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Dielectric and Mechanical Behavior of Thermally Aged EPR/CPE Cable Materials

Aishwarya Sriraman

Iowa State University, saish@iastate.edu

Nicola Bowler

Iowa State University, nbowler@iastate.edu

S.W. Glass

Pacific Northwest National Laboratory

Leonard S. Fifield

Pacific Northwest National Laboratory

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Abstract

Power and instrumentation cables play a crucial role in the safe operation of Nuclear Power Plants (NPPs). Thermal and other stressors present in the reactor environment cause the cable materials to degrade. In this work, dielectric and mechanical properties of cable insulation and jacket materials are studied as they are thermally aged, supporting development of non-destructive evaluation sensors for monitoring cable aging. Materials selected for this study are found in certain types of single-core unshielded power cables. These utilize ethylene propylene rubber (EPR)-based insulation material and chlorinated polyethylene (CPE)-based jacket material. Flat mats of these materials were obtained from the cable manufacturer and thermally aged at 140 °C in an air-circulating oven. Elongation-at-break was measured on tensile specimens stamped from the aged mats, and dielectric properties were measured from 100 Hz to 100 kHz using a parallel plate capacitor and precision LCR meter. In the case of aged EPR-based materials, rapid decrease in elongation at break indicating end of useful life was accompanied by a significant increase in dissipation factor, D , measured at 100 kHz. Capacitive measurement of D shows promise, therefore, as a non-destructive indicator of corresponding mechanical property changes in thermally-aged EPR-based insulation materials.

Keywords

Aging, Dielectrics, Permittivity, Cable insulation, Permittivity measurement, Power cables

Disciplines

Materials Science and Engineering | Power and Energy

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Dielectric and Mechanical Behavior of Thermally Aged EPR/CPE Cable Materials

Aishwarya Sriraman¹, Nicola Bowler¹, S.W. (Bill) Glass², Leonard S. Fifield²

¹Iowa State University, Iowa, 50011, USA

²Pacific Northwest National Laboratory, Washington, 99354, USA

Abstract- Power and instrumentation cables play a crucial role in the safe operation of Nuclear Power Plants (NPPs). Thermal and other stressors present in the reactor environment cause the cable materials to degrade. In this work, dielectric and mechanical properties of cable insulation and jacket materials are studied as they are thermally aged, supporting development of non-destructive evaluation sensors for monitoring cable aging. Materials selected for this study are found in certain types of single-core unshielded power cables. These utilize ethylene propylene rubber (EPR)-based insulation material and chlorinated polyethylene (CPE)-based jacket material. Flat mats of these materials were obtained from the cable manufacturer and thermally aged at 140 °C in an air-circulating oven. Elongation-at-break was measured on tensile specimens stamped from the aged mats, and dielectric properties were measured from 100 Hz to 100 kHz using a parallel plate capacitor and precision LCR meter. In the case of aged EPR-based materials, rapid decrease in elongation at break indicating end of useful life was accompanied by a significant increase in dissipation factor, *D*, measured at 100 kHz. Capacitive measurement of *D* shows promise, therefore, as a non-destructive indicator of corresponding mechanical property changes in thermally-aged EPR-based insulation materials.

I. INTRODUCTION

Degradation as a result of thermal and radiation damage of electrical insulation has been identified as one of the major causes for the aging and ultimate failure of power cables in a nuclear power plant (NPP). Given that there are over 600 miles of such power cables installed in a NPP, it becomes crucial to identify the nature and determine the extent of degradation in cable insulation and jacket materials, while still operating [1]. Ethylene propylene rubber (EPR) is one of the most widely employed materials for medium- and low-voltage cable insulation in NPPs. This work investigates the dielectric and mechanical response of thermally-aged EPR to determine the extent of degradation and assess the effectiveness of dielectric response as a potential non-destructive indicator of aging in samples aged at 140 °C for up to 70 days. To assess the effect of the presence of cable jacket upon the aging of EPR, one set of EPR samples was aged in the presence of chlorinated polyethylene (CPE), a common cable jacket material. Separate CPE-based samples were also aged and tested.

