

Dielectric Breakdown Strength of Polypropylene Blended with Ethylene Octene Elastomer

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Abstract: Polymer blends have become a major focus of research in exploring the potential for new dielectric material applications, particularly in the insulation of high voltage systems. In the current research area, polypropylene (PP) is being investigated as an insulation material for high voltage alternating current and direct current power cables. However, PP must be treated with rubbery materials such as elastomers to lessen its overall stiffness for power cable extrusion. While various promising results have been published on the potential use of PP/elastomer blends as dielectric materials, the dielectric effects of adding ethylene octene elastomer to PP have been less explored. This paper discusses the alternating current (AC) and direct current (DC) breakdown strength of PP that contains different amounts of ethylene octene elastomer (10, 30, and 50 wt%). The addition of ethylene octene elastomer to PP affects the breakdown performance of the blend systems under both AC and DC fields. Significantly, an increase in elastomer contents results in a notable reduction in the AC and DC breakdown strength. A discussion is presented on the mechanisms underlying the change in the breakdown strength caused by the different amounts of ethylene octene elastomer blended with PP.

Keywords: Polypropylene, elastomer, blend, breakdown strength, dielectric

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1. INTRODUCTION

A growing electrical industry requires environmentally friendly, reliable, and high-performance electrical insulation materials. In high voltage engineering, polymers are frequently chosen as dielectric materials in cable insulation systems because of their outstanding electrical, mechanical, chemical, and thermal properties. As a result of its exceptional electrical and mechanical characteristics, crosslinked polyethylene (XLPE) is widely used as the main material for insulation. However, XLPE cables have a maximum normal operating temperature of around 90 °C and thereby limiting their electrical power capacity to be transmitted through them. Moreover, since XLPE is a thermoset, it is therefore difficult to be disposed of at the end of its lifetime because of crosslinking processes. Concerns are also raised about the manufacturing complexity of the XLPE crosslinking process and the degassing of the crosslinking byproducts [1].

The development of new materials for cable insulation becomes important in view of the constraints imposed by XLPE. Due to their unique qualities in both high voltage alternating current (HVAC) and high voltage direct current (HVDC) systems, thermoplastic polymers like polypropylene (PP) have recently attracted research attention as potential insulators [2–4]. PP is being explored as a potential substitute for XLPE in future power cable insulation, due to its melting temperature of up to 170 °C and promising electrical properties such as excellent electric resistivity and low dielectric loss [5, 6]. Therefore, PP has been considered an attractive alternative to cable

insulation. This is due to its easy reusability, environmental friendliness, and non-existence of byproducts during manufacturing.

A number of studies have been carried out to explore how PP can be adapted in order to respond more flexibly. As reported by Zhou et al. [7] and Hosier et al. [8–10], for the purpose of obtaining desirable dielectric properties, mixing polymers is an effective way to soften and improve the characteristics of different materials. By using toughening agents such as ethylene diene propylene monomer (EPDM), ethylene-octene copolymer (EOC), and propylene-based copolymer (PBC), it is possible to improve the electrical and mechanical properties of PP. In numerous research studies, PP blend systems have demonstrated high melting temperatures, excellent mechanical flexibility, and excellent dielectric properties when PP and elastomers are mixed [11–13]. These properties make PP blends ideal for use in electrical and electronic applications. Furthermore, the strength and flexibility of PP can be enhanced by adding elastomers, which could make it better suited for industrial applications.

Thus far, most of the research on PP/elastomer blends has concentrated on how different elastomers influence dielectric features. In particular, the interplay of polymers and elastomers is vital from the dielectric point of view. However, the effect of varying the amount of elastomer on the dielectric features of PP/elastomer blends has yet to be thoroughly explored. In order to examine the effects of different weight percentages (10, 30, and 50 wt%) of a type of elastomer, namely, ethylene-octene copolymer (EOC),

on the structure and dielectric properties of a PP/elastomer blend systems, the work reported here was carried out.

