

## ENVIRONMENTALLY SOUND LEAD-FREE INSULATION MATERIAL FOR MEDIUM VOLTAGE ENERGY CABLES

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### ABSTRACT

*Traditionally, tree-retardant crosslinked polyethylene (TR-XLPE) and crosslinked ethylene-propylene rubber (EPR)\* filled insulations are extensively used to insulate medium voltage power cables. For the past two decades, environmental initiatives (including proposed RoHS initiative, REACH) and legislation around the globe (especially in Europe) drives research and development initiatives to eliminate lead stabilizers completely from "fairly conservative" medium voltage filled insulation energy cables. Our recent study on a full size cable has proven that this unique environmentally sound "lead-free" materials technology offers better flexibility, superior thermal stability and similar wet electrical performance as a standard "leaded" filled EPR insulation.*

*This paper will examine the suitability of a new generation "lead-free" filled ethylene alkene insulation material and will provide cable test data in comparison to traditional EPR based filled insulation available today. Test data will include Association of Edison Illuminating Companies (AEIC) and Insulated Cable Engineers Association (ICEA) standards qualification data, among others.*

### KEYWORDS

Lead-Free, RoHS, Medium Voltage Cable, Filled Insulation, Ethylene Alkene Copolymer

### INTRODUCTION

Thermoset polymer insulated power cables have been in service for at least four decades. The medium voltage filled insulation market is dominated by EPR based leaded insulations. A successful insulation formulation published by DuPont has been used in the cable industry for years [1]. Additional developments around this formulation have resulted in many variations of the formulation designed to optimize properties. However, recent demanding product requirements and environmental concerns have required more significant changes to the base polymer and stabilization package. An alternate base polymer may produce a compound with differentiated properties in some applications. In addition, future developmental work is being pushed towards lead-free compositions to comply with environmental concerns.

\*The designation EPR is generally used to describe an ethylene propylene copolymer, where the terpolymer of ethylene, propylene and diene monomer is referred to as EPDM. This paper will use the nomenclature EPR to describe resins with ethylene and propylene components, regardless of their diene monomer content, as accepted in industry specifications.

### Ethylene Alkene Copolymer (EAM)

Historically, filled medium voltage insulations have been made with a base polymer of ethylene propylene rubber (EPR). With polymer catalyst technology advances, increasingly diverse comonomers can be incorporated while still maintaining control over polymer architecture, molecular weight, and polydispersity. More polymer choices are becoming available that may meet the demanding physical and electrical requirements of medium voltage products. Butene, hexene and octene are among the comonomers that can be polymerized with an ethylene backbone to produce longer chain branches. These materials are referred to as ethylene alkene copolymers, with the designation of EAM. As the length of the comonomer changes, a greater amount of flexibility is incorporated into the compound [2], potentially providing a significant advantage during cable installation.

### The Role of Lead

Medium voltage power cables are expected to perform and maintain their properties in harsh environments. To meet these requirements, varying fillers and additives are incorporated into polymers to allow for adequate aging performance, electrical properties and processability. Red lead oxide is commonly used as a stabilizer in insulation compounds due to its ability to act as an anion scavenger. Anions may arise in the compound from residual catalyst [3]. Previous work has shown that bowtie trees are initiated at catalyst residue sites and degrade and weaken the insulation at this point [4]. Filled insulations tend to possess inherently higher ionic character than unfilled polyethylene due to the presence of ions in the fillers themselves [5]. This can result in inferior electrical properties, including dissipation factor. Without the addition of lead oxide or alternative stabilization, cables with filled insulation would be prone to physical degradation at elevated temperatures and in wet environments, and unstable electrical properties.

The Restriction of Hazardous Substances Initiative (RoHS) calls for reduced lead concentration (< 0.1%) in many electric and electronic products [6]. Medium voltage cables are not covered in this initiative due to their elevated operating voltage. However, the dangers and health concerns associated with lead are well documented, and actions to remove this harmful product from cables are an important step towards a more environmentally conscious product.

As well as being environmentally acceptable, a lead-free cable must meet the demanding requirements of the industry and should perform similarly to current compositions which do contain lead. Previous work has shown this is not a simple task. An attempt to simply remove the lead from a commercial insulation resulted in a product that had poor wet aging performance [7],

proving that an alternate stabilization package is necessary.

In order to compensate for the advantages lead provides, a hindered amine light stabilizer (HALS) has been incorporated in a modified stabilization package. HALS acts to trap free radicals, with the additional benefit that it is a cyclical reaction that can lead to long term stability [8].

In this work the properties of lead-free EAM and EPR based cable compounds with proprietary stabilization packages are compared. The properties of these materials are designed to meet or exceed those of a commercial, leaded EPR counterpart.

