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A Strategy of Nano-Calcite Fillers for Enhancing the Mechanical and Thermal Properties of Polypropylene Polymers

Haydar U. Zaman[1,]*

Abstract

Particulate polymer composites have gained popularity because of their many uses. For some, using high loadings to achieve desired attributes without compromising the material's mechanical properties or restricting its processability is desirable. It is possible to use surface active agents to improve characteristics and increase solid loading. Interface characteristics in highly packed particulate composites based on nano-calcite (nano-calcium carbonate) and polypropylene as a binder are the focus of the current study. Nano-calcite particles treated with pimelic acid were created by means of the surface modification technique. To create binary composites, four distinct amounts of nano-calcite were introduced to polypropylene. The mechanical property measurements revealed that the inclusion of fillers initially increased the composites' elastic modulus and impact strength before decreasing them. At the same time, the tensile yield stress fell. Furthermore, pimelic acid was added to the composites, increasing their elastic modulus and impact strength. The pimelic acid treatment improved the interfacial adhesion between the filler and the matrix, according to the results of scanning electron microscopy. This suggests that the compatibility between the filler and matrix has improved, which is what caused the improvement in mechanical properties. Differential scanning calorimetry was used to examine the crystallization characteristics of virgin polypropylene and its composites. In contrast to virgin polypropylene and nano-composite, the results showed that adding pimelic acid-treated nano-fillers increased the crystallization temperature while simultaneously improving nucleation and crystallization.

Keywords: Nanocomposites, pimelic acid, mechanical properties, scanning electron microscopy (SEM), thermal properties

INTRODUCTION

A novel class of particle-filled polymer composites known as polymer nanocomposites are made up of particles that are scattered in at least one dimension that is in the nanoscale range. Recent years have seen a rise in interest in polymer nanocomposites due to their notable enhancement of physical and/or chemical characteristics over matrix polymers [1–3]. It is commonly known that nanoparticles are crucial to the use of polymer nanocomposites. Since the incorporation of nanoparticles increases stiffness, toughness, and dimensional stability, polymer-based nanocomposites have been the subject of much research and application. However, because of their high surface energy, the nanoparticles' tendency to aggregate significantly reduces the characteristics of the nanocomposites, severely restricting their engineering uses. Numerous studies have shown that the particle dispersion, which is

*__Author for Correspondence__
Haydar U. Zaman
E-mail: haydarzaman07@gmail.com

[1]Assistamt. Professor, Department of Physics, National University of Bangladesh and Institute of Radiation and Polymer Technology, Bangladesh Atomic Energy Commission, P.O. Box-3787, Savar, Dhaka, Bangladesh

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closely related to the manufacturing process, is a determining factor in the exceptional properties of nanocomposites [4, 5]. The composites have been made using a variety of production techniques, including in situ polymerization [6], intercalation method [7], sol-gel method [8], and melt compounding [9]. Because of its affordability, practicality, and environmental friendliness, melt compounding has been considered a popular method among all of these. One of the most often utilized semicrystalline polymers in commerce is polypropylene (PP). Its excellent performance-to-cost ratio is PP's primary selling point. But due of its low service temperature and weak impact strength, its application has been restricted. Moreover, it is simple to alter PP to obtain much improved qualities. Using inorganic fillers to improve PP's stiffness, toughness, hardness, chemical resistance, dimension stability, and gas barrier properties is now widely acknowledged to be beneficial [10, 11]. The size, shape, aspect ratio, interfacial adhesion, surface features, and degree of dispersion of the inorganic fillers have a significant impact on the mechanical and physical properties of the PP composites [12, 13]. Calcium carbonate ($CaCO_3$) is the most widely utilized of these inorganic fillers, mostly due to its affordability and easily useable form. As a result, PP composites containing micro- and nano-$CaCO_3$ (mCC and nCC, respectively) have been thoroughly investigated [14–16]. Since it is thought that the enormous interfacial area between the filler and the polymer greatly influences the composite's properties, PP/nCC composites have garnered a lot of attention in comparison to PP/mCC composites. Yang et al. [15] showed that nCC particles outperformed mCC particles in their toughening action, increasing the impact strength of the PP matrix. Nevertheless, there is poor adhesion between the thermoplastic matrices and the fillers. Since PP is a nonpolar material, it is difficult for it to mix with the polar $CaCO_3$. Additionally, the flaw becomes much more noticeable when the size of the $CaCO_3$ particles reaches the nanometer range: as the particle size decreases, the specific surface area increases and the surface free energy and cohesion forces strengthen, making it challenging to achieve good dispersion in the PP matrix due to particle reunification. Therefore, research into nCC surface modification is required to enhance the nanocomposite's characteristics. Coating the particles with an organic substance, such as titanate coupling agents and stearic acid, is the standard surface treatment. The surface of the particles is also altered by irradiation-induced graft polymerization [17] and macromolecular compatibilizer [18]. A novel technique for altering the surface of inorganic particles is the coating process of chemical deposition [19]. On the other hand, the modification of nCC particles coated with pimelic acid (Pa) has not received much attention. Recent research has shown that Pa may effectively modify the surface of wollastonite [20], which implies that it may have a similar impact on $CaCO_3$ [21]. Pa was therefore applied to nCC as a surface modification. Because surface treatment altered the interfacial interaction between nCC particles and the PP matrix, it had a considerable impact on the crystallization behavior of PP/nCC composites. The heterogeneous nucleation impact of nCC on PP may be altered by surface treatment. Aluminate coupling agent modification of the surface produced a similar outcome [22]. Our primary goal in this work was to investigate the crystalline and mechanical characteristics of PP/nCC-Pa composites.

