Development of a Halogen-free Insulation Material for Overseas Railway Rolling Stock Lightweight Electric Wire

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ABSTRACT Electric wire for overseas railway rolling stocks is requiring a high abrasion resistance, in addition to a vertical flame resistance, a high heat resistance and a high temperature oil resistance, to withstand vibration and other conditions experienced during railway operation. On the other hand, a thinning of the wire insulation materials is desired for further reduction in weight of railway rolling stocks. Generally, engineering plastic is used as an insulation material, but it has issues with its flexibility and its wire stripability.

Using general-purpose polyolefin as a base material for the insulation material and adopting our own technique of polymer materials this time, we have successfully developed a halogen-free insulation material which is also superior in flexibility and in wire stripability, in addition to characteristics equivalent to those of the engineering plastic, and which is reduced its thickness compared to conventional electric wire, and therefore can achieve a reduction of approximately 15-35 % in weight.

1. INTRODUCTION

In recent years, while a concern about environmental issues grows in the world, rail transportation has a less energy consumption and less carbon dioxide emissions than other means of transportation. Therefore, it draws the attention as an eco-friendly mean of transportation, and the current worldwide market size related to railway is as large as 14 trillion and continues to grow at an annual rate of about 2-3%.[1] Especially, improvements of railway systems are currently pursued in overseas markets mainly in Europe and in Asia, and subsequently, it is expected that the railway construction will accelerate in South America and in the continent of Africa. Insuch situation, demands for various components which are used in the railway rolling stocks will increase, and it is estimated that business related to the railway rolling stocks will grow larger in the future.

For the future development of the railway rolling stocks, the weight reduction of the railway rolling stock body is also discussed.[2] When the railway rolling stock is reduced in weight, not only further energy saving and speeding up of railway are expected, but also preventing noise and less loading to the rails and others will be provided, and an attenuating effect for the truck maintenance work are also expected. Therefore, as the purpose of weight reduction on the electric wire for the railway, further thinning of wire insulation material thickness is considered.

In the above the context, in the area of the wires for railway rolling stock, this time, we have focused on the light weight electric wire which is used mainly for railway signals and have developed its new insulation material.

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2. ELECTRIC WIRE DEVELOPED FOR OVERSEAS RAILWAY ROLLING STOCK

The electric wires for overseas railway rolling stock mainly in Europe and in Asia are required, in addition to the thinning of the wire insulation material thickness, the high levels of abrasion resistance, the vertical flame resistance and the high temperature oil resistance which comply with an EN Standard (European Norm, European Standard) to withstand the vibration experienced during the railway construction or the railway operation. Therefore, the engineering plastic which is superior in its strength properties and in its heat resistance have been used as a base material. However, such material is generally rigid and poor in flexibility, and it has been considered that its wiring to the thin part of the railway rolling stocks and its included components have been difficult.

This time, we have developed a new polymer material made entirely of a general-purpose polyolefin resin, without using an engineering plastic. By using it as the insulation material for the electric wire, it complies with the mechanical properties, such as abrasion resistance, heat resistance, high temperature oil resistance and others, which meet requirements of EN 50264-3-1and EN 50306-2 which are the standards for electric wires with thin-walled insulation and right weight, vertical flame resistance of IEC 60332-3-24, Category C (EN 50264-1) and low smoke generation property and others of IEC 61034 (EN 50264-1). Additionally, we have developed an insulation material for the railway rolling stock light weight electric wire, which has an advantage in the flexibility and the stripability of terminals which are concerning issues for the conventionally used engineering plastic.

3. CONSTRUCTION OF THE OVERSEAS RAILWAY ROLLING STOCK LIGHTWEIGHT ELECTRIC WIRE

The construction of the overseas railway rolling stock lightweight electric wire is shown in Table 1. The insulation thickness of this electric wire is 0.4 mm, which is approximately 1/2 of thickness compared with that of the conventional railway rolling stock electric wire. Therefore, the electric wire is reduced in weight and has a construction accommodated to the energy saving. At the same time, since the insulation thickness becomes thinner, the insulation material requires various tough properties such as a further higher strength, a higher level of abrasion resistance and other properties.

Table 1 Structure of the lightweight electric wire developed for the overseas railway rolling stock.