II. SAMPLE PREPARATION

A. EPR Insulation and CPE Jacket Material

Pressed mats of pink EPR-based cable insulation and black CPE-based jacket material, with trade names Okoguard® and Okolon®, respectively, produced by The Okonite Company, were obtained directly from the manufacturer. These mats were cut into squares with dimensions of approximately 51 x 51 x 1.6 mm³ (EPR) and 51 x 51 x 2.0 mm³ (CPE) for dielectric testing, while tensile dog-bone specimens were stamped from the pressed mats using a one-half scale Die C geometry die from NAEF Press & Dies, Inc.

B. Accelerated Aging

The samples were suspended from a rack in an air-circulating oven maintained at a constant temperature in order to induce aging representative of long-term oxidative thermal aging that the material might experience under normal nuclear power plant operating conditions. Two sets of EPR samples were aged at 140 °C, (i) EPR samples aged for up to 70 days (10 weeks) in the absence of CPE jacket material, denoted 'EPR', and (ii) EPR samples aged for up to 49 days (7 weeks) in the presence of CPE which caused blackening of the EPR, denoted 'EPR-b.' Scanning electron microscopy (SEM) with energy dispersive spectrometry (EDS) analysis was conducted to characterize the black deposit on the surface of EPR-b, confirming that a major component is chlorine, which outgassed from the CPE material during the aging process, Fig. 1. CPE samples were aged at 140 °C for up to 35 days. Sample thickness was measured at ten locations on each sample, using a Fowler Ultra Digit Mark IV micrometer with systematic uncertainty of 1 μm, and the mean thickness values with standard deviation were computed.

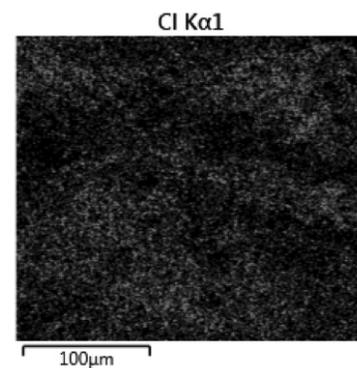


Fig. 1. A dot map obtained by EDS analysis showing the presence of chlorine on the blackened surface of EPR-b aged for 49 days at 140 °C.

III. EXPERIMENTAL MEASUREMENTS

A. Elongation at Break (EaB)

Tensile elongation at break (EaB) data was obtained by following ASTM D412 procedure, using a Lloyd instruments® (Ametek®) LFPlus testing machine with NEXYGEN DF software and a grip separation rate of 127 mm/min. Video extensometry was used to measure strain from an initial nominal gauge length of 15 mm. Three replicates were measured and the average value determined for each aging condition.

B. Dielectric Spectra

Broadband relative permittivity and dissipation factor were measured using an Agilent E4980A Precision LCR Meter with Agilent 16451B test fixture. The test fixture employs a 56-mm-diameter unguarded electrode and a connected 38-mm-diameter guarded electrode, which together form a parallel plate capacitor. Capacitance (C) and dissipation factor (D) were measured with the electrodes positioned at three different regions on each sample, over the frequency range 100 Hz to 100 kHz. Electrode separation was measured for each trial, in order to compute the relative permittivity of the sample from C according to the familiar formula $C = \epsilon\epsilon_0 A/s$ wherein ϵ is the relative permittivity of the sample, $\epsilon_0 = 8.85419 \times 10^{-12}$ F/m is the permittivity of free space, A is the area of the smaller electrode and s is the separation between the electrodes. A high frequency laminate, RO3003™ by Rogers corporation, with relative permittivity 3.00 ± 0.04 (at 10 GHz) [2] was used as a reference standard for bias correction. In the dielectric spectra obtained, the reported uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 1$, providing a level of confidence of approximately 68%, computed in accordance with NIST standards [3][4].