## EXPERIMENTAL

### Thermal Aging

Plaque samples were produced by press curing compound at 177°C. Heat aging samples were dried from these plaques and placed in a 136°C, ASTM D573 oven calibrated at 100 to 200 air exchanges per hour. Five samples were removed and tested weekly and compared to initial tensile and elongation results. All samples were pulled at a rate of two inches per minute per ASTM D638. The ICEA S-94-649-2004 Standard requires 75% retention of properties after one week. Testing was continued to five weeks to demonstrate heat aging stability.

### Flexibility Testing

Insulation samples were removed from a cable sample and processed to a specimen four inches long, a half inch wide, and 0.075 inches thick. The samples were flexed at a rate of 0.5 in/min while the force to bend these samples by 0.25 total inches was measured, as specified in ASTM D790.

### High Voltage Time Test and Water Tree Assessment

The performance of lead-free EAM and EPR cables were assessed by means of the high voltage time test (HVTT) procedure associated with an ICEA cable core qualification test conducted to the S-94-649-2004 Standard [9]. The ICEA core qualification test includes the accelerated water treeing test (AWTT) and this was performed on both cable types. Prior to entry into AWTT, cables were dry preconditioned for 14 days under a load cycling profile of 130°C conductor temperature, for 8 hours on and 16 hours off. In the AWTT, cables are aged in water at 150V/mil (5.9kV/mm) average stress, with load-cycling 5 days per week to achieve a 45°C insulation shield surface temperature in water for 120, 180 and 360 days. After each aging period, the cables are subjected to ac voltage breakdown strength testing in a 5-minute step-rise high voltage time test. HVTT results from load-cycled specimens are also shown in Figure 4 as aging time zero. After aging, the cable samples were examined to identify the length and density of trees present in the insulation, an indication of the degradation caused during aging.

### Hot Impulse Testing

Hot impulse testing involves heating the cable conductor to emergency overload temperature and subjecting the samples to increasing negative impulse voltages until failure after an initial conditioning procedure is complete. This test is carried out before and after a 14-day thermal load cycling profile, of 130°C conductor temperature during the last four hours of the eight hours of current applied in each 24-hour period.

### Dry Electrical Ageing

Dry electrical testing in accordance with the ICEA S-94-649-2004 Standard monitors the dissipation factor at various temperatures for an extended time. Samples are current loaded to 140°C conductor temperature and maintained at rated voltages for the length of the test. Requirements state that the dissipation factor measured over any three-week period cannot result in a difference greater than 10% of the original measurement of that period.

## RESULTS AND DISCUSSION

### Physical Testing

EPR insulations have been valued for their thermal stability and oxidative stability due to its saturated backbone which inhibits degradation [10]. The addition of lead is known to further improve this property [11].

Figures 1 and 2 show that lead-free EPR insulations can match the heat aging performance of a leaded counterpart. Furthermore, a change to an EAM based insulation system will not negatively affect the performance. EAM insulation systems have inherently higher elongation and the ability to retain this property through high temperature aging, as depicted in Figure 1. Figure 2 illustrates the ability of all the tested samples to retain their initial tensile strength.