EXPERIMENTAL

Ingredients

The PP grade utilized in this project was LG Chem Korea's SEETEC homopolymer PP. This serves as the matrix. The homopolymer PP has a melt flow rate of 14 g/10 minutes (2.16 kg at 230°C) and a density of 0.90 g/cm^3. We investigated both unmodified and nCC surfaces changed by pimelic acid (an analytical reagent also known as Pa), both kindly provided by SK Corporation, South Korea, because we were interested in how surface modification of filler particles affected the dispersion and characteristics of compounds. The analytical reagent, ethanol, was purchased commercially and utilized exactly as supplied. Shiraishi Kogyo Kaisha Ltd., Japan, provided the calcium carbonate ($CaCO_3$) nanoparticles, which had a diameter of 60 to 80 nm and a density of 2.7 g/cm^3.

Preparing the Sample

Processing of $CaCO_3$ Nanoparticle Surfaces

To prepare unmodified nCC, its water suspension was dried to constant weight in an oven set at 100°C. The following was the surface treatment of nCC: A 500 mL three-necked flask with a mechanical stirrer was filled with 150 g of nCC. A 1.5 g Pa (1% Pa) or 4.5 g Pa (3% Pa) solution in 250 mL of ethanol was then added. The mixture was vigorously stirred and reacted for 1 hour at 80°C. Following the distillation of the ethanol, the Pa-treated nCC was dried at 90°C to constant weight.

Producing PP/nCC-Pa Composites

Prior to melt mixing, PP and surface-treated $CaCO_3$ nanoparticles were allowed to cool to room temperature after being dried for 6 hours at 80°C in a vacuum oven. Before processing, the materials were kept in a desiccator. Binary composites were created by adding nCC to PP in four different concentrations (5, 10, 15, and 20 weight percent). Following prior mixing, all of the ingredients were introduced to the extruder at once. Blending was done in a twin-screw extruder (Brabender plasticorder, model: PLE-331) with varying filler concentrations. The capacity of the mixing chamber is 30 mL. The blending time, rotor speed, and processing temperature were all set at 10 minutes, 60 rpm, and 180°C, respectively. A weight of 60 g was the controlled sample weight for each blending. The Brabender apparatus's mixing chamber was unsealed and the resulting mixing was removed after ten minutes. In a hot press set at 190°C for 5 minutes without any pressure, the resulting mixture was compression-molded. This was followed by 5 minutes of 7 MPa pressure, and then the platelets with fluid coils were pressed. The mold was eventually taken out of the plates after the pressure was released. After that, two thick metal blocks were placed at room temperature and allowed to cool to room temperature. To guarantee a consistent film thickness of 1 mm, a template frame was employed. In accordance with ASTM D-638-91, the samples were cut into specified sizes and forms in order to assess their mechanical qualities. After that, the samples were placed in plastic bags to await processing and examination. In this experiment, the Pa concentrations were 0, 1, and 3 weight percent for the three composites, PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa. When the concentration of nCC was zero percent, the concentration of PP was 100 weight percent.

Measurements of Mechanical Properties

Tensile and impact tests were used to examine the mechanical characteristics of virgin PP and PP/nCC nanocomposites. Samples of standard specimens were taken from the compression-molded sheet and conditioned for 24 hours at (25 ± 2)°C and 50 ± 5% relative humidity. A screw-driven universal testing machine (Instron 4466) with mechanical grips and a 10 kN electronic load cell was used for tensile testing. A computer collected the data during the tests, which were carried out at a crosshead speed of 30 mm/min. To obtain an average result, five replicates of each sample were evaluated in accordance with the ASTM D-638-91 standard. In accordance with ASTM D256-93a, Izod impact tests of notched samples were conducted using a Ceast pendulum impact tester (Model 6545/000). The specimens were $63.50 \times 13 \times 3.20$ mm^3 in length, width, and thickness, respectively.

The Morphological Observation

Scanning electron microscopy (SEM; JEOL, Japan JSM-6360LV) was used to examine the fracture surfaces of every sample being evaluated. After 30 minutes in liquid nitrogen, the SEM samples were split in half. A thin layer (10–20 nm) of gold palladium was applied to the specimen's shattered surfaces.

