

Influence of Compatibilizers on the Morphology, Mechanical, Thermal and Rheological Properties of Polypropylene/Organomuscovite Nanocomposites

Haydar U. Zaman*

Abstract

In this study, the effects of two different compatibilizer types-maleated polypropylene and hexamethylenediamine modified maleated polypropylene-on the characteristics of a polypropylene/maleated polypropylene/organo-muscovite clay nanocomposite were investigated. By combining polypropylene with three different levels of organo-muscovite clay content, two distinct compatibilizers were used to make the nanocomposites, each with a fixed amount of 10 weight percent. The compatibilizer's effects on the morphological, mechanical, thermal, and rheological characteristics of nanocomposites were then examined. Photomicrographs obtained with transmission electron microscopy (TEM) demonstrated that organo-muscovite clay was partially exfoliated during melt mixing and intercalated in the presence of maleated polypropylene or hexamethylenediamine modified maleated polypropylene. Furthermore, SEM demonstrated that the polypropylene matrix's extensive plastic deformation also had a role in the polypropylene nanocomposite's increased strength. Compared to maleated polypropylene, hexamethylenediamine modified maleated polypropylene showed superior organo-muscovite clay dispersion and exfoliation. In comparison to the polypropylene/maleated polypropylene/organo-muscovite clay system and the maleated polypropylene compatibilized case, the hexamethylenediamine modified maleated polypropylene compatibilized system offered better strength, modulus, hardness, and decreased elongation at break. Compatibilizers containing organo-muscovite clay improve the nanocomposite's tensile properties, thermal stability, heat deflection temperature, melting and crystallization temperature, crystallinity, and rheological behaviors. Compatibilizers also impose strong interfacial interactions on these properties.

Keywords: Polypropylene, organo-muscovite clay, nanocomposites, compatibilizers, mechanical properties, crystallization, rheological behaviors

INTRODUCTION

Over the past several years, there has been a greater focus on preparation and scientific research on the properties of polymer nanocomposites with the overall goal of developing novel polymer materials with more enhanced abilities [1-4]. When compared to plain polymers or conventional micro- and macro-composites, polymer/organoclay nanocomposites frequently reveal a broader spectrum of mechanical, thermal, and other properties, which makes them highly promising for use in industry and academia [5].

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Received Date: May 26, 2024

Accepted Date: June 06, 2024

Published Date: July 31, 2024

Citation: Haydar U. Zaman. Influence of Compatibilizers on the Morphology, Mechanical, Thermal and Rheological Properties of Polypropylene/Organomuscovite Nanocomposites. International Journal of Applied Nanotechnology. 2024; 10(1): 25–36p.

A hybrid based on organic polymers and inorganic clay minerals including layered silicate is one of the promises of maximal nanocomposites [6]. When the Toyota research team tested polyamide-6/clay nanocomposites for the first time, they found

that the clay filler's mechanical and thermal characteristics had developed at a far lower load stage than conventional composites [7]. Scientific publications have reported on polymer/clay nanocomposites [8-10]. According to López-Quintanilla et al. [11], three different kinds of polymer/clay nanocomposites were frequently intercalated like a traditional nanocomposite, allowing for the dispersion of some polymer components between exfoliated and layered silicate nanocomposites.

Polypropylene (PP)/organoclay nanocomposites are currently a topic of intense research interest. PP is a thermoplastic engineering polymer that increases its appeal with its many essential qualities, including high thermal deformation temperature, flame interruption, precision, dimensional durability, and strong impact strength. Moreover, PP improves filling and is excellent for combining. However, because conventional PP has a low polarity, it is impossible to see the homogeneous dispersion of silicate layers in PP. In this instance, PP's features will be further advanced through the usage of nanotechnology. The most often utilized polymers in nanotechnology are those like montmorillonite (MMT) and kaolinite, which expand and layer when combined with silicate nanocomposites to provide ion-exchange capabilities. The potential of other forms of clay is equivalent to that of muscovite and vermiculite. Muscovite is far less expensive than MMT and represents the maximum degree of charge concentration and uniform charge parceling. However, with compatibilizers such functional oligomers, PP/clay nanocomposites are now a more viable option. For these compatibilizers to interact with the silicate layer and smoothly integrate bulk PP, they need to have sufficient polarity [12]. Researchers have typically utilized maleic anhydride (MA) [13, 14], which can develop the polarity of polymer molecules, to promote the isolation of mineral clay in the PP matrix. The majority of research on PP/clay nanocomposites has employed maleated polypropylene (PPMA) since it has demonstrated the highest level of performance among all modified polyphenylene sulfide (PPS) studied too far. In the current study, organo-muscovite clay (OM) was created by organo-modifying muscovite with cetyltrimethylammonium bromide (CTAB) as an alkyl ammonium. In the PP/OM nanocomposite, we investigated compatibilizers such maleated polypropylene (PPMA) and hexamethylenediamine modified maleated polypropylene (PPHMDA). To the best of the writers' knowledge, there is no literature that addresses the impact of specific compatibilizers on the mechanical, thermal, rheological, and morphological characteristics of PP/PPHMDA/OM or PP/PPMA/OM nanocomposites that are created by the blending process. Following that, the reaction of nanocomposites is linked to how organic alterations affect their rheological, mechanical, thermal, and dispersion behavior in a number of compatibilizers.

