20% ammonium thiocyanate(NH_4SCN) solution at 50°C was measured. The core wire of HPS 15.2mm and CPS 15.2mm were used as specimens. The results are shown in Figure 4 using Weibull distribution. Figure 4 shows that minimum fracture times of both HPS and CPS are more than 2 hours and median fracture time are more than 5 hours and they meet *fib* Bullten 30:"Acceptance of stay cable systems using prestressing steels".

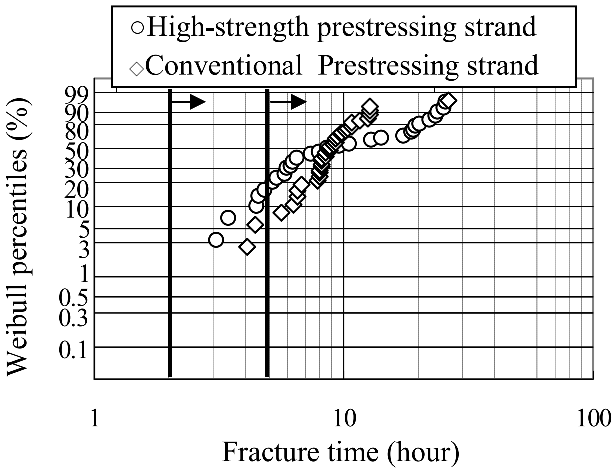

Figure 4. Results of FIP test

Hydrogen Diffusion Coefficient. The time to fracture in hydrogen embrittlement is affected by the hydrogen diffusion rate into the material. Then hydrogen diffusion coefficients of both HPS and CPS at the room temperature were measured using the core wire HPS 15.2mm and CPS 15.2mm. Their results are shown in Table 2. At the room temperature, hydrogen diffusion coefficient of HPS is equivalent to one of CPS.

Table 2. Hydrogen diffusion coefficient

Hydrogen diffusion coefficient of HPS (cm^2/s)	Hydrogen diffusion coefficient of CPS (cm^2/s)
8.9×10^{-8}	8.4×10^{-8}

Cathode Hydrogen Charging Test. In this test, the effects of hydrogen charging rates and storage capacity for the time to fracture of both HPS and CPS were investigated. A schematic diagram of this test is shown in Figure 5. Amount of absorbed hydrogen was changed by current density and with or without ammonium thiocyanate (NH_4SCN). The core wire of HPS 15.2mm and CPS 15.2mm were used as specimens. The specimens immersed in sulphuric acid solution of pH3 were applied the current density of 9, 1, 0.1, 0.01, 0.001, 1×10^{-6} mA/cm^2 under 80% of actual maximum load. Furthermore, the specimens immersed in the solution mixed 0.05mol/l as additive were applied the current density of 9mA/cm^2. The NH_4SCN has the effect of preventing adsorbed hydrogen atoms from changing hydrogen molecule on the wire surface, and absorbing hydrogen atom easily into the material. The results are shown in Figure 6. Figure 6 shows that the fracture time is not influenced by current density, but is influenced a great deal by existence of NH_4SCN. And in the fracture time there is no difference between HPS and CPS at the condition of each current density. Furthermore, using the fracture parts of both HPS and CPS at the condition of current density 9mA/cm^2 and the solution mixed NH_4SCN, amount of absorbed hydrogen just behind fracture was evaluated by Thermal Desorption Spectrometry. The hydrogen charging rate at this condition is the fastest. The results are shown in Figure 7. Figure 7 shows that there is not a clear difference in amount of diffusible hydrogen between HPS and CPS.