Measurements Using Differential Scanning Calorimetry (DSC)

A Perkin Elmer DSC-7 (Perkin Elmer, Inc., Wellesley, MA, USA) was used to analyze the melting and crystalline behaviors of virgin PP and samples. To get rid of all the thermal history in the materials, virgin PP and samples were first heated for 10 minutes from 25°C to 250°C. To determine their crystalline properties, the samples were next chilled to 25°C at a cooling rate (R) of 10°C/min. To determine their melting properties, the samples were then heated to 250°C at a rate of 10°C per minute. The melting scans of high-purity indium and zinc samples at the same heating rate were used to calibrate the temperature and heat capacity scales. Every measurement was performed in an atmosphere of nitrogen. The sample weighed between 5 and 8 mg.

RESULTS AND DISCUSSION

Mechanical Characteristics and Nanoparticle Dispersion in a PP Matrix

The addition of calcium carbonate nanoparticles to PP homopolymer improved the matrix's reinforcing and impact strength. Elastic modulus (E_c) of PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa composites is affected by the concentrations of nCC, nCC-1Pa, and nCC-3Pa, respectively, as illustrated in Figure 1. It is evident that E_c of all three composites rises with increasing ϕ and then falls when the weight fraction of nCC is less than 15%, or $\phi < 15$ wt %. At 15%, E_c reaches its maximum value. A value of 793.8 MPa was the highest E_c value of the PP/nCC composite. PP/nCC-1Pa and PP/nCC-3Pa composites, on the other hand, had maximum E_c values of 835.8 and 865.3 MPa, respectively, which were roughly 31% and 36% higher than those of virgin PP. The PP/nCC-3Pa composite rose more visibly than the PP/nCC composite, based on the trend of the E_c variation. An effective stress transmission from the polymer matrix to inorganic fillers is suggested by the significant increase in E_c. The E_c showed a notable rise at 15 wt% nCC, and the values began to decline after that. The decrease was linked to the increased filler (nCC) content in the PP matrix structure, which resulted in weaker binding strength, adhesion, or poorer molecular interaction [23]. The stiffness and elastic modulus were typically raised by nCC. Despite the fact that nCC strengthened the binding and that high stress caused the molecular interaction to weaken, the filler and PP shrank. Nevertheless, in this investigation, the modulus decreased when over 15% nCC was added to PP. In addition to increasing stress, adding more than 15% nCC also led to an increase in microcracks and poor adhesion between the matrix and filler. In particular, the modulus dropped when the filler content exceeded 15%.

One crucial factor in determining a material's impact toughness is its impact strength. The link between the impact strength (S_{IC}) and the nCC content is depicted in Figure 2. Figure 2 further shows that the S_{IC} of all three composites rises with increasing ϕ and subsequently falls when $\phi < 15\%$. The S_{IC} reaches its maximum at 15%. The findings indicate that adding an appropriate concentration of nCC to PP can somewhat increase its impact toughness. The nCC fillers will function as inclusions that create stress concentration, which will lead to matrix yielding and plastic deformation that will absorb a portion of the impact energy and improve impact toughness accordingly. This is the explanation for the peak phenomenon of the S_{IC} versus ϕ curve. The S_{IC} of PP/nCC composites dropped as the nCC concentration increased. This is ascribed to PP and nCC's poor compatibility. The molten matrix was unable to moisten the nCC particles because of their polar, hydrophilic surfaces and high surface free energy, which were incompatible with the nonpolar, hydrophobic, and low free energy PP. The mechanical characteristics suffered as a result of the loss of stress concentrators caused by the addition of unmodified nCC to the PP matrix. As a result, the S_{IC} of PP/nCC composites dropped. Pa is added to PP/nCC composites to enhance the filler's dispersion within the polymeric matrix and boost the interfacial

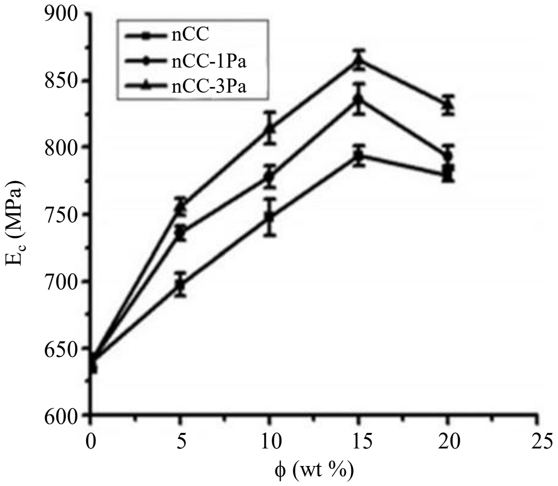

Figure 1. Elastic modulus (E_c) of PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa composites according to the filler content (ϕ, wt%). PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

