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Thermal Aging Tests on XLPE and PVC Cable Insulation Materials of Saudi Arabia

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Abstract: Saudi Arabia has four cables manufacturers, and one raw polymer material producer. XLPE and PVC are the most widely used materials in cable insulation industries. The sever weather environment of the Kingdom adds tremendous factors in stressing these cable insulations and shortens their lifetime.

The study presents preliminary results of a comprehensive thermal aging investigation on medium and high voltage cable insulation materials using different analytical techniques; especially weight loss method, to determine how "good" and "safe" are the insulation materials used in cables manufacturing. Since weight loss is a significant physical property that considered to be influenced by thermal degradation, this method is used as a diagnostic procedure to detect the degree of aging.

Introduction

Power transmission cables generally consist of a metal conductor surrounded by multiple insulation layers. For protection against mechanical damage and water contact, jacketing is extruded around one or more of the insulated conductor wires. Polyethylene (PE) and polyvinylchloride PVC are the principal materials used in the wire and cable industry. They provide insulation and jacketing for more than 30,000 different types of wire and cable products [1].

The easy processing and good insulation performance of polyvinyl chloride (PVC) make it the polymer of choice in power cable construction. However, the recent technological improvement in insulation manufacturing trends toward using cross-linked polyethylene (XLPE) and other polymers that are more resistant to degradation from treeing, in addition to PVC, in EHV cable construction [2, 5]. Much of these insulating materials are colored to standard shades for ready identification. The colorants must be carefully chosen to maintain the insulation properties of the polymer. Although the low thermal stability of PVC has been an area of intensive research, the relationship between microstructure and degradation behavior is still not fully understood.

During insulation manufacturing, plastics are exposed to heat that lead to degradation. The final product depends on the type of plastic, the additives used, and the processing temperature. Although degradation can not be eliminated completely, it must be held to a minimum to keep the quality of the final products high.

Thermal degradation of polyvinyl chloride (PVC) and cross-linked polyethylene (XLPE) raw and cable-manufactured materials are experimentally investigated using weight loss method to simulate the thermal stress to evaluate the quality and main properties of the insulation materials. Effect of the standard color used in cables and thermal treatment over the cable insulation process is also correlated.

These investigations and experimental results also should yield a better understanding of the different thermal effects in the industrial processes of the insulation materials used in cable fabrication in Saudi Arabia.

Insulations of electric power cables are stressed by severe weather environment of the kingdom of Saudi Arabia, that adds tremendous factors in stressing cable insulations and shortens their lifetime. The petrochemical industries in Saudi Arabia are striving to improve the quality of the polymers raw materials used in cable insulation industries.

PVC can be compounded to retain its performance properties over a broad temperature range. Most PVC is rated for safe use at 90°C and 75°C in wet conditions, but some can be used safely up to 105°C. Most XLPE is rated for 90°C in both wet and dry conditions. XLPE generally has higher tensile strength with higher resistance to abrasion and weathering. Development work continues to increase the maximum temperature rating of both compounds to 105°C, in order to increase the capacity to carry current. Thermoplastic PE will not operate satisfactorily at temperatures of 90°C, since it softens and melts near this temperature. Above about 107°C, XLPE softens somewhat, but is still more resistant to deformation than PVC, and continues to provide good insulation at temperatures up to about 150°C. [1]

As thermoplastics, the processing of PVC, thermoplastic PE and TPE wire and cable is a relatively straightforward extrusion process. In contrast, the processing of XLPE is a reactive system, which can require special handling of multiple raw material components, unique product curing technologies and increased process control requirements.

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The manufacturing of coated wire and cable is a multi-stage process. Raw materials are combined in a series of manufacturing steps including resin and additive manufacturing; resin compounding, wire drawing, extrusion, cabling, and jacketing. All polymers undergo degradation and decomposition when exposed to heat during formulation or molding into products. They also tend to break down when subject to the mechanical stress of molding or extrusion.

Colorants are added to wire and cable resins for identification purposes. There are two major types of colorants pigments and dyes. A pigment is insoluble and is dispersed as discrete particles throughout a resin to achieve a color. Pigments can be either organic or inorganic compounds. A dye is soluble in the resin and always an organic based material.

PE and XLPE have better insulating properties than PVC and are used in more applications. In the middle to late 1950s, cross-linkable polyethylene compounds were introduced for coating power cable [8]. The unusual and excellent electrical properties of polyethylene are extended to higher operating temperatures when used in cross-linkable materials.