Conductor		Insulation thickness (mm)	Overall diameter (mm)
Nominal cross-section area (mm^2)	Conductor diameter (mm)		
0.30	0.7	0.4	1.5 ± 0.2
0.50	0.9	0.4	1.7 ± 0.2
0.75	1.1	0.4	1.9 ± 0.2
1.00	1.3	0.4	2.1 ± 0.2
1.25	1.5	0.4	2.3 ± 0.2
1.50	1.6	0.4	2.4 ± 0.2
2.00	1.8	0.4	2.6 ± 0.2
2.50	2.2	0.4	3.0 ± 0.2

4. THE REQUIRED PROPERTIES AND THE TEST METHODS FOR THE INSULATION MATERIALS FOR THE OVERSEAS RAILWAY ROLLING STOCK ELECTRIC WIRE

4.1 Hot-set Test

As per EN Standard (EN 50264-3-1 and EN 50306-2), it is required to meet the hot-set property as the evaluation method to confirm that the insulation material of the electric wire maintains its strength without melting at high temperature. The method of the hot-set test is shown in Figure 1. In accordance with EN 50305, the test was conducted such that the tubular test sample is kept in a high temperature environment of 200℃ for 15 minutes, with the suspension of a load weight of 20 N/cm^2. To pass the test, the sample is required that the limit of elongation between gage points must be ≦100% after 15 minutes and also that the limit of permanent elongation between the gage points after the load is removed, must be ≦25%.

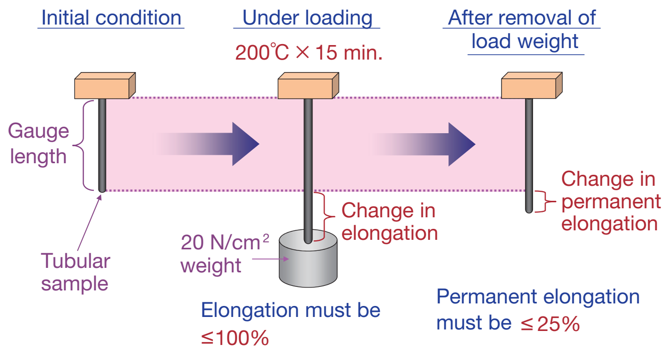


Figure 1 Hot-set test.

4.2 Abrasion Resistance Test

The present insulation material is required to meet the abrasion resistance test conducted in accordance with EN 50305. This test method is shown in Figure 2. This test was conducted in such a manner that the load weight of 9 N was applied on the horizontally set electric wire sample and the insulation material was abraded by using a steel blade of 0.45 mm diameter. The blade continuously ran back and forth until it reached the conductor of the test sample. Abraded parts were 4 sections in total as circumferential direction of 90, 180, 270, and 360 degree for each sample. EN 50306-2 requires ≧100 cycles per each section and ≧150 cycles in average of the 4 sections.

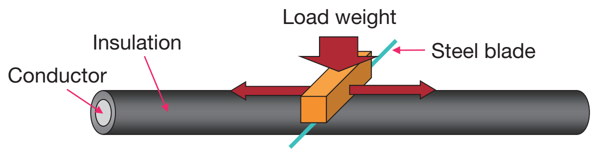


Figure 2 Abrasion resistance test.

4.3 Vertical Flame Resistance Test

The present insulation material is required to meet the vertical flame resistance test conducted in accordance with the flame resistance of IEC60332-3-24, Category C (EN 50264-1). This test method is shown in Figure 3. As shown in Figure 3, the electric wire samples trimmed at a length of 3500 mm were vertically installed with no space in-between. The bottoms of the samples were exposed to ignite for 20 minutes by a burner, and then the flame was removed and the samples were left until the fire self-extinguished. The sample passes the test if the length of the charred section from the burner ignition point is 2500 mm or less after the fire has completely extinguished itself.

