

The Potential of Using Graphene Nanoplatelets for Electrically Conductive Compression-Molded Plates

Radwan Dweiri^{a b, *}

^aDepartment of Materials Engineering, Faculty of Engineering, Al-Balqa' Applied University-BAU, 19117 Al-Salt, Jordan

^bFuel Cell Institute, The National University of Malaysia, 43600 UKM Bangi, Selangor, Malaysia

Received 19 Feb 2014

Accepted 31 Jan 2015

Abstract

This study aims to investigate the effect of using exfoliated graphene nanoplatelets (xGNP) on the electrical and mechanical properties of the composite plates of polypropylene (PP). Synthetic Graphite (SG), Carbon Nanotubes (CNTs), and Carbon Black (CB) were used. The composites were prepared by, first, mixing the components by one of three different methods: direct mixing using internal mixer, ball milling then mixing, and milling only. The milled or mixed components were then compression molded into plates. The in-plane and through-plane electrical conductivity, flexural strength and modulus were measured and related to the morphologies of the fractured surfaces. Among all composites, the direct mixed PP/SG/xGNP/CNT composites produced plates with the highest in-plane, through-plane conductivity and flexural strength. The control sample (PP/SG/CB) had the only plates which showed a higher flexural strength than the PP/SG/xGNP/CNT composites. For the composites containing CB, ball milling of the components is found to have a positive impact on electrical and mechanical properties. The use of xGNP as primary filler had a more pronounced effect on the properties of the composites containing CB than using it as a secondary filler and this is opposite to CNT composites. Ball milled-mixed PP/xGNP/CB composites showed the highest in-plane and through-plane conductivity and a fair flexural strength.

© 2015 Jordan Journal of Mechanical and Industrial Engineering. All rights reserved

Keywords: : Graphene Nanoplatelets; Mixing; Electrical Properties; Mechanical Properties; Microstructure.

1. Introduction

A lot of work has been done in the literature concerning the use of polymeric bipolar plates in polymer electrolyte membrane (PEM) fuel cells which must exhibit excellent electrical and thermal conductivity, adequate mechanical strength, good chemical corrosion resistance, and low gas permeability that meets with the US Department of Energy (DOE) target. The good processability and low manufacturing cost are also required for the commercialization of bipolar plates [1,2].

1.1. Conductive Fillers

Graphite in different forms (natural (NG), synthetic (SG), expanded (EG), graphite oxide (OG)) has been widely used as a primary conductive filler for polymeric bipolar plates. Carbon Black (CB), Carbon Fiber (CF), and Carbon Nanotubes (CNTs) were also used as secondary conductive fillers [3-6]. In 2004, Geim and Novoselov discovered graphene which is a single carbon layer in the crystalline honeycomb graphite lattice with sp²-hybridized carbon atoms tightly bonded in hexagonal rings. Discovering graphene opened the door for the researchers to compete in producing high-quality graphene in large quantities and to explore its reinforcing ability as a new nanofiller in polymer nanocomposites [7-11]. Graphite or graphene nanoplatelet (xGNP), the basic unit obtained by

exfoliation of the natural flaky graphite and having a platelet thickness varying from 0.34 nm (monolayer) to 100 nm (multilayers), is a promising low cost (compared to CNTs) and lightweight alternative to metal- and carbon-based electrically conducting reinforcements for conducting polymer composites. Researchers have shown that exfoliated graphene nanoplatelets (xGNP) possess excellent mechanical and structural properties, superior electrical and thermal conductivity, and extremely low gas permeability [12, 13]. All these excellent properties of GNP make it attainable in many engineering applications such as electromagnetic interference (EMI) shielding devices, rechargeable batteries, electronic devices, light emitting diodes (LEDs), gas sensors, super capacitors, fuel cells and photovoltaic cells [14, 15].

Graphene nanoplatelets (xGNP), supplied by XG sciences in this work, were shipped in granular form; they are friable collections of individual platelets that prevent agglomerations and are easily broken with mechanical agitation. To achieve optimum properties and performance, xGNP must be thoroughly and completely dispersed. The manufacturer of xGNP suggested that, for a better dispersion of xGNP in thermoplastic matrices, a pre-mixing is recommended, preferably with powdered polymers rather than pellets.

* Corresponding author. e-mail: rdweiri@yahoo.com.

1.2. Polymer/Graphene Nanocomposites

Similar to all nanofillers (CNTs, nanoclay, etc.), a well-dispersed homogeneous mixture of graphene in the resins is the clue to successful performance of these nanocomposites. Restacking graphene layers due to Van der Waals surface forces and their low wettability (i.e., low surface energy around 46.7 mJ/m^2 [16]) result in their poor dispersion in polymer matrices with decreased electrical and mechanical properties. The problem of the dispersion of nanofillers becomes a challenge mainly at high nanofiller loading. Drzal with his research group [17-20] reported that polymer/xGNP nanocomposites may have an excellent chance to achieve the desired DOE target for bipolar plates in PEM fuel cells if xGNP is dispersed at a high level. Song *et al.* [21] successfully developed Nylon-6/GNP and epoxy/GNP nanocomposites for bipolar plates. Kakati *et al.* [22] used graphene in a minor quantity (1 wt.%) to reinforce into a composite of 64% NG:5% CB:5% CF in phenol formaldehyde (resole) resin and reported a significant improvement in the electrical and mechanical properties as well as the *I-V* performance of the composite bipolar plate.

An attempt to use PP/xGNP nanocomposites for bipolar plates is investigated in this work according to their electrical and mechanical properties, Direct melt mixing of the polymer matrix and the conductive fillers or only ball milling the components before compression molding them into plates or a combination of ball milling and melt mixing were adopted in this work to prepare the nanocomposites. Ball milling is usually used to grind materials, and to get a smaller size and a higher surface area. Jiang and Drzal fabricated polyphenylene sulfide (PPS)/GNP [23] and HDPE/GNP [24] nanocomposites by Solid State Ball Milling (SSBM), followed by compression molding. The reason behind selecting this compounding method was because of its capability of achieving high electrical conductivity since, in SSBM, it was found that the polymer particles are uniformly coated with GNP platelets which facilitate the forming of conductive pathways during injection or compression molding.