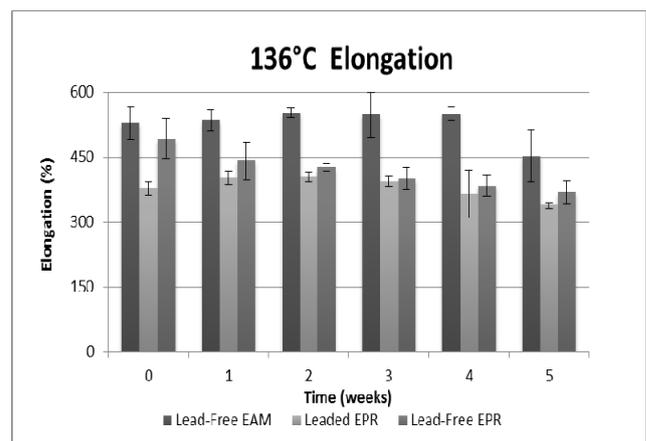


Fig. 1: Elongation Comparison at 136°C

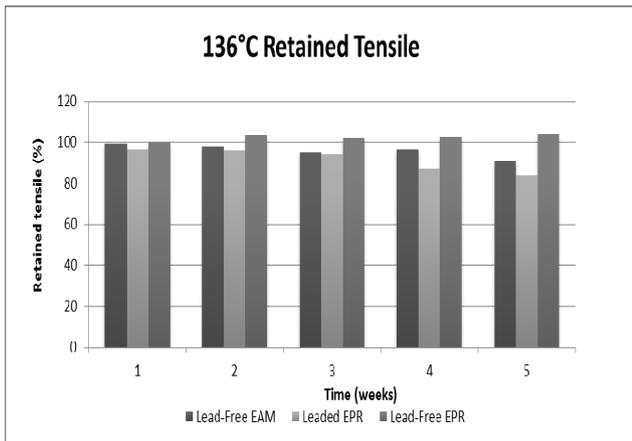


Fig. 2: Retained Tensile Comparison at 136°C

The butene or octene groups common in commercial EAM insulations provide a longer side chain when compared to EPR compounds. This arrangement imparts increased flexibility, a potentially valuable property for power cables. Figure 3 shows that the EAM compound has a 33% reduction in flex modulus compared to the leaded EPR insulation.

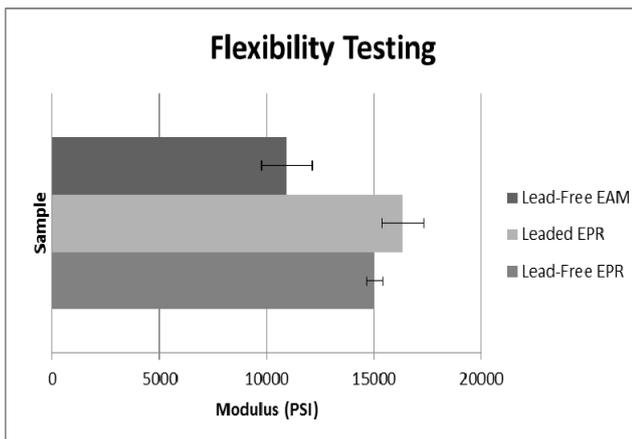


Fig. 3: Flexibility Comparison

**Qualification Testing**

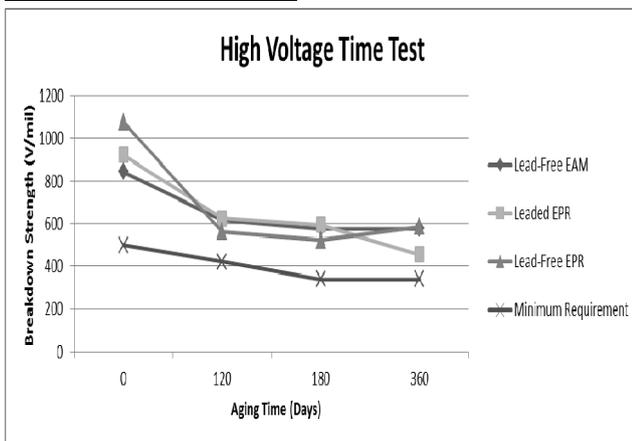


Fig. 4: ICEA AWTT High Voltage Time Test

Figure 4 depicts the eta value obtained through Weibull statistics of the three specimens on test. Data shows that the performance of the leaded and lead-free EPR compounds closely follow the same trend, illustrating that a lead-free cable can maintain similar wet electrical performance to a control leaded cable.

EAM cables show slightly lower initial, cyclic aged breakdown strength than EPR insulations. However the breakdown strength is retained remarkably well over the course of the aging. After 360 days wet aging, the EAM insulation retains 68% of its initial breakdown strength, in comparison to only 49% retained by the leaded EPR. This shows EAM insulations can endure the harsh conditions of this test with less degradation in properties compared to EPR cables.

Tree counts, as described by AEIC CS8-07 were obtained for each AWTT aging period. Figure 5 shows that there were bowtie trees present after aging, but a low amount of trees were observed in all samples. No trees were found after 120 day AWTT, and no trees greater than 20mils (0.51mm) were observed throughout the duration of the test.

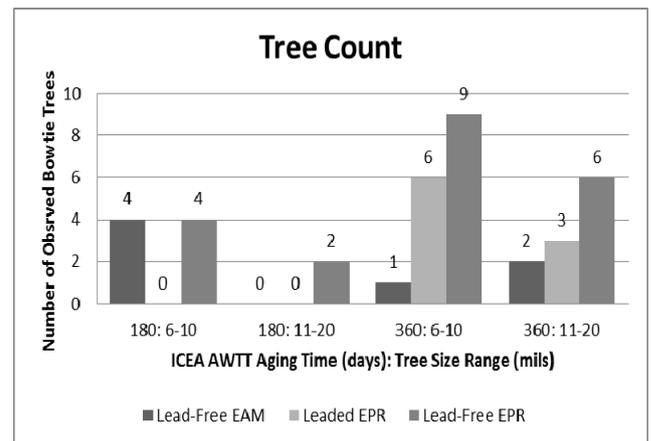


Fig. 5: Comparison of AEIC Bowtie Tree Count

In the hot impulse test, both lead-free formulations displayed a slightly lower strength than the leaded compound. All samples retained their initial strength very well and passed the minimum requirement of 800V/mil (31.5kV/mm), as depicted in Figure 6. The results depicted are Weibull eta values of three samples.

