Highly conductive polymer nanocomposites for emerging high voltage power cable shields: experiment, simulation and applications

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Abstract: High voltage power cables play a critical role in global electricity transmission and distribution. The currently used power cables cannot fulfill the green and sustainable requirement of modern society because of the thermost nature of cable insulation and shields. This study is aimed at developing thermoplastic shields for high voltage power cable, which is one bottleneck restricting the development of environmental-friendly cables. Using carbon black (CB) as the main conductive component and a small amount of carbon nanotubes (CNTs) or graphene as the second filler, highly conductive polypropylene based composite materials were prepared for potential shield applications. It was found that, at a fixed conductive filler loading, the replacement of a small amount CB by CNTs can significantly enhance the electrical conductivity and suppress its temperature dependence. However, when CB was replaced by graphene, only limited enhancement of electrical conductivity could be achieved and the electrical conductivity is still highly dependent on temperature. Dissipative particle dynamics simulations demonstrated that the enhanced conduction property in the CNTs-containing composites could be understood by the shorter average distance between CB and CNTs. Finally, the coordination between the newly developed conductive composites and the environmental-friendly thermoplastic polypropylene insulation was evaluated via high voltage direct current measurements, and the results revealed that the CNTs-containing composites showed excellent suppression effect on the space charge injection and accumulation in the insulation. This research paved a new way for developing environmental-friendly high voltage power cable shields.

1 Introduction

The introduction of conductive filler into an electrically insulating polymer can increase the electrical conductivity of the corresponding composites by more than 10 orders of magnitudes, while maintaining the ease of processing and high flexibility of the polymers [1, 2]. This makes conductive polymer composites (CPCs) have versatile applications in power delivery, energy storage devices and systems, sensors, anti-static and electromagnetic shielding components.

The electrical conductivity of CPCs generally follows the percolation theory [3]. Namely, the electrical conductivity of the composites increases slowly at very low filler loading and then increases sharply with the further increase of loading level until undergoing an insulator-to-conductor transition at a critical concentration (i.e. percolation threshold) [4]. Above the percolation threshold, the electrical conductivity of CPCs increases smoothly with the increase of filler content [5]. So far, the percolation phenomenon has been well understood by the formation of continuous electron paths between the conductive fillers [6]. Below the percolation threshold, electrons cannot form continuous conductive pathways and the electrical conduction is dominated by the polymer matrix. Therefore, the conductive filler loading must be higher than the percolation threshold in order to achieve highly conductive composites for engineering applications.

Previous studies extensively focused on the reduction of percolation threshold of conductive filler in the insulating polymer matrix [7]. The effects of numerous parameters on percolation threshold have been documented, including filler size and shape, filler dispersion and distribution, filler synthesis method, filler modification and treatment, filler hybrid, filler assembly and dimensionality, polymer matrix type and composite preparation methods [1, 8–11]. Due to high aspect ratio and high electrical conductivity, carbon nanotubes (CNTs) and graphene have been widely used to prepare composites with low percolation threshold [2, 12]. Using aligned multi-walled CNTs (MWCNTs) as filler and amine cured epoxy resin as matrix, a low percolation threshold of 0.0021 wt% was observed by Sandler and Windle [13]. In polystyrene/graphene nanocomposites, Nguyen and Ruoff documented a low percolation threshold near 0.1 vol% [2]. Using in-situ radical polymerisation and thermally reduced graphene, Macosko and Liao successfully prepared polyurethane acrylate based nanocomposites with an ultralow percolation threshold of 0.07 vol% (0.15 wt%) [14].

Despite its importance in practical applications, the magnitude of electrical conductivity of CPCs did not attract enough attention in the previous research. In fact, the electrical conductivity value is a critical parameter in evaluating the property of CPCs. For example, semi-conductive shields are key components in extruded high voltage power cables Fig. 1, where both conductor and insulation should be coated by semi-conductive shields to eliminate the electric field distortion and to form uniform electric field within the insulation. For this purpose, the shields should have high enough electrical conductivity and ultrahigh surface smoothness [15–19]. Taking the extruded 110 kV cables as an example, the electrical conductivity of the semi-conductive shields should be higher than 0.01 S/cm at room temperature [20]. Carbon black (CB) has been extensively used as conductive filler to fabricate composite shields because of its low cost and high electrical conductivity. However, usually CB loading near 50 phr is needed to fulfill the high electrical conductivity requirement of the semi-conductive shields [21]. Such a high CB concentration leads to numerous problems during the cable processing, including high extrusion viscosity, difficult filtering and high surface roughness of the extruded semi-conductive shields [22].

