Block polypropylene/styrene-ethylene-butylene-styrene tri-block copolymer blends for recyclable HVDC cable insulation

Yue Liang, Ling Weng, Wenlong Zhang and Chunyu Li

1 College of Material Science & Engineering, Harbin University of Science and Technology, Harbin 150080, People’s Republic of China
2 Key Laboratory of Engineering Dielectrics and Its Application, Ministry of Education, Harbin University of Science and Technology, Harbin 150080, People’s Republic of China
3 Yangzhou Longda Electrical Material Co. Ltd, Yangzhou 225222, People’s Republic of China

E-mail: zhangwenlong2004@yeah.net

Abstract

Polypropylene (PP) is regarded as the most promising candidate for eco-friendly high-voltage direct current (HVDC) cable insulation material due to its excellent thermal and electrical properties. In this paper, a block polypropylene (BPP) was selected as the matrix and blended with styrene-ethylene-butylene-styrene tri-block copolymer (SEBS) by melt blending. The thermal behavior, dynamic mechanical behavior, crystallization behavior, and mechanical and electrical properties of the BPP/SEBS blends were investigated. It was found that SEBS could efficiently improve the flexibility while maintaining the excellent heat resistance of PPB. Furthermore, adding an appropriate amount of SEBS had a positive effect on suppressing the space charge and increasing the breakdown field strength. For the BPP/SEBS blend containing 20 wt% SEBS, a desirable combination of thermal, mechanical, and electrical properties was achieved. This work may help pave the way for developing eco-friendly PP insulating material in HVDC cable applications.

1. Introduction

Cross-linked polyethylene (XLPE) is widely adopted as the insulation material for modern extruded high-voltage direct current (HVDC) cables due to its extraordinary properties, such as its thermo-mechanical stability, chemical resistance, and electrical properties. However, XLPE cannot easily be recycled at the end of its service life because of its thermosetting property. In addition, there is some concern about the environmental impact caused by the addition of a peroxide crosslinking agent during the manufacturing process of XLPE [1–3]. Hence, the exploration of novel eco-friendly insulating materials to replace XLPE has been a hot topic in recent years.

Polypropylene (PP), a typical thermoplastic polymer, has been regarded as the most promising candidate for next-generation extruded cables since it possesses high mechanical strength, excellent insulation properties, and superb heat and chemical resistance [4, 5]. In recent years, research on isotactic polypropylene (iPP) and its blends have been extensively reported. Zhou et al. investigated the thermal, mechanical, and electrical properties of PP/POE blends [6]. Zha et al. demonstrated how the space charge accumulation could be effectively suppressed by grafting maleic anhydride onto the molecular chain of PP [7]. Zhang et al. introduced a β-nucleating agent into PP to obtain a comprehensive improvement of electrical properties [8]. Gao et al. investigated the trap distribution and dielectric breakdown of PP/elastomer for DC cable insulation [9]. Zhou et al. documented the effects of different nanoparticles (MgO, TiO2, Al2O3, and ZnO) on the electrical properties of PP [10]. Gao et al. investigated the influence of compatibility between the PP and the elastomer on the charge accumulation behavior [11].

Compared with iPP, block polypropylene (BPP) has a better impact property and flexibility due to the introduction of ethylene groups [12–14]. Zhang et al. investigated the space charge behavior of BPP/Al2O3...
composites for HVDC cables [15]. However, few studies have reported the use of BPP as insulating materials in the field of HVDC cables, thus requiring further development and characterization.

In this study, styrene-ethylene-butylene-styrene tri-block copolymer (SEBS), an outstanding thermoplastic elastomer with excellent flexibility, heat resistance, solvent resistance, and aging resistance, was blended with BPP by mechanical blending. The melting and crystallization behavior, dynamic mechanical behavior, mechanical properties, space charge distribution, and DC breakdown strength were investigated. The present work offers ideas for the development of recyclable HVDC cable insulation material.

