Fabrication of Polypropylene Nanocomposite for Superlative Refrigerated Vehicle Panels

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Abstract

The three-layered, foam-insulated panel of a truck for transporting refrigerated items on the road is sandwiched between two sheets of very thermally conductive aluminum metal. A refrigerated vehicle often experiences an annual loss of insulating value due to a rise in the heat absorption and heat transmission of the metal sheets, which affects the cooling temperature in the panel chamber. The goal of the project is to develop and evaluate low-thermal conductive polymer-based composite materials using nanoclay (NC) particles for use in superior refrigerated vehicle panels, with the goal of fabricating polypropylene nanocomposite for those panels. The pre-treatment of the materials, creation of composite samples, and assessment of the new samples' mechanical, morphological, and thermal characteristics were all part of the melt blending compounding procedure. The study's findings indicate that the mechanical, morphological, and thermal characteristics of the composites were affected by the melt mixing. The processing method, however, displayed an intercalated morphological structure that improved the strength, stiffness, and heat conductivity of the composites. The material with 3% nanoclay by weight showed the best properties and might be suggested for insulation in chilled vehicle panels.

Keywords: Polypropylene; Nanocomposite; Nanoclay; Refrigerated vehicle panels; Maleic anhydride grafted polypropylene

Introduction

Garden-fresh food and its products are transported in temperature-controlled vehicles called refrigerators that have an insulated panel and a cooling system [1, 2]. (see Figure1). In order to meet the growing population, it is crucial to use refrigerated vehicles to transport food supplies and extend shelf life. Because of their high heat conductivity, the aluminum or steel metal panel sheets used in chilled panels use more energy, need more engine power, wear down insulating materials more quickly, and pollute the environment. This vehicle's main function is to maintain the chilled temperature rather than to deliver cooling [3].

The most important factor in preserving the shelf-life of perishable foods is the temperature in a refrigerated vehicle [4, 5]. One of the methods that has been the most widely utilized so far to prevent the development of bacteria that causes food degradation is refrigeration [6]. Perishable food must be transported to customers at the proper temperature in order for them to be in a fit state for consumption [7].

Cooling is a proactive method for lowering the rate of microbial growth and extending the shelf life of perishable items [5]. The safe refrigeration temperature is generally regarded as 4 °C or below [8, 9]. (see Figure1). Refrigerated vehicles come in a variety of shapes or sizes, such as rigid refrigeration trucks, vans, and semi-trailers [10, 11]. These cars weigh anything from 3.5 to 6 tons, 7.5 to 12 tons, 15 to 18 tons, and 23 to 26 tons [12, 13].

The compression system, which is part of the cooling system in refrigerated cars, is powered by an external power source, such as a generator or the owner of the vehicle [14]. The fan belt powers the compressor unit, which is often found in the engine compartment. Inside the vehicle's insulated compartment, piping connects the compressor to the cooling apparatus [15]. The condenser unit is then installed either on the vehicle's top or in the engine compartment, where an electric standby system is installed [16]. For usage while the vehicle's engine is not operating, a mains-powered compressor is fitted in the condenser compartment [16].

Equation 1 determines the heat conductivity of an insulated panel for a refrigerated vehicle.

$$k_{tot} = k_s + k_g + k_r + k_{con} + k_{coup} + k_{leak} \tag{1}$$

Each of the aforementioned thermal contributions must be kept to a minimum to retain the lowest feasible thermal conductivity.
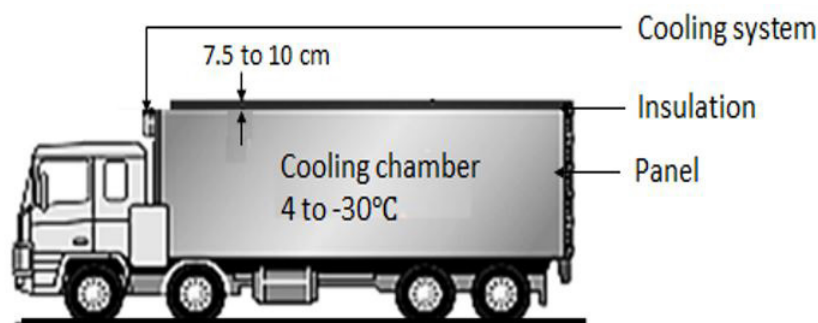

Figure 1: Image of a 7.5–12 tons refrigerated vehicle [17]

The purpose of this work is to manufacture composite materials based on low-thermal conductive polymers for use in excellent refrigerated vehicle panels. This will lessen engine power, payload, fuel consumption, and environmental impact.