Apart from high electrical conduction capability, the dependence of electrical conduction on temperature is also
important to CPCs [23, 24]. There exists positive temperature coefficient (PTC) effect on electrical resistivity (or negative temperature coefficient, NTC, on electrical conductivity) in CPCs because of the higher thermal expansion of polymer matrix, which may result in electrical conductivity variation of several orders of magnitude with in tens of cent degrees [25, 26]. For extruded power cables, semi-conductive shields with low PTC/NTC effect, namely temperature independent electrical conductivity, are highly desirable for long time safe service under a variety of work conditions. However, low PTC/NTC effect is difficult to be achieved in CB filled thermoplastic composite shields [27]. First, this is because the polymer matrix has much higher thermal expansion coefficient in comparison with CB [28]. Second, the electrical conductivity of the composites is extremely sensitive with the average inter-particle distance of CB [29].

Compared with the traditional extruded power cables where cross-linked polyethylene is used as insulation, power cables with polypropylene (PP) based thermoplastic insulation received enough attention, particularly in the academic. In this work, we aimed to develop thermoplastic shields for environmental-friendly high voltage power cables. For the purpose, hybrid carbon (CNT&CB or graphene&CB) filler was used to increase the electrical conductivity and to suppress its dependence on temperature of the semi-conductive composites, while on the other hand maintaining the overall low cost of the composites. It was found that the CNT-containing composites are more promising for environmental-friendly high voltage cable shield applications.

2 Experimental

2.1 Materials

MWCNTs (SMW200, 10 ± 1 nm in out diameter, 3–6 μm in average length) was purchased from Sigma-Aldrich, which have a purity ≥98%. Industrial grade MWCNT (TNM0) series with different aspect ratios (20–1500) and size were provided by Chinese Academy of Sciences Chengdu Organic Chemical Co., Ltd., China. Graphene nanoplatelets (GNPs, 50 μm in size and 3–5 nm in thickness) were provided by SZ Graphene Company, Jiangsu, China. CB used in this work has diameter of 20–40 nm and its dibutyl phthalate absorption is 138 × 10⁻⁵ m²/kg. PPs were purchased from Shanghai Petrochemical Company and poly(ethylene-co-octene) (POE) was purchased from Dow Chemical Company, and both PP and POE have a melt index of 2.5 ± 0.7 g/min.

2.2 Nanocomposite preparation

Masterbatch with CB/POE/lubricant/antioxidant (70/100/3.5/1.5) were first prepared in a single-screw extruder. The extruded masterbatch granulates were cooled in a water bath and then cut into pellets for further compounding. GNP and MWCNTs as the second filler were dried at 80°C for 12 h before use. PP were dried at 40°C in vacuum oven for 12 h. The nanocomposites were processed by blending the masterbatch, PP and the second filler in a torque rheometer (F80WZ, Harbin Plastics Machinery Co., Ltd., China) at 180°C, 50 rpm for 15 min. The total filler (CB + GNP or MWCNT) content in the composites was set as 30.0 wt-%. Therefore, the sample named 1.0% CNT refers to the composite with 29.0% CB and 1.0% CNT. The mixed nanocomposites were hot pressed into square plates with 1 mm in thickness for all measurements. All the nanocomposite samples were annealed at 80°C for 24 h to eliminate the thermal stress prior to any measurement.

2.3 Characterisation

Dynamic rheological tests were conducted on the AresG2 Rheometer (Malvern Panalytical Ltd, England) in parallel plates at oscillatory mode from 0.01 to 100 rad/s at 190°C. Samples for rheological test were 25 mm in diameter and 1.0 mm in thickness. The dynamic mechanical analysis (DMA) was performed from −80 to 135°C on Q800 dynamic thermomechanical analyser, with sample size 8 mm × 6 mm × 1 mm, at a frequency of 1 Hz and a heating rate of 3°C/min, and the strain amplitude was maintained at 1%.

The volume electrical resistivity was measured using four-electrode method according to IEC 60840 [20]. The sample was cut into disk of 5 cm × 2 cm × 0.1 cm. The electrical resistance was automatically recorded with the increase of temperature from room temperature to 140°C at a heating rate of 1°C/min. After the samples were cooled to room temperature in air then the measurement was performed again and the data obtained at this measurement were used for analysing.