EXPERIMENTAL

Ingredients

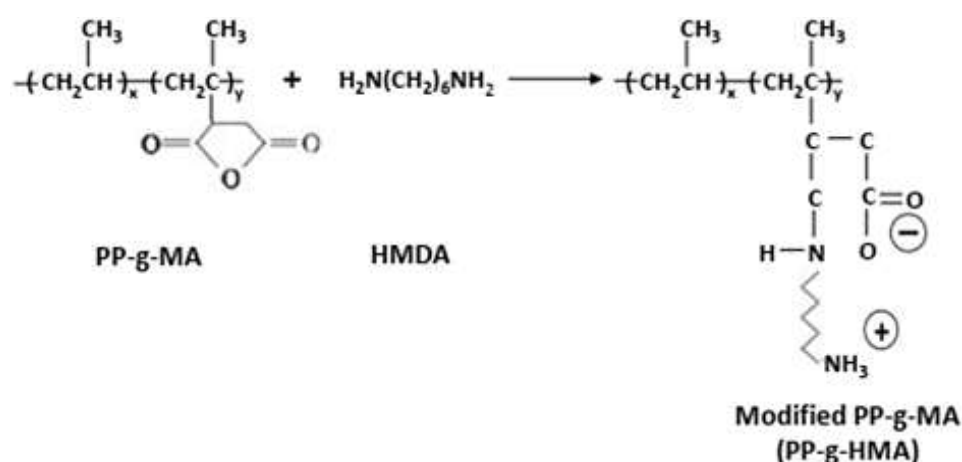
The thermoplastic polymer matrix PP, which has a specific gravity of 0.91-0.92 and a melting point of 160–170°C, was acquired as pellets from MTBE (Malaysia) Sdn. Bhd. The Bidor Minerals (M) Sdn. Bhd. produced unispensible muscovites, with an average size of roughly 20 micrometers. By exchanging the cations of lithium nitrate (LiNO_3) and cetyltrimethylammonium bromide (CTAB), which were provided by Sigma Aldrich (M) Sdn. Bhd., modified muscovite, also referred to as organomuscovite (OM). Sigma Aldrich (M) Sdn. Bhd. provided the 8–10 weight percent maleic anhydride (MA) in the Poly(propylene-g-maleic anhydride) copolymer (PPMA). Sigma Aldrich provided the hexamethylenediamine, which has the following properties: $M_w = 116.21 \text{ g/mol}$, $T_m = 42^\circ\text{C}$, $\rho = 840 \text{ kg/m}^3$, and water solubility = 490 g L^{-1} .

METHODS

The Configuration of PP/OM Nanocomposites

PPMA was subjected to HMDA treatment (designated as PPHMDA) in xylene solution at 110°C for 1.5 hours. Following this, the mixture was mechanically mixed in a 1:17 ratio, filtered through distilled water, rinsed in hot water, and dried at 80°C for a full day. The PPHMDA preparation is depicted in Scheme 1. After that, the mixture was heated for 12 hours at 250°C in a furnace. The final product was dried for 12 hours at 100°C after being soaked in 200 mL of distilled water and filtered.

Li-muscovite is the name given to this substance, which was obtained as silver powder. At room temperature, the Li-muscovite was combined with the CTAB aqueous solution. Following that, the mixes were placed in a 100 mL hydrothermal reactor with a Teflon-lined stainless-steel autoclave, and they were heated for 12 hours at 180°C. Following the reactions, all of the surfactant-muscovite (organoclay) products were filtered, followed by three ethanol washes, and a room-temperature vacuum oven drying process. Organomuscovite (OM) is the term given to the acquired CTA⁺-muscovite samples. The PPHMDA/OM nanocomposites were made by combining PPHMDA, xylene solution, and organically modified muscovite clay at 120°C for six hours. After using too much deionized water to precipitate the PPHMDA/OM nanocomposites, they were cleaned in hot water and vacuum-dried for 12 hours at 100 degrees celsius. All of the raw components were dried to constant weight in a vacuum oven at 80°C for at least 12 hours before being compounded. They were then cooled to room temperature. The nanocomposite samples were made using different weight percentages of OM (3, 5, and 7 wt%) and preweighed amounts of PP with two different compatibilizer types (PPHMDA or PPMA) at a set 10 wt%. Table 1 lists the compositions of the assembled nanocomposites. A co-rotating twin-screw extruder (Brabender Plasticorder, model: PLE-331) was used to blend the melt. The temperature profile and screw speed were adjusted to 60 rpm and 160-180-200-180°C, respectively. In a sealed plastic bag, the PP pellets were tumble-mixed with OM along with compatibilizers and antioxidants (Irganox-B225). After mixing all components for six minutes at 25°C, a twin-screw extruder was used to fill the mixture and combine it. After being hot-pressed for five minutes at 180°C with a pressure of 10 MPa, the extruded samples were cooled to 25°C. Different measures were taken using the received specimen sheets.



Scheme 1. An outline showing how PPHMDA is prepared conceptually.

Table 1. Compositions of nanocomposites.

Sample	Sample Code	PP (wt%)	OM (wt%)	PP-g-HMDA (wt%)	PP-g-MA (wt%)
PP	PP	100	—	—	—
PP/OM3	M3	97	3	—	—
PP/OM5	M5	95	5	—	—
PP/OM7	M7	93	7	—	—
PP/PP-g-MA/OM5	M5M10	85	5	—	10
PP/PP-g-HMDA/OM5	M5HM10	85	5	10	—

Analysis of Morphology

The transmission electron microscope (TEM; JEOL JEM-2010), operating at an accelerating voltage of 200 kV, was used to examine nanocomposite samples. Using a Leica Ultracut UCT diamond knife, extruded samples were microtomed into extremely thin pieces with a thickness of around 100 nm. These

fragments were then photographed in a TEM. After extruded samples were broken in liquid nitrogen, their fracture surfaces were examined with a scanning electron microscope (SEM; JEOL, Japan JSM-6360LV) operating at a 15 kV acceleration voltage. A thin layer of tin (10–20 nm) was applied to the sample's fracture surfaces in order to shield the gold.

Evaluation of Bulk Tensile and Hardness Features

Tensile characteristics of the virgin PP, PP/OM, PP/PPMA/OM, and PP/PPHMDA/OM nanocomposites were assessed. These characteristics included strength, modulus, and elongation at break. Composite samples were produced using a screw-driven universal testing machine (model: Instron 4466) in accordance with ASTM standard procedure. The gauge length was 10 mm, and the crosshead speed was 20 mm/min. The Japan Shore Hardness Testing Machine (Type D) was used to assess the composite samples' shore hardness. The ASTM D790 standard was followed when conducting the test. The conditions for all the samples were set at 25°C and 55% relative humidity. For every case, five samples were tested, and the mean values were computed.