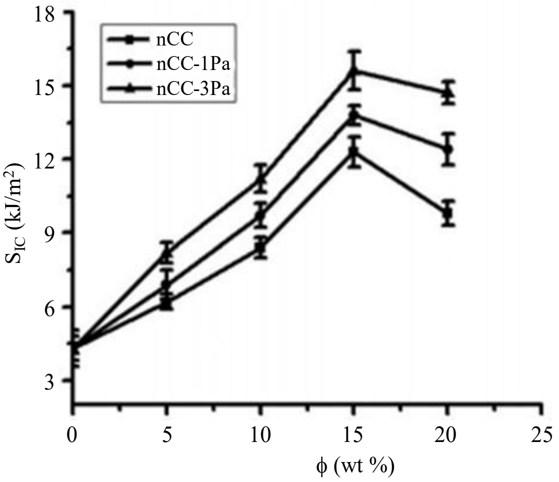

Figure 2. Impact strength (S_{IC}) of PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa composites according to the filler content (ϕ, wt%). PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

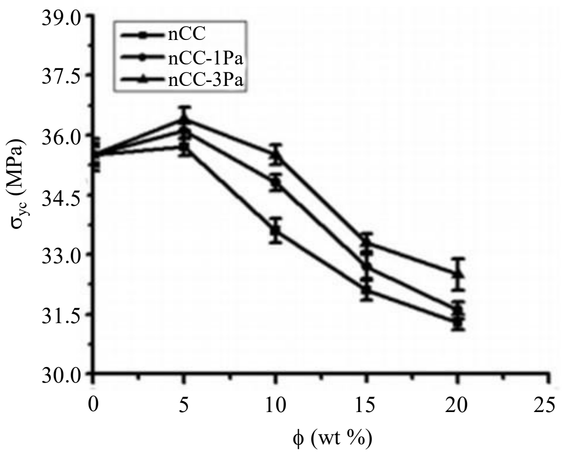

Figure 3. Tensile yield stress (σ_{yc}) of PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa composites according to the filler content (ϕ, wt%). PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

adhesion between the filler and matrix. The impact properties of PP/nCC composites that have been treated with Pa are superior to those of virgin PP and PP/nCC composites, and they get better as the Pa content rises. The PP/nCC-1Pa and PP/nCC-3Pa composites had maximum S_{IC}s of 13.8 and 15.6 kJ/m^2, respectively, which were around 221% and 263% higher than those of virgin PP. As previously mentioned, Pa made the PP matrix and nCC more compatible. Calcium pimelate was created concurrently by the reaction of nCC with Pa. The dispersion of nCC in PP is thought to be improved by Pa's ability to cover or pack nanoparticles, lowering their surface energy. As a reactive polar small molecule, however, Pa has a tendency to diffuse into nanoparticle agglomerates and stop them from agglomerating. During the process, Pa can homopolymerize or graft to PP due to the action of high temperature and shear stress. This enhances the interfacial action between the nanoparticles and the matrix and increases the impact characteristics of the composites.

The relationship between the tensile yield stress (σ_{yc}) and the amount of nCC in three nanocomposites is shown in Figure 3. Upon adding 5%, it is evident that the tensile yield stress of each of the three composites rises marginally. While σ_{yc} gradually drops for 5%, PP/nCC-3Pa and PP/nCC-1Pa were higher than PP/nCC. At 5%, the maximum is visible. It indicates that when PP is loaded with an appropriate amount of nCC, the tensile yield stress of PP can be somewhat increased. The agglomeration of the nCC particles was responsible for the decrease in the tensile yield stress of the obtained composite at higher filler content ($\phi > 5\%$). This was because there was weak interfacial adhesion between the PP matrix and the nanoparticles, which reduced the load-bearing capacity of the cross-sectional area of composites. Additionally, only a small amount of stress could be transferred from the matrix to inorganic particles, which is why the tensile stress showed a decrease in magnitude. In this instance, the agglomerated particles readily debonded from the matrix and were unable to withstand any fraction of external load, eventually lowering the tensile stress. These findings align with those of the research study conducted by Li et al. [24]. On the other hand, it was shown that Pa-treated nCC (nCC-Pa) increased the TS of PP composites with remarkable efficacy. In the composites filled with nCC-Pa, the TS first noticeably increased and subsequently declined as the filler concentration rose. The highest TS for nCC-1Pa and nCC-3Pa with a filler content of 5 wt% was 36.1 MPa and 36.4 MPa, respectively. These values were 2% and 3% higher than those of the unmodified composite. The combined mechanical characteristics of the three composites were as follows: When the filler loading was 15 wt%, a composite with good mechanical properties could be produced PP/nCC-3Pa > PP/nCC-1Pa > PP/nCC.

