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Development of Recyclable Insulating Material for Power Cables

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Abstract

Progress of recyclable thermoplastic insulating materials essentialized the requirement in the present era, especially for power cable insulation signifies a forward step towards sustainable energy infrastructure. The development and characterization of Polypropylene (PP) based recyclable composite materials for power cable insulation have been discussed in this study. Four different types of fillers viz. conventional Carbon Black (CB), Modified Carbon black (MC), Coconut Coir (CC) and Reduced Graphene Oxide (RGO) were used for this research work. CB was modified by using a Vinyl Tri-Methoxy Silane (VTMS) coupling agent. CC was used in the composite after pyrolysis and reduced graphene was prepared by Hummers' method. The thermal and electrical properties of the developed composites were explored as potential candidates for power cable insulation. Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) verified that the composites exhibit good thermal stability. The composites also possessed high Breakdown Voltage (BDV) at 70°C and Volume Resistivity (VR). These composites met several critical criteria: they possess high breakdown voltage, can be operated under elevated thermal conditions, exhibit thermal stability, and ideally be recyclable or environmentally friendly. PP-based recyclable composites not only advance cable-insulating materials but also contribute to the sustainability of electrical infrastructure.

Keywords: Carbon Black, Coconut Coir, Polypropylene, Recyclable Insulation, Reduced Graphene Oxide

1. Introduction

Cross-linked polyethylene (XLPE) has excellent electrical insulation properties, with high dielectric strength and low dielectric constant, making it suitable for high-voltage applications. Especially for power cables, XLPE is the most common insulating system due to its excellent electrical properties, thermal stability, and resistance to stress cracking and chemical attack. Non-degradability is the major drawback of XLPE, *i.e.*, difficult to melt and reform due to its chemical structure and the cross-linking process. This is the prime time to go for a sustainable insulating system which can offer the required electrical and thermal protection with environmental compatibility. The development of recyclable composites for power cables based on PP, represents a significant advancement[1]. PP possess quite similar characteristics to XLPE like high breakdown voltage, high operating conditions, good thermal stability, along recyclability. Along with these factors, PP is considered more environmentally friendly than XLPE, mainly due to its more straightforward production process and greater ease of recycling. Even so, PP can accumulate a high amount of space charges in the DC electrical field while it can be a good component for AC electrical applications. High-voltage cables operate at elevated temperatures, and the insulation material should maintain its mechanical and electrical properties over the operating temperature range. PP has a higher melting point compared to XLPE. Developing PP-based recyclable composites for high-voltage and high-temperature applications can be an exciting opportunity still several challenges remain[2]. The dispersion of fillers, compatibility of composite components, and maintaining recyclability while enhancing performance are the significant hurdles. By addressing these challenges, the development of polypropylene-based recyclable composites for power cables with high breakdown voltage not only advances the field of electrical insulation materials but also contributes to the sustainability of electrical infrastructure. Incorporation of fillers (micro and nanoscale) into the PP matrix can significantly enhance its dielectric and thermal properties[3].

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This research also directed to the development of bio-based fillers with advanced compatibilization techniques for compounding materials. Attempts were also initiated to enhance the properties of the PP matrix and verify its applicability for cable insulation.

2. Materials

Isotactic polypropylene (i-PP) was supplied by Haldia Petrochemicals Ltd. Carbon black was provided by Phillips Carbon Black, and Reduced graphene oxide was prepared in-house using Hummer's method followed by reduction with hydrazine hydrate[4]. Coconut coir natural carbon black filler was also prepared in the laboratory.

3. Experimental

3.1 Surface Modification of CB

CB was dried in a hot air oven for 30 min at 100°C to remove the moisture. 10 g of dried CB was sonicated with 50 ml of isopropanol for 30 min followed by the addition of 2 ml Vinyl Trimethoxy Silane (VTMS). The solution was filtered after 4 h sonication and washed thoroughly with DI water. Filtered carbon black then dried in a hot air oven at 100°C for 2 h.

3.2 Preparation of Polymeric Composites

Carbon Black (CB), surface Modified Carbon Black (MCB), Reduced Graphene Oxide (rGO) and natural carbon black, *i.e.*, Coconut Coir (CC) black were mixed separately with PP in a twin-screw extruder at 180°C for 10 minutes at a 250-rpm speed. 1 wt% of maleic anhydride grafted PP (MA-g-PP) was used with each composition during mixing[5]. The wt% of filler in the composite and the corresponding sample codes are given in Table 1. The obtained mixture was further compressed in a compression moulding machine at 20 MPa and 200°C for 10 min to get a 2 mm thick sheet and shown in Figure 1.