Thermal Properties

The thermogravimetric analyzer (TGA, TA instruments Q500) was used to test the thermal fixity of the nanocomposites (8–10 mg) at a temperature of 20°C/min in a N₂ environment. ASTM D 648 was used to assess the heat distortion temperature (HDT) of PP and its nanocomposite using dimensions specimens measuring 125 × 12.50 × 3.0 mm³. With a heating rate of 2°C/min, the Advanced HDT/Vicat softening point apparatus (Ray Ryan Test Equipment, Ltd.) was used to conduct the test.

Differential Scanning Calorimetry (Perkin Elmer DSC-7, Wellesley, MA, USA) was used to determine the melting and crystallization temperatures as well as the crystallinity of the samples. The heating rate was set to 10°C/min in a N₂ atmosphere. The sample weighed between five and eight milligrams.

Using the formula below, the percentage crystallinity (X_c) was determined:

$$X_c (\%) = (\Delta H_m / \Delta H_f) \times 100$$

where ΔH_f is the heat fusion of crystalline PP and ΔH_m is the melting enthalpy of semicrystalline PP.

Measurements of Rheology

An instrument called the Paar Physica UDS was used to measure the nanocomposites' rheological characteristics. Nanocomposites were compression molded at a frequency range of 0.1-100 rad/s in a hot press set at 220°C to create a disc sample.

RESULTS AND DISCUSSION

The Dispersion of Muscovite Organoclay

TEM Studies

Figure 1 shows TEM photomicrographs of PP/OM nanocomposites made up of 5 weight percent OM (designated as M5) and PP/10 weight percent PPMA/5 weight percent OM (denoted as M5M10) or PP/10 weight percent PPHMDA/5 weight percent OM (marked as M5HM10). Figure 1 (a) shows significantly larger OM elements, which are not intercalated and likely form a "micro composite" structure, possibly as a result of the absence of PPMA or PPHMDA. The black shape (piled silicate platelets) shows the OM tactoids, and the remaining area represents an uninterrupted PP. However, some black shapes might represent some weakly dispersed OM aggregates. Figure 1(b) shows comparatively smaller OM elements than Figure 1(a), and the OM elements were separated into lighter parts by the blending process. In any case, the addition of PPHMDA as a compatibilizer-which functions as an intercalator between PP and OM-can result in a greater dispersion (Figure 1c). Since there is less black shape in the PPHMDA system's PP matrix than in the PPMA system, the OM dispersion is better and more uniform in PPHMDA systems. In order to improve OM dispersion in the matrix and boost tensile characteristics, compatibilizers should be used with OM and matrixes.

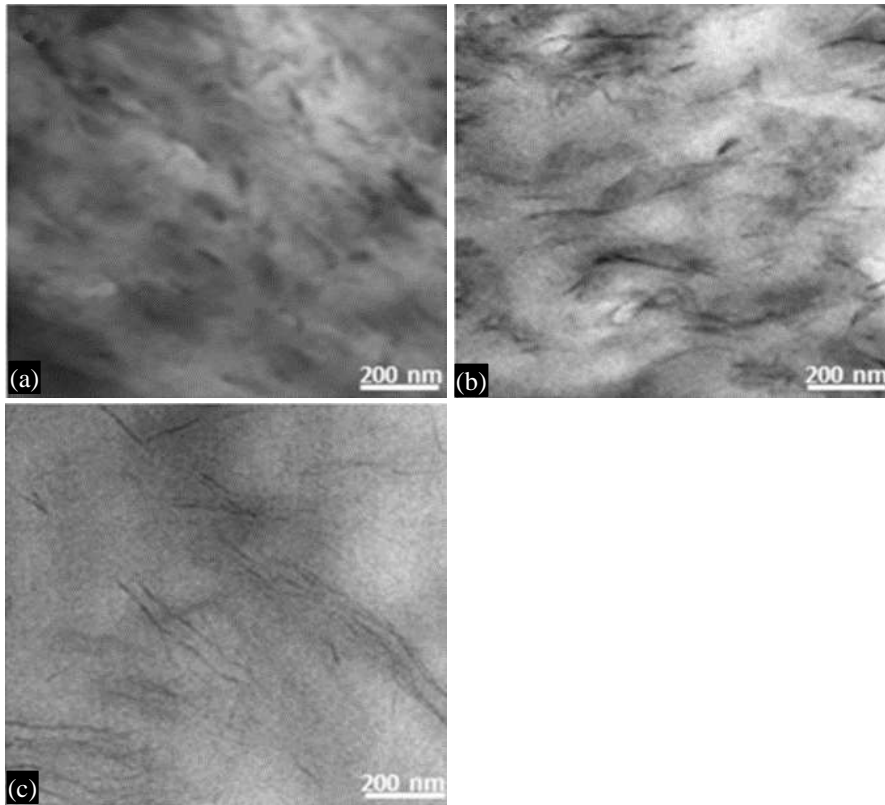


Figure 1. TEM micrograph of (a) M5, (b) M5M10 and (c) M5HM10 nanocomposite.

SEM Analysis

The SEM photomicrographs of the M5, M5M10, and M5HM10 nanocomposites are shown in Figure 2(a–c), respectively. In the PP matrix, the OM particles in Figure 2(a) were dispersed randomly, with some sizable sections exposed above the fracture surface. Large components are dispersed throughout the PP to PP/OM nanocomposite in such a way that there is no functional polymer visible and the interfaces seem to be individually wet and/or weak to the component adherence. The morphology varies when PPMA or PPHMDA are present. Compared to the M5 system, the average particle size in the M5M10 system was lower and it had some large components. The M5HM10 system was more evenly distributed in the PP matrix than the M5M10 system, as seen in Figure 2(c). Particle size and interface changes suggest that PPMA or PPHMDA aid in the disintegration of particles and alter interfacial interactions. The results of the tensile characteristics in Figure 4 are consistent with this result.