2. Experimental section

2.1. Materials

The block polypropylene (BPP, K8003) used in this study was supplied by Shaanxi Yanchang Coal Yulin Energy and Chemical Co., Ltd, China. Antioxidant 1010 was provided by Guangzhou Telei Chemical Co., Ltd, China. The styrene-ethylene-butylene-styrene tri-block copolymer (SEBS, 503T) was purchased from Sinopec Baling Petrochemical Co., China. Analytical grade xylene was obtained from Tianjin Fuyu Chemical Co., Ltd, China.

2.2. Preparation of the BPP/SEBS blends

The BPP/SEBS blends of various SEBS contents ranging from 0 wt% to 25 wt% (table 1) were prepared by melt blending using a HAPRO RM-200C torque rheometer. A processing temperature, screw speed, and time of 210°C, 50 rpm, and 10 min, respectively, were chosen. For ease of description, the details in table 1 represent the blends at different SEBS contents.

All samples of different thicknesses for later testing were prepared by hot pressing using a flat vulcanizing machine. The procedure was as follows. First, the blend was placed in a preheated stainless steel mold and heated at 200°C for at least 8 min. Compression molding was then conducted under a pressure of 15 MPa for 5 min. Finally, the sheet was cooled using circulating water under the same pressure for 3 min. To eliminate the thermal history generated during the sample preparation, normalization processing was executed on all the samples before each batch of measurements.

2.3. Characterization

A tensile test was carried out via an electronic universal testing machine (AG-J10KN, SHIMADZU) according to ASTM D638-2003. The dumbbell-shaped specimens with a gauge length of 25 mm and a cross section of 6 mm × 1 mm were stretched at a crosshead speed of 50 mm min⁻¹ at room temperature. A minimum of five specimens for each composite were repeatedly measured, the reported results of which were averages.

Differential scanning calorimetry (DSC) was performed using a power-compensation PerkinElmer DSC equipped with Pyris software to investigate the thermal properties and crystallization behaviors of the blends. Samples of approximately 5 mg to 8 mg were encapsulated in standard aluminum pans. The DSC measurements were run across a temperature range from 40°C to 200°C with a heating/cooling rate of 10°C min⁻¹ under an N₂ atmosphere. The instrument was routinely calibrated by means of high-purity indium.

Dynamic mechanical thermal analysis (DMTA) measurement was carried out on TA Q800 equipment to evaluate the thermo-mechanical properties of the blends. The rectangle specimens with dimensions of 90 × 10 × 1 mm were examined from −80°C to 160°C in tension mode, with a fixed frequency of 1 Hz and a heating rate of 3°C min⁻¹.

X-ray diffraction (XRD) analysis was performed on an Empyrean intelligent X-ray diffractometer with Cu Kα radiation. The samples were measured from 5° to 60°.

The space charge measurement was conducted by using a pulsed electro-acoustic (PEA) system equipped with a LeCroy WaveRunner 610Zi (1 GHz, 10 GSa s⁻¹ digital oscilloscope) under a 40 kV mm⁻¹ DC electric field for 1,800 s. The experiments employed a generator with an amplitude of 400 V, a pulse width of 8 ns, and a frequency of 2 kHz. A polyvinylidene fluoride (PVDF) sensor with a thickness of 9 μm was also used.

| Table 1. Blends prepared in this investigation. |
|-----------------------------------------------|
| Designation | BPP Content (wt%) | SEBS (wt%) |
| BPP-0       | 100              | 0          |
| BPP-5       | 95               | 5          |
| BPP-10      | 90               | 10         |
| BPP-15      | 85               | 15         |
| BPP-20      | 80               | 20         |
| BPP-25      | 75               | 25         |
thickness of the film sample was approximately 260 μm. Prior to the test, the aluminum was evaporated on both sides of the sample, after which the sample was short-circuited for 24 h under vacuum at 80 °C. The DC breakdown strength was evaluated by using a CS2674C dielectric strength tester. The sample was sandwiched between two opposing plate electrodes and immersed in silicone oil. The lower electrode was earthed, and an increasing DC voltage was applied to the upper electrode until breakdown. Breakdown voltage was recorded, and the sample thickness at the breakdown spot was measured. The corresponding field intensity could be obtained according to the formula:

\[ E_B = \frac{U_B}{d} \]

where \( E_B \) represents the breakdown strength, \( U_B \) is the breakdown voltage, and \( d \) is the sample thickness at the breakdown spot. Fifteen points were tested for each sample, and the two-parameter Weibull statistical distribution method was employed for data analysis.