Table 1. Composition details and sample code

S. No.	Sample Code	PP	MA-*g*-PP	Fillers
1	PCB_1	98 wt%	1wt%	CB: 1wt%
2	PCC_0.2	98.8 wt%	1wt%	CC: 0.2wt%
3	PMCB_0.1	98.9 wt%	1wt%	MCB: 0.1wt%
4	PrGO_0.02	98.98 wt%	1wt%	RGO: 0.02wt%

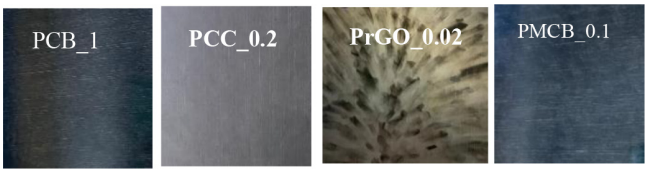


Figure 1. Prepared composite samples in sheet form.

3.3 Characterization

3.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

Thin pellet samples were prepared for FTIR analyses by mixing a very small quantity of specimen with a sufficient amount of potassium bromide (KBr), which is transparent in the IR range and the mixture is then compressed into a thin disc. A Thermofisher made FTIR Spectrometer was used and the spectra were recorded through a very thin disc from wave number 4000-400 cm^{-1}.

3.3.2 Differential Scanning Calorimetry (DSC)

DSC analysis was used to characterize the thermal properties such as melting points, crystallization or thermal stability of the composites. DSC was performed from room temperature to 250°C at a rate of 10 °C/min in a nitrogen atmosphere by using a Q 100 V 8.1 apparatus by TA instrument, USA. The minimum peak of the DSC thermogram was reflected as the melting temperature (T_m).

4. Thermogravimetric Analysis (TGA)

Thermal stability and degradation characteristics of the prepared composites were analysed by Thermogravimetric Analysis (TGA). The analysis was carried out in a TGA Q500 model of TA Instruments, USA run from room temperature to 600°C; at heating rates of 10°C/min in an inert Nitrogen gas medium (gas flow rate of 60ml/min).

5. Break Down Voltage (BDV)

Break down voltage test was conducted on the sheet sample by using two 25mm diameter; 25mm thick cylindrical brass electrodes in transformer oil at ambient temperature (28±2°C) and at elevated temperature (70±2°C) using a high voltage source (100kV Test Transformer, Peak/RMS Voltmeter) and rate of rise of voltage was 2kV/sec.

6. Volume Resistivity

Volume Resistivity (VR) of the composites was typically measured by using a Sefelec Megohm Meter, model M 1500P and an ETS Model 803B Resistivity Probe. 500V DC voltage was applied for a duration of 60 sec to measure electrical resistance as per ASTM D257-21.