The Impact of OM Loads

Due to poor interfacial interactions between the components, immiscible mixtures without compatibility typically have weak tensile properties (tensile strength, TS; tensile modulus, TM; and elongation at break, Eb (%)). Tensile properties of virgin polypropylene and its nanocomposites with OM contents varying from 3 to 7 weight percent were measured. Figure 3(a) shows how the TS and TM of the nanocomposites vary with the amount of OM. Because OM had a stronger effect at higher proportions, the value of TS and TM grew as the OM level climbed up to 5 weight percent before declining. The virgin PP's TS and TM were roughly 32.5 MPa and 1158 MPa, respectively, which confirms the Figure's 0% OM content. It demonstrated that when 5 weight percent OM was used, TS grew noticeably by 15.6% and TM by 17.8%, and this had a positive strengthening effect. An additional increase in OM loading reduces the strengthening effect and impairs its ability to effectively transfer stress. For ingredients of this class, elongation at break is also a key tensile characteristic. Polymeric components containing OM typically exhibit a reduction in elongation at break. Figure 3 (b) shows the results of elongation at break (%). As the amount of OM content has increased, the value of elongation at break has dramatically dropped.

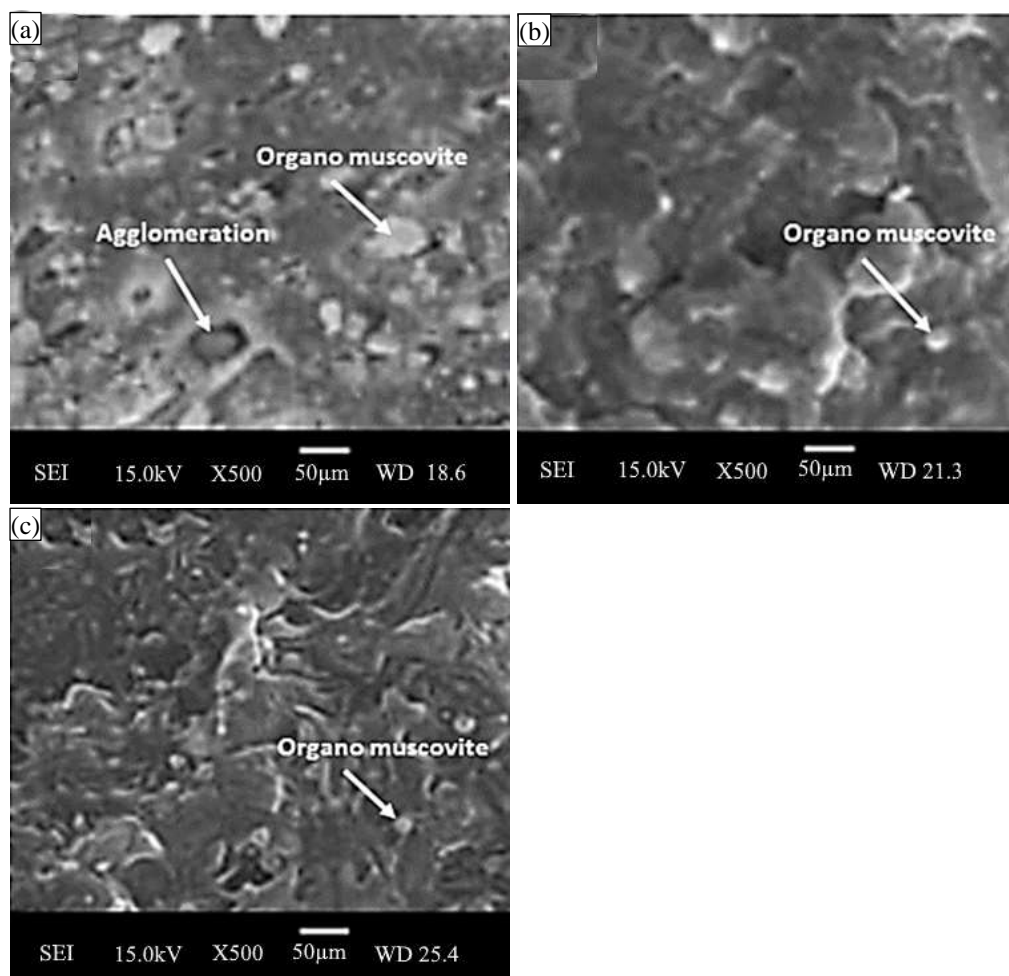


Figure 2. SEM photographs of the following nanocomposites: (a) M5; (b) M5M10; and (c) M5HM10.

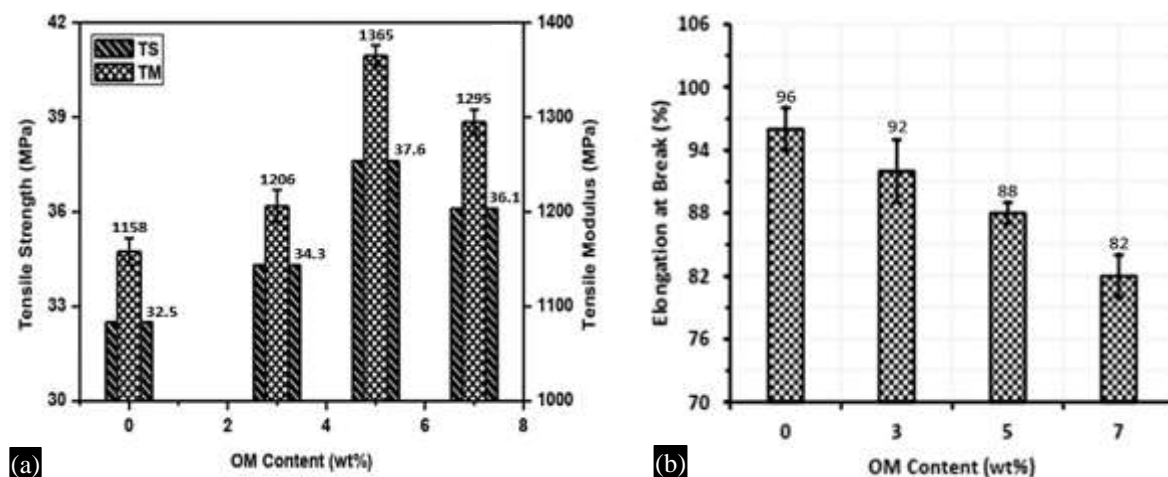


Figure 3. The virgin polypropylene and its nanocomposites' (a) tensile strength and tensile modulus and (b) elongation at break (%) are presented.

