

New Approach to Predict Mechanical and Tribological Behaviour Through Rheological Properties of Polypropylene Composites

Nizar Jawad Hadi¹, Ammar Al-kawaz²

Faculty of Materials Engineering /Dept. of Polymer and Petrochemical Industries University of Babylon /Iraq
e-mail: nizarjawad63@uobabylon.edu.iq,
mat.ammar.emad@uobabylon.edu.iq

Ahmed Fadhil Hamza³, Dhey Jawad Mohamed⁴

Faculty of Materials Engineering /Dept. of Polymer and Petrochemical Industries University of Babylon /Iraq
e-mail: ahmedfadhil81@gmail.com, dy.jawad@gmail.com

Abstract—Polypropylene is an adaptable polymer since its properties can be changed to meet particular issues. The effect of mineral fillers (CaCO_3 and wollastonite) with a distinction in the size on the rheological, mechanical and tribological properties of polypropylene (PP) have been examined. Variety concentrations of CaCO_3 and wollastonite are blended with polypropylene utilizing the velocity of the twin-screw extruder was 25 rpm and 190°C. Shear viscosity, shear stress and shear thinning effect were tested using SR20 Single pore Capillary rheometer. Tensile strength, elastic modulus, impact resistance, hardness, and coefficient of friction were examined. Likewise, surface topography wear track and surface morphology were examined utilizing AFM and light microscopy. The rheological result shows that both composites melt exhibited the shear-thinning effect. The PP/ CaCO_3 melt possess higher shear thinning effect than PP/Wollastonite melt. The reduction in viscosity and critical shear stress were observed for high wollastonite content. The outcomes demonstrated a huge upgrade in the mechanical and tribological performance for the resultant composites with increasing the concentration of both fillers especially the PP/wollastonite composites. Additionally, the results of AFM and light microscopy demonstrated that the roughness of the surface diminished with the decreasing of shear viscosity of the composites. In general, a great correlation between shear viscosities conducts with mechanical properties and surface quality for both PP composites.

Keywords-polymer nanocomposite; rheology; shear thinning tribology; mechanical properties; wollastonite and CaCO_3

I. INTRODUCTION

Rheology is an indirect study to predict the structure of the polymer. Molecular weight, molecular weight distribution, and morphology of chains are the main factors effect on the polymer structure. Shear viscosity, shear stress, shear thinning effect, pressure, temperature, additives, and polymer type where strongly related to the structural behavior and final polymer products properties. Molecular weight can be determined by using shear viscosity and molecular weight distribution obtained through analyzing of shear thinning behavior [1], [2].

Polypropylene (PP) exorbitantly utilized thermoplastics, particularly in the car, electric and bundling application because of its excellent properties, for example, good processing, heat deformation temperature over 100 °C, recycling capacity, perfect insulating properties, a small dielectric constant, good stress crack resistance and chemical

resistance [3] [4][5]. Regardless of its exquisite properties, the PP is often modified with particulate fillers such as talc, calcium carbonate, glass beads, glass fibers, mica, silica, and wollastonite [3].

Friction and wear represent critical issues in numerous applications. Polymer composites containing diverse fillers and/or reinforcements are utilized for these reasons. Inorganic particles are outstanding to upgrade the mechanical properties of polymers. It has been discovered that the size of the particles plays an essential role to improve, in particular, stiffness and toughness simultaneously[6]. Keeping in mind the end goal to enhance the mechanical and electrical properties, warm protection, radiation protection, rheological and physical, CaCO_3 at nanometric scale are blended with PP matrix [7]. Calcium carbonate (CaCO_3) is broadly utilized as an inorganic filler in the polymer because of their minimal price and accessibility [7][8].

The wear execution of the resultant composite exceptionally impacted by the bulk hardness and the physical properties of the filler material [9]. The physical, chemical and mechanical properties of a polymer are influenced by its microstructure and construction, so a detailed information of the morphology is required to understand the distortion manner of a polymer during the tribological and mechanical process[10].

Wollastonite with needle-like structure gives impressive processing and execution benefits, including enhanced hardness and quality. Wollastonite is a calcium silicate (CaSiO_3), which is utilized as an effective filler in plastics [3].