7. Results

7.1 FTIR Analysis

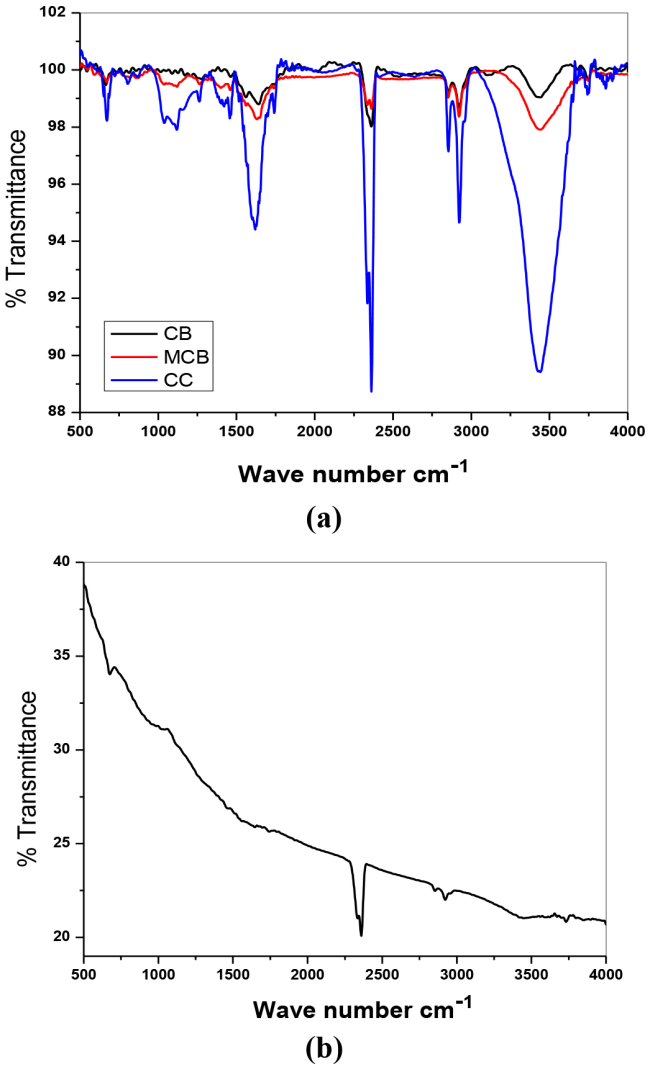


Figure 2. **(a)** FTIR of CB, MCB and CC, **(b)** FTIR of rGO filler.

FTIR analysis is a valuable technique for characterizing the chemical structure and functional groups present on the surfaces of the fillers used for the study (CB, MCB, CC and rGO). FTIR plots of CB, MCB, and CC are depicted in Figures 2(a), (b) shows the plot of rGO. CB predominantly shows absorption features due to the vibrations of carbon-carbon bonds and surface functional groups. FTIR bands at 1630 cm^{-1} conform to the sp^2 C–C stretching vibration and 2930 cm^{-1} represents the sp^3 C–H stretching vibration corresponding to the open edges of the CB. Whereas 3400cm^{-1} (broad) represents O-H Stretching of surface functional group[6]. VTMS was used to functionalize the surface of CB for better compatibility with MA-g-PP. A broad Si-O-Si stretching peak was found around 1000-1100 cm^{-1}; which was a strong indication of siloxane (Si-O-Si) linkages in CB after silane treatments along with another absorption band of CB. FTIR spectrum of pyrolyzed CC portrayed the typical characteristics peaks of lignin at 680 and 830 cm^{-1}. Characteristic peaks at 1263 cm^{-1} and 1119 cm^{-1} correspond to the C-O stretching of guaiacyl units in lignin. Peaks appearing at 1456 cm^{-1}, and 1617 cm^{-1} corresponded to the C-C ring vibrations in phenyl-propane structures and a small peak at 1740 cm^{-1} carbonyl ester or acetyl groups of lignin[7]. Figure 2(b) shows the FTIR spectra of rGO. All the fillers in this study exhibited peaks at 2370, 2923 and 3430 cm^{-1} corresponding to CO_2, C–H and O–H stretching.

7.2 DSC

DSC thermogram curves of PP and the composites are presented in Figure 3 to analyse the melting temperature (Tm) and crystallization characteristics and the results are summarized in Table 2. A sharp melting point was detected for PP whereas broad melting characteristics were observed for the composites and it is also clearly identified that Tm improved after the inclusion of CB, MCB, CC and rGO. The addition of only 0.2 wt% of CC improved the Tm by 3.5°C. Modification of CB enhanced the Tm of the composite with merely 0.1 wt% addition (1/10 of CB addition) by 2.5°C than PCB_1 composite. Further 2.5°C Tm increment was found with just 0.02 wt% RGO incorporation in the PP matrix. The melting behaviour of semicrystalline PP is thus affected by the additives even at low concentrations which influences the overall composite characteristics[8].

Table 2. DSC melting points of PP and its composites

Sample	Melting point (°C)
PP	160.0
PCB_1	160.5
PCC_0.2	163.5
PMCB_0.1	163.0
PrGO_0.02	162.5

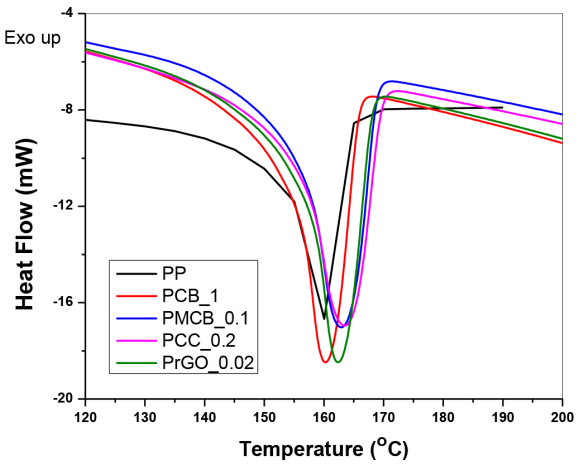


Figure 3. DSC thermograms PP and its composites.