The most important advantage of cross-linked polyethylene (XLPE) over thermoplastic polyethylene is the improved heat resistance. An XLPE insulated power cable can operate at conductor temperatures of 90°C, while the thermoplastic polyethylene insulated cable operates at 75°C. Since conductor temperature is proportional to the amount of loading current through the cable, more power can be transmitted through an XLPE cable than through a non-cross-linked cable of the same size.

After 1950, as the materials were diversified and the electrical appliances were made smaller and better in performance through the development of the molecular industry, the importance of the thermal endurance test was recognized and the number of reports concerning thermal aging and thermal endurance of various materials increased. [4]

Thermal Aging

The main stress for insulating materials is the electrical one, because voltage is always applied to them. However, insulation is usually exposed to multi-stress conditions: such as, high temperatures, pollution, humidity, radiations, vibrations and so on. Even when other stresses have a much greater effect than the electrical gradient, failure is still due to electrical breakdown. This occurs when electric strength, because of aging, decays to the value of the applied electrical gradient. Decline of electric strength is due to all the stresses acting on the material which are the cause of its aging. [7]

Life tests are normally carried out to assess endurance of insulating materials. They consist of exposing specimens of the insulating material to constant stress until they fail. The time to failure in operating conditions should be predicted from a statistical point of view from these tests. Since this result must be obtained in times much shorter than the expected life in service, the tests are performed in heavier conditions than the operating ones. [7]

Electrical insulation, organic materials in particular, exposed to elevated temperatures are subject to deterioration. Deterioration produces changes in the physical properties of materials so that they become unable to meet their functions after a certain time.

Therefore, thermal stress can produce failure without destroying the specimen, and for this reason the limiting value is established according to a criterion, which must take into account the function that the material is expected to meet in service. Since the rate of deterioration increases rapidly with rising temperature, which causes an acceleration of the chemical reactions occurring in materials, therefore, it is necessary to limit the temperature to ensure long life of electrical equipment. Because thermal behavior of materials considerably changes from one material to another, insulating materials have been classified according to the maximum temperature they are able to endure for a satisfactorily long period of time. [7]

Since thermal deterioration is due to the acceleration of chemical reactions produced by increasing temperature, the aging rate can be assumed proportional to the rate of chemical reactions. Therefore, the aging rate dependent on temperature according to the following relationship known as the Arrhenius law:

$$R = R' \exp\left(-\frac{W}{KT}\right) \qquad (1)$$

Where W is the activation energy, K Boltzman's constant and T the absolute temperature ($T = 273 + \theta$). The material life, that is the time to reach the failure criterion, is:

$$L = L' \exp(B/T) \qquad (2)$$

Where $B = W / K$ and L' is a constant for the material under consideration that equals the life of material when temperature tends to infinity.

According to (2), L becomes infinite only at absolute zero temperature, because only at that temperature the chemical reactions are ceased. However, if a material is kept at room temperature without any stress applied, its life is practically infinite. Therefore, life at room temperature, L_o, is introduced instead of L'. Therefore:

$$L_o = L' \exp\left(\frac{B}{T_o}\right) \qquad (3)$$

Where, T_O is the absolute room temperature, it follows that:

$$L = L_o \exp(-B \quad cT) \qquad (4)$$

Where,

$$cT = \frac{1}{T_o} - \frac{1}{T} = \frac{T - T_o}{TT_o} \qquad (5)$$

is the conventional thermal stress.

Since cables are mainly subjected in service to electrical, thermal and mechanical stresses, the properties measured in the aging tests are electric strength, weight, tensile strength and modulus. The selected property for thermal aging evaluation is the weight. IEC Standard 216 establishes recommended end points and properties to obtain thermal endurance line for each studied material. A decrease of electric strength to 50 % of its initial value provides thermal endurance line close to those obtained by 50 % drop in tensile modulus and a 0.5 % decrease of weight [6]. The test temperatures are 220, 170 and 130 °C.

PVC and XLPE insulations are the major insulating materials used in cable insulation industries. Different samples of these insulation materials are tested in this experiment.

Two main categories of PVC and XLPE are used in this study; namely, raw and manufactured insulated materials. For example, raw PVC is the plastic used in cable insulation, while manufactured PVC insulation specimens are collected from new cables. Colorant effect on insulation material stability will be investigated by considering colored and non-colored samples as well.

