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Enhancing Sustainability in the Injection Moulding Process via Reprocessing of Polypropylene Nanoclay Nanocomposites

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Abstract

A study investigating the impact of reprocessing cycles on the hardness and impact strength of polypropylene-nanoclay nanocomposites (PPNC) has been conducted. The PPNC was composed of 80wt.% TITANPRO SM240 polypropylene (PP), 15wt. % Orevac CA100 maleic anhydride grafted polypropylene, and 5wt.% Cloisite 15A nanoclay. The research commenced by conducting an injection moulding technique on PPNC. The generated samples were assessed based on their impact strength and hardness. Subsequently, the materials were pulverized into pellets in order to undergo additional reprocessing cycles. The reprocessing procedure was iterated four times. The hardness and impact strength were measured using the Shore hardness test and the tensile testing method, respectively. For the purpose of comparison, pristine polypropylene (PP) also underwent the identical reprocessing procedure as PPNC. According to this study, it was shown that when the reprocessing cycle of PPNC grew, there was a drop in both the hardness number and impact strength of PPNC. The hardness of PPNC was reduced by a total of 6.56% from the first reprocessing cycle to the fourth reprocessing cycle. However, the impact strength of PPNC decreased from the second reprocessing cycle to the fourth reprocessing cycle. The whole decline amounted to 14.29%. The reprocessing cycle has had a greater impact on the impact strength of PPNC than on its effect on the hardness of PPNC. However, in comparison to PPNC, plain PP exhibits superior hardness and impact strength. Thus, PP proved to be a superior choice for reprocessing material in comparison to PPNC.

1. Introduction

The study investigates the impact of reprocessing cycles on the mechanical properties of polypropylene-nanoclay nanocomposites. Nanocomposites have exceptional barrier properties for both flexible and rigid food packaging [1]. The material is suitable for food packaging and possesses distinctive characteristics that enable it to be utilised in various manufacturing processes. Utilise the process of recycling polypropylene nonwoven fabric composite (PPNC) in order to manufacture more products.

This research commences with the exploration of injection moulding and PPNC. Injection moulding is utilised to produce test samples due to its high efficiency. This optimises efficiency and streamlines the process of PPNC reprocessing. Samples are evaluated for impact strength and hardness. The process of pulverising the product into pellets for subsequent reprocessing is carried out. This occurs on four occasions.

This study investigates the impact of reprocessing cycles on the mechanical properties of PPNC. The PPNC undergoes four rounds of reprocessing to evaluate the decrease in hardness and impact strength and study the effects. The examination assesses the recyclability of PPNC for future use in a new product. Alternatively, pristine polypropylene (PP) is recycled as PPNC. This analysis examines the test findings of these two materials.

2. Literature Review

2.1 Injection Moulding

The injection moulding method forces molten plastic into a mould cavity. This method works with many materials, including metals. From microscopic to large items, it is employed in manufacturing.

In modern manufacturing, this procedure is utilised to make plastic parts. Since this procedure is now called plastic injection, it produces a wide range of plastic items with different sizes, complexities, and uses. The method has many drug development benefits. Eliminating water or other solvents reduces production costs, allows continuous manufacturing, scales, and increases patentability.

The technology also allows for varied design and composition of moulded objects and the production of solid molecular dispersions or solutions of the active ingredient, which have technological and biopharmaceutical benefits [2]. An injection moulding machine melts and injects plastic into a mould. The final product is made when the plastic cools and hardens in the mould. The plastic component can be removed after cooling. The injection moulding process takes two seconds to two minutes [3].

An injection moulding machine, raw plastic, and a mould are needed. The injection and clamping units make up the injection moulding machine. The injection device has plastic granules, a hopper, a reciprocating screw, and a heater [4]. The clamping unit stage of injection moulding includes the mould cavity and mould, as shown in Figure 1.

