Aging characteristics of insulating materials and development of protective Materials for insulated boom trucks under low-temperature freezing-thawing cycles

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ABSTRACT

Insulated reach trucks are used to carry the high-voltage power-distribution equipment in live-line work. Working-stability requirements for polymer insulating materials in the main parts of live-line equipment, such as insulated arms and buckets, directly affect the safety and reliability of live-line work. In the cold regions of northern China, where the difference in temperature between day and night is relatively large, there are many freeze-thaw cycles during the winter, and these insulating materials are repeatedly subjected to a combination of low-temperature freezing and ambient-temperature thawing, leading to damage of the microstructure, a reduction in mechanical properties, and a decrease in electrical insulation performance. The problems will reduce the service life and increase the risk of power grid failure. Commonly used epoxy resin, fiberglass-reinforced plastic (FRP), and rubber insulating materials in insulated reach trucks are selected as the subjects of this study, and their aging mechanisms under low-temperature freeze-thaw cycling are systematically analyzed to examine changes in mechanical properties, electrical characteristics and surface morphology. Directed research has been carried out to develop composite protective coatings that are resistant to low-temperature freeze-thaw cycles, and experiments have verified their effectiveness. The above experiments show that freeze-thaw cycles can start and spread internal microcracks in insulating materials more rapidly, significantly reducing both the toughness and the breakdown field strength. A composite coating of the novel material can be used to reduce water infiltration and alleviate the damage caused by low-temperature stress; thus, it will be more durable in freezing and thawing conditions. The above results offer basic support for the maintenance protection and material optimisation of insulated reach trucks in a cold environment.

Keywords: Insulated reach truck; Insulating materials; Low-temperature freeze-thaw cycles; Aging characteristics; Protective materials

1. INTRODUCTION

With the widespread adoption of overhead line operations in distribution networks, insulated bucket trucks have become indispensable equipment for line maintenance, component replacement, and fault isolation due to their flexibility, efficiency, safety, and reliability, and are extensively utilized in urban and rural power grid management. The functionality of these vehicles relies on polymer-based insulation components—including insulated arms, buckets, and base plates—which must ensure electrical insulation performance; both insulation quality and mechanical strength are critical for operator safety and grid stability. This study conducted aging characterization experiments under actual low-temperature freeze-thaw cycles, systematically analyzing aging patterns at mechanical, electrical, and microstructural levels while investigating the fundamental mechanisms of freeze-thaw aging. A specialized composite protective material was developed, combining excellent low-temperature resistance, anti-permeation properties, and strong adhesion. Performance test results validated the material's effectiveness, providing theoretical foundations and technical solutions for long-term protection and service life extension of insulated-arm cranes in extreme cold environments[1].

2. ANALYSIS OF THE AGING MECHANISM FOR INSULATING MATERIALS UNDER LOW-TEMPERATURE FREEZE-THAW CYCLES

The main insulating materials of insulated reach trucks are epoxy resin-based glass fibre-reinforced plastics, modified rubber, and polyurethane insulating materials; all are polymer compounds with performance determined by stable

molecular chain structures, cross-linked networks and dense microstructures. Low-temperature freeze-thaw cycling is an aging process that occurs due to the combined effects of thermal stress and moisture erosion; it is not the same as damage caused by a single environment, and its damage shows the characteristics of “cumulativity, irreversibility, and multidimensional coupling”, with three specific aging mechanisms: thermal-stress damage, moisture phase-change damage, and microstructural degradation.

2.1. Mechanism of Low-temperature temperature-induced stress damage

Polymers are expanding and contracting at the same time. Low-temperature freeze-thaw cycles are repeated frequently, and thus there is frequent thermal stress in the material. When the temperature drops below the freezing point, the movement of molecular chains is hindered; thus, the chains contract in segments, decrease the space between them, and reduce the overall volume; after heating up and melting, molecular chain movement is restored, and a slight expansion in volume occurs. Due to the uneven cross-linking in the molecular structure and the presence of microscopic pores and defects, the contraction and expansion rates of different areas in the material are not uniform, leading to internal stress[2].

