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AGING INDEX AS AN INDICATOR OF DEGRADATION OF LOW VOLTAGE ELECTRICAL CABLES INSULATED BY PVC

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Abstract: Low voltage electrical cables insulated by PVC are widely used in low voltage building electrical installations. The use of these cables beyond their useful life can cause material or human damages, since under this condition the installation is subject to current leakage, short circuits and even fires. Tests currently used to evaluate end-of-life of these cables require specialized labor and high technology equipment. Thus, they are high costs tests. This paper evaluates and concludes that aging index, a low-cost test, can be confidently used to evaluate the thermal degradation of low voltage electrical cables insulated by PVC, once it presents similar results to other currently performed tests.

Keywords: Thermal degradation. Low voltage cable. Insulating plasticizers.

ÍNDICE DE ENVELHECIMENTO COMO INDICADOR DA DEGRADAÇÃO DE CABOS ELÉTRICOS DE BAIXA TENSÃO ISOLADOS POR PVC

Resumo: Cabos elétricos de baixa tensão isolados por PVC são amplamente utilizados em instalações elétricas prediais de baixa tensão. O uso desses cabos após o final de sua vida útil pode causar danos materiais ou humanos, uma vez que, nesta condição, a instalação está sujeita a fugas de corrente elétrica, curtos-circuitos e até incêndios. Os testes atualmente empregados para avaliar o fim de vida desses cabos requerem equipamentos de alta tecnologia e mão-de-obra especializada, sendo assim de custos elevados. Este artigo avalia e conclui que o índice de envelhecimento, um teste de baixo custo, pode ser usado com confiabilidade para avaliar a degradação térmica de cabos elétricos de baixa tensão isolados por PVC, uma vez que apresenta resultados similares a outros testes atualmente empregados.

Palavras-chave: Degradação térmica. Cabos elétricos de baixa tensão. Polímeros isolantes.

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1. INTRODUCTION

Most of low voltage installations use cables insulated by PVC (polyvinyl chloride) (BABRAUSKAS, 2005; KRUIZINGA; WOUTERS; STEENNIS, 2016) because it is cheap, durable and widely available. The low voltage electric cables have a limited lifetime, which is a function of the thermal degradation of insulation material (SHWEHDI; MORSY; ABUGURAIN, 2003). Degraded insulation PVC allows the occurrence of short circuits and leakage currents that can cause accidental fires if the protection devices do not interrupt them (WONG; PATHAK; YU, 2009). Thus, inspections of low voltage cables, that could estimate the degradation of the insulating material and its lifetime, would be important for corrective interventions, reducing the occurrence of fire due to faults in electrical installations.

In general, tests commonly used to evaluate the PVC degradation, spectroscopy of absorption in the infrared Fourier transform (FTIR), differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), etc., require removing PVC specimens for laboratory tests (MELO NOBREGA; BARREIRA MARTINEZ; ALENCAR DE QUEIROZ, 2013; TAWANCY; HASSAN, 2016). Mechanical tests, such as elongation-at-break (tensile strength), also require collecting specimens of the insulation (BESSISSA; MAHI, 2016; HASHEMIAN et al., 2013; VERARDI; FABIANI; MONTANARI, 2014; YORK et al., 2015). In addition, these tests have relatively high costs for predictive maintenance in residential electrical installations, according to our market research of around $ 200 per sample for each trial.

Few techniques are used in low voltage cables to detect the lifetime end because these cables do not have monitoring characteristics or symptoms. These cables do not have armor and usually the installation does not follow a particular spacing in their conduits, making unfeasible application of tests about impedance, partial discharge, capacitance or tan delta, for example (HA; LEE, 2014; HASHEMIAN et al., 2013; MELO NOBREGA; BARREIRA MARTINEZ; ALENCAR DE QUEIROZ, 2013; VILLARAN; LOFARO, 2009). So, step voltage insulation test at dc (direct current) voltage is usually performed to assess electrical insulation degradation (MEGGER, 2006; TIWANA;

REDDY, 2016). Current increase over the proportional increase of voltage in step voltage indicates aged insulation.