3. Results and discussion

3.1. Thermal analysis

Figure 1 presents the melting and the crystallization curves of the BPP/SEBS blends. The crystallinity degree \( (X_c) \) was calculated according to the DSC melting curves using the following equation:

\[ X_c = \frac{\Delta H_m}{\Delta H_m^\infty} \]

where \( \Delta H_m \) is the melting enthalpy of the blends, and \( \Delta H_m^\infty \) is the melting enthalpy of 100% crystalline PP homo-polymer. A value of \( \Delta H_m^\infty = 209 \text{ J g}^{-1} \) [16] was taken for calculating the crystallinity.
According to figure 1(a), the BPP exhibited a high melting point of 166 °C, which is beneficial in raising the operating temperature and increasing the transmission capacity of the cables. When adding different amounts of SEBS into the BPP, virtually no change in the melting point was observed. Therefore, BPP and its blends were all suitable for HVDC cable insulation applications from the point of view of their melting behavior. In addition, the BPP/SEBS blends displayed a lower $X_c$ than the virgin BPP. The SEBS content increased from 0 wt% to 25 wt%, whereas the $X_c$ was gradually reduced from 45% to 32% given that the distribution of SEBS in BPP hindered the orderly arrangement of BPP chains, thus restricting the BPP crystallization process \[17\]. The reduction of crystallinity is favorable to improving the mechanical properties of BPP \[18\].

It is evident from figure 1(b) that the crystallization temperature slightly decreased as the SEBS content increased. The crystallization temperature of the BPP/SEBS blend containing 25 wt% SEBS was lower than that of virgin BPP by 0.4 °C; thus, no nucleation effect was observed for SEBS considering the decrease in the crystallization temperature.

### 3.2. Thermal mechanical analysis

For practical HVDC cable insulation, the material should have not only adequate flexibility at room temperature to meet the requirements of cable installation but also appropriate rigidity at a high temperature to meet the cable operation requirements \[2, 3, 17\]. Therefore, it is necessary to focus on the dynamic mechanical thermal analysis. The plots of the storage modulus ($E'$) and loss tangent (tanδ) as a function of temperature for the BPP and BPP/SEBS blends at various compositions are presented in figure 2. All samples exhibited a rather similar tendency wherein the storage modulus decreased as the temperature increased (figure 2), which was in accordance with the polymer relaxation properties. The virgin BPP exhibited a storage modulus of approximately 1,600 MPa at room temperature, which was far greater than that of XLPE \[3\]. Consequently, virgin BPP cannot be practically used in cable manufacturing due to its high rigidity. The introduction of SEBS into the BPP matrix significantly decreased the storage modulus of the blends given the decrease in crystallinity of the blends, as evidenced in the DSC study, and the elastic character of the SEBS. For BPP-25, the storage modulus decreased to approximately 600 MPa. This suggests a great decline in the rigidity and enhanced flexibility, which is desirable for HVDC cable installation. Furthermore, BPP-25 showed a remarkably improved modulus at temperatures above 110 °C compared with XLPE \[3\], which ensured sufficient mechanical integrity of the cable without the need for crosslinking and is an advantage for cable operation under high temperature.

According to the tanδ curves, the BPP exhibited two obvious loss peaks at around 8 °C and −40 °C. PPB was synthesized via two-step polymerization. In the first stage, propylene homopolymerization was performed, and ethylene–propylene copolymerization was carried out in the second stage. The resulting PPB was a multicomponent system \[19–21\]. The peak at 8 °C is associated with the glass-transition temperature of polypropylene in the amorphous regions (labeled as $T_g$), while another peak at −40 °C is attributed to the glass-transition temperature of ethylene propylene rubber (EPR) (labeled as $T_g$) \[19\]. When SEBS was added into BPP, a new loss peak corresponding to the EB segment relaxation at approximately −50 °C was not observed, even when the SEBS content reached 25 wt%. Moreover, the peak position of $T_g$ shifted toward the lower temperature, and the peak area of $T_g$ increased with increasing SEBS content. In general, if two polymers have excellent compatibility, their $T_g$ shift toward each other, and ultimately only a single $T_g$ exists if they are in complete miscibility \[22–24\]. Petermann and Gohil \[25\] reported good compatibility between PP and poly(1-
butene) due to rather similar molecular configurations of both polymers. Thus, the above results indicate strong interaction and good compatibility between the EB segments of SEBS and the EP segments of EPR. It is believed that the lower glass-transition temperature and the increased peak area of Tg2 play important roles in the enhanced toughness of the BPP/SEBS blends [13].