IV. RESULTS AND DISCUSSION

A. Dielectric Properties

1) EPR aged in the absence of CPE

The measured relative permittivity and dissipation factor of EPR are plotted in Fig. 2 as a function of frequency. For all samples tested, EPR displays the beginning of a broad relaxation over the four decades of frequency measured. EPR is predominantly a copolymer with a stable saturated backbone, that provides for good thermo-oxidative stability, and unsaturated side groups that promote inter-chain crosslinking. As a consequence of this structure, during the thermal aging process, backbone degradation due to chain scission is opposed by inter-chain cross linking of the rubber vulcanizate. Cross-linking processes contribute to a decrease in EPR permittivity whereas chain scission causes it to increase. At sufficiently long aging times, chain segment mobility increases with increasing chain fragmentation, and dipoles become free to orient with the applied electric field resulting in an overall increase in ϵ with aging time. The dissipation factor, Fig. 2(b), is representative of the viscous (loss) versus elastic (storage) behavior of the polymer, and an

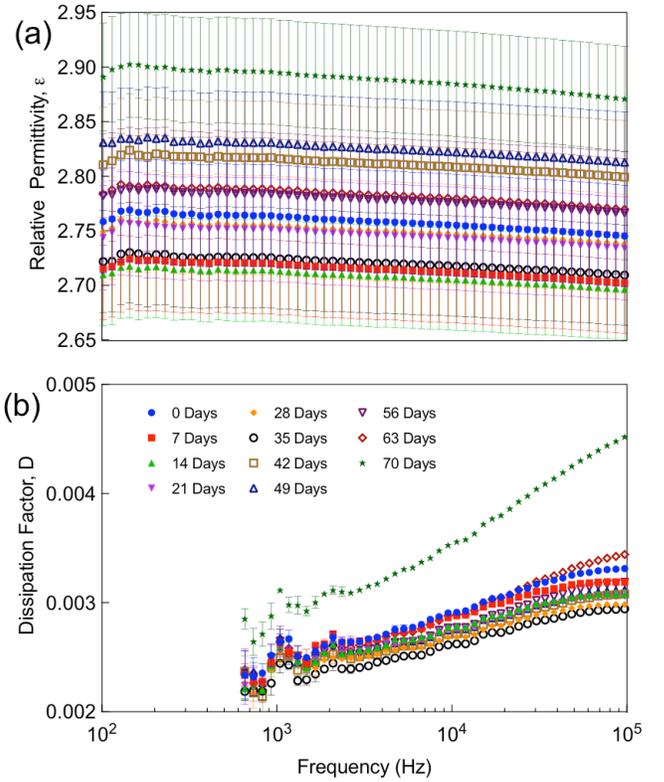


Fig. 2. Measured (a) relative permittivity and (b) dissipation factor of EPR thermally aged at 140 °C for up to 70 days. For frequencies less than 600 Hz, dissipation factor values fell below the range measurable by the instrument.

increase in its value with aging time indicates chain scission and increased dipole mobility [5]. Consequently, an increase in D reflects a decline in insulating ability.

The low values of D, and small changes in ϵ observed over the entire range of aging times tested, demonstrate the excellent thermal stability exhibited by EPR. The significant increase in the values of permittivity and dissipation factor measured on the most aged EPR sample (70 days), as compared to those for samples with shorter aging times, coincides with a complete loss of elasticity as discussed in Section IV.B.

2) CPE

CPE may be considered a terpolymer consisting of i) ethylene, ii) vinyl chloride, and iii) vinylidene chloride monomeric units [6]. When exposed to high temperatures, CPE is observed to undergo dehydrochlorination as a consequence of thermo-oxidative degradation leading to loss of mechanical properties [7]. Fig. 3 shows the dielectric spectra of thermally aged black CPE mats. Unaged CPE is observed to have considerably higher permittivity ($\epsilon = 5.65 \pm 0.05$, at 10 kHz) than pristine EPR ($\epsilon = 2.75 \pm 0.05$, at 10 kHz). In Fig. 3(a), a significant decrease in relative permittivity with increase in frequency is observed in CPE for both aged and unaged samples. Over the entire frequency range, permittivity and dissipation factor are found to predominantly increase with aging time.