Morphologies of the nanocomposites were observed on a Nova NanoSEM450 scanning electron microscope (SEM, FEI Ltd, USA). The samples were fractured in liquid nitrogen, then sprayed with gold for measurement. A JEM-2100 transmission electron microscope (TEM, Japan) was used to further investigate the microstructure of the composites, and the samples (about 70 nm in thickness) were prepared by ultrathin sectioning at about −70°C.

Space charge measurement was performed using the pulse electrode acoustic (PEA) method. The PP sheets with diameter of 50 mm and 200 μm thick were used as samples. In the
measurement, a small disk (20 mm diameter and 1 mm thick) like semi-conductive composites were used as the upper electrodes (i.e. anode) and aluminium plates were used as the lower electrodes. Different electric fields, namely 10, 20, 30, 40, 50 and 60 kV/mm, were successively applied and each voltage was held for 600 s at room temperature (∼25°C). After the electric field application (polarisation process), the samples were short-circuited for 1800 s and the space charge profiles of this depolarisation process were also recorded.

3 Results and discussion

3.1 Morphology and microstructure

The electrical conduction behaviour of CB composites near percolation threshold is highly dependent on the CB dispersion and distribution [4]. Therefore, the microstructure of different composites was investigated. Fig. 2 shows the SEM images of cryo-fractured cross-sections of different composite shields. One can see that the CB was uniformly distributed in each samples in the form of cluster networks. This is reasonable because that CB usually exists in the form of aggregates. The CB aggregates consist of small primary spheroidal particles in diameter of several to tens of nm (30–40 nm in this work). In the composites with CNTs, the broken CNT terminals can be clearly seen. In addition, the CNTs were not pulled out and their dispersion is uniform. CNT aggregates were not found throughout the cross-sections of any CNT-containing composite samples. In the case of composites with GNP, one can see some large-sized nanoplatelets can be seen and they were also uniformly dispersed in the composites. These results suggest the highly loaded CB can prevent CNTs or GNP from aggregating, which is consistent with previous research [1].

In order to show the microstructure in detail, TEM images of the ultrathin sections of different composites were provided. As shown in Fig. 3, the irregular CB aggregates were dispersed in the matrix, forming a cluster network. Since the final composites were prepared by mixing the POE/CB masterbatch with PP, it is reasonable to speculate that the CB rich area is mainly consisting of POE and the matrix rich area is mainly consisting of PP. CNTs cannot be seen clearly in the images with low magnitude of enlargement (Fig. 3c), while they can be recognised in the images with high magnitude of enlargement (Fig. 3d), where some CB clusters are bridged by CNTs (indicated by arrows). In addition, the CNTs can be highly bended and even twisted. In contrast, the distortion of GNP is significantly restricted although they can be clearly seen and largely bended in the composites. Such a microstructure may significantly affect the electrical properties of the composites, which will be demonstrated and analysed in the following sections.

3.2 Dynamic mechanical behaviour

As shown in Figs. 2 and 3, the partial replacement of CB by CNTs or GNP affects the conductive network structure of the composites. This may consequently affect the movement of polymer chains and the filler/matrix interaction. For revealing the potential influence, DMA curves of the selected composites were provided in Fig. 4 to reveal the different relaxation behaviour of the polymer matrix and the influence of filler on the thermomechanical properties of the composites from −80 to 125°C. One can see that there are two main peaks of macromolecular relaxation. The peak at the lower temperature of about −37.5°C is ascribed to the glass transition (Tg) of POE, while that at the higher temperature of about 0°C should be attributed to the glass transition (β relaxation)
of PP. The appearance of two glass transitions suggests that POE and PP in the matrix of composites are partially compatible, maintaining non-interfering crystalline regions [35]. The mechanical loss tangent (\(\tan \delta\)) starts to increase fast from 50°C with temperature and the increase slows down at about 75°C, which is attributed to the transition in crystal region (\(\alpha\)) in PP. It is worth noting that compared with the CB filled composite samples, Fig. 4b demonstrates slightly lower glass transition temperatures of POE but a slightly higher glass transition temperatures of PP after the addition of CNTs or GNPs, suggesting that the existence of CNTs or GNPs facilitates the motion of the POE chain segments but restricts the motion of the PP chain segments. Meanwhile, the existence of CNTs or GNPs results in different influence on the molecular chain movement of PP above 75°C, where the molecular movement is mainly from the amorphous phase of PP. As shown in Fig. 4b, CNTs suppressed the mechanical loss but GNPs enhanced the mechanical loss, also indicating that the CNTs can strongly enhance the conductive network in the composites while GNPs only result in marginal influence on the conductive network.