1.3. Objectives

In this study, plates of PP/SG/xGNP/CNT, PP/SG/xGNP/CB, PP/xGNP/CNT, PP/xGNP/CB were produced in three different methods and compared to the control samples of PP/SG/CNT and PP/SG/CB. The efficiency of the mixing technique and the efficiency of using xGNP as a primary and as secondary conductive filler were investigated. All samples were judged according to their electrical, mechanical, and morphological properties. It is worth mentioning that the present study was started based on some thoughts from the literature; first, a filler content higher than 60 wt.% was usually used in the literature to achieve the DOE target for bipolar plate and 60 wt.% was only chosen in this study to highlight the potential of using xGNP. Second, a multi-filler system by adding CB or CNTs in minor quantities is effective to enhance the performance of plates, and, finally, a combination of small and large sizes of xGNP was found, in the literature, to be effective in improving the electrical properties.

2. Experimental

2.1. Materials

In the present study, the PP powder was supplied by Goonvean Fibers Ltd, UK, with a melt flow index of 45 g/10 min, a density of 0.90 g/cm^3 , and a melting point of 165°C . Different conductive fillers were used and their characteristics are shown in Table 1. xGNP was supplied from XG Science, Inc, USA; Nanocyl™ NC7000 pristine MWCNTs from Nanocyl SA, Sambreville, Belgium, SG and CB were supplied by Asbury Carbons Inc., US.

Table 1. Characteristics of conductive fillers as received by the suppliers

Filler	Diameter	Thickness	Length	Surface area	Density	Carbon content
	(μm)	(nm)	(μm)	(m^2/g)	(g/m^3)	(%)
xGNP-1	15 μm	5-8	-	120-150	2.2	>99.5
xGNP-2	<2 μm	1-5	-	500	2.2	>99.5
MWCNTs	9.5nm	-	1.5	250-300	2.1	>90
SG	74nm	-	-	1.5	1.8	99.7
CB	30nm	-	-	254	1.8	99.7

2.2. Preparation of Composite Plates

Three different mixing methods were adopted to prepare a mixture of the PP and the conductive fillers before the mixture being compression molded: (i) direct melt mixing of the components, (ii) ball milling the components and then melt mixing them, and (iii) only ball milling of the components. The ball milling was performed as follows: initially, a mixture of conductive fillers was ball milled at different weight percentages using a planetary ball mill (pulverisette 6). A 3:1 weight ratio of balls to fillers was used, with 10-mm diameter stainless balls rotating at a speed of 200 rpm for 0.5 h. The PP powder was then added to the mixture of fillers and again they were ball milled for another 0.5 h. The melt mixing of the components was performed using an internal mixer with a Haake torque rheometer at a temperature of 190°C for 5 min at a rotational speed of 100 rpm. The PP coated with fillers, after ball milling or the compounds after melt mixing, were compression molded into plates ($10 \times 10 \times 0.3$) cm^3 for 12 min in three steps: 2 min without pressure at 220°C , 5 min under 7 MPa at 210°C , 5 min under 14 MPa at 200°C . The types of different composites and their composition are shown in Table 2. Each type was prepared in three different methods, so the total number of samples was 18. The weight ratio of xGNP-1 to xGNP-2 was kept at 3. The percentage of CB or CNT was 5 wt.% in all the composites.

Table 2. Formulations of the different types of composites

Composition (wt.%) Sample type	PP	SG	xGNP-1	xGNP-2	CNT	CB
PP/SG/CNT	40	55	0	0	5	0
PP/SG/CB	40	55	0	0	0	5
PP/xGNP/CNT	40	0	42	13	5	0
PP/xGNP/CB	40	0	42	13	0	5
PP/SG/xGNP/CNT	40	45	7.5	2.5	5	0
PP/SG/xGNP/CB	40	45	7	2.5	0	5

2.3. Characterization of Composite Plates

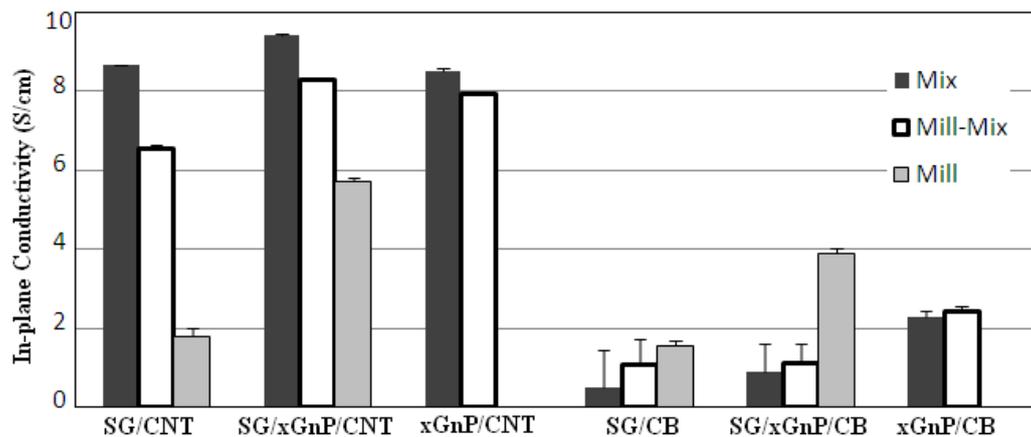
The in-plane electrical conductivity of the plates was measured using a Jandel Multi-Height Four-Point Probe combined with RM3 Test Unit which had a constant current source and a digital voltmeter designed especially for the four point probe measurement. The through-plane electrical conductivity was measured by a through-plane electrical conductivity tester manufactured at ZBT in Duisburg, Germany. The flexural properties were measured using a three-point bending test according to ASTM D790-03 standard at room temperature by a universal testing machine (UTM) Model Instron 5567 at across-head speed of 1 mm/min. The dimensions of the specimens were $100 \times 12.7 \times 3.0$ mm³, and the support span length of the specimens was fixed at 50.8 mm. Fractured surfaces of the composite plates were observed using scanning electron microscopy (FESEM, Model Supra 55/55VP) to observe the dispersion of the conductive fillers in the polymer matrix and other microscopic features of the fracture surfaces.