This behavior can be attributed to fragmentation of the saturated backbone, followed by breakdown due to thermal degradation during which dehydrochlorination at backbone sites occurs simultaneously with oxidation. This breakdown is reflected in a dramatic change in the dielectric constant of samples aged for 28 and 35 days, suggesting end of useful life. The rapid decline in ϵ observed in the frequency range from 100 Hz to 10 kHz is accompanied by a relaxation peak observable in dissipation factor for the aforementioned samples, Fig. 3(b). The rapid decrease in ϵ and corresponding peak in D in the 100 Hz to 10 kHz frequency range is a prominent feature of the dielectric response of CPE. The relaxation process within this frequency range may be attributed to the C-Cl dipoles of the vinyl chloride groups in the rubber. The local movements of the vinyl chloride groups are identified as contributors to a β relaxation process in the 10 kHz to 100 kHz frequency range [8]. Further understanding of this process in CPE requires information about the dielectric response at higher frequencies. For lower aging times, D is seen to increase almost linearly with increasing frequency. Further, the relatively quick breakdown of the material within a very short aging period of 28 days shows its lower thermal stability as compared to EPR for which end of useful life is observed only at 70 days of aging at the same temperature.

3) EPR-b aged in the presence of CPE

The dielectric response of aged EPR-b is plotted in Fig. 4. By contrast with EPR, Fig. 2, for which a small but significant increase in ϵ of approximately 0.14 and in D of approximately 0.001 is observed for the most heavily aged sample (70 days aging), it is seen in Fig. 4(a) that there is larger increase in permittivity with aging time, of approximately 0.36 for the most heavily aged sample (49 days) and dramatic changes in D are observed. The increase in permittivity observed for the sample aged for 49 days suggests that the material undergoes thermal breakdown earlier and more severely than EPR aged in the absence of CPE, which displays good thermal stability until 70 days aging time, Fig. 2. Comparing Figs. 4(a) and 3(a) some similar features are observed. The rapid decline in ϵ as frequency increases from 100 Hz to approximately 1 kHz is observed in both CPE and EPR-b for samples aged for 21 and 28 days, for example. Further, the dissipation factor trend seen in Fig. 4(b) indicates participation of the black chlorine-based deposit in the overall dielectric response of the EPR-b material. No clear trend is immediately apparent in the change of permittivity with aging time due to the multiple aging mechanisms occurring simultaneously in the black deposit layer and EPR itself, likely including rapid chain scission, macromolecular mobility and chain oxidation. Additionally, dissipation factor values for EPR-b lie between those of EPR, Fig. 2(b), and CPE, Fig. 3(b), also suggesting multiple contributions to property changes as the aging process takes place. The dissipation factor for EPR-b is larger by up to an order of magnitude when compared to that of EPR, indicating a significant loss in insulating performance for EPR samples aged in the presence of CPE compared with those that are not.

