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Development of Color Cable for Suspended Structures

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Abstract:

As bridges have seen increasing emphasis placed on their aesthetic design to ensure harmony with the environment in recent years, bridge cables are being called for to possess higher aesthetic properties as well as mechanical properties. Nippon Steel Corporation has developed a color cable with high strength and highly corrosion resistant NEW-PWS for use in bridges that is shop coated with colored fluoropolymer with outstanding weathering durability. When the fluoropolymer was selected as the color cable coating material, it was analyzed as to its properties and subjected to exposure test. The analysis and test results confirmed that fluoropolymer excels in such important weathering properties as weathering durability and color and gloss retention. This paper also describes the coated layer properties and installation characteristics of the fluoropolymer-coated color cable as tested in various ways.

1. Introduction

In Japan's bridge construction field, suspension bridges and cable-stayed bridges have remarkably increased in span length, creating demands for cables with superior functionality and durability. Long cable-stayed bridges call for cables with high mechanical strength, excellent corrosion resistance, and great ease of installation. Hangers of long suspension bridges must possess superior mechanical properties and must be maintenance free over a long period of service. To meet these needs, Nippon Steel Corporation developed a new type of parallel wire cable that is shop coated with polyethylene for corrosion protection and is designated NEW-PWS. The NEW-PWS has been used on many bridges, including such long cable-stayed bridges as the Yokohama Bay Bridge and the Ikuchi Bridge.

In recent years, bridges have come to be required to have aesthetic effects on the surrounding landscape as well as to possess superior mechanical properties. When polyethylene is used as the protective coating of cables, its color is limited to black from the point of view of long-term weather resistance. Given this condition, Nippon Steel carried out the development of a color cable of the fully prefabricated type using fluoropolymer having outstanding weather resistance as the cable coating material. The material properties, weather resistance, and structural characteristics of the color cable are reported here.

2. Structure and Characteristics of Color Cable

Polyethylene, when used as the protective coating on the surface of a cable, has carbon black added to prevent degradation by ultraviolet radiation. The carbon black turns the polyethylene coating black. Polyethylene can be colored other than black by using coloring pigments, but the weathering resistance of cable thus colored cannot be assured, because it degrades in the open air in a short period[1].

A black cable may be colored by wrapping it with a color tape or covering it with a metal material, for example. These methods,

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however, involve the problems of tape joint durability and cover joint contamination, are not preferred from an aesthetic point of view. Further, they need installing equipment and time to apply such tapes or metallic covers at site coloring by paining requires special working apparatus to ensure uniform color quality and for long-term maintenance after installation.

After investigations on a maintenance-free cable coloring method, Nippon Steel succeeded in developing and commercializing the technique whereby a polyethylene-coated cable is shop coated with colored fluoropolymer with excellent weather resistance (see **Fig. 1** and **Photo 1**).

The main characteristics of the color cable are as follows:

(1) It has at least the same weather resistance as the black polyethylene-coated cable, and marks superior durability.
(2) It is completely prefabricated so that it needs no additional work after installation at site.
(3) It comes in 15 standard colors selected for freedom from discoloration and fading, among which the user can choose for matching with the environment.
(4) It has excellent heat resistance, and can withstand such heavily polluting conditions as exhaust gas and salt-laden air.
(5) When damaged, it can be readily repaired.

3. Material Characteristics of Color Cable

3.1 Fluoropolymer

The color cable has the conventional polyethylene coating with its peripheral surface additionally coated with colored fluoropolymer. The material was selected paying due consideration to the following requirements:

(1) It should have excellent weather resistance and durability.
(2) It should have high mechanical strength.
(3) It should allow the extrusion coating process.

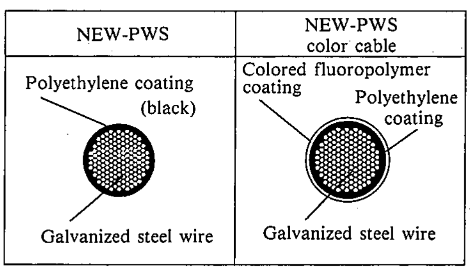

Fig. 1 Cross section of color cable

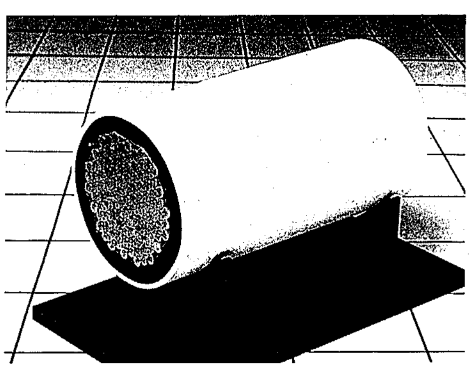

Photo 1 Color cable

As a polymer to meet these requirements, fluoropolymer was selected from among various materials (see **Table 1**)[2,3].