2. EXPERIMENTAL

2.1 Materials

A polypropylene (PP) blend composed of 90:10, 70:30 and 50:50 wt% of PP homopolymer and elastomer was the matrix used in this study. The PP was manufactured by Lotte Chemical Titan (grade TITAN PRO 6531M). EOC representing the elastomer, was obtained from Borealis (Queo 7007LA) and abbreviated as EA. Tables 1 and 2 illustrate the niche properties of the PP and elastomer.

2.2 Sample Preparation

PP/elastomer blends were prepared using a Brabender melt mixer using the following parameters: 180 °C, 50 rpm, and 10 min. All the samples were vacuum dried at 70 °C for 24 h to remove any potential moisture. For producing a disc-shaped sample of PP/elastomer blend, a hydraulic laboratory hot press was used at 180 °C temperature and a load of 2.5 tons. Each pressed sample was approximately 100 μm in thickness. Until use, the prepared samples were stored in a desiccator to avoid moisture absorption. For simplicity, all materials were defined using the symbol "P/E/A". As shown in Table 3, P indicates the polymer, E corresponds to the elastomer, and A refers to the percentage of elastomer.

Table 1. Polymer Properties

Type of Polymer	PP
Melt Index	3.5 g/10 min
Density	0.9 g/cm ³
Tensile strength	360 kg/cm ²

Table 2. Elastomer Properties

Elastomer	Queo 7007LA
Ethylene content	77.0 wt%
Octene content	23.0 wt%

Table 3. Material Designation

Designation	Description		
	Polymer (P)	Elastomer (E)	Amount of elastomer (A)
PP	PP	No elastomer	0 wt%
PP/EA/10	PP	EA	10 wt%
PP/EA/30	PP	EA	30 wt%
PP/EA/50	PP	EA	50 wt%

2.3 Characterization

Fourier transform infrared (FTIR) spectroscopy (spectrometer type IRTracer-100: Shimadzu) was employed to acquire chemical information on the PP/elastomer blends. The data were recorded at wavenumbers ranging from 500 cm^{-1} to 4000 cm^{-1} over 32 scans with a resolution 4 cm^{-1} . For that purpose, a sample with a thickness of ~ 100 μm was prepared.

The thermal characteristics of the PP/elastomer blends were analyzed using a different scanning calorimetry (DSC) technique (TA Instrument DSC 25). The mass of each specimen was 5 mg. A sealed aluminum pan was used to hold the sample. The DSC was performed at a temperature range between 60 °C and 180 °C by means of a scanning rate of 10 °C min^{-1} within the nitrogen atmosphere.

A Hitachi Model TM-3000 scanning electron microscope (SEM) was used to examine the morphology of the PP and PP blends. The samples were fractured in liquid nitrogen and sputtered coated for 1 min at 15-18 mA using a Quorum SC 7620 automated platinum sputter coater with an Edwards E2M2 high vacuum pump (repeated three times). The SEM images were taken at a 30 mm work distance with 15 kV acceleration voltage while performing the analysis.

A dielectric strength tester was used to perform AC and DC breakdown tests. The test was carried out under the American Society of Testing and Materials (ASTM) D149 standard for AC breakdown testing and ASTM D3722 standard for DC breakdown testing. Each test sample had a thickness of ~ 100 μm . To avoid surface flashover, the sample was placed in between two 6.3 mm diameter spherical ball electrodes and dipped in silicone oil. At room temperature, until breakdown, 1 kV (AC testing) and 2 kV (DC testing) of every 20 s step voltage was applied until the sample failed. In each type of sample, 15 breakdown data were identified and analyzed according to the two-parameter Weibull statistical distribution method.