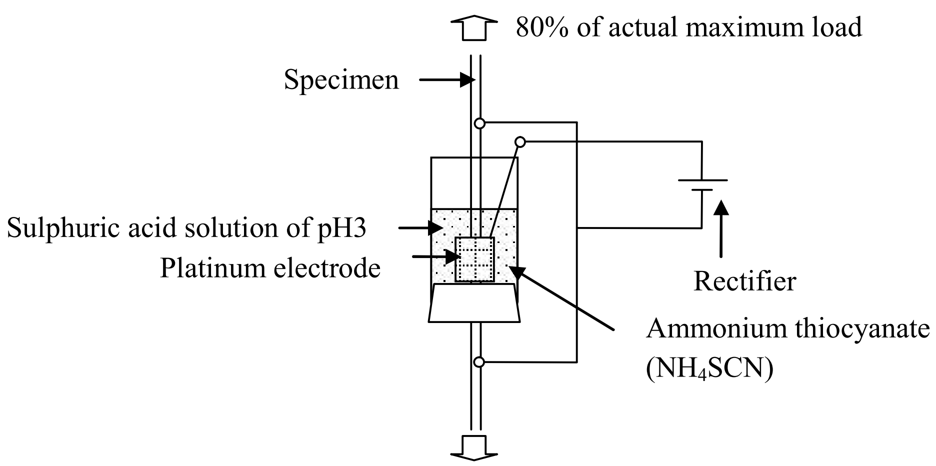

Figure 5. A schematic diagram of cathode hydrogen charging

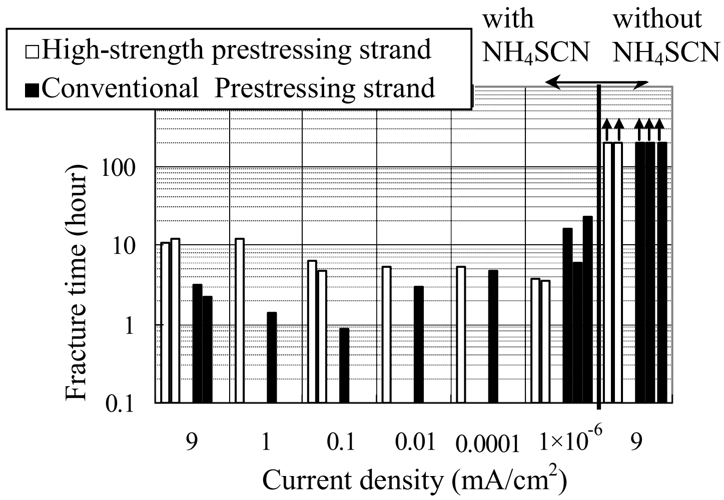

Figure 6. Fracture time in cathode hydrogen charging test.

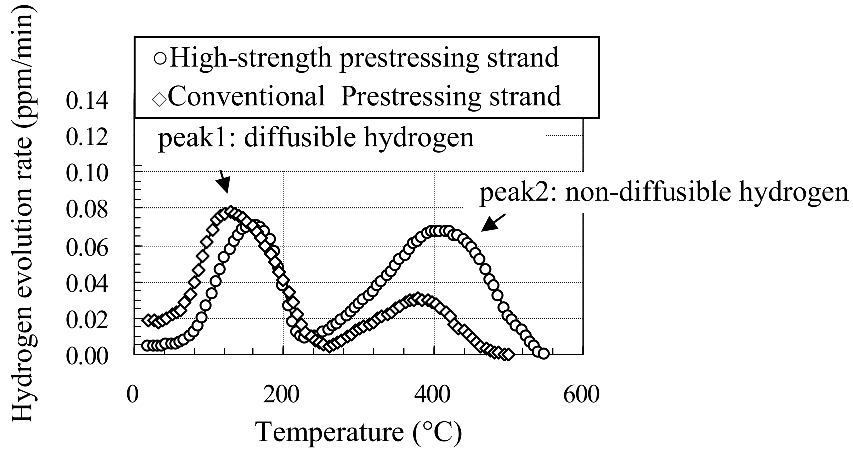

Figure 7. Hydrogen evolution rate at the condition of current density 9mA/cm^2 and the solution mixed NH_4SCN in cathode hydrogen charging test

Amount of Absorbed Hydrogen in Salt Spray Test. Salt spray test was conducted because prestressing strands were sometimes damaged by salt erosion in real environment. After the salt spray test for 96 hours in 35°C and 5 mass% salt water, Thermal Desorption Spectrometry of the core wires of HPS and CPS was conducted. The results are shown in Figure 8. Figure 8 shows that there is no difference between diffusible hydrogen affecting hydrogen embrittlement of HPS and one of CPS.