Aging index or step voltage test reveals aging of insulation or mechanical damage from insulating resistance measurements and analysis. While dirt, dust and moisture can be detected by traditional absorption and polarization index, an insulation weakness can be detected by comparing resistance measurements at two voltage levels, once aging or mechanical damage may not be revealed at low stress, once dielectric characteristics of the polymer electrical insulation are correlated to their thermal degradation (VERARDI; FABIANI; MONTANARI, 2014). Generally, weak insulation points fail by increasing the voltage test. Thus, the step voltage test consists on a significant increase in the test voltage in the second insulation resistance measurement. If there are weak points in the insulation, it is expected a considerable reduction in the insulation value measured (CHAUVIN ARNOUX, 2010; MEGGER, 2006).

It is recommended a ratio from 1 to 5 between voltage steps, and each step must last the same time (typically 1 to 10 minutes). The recommended maximum test voltage must not be exceeded, typically (2 U_N + 1000) V, where U_N is the nominal voltage of the cable (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1981, 2010; IEEE POWER AND ENGERGY SOCIETY, 2009; INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERS, 2014). A reduction of 25% or more between the first-step and second-step insulation resistance values is a sign of insulant deterioration usually linked to the presence of contaminants (CHAUVIN ARNOUX, 2010; MEGGER, 2006).

Insulation resistance and, consequently, aging index, can be measured by using a megohmmeter, an instrument that costs from US$ 200 up to US$ 2,000, according to our market search. By this cost, one can buy a megohmmeter that can conduct measurements under many voltage levels, a mandatory characteristic to perform aging index. Conducting the test requires no more than a few minutes, and a vessel with conductive water, enabling the insulation measurement from the conductive core of the cable against all its insulation dipped in water (ASSOCIAÇÃO BRASILEIRA DE NORMAS

ISSN: 2359-4799

TÉCNICAS, 1981). If properly planned, the test can be conducted by a professional of a lower-level educational in the electricity area.

Thus, this paper evaluates whether the aging index, which is easier to perform and cheaper than traditional laboratory tests, can be confidently used to evaluate the aging of PVC insulation of low voltage electrical cables.

2. MATERIALS AND METHODS

2.1. Thermal aging

Depending on particular application and environmental conditions, the life expectancy of low-voltage cables insulated by PVC ranges from (20 to 50) years (TAWANCY; HASSAN, 2016). This life expectancy is strongly correlated to its operational temperature (YORK et al., 2015). In general, the electric insulator has a lifetime of (20,000 to 30,000) hours when continuously subjected to its thermal class temperature (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2013; SMITH; WARD; BRINTNALL, 2017). However, mainly for research purposes, aging can be accelerated in an oven under a temperature higher than the thermal class temperature. An increase of 10 °C in aging temperature causes a 50% decrease in the expected lifetime for isolation (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2008, 2013).

In order to assess the feasibility of inspection by infrared thermography in the estimation of the thermal degradation of PVC on low voltage cables, 70 °C temperature class, it was designed an experiment that thermally degrades cable specimens through an accelerated manner (INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2008). For this experiment, the aging temperature was determined as 100 °C, 30 °C above the thermal class of the material to be studied, shortening the expecting life by a factor of 2^3, which generated a lifetime expectancy of approximately 3,750 h. Eight consecutive aging cycles of 21 days (504 hours) each were determined. Consequently, nine specimens were generated to be analyzed considering the specimen from the new cables. The experiment was conducted in a forced air circulation oven with temperature control oscillating from (95 to 100) °C. For this purpose, PVC insulated low voltage electrical cables, copper conductors, 4 mm^2

cross section, 750 V voltage class, 70 °C temperature class, of the manufacturer Sil, black and light blue colors, commonly used in living conductors of Brazilian electrical installation, were purchased on the market.

During the process of thermal aging, every 21 days aging cycle, cables specimens were taken. Those specimens were subjected to tests established in the literature to evaluate their degradation, which are considered reference tests, and the thermographic inspection that has “emissivity” as evaluated variable.

2.2. Aging tests

Many authors have studied the specific PVC degradation process. PVC can be thermally degraded by three main mechanisms: dehydrochlorination, oxidation and loss of plasticizers (TAWANCY; HASSAN, 2016). However, considering that PVC insulated cables usually operates below 70 °C, the degradation mechanisms are limited to the physicochemical events below this temperature, that is, thermal (natural) degradation by dehydrochlorination (BABRAUSKAS, 2005).