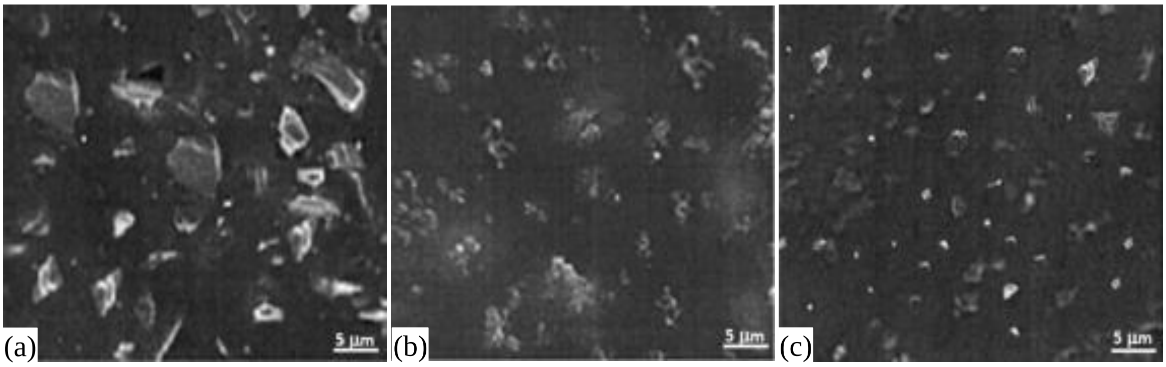

Figure 4. Composites with 10 wt% filler are shown in the following scanning electron micrographs: (a) PP/nCC, (b) PP/nCC-1Pa, and (c) PP/nCC-3Pa. PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

The impact-fracture surface of PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa nanocomposites, respectively, with 10% filler, is shown in SEM micrographs in Figures 4(a)–(c). The nCC particles in Figure 4(a) were unevenly distributed throughout the PP matrix, and several large aggregates with a particle size larger than 3 µm were visible on the fracture surface. We discovered by looking at these aggregations that they were made up of several fundamental particles. The particles in the PP/nCC sample were big, measuring 3 to 4 µm. Based on a mechanical property examination, we found that this composite had impact energy that was significantly lower than that of the PP/nCC-3Pa composites and only marginally greater than that of virgin PP. Photographs of the impact fracture surface of PP/nCC-1Pa and PP/nCC-3Pa composites are shown in Figure 4(b) and (c). Aggregates did not form in PP/nCC-1Pa, and the average particle size was lower than in nCC. Figure 4(c) shows that the dispersion of the nCC-3Pa particles in the PP matrix became more uniform as the amount of pimelic acid covering the nCC particles increased. The primary cause of the high toughness was the intimate coupling of nCC-3Pa particles and the PP matrix, with the majority of nCC-3Pa particles being less than 80 nm.

Melting and Crystallization Properties of Polypropylene and Its Nanocomposites

The PP and PP/10 wt% nCC (nCC10), PP/nCC10-1Pa (nCC10-1Pa), and PP/nCC10-3Pa (nCC10-3Pa) composites' non-isothermal crystallization curves are displayed in Figure 5 at a cooling rate of 10°C/min. These graphs demonstrate how the crystallization behavior of PP is considerably altered by the addition of nCC10, nCC10-1Pa, and nCC10-3Pa fillers. It is discovered that the specimens' crystallization peak moves to a high temperature, with nCC10-3Pa migration being the most noticeable. The DSC values for nonisothermal melting and crystallization are shown in Table 1. T_{oc}, T_{pc}, T_{mp}, H_m, ΔT, and X_c stand for the onset, peak, and melting crystallization temperatures, respectively, as well as the melting enthalpy, crystallization ratio, and crystallinity value As a function of cooling rate (5°C, 10°C, 15°C, and 20°C), Figure 6(a) and (b) displays the onset crystallization temperatures (T_{oc}) and peak crystallization temperatures (T_{pc}) of PP and its nanocomposites. At varying cooling speeds, it is evident that the addition of nCC10-1Pa and nCC10-3Pa fillers raises the T_{pc} by 4°C to 9°C above that of PP, suggesting that fillers can function as PP nucleating agents. For PP crystallization, nucleation effects were also seen in a large number of different nanoparticles [16, 25]. At various cooling speeds, nCC10 only slightly raised the crystallization temperature (T_{pc}), which ranged from 1°C to 3°C.

The samples were warmed following the crystallization procedure. Figure 7 shows the DSC heating curves for PP and nanocomposites. It shows that the curves' shapes for virgin PP and nanocomposites hardly vary at all. The melting temperature (T_{mp}) of virgin PP and nanocomposites appears to be the same. Table 1 presents these values. The following formula can be used to determine the degrees of crystallinity X_c for virgin PP and its nanocomposites based on the area of heating curves in Figure 7 [26].