3. RESULTS

3.1 Structure and Morphology

3.1.1 Fourier Transform Infrared Spectroscopy

Figure 1 depicts a set of FTIR spectra of the PP/elastomer blends with different weight percentages of EA (0, 10, 30, and 50 wt%). For the unfilled PP, the characteristic absorption bands are 2840-2950 cm^{-1} , 1455 cm^{-1} , 1375 cm^{-1} , 1169 cm^{-1} , and 841 cm^{-1} . The absorption band between 2840-2950 cm^{-1} indicates C-H bonds, representing the alkane functional group of PP. The peaks at 1458 cm^{-1} , 1375 cm^{-1} , 1169 cm^{-1} , and 841 cm^{-1} indicate the stretching vibrations of the C-H bonds of PP. For PP/EA/10, PP/EA/30, and PP/EA/50, similar FTIR spectra was obtained. It is noteworthy that the EOC bond is represented by a characteristic band at 720 cm^{-1} . With the addition of increasing elastomer contents, the absorption band at 720 cm^{-1} becomes visible. All the spectra correspond well with those previously reported [14, 15].

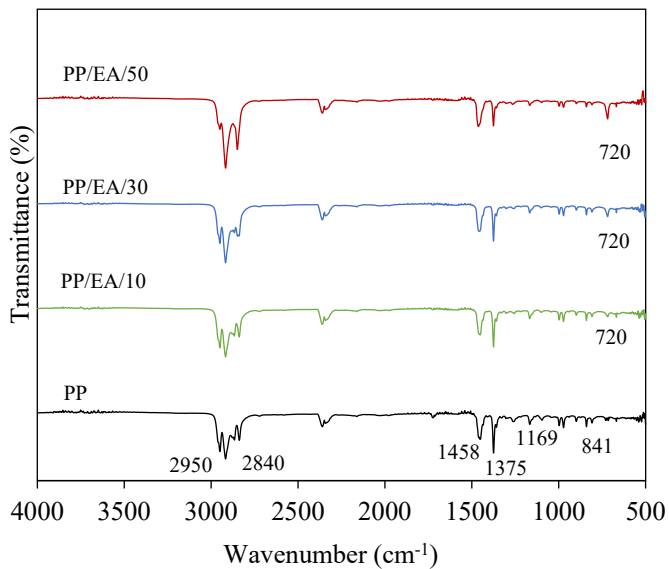


Figure 1. FTIR spectra for PP, PP/EA/10, PP/EA/30, and PP/EA/50

3.1.2 Differential Scanning Calorimetry

DSC melting traces of PP/elastomer blends containing different weight percentages of EA (0, 10, 30, and 50 wt%) are displayed in Figure 2. According to the DSC curve, the sample's melting traces had a peak temperature (T_m) of 162°C, which agrees with previous literature [16]. From the melting traces, the peak temperature of PP, PP/EA/10, PP/EA/30, and PP/EA/50 are comparable regardless of different weight percentages of elastomers. Meanwhile, Figure 3 shows the samples' DSC cooling traces. The crystallization temperature (T_c) of all samples is approximately 118 °C and is comparable regardless of different amounts of elastomer, consistent with prior literature [17]. As a result, the lamellar thickness of each material is not affected by the addition of an elastomer.