Tensile Properties of Nanocomposites

Figures 4(a) and 4(b) show the TS, Eb(%), and TM of the PP/OM nanocomposites, respectively. When compatibilizers were present, the tensile properties of virgin PP and PP/OM were maintained at 10 wt% and loaded with OM at the recommended level of 5 wt%. Similar to Figure 4(a), the TS of

virgin PP was roughly 32.5 MPa, and the nanocomposite's relevant value of 5 weight percent OM load was increased to 37.6 MPa, which represents a 17% increase over PP. The long aliphatic chain in OM that creates a rich interfacial interaction between the matrix and the OM may be the cause of increased TS. The TS of M5HM10 was roughly 42.3 ± 0.8 MPa, greater than both PP and M5M10 (39.8 ± 0.5 MPa). The improved solid-state adhesion that may transfer more stress from the matrix to the dispersion stage and the good distribution that the compatibilizer produces are the two main indicators of the compatibilized system's increased TS. These results align with the findings of studies carried out by W.C. Chen and colleagues [15]. Dispersed compatibilizers may modify matrix features to aid in the observation of the tensile characteristics of nanocomposites, as previously mentioned in TEM. As a result, M5M10 received less TS during the interphase than M5HM10. These findings support the pioneering hypothesis proposed by Szazdi et al. that layered silicate nanocomposites could not achieve greater TS by the use of PP/OM nanocomposites as PP-g-MA [16].

The TM of virgin PP was around 1158 ± 45.3 MPa, as Figure 4(b) illustrates. The nanocomposite's relevant value of 5 wt% OM load was enhanced to 1365 ± 51.2 MPa, which represents an increase of 18% above PP. The dispersion of OM, which can stabilize the polymer phases and provide increased stiffness, may be the cause of the stiffness [17]. Furthermore, there was a 9% increase in the TM of the M5HM10 nanocomposite (1619 ± 48.6 MPa) compared to the M5M10 nanocomposite (1483 ± 53.5 MPa). As seen in Figure 4(a), all nanocomposites made of the identical OM and M5M10/M5HM10 materials had decreased elongation at break in comparison to PP. The filler is caused by matrix distortion, which is theoretically reduced by the insertion of mechanical restriction.

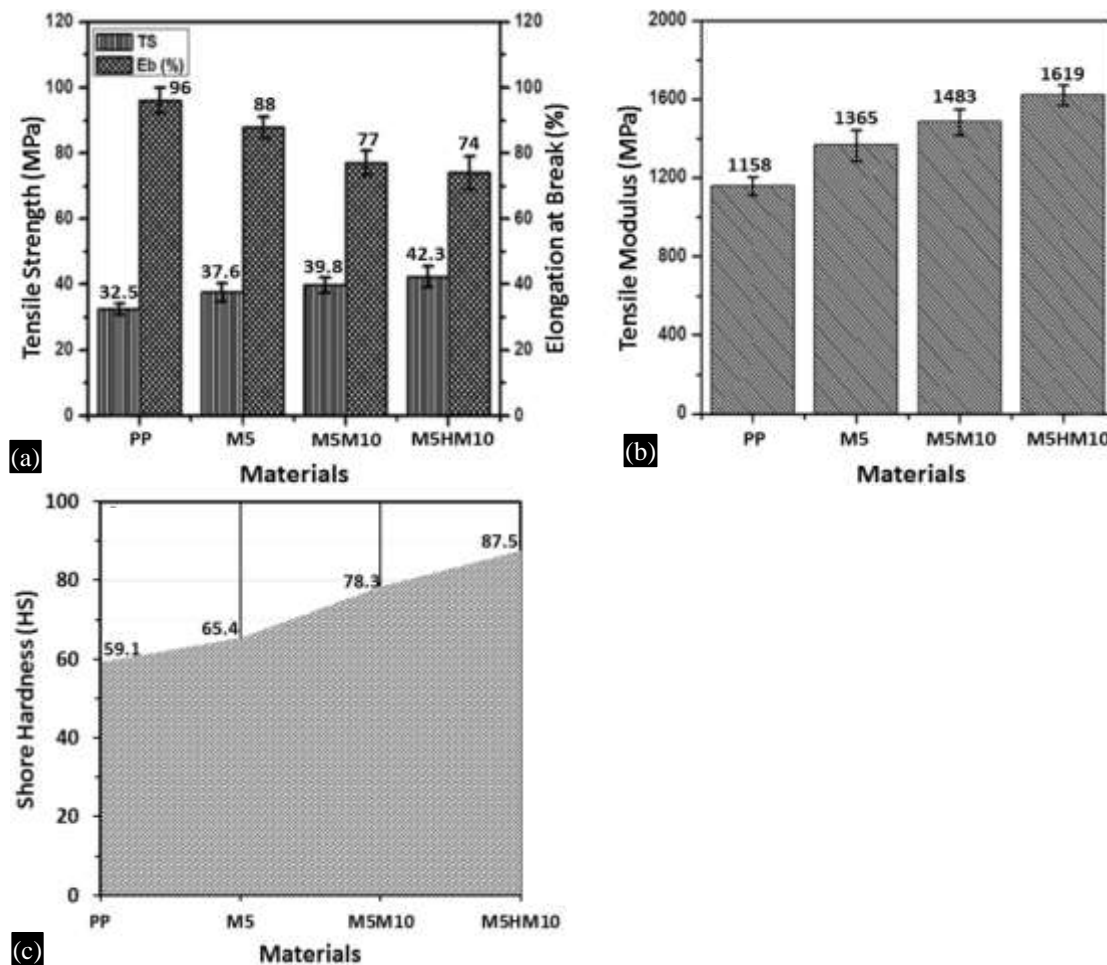


Figure 4. The virgin polypropylene and its nanocomposites' (a) tensile strength and elongation at break (%), (b) tensile modulus, and (c) hardness characteristics.