$$X_c = \frac{\Delta H}{(1-\phi)\Delta H_0} \times 100\%$$

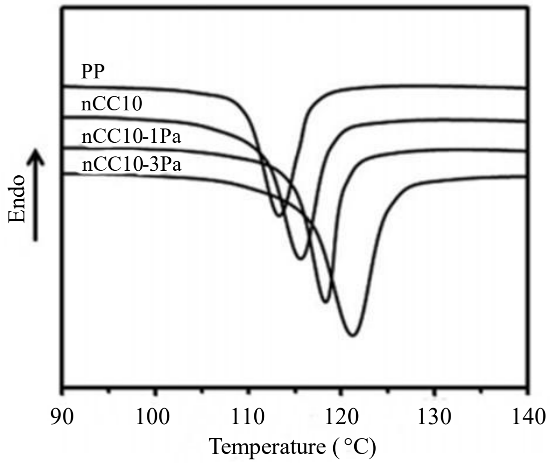

Figure 5. DSC crystallization curves for virgin PP, composites of PP/10 wt% nCC (nCC10), nCC10-1Pa, and nCC10-3Pa. DSC, differential scanning calorimetry; PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

Table 1. DSC crystal properties of virgin PP and composites.

Sample	T_{oc} (°C)	T_{pc} (°C)	T_{mp} (°C)		T_{mp} - T_{pc} = ΔT (°C)	X_c (%)
Virgin PP	119.5	113.6	163.8	84.3	50.2	46.4
nCC10	122.5	115.4	164.4	86.2	49.0	47.6
nCC10-1Pa	124.8	118.5	165.1	85.7	46.6	46.8
nCC10-3Pa	128.4	121.1	165.3	87.4	44.2	48.3

DSC, differential scanning calorimetry; PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

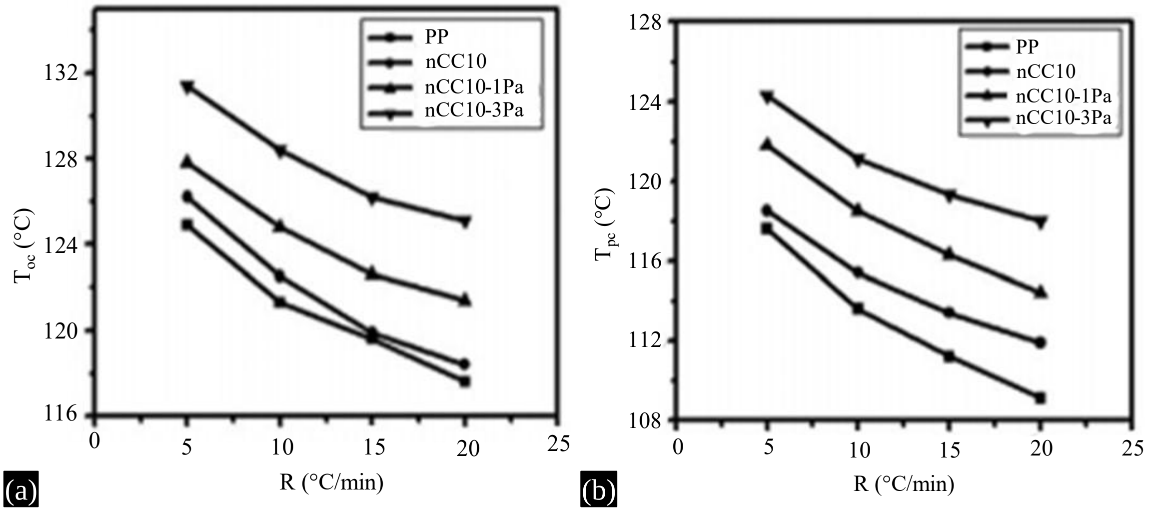

Figure 6. (a) The virgin PP, nCC10, nCC10-1Pa, and nCC10-3Pa composites' onset crystallization temperatures (Toc) and (b) their peak crystallization temperatures (Tpc). PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

In this case, ϕ represents the mass fraction of the filler, ΔH represents the endothermal enthalpy of the sample, and ΔH_o represents the endothermal enthalpy of PP upon full crystallization. Additionally shown in Table 1 are the X_c values for PP and nanocomposites. Nanocomposites have a higher degree of crystallinity than virgin PP. Comparing nCC10-1Pa and nCC10-3Pa to virgin PP, the degree of crystallinity rose by up to 1% and 4%, respectively.

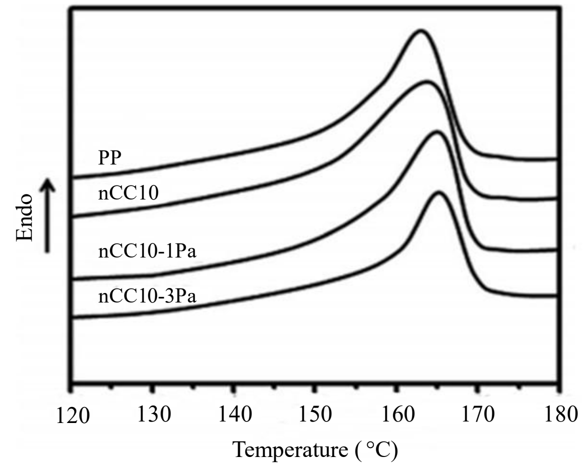

Figure 7. DSC melt curves for composites made of virgin PP, nCC10, nCC10-1Pa, and nCC10-3Pa. DSC, differential scanning calorimetry; PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

