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High-Performance Wire Rods Produced with DLP

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Abstract

DLP (Direct in-Line Patenting) wire rods multiplied equal to or more than 20 years from the entry into production and the dosage expanded steady by them. The product basic concept of the DLP wire rods is the energy saving wire rods which can omit the lead patenting processing which is implemented by the customer. Also, one reason why DLP wire rods are increasingly used is that the heat-treatment is in line with efforts to protect our global environment because lead is not applied. This paper introduces the basic characteristics of the DLP wire rods and high-strengthened DLP wire rods which were commercialized recently in the market.

1. Introduction

DLP (direct in-line patenting) wire rod products have been used since the start of their production in 1985 as products that satisfy the needs of the age, contributing to energy saving and protection of the environment. The main selling point of the DLP wire rods in the early days of their production was the omission of lead patenting that had been used in wire rod user fabrication processes. In fact, the characteristic merit of the wire rods has successfully helped to conserve energy at users. In a later phase of the market situation, moreover, they favorably met the new concept of global environment improvement to increase the number of wire rod users year after year who use DLP wire rods do not contain lead. Recently, studies are being conducted on fluidized bed patenting with the use of high-speed jet gas cooling to completely supersede lead patenting which is conventionally used as intermediate patenting[1].

The DLP wire rod is one of the main in-line heat-treated products of Nippon Steel and is the only product that has maintained its product position constantly for over 20 years since the start of production, supported by metallurgical operation know-how, hot molten salt treating equipment, and equipment maintenance technology/know-how. This report describes the basic performance of the DLP wire rod and some examples of its recent applications to high-strength uses to meet market demands in the form of galvanized steel wires for high-strength PC strands and high-strength bridges.

2. DLP Wires and Rods

2.1 General description of DLP wires and rods

Fig. 1 is an outline of the DLP equipment to directly heat-treat steel wire rods by patenting, using a molten salt as a refrigerant. The equipment comprises a separate cooling bath and a thermostatic bath. The cooling bath can be set to any temperature suited for specific wire rod to be treated, with an initial cooling rate taken into account. The thermostatic bath causes to produce fine pearlite by treating the work at a pearlite transformation nose temperature to assure an

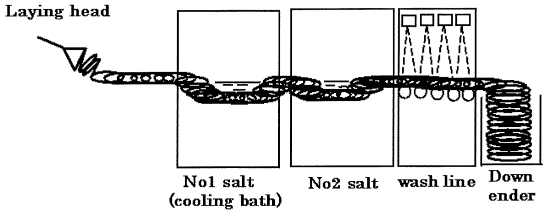

Fig. 1 Outline of the DLP equipment

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efficient transformation at a constant temperature.

2.2 Microstructure of DLP wire rod

Photo 1 shows the SEM microstructures of a high-carbon steel wire rod (SWRH 82B, 11mmφ), heat-treated by DP (Stelmor cooling), DLP (direct in-line patenting), and LP (lead patenting), shown in **Fig. 2**.

As shown in Photo 1, the lamellas are coarsest in the Stelmor-cooled structure. By contrast, the DLP-treated wire rod shows a fine pearlitic structure with the interlamellar clearances obviously narrower than those of the Stelmor-cooled structure and similar to those of the LP-treated structure. The Stelmor-cooled wire rod cools at a lower speed and begins to undergo transformation at a higher temperature than the other two wire rods, and consequently develops a coarser structure than the DLP- and the LP-treated wire rods in which transformation begins at near the pearlite transformation nose. The DLP and the LP wire rods are heat-treated at an ideal constant transformation temperature and therefore develop a fine pearlitic structure.