Nanocomposites

Review of automotive applications of polymer nano-composites

Polymers can be used in cars to reduce weight and improve insulation [18]. These polymeric materials have the ability to lower engine output, carbon emissions, and energy usage. Based on their intended uses, the various types of polymers used in vehicles may be divided into sandwich panels made of polymers, high-performance polymers, reinforced polymers, and polymer/metal hybrid systems [19]. Table 1 lists the many polymer varieties and their areas of use in autos.

The 2002 General Motors Commercial and Passengers Safari, Chevrolet Astro, and the 2003 and 2004 generations of commercial vehicles all employed nanocomposites to help with the outside [20]. The body side molding of the 2004 Chevrolet Impala, the company's most popular vehicle, features PP/

nanoclay composite from GM as well [21, 22]. In collaboration with Basell North America and Southern Clay Products, the GM Research and Development Center in Warren, Michigan, created the chemical [23]. On the 2005 GM Hummer H2 Sport Utility Truck, nanocomposite is used for the first time (SUT). For its box-rail protector, sail panel, and center-bridge, this vehicle's cargo bed requires around seven pounds of molded-in-color nanocomposite components [24]. Additionally, Basell's Profax CX-284 reactor Thermoplastic Polyolefin with nanoclay is the material used on the GM Hummer H2 SUT [25]. Carbon nanotubes increase electrical and thermal conductivity, whereas nanoclay gives polymers more strength [26]. However, since the late 1990s, nearly every automobile built in the US has had some carbon nanotubes, often mixed into nylon to guard against static electricity in the fuel system [27].

Electrical parts, external trim, lights, bumpers, hood components, interior trim, upholstery, seats, dashboards, fuel systems, body panels, and other reservoirs have all seen the use of PP in vehicles [28, 29]. (see Table 2).

Table 1: An overview of polymers, their characteristics, and their potential uses in vehicles [30, 31, 32, 33, 34].

Name of polymer/matrix	Properties of polymer	Application in automobile
Polyetheretherketone	Heat-resistant, abrasion-resistant, and chemically resistant.	Components for the gearbox, an oil pump, a ball joint, a washer, and a bearing.
Polybutyleneterephthalate	Rigidity, electrical insulation, heat resistance, and dimensional correctness.	Plugs, electronic housings, bumper covers, connector housings, and external vehicle body components.
Polymethylmethacrylate	Scratch-resistant, stress-cracking-resistant, ultraviolet resistant, and transparent.	Headlamp lenses and rear lamps for the blinker.
Polyethyleneterephthalate	Tensile strength, high barrier effect, and rigid.	Seat belts, covers, fabrics, and airbags.
Acrylonitrile Butadiene Styrene Copolymer	Solid, dimensionally stable, and electroplatable.	Dashboard, interior panelling, radiator grills, and wheel Panels.
Polyoxymethylene	Thermally stable, abrasion-resistant, low tendency to creeping, impact-resistant, and chemical resistance	Bearing components, connectors, and clips.
Polyvinylchloride	Low cost, weather-resistant, good haptic, and non-inflammable.	Cable insulation, protective bordering, underbody protection, and interior panelling.
Polyamide	Rigid, temperature-stable, aging-resistance, low gas permeability, and permanent solid.	Connector housing, wheel panels, plugs, motor covering, suction elbows, mirror housing, and door handles.
Polyethylene	Low cost, chemical resistance, good solidity, and, aging-resistance.	Fluid containers, windshields, and fuel tanks.
Polycarbonate	Impact-resistant, transparent, and ultraviolet resistant.	Exterior auto body parts, tail light cover, headlight lenses, and bumper coverings.
Polyurethane	Damping, good elasticity, and low heat conductivity.	Exterior elements, dashboard, seat upholstery, and roof padding.
Polypropylene	Chemical resistance, good solidity, and low-cost.	Crash panel, wheel housings, guide channels, containers, side panels, air filter housings, door trim, battery case, seats, and bumpers.

Review of nanocomposites based matrix

Due to their promising features that may be attained with very little filler content, polymer matrix nanocomposites, a combination of polymers and nanocomposites, have some promise for application in the production of insulating materials [35, 36]. As is well known, these composites function better when clay particles are well distributed throughout the polymer matrix and there is intercalation between the macromolecules of the matrix and the clay lamellae [37, 38].