3.3. Mechanical properties
It is of paramount importance to take mechanical properties into account in the choice of cable insulating materials. The tensile stress–strain curves of BPP/SEBS blends at various compositions are presented in figure 3. The corresponding values of the tensile strength, elastic modulus, and elongation at break obtained from the tensile test are listed in table 2. The stress and elongation curves with the fracture point are shown in figure 4. One can see that the incorporation of SEBS softened the BPP, as expected. Furthermore, a sharp increase in the elongation at the break of the BPP/SEBS blends with increasing SEBS content was detected, indicating that the toughness of the blends improved [13]. As discussed above, this is attributed to a decrease in the crystallinity of the blends and the elastic character of the SEBS. Interestingly, the addition of SEBS to the BPP matrix first resulted in a slow increase and then a rapid increase in the tensile strength. The tensile strength increased from 24.7 MPa of BPP to 37.2 MPa of BPP-25, suggesting that the capability of resistance to the external force damage of the BPP/SEBS blends substantially improved, which is of great significance for practical cable applications. The increase in the tensile strength of the BPP/SEBS blends can be explained as follows. First, an increase in the SEBS content resulted in a decrease in the crystallinity, which loosened the intermolecular arrangement and led to a decrease in stress [26, 27]. Second, as the PS segment of the SEBS was in a glassy state at room temperature, it was difficult to move and thus acted as a physical crosslinking point, which hindered the slip between the molecular chains and increased the stress [28–30]. Third, a strong interaction was observed between PPB and SEBS due to the presence of EPR in the PPB, which strengthened the intermolecular mutual entanglement. As a result, more force was required to untangle the molecules during stretching, thus increasing the stress [31].

| Designation | Tensile strength (MPa) | Elongation at break (%) | Elastic modulus (MPa) |
|-------------|------------------------|-------------------------|----------------------|
| BPP-0       | 24.7                   | 537.1                   | 906.5                |
| BPP-5       | 24.8                   | 559.7                   | 820.3                |
| BPP-10      | 25.0                   | 661.8                   | 773.7                |
| BPP-15      | 28.3                   | 836.3                   | 651.9                |
| BPP-20      | 33.6                   | 1024.2                  | 601.7                |
| BPP-25      | 37.2                   | 1109.1                  | 539.3                |

Figure 3. Tensile stress–strain curves of the BPP/SEBS blends.
Clearly, the experimental results showed that the influence of the latter two factors was greater than that of the former, such that the tensile strength increased with an increase in the SEBS content.

### 3.4. XRD analysis

XRD measurements were performed to further investigate the effect of SEBS incorporation on the BPP crystal structure. Figure 5 presents the XRD diffraction patterns of the BPP blends with various SEBS contents. The virgin BPP sample exhibited characteristic diffraction peaks at $2\theta$ of 14.1°, 16.9°, and 18.5°, which corresponded to the (110), (040), and (130) lattice planes of the $\alpha$-monoclinic crystal of PP, respectively [32]. The same diffraction peaks were also observed in the diffraction patterns of all the blend compositions. Furthermore, no other additional peak related to other crystal phase was observed, implying that the addition of SEBS did not change the crystalline form of PP.