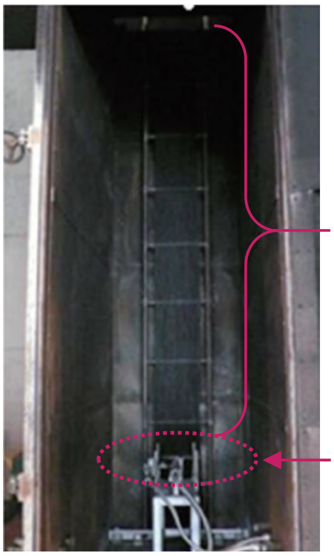


Figure 3 **Vertical flame resistance test in accordance with IEC60332-3-24, Category C.**

4.4 Smoke Generation Property Test

The present insulation material is required to meet the 3 m cube smoke test conducted in accordance with IEC61034 (EN 50264-1) for its smoke generation property. The samples trimmed at a length of 1000 mm were burned for 40 minutes by a burner in the 3 m cube test chamber. Light transmissibility in the test chamber which is filled with smoke generated from the insulation material, was measured. The sample passes the test if this light transmissibility is 70% or more.

4.5 High Temperature Oil Resistance Test

The present insulation material is required to meet the high temperature oil resistance test defined by EN 50305. The test was conducted in such a manner that the tubular insulation material was immersed for 24 hours and 72 hours in the oil of ASTM IRM 902 which was already 100℃ hot, and then the tensile test was carried out. The sample passes the test if the each residual of the tensile strength and residual of the elongation at break is within the range of 70-130% and 60-140% respectively, after a 24 hours immersion for the standard oil resistance of EN 50264-3-1 and after a 72 hours immersion for the special oil resistance of EN 50264-3-1.

4.6 Long-term Heat Resistance Test

The present insulation material is required a long-term heat resistance at 105℃ or higher temperature. The heat aging test is conducted usually at more than three different temperatures and a long-term heat resistant temperature is determined by the Arrhenius plot from the ending points of each temperature. The heat aging test for this time was conducted at the three points of 180, 158 and 133℃ and the time (ending point) on which the elongation, at break achieves 50% for each temperature, was investigated. The long-term heat resistant temperature was calculated for 20,000 hours by the Arrhenius plot from the ending points of each temperature.

4.7 Flexibility Test

An evaluation method of wire flexibility is shown in Figure 4. The electric wire was cut out in 280 mm length and both of the wire ends were connected to each other to make a loop. The looped sample was hanged on a mandrel of 4.0 mm diameter and suspended a load weight of 3.4 N.

The flexibility of the electric wire was measured by measuring the minor axis diameter of the looped sample suspended with the load weight. As short as the minor axis diameter of the looped electric wire is, as flexible the wire.

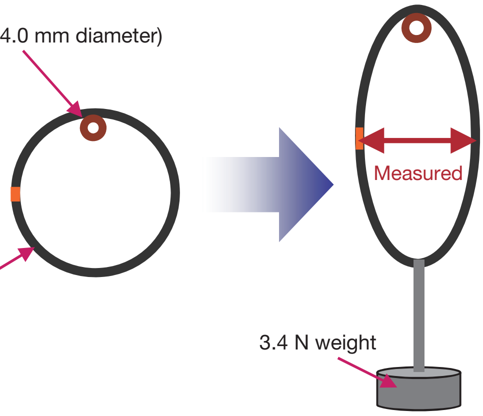


Figure 4 **Evaluation of wire flexibility.**

5. DEVELOPMENT OF THE POLYMER MATERIAL WHICH MEETS THE REQUIRED PROPERTIES IN ACCORDANCE WITH EN STANDARD

For the required properties in accordance with EN Standard of section 4 of the above, we have developed the insulation material for overseas railway rolling stock, from a general-purpose polyolefin resin. The present material development is described in the followings.

First, in the case that a general-purpose polyolefin resin is provided to the hot-set test at 200℃, and since the melting point of the polypropylene resin is around 160℃ even though it is the highest melting point in polyolefin, the resin melts in a short period and can not comply with the EN Standard. Therefore, we have provided electron beam cross-linking to the general-purpose polyolefin resin for this time.

Secondly, abrasion resistance property is described. To improve the abrasion resistance, the usage of a high-density polyolefin resin and a cross-linking treatment such as electron beam cross-linking are effective, however the high-density polyolefin is generally rigid and its flexibility is of concern. Although the present insulation material also requires a flame resistance, such high-density resin has a low acceptability of fillers such as flame retardant, and it is difficult to provide a sufficient flame resistance. Therefore, to ensure the flexibility and the acceptability of fillers, it is necessary to select the resin, ethylene-based polymer (for example, ethylene-vinyl acetate copolymer, EVA) or others with a certain level of low-density. However, these materials are inferior in mechanical strength. Also, even if an electron beam cross-linking is provided to these materials, it is difficult to provide the abrasion resistance property of EN Standard. Therefore, we adopted the new cross-linking technique of our own that ionically-bonds polymer and metal hydroxide as a flame retardant (Figure 5). With this technique, it is possible to provide the hardness of an inorganic filler to polymer, and to improve substantially the abrasion resistance property. Also, this technique can improve the abrasion resistance property if the introduction amount of the metal hydroxide is large at some level, therefore a high-level of flame resistance property can be additionally reached. Although the technique has been used mainly for high-strength wires of electronic devices and automobile, we provided cross-linking which is more stable for the current development than of those products.