Studies of Hardness Properties

Figure 4(c) shows the hardness of virgin PP and its nanocomposites. The hardness of virgin PP was approximately 59.1 Hs, and the relevant value of 5 wt% OM load for nanocomposite was raised to 65.4 Hs, an 11% increase over PP. This may be because the PP matrix contains intercalated/exfoliated OM platelets. The surface hardness of the PP improved with the inclusion of M5M10 and M5HM10, reaching 78.3 Hs for the M5M10 and 87.5 Hs for the M5HM10. This is mostly explained by M5M10's or M5HM10's reinforcing behavior. Therefore, based on the observation of surface tensile features, the integration of OM and two types of compatibilizers in PP must modify the surface features of nanocomposite components.

THERMAL FEATURES

Thermal Steadiness

Figure 5(a) displays the TGA thermograms of virgin polypropylene and its nanocomposites. Table 2 lists the decomposition temperatures of both virgin polypropylene and its nanocomposites. Using the initial decomposition temperature (T_{onset}) as an example, Figure 5(a) and Table 2 show that the T_{onset} increased for M5 system with a char residue of 20.9 wt% from 333.4°C for virgin PP to 349.1°C, suggesting that the thermal stability of PP was developed. The nanocomposite's T_{onset} for the M5M10 system was roughly 19.8°C lower than the PP's. There were two probable explanations: either the M5M10 system itself increased thermal stability, or the M5M10 system's intercalating impact improved the distribution of OM in PP and further increased its thermal stability. The T_{onset} for the M5HM10 system rose from 333.4°C in virgin PP to 369.2°C. The T_{onset} of M5M10 had a larger char residue of around 34.9 wt%, indicating that the distribution state of OM in the matrix played a crucial impact in thermal characteristics. This further improved the thermal stability of PP with the introduction of the M5HM10 system. The $T_{25\%}$ and $T_{60\%}$ values for the M5M10 and M5HM10 were, as predicted, 10.2°C, 21.3°C, 11.1°C, and 39.1°C higher than those of the M5. The fact that M5M10 or M5HM10 had a higher $T_{60\%}$ than M5, which aided in the development of the thermal stability of nanocomposites, could be one explanation for this. Possible additional factors included the fine distribution of OM in the PP matrix and the intercalated influence of M5M10 or M5HM10.

Heat Distortion Temperature (HDT)

Figure 5(b) displays the thermal behavior of virgin polypropylene and its nanocomposites, expressed as HDT. The PP's thermal stability was developed, as evidenced by the HDT of the M5 system, which was roughly 6.5°C higher than that of the virgin material. This is consistent with the previously reported TEM findings. Not a rise in melting temperature, which was notable in nanocomposite compared to virgin PP, but the presence of strong hydrogen bonds between PP and OM surfaces can be credited to the enhancement of HDT and higher mechanical stability of the nanocomposite. The M5M10 system exhibits superior HDT enhancement in comparison to the M5 system because of improved OM dispersion and exfoliation inside the PP matrix. Moreover, the highest HDT values are displayed by the M5HM10 system. The TEM data that were previously mentioned confirm that the M5HM10 system has a more sophisticated exfoliated structure.

Table 2. Thermal degradation temperatures of virgin PP and its nanocomposites.

Sample	T_{onset} (°C)	$T_{25\%}$ (°C)	$T_{60\%}$ (°C)	Char residue at 600°C (wt%)
PP	333.4	364.9	386.2	18.1
M5	349.1	378.6	404.7	20.9
M5M10	353.2	388.8	415.8	27.8
M5HM10	369.2	399.9	434.8	34.9

Notes: T_{onset} : initial decomposition temperature at which 5% weight loss occurred;
 $T_{25\%}$: the temperature at which 25% weight loss occurs;
 $T_{60\%}$: the temperature at which 60% weight loss occurs.

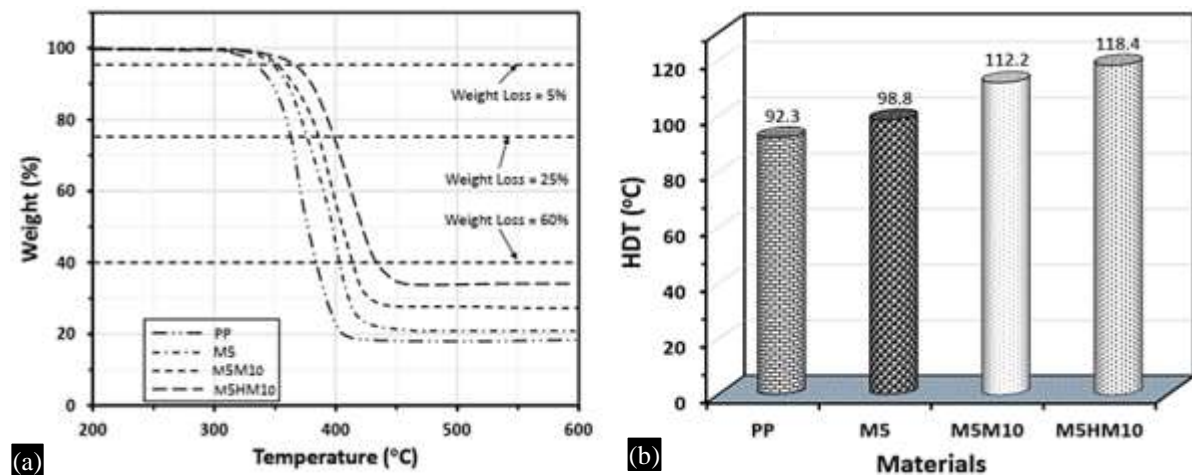


Figure 5. The virgin PP and its nanocomposites' (a) TGA curves and (b) heat distortion temperature.