7.3 TGA

The thermal decomposition of PP and other composites with different fillers was studied by determining their mass loss during heating. Weight loss and the Derivative Weight Loss (DTG) of all studied samples are presented in Figures 4(a, b). All the samples showed a single step of degradation. The onset of degradation i.e., the temperature of 5wt% degradation ($T_{5wt\%}$) of PP was found 396°C. Comparingly, $T_{5wt\%}$ shifted 14°C, 15°C and 22°C towards higher temperature for PCB_1, PCC_0.2 and PMCB_0.1 composites. Whereas, 0.02wt% rGO addition caused early $T_{5wt\%}$ by 33°C. Maximum degradation Temperature (T_{max}) also shifted to higher temperatures by 6°C, 11°C and 13°C for PCB_1, PCC_0.2 and PMCB_0.1 where PrGO_0.02 showed only 450°C T_{max} (5°C less than pristine PP). The onset degradation temperature and maximum degradation temperature of PP and its composites are presented in Table 3. TGA studies also showed that PP completely decomposed with no leftover residue. Only 0.33% and 0.32% residue remained for PCB_1 and PMCB_0.1 composites. PCC_0.2 and PrGO_0.02 finished with 1.9% and 1.8% residue. Noticeably, MCB filler delayed the decomposition process of PP but RGO reduced the degradation stability.

Table 3. Onset degradation temperature and maximum degradation temperature of PP and its composites

Sample	$T_{5wt\%}$ (°C)	T_{max} (°C)	Residue (%)
PP	397.00	455.50	0.00
PCB_1	411.00	461.00	0.33
PCC_0.2	412.00	466.00	1.90
PMCB_0.1	419.00	468.00	0.32
PrGO_0.02	364.00	450.00	1.80

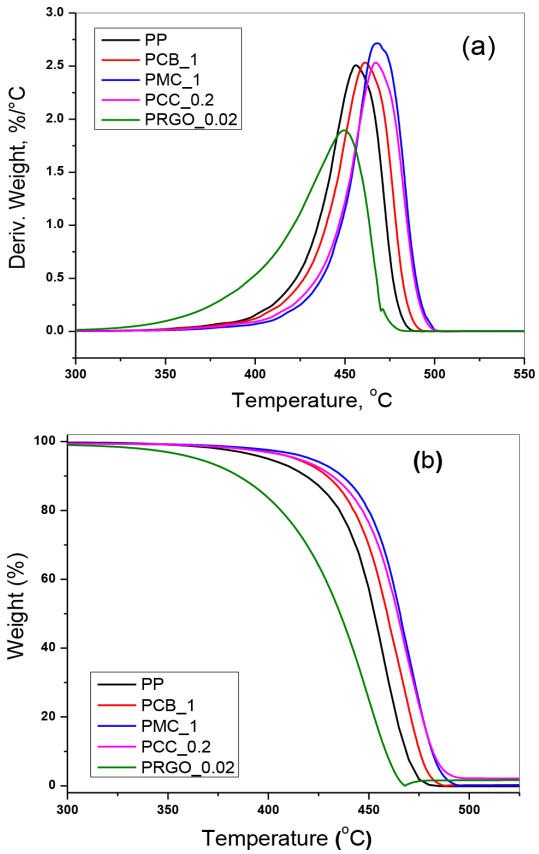


Figure 4. **(a)** TGA, **(b)** DTG thermograms.

7.4 BDV

BDV is a critical parameter, indicating the maximum electric field the material can withstand before electrical breakdown occurs. BDV of PP and its composites at room temperature (*i.e.*, 28±2 °C) and elevated temperature of 70±2 °C have been evaluated and presented in Figures 5(a, b), respectively. Incorporation of fillers (CB, MCB, CC and rGO) into the PP matrix significantly deteriorated the BDV at room temperature. The BDV of the base polymer is 55kV/mm. CB filler being conductive reduced the BDV to 35 kV/mm. Similarly, rGO filler also reduced the BDV to an equal extent as it created agglomerated dispersion into the matrix that aided in carrying the charges. Better interaction between PP/MA-g-PP and CC (lignin structure) was expected which enhanced the BDV than CB. In the PMCB_0.1 composite, the quantity of MCB was only 0.1wt% which means the distance between the particles was more which provided a better BDV value. Reverse effects have been found at elevated temperature of 70±2 °C i.e. fillers effectively improved the BDV at elevated temperature. According to the DSC study, the melting order of the composite is PCC_0.2>PMCB_0.1> PRGO_0.02>PCB_1>PP. A similar order BDV trend

was found at elevated temperatures. Hence, the thermal stability of the composites improved the BDV at elevated temperatures.