According to three geometries—rod or fiber-like, equi-axial or particles, and sheet—nanofillers are often categorized [39, 40]. The high surface-to-volume ratio of tiny particles, which varies depending on the particle shape, is a significant benefit. The kind of nano-scale fillers utilized in the composite may be used to explain properties of polymer nanocomposites. Although clay or Montmorillonite (MMT) is one of several forms of nanofillers, including carbon, clay, aluminum oxide, and silica, that are commercially accessible today, it is also one of the most researched in polymer nanocomposites [41, 42].

When nanoclays are incorporated into a host polymer matrix, they merely turn "nano," making it impossible to differentiate or separate them from the bulk polymer and other components [43, 44]. In addition to serving as high aspect ratio reinforcements, nanoclays also serve important roles by having complementary thermal, barrier, and flame retardant qualities. Exfoliation (involve dispersion and delaminating), interfacial adhesion or wetting, and intercalation (involve surfactant and polymer) are some of the elements responsible for effective performance in nanocomposites [45, 46, 47, 48, 49].

One of the most often used thermoplastic materials in the plastics industry is PP, a form of polyolefin polymer [50]. A well-developed PP/clay nanocomposite offers a lot of promise for use in many different industrial sectors, including packaging, bottles, cars, and films, among others [51, 52 & 53]. However, due to polypropylene's non-polar nature, it is challenging to exfoliate clay layers and achieve homogenous clay layer dispersion in the PP matrix [54]. This is so because only polymers with polar functional groups may be used with the organophilic clays,

Table 2: Summary of materials and their nanocomposites properties [64, 65, 66]

Material	Features	limitation	Nanocomposites of the material based on matrix	Advantages of nanocomposites
Metal	Ductile, toughness with high strength and modulus, electrical and heat conductivity.	Highly corrosive	Metal matrix nanocomposites (MMNC).	High electrical and thermal stability, wear and chemical resistance, as well as strength in shear or compression operations.
Ceramic	Good wear resistance and high thermal and chemical stability.	They are brittle or low toughness	Ceramic matrix nanocomposites (CMNC)	Due to the crack-bridging function of nanofillers, mechanical parameters such as fracture toughness, stiffness, and strength are improved. The magnetic, electrical, optical, or catalytic capabilities of ceramic in matrix nanocomposites are stunning, and their biodegradability has been dramatically improved.
Polymer	Widely used in industry due to its ease of production, lightweight, and ductility.	Low modulus and strength.	Polymer matrix composites (PMNC)	Inorganic materials such as polymers improve mechanical strength, heat and impact resistance, flame retardancy, and gas permeability with regard to oxygen and water vapor. The magnetic, electrical, optical, or catalytic capabilities of polymer/metal or ceramic materials are impressive, and their biodegradability has dramatically improved.

which have polar hydroxyl groups [55]. Compatibilizers such maleic anhydride grafted polypropylene (PP-g-MA) and the hydroxyl groups' grafted polypropylene are utilized to overcome the incompatibility between no polar polymer and polar clay [56, 57, 58]. Polar functional groups found in the compatibilizer improve the interface contact between the PP matrix and the clay [59, 60, 61, 62, & 63].

In order to minimize consumption, engine power, and weight while maintaining the other distinctive qualities of the present panel materials, the goal of this work is to create a low thermal conductivity polypropylene nanocomposite for use as an insulator in superior refrigeration vehicle panels. The materials employed in this investigation were PP, NC, and MA-g-PP.