Recently, high durability and high functionality have come to be required of materials in many industrial fields. Fluoropolymer has been used as a material having weather resistance, heat resistance, chemical resistance and non-tackiness, among other properties. Fluoropolymer excels particularly in weather resistance. This outstanding property led to its application to bridge cables.

3.2 Properties of fluoropolymer

Eight types of fluoropolymers are currently used in various fields[2]. Polyvinylidene fluoride (PVDF), a fluoropolymer with superior mechanical strength and optimum extrusion coating property, was selected as the outer coating material of the color cable taking into account the following points.

The basic mechanical properties of fluoropolymer were investigated before using it as the outer coating material of the color cable. The results are as shown in **Fig. 2**. From the figure, it is clear that the fluoropolymer has a slightly higher tensile breaking strength than high-density polyethylene (HDPE), but the temperature dependence of its tensile breaking strength is almost the same as that of HDPE.

Fluoropolymer has been in use in the construction industry for such a short period that its material standardization is still to be established. Accordingly, its properties for use in color cables were set to meet those of high-density polyethylene shown in **Table 2** by referring to the specifications of JIS K 6896 - Polytetrafluoroethylene Powder for Molding and Extrusion Materials and so forth.

The outer fluoropolymer coating is applied by the same melt

Table 1 Comparison of properties of fluoropolymer with other polymers

Property	Fluoropolymer	Nylon 6	Polypropylene	Polyvinyl chloride
Specific gravity	1.7-2.2	1.13	0.90	1.35-1.45
Tensile strength (kgf/cm^2)	140-460	720-820	200-400	350-620
Elongation (%)	100-400	25-320	600-800	2-40
Weather resistance	○	×	×	×
Heat resistance (°C)	150-260	80-120	100-120	60
Chemical resistance	○	×	△	△
Non-tackiness	○	×	○	×
Moldability	○	○	○	○

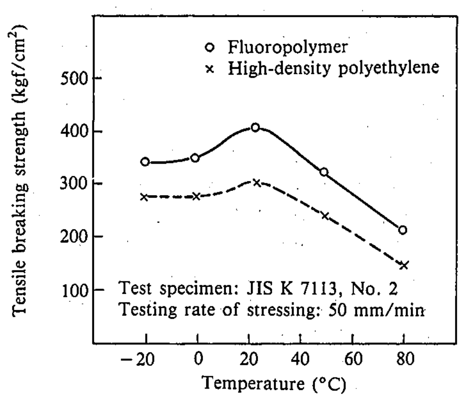

Fig. 2 Tensile breaking strength of fluoropolymer

extrusion coating process as the inner polyethylene coating. Therefore, residual stress remains in the coating. Elongation by tension introduced and a temperature change add stress to the cable structure. Aging under such a stressed state suddenly initiates cracks in some polymers, which propagate through the polymer and eventually lead to its brittle fracture. In view of this possibility, the fluoropolymer was investigated also for environment stress cracking resistance. This property of fluoropolymer was tested by referring to the constant-strain environmental stress cracking (ESCR) test method specified in JIS K 6760. The ESCR test results confirmed that fluoropolymer develops no cracking at all after 1,000 h and is as satisfactory as polyethylene so far as environmental stress cracking resistance is concerned.

4. Weathering Resistance of Color Cable

4.1 Weathering test methods

Weathering test is designed to evaluate the service and appearance durability of materials against weather conditions, such as outdoor light (ultraviolet radiation in particular), heat and rain, and is divided into outdoor natural exposure test and accelerated exposure test (see **Fig. 3**). The natural exposure test method exposes specimens in a natural environment and provides reliable data, but takes a long time to complete. A conventional accelerated exposure test method uses various artificial light sources in the laboratory to simulate the natural environment of interest, and is simple to perform. The outdoor accelerated exposure test (EMMAQUA test)[4] concentrates sunlight on specimens by mirrors, can evaluate the weather resistance of specimens within a short period of time, and is often used to evaluate new materials.