3.3 Electrical conductivity

Temperature dependent volume electrical resistivity of different composites was measured to evaluate the influence of partial replacement of CB by CNTs or GNPs on electrical properties of the composites. As shown in Fig. S1, all the samples show a decrease of volume electrical resistivity with the increased replacement of CB by CNTs or GNPs. The volume electrical resistivity of the composites with CNTs shows an apparent decrease when 0.25–2.00% CB was replaced by CNTs and reaches to saturation when 2.50% CB was replaced by CNTs. On the other hand, the volume electrical resistivity of the composites with CNTs shows a decreased dependence on temperature with the increased replacement of CB by CNTs. The volume electrical resistivity of the composites with CNTs shows a decreased dependence on temperature with the increased replacement of CB by CNTs. When 1.00% CB was replaced by CNTs, the composites start to show weak dependence of volume
electrical resistivity on temperature. In the case of the composites with GNP, however, all the samples show a slowly decreased but still strong temperature dependence of volume electrical resistivity with the increased replacement of CB by GNP up to 2.00%.

In order to understand the effect of the introduced CNTs or GNP on the electrical property of the composites, we provided the temperature-dependent volume electrical resistivity of the composite with 30.00% CB, the composite with 29.00% CB plus 1.00% CNT and the composite with 29.00% CB plus 1.00% GNP in Fig. 5. First, one can see that the volume electrical resistivity shows the order of the CB composite > the CB/GNP composite > the CB/GNP composite. Near the room temperature, the increase of temperature has little effect on the volume electrical resistivity as the conductive network in the composites is all stable at this stage. This is consistent with the DMA curves shown in Fig. 4b. As the temperature increases, the volume electrical resistivity of the composites increases with the temperature, exhibiting a PTC. This is because that POE begins to melt when the temperature reaches 50°C and the movement of the polymeric chains causes a rapid volume expansion. In this case, the conductive clusters become deformed, resulting in a rapid increase of volume electrical resistivity. There exists a temperature near 80°C where the increase rate of electrical resistivity starts to decrease, defined as the termination temperature $T_t$. In addition, there also exists a temperature (around 115°C) at which the electrical resistivity reaches the maximum value $\rho_{\text{max}}$, defined as $T_{\text{max}}$. Thereafter, the volume electrical resistivity begins to decrease due to the migration of conductive aggregates to the amorphous region of polymer matrix, where re-agglomeration rearranges into new conductive paths. Fig. 5b shows that the partial replacement of CB by CNTs always results in much higher electrical conductivities at room temperature ($T_0$) and $T_{\text{max}}$ in comparison with the replacement of CB by the same fraction of GNP.

PTC intensity ($I_{\text{PTC}}$) is a key parameter measuring the temperature dependence of volume electrical resistivity, defined as the logarithm of the ratio of the maximum volume electrical resistivity ($\rho_{\text{max}}$) to the volume electrical resistivity ($\rho_0$) at room temperature, as shown in the following equation:

$$I_{\text{PTC}} = \log\frac{\rho_{\text{max}}}{\rho_0} = \log\rho_{\text{max}} - \log\rho_0$$ (1)

According to (1), a lower $I_{\text{PTC}}$ suggests a more stable volume electrical resistivity on temperature variation, which is highly desirable for semi-conductive shields of power cables [24]. Fig. 5c shows that within 2.00% replacement of CB by the second filler, the $I_{\text{PTC}}$ value decreases fast with the increase of CNTs, but shows a slight decrease with the increase of GNP loading. These results suggest that compared with GNP, CNTs are much better in reducing the temperature dependence of electrical conductivity.
The conductivity of CNTs on the electrical conductivity of their composites. For evaluating the effect of intrinsic electrical conductivity of CNTs used in this work have the similar intrinsic electrical conductivity of the composites was not considered. As shown in Fig. 6, the electrical conductivity of the composites has the same variation tendency at room temperature ($T_0$) and $T_{\text{max}}$. Namely, higher aspect ratio of CNTs generally results in higher electrical conductivity in their composites. On the other hand, as shown in Fig. 6b, $I_{\text{PTC}}$ decreases to 0.3 from 0.9 with the increase of CNT aspect ratio. Since all CNTs have he similar outer diameter, these results suggest that the conductive network between CB and longer CNTs is more stable and thus the composites with longer CNTs exhibit temperature insensitive electrical conductivity.

