Mechanical Behavior of Aged EPDM Insulation of High-Voltage Cable Joints in Thermal-Oxidative Environment

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Abstract. In this thesis, the thermal aging behaviour at 130°C, 145°C and 160°C for 220kV cable joint EPDM insulation was investigated. The tensile strength and elongation of EPDM insulation both before and after the thermal-oxidative aging were measured, and the microstructure of materials was observed by SEM. The microstructure observation showed that pores formed and expanded into pieces inside the EPDM insulation with thermal aging course, the cracks would appear at the end of aging process. Both tensile strength and elongation of EPDM insulation decreased with aging process lasting, and decreased more gradually with increasing aging temperature. The tensile strength was more sensitive than elongation for aging process. The results can provide theoretical support for the fabrication, operating and maintenance for EPDM cable joint.

1. Introduction

Ethylene propylene diene monomer (EPDM) is widely used in the integrally prefabricated cable joint insulation [1], which has the advantages of favorable resilience, excellent electrical properties, good aging resistance, and superior structural stability [2]. Electrical and thermal stress and their synergism result in the aging of insulation materials in cable systems [3, 4]. Cable joints need to have a certain degree of flexibility and holding force to generate proper surface pressure to protect the cable insulation [5]. It is known that insufficient interface pressure between cable joints and cross-linked polyethylene is the key factor that causes creeping discharge and affects the breakdown strength [6], and excessive mechanical stress on the prefabricated parts of cable accessories may also cause structural damage in the medium of the insulation [7]. It is essential to ensure the cable joint has sufficient mechanical properties for the safe operating of the cable joint.

At present, there were many researches about mechanical behavior for aging of EPDM. Quanlin Zhao et al. [8] used a artificial climate box with xenon lamp to conduct artificial weathering tests on EPDM, and found that sample’s tensile strength, tear strength, and hardness increased after aging. Chou et al. [9] investigated the fatigue life and fracture energy under static and cyclic loading of carbon black as a rubber-reinforcing filler at different thermal oxygen aging stages. The results showed that the fatigue life of carbon reinforced EPDM decreased with increasing the aging time. Pourmand P et al. [10] studied the high-filled EPDM insulation of nuclear power station cable joint with thermal aging at different temperatures in air, it was found that the elastic modulus increased and
the elongation at break decreased after aging. Xiaohong Yang et al. [11] found that during the thermal aging of EPDM with oxygen, the compression stress relaxation decreased gradually and the tensile strength increased gradually, but the changing trend slowed down in the later aging period. The higher the aging temperature, the more obvious the aging behaviors. In the process of EPDM thermal-aging with oxygen, the plasticizer migrates to the surface. At the same time, the surface of the material becomes not smooth, which will affect the mechanical properties. Bouguedad D et al. [12] found that during EPDM aging, the tensile strength firstly increased and then decreased, while the elongation at break gradually decreased. However, the trend of the parameters which characterize the mechanical properties have a large difference during the different types of EPDM thermal-oxidative aging, and the aging research on the EPDM of integrally prefabricated cable joint is not enough.

In this research, the 220kV integral prefabricated EPDM cable joint was used to carry out the thermal aging test, mechanical properties and microstructure of EPDM during aging process were investigated, the mechanism of thermal aging for EPDM in air was discussed.

2. Experiment

2.1. Test samples

The research object of this article was a 220kV integral prefabricated EPDM cable joint (YJJJI2-127/220kV1×2500mm²). In order to facilitate material performance testing, the prefabricated cable joint EPDM insulation was cut into size of 65mm(length) × 65mm(width) × 1mm (thickness). The specimens were subjected to thermal aging tests in an aging oven at 130°C, 145°C, and 160°C for seven stage (as shown in Table 1).

| Temperature/°C | Stage 1 /h | Stage 2 /h | Stage 3 /h | Stage 4 /h | Stage 5 /h | Stage 6 /h | Stage 7 /h |
|---------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 130           | 136       | 1152      | 1536      | 1920      | 2304      | 2688      | 3072      |
| 145           | 144       | 288       | 384       | 480       | 576       | 672       | 768       |
| 160           | 48        | 96        | 144       | 192       | 240       | 264       | 288       |

2.2. The microstructure observation

Microstructure of the sample was observed by Scan electron microscope (SEM, VE-9800, Keyence Ltd. Japan). An ion sputtering equipment was used to spray gold on the surface of the sample, and a 15kV scanning acceleration voltage was applied in vacuum mode during observation.

