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Development of material formula and structure property indicators for low cold-resistant characterization of Cables' Material

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Abstract. Alpine regions account for about 27.9% of total land area in China. Northeast China, Inner Mongolia, Northwest China and other regions are located in alpine regions, wherein the above regions are rich in energy. However, the low-temperature impact embrittlement temperature of traditional PVC cable materials is between -15℃ and -20℃, which is far lower than actual operation requirements. Cable insulation and sheath are always damaged during cable laying in alpine regions. Therefore, it is urgent to develop low-temperature-resistant cables applicable to low-temperature environment in alpine regions, and safe and stable operation of power grids in the alpine regions can be guaranteed. In the paper, cold-resistant PVC formula systems were mainly trial-manufactured and studied. Appropriate production technologies and formulas were determined through selecting raw materials and modified materials. The low-temperature impact embrittlement temperature was adjusted below -50℃ under the precondition that PVC cable materials met national standard property requirements. Cold-resistant PVC cable materials were prepared, which were characterized by excellent physical and mechanical properties, and sound extrusion process, and cold-resistant PVC cable materials can meet production requirements of low-temperature-resistant cables. Meanwhile, the prepared cold-resistant cable material was used for extruding finished product cables and trial-manufacturing sample cables. Type tests of low temperature elongation ratio, 15min withstand voltage, etc. were completed for 35kV and lower sample cables in Mohe Low-temperature Test Site. All properties were consistent with standard requirements.

1. Introduction

Alpine regions account for about 27.9% of total land area in China. Cable insulation and sheath are always damaged during cable laying due to influence of high-cold climate. Cable cracking and strand breaking are available sometimes, thereby directly threatening safe and stable operation of the power grid. with implementation of global energy interconnection and 'Arctic Circle and Equator' strategy. UHV project goes through alpine region inevitably. Low temperature environment of alpine region seriously affects safe operation of cable and other power transmission and transformation equipment as well as the reliability of the power grid. However, low-temperature impact embrittlement temperature of traditional PVC cable material is between -15℃ and -20℃, which is far less than actual operation requirements [1].

In the paper, cold-resistant PVC formula system was trial-manufactured and studied. The low-temperature embrittlement temperature was dropped below -50℃. Cold-resistant PVC cable materials with excellent physical and mechanical properties and sound extrusion process were prepared, wherein the production requirements of low-temperature-resistant cables were satisfied. The optimum cold-resistant cable processing technology meeting actual operation environment in the alpine regions were determined. 35kV and lower cold-resistant power cables and control cables were completed. Low temperature type tests of sample cables were completed in Mohe Low Temperature Test Site. All properties were consistent with standard requirements.

2. Research on cold-resistant cable material formula

2.1. Determination of research method and plan

Since there were no national standards about low-temperature-resistant PVC cable materials, related property indicators of low-temperature-resistant PVC cable materials were formulated in the paper according to GB/T8815-2008 'Soft Polyvinyl Chloride Plastic for Wires and Cables', wherein low-temperature impact embrittlement temperature was lower than PVC common cable materials by 30℃.

Strong interaction force among ordinary PVC molecules will lead to relatively poor low-temperature impact properties of cable materials. In addition, it is difficult for PVC products to produce relative displacement change in the case of external shock. External shock cannot be converted to internal friction heat, thereby leading to structure fracture of material ontology [2]. There are many methods to reduce PVC intermolecular forces. For example, a large amount of plasticizer, chlorinated polyethylene (CPE), etc. can be added. However, plasticizer is composed of low molecular weight organic compounds, which can precipitate out easily due to excessive addition. The plasticizer can be volatilized, thereby leading to anti-plasticization. The properties of the material are not substantially improved [3]. In comparison, chlorinated polyethylene is composed of high- molecular polymers. It is not necessary to consider precipitation, evaporation and similar problems. However, the vitrification temperature is above -10℃. Therefore, low-temperature impact properties also cannot be improved. In the paper, high molecular weight modified plastification material and cold-resistant plasticizer were selected for replacing a part of traditional plasticizer, thereby reaching the purposes of permanent plastification, no precipitation, migration resistance, etc. PVC intermolecular forces can be significantly reduced. Vitrification temperature can be greatly reduced. The following defects can be overcome, for example CPE has high vitrification temperature, plasticizer is prone to anti-plasticization, etc. Therefore, the technical key in the paper is shown as follows: the low-temperature impact embrittlement temperature is reduced to -50℃ or lower level on the basis of guaranteeing conventional properties of PVC cable materials.