4 Discussion and simulation

In the CB composites with the second conductive filler (i.e. CNTs or GNP), three factors should be considered in analysing the electrical conduction enhancement of the corresponding composites. One is the microstructure change of CB induced by the second filler. It was revealed from Fig. 3 that the introduction of the second filler results in indistinguishable influence on the microstructure of CB, and in this case, it is suggested that the microstructure change of CB would be not considered in analysing the effect of the second filler on the composites. The second is the formation of additional conductive network formed by the second filler. This was not possible because of the physical barrier effect of the highly loaded CB, as revealed from Fig. 3.

The third is the bridging effect of the second filler on the conductive CB network. There exist a three-dimensional interconnected conductive structure in the highly loaded CB composites, where the conductive skeleton was formed by connecting the CB aggregates. When CNTs or GNP were introduced into the CB-containing composites, the CB aggregates isolated by the polymer matrix can be connected or bridged by CNTs or GNP. Thus, it is to say, the interconnected conductive pathways in the CB-containing composites become more densely after the introduction of the second filler and such a microstructure has already been demonstrated in Fig. 3.

In the conductive composites with filler loading higher than the percolation threshold, the effective charge transfer across the bulk composites can be demonstrated by tunneling-enhanced electron transport mechanism [5]. The tunnelling conductivity ($\sigma_{\text{tunnel}}$) between two neighbouring conductive particles is susceptible to the distance between the two particle surfaces, and can be described by the following formula [36, 37]:

$$\sigma_{\text{tunnel}} = \frac{A e^2}{\hbar d} \frac{2m^*}{\lambda} \exp\left(-\frac{4\pi kd}{h} \sqrt{\frac{m^*}{\lambda}}\right)$$

where $A$ denotes the cross-sectional area of tunnel conductance, $e$, $m^*$, $\lambda$ and $h$ are the quantum of electricity, electron mass, barrier height of the matrix and the Planck’s constant, respectively, and $d$ is the surface to surface distance between CB and the second conductive filler. Equation (2) shows that the electron transport enhanced by the tunnelling effect should drastically increase as the distance $d$ decreases. It can, thus, be concluded that the surface to surface distance between CB and the second conductive filler has appreciable contribution to the overall electrical conductivity of the composites. Dissipative particle dynamics (DPD) simulations were employed to achieve insights into the role of the second conductive filler in the composite materials with fixed loading level. A brief introduction to the specific model construction, parameter setting and calculation method of the DPD simulation can be seen in the Supporting Information. Experimental and simulation researches showed that CNTs have excellent structural flexibility [38, 39], while the flexibility of GNP decreases as the layer number increases. In this research, the GNP have a thickness of 3–5 nm and thus the layer number GNP is 10 to 20, suggesting a significantly decreased flexibility. Fig. 7 presents the typical simulated images showing the dispersion of CNTs or GNP. As a consequence, the CNTs can be dispersed into the highly structured CB aggregates, and exhibiting an effective dispersion. Instead, GNP cannot be effectively entangled with the CB aggregates. These results are consistent with those observed in Fig. 3.

In order to evaluate the interactions or distance between CB and the second filler, the distribution of CB near CNTs and GNP was characterised by radial distribution function. As shown in Fig. S2, the distribution functions of CNTs and GNP in their respective systems are very similar at different proportions. The CNT-containing composite system has obvious distribution peak around $r = 5$ position (Fig. S2a). However, there were no obvious distribution peaks in the GNP-containing composite system (Fig. S2b). Furthermore, the two composite systems were quantitatively compared by counting the number of particles within the certain range $l$. Here, the adopted $l$ is not a random choice, but based on the position of the valley behind the first peak, so $l=7.05$ is used throughout the research. It has shown in Fig. 8 that at the same weight ratio of CB to the second filler, the integrated particle number of CNTs is greater than that of GNP at the selected distance range. That is to say, at the same distance from the second filler, the probability of finding CB is higher in the case of CNTs. This conclusion clearly demonstrates that CB has a shorter distance from the surface of CNTs, and thus, the corresponding high electrical conductivity of CNT-containing composites can be understood according to (2). In addition, we studied the role of the aspect ratios of CNT. As shown in Fig. 8b, when the aspect ratio is small, the integrated number of particles is also small. With the increase of aspect ratio, the integrated number of particles increases sharply. This also explained the increased electrical conductivity of the composites.
conductivity in the composites with high-aspect-ratio CNTs. Although limited by the size of the computing system, our calculation did not reach the stable platform area, the overall change trend was completely consistent with the experimental results.

