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PREPARATION AND CHARACTERIZATION OF PHYSICO-MECHANICAL AND STRUCTURAL PROPERTIES OF PHTHALIMIDE DERIVATIVE POLYMERIC NANOCOMPOSITES

by

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In this study, phthalimide derived polymer- TiO_2 nanocomposites were prepared by direct mixing method and their mechanical properties were compared. The high content filler polymer nanocomposites with sufficient interface bonding with the polymer matrix have been prepared to maximize the properties of the filler. In the direct mixing method, the polymer obtained by free radical polymerization of the monomer was mixed with TiO_2 in high weight percentages. The pulse-echo method was used to characterize the elastic constants of the polymer and polymer-TiO₂ nanocomposites through detection of the ultrasonic waves. Transverse and longitudinal ultrasonic velocities have been used to calculate Young's modulus of these samples. The ultrasonic velocity and Young's modulus values of polymer-TiO₂ nanocomposites showed a linear relationship with the weight percentage of the polymer, which is due to the strong and effective interaction between the particles resulting from by reinforcing TiO_2 to the polymer structure. The clustering that emerged with the increase in the amount of reinforcement in the SEM images became more pronounced and it was observed that pure polymer and TiO_2 were homogeneously distributed. The porosity and hardness measurements of the polymer and polymer-TiO₂ nanocomposites were examined. The hardness and porosity of the polymer structure approximately increased as the percentage values of TiO_2 increased. Moreover, TGA results of polymer nanocomposites obtained by direct mixing showed that the thermal stability increased linearly as the weight ratio increase of TiO_2 in comparison with the pure polymer.

Key words: nanocomposite polymers, polyphthalimide, young's modulus, ultrasonic non-destructive testing, porosity, hardness

Introduction

Nanotechnology and nanoscience works have been brought about serious developments in many sectors such as health, defense, textile, industry, and computer systems. A major advance in this area is the synthesis of nanocomposites, which can control the structural order in the material at the nanometer scale [1]. Also, polymer nanocomposites reinforced with nanoparticles have become required materials in engineering with their low friction and superior mechanical properties in nowadays. These materials with many desired properties such as impact resistance, lightness, flame retardancy, durability, flexibility, and resistance to environmental conditions can be used in many applications. Polymer nanocomposites combine the advantages

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of inorganic and organic materials and often exhibit unexpectedly improved properties. The polymeric nanocomposite can be enhanced depending on the type, size, shape, concentration of the nanoparticles, and the interaction of the nanoparticle with the polymer matrix. Thus, materials with high area-to-volume ratios and superior physico-mechanical properties are obtained. These polymeric nanocomposites, which combine the flexibility of polymers and the strength of nanoparticles, have been frequently used in various fields such as automotive, aircraft, safety, optical devices, healthcare, and electronics [2].

Among nanoparticles, TiO₂, has emerged as a platform combining both biocompatibility and physical-chemical and mechanical properties that make it a demanded material in elevated areas such as photovoltaic cells and batteries, medical implants, cancer prevention and treatment, hydrogen generation, and storage [3]. In addition, it is frequently utilized as a nanofiller in the production of nanocomposite polymers due to its non-toxicity, inertness, high thermal and chemical stability properties. Many researchers obtained high yield polymer-TiO₂ nanocomposites from modified TiO₂ and pure TiO₂ by in situ polymerization and direct mixing method and made characterization studies [4, 5]. Polymers grafted from surface-functionalized nanoparticles [6, 7] or on the particle surface [8] were often used to form polymer-TiO₂ nanocomposites, too. Vergnat et al. [9] prepared polymer/TiO₂ nanoparticle composite samples either by grafting method or direct mixing method and investigated their mechanical properties. When they compared the hybrid grafted composites and hybrid mixed composites, they saw that the structural and mechanical properties were interrelated. Most of the published research describes the mechanical properties of the hybrid polymers prepared by directly mixing with nanoparticles. Today, nanocomposites are developed mostly according to their elastic modulus [10-12], yield resistance [13], and strength [14-16].

Polymers bearing phthalimide moiety are used to improve therapeutic drug profiles, semiconductors in solar cells, optical brightening agents, and ion-exchanging polymer stabilizers due to excellent heat resistance, good solubility, and transparency properties and attracts attention with their optical, conductivity and mechanical properties [17-19].