Techniques for making nanocomposites

It is beneficial to have the nano particles distributed equally throughout the matrix for the improvement of a particular matrix material attribute, such as the improvement of the matrices' electrical, mechanical, or optical capabilities [67]. Due to the Van der Waal forces between the nano additives that lead to agglomeration of the nanoparticles, achieving a proper dispersion can be difficult [67]. Numerous techniques have been researched and used over the years to get a good dispersion of these compounds, and the results are recorded in the literature [67]. According to three various schemes depicted in Figure 2, the usual preparation procedures of nanocomposites are described. In this work, polypropylene nanocomposite was prepared using the Scheme II process for use in an excellent insulated panel for chilled vehicles.
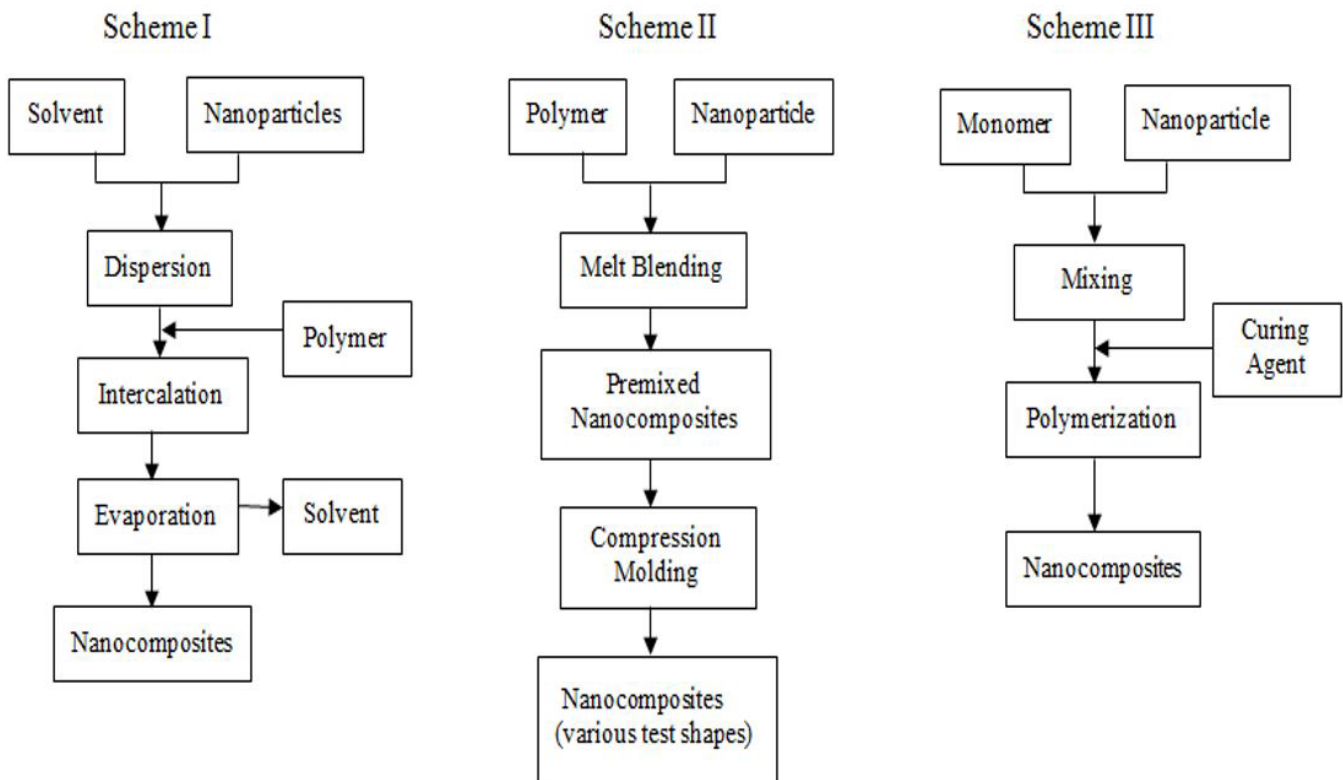

Figure 2: Methodologies for Common Nanocomposites Preparation [67]

Experimental

Materials

Maleic anhydride grafted polypropylene with product name EastmanTM G-3003 and CPV340 grade polypropylene impact copolymer with tensile strength of 1400 MPa and density of 0.905 g/cm3 are the raw materials that were used in this investigation.

It came from Southern Clay Products in the USA. Eastman Chemical Company, USA, provided the nanoclay with the type name Cloisite® 20A, grade name Cloisite®, and maximum tensile strength of 101MPa, with a density of 1.77 g/cc. The Cloisite 20A Nanoclay type was chosen above the Cloisite Na+, Cloisite 93A, and Cloisite 30B Nanoclay kinds because it has greater property improvements and a higher miscibility with polypropylene [68].

Experimental process

Before being prepared using PP CPV340 type, the NC Cloisite® 20A grade and MA-g-PP G-3003 materials underwent pre-treatment (see Figure 3a). Because it is both economical and ecologically benign, melt blending compounding approach was utilized in the study with a Haake Polylab rheomixer. In order to ensure even and homogeneous dispersion of the nanoclay in the resulting composites, a rheomixer compounding device was also used; this distinguishes it from conventional processing methods, which have drawbacks like weak bonding, shrinkage, agglomeration, low wearing resistance, high permeability, and difficult control of porosity and voids [69].