3. Results and Discussion

3.1. Electrical Conductivity Results

The results of the in-plane conductivity of the 16 samples are shown in Figure 1. Plates of PP/xGNP/CNT or

PP/xGNP/CB, when the components were mixed by ball milling only, were not successfully produced. An average of five readings on the surface of each plate was taken. In general, composites containing CNT showed higher conductivity values than those containing CB. For the composites containing CNT, direct melt mixing of the components produced plates that had the highest reading of conductivity (e.g. ~8.7 S/cm for PP/SG/CNT and ~9.3 S/cm for PP/SG/10%xGNP/CNT), whereas the ball-milled composites showed the lowest values of conductivity (e.g. ~1.8 and ~5.7 S/cm respectively for the same type of composites). However, for the composites containing CB, the milling method resulted in producing plates with the highest values (e.g. ~3.9 S/cm for PP/SG/xGNP/CB), whereas the direct method lowered the value to about ~0.87 S/cm for the same composite. On the other hand, and regardless of the mixing method used, among all the composites containing CNT, the composites containing xGNP as a secondary filler (10 wt.%) showed the highest reading of conductivity which was, of course, higher than that of the control sample (PP/SG/CNT) or that of the sample with xGNP as a primary filler (PP/55%xGNP/CNT). The improvement in conductivity of the direct-mixed and of the milled-mixed PP/SG/10%xGNP/CNT is about 8.5% and 27%, respectively, compared to their counterparts of PP/SG/CNT prepared by the same methods. For the composites containing CB, the effect of using xGNP as a primary filler with CB was more pronounced on conductivity than it was when using xGNP as secondary filler with CB. This is true except for ball-milled PP/SG/10%xGNP/CB which showed about 152% increase in conductivity compared to ball-milled PP/SG/CB. The increase of the conductivity of composites containing xGNP compared to that of the control sample indicates a positive synergistic effect between xGNP and SG, CNT, or CB. The standard deviations for samples containing CNT were smaller than their values for CB composites as can be seen in Figure 1. The deviation from the average value increases for composites containing CB prepared by direct mixing.

**Figure 1.** In-plane electrical conductivity of PP composites.

The results of through-plane conductivity for all types of the composites are shown in Table 3. The results in Table 3 show a similar trend as the results of the in-plane conductivity. The through-plane conductivity reaches its highest value (up to 7 S/cm) for directly mixed composites containing CNT and it is the lowest (~ 1 S/cm) for ball-milled CNT composites. A slight improvement in conductivity occurs for milled-mixed (~ 0.51 S/cm) and the directly mixed (~ 0.33 S/cm) composites containing 10% xGNP/CB compared to the control sample PP/SG/CB. An increase of about 248% occurs in conductivity for ball-milled PP/xGNP/CB compared to ball-milled PP/SG/CB. The through-plane conductivities are much lower for the composites containing CB (up to 2 S/cm) compared to their counterparts containing CNT (up to 7 S/cm). There is a small increase (up to 15%) on conductivity by using xGNP as secondary (10 wt.%) or primary (55 wt.%) filler with CNT compared to the control sample (PP/SG/CNT). The effect on conductivity is more pronounced by using xGNP as a primary filler with CB ($> 600\%$ increase compared to the control sample) than by using xGNP in a minor quantity with CB (an increase up to 18%). The milled-mixed composites show intermediate values of in-plane and through-plane conductivities between the ball-milled and direct-mixed composites.

Table 3. Through-plane electrical conductivity of PP composites

Sample Type	Through-plane conductivity (S/cm)		
	Mix	Mill-Mix	Mill
	PP/SG/CNT	6.34 \pm 0.030	5.56 \pm 0.197
PP/SG/xGNP/CNT	7.30 \pm 0.055	6.70 \pm 0.130	0.73 \pm 0.065
PP/xGNP/CNT	6.18 \pm 0.071	5.46 \pm 0.035	-
PP/SG/CB	0.30 \pm 0.005	0.43 \pm 0.007	1.22 \pm 0.032
PP/SG/xGNP/CB	0.33 \pm 0.007	0.51 \pm 0.017	1.15 \pm 0.025
PP/xGNP/CB	2.18 \pm 0.019	2.30 \pm 0.017	-

3.2. Flexural Test Results

The results of flexural strength and modulus are shown in Figures 2 and 3, respectively. The flexural strength of

the neat PP plates is found to be about 65 MPa and their flexural modulus is about 2.7 GPa. A clear decrease (to half the value of that of the neat PP or more) in the values of flexural strength can be observed from Figure 2 for all the types of composites. On the other hand, the values of flexural modulus for these composites are distinctly increased compared to those of the neat PP sample. There were considerable deviations from the average values in measuring the flexural strength and modulus for some samples which can be related to the inhomogeneity of the produced plates. Among all the samples, the control samples of PP/SG/CB show the highest values of flexural strength regardless of the mixing method being used. No improvement in flexural strength is reported by using xGNP as a secondary or as a primary filler with CNT or with CB composites when comparing them with their counterparts of the control samples. The values of flexural strength for PP/SG/10% xGNP/CNT are higher than those of PP/xGNP/CNT and, on the contrary, the flexural strengths of PP/SG/10% xGNP/CB are lower than those of PP/xGNP/CB when they are compared with the same mixing method. This means that using xGNP as a primary filler improves the flexural strength in a better way than using it as a secondary filler in case of CB composites and the opposite is correct for CNT composites. The xGNP possesses stiffer and rigid properties than those of SG. Therefore, the flexural modulus is increased from ~ 6.3 GPa for directly melt-mixed PP/SG/CNT composites to ~ 8.0 GPa for PP/55% xGNP/CNT nanocomposites. In case of CB composites, it is increased from ~ 7.5 GPa for PP/SG/CB composites to ~ 9.7 GPa for PP/55% xGNP/CB nanocomposites. Among all the composites, the ball-milled composites show the lowest flexural modulus values and this is due to its high porosity. In general, the milled-mixed CNT composites show intermediate values of flexural strength and modulus between the ball-milled and the direct-mixed composites. This is true except for the milled-mixed PP/SG/CNT composite which show the highest values. The milled-mixed CB composites have the highest value of flexural strength only for PP/SG/CB composite and the highest modulus for both PP/SG/CB and PP/CB/xGNP/CB composites.