A number of sample sets have been prepared for the experiment. Each set includes seven samples of PVC and XLPE insulations as illustrated and coded in table 1.

Table 1: Insulating materials used in the experiment

Sample #	Insulating material type	Code
1	Raw* PVC non-color	RPVN
2	Raw* PVC black-color	RPVB
3	Raw* PVC red-color	RPVR
4	New** PVC red-color	NPVR
5	New** PVC black-color	NPVB
6	Raw* XLPE non-color	RXLN
7	New** XLPE non-color	NXLN

* Raw materials used in cable industry.

** Manufactured power cables insulation.

PVC Results

The results of weight property of two PVC insulations at different testing temperatures are plotted against time in figures 1 and 2. The code used in table I will be used here to identify the samples. From these results the thermal life-lines of the tested PVC insulations are obtained.

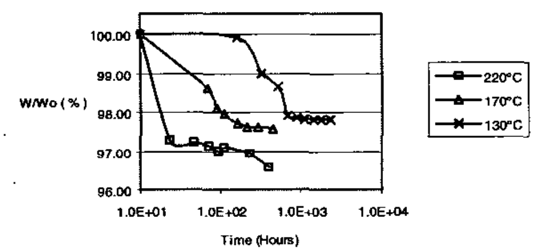

Figure 1: Weight property against aging time for RPVB.

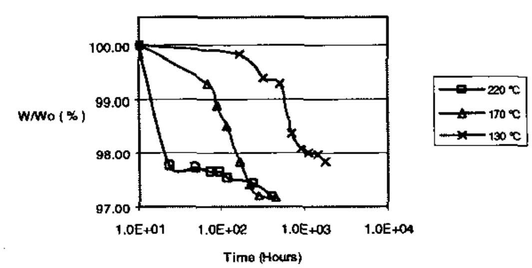

Figure 2: Weight property against aging time for NPVB.

The effect of temperature can be noted very clearly from the results of the weight loss test. The thermal life-lines in figure 3 indicate that the life of the insulating material is inversely related with the temperature. The life of the insulation shortens as the temperature increases.

Figure 4 shows the thermal life-lines of different colored raw PVC samples. There is a slight difference between the three lines, which indicates higher endurance of RPVR in low temperatures up to the operating range (105 °C) followed by RPVB. This means that colorants enhance the thermal resistance of PVC insulations.

The effect of manufacturing process on PVC insulating materials is shown in figure 5. The black-colored manufactured PVC insulation has better thermal resistance than the raw black-colored PVC above 100°C.

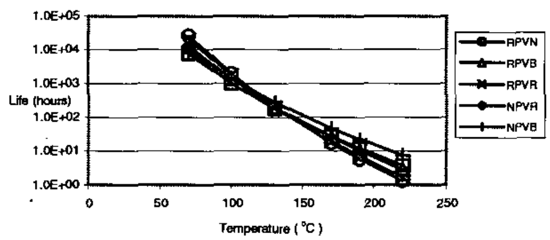

Figure 3: Thermal life-lines of PVC insulations based on weight property results.

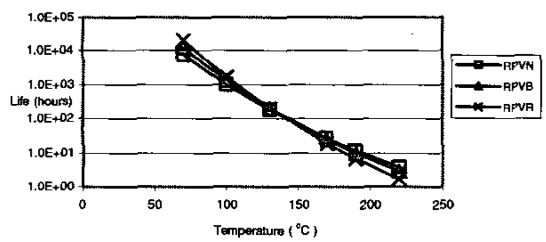

Figure 4: Thermal life-lines of raw PVC insulations based on weight property results.

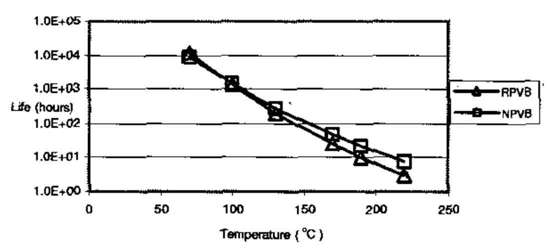

Figure 5: Thermal life-lines of black-colored PVC insulations based on weight property results.

XLPE Results

Weight property results of XLPE samples are shown in figures 6 and 7. The thermal life-lines of XLPE are obtained from the results of weight property.