After several cycles of freeze-thaw, alternating stresses will repeatedly occur inside the material; these stresses cause a concentration of stress, leading to the start and spread of microcracks, as well as the connection of microcracks. Thermoelasticity can be used to quantify the temperature-induced alternating stress caused by freeze-thaw cycling via the following formulas:

$$\sigma = E\alpha\Delta T/(1-\mu)$$

In the formula $\sigma E\alpha\Delta T\mu$: is the internal thermal stress of the material (MPa); is the elastic modulus of the insulating material (MPa); is the linear expansion coefficient of the material (°C); is the temperature difference per freeze-thaw cycle (°C); and is the Poisson's ratio of the material.

2.2. Mechanism of water-vapor phase-change erosion damage

At a high altitude, when the outside humidity is high, the surface and internal pores of the insulating material will be exposed to water vapour and other types of water in the air. At low temperatures, freezing occurs in the pores of these materials; as a result, an expansion force arises, which reduces the wall thickness of the pores, enlarges the micro-pores, and thus introduces new micro-cracks. At the end of the thaw period, the ice will turn into water, be absorbed by the material via capillary action, and thus increase the amount of water in the structure.

Repeatedly freeze-thaw cycling introduces a cycle of water "ice formation and expansion $\to$ melting and infiltration", which continuously damages the internal cross-linked network of the material, resulting in an increase in porosity and a decrease in structural density. The Volume of water increased by about 9% in the formation of ice. The calculation formula for ice-water expansion stress in the pores is as follows:

$$P = \frac{K\Delta V}{V_0}$$

In the formula $PK\Delta VV_0$: is the expansion-compression stress of ice-water mixture (MPa); is the volume modulus of ice (GPa); is the volumetric change due to water freezing (mm); and is the initial pore volume within the material (mm)[3].

3. EXPERIMENTAL STUDY ON AGING CHARACTERISTICS OF INSULATING MATERIALS UNDER LOW-TEMPERATURE FREEZE-THAW CYCLES

3.1. Test samples and equipment

The three primary insulating materials frequently used in the mass production of insulated reach trucks were selected for the experiment: epoxy resin glass fiber reinforced plastic (the main material for the insulating arm), modified chloroprene rubber (the main material for the insulating protective pad), and polyurethane insulating material (the main material for the insulating bucket). All these were processed uniformly into standard specimens and were free from initial cracks or impurities and had a smooth surface. The equipment in this test set includes a high- and low-temperature freeze-thaw cycle chamber, an electronic universal testing machine, an insulation resistance tester, a breakdown voltage tester, and a scanning electron microscope (SEM); separately, they are applied to reproduce freeze-thaw conditions for mechanical property analysis, electrical performance assessment, and microstructural observations[5].As can be seen from Figure 1, with the increase in the number of freeze-thaw cycles, the mechanical properties of the three materials continue to deteriorate, and the deterioration rate gradually accelerates. Among them, the toughness of epoxy resin glass fiber

reinforced plastic (GFRP) decreases most severely, while the mechanical stability of polyurethane material remains the best.

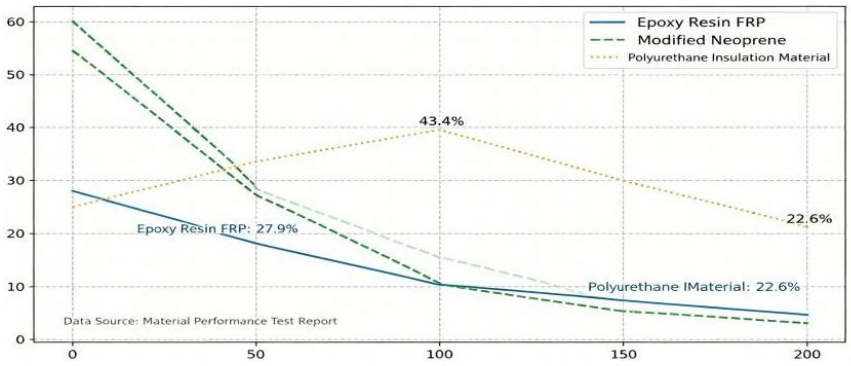


Figure 1. Mechanical property degradation curves of three insulation materials under different freeze-thaw cycles.