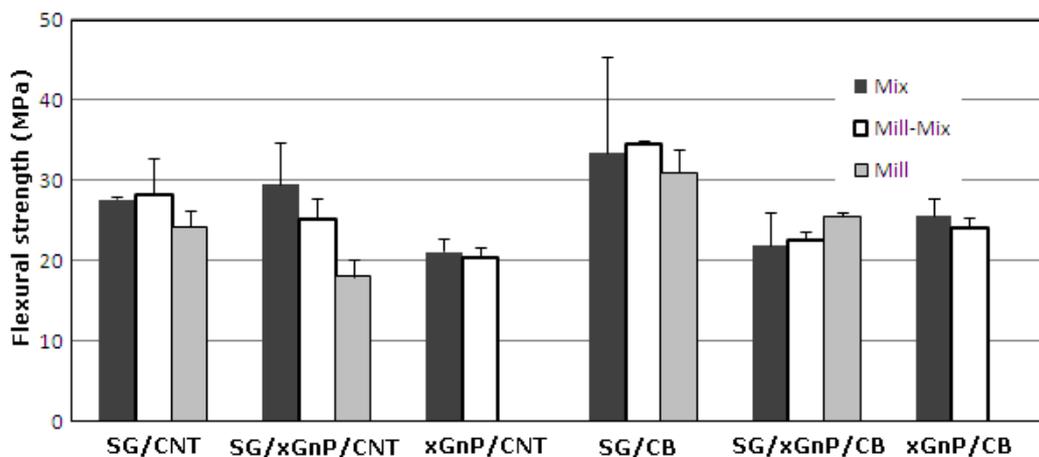


Figure 2 Flexural strength of PP composites.

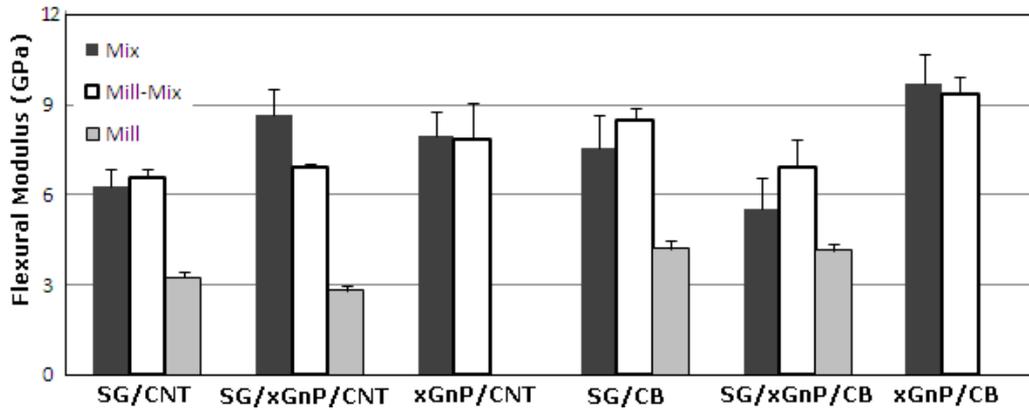


Figure 3 Flexural modulus of PP composites.

3.3. Morphology

The SEM micrographs of the “as received” conductive fillers are shown in Figure 4. SG has a gross or macro-morphology that is somewhat acicular and, at higher magnification, the flaky morphology of SG can be observed. xGNP-1 and xGNP-2 are nanoparticles consisting of short stacks of graphene sheets having a platelet shape. xGNP-2 has aggregates of sub-micron platelets with a very high surface area and micro-porosity. CB exists as primary aggregates composed of spheroidal primary particles fused together. MWCNTs appear as a relatively loosely packed powder having a “combed yarn” structure.

The fracture surface morphologies of the 17 different types of samples are shown in Figures 5, 6, and 7. The image of the melt-mixed PP/SG/CNT composite (Figure 5a) shows the existence of small flaky SG particles dispersed in the PP matrix between the larger SG particles. In melt mixing process, the shear usually breaks down agglomerates and spreads the small particles into the matrix. No evidence on the agglomeration of CNTs could be seen in Figure 5a and CNTs act as bridges for SG particles, increasing the overall connectivity and, hence, the conductivity of the system. The bridging effect of CNTs is visible in Figure 5g. The high aspect ratio of CNTs also improves the electrical conductivity. Ball milling of CNTs results in agglomeration of CNTs which is clearly observed in Figure 5c and this mainly leads to the decrease of the flexural strength and the electrical conductivity besides the other negative impact of ball milling on CNTs which is the decrease of their lengths. The melt mixing, again, leads to breaking the primary agglomerates of CNTs which formed after milling, so that the flexural strength increases again (figure 5b). Numerous CNTs were pulled out from the PP matrix as can be observed from Figure 5a and this phenomenon usually results from the poor compatibility between the fillers and PP matrix [26] and hence the lower stiffness of the composites. Microstructures of PP/SG/CB composites appear in Figures 5d, e, f. The small size and spherical shaped CB particles facilitate to form conducting tunnels between the large graphite particles, and thus increase the electrical conductivity [27]. Király and Ronkay [28] indicated that CB in PP/G/CB composites influenced significantly the distribution of graphite in PP which in turn controls the mechanical and electrical properties. In general, a better wettability of fillers in case of PP/SG/CB composites leads to a higher flexural strength and stiffness compared to PP/SG/CNT composites. This is opposite to the expected results since CNTs are usually used as a

reinforcing filler. The decrease of the lengths of CNTs during both ball milling and melt mixing and the agglomeration are issues that might lower the mechanical properties of CNT composites more than those of PP/SG/CB composites. The increases in the homogeneity and dispersion of CB for ball milled PP/SG/CB composite (Figure 5f) Ball milling and then melt mixing lead to form CB aggregates which are uniformly dispersed throughout the matrix (Figure 5e, h). Moreover, the interparticle distance between SG particles is seen to be better filled by CB which increases the electrical and the mechanical properties.