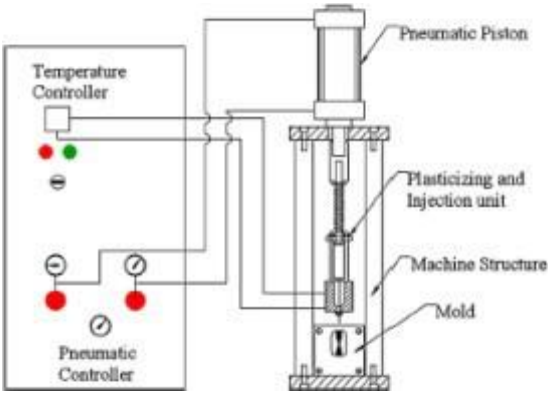

Fig. 1 *Vertical Injection Molding Schematic Diagram [5]*

There are two ways to secure the mould: vertical and horizontal. Horizontal injection moulding is more automated than vertical; hence, most injection moulding industries use it. Basic process control streamlines horizontal machine injection. The moulded part easily detaches when it falls into the container below the machine [6]. The vertical method uses insert moulding. The mould core receives inserts [7]. Additionally, injection moulding machines might be hydraulic, electric, or hybrid. Manual injection uses force to inject resin. However, this method is rarely used due to its inconvenience. RAM is used in hydraulic injection devices. Moulders value the clamping mechanism of the machine. A motor powers the electric injection machine. Energy is only used when closing and opening the clamping unit. The product is faster, quieter, and more precise, but it costs more. Due to development, hybrid injection machines are underutilised [8].

2.1.1 Polypropylene

Polypropylene (PP) is a thermoplastic polymer made from propylene monomers [9]. Many injection moulding applications use synthetic resin [10]. The material can be CNC-milled, injected, thermoformed, or crimped to create a living hinge. Polypropylene may easily produce composite plastics with polyethylene [11]. Polypropylene has a lower tensile yield strength than other injection moulding materials. The tensile yield strength is 35 MPa. Additionally, polypropylene has 180 MPa flexural strength. Polypropylene has 1450 MPa flexural modulus and 32 J/m Izod impact strength. Polypropylene has 102°C heat deflection under load. Polypropylene has a low density of 0.895–0.92 g/cm.

Polypropylene's amazing mechanical qualities are famous among researchers. The reprocessing cycle of polypropylene and the mechanical characteristics of plain polypropylene and polypropylene nano clay after the cycle have been studied extensively. Reprocessing caused different stabilisation concerns than typical stabilisation methods. The reprocessing process handles materials of diverse sources and stability.

For unstabilized polymers, recycling studies are necessary to establish a stability baseline. Studies have shown that thermal reprocessing nanocomposites does not affect their stiffness or crystallisation behaviour. Even after recycling, polypropylene nanoclay exhibits better rheological and mechanical properties than the pure matrix

Packaging consumes about 30% of polypropylene, followed by electrical and equipment production at 13% each. Household appliances and autos make up 10% of the market, while construction materials make up 5%. Food containers made of polypropylene are safe since it doesn't leech chemicals. Home goods, vehicle parts, and marine equipment use polypropylene [12].

2.1.2 Polypropylene-nanoclay nanocomposites

Their high modulus, strength, heat resistance, gas permeability, and flammability make polypropylene-nanoclay (PPNC) nanocomposites appealing [13]. New composites include nanocomposites. PPNC has better mechanical and material qualities than the original polymer, according to studies. Modulus, strength, and heat resistance have improved [14]. The lighter weight of PPNC makes it cheaper than other composites [15]. Raising nanoclay content from 0 to 5 wt.% has boosted PPCN tensile strength. As the clay concentration exceeded 5wt.%, the trend became less effective.

Nanoclay greatly affects polypropylene's plastic and elastic deformation behaviour at the investigated temperatures. Almost all PPCN formulations improve moduli [16]. Improved polypropylene contact transfers stress from the polymer matrix to the inorganic filler. Tensile characteristics improve [17]. Thermal stability is improved by adding clay to polymers. Clay can effectively insulate and block volatile decomposition byproducts [18].

The compatibilizer maleic anhydride-grafted-polypropylene (PP-g-MA) improves PP matrix-organoclay compatibility. The grafting has 1wt.% maleic anhydride. According to ASTM D 1238, the compatibilizer has an average molecular weight (Mn) of 25,000 g/mol, a melt flow index of 150 g/10 min (230 °C, 2.16 kg), and a melting temperature of 167 °C [19].

Organophilic clay nanofiller Cloisite 15A was frequently used in a polymer nanoclay system. It strengthens, flame-resists, and protects polymers and rubber. The manufacturer recommended surface-treating nanoclay before mixing it with hydrophobic polymers like polypropylene. Cloisite 15 A has a specific gravity of 1.66 g/cc. Modified montmorillonite (OMMT) Cloisite 15 A contains dimethyl dihydrogenated tallow (2M2HT). Its C.E.C. is 125 meq.100 g-1 and it contains 65% C18, 30% C16, and 5% C14 [20].