The fluoropolymer was examined by the natural exposure test method that is most reliable in weather resistance evaluation. The colored fluoropolymer used in the color cable had been investigated for about two years by the accelerated outdoor exposure test method to ensure approximately the same evaluation period as the conventional natural exposure test method. The weather resistance of fluoropolymer was also studied by the latest accelerated laboratory test method.

4.2 Natural exposure test

The results of natural exposure tests on fluoropolymer resins are indicated in the References[5,6]. These tests were conducted in the United States. Polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) were used as test materials, continuously exposed for 17 and 20 years, respectively, and indicated no particular changes in strength. This proves that PVDF and PTFE do not suffer any weather aging when exposed to such natural environmental factors as sunlight, rain and gas over at least 17 to 20 years. The test being outdoor exposure, the weather resistance exhibited by the test materials can be taken to represent their performance in actual outdoor service. Fluoropolymer resins exhibited no appreciable loss of tensile strength at the end of the test. It is thus presumed that fluoropolymer resins will not deteriorate semipermanently under weather if their coating thickness is 1 mm or over[7]. The largest factor in the excellent weather resistance of fluoropolymer is its extremely high intermolecular binding energy.

4.3 Accelerated outdoor exposure test

The accelerated outdoor exposure test concentrates sunlight on the specimen surface with a reflecting concentrator system consisting of 10 plane mirrors. The test can be performed while keeping the ultraviolet spectral balance of the sunlight (see **Photo 2** and **Fig. 4**). The testing machines are installed in the Arizonan desert region that is one of the most punishing areas in the United States, where the colored fluoropolymer was tested for weatherability according to this method. The test was conducted according to ASTM G90 and D4364.

Table 2 Properties of fluoropolymer

Property	NEW-PWS fluoropolymer	NEW-PWS polyethylene (JIS K 6748 Class 3 Grade 1)
Density (g/cm^3)	≥1.7	≥0.942
Tensile strength (kgf/cm^2)	≥300	≥200
Elongation (%)	≥200	≥300

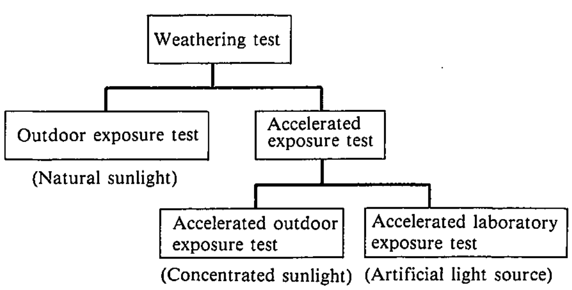

Fig. 3 Weathering test methods

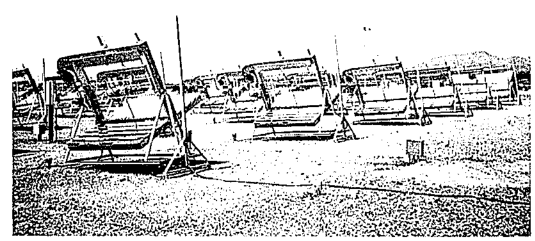

Photo 2 Accelerated outdoor exposure test (EMMAQUA)