Figures 6a-f show the graphs of fracture surfaces of PP/SG/xGNP/CNT and PP/SG/xGNP/CB composites. Homogeneous dispersion of xGNP in PP matrix with a dramatic interface behavior [29] is visible in Figure 6a where the composite is prepared by melt mixing and this might be why this type of composite has higher electrical and mechanical properties among almost all other composites. Kalaitzidou *et al.* [17] reported the role of shear during mixing to break agglomerates of xGNP in PP/xGNP composites. Kim *et al.* [30] stated that the synergistic effect between the homogeneous dispersion and strong adhesion of CNTs and xGNP could be achieved in case of PP/10%xGNP/10%CNTs composites prepared by solution method. The CNTs bridged across adjacent xGNP platelets, forming an extended network of filler in direct contact and this was also stated by Yu *et al.* [25] in hybrid graphite nanoplatelet–CNT filler for epoxy composites. Ball milling of CNTs produces plates where the graphene layers are buckled, deformed and less compacted and CNTs are agglomerated (Figure 6c). This leads to a drastic drop in the electrical and mechanical properties of ball milled composites. There is agglomeration of xGNP and there are micro-gaps between xGNP platelets [24] that are clearly seen for direct mixed PP/SG/xGNP/CB composite (Figure 6d) and this inhibits their interconnection and lowers their electrical and mechanical properties which, again, increases when the ball milling technique is used (Figures 6e,f).

Finally, in PP/xGNP/CNT and PP/xGNP/CB composites, a well dispersed system is shown in Figure 7a,b,d,e but with no sufficient amount of PP to bond the numerous graphene platelets and fail in producing ball milled CNTs or CB composites (Figure 7c).

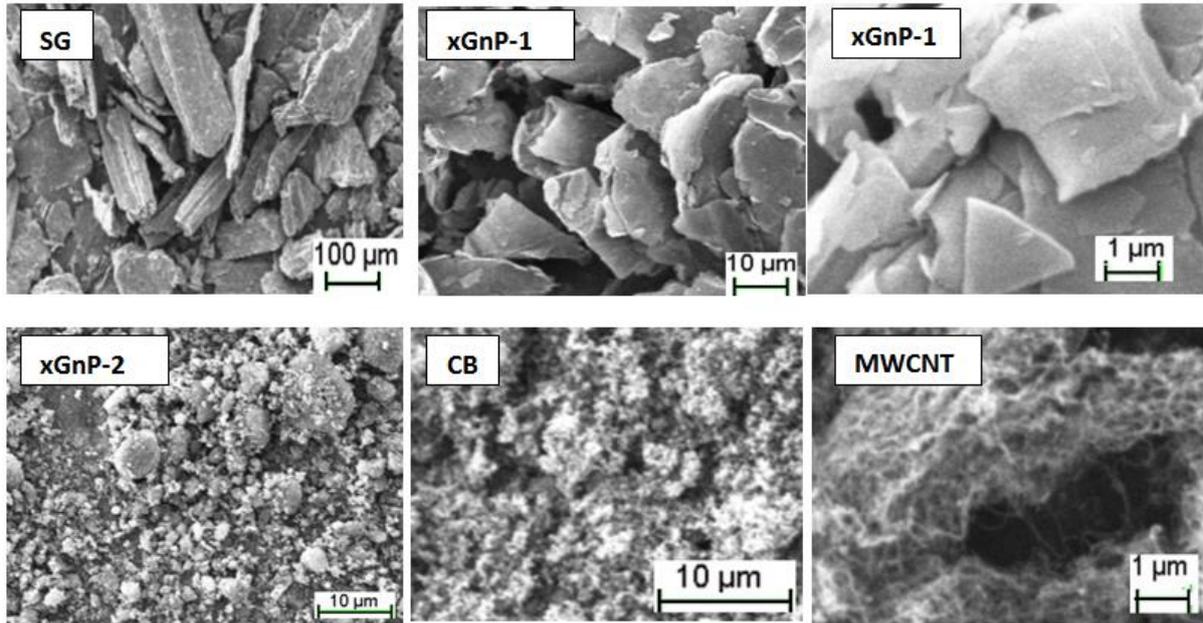


Figure 4 The morphologies of the “as received” conductive fillers.