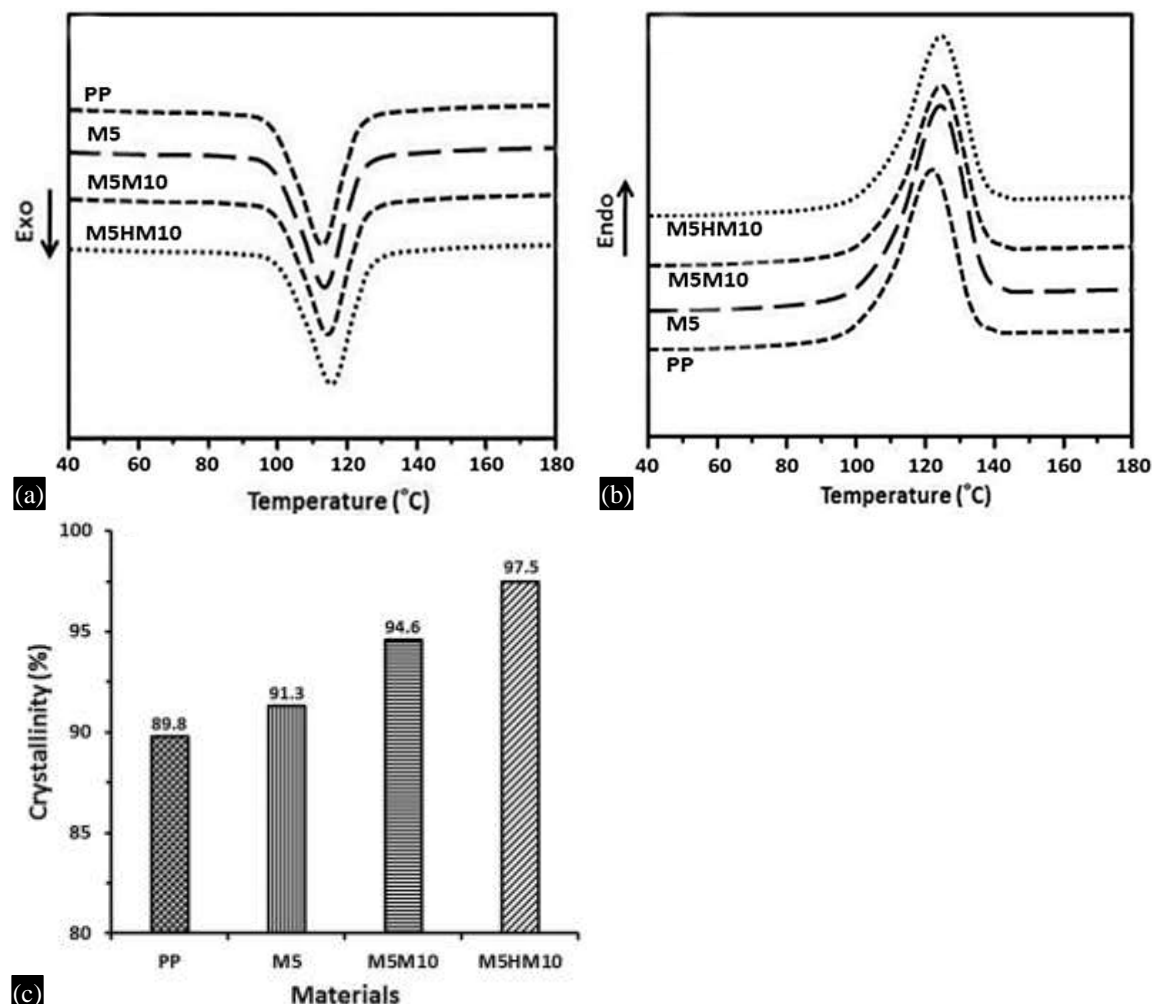


Figure 6. DSC: virgin polypropylene and its nanocomposites' (a) crystallinity; (b) heating thermograms; and (c) crystallization thermograms.

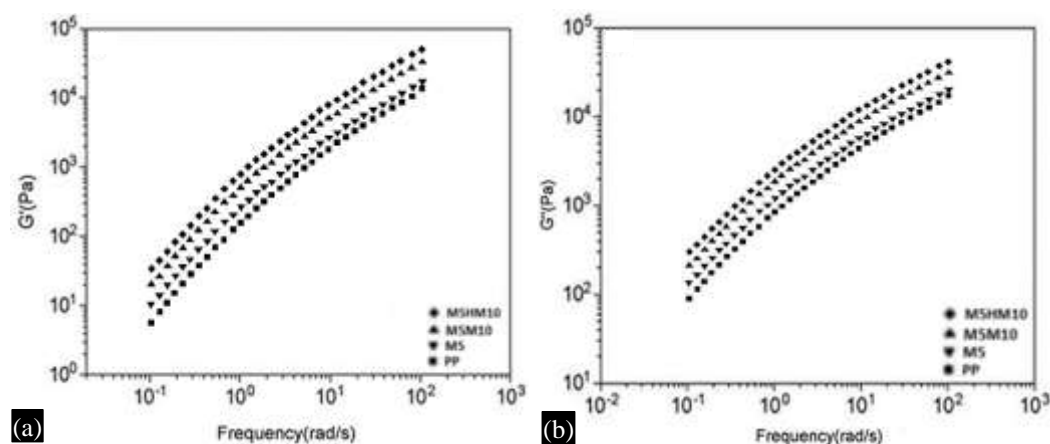
DSC Evaluations

Figures 6(a) and 6(b) show the results of the crystalline and melting peak temperatures of virgin PP, M5, M5M10, and M5HM10 nanocomposites, respectively. Table 3 shows the crystalline peak temperature (T_c), melting peak temperature (T_m), and percentage of crystallinity (X_c , %). The T_c of the