As the temperature of a sample is raised above ambient, the dehydrochlorination initial mechanism is characterized by hydrochloric acid (HCl) molecules released, and a polyunsaturated material is left which is sometimes referred to as polyacetylene. Experiments conducted on PVC wire/cable materials reported higher degradation temperatures (CHEN et al., 2015). In order to characterize cable degradation by evidence of cracks evolution, microscopic images of light blue cable samples were made throughout the aging process. The images were made with zoom 200 times by an optical microscope Leica DM750M and software Leica Application Suite Version 2.0.0. Optical microscope is an instrument used to enlarge and observe small structures that are hardly visible or invisible to naked eyes. It uses visible light and a system of glass lenses that enlarge the image of the samples. Optical microscopy can be used to study degradation of polymers by analyzing their topography (NABHA-BARNEA et al., 2016; NÓBREGA; MARTINEZ; DE QUEIROZ, 2014). To preserve samples' characteristics, no slides were removed from the coating, because in the aged samples any mechanical stress can cause or aggravate cracks, since they already have low elasticity. Therefore, samples of 3.5

ISSN: 2359-4799

cm length were extracted from the cables and analyzed in their central region, as the edges could contain additional damages due to the cable cut procedure.

Then, we conducted topography analysis by microscopic images, that reveals cracks and cavities from aging, as a reference test to evaluate PVC thermal degradation.

The proposed test to have feasibility analyzed is aging index or step voltage test (CHAUVIN ARNOUX, 2010; MEGGER, 2006), that detects insulation or mechanical damage: resistance insulation was measured at two level voltages: (500 and 1,500) Volts. The adopted aging index was the relation between insulation resistances from the two voltage levels respectively. Relations below 0.75 indicate that the insulation is non-reliable (CHAUVIN ARNOUX, 2010; MEGGER, 2006). Insulation from conductor (copper) to insulation (PVC) was measured according to recommendations from (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1981, 2010).

3. RESULTS

3.1. Reference tests for the characterization of thermal degradation

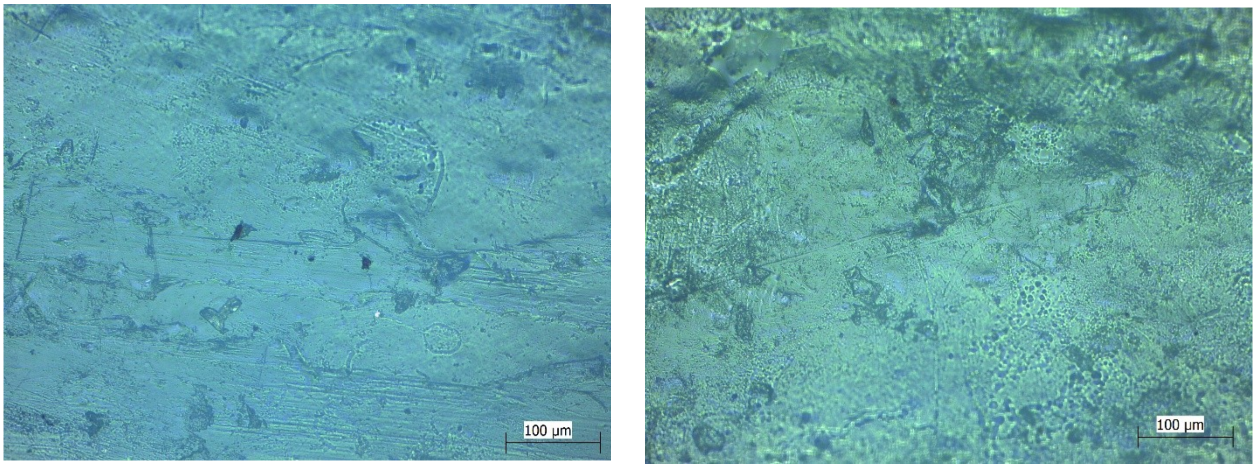
Figure 1 shows microscopic images of light blue cable samples throughout the thermal degradation process. In (a), referring to the sample of new cables not degraded, it is possible to observe superficial grooves originating from handle of the cable. As surfaces of the samples are observed throughout the aging process, the presence and the intensification of cracks along the entire surface, as well as of cavities, are noted.

The presence of cavities is a symptom of thermal degradation of the cables, as they would be evidence of water vapor and other gases release during aging (MELO NOBREGA; BARREIRA MARTINEZ; ALENCAR DE QUEIROZ, 2013).