In this work, polypropylene is reinforced with two types of fillers as composite, CaCO_3 nanoparticles and microparticles of wollastonite with different weight percent using a twin-screw extruder. The capillary rheometer was used to check shear viscosity, shear stress, and shear thinning effect. These properties strongly related to the structure of the polymer and the secondary force bonding between the chains. The correlation between rheological, mechanical and tribological properties has been investigated for both of types of composites.

II. EXPERIMENTAL

A. Materials and Mixing Process

The materials used are polypropylene, Subic 575-S (MFI= 8.3 g/10 min), calcium carbonate nanoparticles

CaCO₃ 16nm and wollastonite with 7.62μm average size with acicular shape (needle-like). The temperature for mixing both types of particles with PP pellets were done by twin screw extruder (display SLJ) [screw speed is (0-320) rpm]. Firstly, different percentage of 3,5,7 and 10% particles filler were dispersed in 20ml of acetone solvent using the ultrasonic device for 30 min, and then mixed with polypropylene pellets. Finally, the mixture extruded using twin screw extruder at 190°C and 25 rpm.

B. Characterization

1) Rheology test

Capillary rheometer SR20 single pore ASTM D3835 used to test the shear viscosity and shear stress at 180°C, L/D=20, preheating=300 sec. and load=300 N. under different shear rate. Viscosity curve and flow curve were obtained for both polymer composite melts.

2) Mechanical tests

Instron 5556 universal testing machine as per ASTM D-638 IV is utilized to perform the tensile behavior, three specimens were examined and the mean value was considered. The crosshead speed was 5 mm/min with 5KN as the load applied.

In order to analyze the influence of CaCO₃ and wollastonite on impact strength of PP composites. Unnotched Charpy impact tests were performed by a pendulum ram impact testing machine using rectangular samples according to ASTM D-256 at ambient temperature. The distance between the supports was 62 mm. All specimens were impacted at an impact velocity of 2.9 m/s. For each composition, at least three samples were tested.

Hardness test was performed on the specimen with a specific end goal to clarify the effect of presence CaCO₃ nanoparticles and wollastonite microparticles on the hardness of PP composites. ASTM D-2240 standard was used for characterized each compound by taking the average value for three test for each property.

3) Wear test

Tribometer test device model MT/ MICROTTEST system was employed to characterize the tribological properties, where friction coefficient can be determined by measuring the force of friction signal by the instrumented arm (deflection of the arm that holds the pin or ball holder). According to (ASTM G99), the balls used in this work are made from steel that had hardness approximately (HV:830) with the diameter of (6 mm) and roughness 0.1 μm fixed to the upper arm using the ball holder. All samples have a diameter of 50 mm and 4mm thickness.

III. RESULTS AND DISCUSSION

A. Rheological Properties

Fig. (1) shows that the non-Newtonian flow of both composites melts exhibit shear thinning behavior, where the viscosity decreased with the shear rate increases. The shear thinning effect of PP/ calcium carbonate was higher than that for PP/ wollastonite, due to the interaction force between the reinforced particles and polymer chains.

The secondary force between polymer chains strongly affected by this interaction. The mechanical properties and surface quality can be attributed to the secondary force bonding value.

It was clear that the low shear thinning of PP/ wollastonite obtained due to the secondary bonding growth at the different level of viscosity and microstructure.

Fig. (1a), indicates that the shear thinning effect increases and the changes in viscosity decrease with the wollastonite content increasing at 5% and 7%, due to the strong interaction between chains and chains-wollastonite particles. In the other side Fig. (1b), illustrates inverse behavior where the shear thinning effect and the change in viscosity increase, with calcium carbonate content, decreasing, because of nanoparticles agglomeration.

The reduction increment in viscosity for PP/ wollastonite at all shear rates was lower than that for PP/Calcium carbonate, this may be explained the difference in shear rate resistance between both composites melts.

Fig(2) shows that the shear stress was increased in general with the shear rate increases for both composites melts, for PP/ wollastonite melt the shear stress indicate lower value at 5% and 7% than that for PP/CaCO₃ melt. This behavior predicts easy process for PP/ wollastonite, especially at these ratios where the lower shear stress exhibited. The shear stress and pressure associated with PP/ wollastonite melt was lower than that for PP/calcium carbonate melt.