Based on this information, in this study, it was prepared new homogeneous polymeric nanocomposites with the high content of nanofiller which may provide the polymer with new properties such as high electrical conductivity, refractive index, dielectric properties, mechanical properties, and unique response to certain stimuli such as pH, light, and thermal. Although polymeric nanocomposites with low nanofillers have been prepared in many studies, it has been emphasized in recent years that it is necessary to produce nanocomposites with a high filler content at least 50% to meet the increasing demands of modern polymer nanocomposites. The high content filler polymer nanocomposites with sufficient interface bonding with the polymer matrix are suggested to use to maximize the properties of the filler in advanced applications [20]. For this purpose, it was used high weight percentage filler in this study, too. The homogeneous distribution of TiO_2 nanoparticle in the structure was achieved with a rotary mixer. Young's modulus values of polymer and nanocomposites were calculated by the ultrasonic method for the determination of mechanical properties. Young's modulus is a mechanical property of the material that can be expressed as modulus of elasticity/elastic modulus. Many studies have shown that chemical bonds and interactions between nanofiller and polymer are key parameters for controlling mechanical properties. The mechanical properties of the materials can be obtained by finding elastic constants from the sample determined depending on the material characterization by ultrasound. Material characterization with ultrasound is evaluated by measurements based on wave velocity and absorption. These ultrasound waves propagating in the environment in ultrasonic applications give information about the environment where

Ozkan Bilici, V., *et al.*: Preparation and Characterization of Physico-Mechanical ... THERMAL SCIENCE: Year 2022, Vol. 26, No. 4A, pp. 3055-3065

they are affected by the structural changes and discontinuities of the environment [21, 22]. The porosity and hardness measurements of the samples were examined by the micrometrics brand mercury porosimeter device and the Shimadzu brand hardness device in Vickers, respectively. As a result, it was observed that the mechanical properties of the nanocomposite polymers were improved by adding filler material with the addition of TiO_2 up to 50 wt.%. The SEM was used to characterize the micro-structure of the prepared nanocomposites and polymer. Their thermal behaviors were revealed using TGA instrument. Although there are studies on the synthesis of methacrylate polymers containing phthalimide, the reinforced polymer with TiO_2 and its physico-mechanical and structural properties of high TiO_2 reinforced phthalimide-containing nanocomposite polymers this study will contribute to polymer researchers.

Experimental

Materials

All chemicals and solvents were analytical grade. They were purchased from Merc and Aldrich Chemical Co. The main chemicals TiO₂, N-(bromomethyl)phthalimide and sodium methacrylate were used as received.

Measurements

The ¹H-NMR and ¹³C-NMR spectra were recorded using a model Bruker GmbH DPX-400 MHz FT spectrometer in DMSO-d₆ at room temperature. The FT-IR spectra were recorded Perkin Elmer Precisely Spectrum One spectrometer on KBr discs in the wave number range of 4000–400 cm⁻¹. Gel permeation chromatography (GPC) analyses were carried out using Agilent 1100 system equipped with a high pressure liquid chromatography pump, a vacuum degasser, and a refractive index detector. The eluting solvent was dimethylformamide (DMF) and the flow rate was 1 mL per minute. Calibration was achieved with polystyrene. The TGA and the glass transition temperature measurements were carried out under a nitrogen flow with a NETZSCH Brand TG-DSC/TG-DTA/TG device at a heating rate of 10 °C per minute.

Synthesis of N-phthalimidomethyl methacrylate

The N-phthalimidomethyl methacrylate (PNPMMA), N-(bromomethyl phthalimide), and sodium methacrylate were synthesized at 85-90 °C with sodium diode and tebax catalyst [23]. At the end of the reaction, the mixture was cooled to room temperature, the solvent was removed and precipitated with enough precipitator (Yield 70%). The mechanism of the reaction is given in fig 1:

- The FT-IR (cm⁻¹, the most characteristic bands): 1784 (C=O asymmetric stretching in phtalimide group), 1727 (C=O ester carbonyl), 1610 (C=C aromatic ring stretching), 1121 (C-O-C stretching),
- The ¹H-NMR (DMSO-d₆, ppm): 7.96-7.88 (4H, aromatic ring protons), 6.02 and 5.71 (2H, CH₂=C), 5.66 (2H, -O-CH₂-),
- The ¹³C-NMR (DMSO-d₆, ppm): 18.05 (CH₃), 41.1(CH₂- N), 61.37 (-OCH₂-), 124.01, 127.29 (on aromatic ring C), 135.4 (= C-), 133.8 (CH₂=), 166.8 (C=O in ester), 165.73 (C=O in phtalimide).