Pre-treatment of materials

NC and MA-g-PP were dried in a vacuum oven for a whole night at a predetermined temperature of 80°C. This is due to the fact that they are hydrophilic by nature, and the procedure helped to remove moisture from them, maintaining their ideal conditions and boosting the bonding efficacy (see Figure 3b).

Preparation of composite samples

As a master batch for reference, a sample of pure PP was created, and then batches of samples with PP, NC, and MAPP at various concentrations were created. PP was weighed into the rheomixer and allowed to melt for two minutes before NC and MA-g-PP were added and allowed to blend for six minutes. The rheomixer, a product of Thermo Electron Cooperation, USA, received a total mass of 50g (See Figure 3c). For the 8 minutes it took to mix each batch, the rheomixer was run at 190°C and a rotor speed of 60 rpm. There were utilized six sets of samples. The control sample, Sample 1, was an impact copolymer made of pure polypropylene (PP). Samples 2, 3, 4, 5, and 6 were nanocomposites with a weighted content of 1%, 3%, 5%, 7%, and 10% nanoclay, respectively (see Table 3).

Additionally, the pre-mixed samples were compression-molded using a Carver laboratory press (Model-3851-0, USA) for 10 minutes at 1500 psi and 190 °C. Then, the mold was let to cure (see Figure 3d and Figure 3e). According to the numerous standards necessary, the test specimen was prepared for mechanical, morphological, and thermal characterizations (see Figure 3f).

The PP, NC, and MA-g-PP mixes mixed according to the theoretical mixing theory. The idea of mixing one component with another may be understood using the thermodynamics of a mixture. According to Gibb's theory on free energy of mixing, mixing of two or more components is advantageous if the free energy value of mixing is negative (see Equation 2).

$$G_{mix} = \Delta H_{mix} - T\Delta S_{mix} \qquad (2)$$

A low free energy value indicates that the mixing procedure is successful. For the gaseous state, Gibb's free energy of mixing was established. Later, Gibb's free energy for the polymer system was adjusted by Flory-Huggins. Equations 3 and 4 below offer the general statement of the Flory-Huggins theory for the free energy of the PP/NC/MA-g-PP systems.

$$\Phi_A = \frac{n_A M_A}{n_A M_A + n_B M_B + n_C M_C} ;$$

$$\Phi_B = \frac{n_B M_B}{n_A M_A + n_B M_B + n_C M_C} ; \Phi_A = \frac{n_B M_B}{n_A M_A + n_B M_B + n_C M_C} \qquad (3)$$

$$\left[\frac{\Delta G_{mix}}{RT}\right] = \frac{\Phi_A}{M_A} In\Phi_A + \frac{\Phi_B}{M_B} In\Phi_B + \frac{\Phi_C}{M_C} In\Phi_C + \chi_{ABC}\Phi_A\Phi_B\Phi_C \qquad (4)$$

Table 3: Composition and proportion of test samples by weight

Sample	PP	MA-g-PP (compatibilizer)	NC
Pure PP	100%	0%	0%
PPNC1	95%	4%	1%
PPNC3	93%	4%	3%
PPNC4	91%	4%	5%
PPNC5	89%	4%	7%
PPNC6	86%	4%	10%

Figure 3: Image of methodology processes: (a) raw materials, (b) oven dryer, (c) rheomixer, (d) compression mold, (e) premixed sample, and (f) molded-shaped samples

Characterization

The Instron 5966 tester (Instron Engineering Corporation, USA) with a load cell of 10 KN was used to measure the tensile strength and modulus, or stiffness, of the samples in accordance with ASTM D638. The test samples' morphology was also looked at using a scanning electron microscope (JEOL JSM-7500F, Germany) with a 15Kv accelerating voltage.