### 3.5. Space charge characteristics

When a high direct current electric field was applied on the insulating materials, space charges were generated and accumulated, which became obstacles for developing HVDC cables [33]. Figure 6 presents the space charge distributions in the BPP/SEBS blends at different SEBS contents during polarization under a DC electric field of 40 kV mm$^{-1}$, which was applied for 1,800 s. A large amount of hetero-charge accumulation was observed in BPP, i.e., the negative charge near the anode and positive charge near the cathode. In general, the hetero-charge is generated from the ionization of impurities or additives, inevitably introducing them into polymers during
With the addition of SEBS, a gradual reduction in hetero-charge was observed. In the case of BPP-20, almost no charge accumulation was observed. The present results suggest that SEBS had a positive effect on the space charge inhibition. Similar results were reported by Dong et al. [37]. In general, aromatic rings can act as strong charge trapping sites [38–43]. Teyssedre et al. computed the effect of the physical and chemical defects on the trap-level distribution in the polymer material using density functional theory (DFT) modeling, the results of which showed that the aromatic rings would introduce deep traps in the polymer material [40, 41]. Li et al. analyzed the space charge characteristics in XLPE that was modified by polycyclic aromatic compounds using the integration current method and quantum chemical calculations. Deep traps in aromatic rings are formed from the deviation of the electron cloud under electric fields, which forces the electron to occupy lower energy levels. The consequent decrement of the lowest unoccupied molecular orbital (LUMO) and increment of the highest occupied molecular orbital (HOMO) led to the appearance of deep trap sites in the aromatic rings. On the macro level, the apparent dipoles of the aromatic rings built pairs of positive and negative potential wells, wherein the electrons and holes served as capture carriers [43]. Thus, the SEBS
containing aromatic rings introduced deep trapping sites into the composites when SEBS was added into PPB. These deep traps could capture the charge carriers that were liberated by the ionization of impurities and block the movement of the charge carriers, thereby decreasing the quantity of carriers transported to the extraction electrode and resulting in the suppression of hetero-charge formation \[^{44-47}\]. On the other hand, an increase in the SEBS content increased the trapping sites and formed a dense trap layer near the cathode and anode, thus capturing the homo-charges injected from the electrodes following the application of the DC electric field. This increase in homo-charge resulted in an apparent decrease in the PPB hetero-charge \[^{48, 49}\]. Thus, the space charges were significantly suppressed due to the deep traps introduced by the SEBS aromatic rings. However, when the content of SEBS exceeded 20 wt% and continued to increase, superfluous trapping sites introduced additional homo-charges. Heavy homo-charge accumulation near the cathode was observed in the bulk of PPB-25 (figure 5). Thus, PPB-20 possessed the optimal space charge suppression performance, which is highly favorable for HVDC cable insulation applications.

3.6. DC breakdown strength

The DC breakdown strength is one of the most important parameters used to evaluate the insulating property of the materials. Figure 7 shows the Weibull plots of the DC breakdown strength of the BPP/SEBS blends with various components at room temperature. One can see that the DC breakdown strength of BPP/SEBS blends increased with increasing SEBS content. When the SEBS content increased from 0 wt% to 20 wt%, the DC breakdown strength increased from 287.8 kV mm\(^{-1}\) to 327.5 kV mm\(^{-1}\). The resonance structure brought by the SEBS chain played an important role in improving the breakdown strength. Thanks to the existence of delocalized \(\pi\)-electrons, the benzene rings could absorb and dissipate the energy of the high-energy electrons by producing relatively stable anions and cation radicals in the transport process, which weakened the attack of the electrons on the polymer molecular chains \[^{50-52}\]. Hence, the breakdown strength was improved. Notably, the DC breakdown strength of BPP-25 was lower than that of BPP-20. This may be attributed to the space charge accumulation, which resulted in serious local electric field distortion and thus decreased the breakdown strength of the insulation materials \[^{53}\].

4. Conclusions

BPP/SEBS blends were prepared by melt mixing, and the feasibility of the BPP/SEBS blends was evaluated for HVDC cable insulation based on the melting and crystallization behavior, dynamic mechanical behavior, mechanical properties, space charge distribution, and DC breakdown strength. All the samples exhibited a high melting temperature of about 166 °C and sufficient high-temperature rigidity, ensuring the BPP/SEBS blends can operate under high temperatures without the need for crosslinking. The addition of SEBS effectively
improved the flexibility of the BPP/SEBS blends. Interestingly, the tensile strength of the BPP/SEBS blends showed a remarkable increase with increasing SEBS content. Meanwhile, BPP-20 presented the optimal space charge suppression performance and the highest breakdown field strength. This work provides a reference for developing environmental protection HVDC insulation material.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (No. 51677045). We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