2.2. Selection of base stock and additives

2.2.1 Screening of PVC resin. Currently, polyvinyl chloride resin with high polymerization degree has been widely used in cable material. However, it should be matched with low polymerization degree resin and modified material. Sheathing material: SH-200 (polyvinyl chloride resin with polymerization degree of 2500) was separately used as matrix resin. It was difficult to process the material although all property indicators reached the indicator requirements. The extruder load was relatively high in actual production, and materials even cannot be plasticized. S-1000 and SH-200 were mixed in use. The low-temperature impact embrittlement property of sheathing material can be as low as -40℃, while the low-temperature impact embrittlement property of insulation material can reach -35℃. Therefore, the requirements cannot be satisfied. WS-1300 and SH-200 were mixed. The low-temperature impact embrittlement properties of sheathing material and insulation material can meet requirements with excellent plasticization. They can be extruded for production. Insulation material: S-800 and S-1000 (polyvinyl chloride resin with polymerization degree of 800 and 1000) were separately used as matrix resin, and the low temperature property was unqualified. It can be matched with WS-1300 resin (polyvinyl chloride resin with polymerization degree of 1300), and the low temperature property was still unqualified. WS-1300 was separately used as matrix resin, and its low-temperature impact embrittlement property satisfied the requirements.

2.2.2 Screening of plasticizer. Plasticizer is a volatile substance. The plasticity can be improved, and the softness thereof can be improved by adding it into plastic. Plasticizer was added into high polymer for reducing the interaction force among resin molecules, thereby reducing resin softening temperature and melting temperature. The plasticizer cold-resistant property was determined by the structure composition. The plasticizer with excellent intermiscibility had relatively poor cold-resistant property. Especially when the plasticizer contained annular structure, cold - resistance was significantly reduced. On the contrary, aliphatic esters with straight chain methylene (-CH2-) as main body had better ability to resist coldness. The plasticizer with straight chain alkyl had strong ability to resist coldness. In addition, the alkyl chain was longer, the ability to resist coldness was stronger. If the alkyl branched chain was increased, the ability to resist coldness also can be worsened correspondingly [4]. The optimum plan was selected after comprehensive consideration. Dioctyl sebacate (DOS), dioctyl phthalate (DOP) was used asplasticizer of the sheathing material, and dioctyl sebacate (DOS), di-iso-decylphthalate (DIDP) and dioctyl terephthalate (DOTP) were used as plasticizer of the insulation material.

2.2.3 Screening of heat stabilizer. The addition of calcium/zinc compound stabilizer had certain influence on thermal stability time of sheathing material and insulation material. More calcium/zinc compound stabilizer was added, the thermal stability time of sheathing material and insulation material was longer, and the property was better. Main reason is shown as follows: calcium/zinc compound stabilizer can be added for inhibiting the decomposition of PVC effectively and allowing production proceed normally. If less stabilizer was added, the thermal stability time of the sheathing material and the insulation material was very short, thereby burning material during processing. It was impossible to continue production normally. In the formula, calcium/zinc compound stabilizer 8890 was finally selected as the formula system heat stabilizer of sheathing material and insulation material through rigorous screening.

2.2.4 Screening of lubricant. Lubricant is mainly used for improving the liquidity of the plastic melt. However, the shear friction effect of the compound can be greatly reduced if it is excessively used, thereby prolonging the plasticizing time prominently. It even cannot be melted and plasticized completely. Polyethylene wax has excellent thermostability and chemical resistance as lubricant. Its molecular structure belongs to a very long non-polar carbon chain with very stronger polar center. In the experiment, some parts in the polyethylene wax structure, compatible with PVC polarity, can play a role of internal lubrication. The parts with different polarity from PVC can play a role of external lubrication. Therefore, it can be used as lubricant of PVC pipes. Its lubrication principle is shown as follows: the friction of polymer melt and mold surface can be improved, thereby forming a lubrication film on the surface of finished products. Therefore, polyethylene wax was adopted as lubricant of the formula system during design of the formula.