Figure 1. Synthesis of the PNPMMA

Free Radical polymerization of PNPMMA

Monomer, approximately AIBN 2% by weight of monomer, and 1.4-dioxane solvent was taken into polymerization tube and placed in an oil bath at 70 °C after passing through argon gas for about 15 minutes. After 24 hours, the solution was removed from the oil bath and the solution was precipitated in hexane. The filtered polymer was then dissolved in dichloromethane solvent and precipitated again in petroleum ether, then dried at 40 °C under vacuum:

- The FT-IR (cm⁻¹, the most characteristic bands): 1785 (C=O asymmetric stretching in phtalimide group), 1729 cm⁻¹ (C=O ester carbonyl), 1615 (C=C stretching in aromatic ring). 1121 cm⁻¹ (C=O-C stretching).
- The ¹H-NMR (DMSO-d₆, ppm): 7.83 (4H, aromatic ring protons), 5.66 (2H, -O-CH₂-), 1.84-3.30 (aliphatic protons on the polymer main chain),
- The ¹³C-NMR (DMSO-d₆, ppm): 166.64 (C=O ester), 135.28 (=C-), 134.80 (CH₂=), 124.31, 123.41 (C on aromatic ring), 61.54 (-OCH₂-), 44.58 (CH₂-N). 18.24 (CH₃).

Production of nanocomposites

Preparation of PolyPNPMMA/nanocomposites by direct mixing method

Powder metallurgy method was used in sample forming process. With this method used, the production of the materials was carried out by direct mixing and pressing. Also in the specified compositions, the powders at 20 dv per minute speed were also mixed in a rotating mixer (blender) to obtain a homogeneous mixture for 24 hours. Hybrid nanocomposites were formed by adding TiO₂ to polymer of 10%, 30%, 50%, and 70% in weight after polyPNPM-MA was synthesized as free radical by direct mixing. The prepared powder mixes were then compressed with the help of a 15 mm diameter cylindrical steel mold to give strength and were pressed under the pressure of 150 bar at room temperature by a hydraulic press. nanocomposite samples in approximately 5 mm thickness were obtained.

Ultrasonic measurements

Determining the size and thickness of the samples, the width and the smoothness of the sample surface are the most important factors to be considered in the material characterization studies using ultrasound. It is a great technique used to have information about the internal structure of the material without damaging. In this sense, pulse-echo method is a mostly preferred ultrasound measurement method. This method uses a single transducer (both as a transmitter and a receiver). Longitudinal and transverse ultrasound velocity measurements are obtained with reflection peaks taken from the front and back surfaces in the A-Scan image with the Ultrasonic Pulse-Echo method. The horizontal scale shows the time in terms of the material thickness and illustrates the echo amplitudes in vertical scale on the A-Scan screen. Additionally, the A-Scan screen is the most common form of display in conventional flaw detectors, and it is possible to analyze the location, type and size of the error with this method. Velocity measurements of the samples are performed by Sonatest Sitescan/150 model ultrasound flaw detector. A 4 MHz receiver/transmitter probe (Sonatest SLH4-10) are used for ultrasound longitudinal and transverse velocity measurements.

The ultrasound velocity measurements for each of the nanocomposite were repeated three times. Also, the density of the polymer nanocomposites was measured using the Archimedes technique. The elastic properties of the medium were determined by observing the ultrasound waves sent on the sample. Hence, information was obtained about the internal structure, mechanical, anisotropic, and elastic properties of the medium it passes through. Ultrasonic (longitudinal and transverse) velocity in general is related to the elastic constants and density of

a material. For this reason, the propagation velocities of the transverse and longitudinal waves are measured according to the direction in which they are sent to the solid. Depending on these propagation velocities, mechanical properties such as Young's modulus, *E*, are calculated using:

$$E = \rho V_T^2 \frac{3V_L^2 - 4V_T^2}{V_L^2 - V_T^2}$$
(1)

where $V_{\rm L}$ [ms⁻¹] is the longitudinal ultrasound velocity, $V_{\rm T}$ [ms⁻¹] – the transverse ultrasound velocity, and ρ [kgm⁻³] – the sample density and E is the Young's (elastic) modulus [MPa] [22].