ORCID iDs

Ling Weng @ https://orcid.org/0000-0001-5195-3782
Wenlong Zhang @ https://orcid.org/0000-0002-9235-8194

References

[1] Green C D, Vaughan A S, Stevens G C, Pye A, Sutton S J, Geussens T and Fairhurst M J 2015 Thermoplastic cable insulation comprising a blend of isotactic polypropylene and a propylene-ethylene copolymer IEEE Trans. Dielectr. Electr. Insul. 22 639–48
[2] Hosier I L, Vaughan A S and Swingler S G 2011 An investigation of the potential of polypropylene and its blends for use in recyclable high voltage cable insulation systems J. Mater. Sci. 46 4058–70
[3] Hosier I L, Vaughan A S and Swingler S G 2010 An investigation of the potential of ethylene vinyl acetate/polyethylene blends for use in recyclable high voltage cable insulation systems J. Mater. Sci. 45 2747–59
[4] Zhou Y, Peng S, Hu J and He J L 2017 Polymeric insulation materials for HVDC cables: development, challenges and future perspective IEEE Trans. Dielectr. Electr. Insul. 24 1308–18
[5] He J L, Peng L and Zhou Y 2017 Research progress of environment-friendly HVDC power cable insulation materials High Voltage Engineering, 43 337–45 (in Chinese)
[6] Zhou Y, He J L, Hu J, Huang X Y and Jiang P K 2015 Evaluation of polypropylene/polyolefin elastomer blends for potential recyclable HVDC cable insulation applications IEEE Trans. Dielectr. Electr. Insul. 22 673–81
[7] Zha J W, Wu Y H, Wang S J, Wu D H, Yan H D and Dang Z M 2016 Improvement of space charge suppression of polypropylene for potential application in HVDC cables IEEE Trans. Dielectr. Electr. Insul. 23 2337–43
[8] Zhang L, Zhang Y, Zhou Y, Teng C, Peng Z and Spinella S 2018 Crystalline modification and its effects on dielectric breakdown strength and space charge behavior in isotactic polypropylene Polymers. 10 406
[9] Gao Y, Li J, Yuan Y Q, Huang S H and Du B X 2018 Trap distribution and dielectric breakdown of isotactic polypropylene/ethylene based elastomer with improved flexibility for DC cable insulation IEEE. Access. 6 58645–61
[10] Zhou Y, Hu J, Dang B and He J L 2017 Effect of different nanoparticles on tuning electrical properties of polypropylene nanocomposites IEEE Trans. Dielectr. Electr. Insul. 24 1380–9
[11] Gao Y, Li J, Chen G, Han T and Du B X 2020 Compatibility dependent space charge accumulation behavior of polypropylene/ elastomer blend for HVDC cable insulation IEEE Trans. Dielectr. Electr. Insul. 27 947–55
[12] Huang X Y, Fan Y Y, Zhang J and Jiang P K 2017 Polypropylene based thermoplastic polymers for potential recyclable HVDC cable insulation applications IEEE Trans. Dielectr. Electr. Insul. 24 1446–56
[13] Zhang W, Xu M, Chen G, Hou S, Fu M L and Li W K 2017 Structure and properties of isotactic polypropylene and ethylene-propylene copolymer High Voltage Engineering 43 3634–44 (in Chinese)
[14] Meng P F, Zhou Y, Yuan C, Li Q, Liu J P, Wang H M, Hu J and He J L 2019 Comparisons of different polypropylene copolymers as potential recyclable HVDC cable insulation materials IEEE Trans. Dielectr. Electr. Insul. 26 674–80
[15] Zhang C, Zha J W, Yan H D, Li W K, Wen Y Q and Dang Z M 2018 Effects of trap density on space charge suppression of block polypropylene/Al2O3 composite under high temperature IEEE Trans. Dielectr. Electr. Insul. 25 1293–9
[16] Rozanski A, Galeski A and Debowska M 2011 Initiation of cavitation of polypropylene during tensile drawing Macromolecules 44 20–0
[17] Zhou Y, Dang B, Wang H M, Liu J P, Li Q, Hu J and He J L 2018 Polypropylene-based ternary nanocomposites for recyclable high voltage direct-current cable insulation Compos. Sci. Technol. 165 168–74