2.3. The Mechanical property testing

The mechanical properties were tested by electronic universal testing machine (CMT-4503, Meister Ltd., China). Referring to GB/T 528-2009, The EPDM sample was cut with a 2-dumbbell cutter to obtain a standard dumbbell sample. Five sample were tested for each group of samples, and the average value was obtained.

2.3.1. Tensile strength. Tensile strength was obtained by eq.(1), and the load speed was 250mm/min.

$$\sigma_B = \frac{P_B}{S_B} = \frac{P_B}{b \times d}$$

Where $\sigma_B$ is tensile strength, MPa; $P_B$ is the maximum failure load, N; $S_B$ is the original cross-sectional area of the sample, mm²; b is the original width of the sample, mm; d is the original thickness of the sample, mm;

2.3.2. elongation. Elongation was obtain by eq.(2).

$$\delta = \frac{L_B - L_0}{L_0} \times 100\%$$
Where $\delta$ is elongation at break; $L_0$ is the original length of the sample, mm; $L_B$ is the distance between two lines when the sample breaks, mm;

3. Results and discussions

3.1. Microstructure observation

In the hot atmosphere, the surface of the material is in direct contact with the air. The colour of sample changes, the surface becomes rough, and there are small cracks on surface. The aged samples at 160°C were taken as an example to compare and analyse the micromorphology of EPDM samples (without aging, aged for 96 hours, aged for 192 hours and aged for 288 hours).

![Figure 1. SEM image for Surface microstructure of EPDM samples during thermal aging](image)

Figure 1 shows the change of the surface microstructure of the sample during thermal aging. Figure 1 (a) showed that the surface sample without aging is relatively smooth and flat. After aging at 160°C for 96 hours, a small number of holes began to appear (Figure 1 (b)). After aging at 160 °C for 192h, the pores on the surface of the EPDM sample increased and the pores became larger (Figure 1 (c)). According to Figure 1 (d), after aging at 160 °C for 288h, the EPDM sample surface becomes unsmooth and it appears large consecutive holes and small cracks.

It is seen that more and more holes appeared on the surface of the EPDM sample and gradually expanded into pieces, and cracks appeared with lasting the thermal aging process. It should be caused by following: 1. plasticizers and small molecules volatilize during thermal oxidation, resulting in the emission of gas, leaving the emission channels to form defects; 2. Due to the difference of thermal expansion coefficient between the inorganic fillers and EPDM base materials, the interface between the base material and the filler becomes worse, therefore, the filler near the surface was easy to fall off and precipitates, the precipitated channels form defects. In summary, thermal aging would cause the EPDM samples to be damaged, which would affect the mechanical properties of the samples.
3.2. Mechanical properties

The tensile strength and the elongation of EPDM insulation samples are used to characterize the mechanical properties.

Figure 2. Changes in elongation at break of EPDM specimens during thermal aging

Figure 2 shows the relationship between the elongation and the aging time at 130°C, 145°C, and 160°C. It can be seen that the elongation of EPDM specimens decreases gradually at three aging temperatures with increasing aging time, and the decreasing trends from 130°C to 160°C increase sequentially. Compared with the unaged samples, the elongation after last stage (7th) samples at 130°C, 145°C, and 160°C are reduced by 67.45%, 66.24%, and 68.64%, respectively, according to GB/T 18890.3-2015, the requirements for the performance of prefabricated EPDM insulation materials in the medium must be greater than 300%. Therefore, the EPDM samples in the later period of aging process at 3 aging temperatures have not met the requirements of the standard. It has certain operating risks, and may have insufficient holding power for cable insulation or even cracking of prefabricated parts.