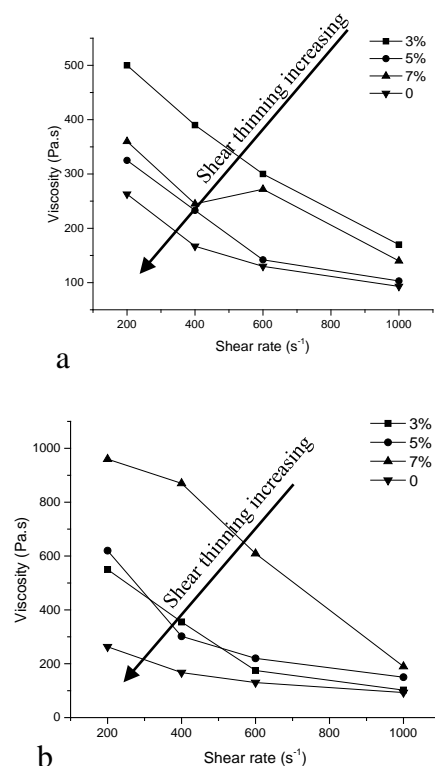


Figure 1. Viscosity behavior with the shear rate increasing at 180°C and L/D= 20 for, a) PP/ wollastonite, b) PP/ calcium carbonate.

The higher shear thinning effect with a lower change in viscosity of 5% and 7% of PP/wollastonite melt produce lower pressure and critical shear stress during extrusion process than that of PP/CaCO₃ melt.

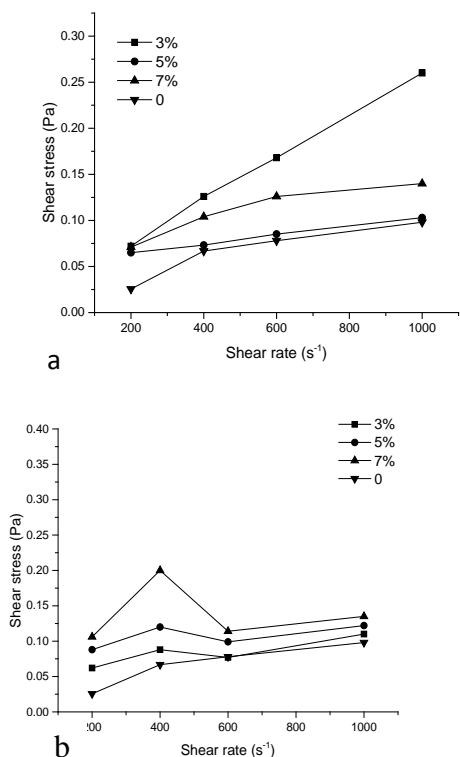


Figure 2. Shear stress behavior with the shear rate increasing at 180 Co and L/D= 20 for, a) PP/ wollastonite, b) PP/ calcium carbonate.

B. Mechanical and Surface Properties

The effect of CaCO₃ and wollastonite percentages on the elastic modulus of PP are given in Fig (3). The outcomes demonstrate that the elastic modulus progressively increased as filler content increased. Broadly, it has been observed that the wollastonite have the largest effect on the enhancing the modulus than CaCO₃.

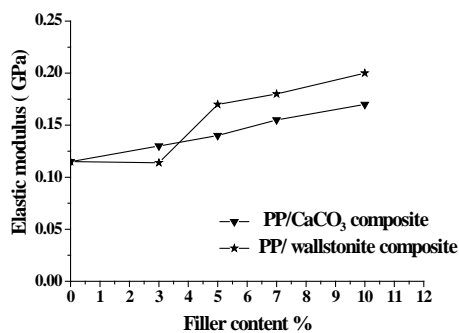


Figure 3. Elastic modulus of PP reinforced with a variety CaCO₃ Nanoparticles and wollastonite percentage.

The measuring of impact resistance for materials can be determined by evaluating the energy that absorbed by the material under load. Fig. (4) Clarified that the impact strength increased by 70% and 83% for PP/CaCO₃ and PP/wollastonite respectively.

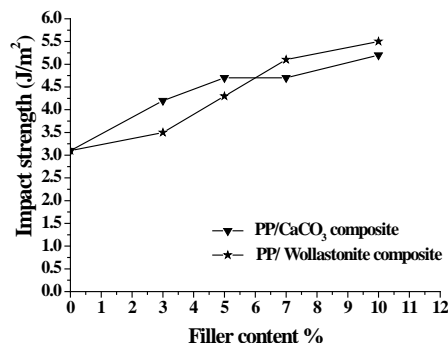


Figure 4. Impact strength behaviour for PP reinforced with different CaCO₃ nanoparticles and wollastonite percentage.