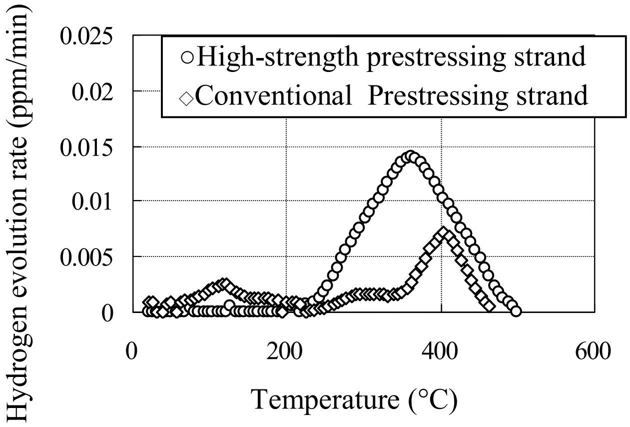

Figure 8. Hydrogen evolution rate after salt spray test

SSRT Test. Recently, SSRT (Slow Strain Rate Technique) test has been used to evaluate the sensitivity of delayed fracture because this test can make the wire brittle with a very small amount of hydrogen and be force to fracture the wire. The core wires of HPS 15.2mm and CPS 15.2mm were used as specimens. Changes of maximum load and fracture elongation before and after salt spray test for 100hours by using SSRT were measured. Their results are listed in Table 3. Table 3 shows that there are no changes of these characteristics before and after the salt spray test in both HPS and CPS.

Table 3. Changes of maximum load and fracture elongation before and after salt spray test by using SSRT

Specimen		Maximum load		Fracture elongation	
		(kN)	Change ratio	(mm)	Change ratio
High-strength prestressing strand	before the test	49.2	1.00	7.29	1.03
	after the test	49.0		7.50	
Conventional prestressing strand	before the test	42.2	1.01	8.89	0.96
	after the test	42.5		8.67	

Change ratio: the value divided a characteristic value after salt spray test by it before the test.

Outdoor Exposure Test. Outdoor exposure test under 70% of characteristic maximum load specified in Table 1 were conducted in HPS 15.2mm and CPS 15.2mm. The appearances of both HPS and CPS after 440 days of this test are shown in Figure 9. Then tensile test of HPS 15.2mm and CPS after 440 days of this test were conducted. The results were listed in Table 4. Table 4 shows that their mechanical characteristics are not deteriorated after 440 days of outdoor exposure test. Furthermore, amount of absorbed hydrogen in these strands were measured. The results are shown in Figure 10. Figure 10 shows that both strands have little diffusion hydrogen and non-diffusion hydrogen after this test.

Figure 9. The appearances of prestressing strands after 440 days of outdoor exposure test (left; test status, center; high-strength prestressing strand, right; conventional prestressing strand)

Table 4. Change of mechanical properties after 440 days of outdoor exposure test

Specimen		Maximum load (kN)	Maximum load Change ratio	Fracture elongation (%)	Fracture elongation Change ratio
High-strength prestressing strand	before the test	322	0.993	8.0	1.03
	after the test	320		8.3	
Conventional prestressing strand	before the test	272	0.996	8.1	0.96
	after the test	271		8.1	

Change ratio: the value divided a characteristic value after outdoor exposure test by it before outdoor exposure test