Aging index values below 0.75 indicates that the insulation material is degraded and non-reliable (CHAUVIN ARNOUX, 2010; MEGGER, 2006). Figure 2 shows the aging index for black PVC cables, from where one can conclude that aging index predominantly indicates thermal degradation for the last samples by values below 0.75 from 105 days aged samples. Tables 1 and 2 show aging index for black and light blue PVC insulation cables, respectively.

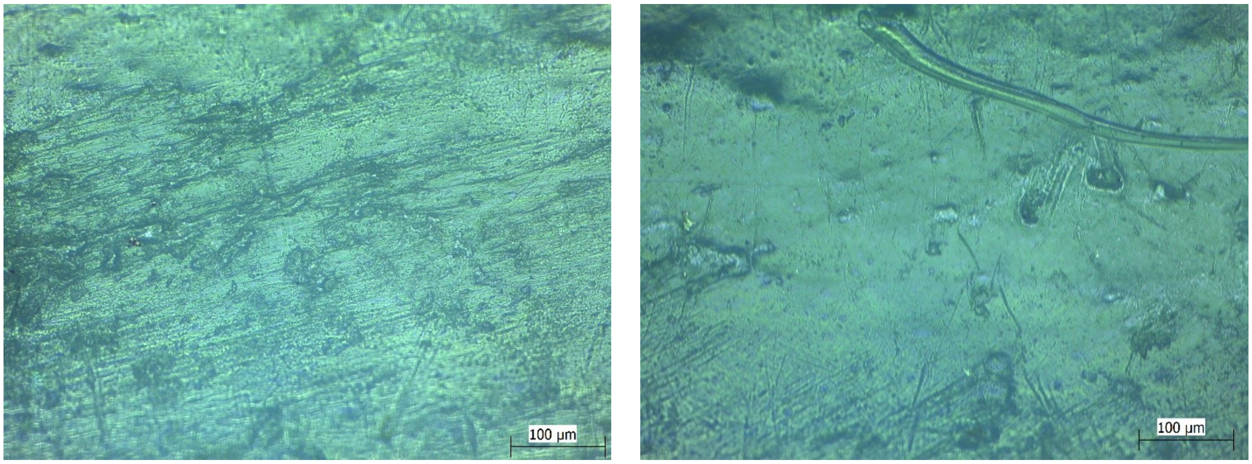
ISSN: 2359-4799

Figure 1 – microscopic images of light blue cable samples.



(a) not aged cable – grooves from handle.

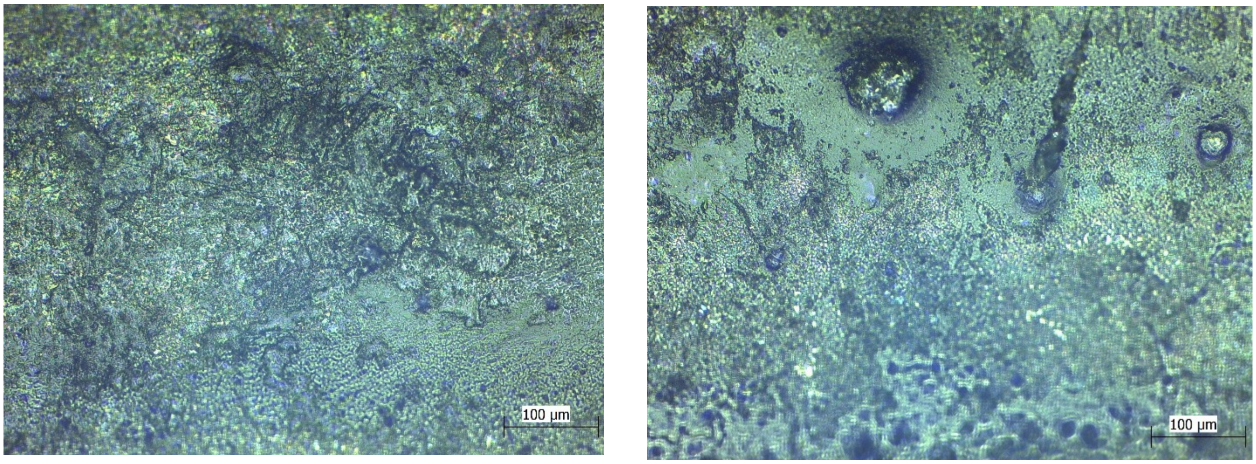
(b) 42 days aged cable – some cracks.