The hardness speaks to the capacity of the material to resist the local deformation. It is, therefore, the ability of a material to resist penetration by other bodies. The hardness is ordinarily tested by applying an indenter normally on a surface. Ordinarily, hardness (H) is calculated from the projected area (A) of indentation and the load P [11].

With increasing concentration of CaCO₃, the hardness of the composites was increased by 16% and wollastonite by 33% Fig. (5). It was clear that the increase in hardness of the composite that reinforced with wollastonite was a double of what it was with CaCO₃ and this due to the wollastonite's hardness and the good bonding between the polymer matrix and wollastonite's particles.

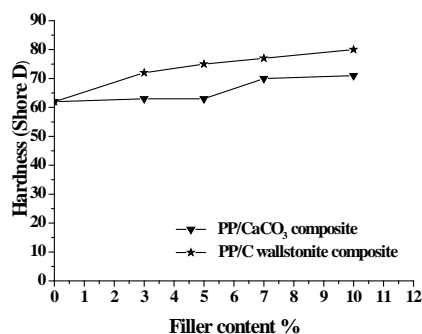


Figure 5. The hardness behaviour of PP reinforced with a variety CaCO₃ nanoparticles and wollastonite percentage.

Fig. (6) Shows the tensile strength at yield. The tensile strength of the composite was increased with increasing wollastonite weight percent due to the increasing the stiffness of the composite, while the tensile strength of the nanocomposite PP/CaCO₃ increase with increasing CaCO₃ weight percent until 5% and then decreased with increasing the concentration of CaCO₃, due to agglomerated

nanoparticles at high concentrations. This result compatible with the rheology test.

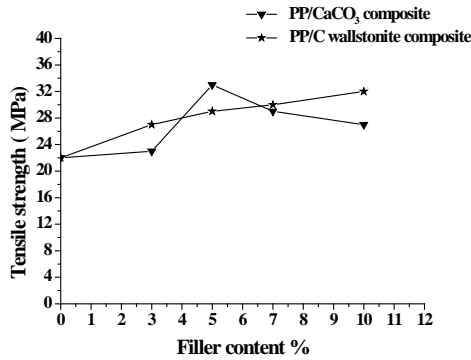


Figure 6. Tensile strength behaviour of PP reinforced with a variety CaCO₃ Nanoparticles and wollastonite percentages.

C. Sliding Wear Performance

Fig. (7) Presents the calculated friction coefficients as a function of the concentration of filler. The experimental results indicate that the friction coefficient for nanocomposites decreased with increasing of the percentage for both fillers, but each type of filler has a different mechanism in how to reduce the friction coefficient of the resulting composite.

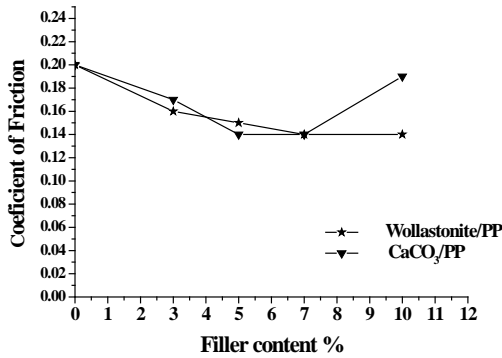


Figure 7. Friction coefficient dependence on the filler substance percentage.

The coefficient of friction can be represented by the following equation:

$$\mu = \frac{F_t}{F_n} \quad (2)$$

$$\text{And } F_t = \tau A \quad (3)$$

where μ is a coefficient of friction, F_t is a tangential force, F_n is a normal force, τ is the interfacial shear stress and A is the contact area, which is roughly inversely proportional to the hardness, in the case of PP/CaCO₃ composites the decreasing in the coefficient of friction as a results of decreasing the interfacial shear stress due to self-lubricant nature of CaCO₃filler. Regarding PP/wollastonite composition, the coefficient of friction was reduced because of decreasing the contact area due to increasing the hardness

of the resultant composite. It is worth mentioning, that the friction coefficient began to increase again at 10% weight percent of CaCO₃, and this may be due to reduced mechanical properties because of the agglomerated the nanofiller.