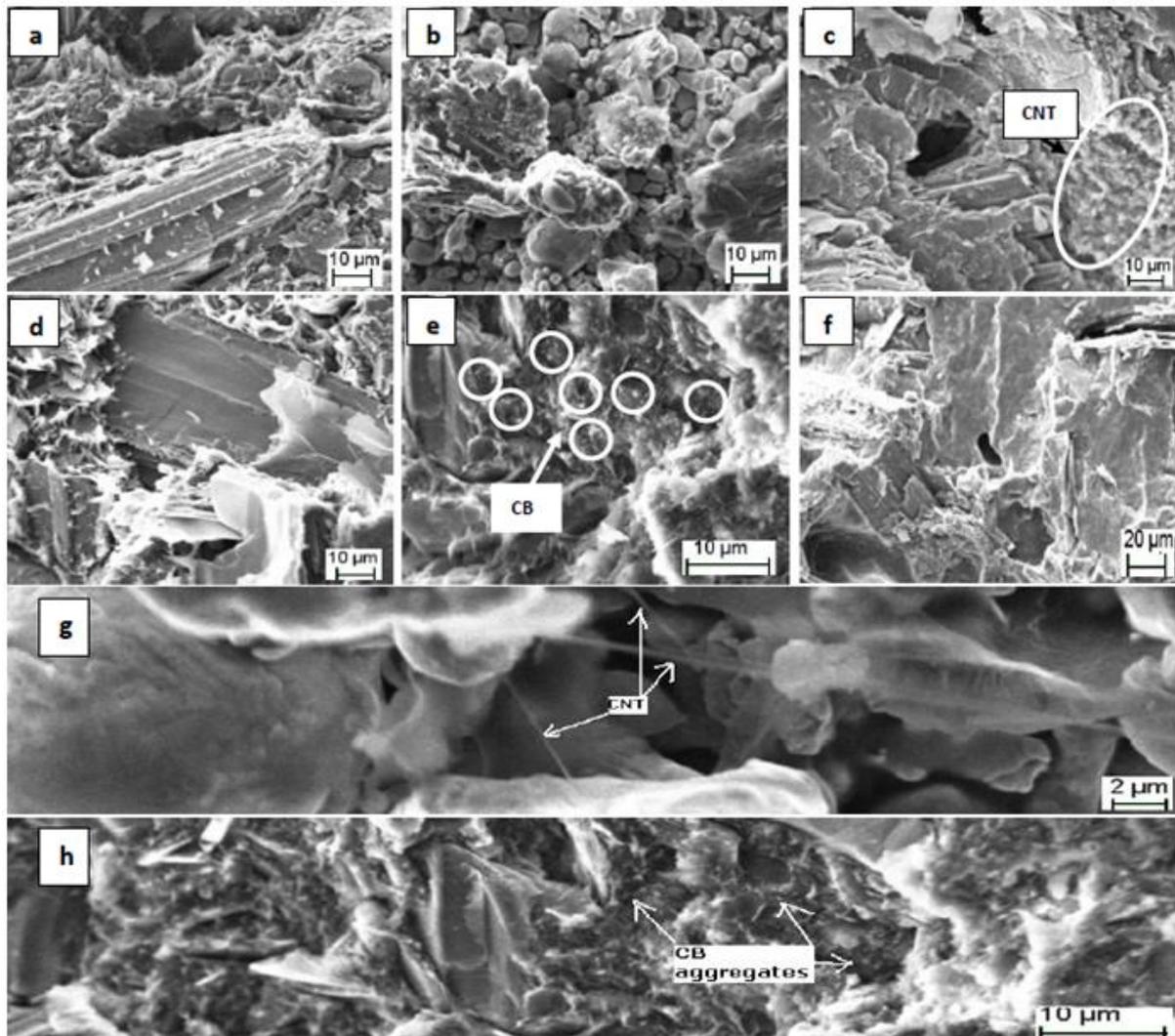


Figure 5 The fracture surface morphologies of the composites of (a,b,c,g) PP/SG/CNT, and (d,e,f,h) PP/SG/CB where (a,d) prepared by mixing, (b,e,g,h) by milling+mixing, and (c,f) by milling.

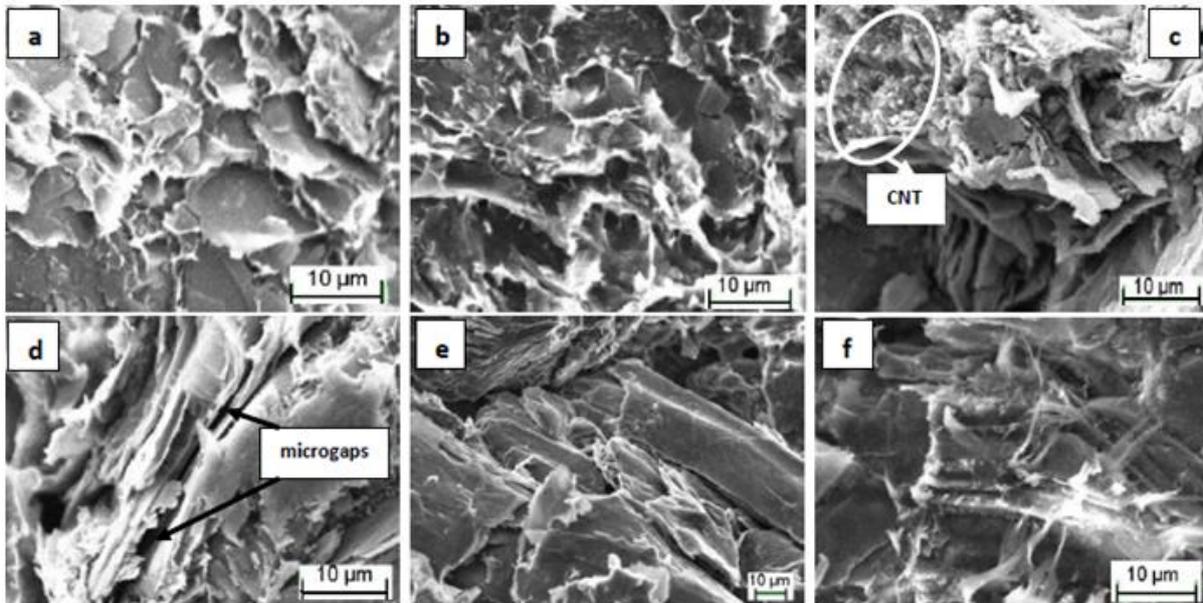


Figure 6 The fracture surface morphologies of the composites of (a,b,c) PP/SG/xGNP/CNT, and (d,e,f) PP/SG/xGNP/CB where (a,d) prepared by mixing, (b,e) by milling+mixing, and (c,f) by milling .