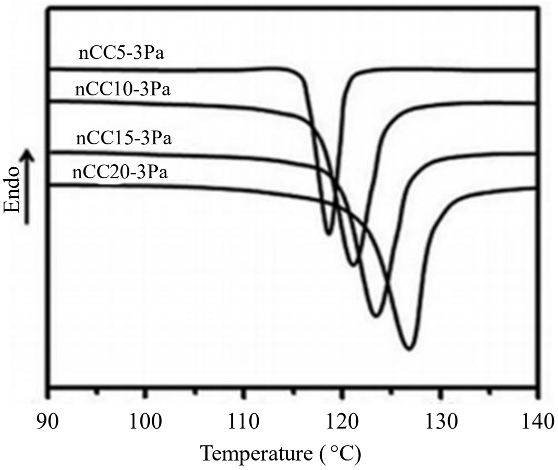

Figure 8. DSC crystalline curves of PP/nCC-3Pa: (1) 5 wt%, (2) 10 wt%, (3) 15 wt%, and (4) 20 wt% with varying filler amounts. DSC, differential scanning calorimetry; PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

Table 2. DSC crystalline properties of PP/nCC-3Pa (nCC-3Pa) with different filler concentrations.

Sample	T_{pc} (°C)	ΔH_c (J/g)	X_c (%)
Virgin PP	113.6	84.3	46.4
nCC5-3Pa	119.1	85.7	46.9
nCC10-3Pa	121.1	87.4	48.3
nCC15-3Pa	123.7	88.1	49.2
nCC20-3Pa	126.9	89.3	52.1

DSC, differential scanning calorimetry; PP, polypropylene; nCC, nano-calcium carbonate; Pa, pimelic acid.

The DSC nonisothermal crystallization curves of nCC-3Pa with varying filler amounts are displayed in Figure 8. These data suggest that as the concentration of nCC-3Pa increased, so did the crystallization temperature. Table 2 lists the DSC crystalline characteristics of nCC10-3Pa with varying filler quantities. The data show that PP crystallites were somewhat affected by the concentration of the nCC10-3Pa fillers; at 5, 10, 15, and 20 wt%, the crystallization temperature rose by 5.5°C, 7.5°C, 10.1°C, and 13.3°C, respectively. Furthermore, the addition of the nCC-3Pa filler raised the degree of crystallinity of PP. At a loading of 20 wt%, the lowest X_c value of nCC20-3Pa was 52.1%. Based on the DSC results, we deduced that the presence of nCC10-1Pa and nCC10-3Pa significantly affected the crystallization behavior of PP following the application of pimelic acid to the nCC particle surface. The inclusion of the fillers also enhanced PP's nucleating capacity.

CONCLUSIONS

We can draw the following inferences from the aforementioned results:

1. Melt blending was used in this work to create PP/nCC, PP/nCC-1Pa, and PP/nCC-3Pa nanocomposites. While the tensile yield stress initially increased slightly and then reduced as the nCC content grew, the PP/nCC composites' elastic modulus (E_c) and Izod impact strength (S_{IC}) clearly increased as the nCC content increased.
2. The E_c and S_{IC} of the notched specimens increase with rising ϕ when it is less than 15%, and then they gradually decrease. In the range of 0% to 20%, the highest elastic modulus and impact strength are found at 15%. Furthermore, the composites' E_c and S_{IC} were further raised by the Pa adjustment.

3. When ϕ is less than 5%, adding ϕ causes the tensile yield stress to rise before gradually falling. In the range of 0% to 20%, it seems that the maximum tensile yield stress happens at $\phi = 5\%$.
4. In contrast to untreated nCC, nCC-Pa distributed effectively in PP and had a consistent size distribution according to SEM micrographs. Following pimelic acid surface modification, aggregation could be prevented and the adhesion between the filler particles and the PP matrix was improved.
5. When compared to virgin PP and PP/nCC, DSC tests revealed that the inclusion of nCC-Pa fillers increased the crystallization temperature while simultaneously improving nucleation and crystallization.