2.2.5 Selection of low-temperature-resistant modified material. Selection of low-temperature-resistant modified material was the key to develop the product. Whether materials were selected correctly or not directly affected final properties of the material. Low-temperature-resistant modifier Elvaloy 4924 (ethylene-vinyl acetate carbonyl (E/VA/CO) copolymer) was used as modifier and dispersed in polyvinyl chloride matrix aiming at cold-resistant sheathing material. A net structure was formed. When the material suffered from external force shock, most energy was absorbed by the elastic

network structure, thereby further improving the material toughness [5]. The low temperature flexibility of polyvinyl chloride can be improved, and the embrittlement temperature can be lowered especially in low temperature environment, therefore excellent property thereof can be kept in continuous low temperature environment. Semi-crosslinked nitrile powder was selected with model P83. When P83 elastomer scattered in polyvinyl chloride matrix, P83 wrapped polyvinyl chloride, and P83 elastomer further formed a continuous net structure. When the material was subjected to strong external shock, the continuous net structure was acted, thereby absorbing most impact energy, preventing materials from serious damage, and protecting the material itself. Small molecule liquid plasticizer can easily migrate and precipitate especially in low temperature environment. However, high polymer solid plasticizer did not migrate and precipitate, thereby guaranteeing the low temperature flexibility of polyvinyl chloride and, improving the impact strength at low temperature.
Low-temperature-resistant modifier thermoplastic polyether urethane elastomer was added in cold-resistant insulation material for improving hardness, tensile property and low-temperature property of cold-resistant insulation material. Therefore, Polyether TPU elastomer was selected as modified material of cold-resistant insulation material suitably.

2.2.6 Selection of antioxidant and protective agent. Antioxidant and protective agent were introduced to inhibit or delay the oxidation of resin and elastomer. Meanwhile, oxidation of plasticizer also can be inhibited, thereby obtaining ideal anti-aging effect [6]. Bisphenol A was adopted in the formula system as antioxidant of the formula system. 4010NA was used as protective agent. After bisphenol A and 4010NA were added, the tensile strength change rate and breaking elongation change rate of the material were improved prominently according to experiment contrast. The material properties were better after aging. It indicates that the aging of PVC sheathing material and insulation material caused by oxygen effect also can be inhibited effectively by adding bisphenol A and 4010NA.

2.2.7 Screening of modified filler. Filler can reduce cost and improve some physical and mechanical properties aiming at PVC cable material. For example: calcium carbonate can improve thermostability and dimensional stability; pottery clay filler can improve electrical insulation property; antimony oxide filler can improve flame retardant property [7], etc. Commonly-used fillers of polyvinyl chloride cable materials include the follows: calcium carbonate, talcum powder, antimony oxide, pottery clay, magnesium hydroxide, aluminium hydroxide, glass fiber, barium sulfate, magnesium silicate, etc. In the paper, Nano calcium carbonate with surface treatment by silane coupling agent was adopted in the formula plan. Plasticizing behavior, mechanical property, etc. of PVC sheathing material and insulation material were improved greatly after addition of Nano calcium carbonate according to experiment contrast.

3. Determination of cold-resistant cable material formula and property test

3.1. Determination of formula system

The following materials were selected for test in research on PVC sheathing material and insulation material formula with low-temperature-resistance of -50℃ through analysis as well as material screening and comparison for many times.

Sheathing material formula plan: polyvinyl chloride resin (model SH-200) with polymerization degree of 2500, polyvinyl chloride resin with polymerization degree of 1300, dioctyl sebacate (DOS), dioctyl phthalate (DOP), calcium/zinc compound stabilizer 8890, polyethylene wax, low-temperature-resistant modifier Elvaloy 4924 (ethylene-vinyl acetate carbonyl (E/VA/CO) copolymer), nitrile rubber powder P83, bisphenol A, anti-aging agent 4010NA and modified Nano calcium carbonate.