2.3 Mechanical properties of DLP wire rods

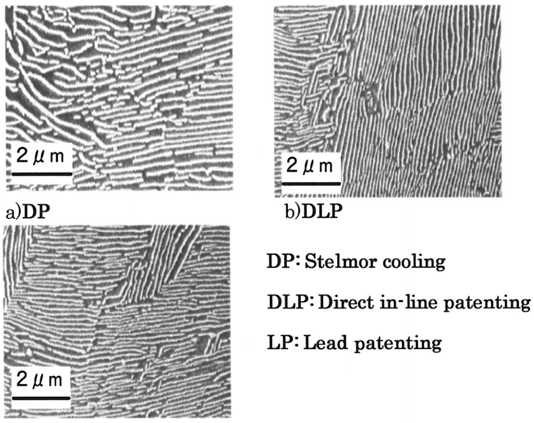
2.3.1 Wire rods

Fig. 3 shows the mechanical properties of the DLP wire rod. As seen from this figure, the strength and the ductility of the DLP wire rod are characteristically better balanced than that of the DP or LP wire rod. More specifically, the DLP wire rod metal begins to undergo pearlitic transformation at the nose temperature in the heat treatment to give rise to fine pearlite and to have a higher strength than the Stelmor-cooled metal as described earlier. While the tensile strength of the DLP wire rod is comparable to that of the LP wire rod, the area reduction rate which denotes the ductility of wire rod is higher in the DLP wire rod than in the LP wire rod, indicating that the DLP wire rod has a better ductility. This means that the LP wire rod is reheated up to an austenitic (γ) level after it was rolled, to result in austenitic crystals of a larger grain size than that of the DLP wire rod which is heat-treated immediately after it was rolled.

2.3.2 Steel wires

Fig. 4 shows the examination results of the mechanical properties of steel wires. The steel wire metal is drawn and worked on to steel wires of various diameters.

As shown in Fig. 4, the tendency of the increase in strength owing to the increase of wire drawing strain is seen throughout the strain region, and the tendency of higher strength increase of the two wires than the comparison DP wire is successive from the wire rod to the wire steel phase. A similar tendency is also seen in regard to drawing, denoting that the DLP wire has a good ductility throughout the strain



a)**DP** b)**DLP** c)**LP**

DP: Stelmor cooling

DLP: Direct in-line patenting

LP: Lead patenting

Photo 1 Typical microstructures of patented wire rods

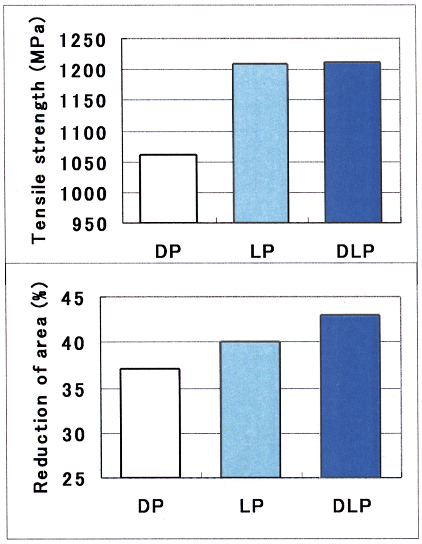


Fig. 3 Mechanical properties of patented wire rods

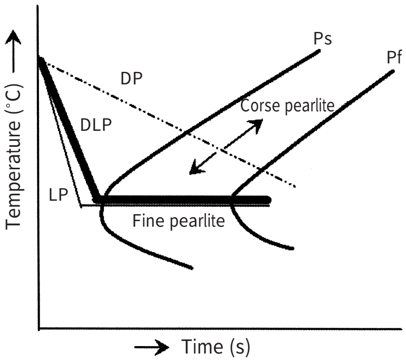


Fig. 2 Scheme of cooling rate and pearlite transformation temperature

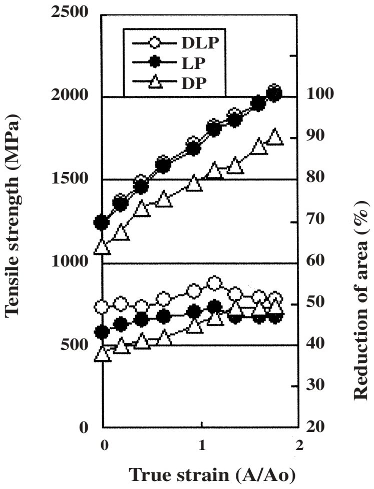


Fig. 4 Mechanical properties of patented steel wires

region. The ductility of the DLP wire rod confirmed in the wire rod drawing stage as superior to that of the LP wire rod is inherited by the DLP steel wire to give it a higher ductility to the LP steel wire.