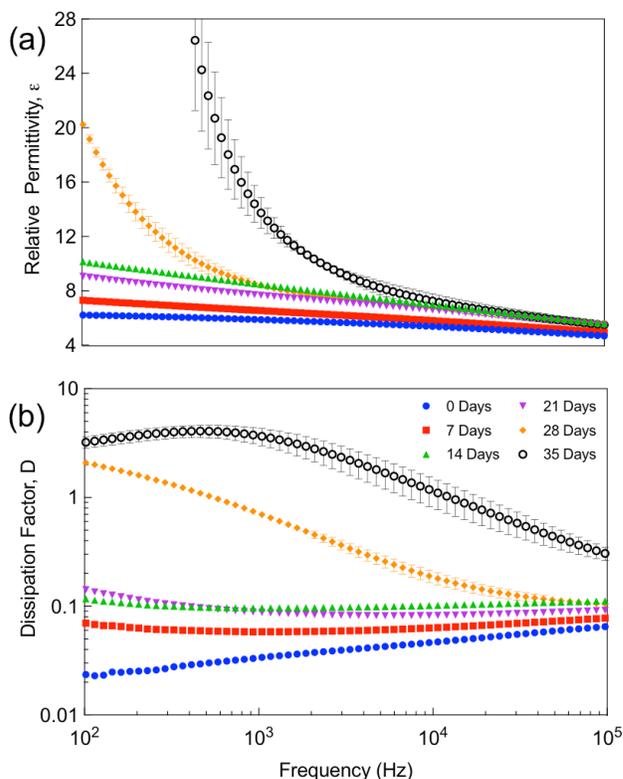


Fig. 3. Measured (a) relative permittivity and (b) dissipation factor of CPE thermally aged at 140 °C for up to 35 days.

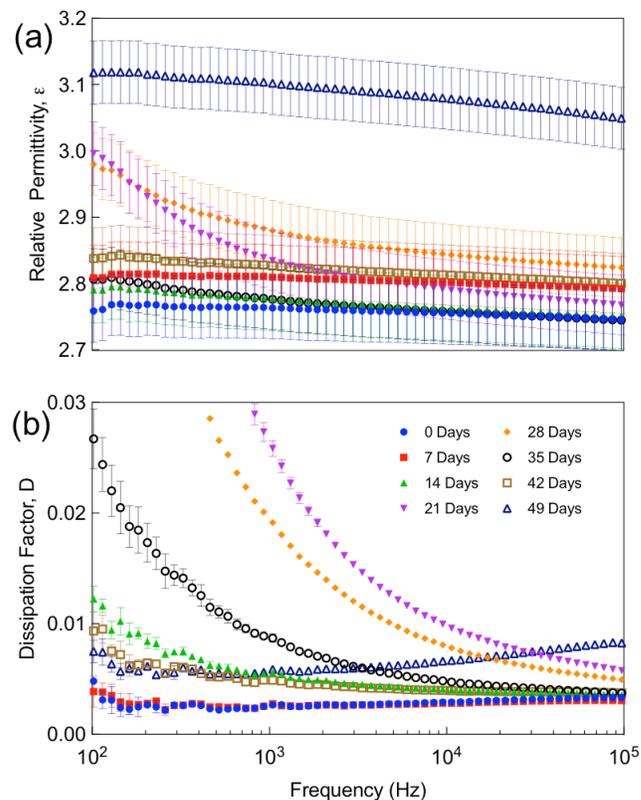


Fig. 4. Measured (a) relative permittivity and (b) dissipation factor of EPR-b thermally aged in the presence of CPE at 140 °C for up to 35 days.

B. Mechanical and Electrical Property Changes

Figures 5, 6 and 7 illustrate the change in EaB and D, measured at 100 kHz, with aging time for EPR, CPE and EPR-b respectively. For EPR, Fig. 5, EaB remains constant whereas D declines only slightly as aging proceeds for up to 35 days. A decline in EaB is observed starting at 42 days of aging while an increase in dissipation factor begins at 42 days. This indicates that the chemical changes in EPR that contribute to the change in the macroscopic mechanical properties of the material also influence the dielectric response. Furthermore, a dramatic increase in dissipation factor corresponds to the almost complete loss of EaB at 70 days. In the case of CPE, Fig. 6, EaB declines rapidly becoming negligible by 21 days of aging. Dissipation factor increases at 35 days of aging, for CPE. In the case of EPR-b, Fig. 7, the subtle changes in EaB are more exaggerated and clearly apparent in the changes in D. The drastic drop in EaB at 49 days indicating end of useful life of the material is also reflected in the considerable increase in D measured on the same sample.