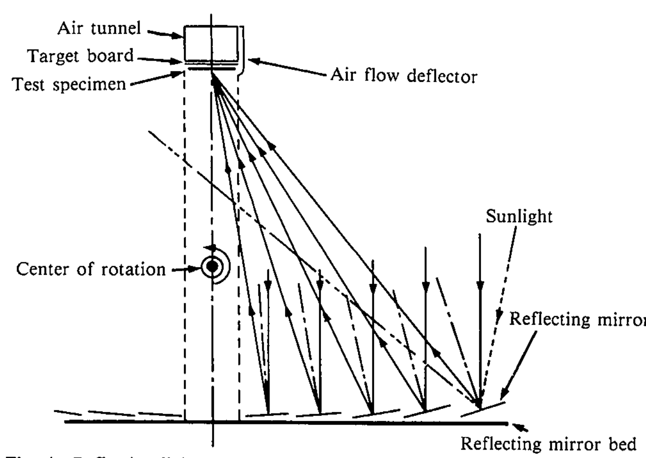

Fig. 4 Reflecting light concentrator of EMMAQUA testing machine

Fig. 5 shows the tensile strength and elongation retention of specimens measured after the outdoor exposure test. The two data exhibit no evidence of deterioration at the ultraviolet radiation dose of 2,500 MJ/m^2, which is equivalent to exposure for about 7.5 years in the Arizonan desert region in the United States. In Japan, the ultraviolet radiation dose differs from place to place ranging from 180 to 240 MJ/m^2 per year (in the wavelength range of 300 to 400 nm) according to literature[8]. If the ultraviolet radiation dose is put at 210 MJ/m^2 for an average area, the results of the accelerated outdoor exposure test correspond to about 12 years of natural weathering in Japan. When corrected for the difference of ultraviolet measurement region between the United States and Japan by referring to the past data, the test results are presumed to correspond to at least 14 to 15 years of natural weathering in Japan.

The state of weather aging can be judged from structural deterioration as well as from the change of mechanical strength. White fluoropolymer was observed by electron microscopy after the accelerated outdoor exposure test. The result confirmed that the test specimens had undergone no chemical degradation at all.

This test examined 1 mm thick white fluoropolymer specimens under conditions close to the actual conditions of use unlike the past natural exposure tests that used uncolored and thin fluoropolymer specimens. The test results confirmed that fluoropolymer resin would suffer practically no weather aging for more than 10 years.

4.4 Accelerated laboratory tests

To investigate the weather resistance of fluoropolymer, a sunshine arc carbon-type weatherometer accelerated test was conducted with polyvinyl chloride (PVC) used as control.

Fig. 6 shows the elongation retention of fluoropolymer and PVC measured after the accelerated test. While PVC degrades in a short time, fluoropolymer shows no appreciable change in elongation retention after 5,000 h and demonstrates as high weather resistance as polyethylene.

A testing machine capable of accelerating natural weathering to a high degree, called QUV (super accelerated weathering test machine) was recently developed. QUV is claimed to accelerate natural weathering by a factor of about 10 as compared with the sunshine carbon arc weatherometer[9]. Using the QUV testing machine, fluoropolymer was subjected to the accelerated exposure test and observed as to surface change. While the PVC resin used as control had its surface structure destroyed in about 200 h, fluoropolymer exhibited no particular degradation even after 10,000 h.

The accelerated laboratory tests were conducted over the ranges feasible at present. Fluoropolymer revealed no apparent deterioration and proved its satisfactory weather resistance as evident from the exposure test results mentioned previously.

The aforesaid various exposure test results demonstrated that the fluoropolymer coating applied to the color cable is free from weather aging for at least 20 years, and has weathering durability equal to or greater than that of the polyethylene coating conventionally applied to bridge cables.

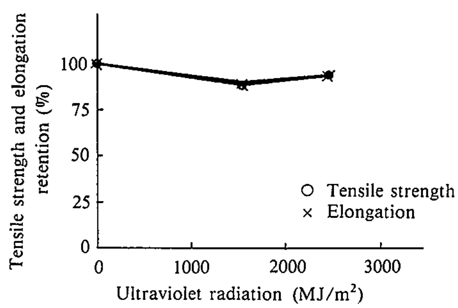

Fig. 5 Accelerated outdoor exposure test results of fluoropolymer

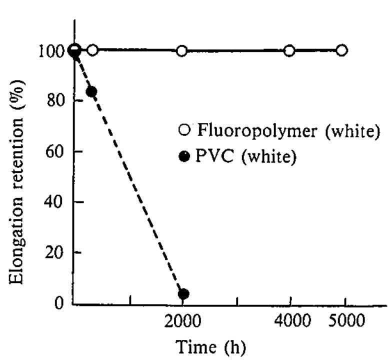

Fig. 6 Accelerated laboratory test results of fluoropolymer

5. Color Change and Fading Characteristics of Color Cable

5.1 Color change and fading test methods

When fluoropolymer is used as a colored coating, changes in its appearance, through discoloration and fading, and its stain resistance as well as weathering durability are important governing factors in the durability of the structure. The change of appearance through discoloration and fading is usually judged by changes in color tone and gloss. These properties are expressed by numerical values of visual factors. Quantitative evaluation may not always be valid, but serves to indicate discoloration and fading due to exposure and stain in air. In the test, the discoloration and fading characteristics of fluoropolymer were determined by the accelerated outdoor exposure test method EMMAQUA.