**Fig. 7** Equilibrium morphology snapshots of CNT and GNP composite simulation systems at different concentrations. L125 CNTs and 25*100 GNPs are shown in green, CB is shown in pink. The polymers are omitted for clarity.

**Fig. 8** Calculated results from Fig. 7
(a) Corresponding integrated particle number of CNTs and GNPs around CBs versus the \( \phi_{\text{CNT}} \) and \( \phi_{\text{GNP}} \).
(b) Integrated particle versus the aspect ratio of CNTs in the semi-conductive composites with 29.0 CB and 1.0% CNT.
Applications of the composites

Extruded high voltage direct current (HVDC) cables are essential components in the future sustainable energy transmission systems, particularly when the electric power needs to be transmitted over very long distances or efficiently delivered through environmentally sensitive (e.g. scenic spot) areas or open-sea applications [40, 41]. In the case of extruded HVDC cables, space charges injection and accumulation in insulation should be suppressed as much as possible. Since PP based thermoplastics have been considered as the emerging HVDC cable insulation because of the higher operation temperature and excellent recyclability [31, 42], here the space charge behaviour of PP was evaluated by using the semi-conductive composites as anodes [43].

Fig. 9 shows the evolution of space charge distributions in PP under various electric fields. When CB/GNP based conductive composites were used as the anode, both homo-charges and hetero-charges can be found near the electrodes in the PP sample. Interestingly, in the case of CB/CNT composite electrode, no apparent charge injection or accumulation can be found in the PP sample even when the electric field increases to 60 kV/mm. These phenomena can also be summarised from the space charge profiles during the polarisation at different polarisation time, which is shown in Fig. 10.

The short-circuited space charge dynamics in the PP insulation with different anodes were also recorded after the polarisation process. The equation proposed by Montanari et al. was used to calculate the average space charge density in volume [44]

$$Q(t) = \frac{1}{L} \int_0^L |\rho(x, t)| dx$$

where $\rho(x, t)$ is the density of space charge in any point, $L$ is the sample thickness, $x$ represents the distance to the anode, $t$ is the depolarisation time and $S$ denotes the electrode area. Fig. 10c provides the calculated average volume space charge densities in PP at different depolarisation time. One can see that both PP samples show rapid decrease of charge density within the depolarisation process, while the PP sample coordinated with the CB/CNT composite electrode has much lower density in comparison with the PP sample with the CB/GNP composite electrode. In summary, the use of CB/CNT composite electrode can effectively suppress the space charge injection or accumulation in PP, suggesting promising shield application in HVDC power cables.

6 Conclusion

In summary, we report the design, fabrication, property and application of highly conductive thermoplastic composites for environmentally friendly power cable shields. Replacing CB by a small amount of CNTs or GNPs in the thermoplastic/CB composites, we investigated the electrical conductivity enhancement and temperature dependence of electrical conductivity of the three-phase composites. It was shown from this study that the addition of a small amount (1.00 wt%) CNTs can remarkably improve the electrical conduction behaviour of the composites, resulting in high electrical conductivity enhancement and weak temperature dependence of electrical conductivity. However, the introduction of GNPs can only induce marginal improvement of electrical conduction behaviour of the composites. DPD simulation were performed to understand the underlying mechanism, and it is concluded that the remarkable improvement of electrical conduction in the CNT-containing composites could be explained by the shorter average distance between CB and CNTs.
space charge injection and accumulation was found in the anode electrodes. These results suggest CNT-containing composite electrodes are promising for environmental-friendly high voltage cable shield applications.

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Fig. 10 Space charge profiles of PP when using the conductive composite as anode electrodes

(a) CB/CNT based composite cathode,
(b) CB/GNP based composite cathode,
(c) Space charge density in PP versus time during the depolarisation process after polarised at 60 kV/mm

Using this CNT-containing composite as electrode, suppressed space charge injection and accumulation was found in the environmental-friendly thermoplastic PP insulation. These results suggest CNT-containing composite electrodes are promising for environmental-friendly high voltage cable shield applications.

8 References

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