V. CONCLUSION

In this work, the dielectric and mechanical properties of EPR-based insulation and CPE-based jacket materials commonly used in low- and medium-voltage NPP cables have been studied during accelerated thermal aging. It was observed that EPR-based insulation materials exhibit good stability for up to 35 days of aging at 140 °C, after which they exhibit significant mechanical and dielectric property changes. The observed increase in D measured at 100 kHz and the observed decline in EaB as a function of aging time follow corresponding trends, for EPR-based insulation materials. It can be concluded that dielectric spectroscopy may be an effective technique for the non-destructive monitoring of these EPR-based cable insulation materials under operating conditions. On the other hand, EaB measured on CPE samples aged at 140 °C declines immediately whereas D measured at 100 kHz on the same samples increases significantly only after 35 days of aging. Building upon the observed significant changes in properties of EPR-b aged in the presence of CPE, compared with those of EPR aged in air only, further work is planned to elucidate any interactions between the jacket and insulation materials under conditions of thermal aging, that may include cross-diffusion of species.

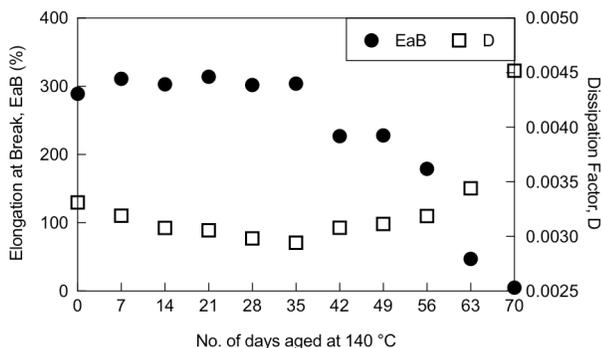


Fig. 5. Measured D at 100 kHz and EaB of EPR aged at 140 °C.

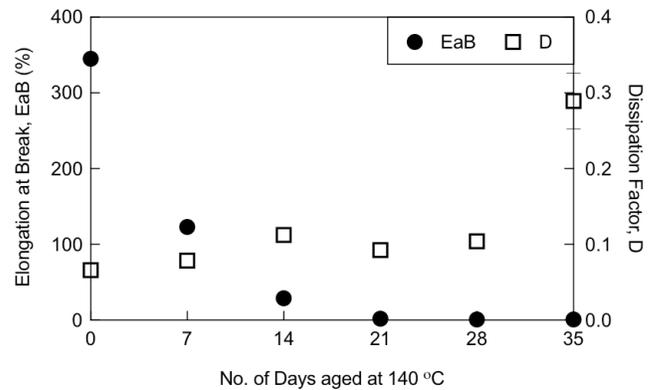


Fig. 6. Measured D at 100 kHz and EaB of CPE aged at 140 °C.

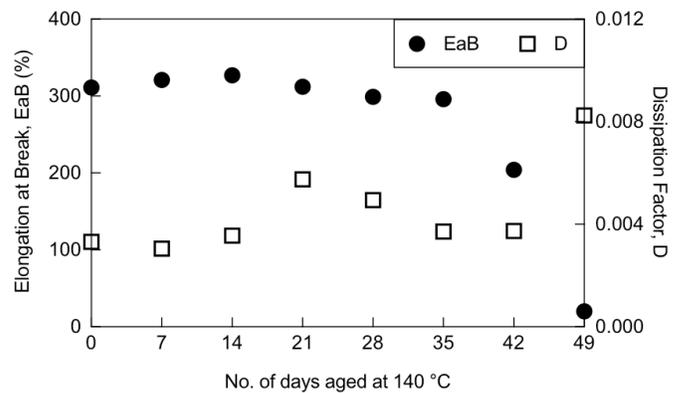


Fig. 7. Measured D at 100 kHz and EaB of EPR-b aged at 140 °C.

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