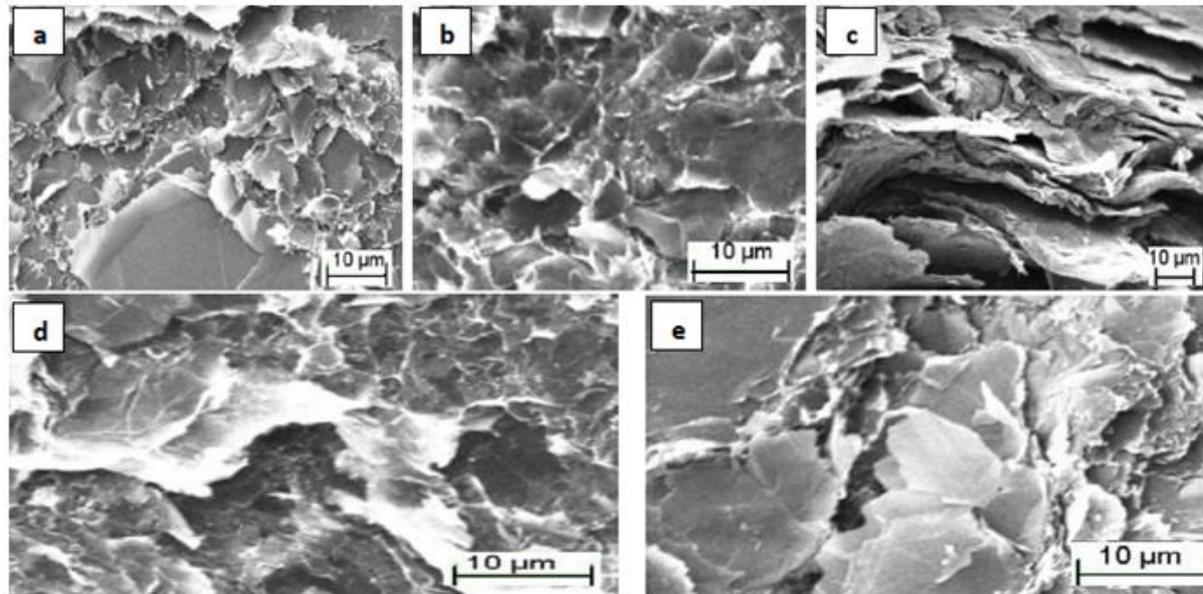


Figure 7 The fracture surface morphologies of the nanocomposites of (a,b,c) PP/xGNP/CNT, and (d,e) PP/xGNP/CB where (a,d) prepared by mixing, (b,e) by milling+mixing, and (c) by milling.

4. Conclusions

The effect of adding xGNP, CNT, SG, and CB on the electrical and mechanical properties of PP composites was studied in the present work; some important conclusions can be drawn as follows:

- The mixing method which was used to prepare the composites has a great effect on the electrical and mechanical properties of the produced plates. The direct melt mixing was found to be more effective for the composites containing CNT and the ball milling is effective in case of the composites containing CB.
- According to the type of composites and the mixing methods, the values of in-plane and through-plane conductivity changes sequentially as follows: mixed CNT composites>milled-mixed CNT>milled CNT with

maximum values of 9.4 S/cm (in-plane) and 7.3 S/cm (through-plane) for mixed PP/SG/xGNP/CNT plate. For CB composites, the values increase inversely and the maximum values are found at 3.9 S/cm (in-plane) for milled PP/SG/xGNP/CB plate and 2.4 S/cm (through-plane) for milled-mixed PP/xGNP/CB plate since the milled PP/xGNP/CB plate could not be produced.

- Regarding the mechanical properties for the composites containing xGNP, it can be generally said that the flexural strength values are higher for CB composites compared to their counterparts of CNT composites which were prepared using the same method. The mixed PP/SG/xGNP/CNT plates have the highest value of flexural strength (29.6 MPa). The maximum value for CB composites reaches about 25 MPa.

- Finally, achieving the DOE target with 60 wt.% of fillers was not possible in the present work and a higher filler content with an optimization procedure for the components of the composite as well as for the mixing and compression parameters is needed in the future. The functional groups existing at the edges of the xGNP can also contribute to a better dispersion if a suitable coupling agent or functionalization procedure is adopted in the future.

Acknowledgements

The authors would like to acknowledge Al Balqa Applied University and the Fuel Cell Institute at The National University of Malaysia for their support.