2.4 Methods for increasing strength of high-carbon steel wires

The available methods for increasing the strength of high-carbon steel wires can be summarily into the three as shown in **Fig. 5**[2,3].

2.4.1 Increase of patented steel wires

Increasing the strength of patented steel wires means ① in Fig. 5. In other words, this method is used to increase the strength of the wire by causing to produce fine pearlite structure under selected optimum heat-treating conditions when the wire is heat-treated for transformation at a constant temperature. The possible additives include C, Si, Cr and V. If an increased amount of C is added to increase the wire strength, reticulate pro-eutectoid cementite may form to significantly deteriorate the wire drawability[4]. By contrast, if the wire is processed in a DLP line, the wire cooling speed in the temperature-constant transformation heat treatment is faster than in Stelmor cooling, and the restraint of pro-eutectoid cementite formation is expectable (see **Fig. 6**). Consequently, it can be an effective means when carbon content is increased for further increasing the strength of high-carbon steel wires.

2.4.2 Strength increase by wire drawing

For increasing the wire strength by wire drawing, the area reduction rate may be increased (as ② in Fig. 5), or the strain hardening rate in the wire drawing process may be increased. For the application of an area reduction rate increase, an optimum area reduction rate and elaborate wire drawing conditions (including cooling conditions and the optimization of die formation) must be set.

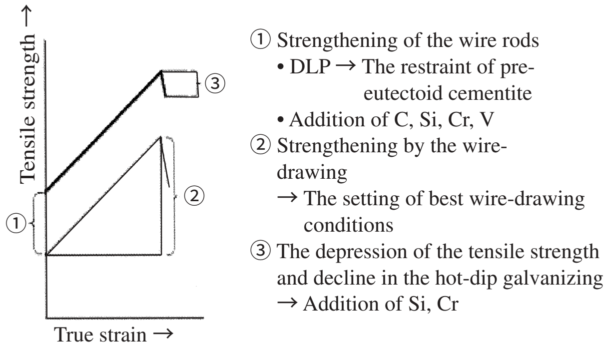


Fig. 5 Way of thinking of the strengthening for the high carbon wires

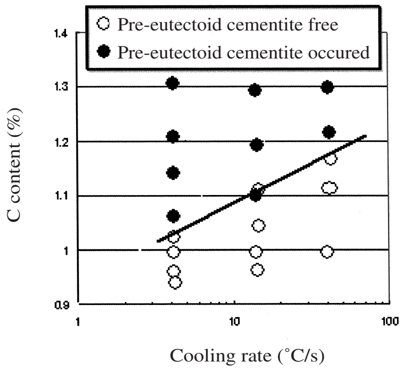


Fig. 6 Effect of the pre-eutectoid cementite formation on the C content and the cooling rate

2.4.3 Restrain of wire strength reduction in hot-dip galvanization

For PC steel wires and steel wires for bridges which are treated by hot-dip galvanizing and bluing after wire-drawing, the restraint of the coating-affected strength reduction (③ in Fig. 5) plays an important role. Details of improvements, however, are not discussed here because of limited space.

2.5 Technical points for strengthening

The most important consideration for increasing the strength of high-carbon steel wires is the use of a steel having an appropriate strength-ductility balance in specific environments where the steel wires are actually used. For this purpose, the composite performance of the steel and materials used with it needs to be evaluated. In other words, the use of steel wires having an increased strength does not necessarily improve the performance of the whole assembly or structure. Even if the performance of steel wires themselves is improved, whether the composite performance of the steel assembly with other materials is also improved or not will always be in question.