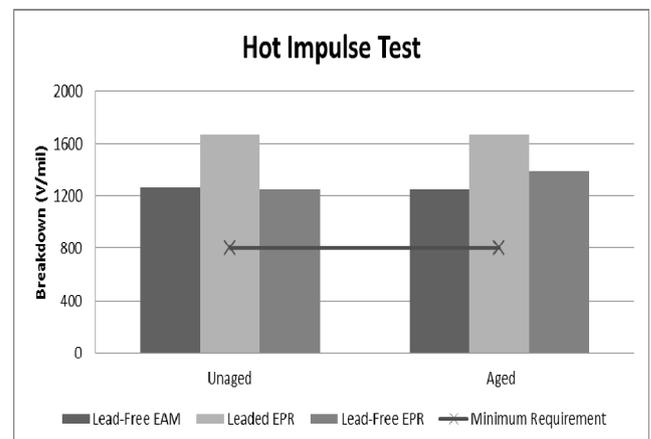


Fig. 6: ICEA Hot Impulse Test

Dissipation factor represents the amount of energy lost as heat in the insulations. This can significantly impact the operating cost of a system if not controlled.

Lead-free EPR insulations show continued passing results through the fifth week of testing when tested as described by ICEA S-94-649-2004. Results at 105°C show a slight rise in dissipation factor that result in values above the stability criteria. The ambient temperature readings remained very consistent over the length of the test. The results are depicted in Figure 7.

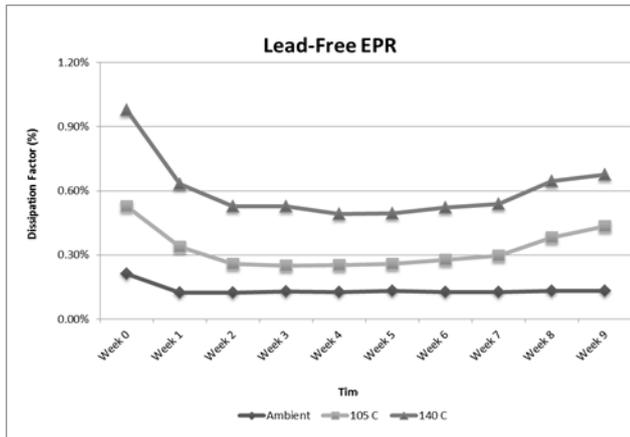


Fig. 7: ICEA Dry Electrical Test of Lead-Free EPR

After initially meeting passing criteria at week three, the EAM cables show a slight rise in dissipation factor. However, the data stabilized and met the test requirements from week seven to the conclusion of the test, as seen in Figure 8.

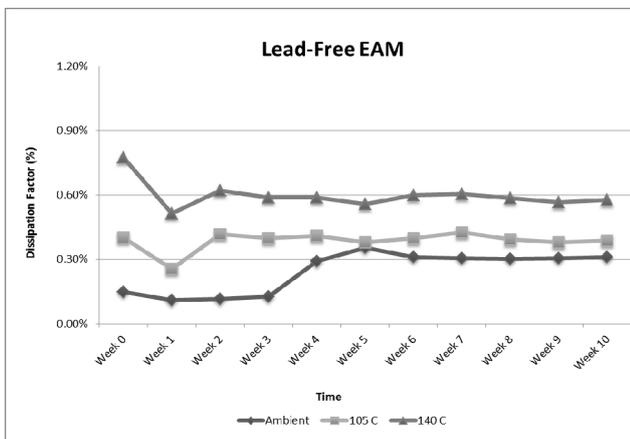


Fig. 8 : ICEA Dry Electrical Test of Lead-Free EAM

## CONCLUSION

Product requirements and environmental regulations have necessitated new compound development for filled medium voltage insulations. These changes cannot be made at the expense of product performance and any new compounds must show similar or superior properties to current commercial compounds. Lead-free EPR insulations showed similar heat aging and ICEA qualification performance to a leaded EPR insulation compound. A compound based on an EAM polymer showed significant improvements in elongation, flexibility,

and wet electrical aging performance. This work shows that the lead-free compounds developed are suitable for use in medium voltage applications.

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