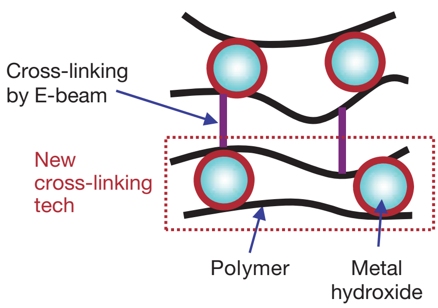


Figure 5 New cross-linking technique.

For high temperature oil resistance at 100℃, as shown in Figure 6, it is considered that no collapse in the crystallinity of the polymer structure is necessary. Therefore, we focused on the polymer structure at high temperature and selected the base material which does not collapse in crystallinity of the polymer structure and has no oil penetration at 100℃.

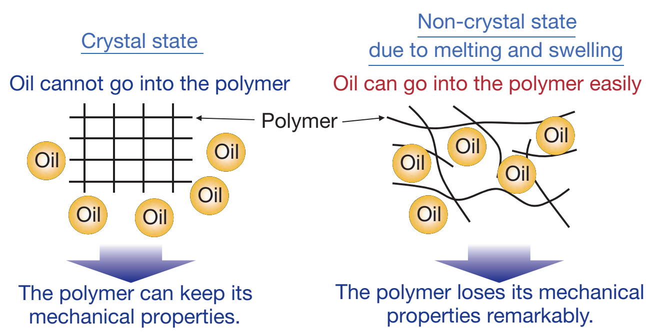


Figure 6 Schematic illustration of the structure of polyolefin at high temperature.

For long-term heat resistance, we adopted the heat resistance technique which we had developed so far with the electric wires for electronic devices and industrial cables.

The above polymer techniques compiled are shown in Figure 7. The present insulation material substantially incorporates our polymer technique in addition to the complex cross-linking technique of electron beam cross-linking and our own new cross-linking.

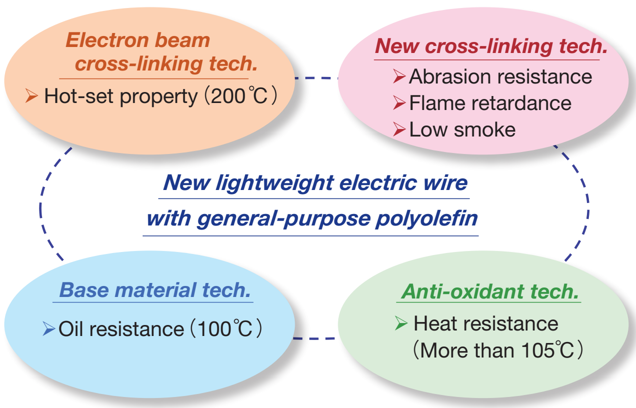


Figure 7 A wide variety of material techniques on the insulation material for railway rolling stock electric wire.

6. RESULTS AND CONSIDERATION

6.1 Hot-set Test

The hot-set test results are shown in Table 2, with non-cross-linking polyolefin material.

Table 2 Results of hot-set tests.

	Requirement	Compared material (non-cross-linking)	Developed material (electron beam cross-linking)
Under loading (%)	≦100	NG with melting	22.6
After load is removed (%)	≦25	NG with melting	8.6

While the non-cross-linking material melted in a short period under the environment of 200℃, on the other hand, our developed material succeeded to meet the hot-set property with providing our own electron beam cross-linking to the polyolefin.

6.2 Abrasion Resistance Test

Result of the abrasion resistance test which was conducted in accordance with the method specified in EN 50305 is shown in Figure 8. The test results, of the conventional electric wire used engineering plastic as the insulation materials for overseas railway rolling stock, and of the electric wire used polyolefin material which is not using the new cross-linking technique, are shown together for comparison purposes.