5.2 Discoloration and fading characteristics

5.2.1 Color tone change

Fig. 7 shows test results on changes in color tone. The difference of color tone before and after the test was measured by a color difference meter and indicated by the color difference ΔE, according to Lab system of the color difference representation method specified in JIS Z 8730. The color tone variation practically depends on the weather resistance property of pigments added to the fluoropolymer. Generally, inorganic pigments are less liable to change in color and tone than organic ones. The present test measured the red, blue, green, gray, brown, yellow, and white colors. An organic pigment was used only for the red color.

From **Fig. 7**, it is evident that the red color suddenly changes at an ultraviolet radiation dose of about 2,000 MJ/m^2 and has the largest color variability among the colors tested. This is probably due to the use of the organic pigment, which is in line with the general tendency. Each of the other colors has a very small color difference ΔE of less than 5 at the ultraviolet radiation dose of 2,500 MJ/m^2 and is very stable. If these results are utilized to design pigments and stable color tones, colored fluoropolymers can work with a minimum of discoloration and fading over a long period of service.

5.2.2 Gloss change

Fig. 8 shows the measured results of changes in gloss. The gloss variation was measured by a gloss meter as gloss difference (60° specular reflectance) before and after the test and was determined by the specular glossiness measuring method specified in JIS Z 8741.

As evident from **Fig. 8**, the colored fluoropolymer changes little in gloss even after 2,500 MJ/m^2 of ultraviolet radiation, and demonstrates a very stable gloss retention of more than 95%. Even the red color that has the greatest tone change is no lower than the other colors in gloss retention. This is probably because the gloss change depends chiefly on material properties, and because the fluoropolymer itself is superior in weather resistance and gloss retention.

5.3 Stain resistance

Another factor responsible for visual degradation is apparent change and fading in color due to the deposition of air pollutants. The staining property widely varies with environmental conditions and is difficult to evenly evaluate. The colored fluoropolymer resins were exposed and tested for the change of color tone in a Tokyo industrial center known for highly staining environment.

Almost all the colored fluoropolymer resins were stained to a saturation point in three months of exposure, whereafter they remained without any appreciable change in color tone. The rate of tone change varies from color to color, and the apparent color difference ΔE ranges from about 3 to 12. Dark brown colors are relatively low in the rate of tone change. Similar data obtained in coastal and mountain regions are not presumed to surpass these data of the Tokyo industrial center.

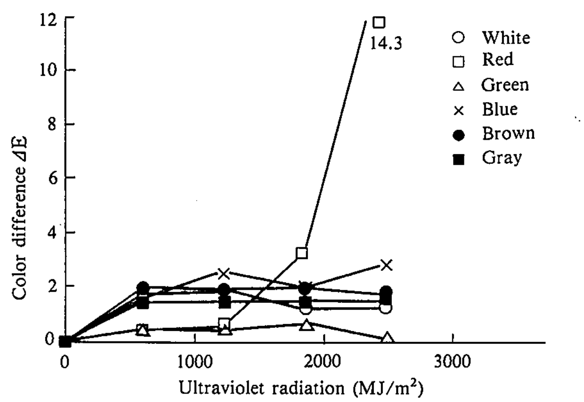

Fig. 7 Discoloration and fading characteristics of colored fluoropolymer

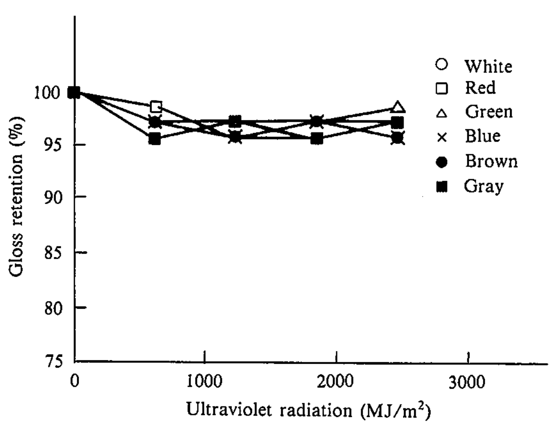

Fig. 8 Gloss change of colored fluoropolymer

Once the stains were cleaned, little or no more tone change was observed, and the color difference ΔE fell to about 1 or close to the original value. Fluoropolymer resins are so high in non-tackiness and chemical resistance that their contaminants can be easily removed by cleaning. This is because the stain remains on their surfaces and hardly penetrates into their bulk. When colored fluoropolymers change in appearance due to environmental staining, they can be restored to the original condition with relative ease by washing and other measures. This indicates that colored fluoropolymer coating is extremely advantageous over painting in long-term maintenance and control.