Recent studies found compatibilizer functionality and organic adjustability. Tensile characteristics can improve with suitable compatibilizers. The PPNC and targeted organic nanoclay alteration were treated with the right compatibilizers [21]. Thus, the current study examines clay classification, amount, chemical properties, and compatibilizer use. For compatibilized nanocomposite types, clay tactoids aligned positively with extrusion shear rate. Shear rate does not affect clay particle alignment in uncompatible hybrid tapes [22].

Maleic anhydride grafted polypropylene (PP-g-MA) was used to compatibilize the clay, improving its dissolubility. Also important for tensile and flexural properties is clay [16]. Utilising PPNC with nanoclay C-15A, which has a high Cation Exchange Capacity (CEC), improved its impact quality. Nanoclay C-20A, which has a low CEC, increases PPNC flexural modulus [23]. A 1:1 C-15A/C-20A mixture increases flexural modulus by 12% and impact strength by fivefold [24]. Stress rises with nanoclay concentration. Strain affects start-up overshoot and relaxation slowdown. A critical nanoclay concentration is assured when the mean activation energy for chain rearrangement and its standard deviation is lowest [25].

Their high aspect ratio, around 100 to 500 for montmorillonite, creates a complicated path for materials through the composite and improves packaging barrier properties [17]. Even with little filler, a new method improved plastics and composites. This is easy with melt intercalation, extrusion, or injection moulding. Increased nanoclay concentration increases moisture absorption and maximum moisture content due to its hydrophilic characteristics and compatibilizing agent. The main aim is restoring tissues damaged by sickness, accidents, or other artificial means [26].

2.1.3 Reprocessing Cycle of Polypropylene

The researchers directly melted 5 wt.% Cloisite 15A and 20 wt.% maleic anhydride-grafted-polypropylene (PP-g-MA) in an internal mixer to make polypropylene-nanoclay nanocomposites. 4 reprocessing cycles were performed on these nanocomposites. WAXS, TEM, and rheological quantification characterise the nanocomposite structure and clay dispersion. In addition to FT-IR, tensile tests, DSC, and TGA have been used to assess reprocessing-induced quality changes [18].

All samples showed a decrease in complex viscosity. This shows that molecular weight reduction was the main effect of reprocessing. After the first cycle, the nanocomposites' thermal and mechanical characteristics dropped significantly. These properties remained mostly unchanged after reprocessing. As reprocessing increased, 40 wt% fibre composites lost flexural strength and modulus. Compared to the original composites, eight cycles of reprocessing reduced the material's tensile stress by 11%. Reprocessing initially increased Young's Modulus but then decreased [28].

Young's Modulus was higher in virgin composites with 50 wt.% fibre than 40 wt.%. Thermal stability was improved by reprocessing. Extrusion moulding using virgin polypropylene and 1:1 blends of virgin and post-consumer polypropylene is studied for 13 processing cycles. This formulation contains Recyclostab 411, an antioxidant. The main effect of recycling polypropylene is chain scission breakdown and molar mass loss. Melt flow rate and crystallinity increase during deterioration. Thermo-oxidative stability decreases with antioxidant depletion and material instability over processing cycles. Oxidative induction time measurements also identified it. Antioxidants prevented degradation and maintained stability [29].

Ultimately, these composites demonstrate great potential for both industrial packaging and medical tissue restoration, provided that the nanoclay concentration and reprocessing history are carefully controlled to prevent catastrophic loss of mechanical integrity.

3. Methodology

Figure 2 depicts a flow chart outlining the comprehensive technique employed in this investigation.