virgin PP, as seen in Figure 6(a), was roughly 111.6°C, indicating the compatibilizer that serves as the nucleator of improved T_c for the M5M10 or M5HM10 system. For the M5 system, the T_c of PP was somewhat raised to 113.2°C. This influence of T_c development on OM's existence can be explained by the likelihood that OM will function as a potent PP matrix nucleating agent. The nucleation influence of M5M10 on the PP matrix is indicated by the increase in T_c to 116.3°C for the M5M10 system. The T_c of M5HM10 improved to 118.7°C, which is significantly higher than that of the PP and the M5M10 system, which is an interesting observation. As a result, the compatibilizer and OM are more severely affected by the PP crystallization process, which may also raise the molten viscosity of the PP in the OM, increase local shear stress, and create a more uniform compatibilizer network in M5HM10. Additionally, the addition of OM and/or compatibilizers had an impact on PP's T_m because of persuaded defective crystalline [Figure 6(b)]. It appears that the compatibilizers associated to the PP structure and crystal formation were unaffected as no isolating impact was detected from either of the compatibilizers. In Figure 6(c), the degree of crystallinity (X_c , %) of virgin PP and its nanocomposites are shown. The compatibilizer greatly increases X_c (%) for M5M10 and M5HM10 systems, whereas OM has no discernible effect on X_c (%). The compatibilizer's influence on PP nucleation can be analyzed by assuming that, in contrast to M5M10, the compatibilizer primarily determines the crystallinity of PP in M5HM10. OM was considered an active nucleating deputation because of its higher surface area during exfoliation, and because the overhead consequences were so naturally appealing. The interface nucleation effectiveness is nevertheless decreased as a result of the effects of welding, plasticizing, and/or defects mentioned. In particular, a large compatibilizer fraction hindered the considerable nucleating efficacy of OM [18].

Rheological Assessments

The virgin PP, M5, M5M10, and M5HM10 systems' storage modulus (G'), loss modulus (G''), and complex viscosity (η^*) as a function of frequency are shown in Figures 7(a)–(c). Using OM resulted in an increase in the G' , G'' , and η^* of the PP. The fact that M5HM10 has the widest frequency study range in G' and G'' (Figures 7a and 7b) makes sense. Specifically, it was observed that the G' and G'' frequencies became unique in the low-frequency condition for M5HM10 and M5M10, which represent the unique characteristics of hard-core components. There is a larger link between OM and PP, as indicated by the increases in G' and G'' at lower frequencies. To ascertain the extent of OM, the behavior and propensity to enhance G' and G'' in the low-frequency zone will be highlighted below. At frequencies of 10^{-1} rad/s, the values of G' and G'' for PP, M5, M5HM10, and M5M10 are 4.9, 12.1, 30.2, 20.1 Pa and 98.3, 158.4, 230.6, 350.6 Pa, respectively. The results suggested that there was no interaction between the PP chains and the OM, and the OM was unable to show any significant filler effect in the absence of any compatibilizer. The M5 system has been classified as a "macro-composite" as a result. Conversely, given the expansion of G' and G'' , it has been verified that M5M10 generates a significant amount of OM-PP interaction, albeit at a lower OM content than M5HM10. For the specific specimen formation, expected OM should show a better dispersion in the M5HM10 system than in the M5M10 system.



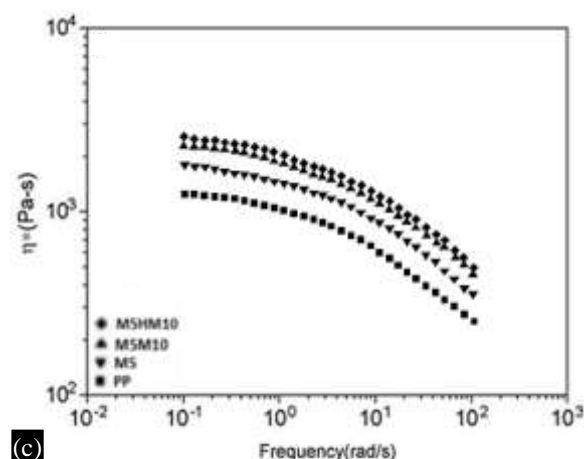


Figure 7. Virgin PP, M5, M5M10, and M5HM10 nanocomposites of (a) G' , (b) G'' , and (c) η^* as a function of the frequency.

Table 3. DSC scans were used to investigate the thermal characteristics and crystallinity of PP and its nanocomposites.

Sample	T_c (°C)	T_m (°C)	X_c (%)
PP	111.6	122.1	89.8
M5	113.2	124.3	91.3
M5M10	116.3	124.6	94.6
M5HM10	118.7	124.8	97.5

T_c : Crystallization temperature; T_m : melting temperature; X_c (%): degree of crystallinity

The complex viscosity (η^*) for virgin PP, M5, M5M10, and M5HM10 systems obtained from the frequency sweep test is shown in Figure 7(c). The η^* shows "non-Newtonian behavior" as it declines with increasing frequency. Due to the shear-thin nature of nanocomposites, compatibilizers have a greater influence on η^* at lower frequencies than at higher ones. However, as compatibilizers are added, this influence decreases with increasing frequency. Though it is less than M5HM10 in a particular OM content, it was found that M5M10 generates significant interaction between OM and PP. The significant increase in the G' or G'' was closely linked to this enrichment effect.

CONCLUSIONS

A mixture of various OM contents and a certain amount of PP-g-MA (PPMA) or PP-g-HMDA (PPHMDA) as a compatibilizer were used to produce PP/OM nanocomposites. Tensile characteristics progress when OM is included, according to investigational results. Compared to PPMA systems and PP/5 wt% OM (M5) systems, PPHMDA systems have better tensile and hardness properties. The morphological characteristics of the results demonstrate the activation of compatibilizers to facilitate the OM delamination. In contrast to the PPMA system, the PPHMDA system exhibited a partial exfoliation of PP/OM nanocomposites. This result was also validated by the specimen's rheological characteristics. TGA thermograms demonstrated that the addition of either PP/10wt% PPHMDA/5wt% OM (M5HM10) or PP/10wt% PPMA/5wt% OM (M5M10) enhanced the thermal stability of PP. The specimens' thermal stability was noted in the following order: M5HM10 > M5M10 > M5 > PP. According to HDT's findings, the M5M10 and M5HM10 systems outperformed the M5 systems. The DSC results showed that there was little effect of virgin PP's crystalline peak temperature in nanocomposites.

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