(c) 84 days aged cable – some cracks.

(d) 105 days aged cable – some cracks.

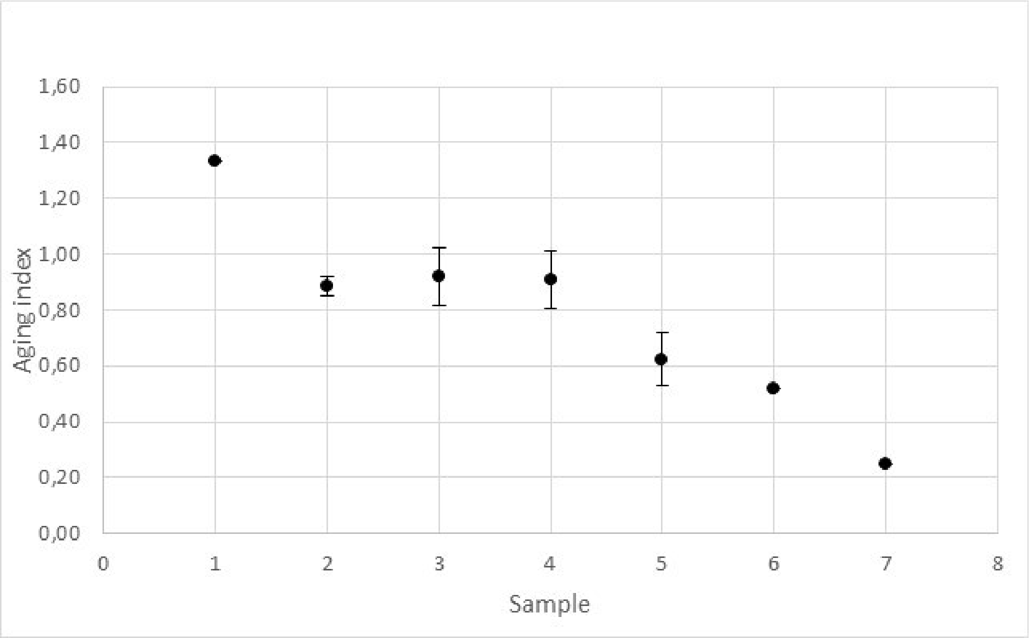
ISSN: 2359-4799



(e) 126 days aged cable – cracks and cavities.

(f) 168 days aged cable – cracks and cavities.

Figure 2 – Aging index for black PVC cables.



Microscopic images revealed presence of cavities in PVC insulation samples, a symptom of thermal degradation, from 126 aged days. Aging index indicates that insulation samples were degraded from 105 aged days. Thus, in an accelerated aging process lasting about 126 days, the reference test (microscopic image analysis) and the under validating test (aging index) showed conclusive time difference of just one sampling interval, 21 days. Thus, aging index presents reliable results for the analysis of thermal degradation of low voltage electrical cables insulated by PVC.

Table 1 – Aging index – black PVC cables.

Sample #	Aging time /days	Aging index (mean ± st. dev.)
1 (new)	0	1.34 ± 0.00
2	21	0.89 ± 0.33
3	42	0.92 ± 0.10
4	63	0.91 ± 0.10
5	84	0.62 ± 0.09
6	105	0.52 ± 0.00
7	126	0.22 ± 0.12
8	168	0.25 ± 0.00

Table 2 – Aging index – light blue PVC cables.

Sample #	Aging time /days	Aging index (mean ± st. dev.)
1 (new)	0	1.25 ± 0.00
2	21	0.94 ± 0.09
3	42	0.87 ± 0.12
4	63	0.97 ± 0.02
5	84	0.76 ± 0.05
6	105	0.59 ± 0.00
7	126	0.12 ± 0.18
8	168	0.36 ± 0.16

4. CONCLUSION

Microscopic images characterize thermal degradation by revealing evolution of cracks and cavities that are symptoms of PVC insulating degradation. By identifying cavities on PVC surface, a thermal degradation symptom, one can diagnose the material aging.

Aging index presented adequate results to indicate the end-of-life of low voltage electrical cables insulated by PVC. This test is simple to be performed, requiring no highly skilled labor, and relatively inexpensive instruments. Therefore, aging index can confidently replace other tests at, probably, a lower cost.

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ISSN: 2359-4799

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