The prepared samples were rectangular and had 10mm x 4mm dimensions. On Netzsch LFA 427 SOP instruments, the in-plane and through-plane thermal diffusivity (a) was measured using the laser flash technique. Nitrogen was utilized to maintain the furnace's temperature or cooling, while argon gas was used to create the environment there. Processing parameters include a temperature range of 25 °C to 100 °C, a laser voltage of 450 v, a pulse width of 0.8 ms, an atmosphere-argon gas flow rate of 100 ml per minute, a heating rate of 50 kilowatts per minute, and a distance of 1 minute. The LFA 427 instruments were used in accordance with ISO 18755 and ASTM E1461 standards. The samples' thermal conductivity was determined using the following formula:

$$k = \alpha \cdot C_P \cdot \rho \qquad (5)$$

Results and discussion

When compared to pure PP, the nanocomposites' strength and modulus increased, according to the findings of the tensile testing (see Figure 4). As can be seen in Figures 4a and 4b, the composite sample with a 3 wt% clay component provided the best mechanical property in terms of strength and stiffness. This is explained by the MAPP's bonding action on the PP and NC combination.

The degree of PP chains' penetration into the NC gallery is exhibited in the SEM micrographs, as illustrated in Figure 5.

The materials' morphology revealed intercalated structures. Rheomixer was used to properly distribute the NC filler throughout the PP matrix (see Figure 5). When compared to pure PP, the nanocomposites' strength and modulus were improved by the homogeneous dispersion of clay in the PP matrix (see Figure 4). Homogeneous clay dispersion was seen at clay levels of 1wt%, 3wt%, and 5wt%, however when NC inclusion in the PP matrix rose, the fracture first appeared at clay concentrations of 7wt%. Once the clay concentration reached 10%, fracture propagation became apparent. SEM micrographs, as seen in Figures 4a and 4b, correlate to changes in the materials' strength and modulus.
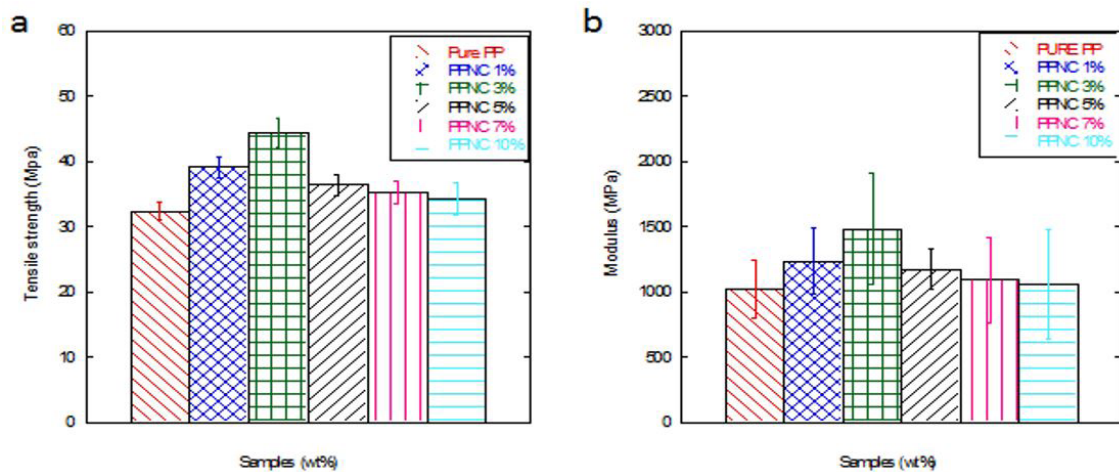

Figure 4: Plots of (a) tensile strength and (b) tensile modulus as functions of nanoparticles wt% inclusion
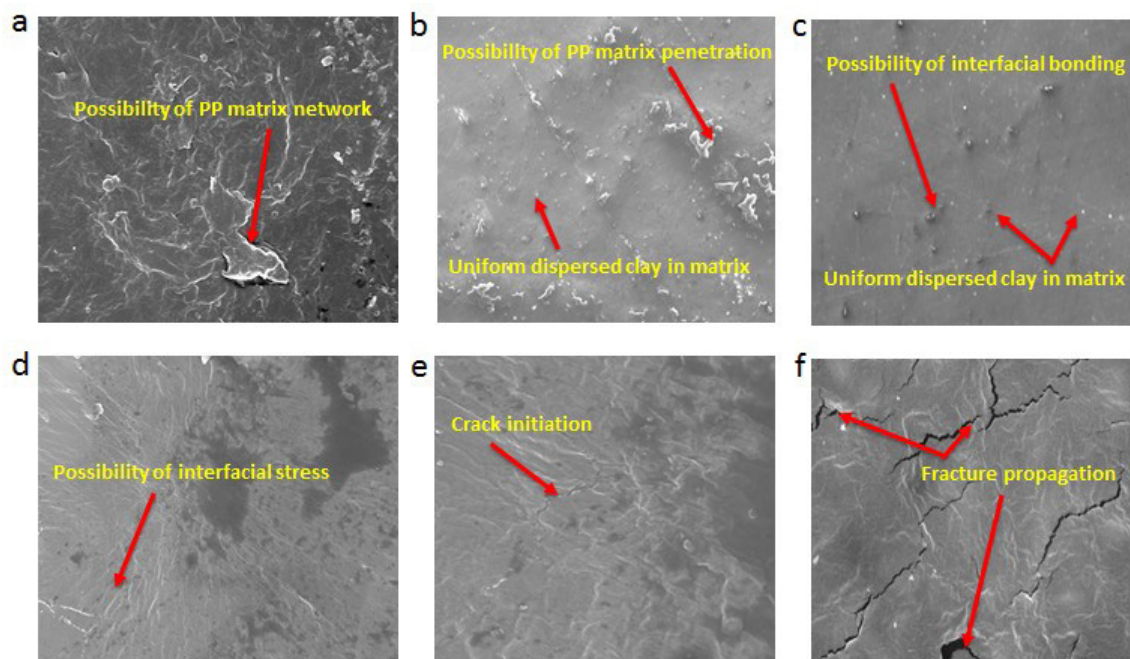