3.2. Formula component

The optimum formula was selected through test and comparative analysis on a series of formula properties. The results are show in table 1 and table 2.

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Table 1. Optimum formula of PVC sheathing material with low-temperature resistance of -50℃.

Raw material	Name	Formula
PVC resin 1	SH-200 (polymerization degree 2500)	50
PVC resin 2	WS-1300 (polymerization degree 1300)	50
DOS	Dioctyl sebacate	15
DOP	Dioctyl phthalate	45
Stabilizer	Calcium/zinc compound stabilizer 8890	8
Lubricant	Polyethylene wax	1
Modifier 1	Elvaloy 4924	5
Modifier 2	P83	5
Antioxidant	Bisphenol A	1
Anti-aging agent	4010NA	1
Filler	Nano calcium carbonate	15

Table 2. Optimum formula of insulation material with low-temperature resistance of -50℃.

Raw material	Name	Formula
PVC resin	WS-1300 (polymerization degree 1300)	100
DOS	Dioctyl sebacate	15
DIDP	Di-iso-decylphthalate	10
DOTP	Dioctyl terephthalate	35
stabilizer	Calcium/zinc compound stabilizer 8890	7
Lubricant	Polyethylene wax	1
Modifier	Polyether TPU elastomer	10
Antioxidant	Bisphenol A	1
Anti-aging agent	4010NA	1
Filler	Nano calcium carbonate	15

3.3. property test

Cold-resistant polyvinyl chloride novel sheathing material formula and cold-resistant insulation material formula were determined through comprehensive study and screening of the above formula. The properties thereof were measured. The results are shown in table 3 and table 4.

Table 3. Measured characteristics of cold-resistant PVC sheathing material.

Content	Standard requirement	Experimental result
Tensile strength /MP	≥16.0	18.3
Elongation at break /%	≥180	306
Thermal deformation /%	≤50	22.7
Impact embrittlement property (test temperature -50℃)	Qualified	Qualified
Thermal stability time at 200℃ /min	≥80	116
Volume resistivity at 620℃ /(Ω·m)	$\geq 1.0\times10^{9}$	3.8×10^{10}

Table 4. Measured characteristics of cold-resistant PVC insulation material.

Content	Standard requirement	Experimental result
Tensile strength /MP	≥15.0	17.9
Elongation at break /%	≥150	324
Thermal deformation /%	≤50	19.6
Impact embrittlement property (test temperature -50℃)	Qualified	Qualified
Thermal stability time at 200℃/min	≥60	89
Volume resistivity at 20℃ /(Ω·m)	$\geq 1.0\times10^{12}$	2.8×10^{12}

4. Research on structure property of cold-resistant cables

In the paper, the influence factors of cable sheath cracking phenomena during cable laying were analyzed. The relationship among mechanical and electrical properties, cable structure and material additives of cold-resistant cable at low temperature was summarized. The structures of 35kV and lower cold-resistant power cables and control cables were designed. Sample cables were trial-manufactured. Their property indicators were verified and analyzed. The low-temperature-resistant property assessment of cold-resistant cable at -50℃ was perfected. Product test standards were perfected, and cold-resistant cable type test was completed.

4.1. Trial-manufacturing of cold-resistant cable samples

In the paper, four sample cables were prepared, including power cables with rated voltage of 26/35kV, power cables with rated voltage of 8.7/10kV, power cables with rated voltage of 0.6/1kV and control cable with rated voltage 450/750kV. Specific structure and dimension are shown in tables 5-8.

Table 5. Structure and dimension of power cable samples with rated voltage of 26/35kV.