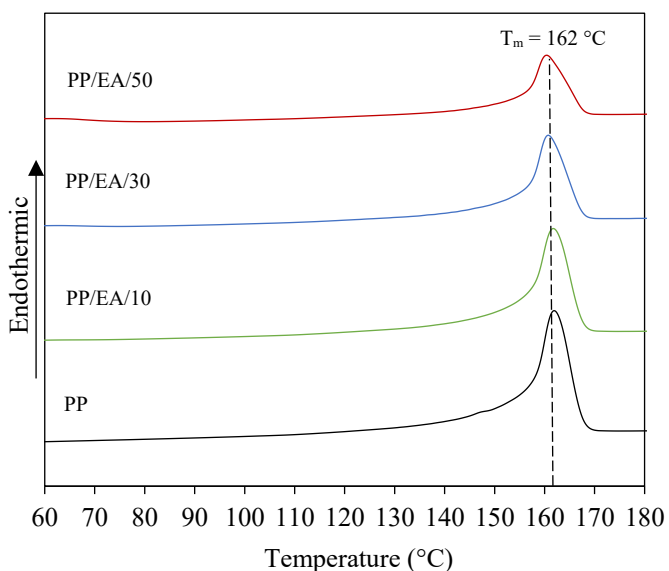


Figure 2. DSC melting traces for PP/elastomer blends

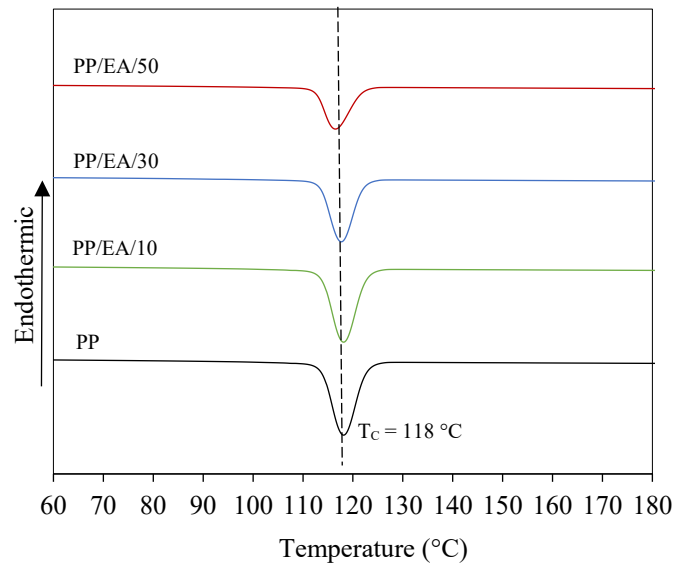


Figure 3. DSC cooling traces for PP/elastomer blends

3.1.3 Scanning Electron Microscopy

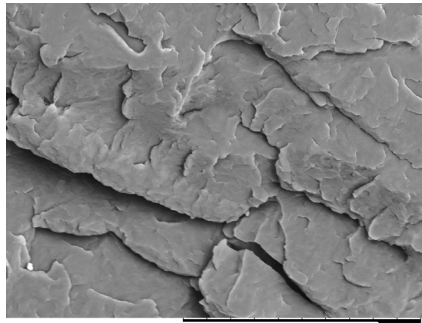
Figure 4 shows the SEM images of the fracture surfaces taken from the PP/elastomer blends. A fractography characteristic was found to affect the SEM images of PP and elastomer blends [18]. The cross-section of the PP/elastomer blends system was different especially with 30 and 50 wt% of EA, in comparison with the virgin PP. Isolated areas on the PP matrix showed that elastomer was homogeneously incorporated into the PP matrix, with an EA shape nearly circular and having a diameter of approximately 1 μm . This showed that there was some compatibility between the elastomers and the PP. The isolated areas of the "sea-island" pattern seem to be growing as the elastomer content in the PP blend increases.

3.1.4 AC and DC Breakdown Strength

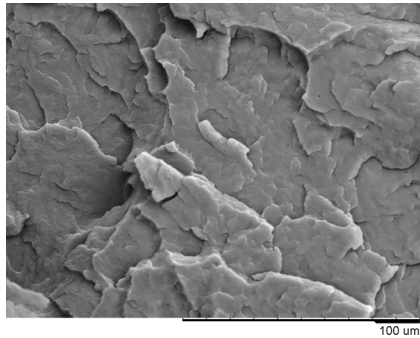
Figure 5 and Table 4 display the Weibull plots and the parameters of AC breakdown performance, respectively. These plots contain the amounts of 0, 10, 30, and 50 wt% of EA in PP. PP has shown the highest breakdown strength for AC at 169 kV mm^{-1} . The breakdown strength becomes 135 kV mm^{-1} by adding EA up to 10 wt%. By increasing the amount of elastomer to 30 and 50 wt%, the trend for breakdown strength decreases significantly; PP/50EA has a particularly low AC breakdown strength of 117 kV mm^{-1} .