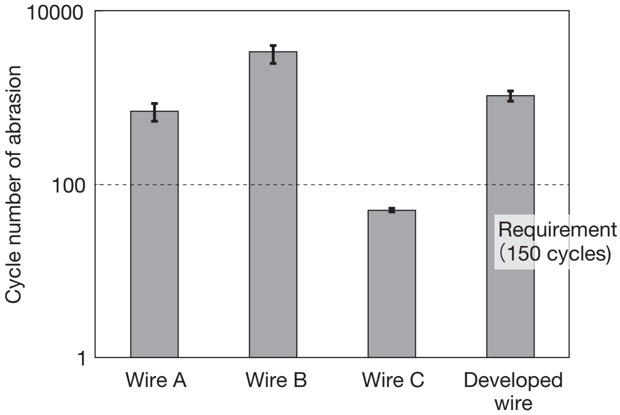


Figure 8 Results of the abrasion resistance tests in accordance with EN 50305 with 0.45 mm diameter steel blade and a load of 9 N.

The conventional electric wires, using engineering plastic as the insulation material for overseas railway rolling stock, are Wire A and Wire B. The electric wire using the polyolefin material which is not using the new cross-linking technique is Wire C. The average cycle number of Wire C which did not adopt the new cross-linking technique is about 50 cycles and it is significantly inferior in its abrasion resistance. This can be considered that the inorganic filler itself contributes to the abrasion of the polymer because the polymer and the inorganic filler are not bonded. On the other hand, using the material adopting the new cross-linking technique, the average cycle number of the wire is improved up to approximately 1000 cycles and it can be seen that the target value of 150 cycles is well satisfied. As just described, it can be seen that the developed material which is adopting the new cross-linking technique has the abrasion resistance specified in EN50306-2 and is comparable to the electric wires using engineering plastic for overseas railway rolling stock (Wire A and Wire B).

6.3 Vertical Flame Resistance Property

The results of the vertical multiple wire flame resistance test in accordance with IEC60332-3-24, Category C are shown in Figure 9.

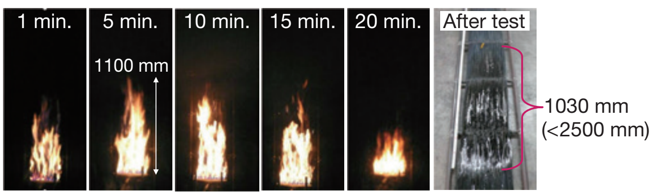


Figure 9 Result of the vertical flame resistance test in accordance with IEC 60332-3-24, Category C.

The height of the flame became 1100 mm in 5 minutes after being ignited, however the fire didn't spread more than that. Also, the time for sustaining flame after the burner is removed was only 90 seconds and the fire self-extinguished. The length of the charred section after the test was 1030 mm. For such vertical multiple wire flame resistance test a high level of flame resistance is required, therefore it is typical to use red phosphorus together as a flame retardant. Alternatively, a flame retardant, such as metal hydroxide, is needed to be added in large amounts; however such prescription significantly impairs mechanical properties such as the abrasion resistance in general. Using the new cross-linking which tightly bonds the polymer and the metal hydroxide, it is confirmed that the high level of flame resistance as well as the superior abrasion resistance can be achieved simultaneously.

6.4 Smoke Generation Property Test

The result of the smoke generation property test in accordance with IEC 61034 is shown in Table 3. Test result of a wire insulated with the material which is adopting 5 pts. mass of red phosphorus against 100 pts. mass of a base resin is also shown in the Table 3 for comparison purposes. From the result of the smoke generation property test, it is found that the wire with the material which used the red phosphorus has 35.4% of light transmissibility and does not meet the standard. To meet the vertical multiple wire flame resistance, the red phosphorus is generally used, however it is found that the wire cannot meet the EN Standard if the present wire is using it. On the other hand, the wire which uses the present developed material has 86.4% of light transmissibility after the flame test and it sufficiently exceeds 70% of light transmissibility as required by the standard. That is, it is confirmed that even if the insulation material burns, the smoke generation is low. With the low smoke generation property, under an enclosed space, for example subway, there is no smoke generation even though the fire breaks of railway rolling stocks occur. Therefore it facilitates the evacuation and the fire fighting without reducing the visibility in the surroundings.