[18] Greco R, Mancarella C, Martuscelli E, Ragosta G and Yin J 1987 Polyolefin blends: 2. Effect of EPR composition on structure, morphology and mechanical properties of PP/EPR alloys Polymer 28 1929–36
[19] Zhang C H, Shangguan Y G, Chen R F, Wu Y Z, Chen F, Zheng Q and Hu G H 2010 Morphology, microstructure and compatibility of impact polypropylene copolymer Polym. 51 4969–77
[20] Liu Y M, Tong Z Z, Xu J T, Fu Z S and Fan Z Q 2014 A highly efficient β-nucleating agent for impact-resistant polypropylene copolymer J. Appl. Polym. Sci. 131 40753
[21] Li C L, Zhang Y K, Leng J H, He B B and Chen X 2018 Synergistic toughening effect of nucleating agent and annealing treatment and morphological research on block copolymerization polypropylene Polym. Plast. Technol. Eng. 58 270–81
[22] Oommen Z, Groeninckx G and Thomas S 2000 Dynamic mechanical and thermal properties of physically compatibilized natural rubber/poly(methyl methacrylate) blends by the addition of natural rubber-graft-poly(methyl methacrylate) J. Polym. Sci., Part B: Polym. Phys. 38 523–36
[23] Khonakdar H A, Wagenknecht U, Safari S H, Hässler R and Eslami H 2004 Dynamic mechanical properties and morphology of polyethylene/ethylene vinyl acetate copolymer blends Adv. Polym. Tech. 23 307–15
[24] George S, Neelakantan N R, Varughese K T and Thomas S 1997 Dynamic mechanical properties of isotactic polypropylene/nitrile rubber blends: Effects of blend ratio, reactive compatibilization, and dynamic vulcanization J. Polym. Sci., Part B: Polym. Phys. 35 2309–27
[25] Petermann J and Gohil R M 1979 A new method for the preparation of high modulus thermoplastic films J. Mater. Sci. 14 2260–4
[26] Dasari A, Rohrmann J and Misra R D K 2003 Microstructural evolution during tensile deformation of polypropylene Mater. Sci. Eng. A 351 200–13
[27] Pontganayut K, Thongpin C and Santawitee O 2013 The effect of rubber on morphology, thermal properties and mechanical properties of PLA/NR and PLA/ENR blends Energy Procedia 34 888–97
[28] Men Y, Rieger J and Strobl G 2003 Role of the entangled amorphous network in tensile deformation of semicrystalline polymers Phys. Rev. Lett. 91 095502
[29] Schrauwen B A G, Janssen R P M, Govaert L E and Meijer H E H 2004 Intrinsic deformation behavior of semicrystalline polymers Macromolecules 37 6069–78
[30] Xu H, Du B X, Li J and Li Z L 2019 Mechanical and space charge properties of polypropylene/elastomer blends High Voltage Engineering 45 3214–20 (in Chinese)
[31] Chen F, Qiu B W, Wang B, Shangguan Y G and Zheng Q 2015 Balanced toughening and strengthening of ethylene–propylene rubber toughened isotactic polypropylene using a poly(styrene–b-ethylene–propylene) diblock copolymer RSC Adv. 5 20831–7
[32] Yang F, Wu T, Xiang M and Cao Y 2017 Deformation and pore formation mechanism of β nucleated polypropylene with different supermolecular structures Eur. Polym. J. 91 134–48
[33] Fabiani D, Montanari G C, Laurent C, Teyssedre G, Morshuis P H F, Bodega R, Dissado R A, Campus A and Nilsson U H 2007 Polymeric HVDC cable design and space charge accumulation. Part 1: insulation/selenium interface IEEE Electr. Insul. Mag. 23 11–9
[34] Peng S, He J L, Hu J, Huang X Y and Jiang P K 2015 Influence of functionalized MgO nanoparticles on electrical properties of polyethylene nanocomposites IEEE Trans. Dielectr. Electr. Insul. 22 1512–9