Materials that can be used in combination with steel wires include glass (in the form of wires sheathed in glass), concrete (PC), coating epoxy, plating metal (hot-dip galvanizing, plating alloy) and rubber. We evaluated the composite performance of steel wires when used with coating epoxy or high-strength concrete which is popularly used for structures.

3. Evaluation Results of Properties

3.1 Evaluation of wire steel application to high-strength PC concrete slabs

At present, the strength of concrete is classified as shown in **Table 1**. The following paragraphs describe by way of example our evaluation of the properties of PC steel strands and high-strength concrete (standard design strength (Fc): 40 N/mm^2) used as composite materials for high-strength PC slabs[5].

3.1.1 Evaluation method

1) Specimen components

For evaluation as the first step in our attempt to increase steel strength, we used 310K steel strands as the test specimen and also used strands of a regular steel for comparison. **Table 2** lists the components of the specimen. After making 13-mmφ steel wire rods of this chemical composition by DLP treatment, we turned them into high-strength PC steel stranded cables of 310K class on actual lines at Suzuki Metal Industry Co., Ltd. The mechanical properties of the PC stranded cables are shown in **Table 3**.

2) Testing method

The materials used in the test are concrete (having a standard design strength of 40 N/mm^2), PC steel strands, reinforcing steel bars

Table 1 Concrete strength repartition

Repartition	Fc
Regular	18 - 35 N/mm^2 (Fc18 - Fc35)
High-strengthened	36 - 60 N/mm^2 (Fc36 - Fc60)
Super - high-strengthened	60 - N/mm^2 (Fc60 -)

Table 2 Chemical compositions of samples

Strength		Chemical composition (mass%)					
		C	Si	Mn	P	S	Cr
310K	High-strengthened	0.98	1.20	0.33	0.010	0.005	0.19
270K	Regular	0.83	0.19	0.74	0.014	0.013	0.01

(arranged in the direction of the slab top and bottom supports and in the direction perpendicular to the supports), and PC steel anchoring parts.

The PC steel strands were prestressed such that the stress of the concrete is within the tolerable range when a concentrated load of 10 tonf is applied (on the assumption of a vehicle wheel load of 10 tons) to the midpoint of the center-to-center distance between the simple supports. The specifications of the two test subjects are outlined in **Table 4**. The HI (21.8 mmφ, 310K) steel strands were spaced so that the amount of their prestress is equal to that of the orthodox 21.8mmφ 270K REG-A strands (**Fig. 7**). A load was applied to the points of x = 0, L/8, 2L/8, and 3L/8, where x is a distance from the center, with the support-to-support distance L = 2,200 mm (see **Fig. 8**). The load applied to the point of x = 0 and L/8, respectively, was varied in the pattern of 0 → 5 → 0 →10 → 0 → 15 → 0 tonf, while the load applied to the point of x = 2L/8 and 3L/8, respectively, was varied in the pattern of 0 → 5 → 0 → 10 → 0 → 15 → 0 → 20 → 0 tonf, all applications after a gradual increase or a gradual decrease. The displacement and strain at each of the application points were measured.

Table 3 Mechanical properties of the stranded cable of the samples

Strength repartiton	Tensile strength (MPa)	Yield-strength (MPa)	Yield ratio (%)	Elongation (%)
310K	2 179	2 035	93.4	6.4
270K	1 920	1 768	92.1	6.6

Table 4 Overview of the load-test body

		REG-A	HI
Name of load-test body		270K	310K
Diameter of strand	mm	21.8	21.8
Spacing of reinforcing steel	cm	25	28.6
Stress of PC strand	kgf/cm^2	137.4	152.8
Axis force of PC strand	tonf	40.3	45.7
Concrete stress (upper side)	kgf/cm^2	134.6	164.5
Concrete stress (lower side)	kgf/cm^2	10.9	10.8