References

- [1] Vielstich W, Gasteiger HA, Lamm A. Handbook of Fuel Cells-Fundamentals, Technology and Applications. Vol. 3. New York: John Wiley & Sons, Ltd; 2003.
- [2] E. Planes, L. Flandin, N. Alberola, "Polymer Composites Bipolar Plates for PEMFCs". Energy Procedia, Vol. 20 (2012), 311-323.
- [3] R.B. Mathur, S.R. Dhakate, D.K. Gupta, T.L. Dhami, R.K. Aggarwal, "Effect of different carbon fillers on the properties of graphite composite bipolar plate". J. Mater. Proc. Tech., Vol. 203 (2008), 184-192.
- [4] S.R. Dhakate, R.B. Mathur, B.K. Kakati, T.L. Dhami, "Properties of graphite-composite bipolar plate prepared by compression molding technique for PEM fuel cell". Inter. J. Hyd. Energy, Vol. 32 (2007), 4537-4543.
- [5] R. Dweiri, J. Sahari, "Electrical Properties Carbon-Based Polypropylene Composites for Bipolar Plates in Polymer Electrolyte Membrane Fuel Cell (PEMFC)". J. Power Sources, Vol. 171(2007), 424-432.
- [6] H. Suherman, A.B. Sulong, J. Sahari, "Effect of the compression molding parameters on the in-plane and through-plane conductivity of carbon nanotubes/graphite/epoxy nanocomposites as bipolar plate material for a polymer electrolyte membrane fuel cell". Ceramics Inter., Vol. 39 (2013), 1277-1284.
- [7] R.J. Younga, I.A. Kinlocha, L.G. Kostya, S. Novoselov, "The mechanics of graphene nanocomposites: A review". Comp. Sci. Tech., Vol. 72 (2012), 1459-1476.
- [8] O.V. Kharissov, B.I. Kharisov, "One of the Hottest Areas in the Nanotechnology: Attention of Chemists is Needed". The Open Inorganic Chemistry J., Vol. 2 (2008), 39-49.
- [9] J.R. Potts, D.R. Dreyer, C.W. Bielawski, R.S. Ruoff, "Graphene-based polymer nanocomposites". Polymer, Vol. 52 (2011) 5-25.
- [10] T. Kuilla, S. Bhadra, D. Yaea, N.H. Kim, S. Bose, J.H. Lee, "Recent advances in graphene based polymer composites". Prog. Poly. Sci., Vol. 35 (2010), 1350-1375.
- [11] J.A. King, M.D. Vial, F.A. Morrison, K.R. Wiese1, E.A. Beach, M.J. Cieslinski, G.R. Bogucki, "Characterization of exfoliated graphite nanoplatelets/polycarbonate composites: electrical and thermal conductivity, and tensile, flexural, and rheological properties". J. Comp. Materials, Vol. 46 (2012), 1029-1039.
- [12] P. Mukhopadhyay, R.K. Gupta, "Trends and Frontiers in Graphene-Based Polymer Nanocomposites". Plastics Engineering, Vol. 67 (2011), 32-42.
- [13] H. Kim, A.A. Abdala, C.W. Macosko, "Graphene/Polymer Nanocomposites". Macromolecules, Vol. 43 (2010), 6515-6530.
- [14] T. Drzal, "Graphene Nanoplatelets: Graphene Nanoplatelets: A Multifunctional Nanomaterial for Polymers, Composites and Energy Generation and Storage Applications. Conference proceedings". Nanotech conference and Expo 2012, Santa Clara, CA, California.
- [15] B.Z. Jang, "Nano Graphene Platelets (NGPs), Graphene Nanocomposites, and Graphene-Enabled Energy Devices". www.nanotxstate.org/presentation/NAC_12_Apr_2010.pdf . Wright State University, College of Engineering presentation Dayton, Ohio, 2010.
- [16] S. Wang, Y. Zhang, N. Abidi, L. Cabrales, "Wettability and surface free energy of graphene films". Langmuir, Vol. 25 (2009), 11078-11081.
- [17] K. Kalaitzidou, H. Fukushima, L.T. Drzal, "A new compounding method for exfoliated graphite-polypropylene nanocomposites with enhanced flexural properties and lower percolation threshold". Com. Sci. Tech., Vol. 67 (2007), 2045-2051.
- [18] K. Kalaitzidou, H. Fukushima, L.T. Drzal, "A Route for Polymer Nanocomposites with Engineered Electrical Conductivity and Percolation Threshold". Materials, Vol. 3 (2010), 1089-1103.
- [19] W. Liu, I. Do, H. Fukushima, L.T. Drzal, "Influence of Processing on Morphology, Electrical Conductivity and Flexural Properties of Exfoliated Graphite Nanoplatelets-Polyamide Nanocomposites". Carbon Letters, Vol. 11 (2010) 279-284.
- [20] X. Jiang, L.T. Drzal, "Improving electrical conductivity and mechanical properties of high density polyethylene through incorporation of paraffin wax coated exfoliated graphene nanoplatelets and multi-wall carbon nano-tubes". Composites: Part A, Vol. 42 (2011), 1840-1894.
- [21] L. Song, J. Guo, A. Zhamu, B.Z. Jang, "Highly Conductive Nano-scaled Graphene Plate Nanocomposites and Products". U.S. Patent No. 7566410, 2009.
- [22] B.K. Kakati, A. Ghosh, A. Verma, "Efficient composite bipolar plate reinforced with carbon fiber and graphene for proton exchange membrane fuel cell". Int. J. Hyd. Eng., Vol. 38 (2013), 9362-9369.
- [23] X. Jiang, L. Drzal, "Exploring the potential of exfoliated graphene nanoplatelets as the conductive filler in polymeric nanocomposites for bipolar plates". J. Power Sources, Vol. 218 (2012), 297-306.
- [24] X. Jiang, L. Drzal, "Synthesis of bipolar plates for fuel cells based on exfoliated graphene nanoplatelets filled polymeric nanocomposites". 11th-Annual Automotive Composites Conference and Exhibition, ACCE, 2011.
- [25] A. Yu, P. Ramesh, X. Sun, E. Bekyarova, M.E. Itkis, R.C. Haddon, "Enhanced Thermal Conductivity in a Hybrid Graphite Nanoplatelet-Carbon Nanotube Filler for Epoxy Composites". Adv. Mater., Vol. 20 (2008), 4740-4744.
- [26] S.H. Liao, C.Y. Yen, C.C. Weng, Y.F. Lin, C.C.M. Maa, C.H. Yang, M.C. Tsai, M.Y. Yen, M.C. Hsiao, S.J. Lee, X.F. Xie, Y.H. Hsiao, "Preparation and properties of carbon nanotube/polypropylene nanocomposite bipolar plates for polymer electrolyte membrane fuel cells". J. Power Sources, Vol. 185 (2008), 1225-1232.
- [27] J.H. Lee, J.S. Lee, T. Kuila, N.H. Kim, D. Jung, "Effects of hybrid carbon fillers of carbon nanocomposite bipolar plates on the performance of direct methanol fuel cells". Composites: Part B, Vol. 51 (2013), 98-105.
- [28] A. Király, F. Ronkay, "Effect of Graphite and Carbon Black Fillers on the Processability, Electrical Conductivity and Mechanical Properties of Polypropylene-based Bipolar Plates". Polym. and Polym. Comp., Vol. 21 (2013), 93-99.
- [29] S. kim, J. Seo, L. Drzal, "Improvement of electric conductivity of LLDPE based nanocomposite by paraffin coating on exfoliated graphite nanoplatelets". Composites: Part A, Vol. 4 (2010), 581-587.
- [30] Kim MS, Yan J, Joo KH, Pandey JK, Kang YJ, SH, Ahn, "Synergistic effects of carbon nanotubes and exfoliated graphite nanoplatelets for electromagnetic interference shielding and soundproofing". J. App. Polym. Sci., Vol. 130 (2013), 3947-3951.