Metallographic examination

The metallographic examinations of the samples were conducted by LEO 1430 VP branded SEM device. The LEO 1430 VP branded SEM device works with W (Tungsten) filament. There are secondary electron, back-scattered electron, and X-ray, energy dispersive X-ray spectroscopy detector (EDX), on the device. Because the attained polyPNPMMA/nanocomposites were not conductive, the surfaces of the samples were covered with carbon and the elementary analysis was conducted. The morphological properties of the prepared polyPNPMMA-TiO₂ nanocomposites, namely the properties such as the structural and textural characteristics of the compounds forming the micro-structure, their relations with one another, dimensions, apparent affluences, propagation, and distributions were revealed by the SEM. The SEM images are, respectively given for the polyPNPMMA-TiO₂ nanocomposites in fig. 2, polyPNPMMA and TiO₂ in fig. 3. Furthermore, hardness and porosity measurements were conducted on the prepared samples for the micro-structure examinations. The average of the hardness values was taken from five different zones on each sample. Microhardness measurements were conducted by SHIMADZU-HMV 2 L hardness measurement device. Hardness test was performed on polymer nanocomposite using Vickers hardness at 0.01 kg load and 5 seconds in loading time. Porosity measurement analyses were performed by micromeritics branded mercury porosimeter. Mercury porosimeter is one of the widely used techniques for determining powder and bulk pore size and pore size distribution, and measurement is taken by allowing 99.99% pure metallic mercury to enter the sample pores.



Figure 2. The SEM images of (a) polyPNPMMA-90% TiO₂, (b) polyPNPMMA-70% TiO₂, (c) polyPNPMMA-50% TiO₂, and (d) polyPNPMMA-30% TiO₂ nanocomposite samples



Figure 3. The SEM images of (a) polyPNPMMA and (b) TiO₂ samples

Results and discussion

Compound monomer containing pendent phthalimide group was synthesized as described previously and characterized by NMR and FT-IR [23]. The polymer of the monomer obtained was carried out by free radical polymerization and the characterization processes were done. The number average molecular weight (Mn) and weight average molecular weight (Mw), and polydispersity index (PDI) of the polymer were determined by gel permeation chromatography (GPC) using polystyrene standards (PS). The Mn = 11.229 g/mol, Mw = 17.896 g/mol, and PDI:1.68, respectively, values of polymer were found. The glass transition temperature of the polymer was recorded as 138.2 °C from the differential scanning calorimeter thermogram of polymer heated in nitrogen atmosphere with a heating rate of 10 °C per minute from room temperature to 260 °C.



Figure 4. The TGA curves of polyPNPMMA and polyPNPMMA-TiO₂ nanocomposites

The polymer has been doped with TiO_2 and the nanocomposites prepared with direct mixing have been attained. The thermograms of the samples heated in a nitrogen atmosphere with a heating rate of 10 °C per minute from room temperature to 800 °C to test the thermal resistance of the polymer and its nanocomposites are shown in the fig. 4 and measurement information is given in tab. 1. The TGA results of polymer nanocomposites obtained by direct mixing showed that the thermal stability increased linearly as the weight ratio increase of TiO_2 in comparison with the pure polymer [24].

Samples	wt.% loss at 200 °C	wt.% loss at 250 °C	wt.% loss at 300 °C	wt.% loss at 350 °C	wt.% loss at 400 °C	wt.% loss at 500 °C	% Remeaning at 800 °C
PolyPNPMMA	5	6	10	41	72	94	5
PolyPNPMMA-30% TiO ₂	2	6	18	29	52	64	35
PolyPNPMMA-50% TiO ₂	2	6	14	22	35	43	57
PolyPNPMMA-70% TiO ₂	1.5	5	9	13	21	25	75
PolyPNPMMA-90% TiO ₂	0.3	1	1.7	3	5	6	94

Table 1. The TGA data for poly(PNPMMA) and polyPNPMMA -TiO₂ wt.% nanocomposites

Nanocomposite samples formed by reinforcing TiO₂ to polyPNPMMA through direct mixing method and then were pressed for other measurements. The signals obtained from electron-sample interactions in SEM provided information about the sample including the external morphology (texture), chemical composition and crystal structure and orientation making up the sample [25]. Considering the SEM images in general, it was seen that the pure polymer and the TiO₂ were homogeneously distributed, they interacted with each other, and their partially existing porosity could be shown. When the reinforcement composites with wt.% TiO₂ were considered, fig. 2, the porosity in the structure increased as the percentage amounts increased and the TiO₂ powders in white state and the pattern structure could be seen. The most clearly seen figure was the inner morphological structure of the pure polymer. When fig. 3(a) was examined, the grain size and grain structure being round, that was, roughly in the form of a ball without any reinforcement and bonding, indicated that there was no mixture, union, or integration in the structure.