[35] Akram S, Yang Y, Zhong X, Bhutta S, Wu G, Castellon J and Zhou K 2018 Influence of nanolayer structure of polyimide film on space charge behaviour and trap levels IEEE Trans. Dielectr. Electr. Insul. 25 1461–9
[36] Akram S, Wu G, Gao G and Liu Y 2015 Cavity and interface effect of PI-film on charge accumulation and PD activity under bipolar pulse voltage J. Electr. Eng. Tech. 10 2089–98
[37] Dong W, Wang X, Jiang Z, Tian B, Liu Y, Yang J and Zhou W 2019 Acetylated SEBS enhanced DC insulation performances of polyethylene Polymers 11 1033
[38] Unger M, Tornkvist C and Christen T 2013 Space charges and deep traps in polyethylene–ab initio simulations of chemical impurities and defects IEEE Int. Conf. Solid Dielectrics (ICSD) 935–9
[39] Sekiguchi Y, Takada T, Miyake H and Tanaka Y 2017 The influences on dielectric and insulating behaviors of introducing styrene groups into polyethylene IEEE Trans. on FM 137 614–9
[40] Teyssedre G, Laurent C, Aslanides A, Quirke N, Dissado L A, Montanari G C, Campus A and Martinotto L 2001 Deep trapping centers in crosslinked polyethylene investigated by molecular modeling and luminescence techniques IEEE Trans. Dielectr. Electr. Insul. 8 744–52
[41] Teyssedre G and Laurent C 2005 Charge transport modeling in insulating polymers: from molecular to macroscopic scale IEEE Trans. Dielectr. Electr. Insul. 12 857–74
[42] Huzayyin A, Bogg S and Rampasad R 2010 Density functional analysis of chemical impurities in dielectric polyethylene IEEE Trans. Dielectr. Electr. Insul. 17 926–30
[43] Li J, Han C L, Du B X and Takada T 2020 Deep trap sites suppressing space charge injection in polycyclic aromatic compounds doped XLPE composite IET Nanodielectrics 3 1–3
[44] Fan L Z, Tu Y P, Chen B Y, Yi C Q, Qin S C and Wang S H 2020 Space charge behavior of polyimide at cryogenic temperatures IEEE Trans. Dielectr. Electr. Insul. 27 891–9
[45] Takada T, Hayase Y, Tanaka Y and Okamoto T 2008 Space charge trapping in electrical potential well caused by permanent and induced dipoles for LDPE/MgO nanocomposite IEEE Trans. Dielectr. Electr. Insul. 15 152–60
[46] Zhang C C, Chang J X, Zhang H Y, Li C Y and Zhao H 2019 Improved direct current electrical properties of crosslinked polyethylene modified with the polar group compound Polymas. 11 1624
[47] Du B X, Su J G, Tian M, Han T and Li J 2018 Understanding trap effects on electrical treering phenomena in EPDM/POSS composites Sci. Rep. 8 8481–95
[48] Cao L, Zhong I S, Li Y G, Zhang K, Gao J H and Chen G 2019 Enhanced high-temperature DC dielectric performance of crosslinked polyethylene with a polysytrene pinning structure Mater. 12 1234
[49] Suh K S, Lee C H, Zhu Y and Lin J 1997 Electrical properties of chemically modified polyethylene IEEE Trans. Dielectr. Electr. Insul. 4 681–7
[50] Dong W, Wang X, Tian B, Liu Y, Jiang Z, Li Z and Zhou W 2019 Use of grafted voltage stabilizer to enhance dielectric strength of crosslinked polyethylene Polymars. 11 176
[51] Zhang H, Shang Y, Zhao H, Wang X, Han B Z and Li Z S 2016 Theoretical study on the tailored side-chain architecture of benzil-like voltage stabilizers for enhanced dielectric strength of cross-linked polyethylene RSC Adv. 6 11618–30
[52] Zhang H, Shang Y, Zhao H, Han B Z and Li Z S 2013 Mechanisms on electrical breakdown strength increment of polyethylene by acetophenone and its analogues addition: a theoretical study J. Mol. Model. 19 8477–85
[53] Montanari G C 2011 Bringing an insulation to failure: the role of space charge IEEE Trans. Dielectr. Electr. Insul. 18 339–64