3.2. Test condition settings

Based on the actual environmental features of winter in the high-altitude cold areas of northern China, a freeze-thaw cycle test condition was set up: a freezing temperature of -30 °C for 4 hours of frozen insulation, a thawing temperature of 25 °C for 4 hours of thawed insulation, each freeze-thaw cycle lasting 8 hours, and a total of 0 (no aging), 50,100, 150, and 200 cycles were set for short-term, medium-term and long-term outdoor service conditions of the equipment, respectively. Set the relative humidity of the test environment to 85% for a high-humidity outdoor freeze-thaw environment. Mechanical and Electrical properties, as well as microstructures, were tested on all sample groups.

3.2.1. Add a multi-factor coupled aging experimental group.

Building upon the original single-cycle freeze-thaw protocol (30°C for 4 h, 25°C for 4 h of thawing, repeated every 8 h), a multi-environment coupled parallel sample group was introduced: each group underwent one of the following tests—① freeze-thaw combined with UV aging (UV irradiation intensity: 0.89 W/cm², continuous UV exposure during freeze-thaw intervals); ② freeze-thaw combined with wind-dust abrasion (using standard quartz dust cyclic erosion to simulate field sand-wind friction wear); or ③ freeze-thaw combined with a triple-factor combination of UV and wind-dust exposure. The microstructural morphology, mechanical properties, and electrical performance of the three insulation materials were simultaneously compared under single freeze-thaw conditions and multi-factor coupled conditions, enabling quantification of multi-factor synergistic aging degradation patterns and accurately reproducing real-world service conditions in northern cold regions.As can be seen from Figure 2, the coupling damage caused by ultraviolet radiation, wind and sand, and freeze-thaw cycles produces a significant synergistic effect of accelerated aging. Compared to a single freeze-thaw environment, the aging rate of materials in a composite field environment is significantly increased.

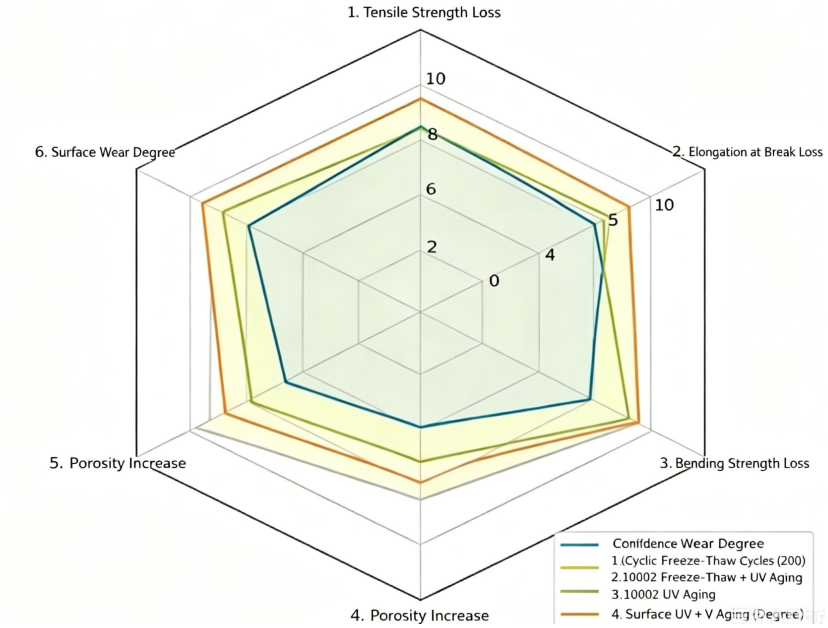


Figure 2. Radar chart of comprehensive aging degree of insulation materials under different environmental conditions.