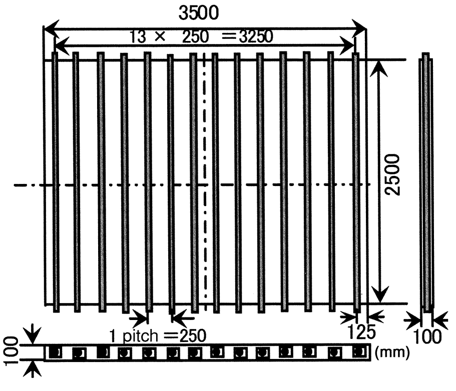


Fig. 7 Sketch out of the load-test body

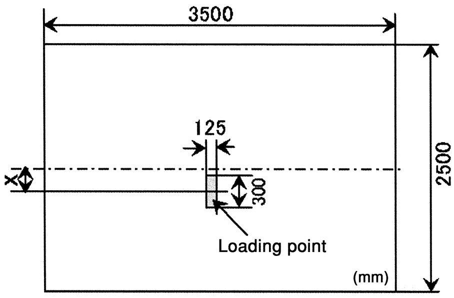


Fig. 8 Schematic of the loading point

3) Test results

Fig. 9 shows an example of the measurements of changes in concrete surface distortion near the anchored areas, caused when the steel strands are tensed, in the manufacture of deck slabs. It can be seen from this figure that prestress is evenly introduced when the tensing work is over. **Fig. 10** shows load-bend curves at the loading point of x = 0 (the midpoint.). Both of the specimens show a linear behavior until the loading point is up to the design load (of 10 tonf at the midpoint), but the behavior becomes slightly nonlinear as the load is increased up to 15 tonf. **Table 5** lists the bends of the specimens at the loading points under the maximum load in the four loading patterns. The deck slab rigidity of the 310K high-strength strand (HI) is higher by 5 to 18 percent than that of the 270K regular strand (REG-A).

The above results indicate that the increase of the strength of steel strands for high-strength PC from conventional 270K to 310K while maintaining the prestress at a constant level assures the interaction between the steel and the concrete to have an effect of tension equivalent to what is conventional. This strength increase leads to another effect of increasing the distances of reinforcing steel members which are spaced in proportion to the strength of PC strands as shown in Table 4, to eventually contribute to reduce PC deck slab manufacturing cost as well as to shorten construction period. These results are were predictable by theoretical study, but our findings by actually making PC deck slabs and actually testing them to verify their effect provided valuable data for us to take further steady steps as a material manufacturer.

On the other hand, technologies in the concrete industry have

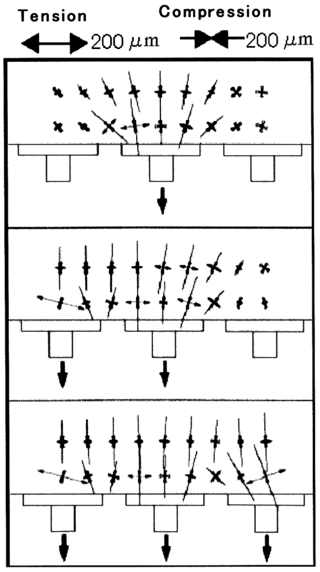


Fig. 9 Distorted deck slab surface main distribution in case of the stranded cable tension (310K)