Table 3 Results of the smoke generation tests.

	Requirement	Compared material (5 pts. mass of red phosphorus)	Developed material (no red phosphorus)
Light transmissibility(%)	≧70	35.4	86.4

6.5 High Temperature Oil Resistance Property

The result of the high temperature oil resistance test is shown in Table 4. The halogen-free electric wires (Wire D, Wire E) which are constructed with insulation material based on the polyolefin resin and which have the typical vertical flame resistance were simultaneously measured.

When the typical polyolefin based insulation material is immersed in oil at 100℃, it loses its crystallinity and swells. Therefore, its mechanical properties become significantly low. On the other hand, for the insulation material of the present electric wire, the crystallinity of its polymer is stable without collapse at high temperature, therefore it is confirmed that oil does not penetrate into the polymer and it is superior in its oil resistance. It is also found that the present developed material meets a tougher special oil resistance as well as a standard oil resistance of EN 50264-3-1.

Table 4 Results of the high temperature oil resistance.

	Requirement	Wire D	Wire E	Developed wire
Standard oil resistance of EN50264-3-1				
ASTM IRM902, at 100℃ for 24 hours				
Residual of tensile strength (%)	70 — 130	40	57	82
Residual of elongation at break (%)	60 — 140	111	167	86
Special standard oil resistance of EN50264-3-1				
ASTM IRM902, at 100℃ for 72 hours				
Residual of tensile strength (%)	70 — 130	—	—	90
Residual of elongation at break (%)	60 — 140	—	—	111

6.6 Long-term Heat Resistance Property

The result of the long-term heat resistance, in 20,000 hours, which is calculated by using the Arrhenius plot, is shown in Figure 10. Continuous operating temperature of the wire with insulation material which is adopting our heat resistance technique is 113℃ and it is confirmed that it sufficiently meets the 105℃ of the standard.

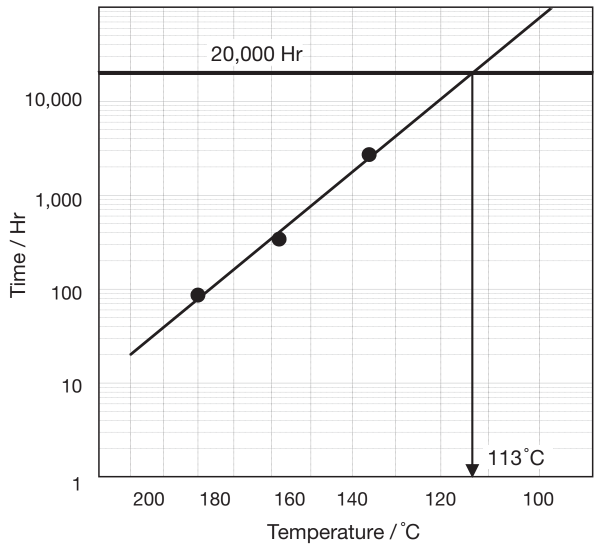


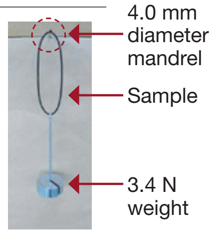
Figure 10 Evaluation of the heat resistance temperature by using Arrhenius plot.

6.7 Flexibility Test

The result of the flexibility evaluation is shown in Table 5. The results of the wires (Wire A, Wire B) for the conventional overseas railway rolling stock, which uses engineering plastic as an insulation material, are shown for the purpose of comparison.

As just described, it is confirmed that the developed wire is significantly superior in its flexibility, compared with the wire which is using engineering plastic as an insulation material. That is, it suggests that the wiring to the thin parts of the railway rolling stocks' inside and its included components contained on becomes easier than ever before.

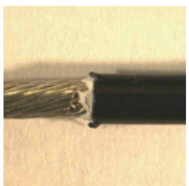
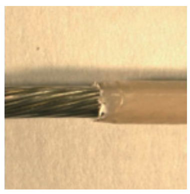
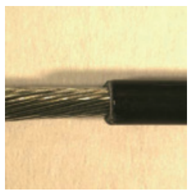
Table 5 Evaluation of the wire flexibility.