3.2.2. Supplementary tests on humidity gradient and water permeability.

Abandoning the original fixed 85% single relative humidity condition, a multi-gradient relative humidity range of 60%,75%,85%, and 95% was established during the thawing phase. A humidity-dependent water permeability was introduced as a quantitative characterization parameter to measure in real time the water absorption rates and saturation water absorption capacities of three materials—epoxy resin FRP, modified chloroprene rubber, and polyurethane—at different thawing humidity levels, thereby aligning with two typical service environments: arid high-altitude regions and coastal areas with high humidity and freeze-thaw cycles, and enhancing the quantification data on moisture-induced permeation damage.

3.2.3. Extend the freeze-thaw cycle test duration.

Original test cycle gradient: 0/50/100/150/200 cycles; new groups with ultra-long acceleration freeze-thaw cycles at 500,800, and 1000 cycles were added. The study continuously monitors material pore evolution, crack connectivity, and trends in mechanical and insulation performance degradation under extended cycles. Based on long-term test data, the long-term cumulative damage resistance and full lifecycle service life of both the matrix insulating material and the self-developed silicone-polyurethane composite protective coating were evaluated.

3.3. Test results and characteristic analysis

3.3.1. Aging characteristics of mechanical properties

Tensile strength, flexural strength and elongation at break of the three materials were determined after freeze-thaw tests using tensile and flexural tests. As shown in the above experiments, after an increase in the number of freeze-thaw cycles, all three types of insulating materials displayed a continuous decrease in their mechanical properties; moreover, the rate of this deterioration also increased incrementally with each cycle. A formula for the rate of degradation in mechanical properties of material aging damage was developed to quantify this extent[6].

$$\eta = \frac{\delta_0 - \delta_n}{\delta_0} \times 100\%$$

In the formula $\eta\delta_0\delta_n$: represents the performance degradation rate (%); denotes the mechanical property parameters of the unaged sample; and indicates the mechanical property parameters of the sample after n freeze-thaw cycles.

The unaged sample has a dense structure and good toughness; the tensile strength of the epoxy resin glass fibre-reinforced plastic is 86.5 MPa, and the fracture elongation is 6.2%. After 200 freeze-thaw cycles, the tensile strength was

reduced to 62.3 MPa (down 27.9%) and the fracture elongation had dropped to 3.1% (down 50%).

Modified chloroprene rubber shows a relatively small drop in low-temperature toughness: the unaged elongation at break is 380%, and after 200 freeze-thaw cycles, it has fallen to 215%, a decrease of 43.4%. The material is less flexible, has slightly hardened, and is now somewhat brittle on the surface. Polyurethane insulation materials have a relatively gradual decline in mechanical properties, and after 200 cycles, their flexural strength has decreased by 22.6%; thus, their deformation resistance is also relatively low. Generally speaking, the damage that freeze-thaw cycling causes to the toughness of a material is much more severe than the damage to its strength; that is to say, the material will become relatively more brittle, both its impact resistance and bending strength will be reduced, and thus the risk of fracture or other damage during operation will increase.

3.3.2. Aging characteristics of electrical performance.

Electrical insulation performance is the basic safety requirement for insulated reach trucks, and the two typical test items are volume resistivity and breakdown field strength after repeated freeze-thaw cycles. Based on the above results, freeze-thaw ageing has substantially reduced the insulating properties of the materials, and the extent of this damage is directly correlated with the number of freeze-thaw cycles. A reduced Pattern of electrical properties, specifically breakdown field strength and volume resistivity, is classified as insulation degradation. Figure 3 shows that the water vapor infiltration and microcrack expansion triggered by freeze-thaw cycles significantly reduce the insulating ability of materials; the attenuation of volume resistivity is greater than the breakdown field strength, leading to a significant increase in leakage current on the material surface and an elevated risk of insulation failure.