Meanwhile, Figure 6 and Table 5 illustrate the respective Weibull plots and Weibull parameters for comparing the DC breakdown strength of PP/elastomer blends containing 0, 10, 30, and 50 wt% of EA. The highest DC breakdown value was recorded for unfilled PP with 379 kV mm^{-1} while the lowest breakdown value was recorded for PP/EA/50 containing elastomer of 50 wt%, which was 211 kV mm^{-1} (i.e., with the highest elastomer loading). Therefore, adding an increasing amount of elastomer (EA) into PP can significantly jeopardize the DC breakdown strength of the material, where the DC breakdown strength reduced with increasing amounts of

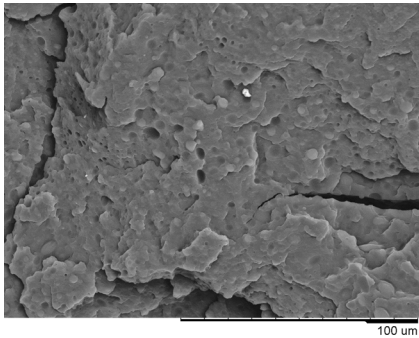
EA. This demonstrates that the addition of EA at 10, 30, and 50 wt% into PP enormously affects the breakdown performance of the blend systems under both AC and DC fields.



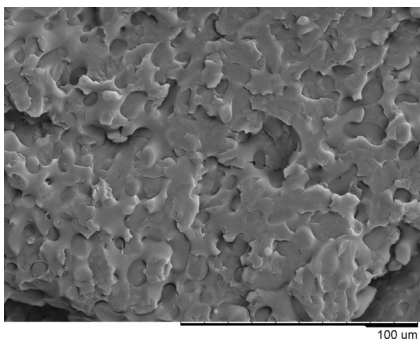
(a)



(b)



(c)



(d)