Model and specification			YJV-26/35 1×300	Remark
No.	Structure	Thickness(mm)	Outer diameter(mm)	
1	Conductor	60/2.68	20.5 (-0.2,+0.2)	Copper conductor
2	Conductor screen	0.9	22.3	
3	Insulation	10.5	43.6	
4	Insulation screen	0.7	45.0	
5	Copper tape screen	1×0.12	45.4	
6	Wrapping tape	1×0.15	45.9	Non-woven fabrics
7	Outer sheath	2.5	50.9±1.5	Sheathing material with cold resistance of -50℃

Table 6. Structure and dimension of power cable samples with rated voltage of 8.7/10kV.

Model and specification			YJV22-8.7/10 3×300	Remark
No.	Structure	Thickness(mm)	Outer diameter(mm)	
1	Conductor	60/2.68	20.5 (-0.2,+0.2)	Copper conductor
2	Conductor screen	0.7	21.9	
3	Insulation	4.5	31.0	
4	Insulation screen	0.7	32.4	
5	Copper tape screen	1×0.10	32.7	
6	Cable		71.6	Filled with rock wool rope
7	Wrapping tape	2×0.15	72.5	Non-woven fabrics

Table 7. Structure and dimension of power cable samples with rated voltage of 0.6/1kV.

Model and specification			YJV22-0.6/1 3×240+2×120	Remark
No.	Structure	Thickness(mm)	Outer diameter(mm)	
1	Conductor	36/3.08 24/2.56	18.4 (-0.2,+0.2) (phase conductor) 12.9 (-0.2,+0.2) (neutral conductor)	Copper conductor
2	Insulation	1.7 1.2	22.0 15.5	
3	Cable		53.9	
4	Wrapping tape	2×0.15	55.1	Non-woven fabrics
5	Inside liner	1.6	58.3	Sheathing material with cold resistance of -50℃
6	Armour	2×0.5	60.3	
7	Outer sheath	2.9	66.1	Sheathing material with cold resistance of -50℃

Table 8. Structure and dimension of power cable samples with rated voltage of 450/750kV.

Model and specification			KVVP2-450/750 14×6	Remark
No.	Structure	Thickness(mm)	Outer diameter(mm)	
1	conductor	1/2.74	2.74±0.02	Copper conductor
2	Insulation	0.8	4.5	Insulation material (yellow) with cold resistance of -50℃
3	Cable		19.9	Filled with rock wool rope
4	Wrapping tape	2×0.05	20.2	Polyester tape
5	Copper tape screen	1×0.06	20.4	
6	Wrapping tape	1×0.15	20.8	Non-woven fabrics
7	Outer sheath	1.7	22.2	Sheathing material with cold resistance of -50℃

4.2. Low temperature type test of cold-resistant cable sample

Low temperature elongation ratio, low-temperature impact, 15min withstand voltage and similar tests were implemented aiming at four sample cables (respectively 80m) at outdoor natural environment of -50℃~-45℃ in Mohe Low Temperature Test Site according to related requirements in GB/T 12706.1-2008, GB/T 12706.2-2008, GB/T 12706.3-2008, GB/T 9330.2-2008 and other standards. Test photos are shown in figure 1, figure 2 and figure 3.

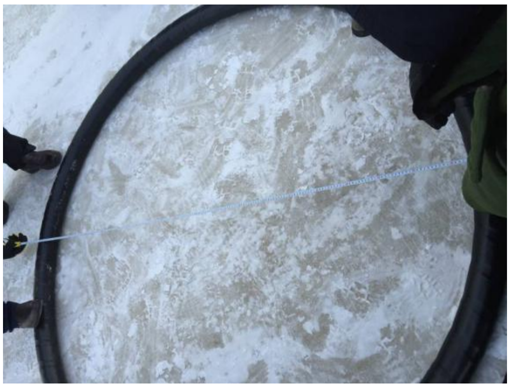

Figure 1. The Experimental field of cable low temperature elongation ratio

Figure 2. Wiring diagram of cable low temperature 15min withstand voltage test

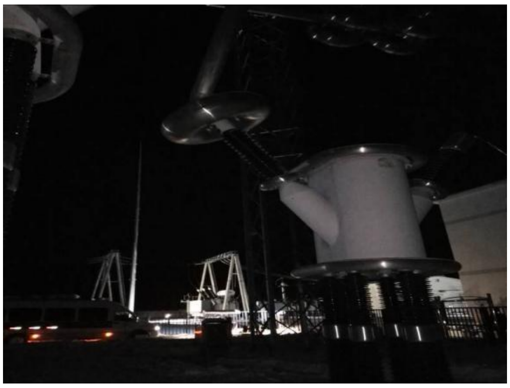

Figure 3. The Experimental field of cable low temperature 15min withstand voltage