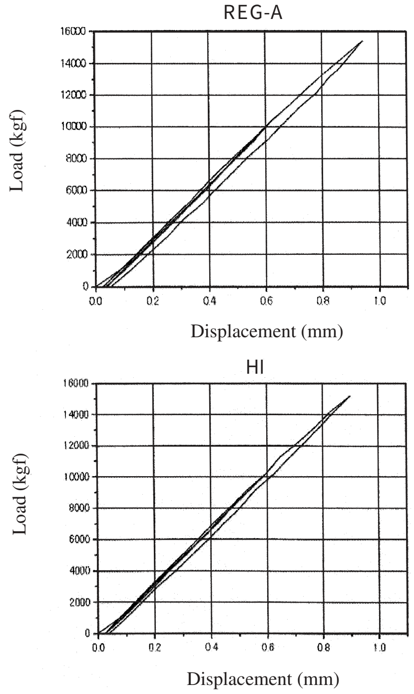


Fig. 10 Load - bend curve on loading point

Table 5 Bend of the load point

Load point, load	REG-A	HI (ratio of REG-A)
0/8L, 15 tonf	0.95 mm	0.90 mm (−5.3%)
1/8L, 15 tonf	0.92 mm	0.82 mm (−11%)
2/8L, 20 tonf	0.77 mm	0.68 mm (−12%)
3/8L, 20 tonf	0.39 mm	0.32 mm (−18%)

been rapidly progressing. The standard design strength in 1955 was about Fc18, but nowadays, reflecting the technological improvements since then, the strength of more or less Fc30 is used even for general apartment houses. For tall apartment house buildings having more than 30 stories, super high-strength concrete having a strength of not lower than Fc60 is beginning to be used[6)].

Moreover, since the appearance of super high-strength concrete having a strength of 3 to 5 times higher than ordinary strength, standard design strengths higher than 100 N/mm^2 came to take place after 1997. They consequently increased the needs for strength-increased steels for PC reinforcement. We then had an opportunity of evaluating the practical performance of 324K-series steels (developed to have higher strength than 310K) in application to super high-strength concrete having a standard design strength of 120 N/mm^2. The following paragraphs present an example of the commercialization of the first-in-the-world combination between a super high-strength concrete and high-strength PC steel strands[7)].

3.2 Strength-increased PC steel strands (324K)

3.2.1 Chemical composition of 324K PC steel strands

Table 6 shows the chemical composition of the steel developed to have a strength of 324K (20% higher than 270K). The PC98 steel wire rods were produced on the DLP line in the Wire Rod Mill at our Kimitsu Works, based on the chemical composition of 310K but with fine adjustments made thereto in an attempt to increase the manufacturing process capabilities. The 324K class produced wire rods were stranded on the actual lines at Sumitomo (SEI) Steel Work Corp.

3.2.2 Specifications and mechanical properties of high-strength PC wire strands

Table 7 shows the specifications of the high-strength PC steel strands, and **Table 8** shows the measured results of their mechanical properties. **Fig. 11** shows load-elongation curves of the PC strands determined by a tensile test. As seen from these results, load to the 324K super high-strength PC strands can be higher by 20 percent than to the 270K PC strands, and the elongations of them are nearly same.

PC steel strands, when used for external cables, are coated with epoxy resin or similar for corrosion prevention. Table 8 shows that coating the 324K super high-strength PC steel strand has no effect on its mechanical properties. It is also known that the basic performance properties of this strand in terms of anchorage rate, relaxation value, and wedge anchor fatigue fully meet the specifications[8)] by the Japan Society of Civil Engineering[7)], although details of these properties are omitted here because of space limit.

3.3 An example of 324K super high-strength PC steel strand application[7,9)]

A redevelopment project of the Tokyo Metropolitan Government called “Akihabara Cross Field” in front of the Akihabara railway stations was implemented as part of the urban development plan and was completed in February, 2006. In this project, super high-strength steel strands were used for the first time in the world in the public bridge deck of a fashionable design connecting the station square with the neighboring main buildings[9)]. The station square had much traffic of vehicles and pedestrians, the number of bridge legs was limited, and the deck was required to have a slender design, satisfying the maximum leg-to-leg span of 33.2 m and a girder high of 1.2 m. The concrete planned to be used was a super high-strength concrete having a standard design strength of 120 N/mm^2, and super high-strength 324K PC steel strands were therefore selected for the concrete reinforcement after elaborate evaluation in comparison with 270K strands.