Figure 5: SEM micrographs of: (a) Pure PP, (b) PPNC 1%, (c) PPNC 3%, (d) PPNC 5%, (e) PPNC 7% and (f) PPNC 10%

As the samples' clay concentrations rose, their thermal conductivity decreased, as seen in Figure 5a. The macromolecular size, molecular weight distribution, crystallinity level, clay content, and crystallite orientation all affect the composites' ability to transmit heat. The composite sample with a 10 weight percent clay component had the lowest thermal conductivity, the greatest value that could be produced, but it failed in terms of strength, as shown in Figure 6. The 10% composite is therefore unsuitable for insulation in refrigeration vehicle panels.
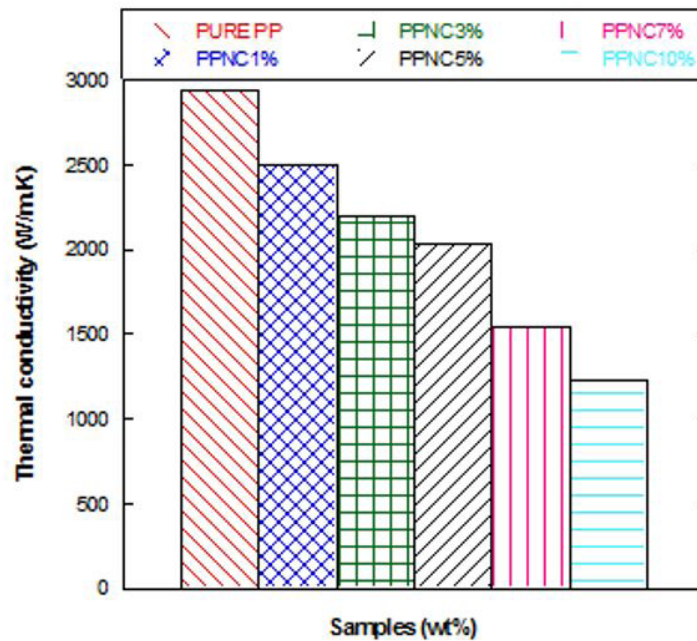

Figure 6: The plot of samples' thermal conductivity

Conclusions

PP nanocomposite is a strong candidate for sustainability since it offers innovative technologies in the automotive and food storage sectors and is also socially and ecologically responsible. According to the study, the dense interface bonds between the matrix and the dispersion phase increased the tensile strength and modulus of PP nanocomposites. The processing procedure, which enabled homogeneous dispersion of NC in the PP matrix with the aid of MA-g-PP as the compatibilizer, was associated to the low thermal conductivity characteristics of PP nanocomposites. Since strength and stiffness are crucial in choosing a composite for the application of the excellent refrigerated vehicle insulation panels, PP/NC 3% provided the most desirable quality.

Declarations

Availability of data and material: Data sharing does not apply to this article as no datasets were generated or analysed during the current study.

Competing interests

The authors declare that they have no competing interests in this study

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Authors' contributions

T designed the work. Z contributed largely to the conception. CA carried out the experimental studies. ER analysed the experimental data. K edited the work. BI revised the work.

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