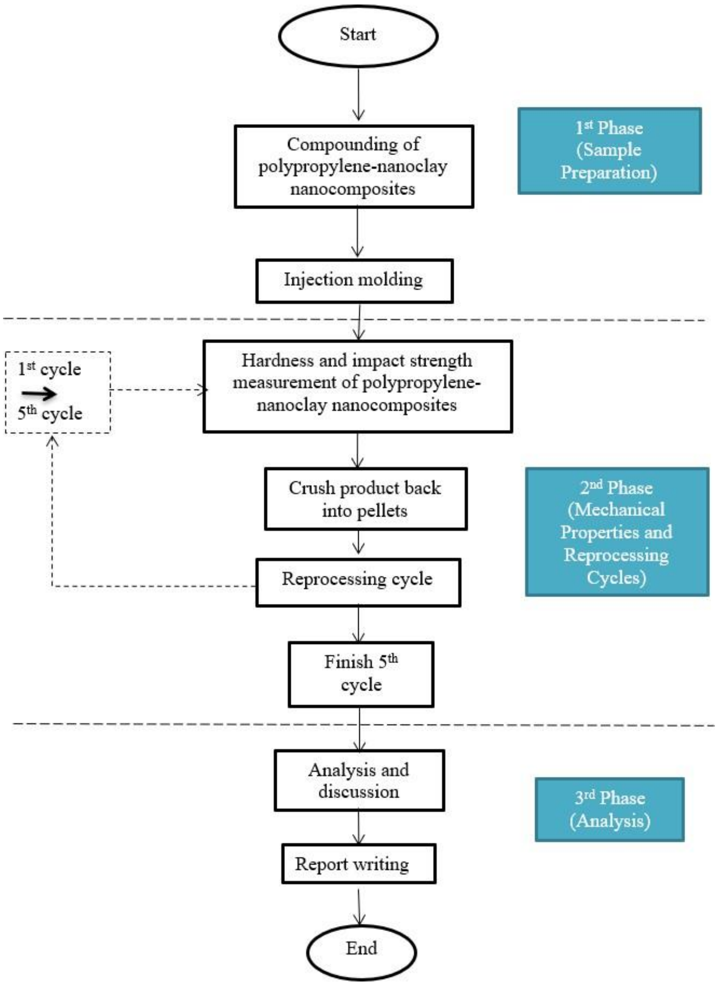

Fig 2 *Flow Chart of Methodology*

3.1 Sample Preparation

The initial step of the process was sample preparation. During this phase, the PPNC and PP compounding technique was combined with the injection molding process to produce the PPNC and PP specimens. This phase focused on the establishment of the experiment.

3.1.1 Injection Molding

MCP 100 KSA vertical injection moulding machine from UTHM Centre for Graduate Studies was utilized. Figure 3 displays the MCP 100 KSA vertical injection moulder.

Fig 3 *MCP 100 KSA Vertical Injection Molding Machine*

Injection moulding required 1960 Bar machine injection pressure. The process took under 2 minutes and had a 200 mm/s injection velocity. The mould temperature of PPNC was 20–80 degrees Celsius, whereas the melting temperature was 220–280 degrees Celsius. The mould cavity resembled a dog bone bar. Figure 4 shows the injection-molded specimens. The specimens measured 7.3 cm long, 1.3 cm wide, and 0.2 cm high.

Fig 4 *A Dog Bone Bar Specimen*

3.2 Hardness and Impact Strength Measurement of PPNC and PP

PPNC and PP hardness after multiple reprocessing cycles was measured using a Shore Instrument Type D2240 Instron Durometer tester. Figure 5 shows Shore Instrument Type D2240 Instron Durometer. ASTM-D 2240 methods were followed to test hardness using the Shore hardness test. The specimen had a level surface for shore hardness testing. Hardness was calculated from the indicating pointer. The hardness, or indentation depth, was determined after constant force was applied to the device. For more accurate measurements, three spots on the object were measured.

Fig 5 *Shore Instrument Type D2240 Instron Durometer*

PPNC's impact strength after reprocessing was also measured using Universal Testing Machine showing in Figure 6. A tensile test is a mechanical testing method used to evaluate the behaviour of materials under uniaxial tensile stress. This test helps determine various properties of the material, such as its tensile strength, yield strength, elongation, and modulus of elasticity. During the test, a specimen is subjected to a controlled tensile force until it fractures, and the stress-strain data is recorded and analysed.

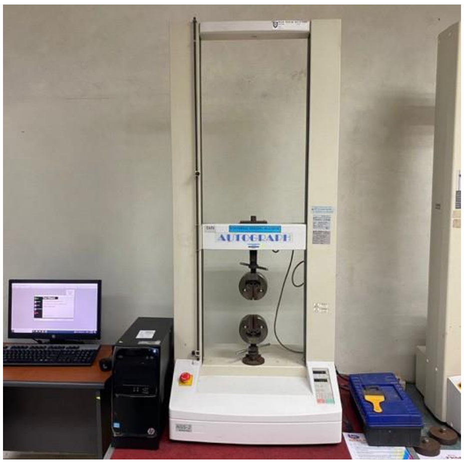

Fig 6 *Universal Testing Machine*

3.3 Sample crushing into pellets

After PPNC mechanical property analysis, the samples were crushed into pellets for reprocessing. This technique used a WSGI high-speed plastic granulator. WSGI technology powers a high-speed plastic granulator in Figure 7. This machine can crush 200–250 kg/h. Therefore, the equipment pulverized materials in under 5 minutes.