Ozkan Bilici, V., et al.: Preparation and Characterization of Physico-Mechanical ... THERMAL SCIENCE: Year 2022, Vol. 26, No. 4A, pp. 3055-3065

Pulse-echo method was used as a non-destructive technique for evaluating the mechanical and the physical properties of polymeric nanocomposites. The Young's modulus of polymer and nanocomposites were measured by the ultrasonic method. The experimental results attained with the ultrasound velocities, Young's (elastic) modulus and density values belonging to the prepared samples are given in tab. 2.

	-		1	
Samples	$V_{\rm L} [{\rm ms}^{-1}]$	$V_{\rm T} [{\rm ms}^{-1}]$	E [MPa]	Density [kgm ⁻³]
PolyPNPMMA	12.000	29.000	5.3	1493.7
PolyPNPMMA-30% TiO ₂	56.241	66.626	53.4	1856.2
PolyPNPMMA-50% TiO ₂	49.000	58.940	50.2	2317.8
PolyPNPMMA-70% TiO ₂	40.004	49.940	28.7	1986.6
PolyPNPMMA-90% TiO ₂	20.000	38.100	14.9	2346.9

Table 2. Ultrasound velocities, elastic modulus and density values of poly(PNPMMA) and polyPNPMMA -TiO₂ wt.% nanocomposites

In addition, the weight percentages of the nanocomposite samples and the relation between the ultrasound longitudinal wave velocity and ultrasound transverse wave velocity are given in figs. 5(a) and 5(b). The relationship between the wt.% fraction of TiO₂ and Young's (elastic) modulus of polyPNPMMA-TiO₂ nanocomposites is shown in fig. 6.



Figure 5. (a) Longitudinal ultrasound velocity and (b) transverse ultrasound velocity graph of polyPNPMMA-TiO₂ nanocomposites samples

When the graphics are examined, it is seen that the longitudinal and transverse wave velocity increases approximately 2-5 times in nanocomposites as compared to the pure polymer. Also, these values decrease in polyPNPMMA-90%TiO₂ that show close value to pure polymer. The fact that the ultrasound transition velocity has a high value on a material shows that the materials have a full and compact structure. As the ultrasound wave passes through a solid, it interacts one-to-one with the particles in the environment, resulting in a decrease in amplitude, in other words, attenuation.



polyPNPMMA and polyPNPMMA-TiO₂ nanocomposites samples

At the same time, the deviation of energy from parallel rays due to reflection, refraction, diffraction and scattering, particle structure and discontinuities in the structure cause attenuation [26]. While polyPNPMMA-30% TiO₂ with the highest wave velocity values has the most compact structure, polyPNPMMA-90% TiO₂ does not show this structure. When the graphics are examined, it is seen that the longitudinal and transverse wave velocity changes approximately. Since the correlation coefficient is the coefficient expression specifying the direction and magnitude of the relationship between the independent variables, the correlation coefficient, R^2 , shows that there is a linear decrease. In the given graphics, R^2 (accuracy factor) of the fitted line is approximately close to 1. The R^2 values of the longitudinal and transverse velocity measured with pulse-echo method are 0.90851 and 0.98529. This situation could be clearly seen when the relation between TiO₂ weight percentage of the polyPNPMMA-TiO₂ nanocomposite samples and the ultrasound longitudinal wave velocity and ultrasound transverse wave velocity is examined.