Figure 4. SEM images of (a) PP, (b) PP/EA/10, (c) PP/EA/30, and (d) PP/EA/50

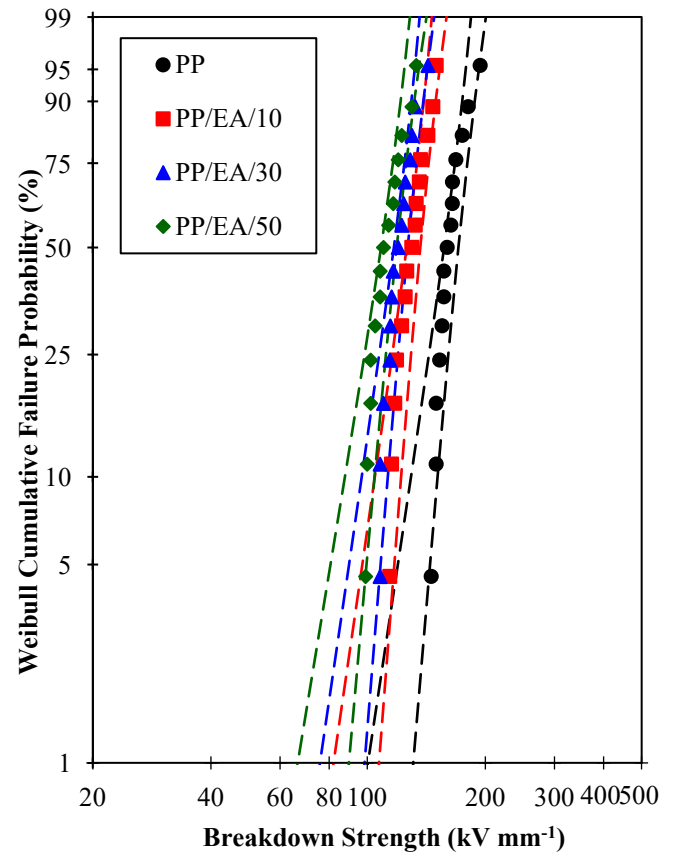


Figure 5. Weibull plots for the AC breakdown strength of PP/elastomer blends

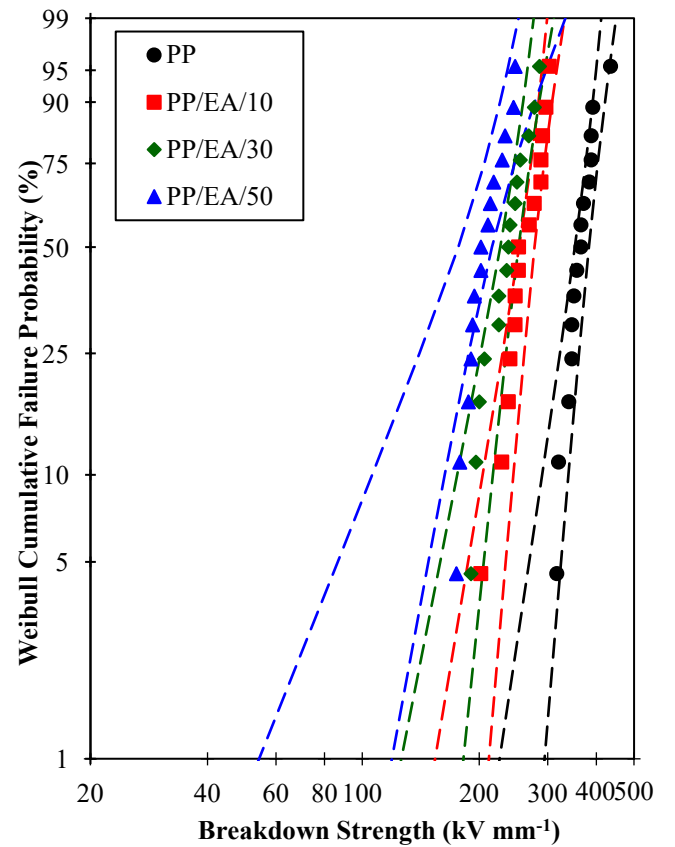


Figure 6. Weibull plots for the DC breakdown strength of PP/elastomer blends

Table 4. AC breakdown strength parameters

Sample	Scale parameter, α (kV mm ⁻¹)	Shape parameter, β
PP	169 ± 7	12 ± 4
PP/EA/10	135 ± 5	13 ± 4
PP/EA/30	125 ± 5	12 ± 5
PP/EA/50	117 ± 5	11 ± 4

Table 5. DC breakdown strength parameters

Sample	Scale parameter, α (kV mm ⁻¹)	Shape parameter, β
PP	379 ± 15	12 ± 4
PP/EA/10	277 ± 9	14 ± 6
PP/EA/30	248 ± 13	9 ± 4
PP/EA/50	211 ± 19	5 ± 2

4. CONCLUSION

Importantly, the need to design local interactions of elastomers and polymers to achieve desired dielectric properties is emphasized when using various weight percentages of elastomer on polypropylene systems. In the current study, the addition of ethylene octene elastomer to PP affects the AC and DC breakdown performance of the blend systems. Specifically, an increase in elastomer contents results in a significant reduction in the AC and DC breakdown strength. It is noteworthy that the current study concentrates only on the structure and dielectric breakdown property relationships of the PP/elastomer blend with one type of ethylene octene elastomer. Further experiments are currently being carried out to understand such effects through different types of elastomers to determine the effect on the chemical, thermal, and breakdown properties of PP/elastomer blends. These will help to further interpret the current results. These challenges are currently being studied to prepare the ground for the future development of polypropylene-based HVAC and HVDC systems.

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