6. Structural Characteristics of Color Cable

6.1 Bending characteristics

The color cable is coated in two layers. The inner layer is polyethylene, and the outer is fluoropolymer. The fluoropolymer can be sufficiently colored to a thickness of about 1 mm, but the coating thickness must be determined from the considerations of bendability during fabrication, installation, and external damage resistance as well.

To determine the bending characteristics of the colored fluoropolymer coating, three types of color cables were bend tested (see **Photo 3** and **Table 3**). When the color cables were bent to a D/d (cable bend diameter versus cable outside diameter) of about 10, they showed no such deformation as buckling. When unloaded, they returned to the original condition and retained no harmful deformation. If the fluoropolymer coating thickness is about 2 mm, the color cables can be successfully bent to a D/d ratio of about 18 during fabrication and installation.

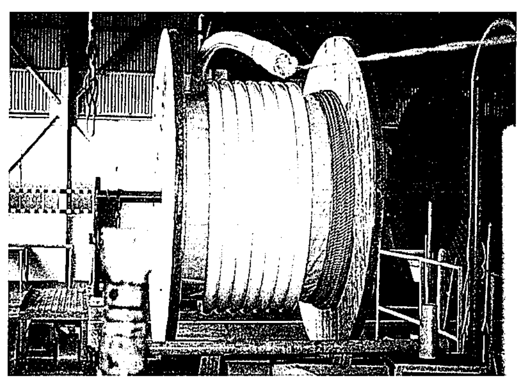

Photo 3 Color cable bending test

Table 3 Color cable bending test dimension

Item	Cable size		
	31 wires in 7-mmϕ each	55 wires in 7-mmϕ each	139 wires in 7-mmϕ each
Strand diameter (mm)	44	58	92
Polyethylene coating thickness (mm)	7	7	9
Cable outside diameter d (mm)	58	72	110
Fluoropolymer coating thickness (mm)	1.1	1.1	1.3
Maximum bend diameter D (mm)	440	580	1070

6.2 Clamping characteristics

Cables may be clamped during installation or against vibration after installation. The clamp design needs determining the coefficient of friction between the color cable and the clamp.

The color cable was fit with a clamp and slip tested by changing the clamping contact pressure in the axial direction (see **Photo 4**). When the contact pressure is from about 30 to 100 kgf/cm^2, the coefficient of friction calculated from the maximum slip load is 0.16 to 0.25, a value approximately equal to that for polyethylene-coated cables (see **Table 4**)[10]. A rubber sleeve is considered effective in ensuring the desired coefficient of friction between the clamp and the fluoropolymer coating as well as in protecting the surface of the fluoropolymer coating.

6.3 External damage resistance

To determine its external damage resistance, the color cable was put to the drop weight test according to JIS C 3005 (impact test) as shown in **Fig. 9**. The color cable was composed of 55 wires of 7 mm diameter, coated with 7 mm of polyethylene and 2 mm of fluoropolymer, and 76 mm in outside diameter. The fluoropolymer coating did not rupture when tested with a drop weight of 20 kgf and drop height of 2 m.

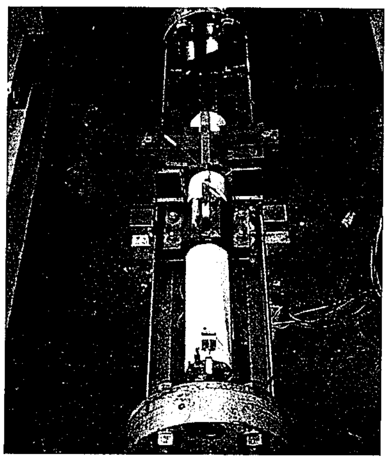

Photo 4 Coefficient of friction test for color cable

Table 4 Coefficient of friction of color cable

Specimen	Contact pressure (kgf/cm^2)	Maximum load (tf)	Coefficient of friction μ	Remarks (rubber sleeve)
No. 1	32.9	10.8	0.25	Yes
No. 2	50.2	15.5	0.23	Yes
No. 3	94.3	20.2	0.16	Yes

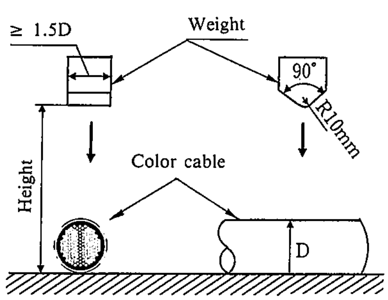

Fig. 9 Drop weight test for color cable

The color cable was evaluated for the progress of damage by assuming that it sustained some damage during installation. A 300 mm long color cable specimen was cut with a notch 1 mm in depth (a half of the coating thickness) or 2 mm in depth (penetration) and 50 mm in length (in the axial and circumferential directions) and was put to thermal shock test between −20°C and +80°C. After 100 8-h cycles, the color cable showed no external damage propagation a cracks and was proved to have sufficiently high external damage durability.