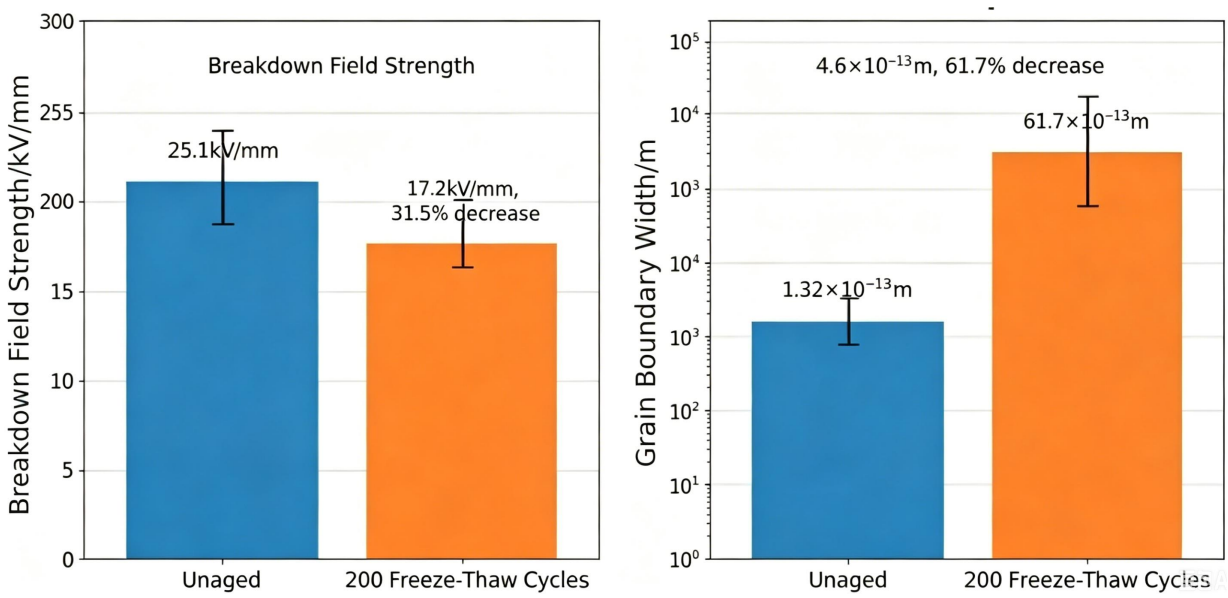


Figure 3 Comparison of Breakdown Field Strength and Volume Resistivity of Materials

$$\lambda = \frac{E_0 - E_n}{E_0} \times 100\%$$

In the formula $\lambda E_0 E_n$: is the electrical performance degradation coefficient (%); is the breakdown field strength of the unaged sample (kV/mm); and is the breakdown field strength of the sample after n freeze-thaw cycles (kV/mm).

The breakdown field strength of aged epoxy resin glass fibre reinforced plastic is 32.6 kV/mm and the volume resistivity is 1.2×10^{14} Ω·cm; after 200 freeze-thaw cycles, both the breakdown field strength and volume resistivity decrease to 21.8 kV/mm and 4.6×10^{13} Ω·cm, respectively, with declines of 33.1% and 61.7%.

Underlying reasons include water-vapor infiltration and the growth of microcracks due to freeze-thaw cycles; consequently, more conductive paths in the material have formed, and surface leakage currents have risen. Simultaneously, the microscopic defects are electric-field distortions that reduce the breakdown strength of the material. Rubber and polyurethane materials have a relatively large pore size, are easily penetrated by water vapour, and thus exhibit a more significant decline in electrical properties. After extended freeze-thaw ageing, the material's insulation

margin has decreased substantially, and the risk of local flashover and insulation failure is now high; thus, it poses a serious safety risk to live-line work.