In order to understand the influence of the CaCO₃ and wollastonite on the friction deformation of PP, the morphologies of the worn surfaces of PP and its composites were observed by optical microscopy. The worn surfaces obtained under 30 N loads. Fig. (8a) shows that pure polypropylene exhibited a ductile cutting deformation. The worn surface of nanocomposites containing 7 % of CaCO₃, Fig. (8b) shows a slight plastic deformation, adhesion, and scuffing, while in the case of PP/wollastonite Fig. (8c), the plastic deformation is almost non-existent. This behavior due to good bonding between PP and wollastonite filler, which makes the resulting composite, stiff, and more resisted for plastic deformation. This behaviour confirm with the viscosity behaviour of PP/wollastonite melt.

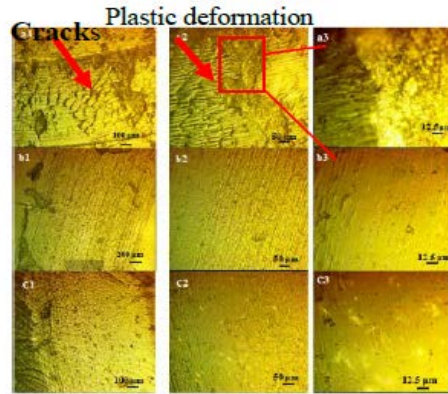


Figure 8. Optical micrograph of wear pin surface showing wear grooves parallel to the sliding direction for a) pure polypropylene b) Polypropylene/ 7% CaCO₃ nanocomposite c) Polypropylene/ 7% wollastonite.

D. Result Analysis by Surface Roughness

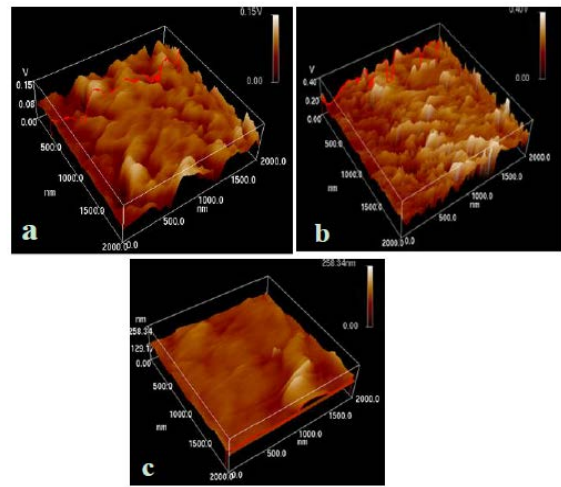


Figure 9. Surface roughness of a) pure PP, b) PP/ 7% Wollastonite composite c) PP/ 7% CaCO₃ composite using AFM.

The surface roughness of the pure polypropylene and polypropylene composites samples (7% concentration) were measured by using AFM Fig. (9). Apparent trends were observed in the performance of the different individual fillers.

The results showed that the average roughness of pure polypropylene was (24.2 nm), and composites reinforced with wollastonite and CaCO₃ have a roughness (10.9 and 0.0427 nm) respectively. This result showed that the roughness of the surface decreased with the secondary bonding between polymer chains.

IV. CONCLUSIONS

A comparative study for polypropylene reinforced with CaCO₃ nanoparticles and microparticles of wollastonite with different weight percent were performed.

The non-Newtonian flow of both composites melts exhibit shear thinning behavior, where the viscosity decreases with the shear rate increases. The shear thinning effect of PP/ calcium carbonate was higher than that for PP/ wollastonite, due to the interaction force between the reinforced particles and polymer chains. The secondary force between polymer chains strongly affected by this interaction. The mechanical properties and surface quality can be attributed to the secondary force bonding value. The 5 and 7% wollastonite content exhibited a lower reduction in viscosity and lower critical shear stress.

A significant enhancement in the mechanical properties such as hardness, elastic modulus and tensile strength for the resultant composites with increasing the percentage for both fillers. The PP/wollastonite shows a higher value than PP/CaCO₃ for elastic modulus, tensile and hardness due to the shear viscosity value and related flow properties difference between these composites. Pure polypropylene exhibited a ductile cutting deformation. The worn surface of nanocomposites (PP/CaCO₃) shows a slight plastic deformation, adhesion, and scuffing, while in the case of

PP/wollastonite, the plastic deformation is almost non-existent. PP/wollastonite was more suitable to enhance surface quality of automobile applications.

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