Table 6 Chemical compositions of sample metal

Metal	Strength repartition	C	Si	Mn	P	S	Al	Cr	V
PC98	324K	1.00	0.87	0.41	0.013	0.002	0.022	0.21	0.07

Table 7 Specifications of the super high-strengthened PC strands

	Diameter (mm)	Nominal cross-sectional area (mm^2)	Tensile load (kN)	Yield load on 0.2% (kN)	Strength (N/mm^2)
Super high-strengthened	15.2	138.7	≧ 313	≧ 266	≧ 2 230
Regular	15.2	138.7	≧ 261	≧ 222	≧ 1 860

Table 8 Mechanical properties of the super high-strengthened PC strands

	Tensile load (kN)	Elongation (%)	Yeild load on 0.2% (kN)
Regular 15.2 mmϕ	272	7.2	243
Super high-strengthened PC strand	326	7.7	289
Super high-strengthened epoxy coated PC strand	329	7.1	297

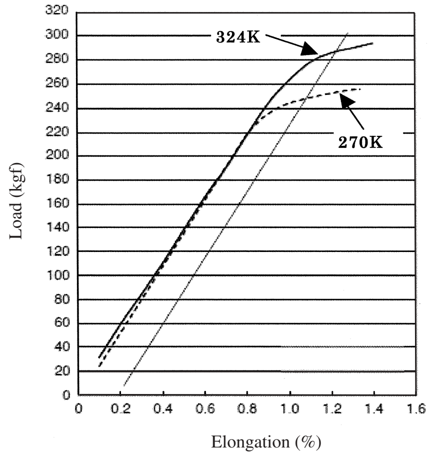


Fig. 11 Load - elongation curve at the time of the tensioned test

Photo 2 Outward appearance photograph at the public deck

Photo 3 Outward appearance photograph in the digit lower part

Table 9 shows the specification of the public deck constructed in the redevelopment project. The basic performance of this combination of the super high-strength PC strands and the super high-strength concrete having a standard design strength of 120 N/mm^2 that were used in this project was verified to be satisfactorily operative as in the case of the standard design strength of 40 N/mm^2 stated earlier⁹⁾. **Photo 2** shows an appearance of the public deck, slim and smart with a girder height of 1.2 m. **Photo 3** shows an appearance of the girder bottom construction having main and transverse high-strength PC strands. Thus, it is found that the super high-strength PC strands and the super high-strength concrete are materials combinable into a composite without impairing the merits of the mating partner.

3.4 High-strength PWS

The strength of PWS needed for bridge construction has been increased, from 5mmϕ - 160 kgf to 5mmϕ - 180 kgf, as longer and bigger bridges were constructed. Notably, the grand Akashi Straits Bridge was constructed as the biggest project in the twentieth century²⁾. The project of constructing a grand Messina Straits Bridge (with a design center span of 3,300 m) which was expected for many years to be the big project next to the Akashi Straits Bridge is said to have been cancelled according to a recent information (in October 2006), only to leave the project in a dream. **Fig. 12** shows the relation between the bridge material strength and the center span.

Table 9 Specifications of the public deck

(1) Bridge type	PC continuous two span
(2) Type of main girder	Super high-strengthened concrete II girder
(3) Activate load	Crowd load
(4) Bridge length	63.803 m
(5) Girder length	63.403 m
(6) Center span	4.087+25.762+33.205 m
(7) Width	8.8 m
(8) Fc	120 N/mm^2