6.4 Repairability

The color cables are shipped in a packaged condition for protection, but are subject to damages by pulling and unreeling during installation. Their repairability was also studied.

Fluoropolymer's melting point is slightly higher than that of polyethylene, but any damage in the fluoropolymer coating can be easily repaired by applying a piece of the same fluoropolymer while heating with a hot-air fan.

To verify the quality of color cable repairs, totally and partly repaired color cable specimens were subjected to thermal cycling test. The test that consisted of 100 8-h cycles between −20°C and +80°C, revealed no abnormality in the repairs, and confirmed the effectiveness of the repairing method.

7. Conclusions

Given their size and shape, bridges have a large impact on the surrounding landscape. Now that great importance is attached to their aesthetic effect in combination with the environment, bridges must be given a greater freedom of color selection. This is true particularly with the cable-stayed bridges that are built in increasing numbers recently for their outstanding beauty with the use of color cables (see **Table 5**).

Color cables are coated with colored fluoropolymer resin to make the most of its excellent weather resistance. The colored fluoropolymer coating ensures not only the aesthetic effect of

Table 5 Field-proven color cable fabrications

Bridge	Bridge type	Length (m)	Owner	Cable data
Mihama Pedestrian Bridge	Cable-stayed	62	Urayasu City	NEW-PWS 31 Gray
Asunaro Overbridge	Cable-stayed	79	East Japan Railway	NEW-PWS 73 Beige
Nakajimagawa Bridge	Nielsen	157	Hanshin Expressway Public Corporation	NEW-PWS 187 Beige
Yliston Bridge	Cable-stayed	192	Finland	NEW-PWS 31 White
Tokimeki Bridge	Cable-stayed	200	Japan Highway Public Corporation	NEW-PWS 199 White
Toyomi Bridge	Cable-stayed	300	Okinawa Development Agency	NEW-PWS 283 White
Gamagori Speedboat Racecourse	Suspension Structure	30	Gamagori City	NEW-PWS 73 White, etc.
Shirakobato Bridge	Cable-stayed	145	Koshigaya City	NEW-PWS 73 White
Oya Bridge	Cable-stayed	23	Kitakyushu City	NEW-PWS 109 White

the bridge against the surrounding landscape, but also its long service life. Long-spanned bridges must last 50 to 100 years and must retain high functionality and durability throughout the period. Color cables are ideal for such bridges. As the need for aesthetic design is likely to increase in the future, the authors intend to continue on the development of color cable technology with a view to expanding its applications to bridges and other suspension structures.

References

1) Institute of Electrical Engineers of Japan: Degradation of Polymers. Corona Publishing, 1960
2) Japan Fluoropolymers Industry Association: Fluoropolymers. June 1970
3) Negishi, A.: Chemistry of Fluorine. Maruzen, 1988
4) Zerlaut, G.A. et al.: Accelerated Outdoor Exposure Testing of Coating by the EMMAQUA Test Method. ECCA Annual Congress, November 1984
5) Abe, K.: Properties and Applications of Polyvinylidene Fluoride (Kynar). Plastic Age. January 1984
6) Du Pont-Mitsui Fluorochemicals: Teflon Application Handbook. 1984
7) Hojo, T. et al.: A study on Weathering Durability of Fluoropolymer. Japan Society of Civil Engineers. (480), VI-21 (1993)
8) Nireki, A. et al.: Proposal for Solar Radiation Dose in Ultraviolet Region in Japan. Journal of Structural and Construction Engineering. (381), 17 (1987)
9) Kijima, Y.: Super Accelerated Weathering Test of Plastic Materials. Plastic Age. 33 (11), 143 (1987)
10) Tawaraya, Y. et al.: Development of NEW-PWS for Cable-Stayed Bridges and Its Practical Application. Seitetsu Kenkyû. (332), 13 (1989)