Figure 7 *WSGI High-Speed Plastic Granulator Machine*

4. Results and Discussion

This section focused on analyzing the gathered data and presenting the outcomes of experimental testing, specifically regarding the hardness and impact strength of polypropylene-nano clay nanocomposites (PPNC) and pure polypropylene (PP). The influence of the reprocessing cycle of PPNC on its mechanical characteristics is shown at the end of this chapter. Moreover, the selection of the optimal material for recycling, specifically between PPNC and PP, was determined.

4.1 Shore Test

To seek out how the reprocessing cycle affects the hardness of plain PP and PPNC, a shore hardness test was conducted. After each round of reprocessing, this test was conducted. The average hardness test results for plain PP and PPNC following each cycle are displayed in Table 1. It is evident from the data that following each cycle, the hardness values for both materials dropped.

In addition, despite the slight difference, it can be observed that neat PP has a greater hardness number than PPNC. Out of all the reprocessing cycle results, the first cycle for both materials produced the best results. The results of the first reprocessing cycle of neat PP produced the highest hardness number, 76 shore, while the fourth reprocessing cycle of PPNC produced the lowest hardness value, 69 shore.

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Table 1 *Hardness Number of PPNC and PP After Each Cycle*

Material	Hardness Number (Shore)			
	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Polypropylene-nanoclay Nanocomposites (PPNC)	75	73	71	69
Polypropylene (PP)	76	75	74	71

4.2 Tensile strength test

Tensile testing has been done to analyse strength of specimens after each reprocessing cycle. After the test has been done, maximum stress data for each cycle was obtained. The table for average maximum stress data is shown in Table 2. Data shows that the maximum stress of PPNC decreased in the four-reprocessing cycle. The data for first cycle was 28.23 N/mm^2 and it decreased to 4.12 N/mm^2 for second cycle. It then decreased to 0.53 N/mm^2 in the third cycle and decreased more to 1.99 N/mm^2 in the fourth cycle.

Meanwhile, for neat PP, the test data decreased steadily after being reprocessed. It can be seen from the table that the test data decreased steadily from 30.49 N/mm^2 to 27.55 N/mm^2 from first reprocessing cycle to second reprocessing cycle. Data then decreased more to 1.26 N/mm^2 in third reprocessing cycle and 1.8 N/mm^2 in fourth reprocessing cycle. Based on the table, it is also clear that PP has higher impact strength than PPNC. For both materials, the impact strength for the first reprocessing cycle was the highest among the other reprocessing cycle. The highest impact strength result obtained was 30.49 N/mm^2 which was the impact strength result for the first reprocessing cycle of neat PP. The lowest impact strength result obtained was 21.59 N/mm^2 which was the result for fourth reprocessing cycle of PPNC.

Table 2 *Maximum Stress of PPNC and PP after each cycle*

Material	Maximum Stress (N/mm^2)			
	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Polypropylene-nanoclay Nanocomposites (PPNC)	28.23	24.11	23.58	21.59
Polypropylene (PP)	30.49	27.55	26.29	24.49

5.0 Conclusion

As a result, test samples of polypropylene-nanoclay nanocomposites (PPNC) have been effectively fabricated using the injection moulding procedure. In addition, the mechanical properties of PPNC have been tested during every reprocessing cycle. Both PPNC and PP have undergone Shore hardness and Tensile strength tests. The hardness and impact strength findings obtained from the first reprocessing cycle were the highest compared to the results from the subsequent reprocessing cycles. The maximum hardness value achieved was 76 shore, observed during the initial reprocessing cycle of pure polypropylene (PP). Conversely, the minimum hardness value recorded was 69 shore, observed during the fourth reprocessing cycle of polypropylene nanocomposite (PPNC). The maximum stress achieved was 30.49 N/mm^2 which was seen during the first reprocessing cycle of pure polypropylene (PP). On the other hand, the minimum stress recorded was 21.59 N/mm^2, which occurred during the fourth reprocessing cycle of polypropylene nanocomposite (PPNC). According to the test results, PP has a greater hardness number and impact strength compared to PPNC. Thus, PP proved to be a superior choice for reprocessing material when compared to PPNC.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Mohd Hilmi bin Othman;* ***data collection:*** *Muhammad Fakhrullah bin Nadzi;* ***analysis and interpretation of results:*** *Muhammad Fakhrullah bin Nadzi, Mohd Hilmi bin Othman;* ***draft manuscript preparation:*** *Muhammad Fakhrullah bin Nadzi. All authors reviewed the results and approved the final version of the manuscript.*

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