On the other hand, there has been a steady tendency to build longer

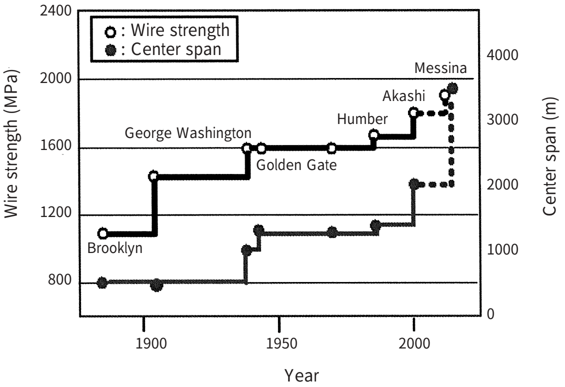


Fig. 12 Changes of the steel cable strength for the bridge and the center span

Table 10 Span length of the cable-stayed bridges

Rank	Tensile strength	Name of bridge	Center span	Complete year	Country
1	High-strengthened	Sutong Yangtze River	1 088	Under construction	China
2	High-strengthened	Stonecutters	1 018	Under construction	China
3	Regular	Tatara	890	1999	Japan
4	Regular	Normandy	856	1995	France
5	High-strengthened	Incheon	800	Under construction	Korea

and bigger cable-stayed bridges, and demands for higher-strength materials are expected to gradually increase. This tendency is actually seen visibly by recent facts shown in **Table 10**. This tendency also clearly denotes the trend for longer center span. The following subsections describe 7mmϕ PWS wires of 1770 MPa class which were commercially realized owing to DLP wires in order to meet increasing demands for PWS wires for recent bigger and longer bridges, and show a few examples of the bridges whose specifications include such PWS wires and which are currently under construction.

3.4.1 Chemical composition

Table 11 shows the chemical composition of the specimen we analyzed. To increase the strength of a high-Si hypereutectoid steel used as a basic steel, Cr was added to it. The Cr-added steel was DLP-treated and rolled into wire rods. Thereafter, they were subjected to the processes of wire drawing down to plating on actual manufacturing lines at Tokyo Rope Mfg. Co., Ltd. to be formed into 7mmϕ PWS wires of 1770 MPa class.

3.4.2 Mechanical properties of rod and wire

Table 12 lists the mechanical properties of the steel rod and the wire. The DLP rod had a tensile strength of the 1434 MPa, and was drawn to wire and hot-dip galvanized to become the final product. The tensile strength of the finally galvanized steel wire was 1896 MPa, proving that it could satisfy the strength required to 7mmϕ PWS wires of 1770 MPa class. On the other hand, it showed an average value of 24 twisting turns, proving that it had a stable ductility capable of meeting the specification for the Akashi Straits Bridge.

3.4.3 Examples of actual applications

As examples of the actual applications of the high-strength wires (7mmϕ , 1770 MPa), they are used in the world's No.2 bridge (Stonecutters, Hong Kong) and the No.5 bridge (Incheon, Korea) that are currently under construction among the cable-stayed bridges listed in Table 12. **Photo 4** shows an anticipated image of the Stonecutters Bridge, when completed.

Table 11 Chemical compositions of the class PWS wire of 1 770 MPa of 7 mmϕ

Metal	C	Si	Mn	P	S	Cr
S87AM	0.88	1.03	0.40	0.012	0.007	0.23

Table 12 Mechanical properties of high-strengthened PWS (the class of 1 770MPa of 7mmϕ)

	Rod	Galvanized wire		
	Tensile strength	Tensile strength	Number of twist	
Metal	(MPa)	(MPa)	Ave.	Min.
S87AM	1 434	1 896	24	20
Specification		1 770 / 1 960	≧ 12 times	

Photo 4 Complete image figure at the stonecutters bridge

4. Conclusion

The importance of the development of DLP-treated wire rods will increase not simply to replace wire rods that used to be LP-treated at wire rod users, but more positively with focus on the intrinsic properties of high strength and high ductility of the material. Technological innovation is making remarkable progress in recent years, particularly for developing higher strength of prestressed concrete. The collaboration of the steel strength improving technology with the concrete technology has the possibility of developing more excellent composite materials. With this view in mind, we will continue R&D activities to realize higher-strength materials.

5. Acknowledgement

We thank the people of Suzuki Metal Industry Co., Ltd. and Sumitomo (SEI) Steel Wire Corp. who helped us for the manufacture and evaluation of high-strength PC steel strands and the people of Tokyo Rope Mfg. Co., Ltd. who cooperated with us for the manufacture and evaluation of high-strength PWS.

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