Figure 3. Changes in tensile Strength of EPDM specimens during thermal aging

Figure 3 shows the relationship between the tensile strength and the aging time at 130°C, 145°C, and 160°C. It can be seen that the tensile strength of the EPDM sample decreases with increasing aging time, and the aging stage (stages 6 to 7) of the three aging temperatures has a tendency to decrease and slow down. Compared with the unaged samples, the tensile strength of the seventh-stage samples aged at 130°C, 145°C, and 160°C decreased by 67.60%, 68.83%, and 74.70%, respectively. The later period of aging process is approaching the lower limit of the standard GB / T 18890.3-2015 (5Mpa).
The tensile strength of the aged sample is slightly increased in the first stage of aging. The reason should be that the initial thermal aging process of the prefabricated joint promotes the re-crosslinking reaction of the EPDM molecular structure, the cross-linking network is tighter, the molecular chain is not easy to slip when subjected to stress, and the rigidity of the material is slightly increased, so that the tensile strength is aging Slightly improved in the early stage.

4. Conclusions

1) During aging process, EPDM material is damaged gradually. In the later stage of aging process, large holes and cracks appear on the surface of the EPDM sample, which will directly affect the mechanical properties of the sample.

2) The thermal aging process at three temperatures is affected by structural deterioration. The tensile strength and the elongation, which characterize the mechanical properties of EPDM specimens are decrease gradually. The difference is that the tensile strength is slightly increased in the first stage of aging. The higher the aging temperature, the faster the degradation rate of mechanical properties.

3) The decrease extent of the tensile strength of the EPDM sample is greater than the elongation, and considering that the tensile strength of the EPDM sample at the initial stage of aging is slightly increased, the tensile strength is more sensitive to the mechanical properties.

References

[1] ZHANG Yachun, ZHAO Zhiqiang, ZHOU Changcheng, et al. Applications of Silicone Rubber in High Voltage Cable Accessories, [J]. Silicone Material, 2013(5):365-367.
[2] ZHAO Quanlin, LI Xiaogang, GAO Jin, et al. Aging Research of Ethylene-propylene-diene Monomer (EPDM) Rubber, [J]. Insulating Materials, 2010,43(1):37-41
[3] ZHOU Yuanxiang, ZHANG Yunxiaoz, ZHANG Xu, et al. Influence of Thermal Aging Time on Electrical Tree Initiation of Silicone Rubber, [J]. High Voltage Engineering, 2014,40(4):979-986.
[4] FEI Yijun, ZHANG Yunxiao, ZHOU Yuanxiang, Thermo characteristics of Silicone rubber and its effects on operational reliability of extra-high voltage cable accessories, [J]. Advanced Technology of Electrical Engineering and Energy, 2014,33(12):30-34.
[5] FENG Chen, Study on Surface Electrical Tracking Fault Diagnosis of the Cable Used Ethylene Propylene Rubber Based on Insulation Resistance, [D]. Taiyuan University of Technology, 2016.
[6] Du BX, Gu L, Zhang X, et al. Fundamental research on dielectric breakdown between XLPE and silicon rubber interface in HV cable joint[C]. IEEE 9th International Conference on the Properties and Applications of Dielectric Materials, 2009: 97-100.
[7] WANG Xia, LIU Xia, ZHENG Mingbo, Formation Mechanism of Space Charge Accumulation at SR and XLPE Interface Under Temperature Gradient, [J]. High Voltage Engineering, 2011,37(10):2424-2430.
[8] ZHAO Quanlin, LI Xiaogang, GAO Jin, Artificial weathering of ethylene-propylene-diene monomer (EPDM) rubber, [J]. Journal of University of Science and Technology BeiJing, 2008,30(12):1422-1427.
[9] Chou H W , Huang J S , Lin S T . Effects of thermal aging on fatigue of carbon black – reinforced EPDM rubber[J]. Journal of Applied Polymer Science, 2007, 103(2):1244-1251.
[10] Pourmand P, Hedenqvist MS, Furo I, et al. Deterioration of highly filled EPDM rubber by thermal ageing in air: Kinetics and non-destructive monitoring, [J]. Polymer Testing, 2017, 64: 267-276.
[11] YANG Xiaohong, XU Jin-sheng, ZHOU Chang-sheng, Microcosmic Structure and Mechanics Performance of EPDM Rubber in Hot-Oxygen Aging, [J]. Transactions of Beijing Institute of Technology, 2017,37(2):126-130.
[12] Bouguedad D, Mekhaldi A, Boubakeur A, et al. Thermal Ageing Effects on the Properties of Ethylene-Propylene-Diene Monomer (Epdm)[J]. Annales De Chimie-Science Des Materiaux, 2008, 33(4): 303-313.