The Experimental results of four sample cables are shown in table 9, table 10, table 11 and table 12. All properties of four sample cables were consistent with standard requirements according to actual tests.

Table 9. The experimental results of power cable samples with rated voltage of 26/35kV.

Experimental project	Unit	Standard requirement	Experimental result	Evaluation
Bending experiment	Time	3	Carry out six times experiments on a cylinder with the diameter of 1450mm	Meet the requirements
15min withstand voltage	kV	91	Pass the experiment	Meet the requirements
Low temperature elongation ratio	%	≧20	185	Meet the requirements
Low-temperature impact	-	Crack-free	Crack-free	Meet the requirements

Table 10. The experimental results of power cable samples with rated voltage of 8.7/10kV.

Experimental project	Unit	Standard requirement	Experimental result	Evaluation
Bending experiment	Time	3	Carry out six times experiments on a cylinder with the diameter of 1700mm	Meet the requirements
15min withstand voltage	kV	30.5	Pass the experiment	Meet the requirements
Low temperature elongation ratio	%	≧20	185	Meet the requirements
Low-temperature impact	-	Crack-free	Crack-free	Meet the requirements

Table 11. The experimental results of power cable samples with rated voltage of 0.6/1kV.

Experimental project	Unit	Standard requirement	Experimental result	Evaluation
Low temperature elongation ratio	%	≧20	192	Meet the requirements
Low-temperature impact	-	Crack-free	Crack-free	Meet the requirements

Table 12. The experimental results of power cable samples with rated voltage of 450/750kV.

Experimental project	Unit	Standard requirement	Experimental result	Evaluation
Low temperature elongation ratio	%	≧20	187	Meet the requirements
Low-temperature impact	-	Crack-free	Crack-free	Meet the requirements

5. Conclusion

(1) Property indicators of cold-resistant cable insulation and sheath materials were set. The optimum cold-resistant cable design formula was determined. Cold-resistant PVC cable material with excellent physical and mechanical properties and sound extrusion technology was prepared, wherein the material met production requirements of low-temperature-resistant cables.

(2) The low-temperature property of the prepared cold-resistant sheathing material and cold-resistant insulation material was qualified in -50℃ low-temperature impact embrittlement experiment. The heavy metal content in the formula system was consistent with requirements of green environment protection design and manufacturing.

(3) The processing technology of cold-resistant cable insulation and sheath materials were mastered through formula difference contrast and process combination design. Cold-resistant cable insulation and sheath properties were analyzed. The optimum cold-resistant cable processing technology meeting actual operation environment in the alpine region was determined. In addition, processing technology temperature of cold-resistant (below -50℃) cable PVC plastic was determined through material trial-manufacturing and test for many times. The developed cold-resistant sheathing material and cold-resistant insulation material had stable extrusion technology properties.

(4) The relationship among mechanical and electrical properties, cable structure and material additives of cold-resistant cables at low temperature was summarized. The structures of 35kV and lower cold-resistant power cables and control cables were designed. Meanwhile, the developed cold-resistant sheath and insulation materials were used for finished product cable extrusion experiment and trial-manufacturing sample cables. Type tests of low temperature elongation ratio, low-temperature impact, 15 min withstand voltage, etc. were completed for 35kV and lower sample cables in Mohe Low-temperature Test Site. All properties were consistent with standard requirements.

(5) The cold-resistant cable developed in the paper was applicable to -50℃ low temperature operation environment. Seasonality of cable laying in alpine regions was broken, thereby effectively guaranteeing operation reliability of cable lines and filling the blank of domestic and foreign related technology fields.

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