REFERENCES

1. Luyt AS, Dramićanin MD, Antić Ž, Djoković V. Morphology, mechanical and thermal properties of composites of polypropylene and nanostructured wollastonite filler. Polym Testing. 2009; 28: 348–356.
2. Saminathan K, Selvakumar P, Bhatnagar N. Fracture studies of polypropylene/nanoclay composites. Part I: effect of loading rates on essential work of fracture. Polym Testing. 2008; 27: 296–307.
3. Chen N, Wan C, Zhang Y, Zhang Y. Effect of nano-$CaCO_3$ on mechanical properties of PVC and PVC/Blendex blend. Polymer. 2004; 45: 5985–5994.
4. Gopakumar TG, Page DJYS. Polypropylene/graphite nanocomposites by thermo-kinetic mixing. Polym Eng Sci. 2004; 44 (6): 1162–1169.
5. Kiss A, Fekete E, Pukanszky B. Aggregation of $CaCO_3$ particles in PP composites: effect of surface coating. Compos Sci Technol., 2007; 67 (7–8): 1574 ‑ 1583.
6. Jiang XW, Bin YZ, Matsuo M. Electrical and mechanical properties of polyimide-carbon nanotubes composites fabricated by in situ polymerization. Polymer. 2005; 46 (18): 7418 ‑ 7424.
7. Xu JY, Hu Y, Song L, Wang QG, Fan WC, Liao GX, Chen ZY. Thermal analysis of poly (vinyl alcohol)/graphite oxide intercalated composites. Polym Degradat Stabil. 2001; 73 (1): 29 ‑ 31.
8. Sonobe K, Kikuta K, Takagi K. Dispersion and alignment of organic-clay composites with in polysilicate thin films by the sol-gel method, Chem Mater. 1999; 11 (4): 1089 ‑ 1093.
9. Dondero WE, Gorga RE. Morphological and mechanical properties of carbon nanotube/polymer composites via melt compounding. J Polym Sci Part B Polym Phys. 2006; 44 (5): 864–878.
10. Bartczak Z, Argon AS, Cohen RE, Weinberg M. Toughness mechanism in semi-crystalline polymer blends: II. High-density polyethylene toughened with calcium carbonate filler particles. Polymer. 1999; 40: 2347–2365.
11. Tabtiang A, Venables R. The performance of selected unsaturated coatings for calcium carbonate filler in polypropylene. Eur Polym J. 2000; 36: 137–148.
12. Mitsuishi K, Kodama S, Kawasaki H. Mechanical properties of polypropylene filled with calcium carbonate. Polym Eng Sci. 1985; 25: 1069–1073.
13. Demjen Z, Pukanszky B, Jozsef N. Evaluation of interfacial interaction in polypropylene/surface treated CaCO3 composites. Compos Part A. 1998; 29: 323–329.
14. Ma CG, Mai YL, Rong MZ, Ruan WH, Zhang MQ. Phase structure and mechanical properties of ternary polypropylene/elastomer/nano-CaCO3 composites. Compos Sci Technol. 2007; 67: 2997–3005.
15. Yang K, Yang Q, Li GX, Sun YJ, Feng DC. Mechanical properties and morphologies of polypropylene with different sizes of calcium carbonate particles. Polym Compos. 2006; 27: 443–450.
16. Huang YP, Chen GG, Yao Z, Li HW, Wu Y. Non-isothermal crystallization behavior of polypropylene with nucleating agents and nano-calcium carbonate. Eur Polym J. 2005; 41: 2753–2760.
17. Ma CG, Rong MZ, Zhang MQ, Friedrich K. Irradiation-induced surface graft polymerization onto calcium carbonate nanoparticles and its toughening effects on polypropylene composites. Polym Eng Sci. 2005; 45: 529–538.

18. Avella M, Cosco S, Lorenzo D, Errico ME. Influence of CaCO3 nanoparticles shape on thermal and crystallization behavior of isotactic polypropylene based nanocomposites. J Therm Anal Calorimetry. 2005; 80: 131–136.
19. Hanprasopwattana A, Srinivasan S, Sault AG, Datye AK. Titania coatings on monodisperse silica spheres (characterization using 2-propanol dehydration and TEM. Langmuir. 1996; 12: 3173–3179.
20. Meng MR, Dou Q. Effect of pimelic acid on the crystallization, morphology and mechanical properties of polypropylene/wollastonite composites. Mater Sci. Eng Part A. 2008; 492: 177–184.
21. Dou Q. Effect of metallic salts of pimelic acid and crystallization temperatures on the formation of crystalline form in isotactic poly (propylene). J Macromol Sci Phys. 2007; 46: 1063–1080.
22. Wan WT, Yu DM, Xie YC, Guo XS, Zhou WD, Cao JP. Effects of nanoparticle treatment on the crystallization behavior and mechanical properties of polypropylene/calcium carbonate nanocomposites. J Appl Polym Sci. 2006; 102: 3480–3488.
23. Barbosa SE, Capiati NJ. Processability and mechanical properties of ternary composites PP/EPDM/GF. Polym Compos. 2000; 21: 377–386.
24. Li XH, Tjong SC, Meng YZ, Zhu Q. Fabrication and properties of poly (propylene carbonate)/calcium carbonate composites. J Polym Sci Part B Polym Phys. 2003; 41: 1806–1813.
25. Hao S, Yuhai W, Kancheng M. Non-isothermal crystallization behavior of PP/$Mg(OH)_2$ composites modified by different compatibilizers. Thermochem Acta. 2007; 457 (1–2): 27–34.
26. Turi EA, editor. Thermal Characterization of Polymeric Materials. New York, NY, USA: Academic Press; 1981.