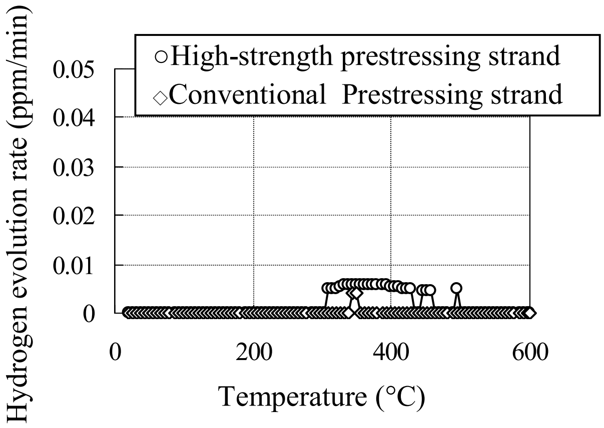

Figure 10. Hydrogen evolution rate after 440 days of outdoor exposure test

Wet-Dry Cyclic Test. Wet-dry cyclic tests with salt water maintaining the concentration of 3 to 4 mass% were conducted in HPS 15.2mm and CPS 15.2mm under 70% of characteristic maximum load specified in Table 1. These strands were repeated falling in drops of salt water for 3hours and drying for 21 hours. The appearances of these strands after 440 days of wet-dry cyclic test are shown in Figure 11. Maximum load and fracture elongation of HPS and CPS after 440 days of this test were also measured. The results are listed in Table 5. Figure 11 and Table 5 show that both mechanical characteristics of HPS and CPS are deteriorated a little bit by corrosion wastage. However there is no difference between the reductions of these characteristic. Furthermore, amount of absorbed hydrogen in these strands were measured. The results are shown in Figure 12. Figure 12 shows that amount of absorbed hydrogen after this test is detected 0.5ppm in both strands. However, most of them are non-diffusion hydrogen, not affect a delay fracture.

Figure 11. The appearances after 440 days of wet-dry cyclic test (left; test status, center; HPS, right; CPS)

Table 5. Change of mechanical properties after 440 days of wet-dry cyclic test

Specimen		Maximum load (kN)	Change ratio	Fracture elongation (%)	Change ratio
High-strength prestressing strand	before the test	322	0.916	8.0	0.95
	after the test	295		7.6	
Conventional prestressing strand	before the test	272	0.875	8.1	0.93
	after the test	238		7.5	

Change ratio: the value divided a characteristic value after wet-dry cyclic test by it before wet-dry cyclic test

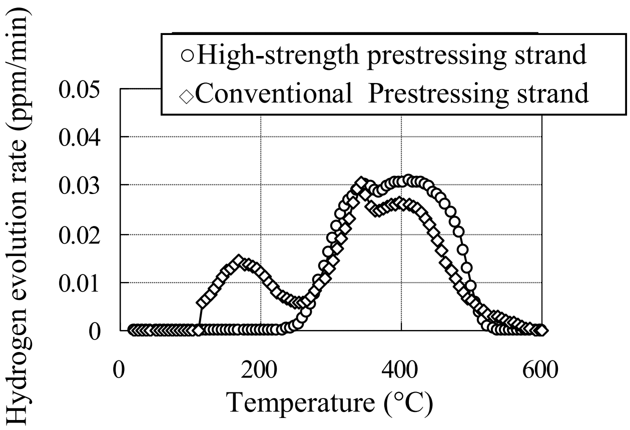

Figure 12. Hydrogen evolution rate after 440 days of wet-dry cyclic test

DISCUSSION

Both HPS and CPS were fractured at the condition of aggressive hydrogen intrusion rate like FIP test and cathode hydrogen charging test. In the fracture time and amount of hydrogen after fracturing there were no difference between HPS and CPS. Furthermore, at the room temperature hydrogen diffusion coefficient of HPS was equivalent to CPS. On the other hand, they were not fractured at the condition of small hydrogen intrusion rate like the outdoor exposure test and the wet-dry cyclic test under tension. Then there were not a clear difference between the changes of mechanical characteristics before and after these tests in HPS and CPS. Furthermore, in SSRT test after 100 hours of salt spray test, there were no changes of mechanical characteristics in HPS and CPS. It is supposed that, because of small hydrogen intrusion rate, part of intruding hydrogen is released from the air and the other part of intruding hydrogen is strongly-trapped in high density dislocation produced by hard-drawing, i.e., becomes non-diffusion hydrogen which does not contribute to delayed fracture. Accordingly, it is considered that the sensitivity of hydrogen embrittlement of HPS is equivalent to CPS.

CONCLUSIONS

HPS has been developed that the tensile load is 20% higher at 7-wire strand and 15% higher at 19-wire strand than CPS specified in JIS G 3536. Other characteristics are satisfied with JIS G 3536. And there are little differences between HPS and CPS in the characteristics of like tensile fatigue and deflected tensile. Furthermore, in the sensitivity of hydrogen embrittlement there is also little difference between them. Therefore, HPS is available in the same way as the conventional prestressing strand.

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