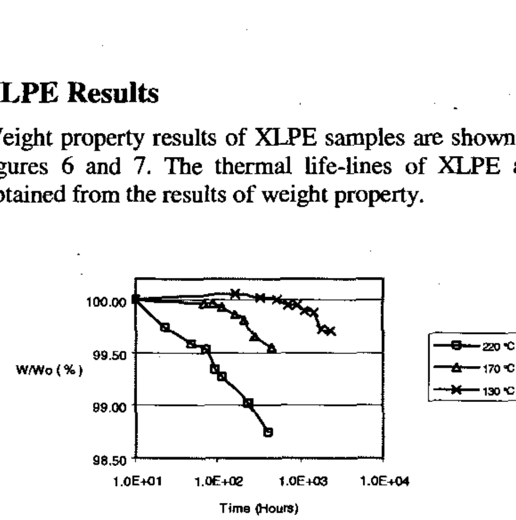

Figure 6: Weight property against aging time for RXLN.

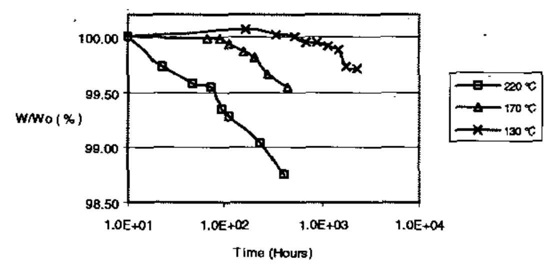

Figure 7: Weight property against aging time for NXLN.

The thermal life-lines of XLPE insulations are plotted in figure 8. The life of XLPE insulations is shortened as the temperature increases. Also, figure 8 shows the effect of the manufacturing process on XLPE insulation. The raw XLPE insulation is better than the manufactured XLPE. The manufacturing process decreases the thermal endurance of XLPE insulation.

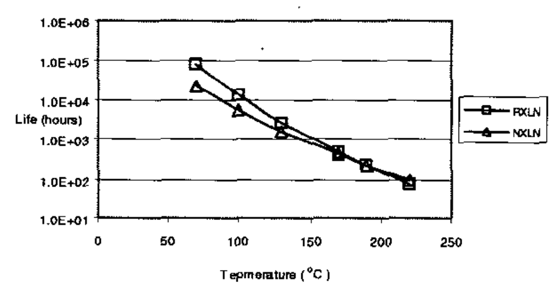

Figure 8: Thermal life-lines of XLPE insulations based on weight property results.

Comparison Between PVC and XLPE

The thermal life-lines of XLPE and PVC insulations are illustrated in figure 9 based on weight property results. It is clear that XLPE is more endurable than PVC. For example, at 100 °C XLPE lifetime is more than 10,000 hours, while PVC lifetime is around 1,000 hours. However, both XLPE and PVC insulations exhibit low thermal endurance at high temperatures.

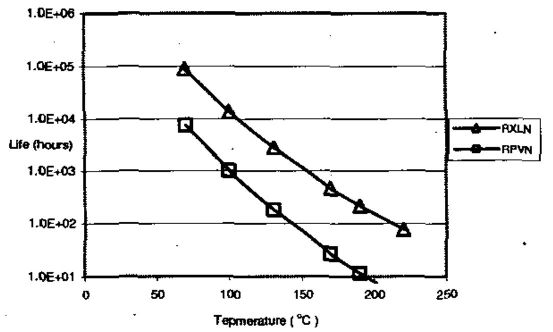

Figure 9: Thermal life-lines of PVC and XLPE insulations based on weight property.

Conclusion

Because insulating materials deteriorate with heating over time, thermal history of cable insulations is essential to predict the cable life. Thermal history consists of two factors, which are the temperature and the exposure time. Cable insulations suffer various thermal stresses in its production process and in field such as, environmental conditions and applied load variations.

The results show clear evidence that the thermal behavior of XLPE insulation is better than PVC insulation. The manufacturing process improves the thermal behavior of PVC while it affects that of XLPE. Also, the results indicate that colorants enhance the thermal resistance of the PVC insulating material.

The results of this experimental work show the following important aspects to be taken into account in the manufacturing of cable insulations. First, a caution should be taken in selecting the colorants used in PVC insulations.

Second, the manufacturing process affects the XLPE thermal behavior, while it improves the PVC insulation. This means, the processing temperature of XLPE insulation should be maintained to a lower range in order not to affect the final product of XLPE insulation. Some recommendations are to be supplied to Jeddah Cables Company whose insulating materials samples are tested.

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