	Wire A	Wire B	Developed Wire
Photographs of the flexibility evaluation with 3.4 N load weight			
Before test (mm)	84	84	84
With 3.4 N weight (mm)	62	57	37

6.8 Evaluation of the Wire Stripability by General Insulation Striper

The evaluation results of the stripability by general insulation striper for each wire are shown in Table 6.

Table 6 Evaluation of the wire stripability by general insulation striper.

Wire A	Wire B	Developed Wire
		

The results of the wires (Wire A, Wire B) for conventional overseas railway rolling stock, which uses engineering plastic as an insulation material, are shown for the purpose of comparison.

The wire which uses the developed material has no leaving, such as burrs at the stripped cutting site and is significantly superior in its stripability.

6.9 Other Properties

It is found that the results of evaluating other properties for the wire which uses the material developed in accordance with the relevant EN Standards are shown in Table 7.

Table 7 Properties of the lightweight electric wire developed for overseas railway rolling stock.

Test item	Relevant standard	Requirement	Developed Wire
Tensile strength (MPa)	EN 50264-3-1	≧10	25
Elongation at break (%)		≧150	167
Heat aging test	EN 50264-3-1		
at135℃ for 168 hours			
Residual tensile strength (%)		70－130	112
Residual elongation at break (%)		70－130	93
Flame resistance	EN 50264-3-1		
ASTM IRM903, at 70℃ for 168 hours			
Tensile strength (%)		70－130	92
Elongation at break (%)		60－140	99
Acid resistance	EN 50264-3-1		
0.5 mol of oxalic acid aqueous solution, at 23℃ for 168 hours			
Residual tensile strength (%)		≧70	91
Elongation at break (%)		≧100	183
Alkali resistance	EN 50264-3-1		
1.0 mol of sodium hydroxide solution, at 23℃ for 168 hours			
Residual tensile strength (%)		≧70	91
Elongation at break (%)		≧100	183
Bending test at low temperature at -40℃	EN 50264-3-1	No cracks	Pass
Impact test at low temperature at -25℃	EN 50264-3-1	No cracks	Pass
Dynamic cut-through (N)	EN 50264-3-1	≧100	123
Ozone resistance	EN 50264-3-1	No cracks	Pass
Notch propagation	EN 50306-2		
at -15℃ for 3 hours → 1.0 kV for 1 minute		No breakdown	Pass
at 20℃ for 3 hours → 1.0 kV for 1 minute		No breakdown	Pass
at 85℃ for 3 hours → 1.0 kV for 1 minute		No breakdown	Pass
Flexibility (°)	EN 50306-2		
at 20℃ for 72 hours, 15 N		＜45	34.7
Shrinkage (mm)	EN 50306-2		
300 mm, at 150℃ for 1 minute → 20℃		＜1.5	0.33
Stress cracking	EN 50306-2		
at 160℃ for 168 hours, Cone type mandrel → 1.5 kV for 1 minute		No insulation breaking	Pass
Blocking of core	EN 50306-2		
at 150℃ for 168 hours, Adhesion with PTFE		No damage on external layer	Pass

It is found that the developed wire was superior in properties such as mechanical property, heat resistance, abrasion resistance, oil resistance, chemical resistance, low-temperature capability, flame resistance, smoke generation property and flexibility, and met the EN Standard required for the electric wire of railway rolling stock. The thickness of its insulation was reduced to 1/2 comparing with that of the conventional wire, and it was successful in the reduction of approximately 15-35% of its weight.

7. CONCLUSION

We have developed a halogen-free insulation material for overseas railway rolling stock lightweight electric wire by using a variety of our own polymer material technique based on general-purpose polyolefin resin. Using this material as an insulation material, not only it meets the properties complying with EN Standards, but also the insulation thickness can be thinner than that of the conventional electric wire. Therefore it is possible to obtain the wire that meets the energy saving which suits the needs of weight reduction in the railway rolling stock development in the future. Since this developed material consists of a general-purpose polyolefin resin, it is superior in its flexibility to the conventional electric wire for overseas railway rolling stock which uses engineering plastic and also superior in its stripability. Therefore, it can be stated that it is superior in mass productivity and in wiring workability for the practical assembling of rolling stocks and various components that it include.

The electric wire adopting this developed material can be expected to be in high demand as a lightweight electric wire for overseas railway rolling stock in the future.

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