Elastic modulus is one of the most important mechanical predictions parameter for making the structural analysis and design of the materials and a measure of the interatomic bonds force [27]. As can be seen from the graph, while pure polymer has the lowest elastic module value with 5.3 MPa, the Young's modulus values obtained with adding TiO_2 to pure polymer increase approximately 10-fold. The Young's (elastic) modulus with adding of TiO_2 in nanocomposites has the high value which shows that the transfiguration skill of the polymer structure has decreased, and it has turned into a more rigid state [28-31]. This may result from the increase interface area in the structure content of the nanocomposite, and it means that the strain transmission productivity will increase at a small tension range [32]. The improvement in mechanical properties result from the strong interaction and cohesion between TiO₂ and polyPNPMMA matrix, which provides efficient load transfer between these two-components. Therefore, it can be concluded that polyPNPMMA-90% TiO₂ and polyPNP-MMA (pure polymer) have greater transformation ability and more fragile structure than polyPNPMMA-30% TiO₂, polyPNPMMA-50% TiO₂, and polyPNPMMA-70% TiO₂. The fact that the Young's modulus value is the highest in polyPNPMMA-30%TiO₂ shows that the interaction between the polymer and TiO_2 is the strongest in this material. It is seen that this interaction decreases as the percentage of polymer by weight decreases. The polymer-nanofiller interaction decreases in the range of than 50% TiO₂ content. It can be claimed that the high polymer ratio and the presence of sufficient number of nanomaterials that the polymer can affect can increase the interaction in nanocomposites. The higher values of Young's modulus in polymer nanocomposite samples with compared to pure polymer could be attributed to a host of factors such as favorable particle size, greater degree of polymer-filler interaction and more uniform dispersion. The lack of sufficient amount of polymer in polyPNPMMA-90% TiO_2 to interact with the nanoparticle and the presence of aggregates cause the lowest value.

Table 3.	Microhardness	and poros	ity values	of polyPNPMMA
and pol	vPNPMMA-TiO)2 wt.% na	nocompos	ites

Samples	Microhardness [HV]	Porosity [%]
PolyPNPMMA	4.2	36.5
PolyPNPMMA-30% TiO ₂	4.9	39.9
PolyPNPMMA-50% TiO ₂	5.0	43.5
PolyPNPMMA-70% TiO ₂	5.2	44.7
PolyPNPMMA-90% TiO ₂	4.8	31.1

The changes of the microhardness and porosity values of the polyPNPMMA and nanocomposite samples according to the weight percentage of TiO_2 are shown in fig. 7 and in tab. 3. When the graph in fig. 7 is examined, it is seen that they have values very close to each other. When the performed reinforcement is considered, the hardness of the polymer composite structure has increased as the percentage values of TiO_2 have increased. A decrease in hardness values was observed only when the TiO_2 value was 90%. This is thought to be due to the weak adhesion between the polymer matrix and TiO_2 , the absence of new bonds, aggregation in certain regions, and the

decrease of the polymer amount. When the porosity values observed against polyPNPMMA-TiO₂ and polyPNPMMA are considered, the same relationship is existent in porosity, too. The porosity amount increased as the TiO₂ ratio increases. Also, the impact of compression on porosity is a well-known fact [33]. For this reason, all nanocomposites and pure polymer were pressed under the same compression. The change in the volume fraction/ density of the pores of the samples, it was thought that the observed variations in ultrasonic parameters were related to the interaction between the polymer and nanomaterials and the homogeneity of the structure.



Conclusion

The PolyPNPMMA-TiO₂ hybrid materials were prepared through direct mixing method at 10%, 30%, 50%, and 70% polymer weight percentages. The ultrasound velocities, Young's modulus values, microhardness and porosity for polymeric nanocomposites were calculated. The correlation values were confirmed that there was a clear relationship between velocity values and increasing polymer weight percentage. According to Young's modulus values, it is observed that there can be interaction between particles by strengthening the polymer structure with the addition of TiO_2 up to 50%. The strongest interaction is in the 30% TiO_2 content. While the hardness and porosity values with the TiO_2 value increased were increased, these values in polyPNPMMA-90% TiO₂ nanocomposite were decreased. This decrease in hardness and porosity could be attributed to the agglomeration and no amount of polymer that can create interaction with nanomaterial. The SEM images illustrated that TiO₂ nanoparticles were homogeneously distributed in a polymer matrix. Furthermore, the thermal stability of nanocomposites with different TiO_2 loadings increased as compared to pure polymer. In conclusion, polyPNPMMA-TiO₂ hybrid materials were synthesized as a new derivative nanocomposite considering the possibility of using polymer/nanocomposites in the materials industry. Based on the method used and the results obtained, it can be concluded that the high performance polyPNPMMA-TiO₂ hybrid materials up to 50% nanomaterial content by weight could be produced easily with homogeneous micro-structure and full density at low cost. The high content filler polymer nanocomposites with sufficient interface bonding with the polymer matrix could use to maximize the properties of the filler in advanced applications.

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