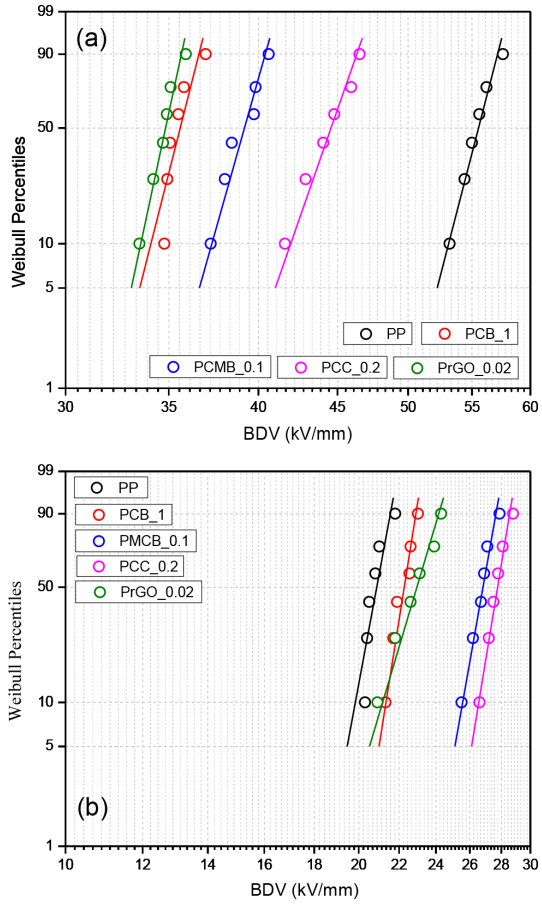


Figure 5. BDV of PP and its composites at **(a)** 28±2°C and **(b)** 70±2°C.

7.5 Volume Resistivity

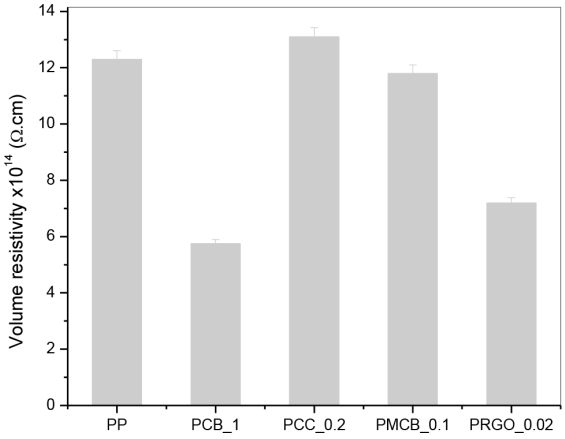


Figure 6. Volume resistivity of PP and its composites.

The volume resistivity of PP and its composites are presented in Figure 6. CC natural filler enhanced the VR though CB and rGO reduced the VR to almost half of PP. The filler loading in PCB_01 is comparatively higher than others and the CB particles were close to each other to allow more electron hop. Whereas, the volume and surface energy of rGO are maximum to form an agglomerated heterogenous structure to reduce the VR magnitude. Less quantity of MCB (0.1 wt%) and CC (0.2wt%) formed ample deep traps due to good PP-filler interactions[9]. As a consequence, carrier charge mobility decreased and the potential barrier increased to offer good electrical resistivity.

8. Conclusion

In this study, an important filler obtained from coconut coir natural resources was prepared successfully as an alternative to petroleum-based CB. The investigation of recycled insulating systems based on PP with four different types of fillers including CB, MCB, CC and rGO have been developed effectively. Composite material based on commodity PP resin with very low filler loading has been achieved for desired thermal stability and electrical insulation. Interestingly better PP-CB interaction has been found upon slight modification of CB surface. The main functional group of CC filler is lignin which created a stable interphase via H-bonding with PP/MA-g-PP and offered excellent thermal stability, improvement in BDV and synergized volume resistivity. Besides, proper dispersion of rGO in the PP/MA-g-PP matrix has not been achieved so it's inconsistent performance.

9. Acknowledgement

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10. References

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