3.3.3. Microstructural aging characteristics.

Microstructure analysis by SEM shows that the unaged insulating material is smooth and dense at the surface, without pores or cracks, and has an unbroken molecular cross-linking network. After 50 freeze-thaw cycles, minute pores and localised unevenness appear on the surface; after 100 cycles, the number of pores increases and their diameter enlarges; numerous fine cracks form at this time; and after 200 cycles, these microcracks are interconnected to form a network of defects, resulting in surface delamination and loosening. Based on the SEM microscopic observation results (Figure 4), it can be seen that the freeze-thaw cycle exhibits cumulative and irreversible damage characteristics: the more cycles there are, the higher the porosity of the material becomes, the more developed the microcrack network becomes, and the integrity of the microstructure continues to be destroyed.

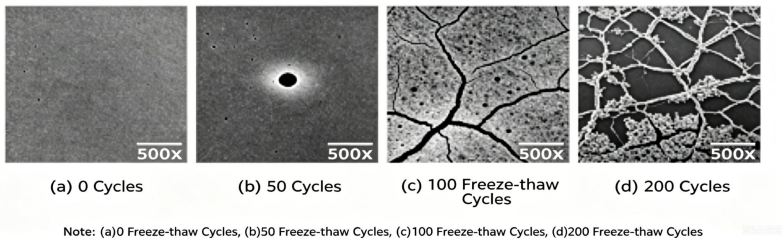


Figure 4. Microscopic morphology (SEM) of epoxy resin glass fiber reinforced plastic surface under different freeze-thaw cycles.

A reduction in the degree of microstructural organisation generally results in a decrease in the overall performance of the material; therefore, low-temperature freeze-thaw cycles can disrupt the arranged state of these materials, break molecular cross-links, and thus reduce both mechanical and electrical properties. Age-related damage is permanent and cumulative; the more times it has been used, the more severe the structural damage has become, and its service life has decreased. To show the increase in microstructural damage more obviously, a formula for the difference in porosity has been proposed:

$$\varphi_n = \frac{S_n - S_0}{S} \times 100\%$$

In the formula $\varphi_n S_0 S_n S$: represents the porosity (% of the material) after n freeze-thaw cycles; represents the effective load-bearing area of the initial defect-free sample (μm); represents the total defect area of the sample after freeze-thaw aging (μm); and represents the total observed area of the sample (μm).

Building upon conventional SEM observation techniques, the microtesting methodology incorporates acoustic emission-based non-destructive online monitoring: it continuously collects real-time acoustic signals throughout the entire freeze-thaw cycle to track the initiation, propagation, and propagation of micro-cracks in samples, enabling early non-destructive detection of micro-damage and allowing continuous monitoring of internal damage evolution without specimen disruption.

4. CONCLUSION

This study systematically investigated the aging phenomena and underlying damage mechanisms of core insulating materials in insulated trolleys during low-temperature freeze-thaw cycle aging tests. By successfully validating their performance, targeted development of low-temperature-resistant composite protective materials was achieved.Subsequent research has focused on two key aspects. First, a "freezing-thaw-ultraviolet-wind-dust multi-field coupled accelerated aging test system" was developed to investigate the coupling mechanisms between microstructural damage and performance degradation of insulating substrates under combined environmental influences. The multi-gradient thawing humidity tests were refined, and an moisture-induced aging evaluation model based on humidity-dependent water permeability was established to accommodate diverse operational scenarios in cold regions and coastal areas. The accelerated aging tests were expanded to 500–1000 freeze-thaw cycles, enhancing the long-term cumulative damage and life assessment database. Second, centered around the self-developed composite protective coating, a "regular inspection and standardized maintenance framework for insulating arm coatings" was established. Acoustic emission non-destructive testing was integrated into routine equipment maintenance procedures, enabling early detection

of internal micro-cracks through non-destructive monitoring results, thereby forming a comprehensive technical system spanning formula optimization, field inspection, and operational maintenance.

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