Flow Study of Wood Plastic Composite Through a Circular Die in an Extrusion Process

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Abstract: This paper presents a theoretical study on wood plastic composite's (WPC's) flow, based on empirical data provided by a twin screw extruder and experimental data from a rotational rheometer. Four circular extrusion dies were designed and manufactured to produce rod shaped products with various diameters (D) and length-to-diameter ratios (L/D). Also other parameters such as screw speed (N), polymer matrix type, polymer viscosity (μ) and percentage of wood content (W) were selected as the process or material factors to investigate the relationship between the flow characteristics and the above mentioned factors. Moreover, frequency sweep experiments were performed on the selected composites using rotational plate rheometer. The results from these experiments have been studied by using power law and Bingham plastic models which are believed as proper models for WPC in the literature. The results show that Bingham plastic model can explain the flow characteristics of this composite much better. Moreover, although the results of a frequency sweep test can give the required values for parameters in the Bingham plastic model, these quantities will be different with those from empirical experiments.

Keywords: Bingham plastic Model, Circular die, Extrusion, Flow, Power law Equation, Rotational rheometer, Wood plastic composite (WPC)

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1 INTRODUCTION

Wood-plastic composites (WPC) include a wide range of composites in which different polymer materials, cellulose fillers, and additives (lubricants, coupling agents, pigments, etc.) are compounded [1]. This new composite has expanded the concept of wood products from particle-board and medium density fiber board (MDF) into a new category of products having superior performances [2]. While wood particles have been used in plastics to make composites since last century, it was not until recent decades that special attention have been attracted to these new materials [3]. Capability of using traditional and common processing techniques in WPC production and recycling them at the end of their life time is of the main reasons for this attraction [4]. WPC materials are made by compounding plastic and cellulose fibers with additives and manufactured using a high volume process such as extrusion or compression or injection molding. Plastic, in this context, usually is chosen from industrial thermoplastics such as polyethylene, polypropylene, and polyvinyl chloride [1], [5-7].

Natural fibers have recently become attractive to researchers, engineers and scientists as an alternative reinforcement for fiber reinforced polymer (FRP) composites. Low cost, low density, non-irritative to skin, reduced energy consumption, less health risk, renewability, recyclability and bio-degradability are the advantages of using natural fibers instead of glass and carbon fibers in the composites [8]. Wood particles are typically in the form of milled wood products or particles of waste lumber, bleached cellulose fiber or natural fiber of different grades and origins [1], [5-7]. There are many factors such as polymer matrix, volume fraction, size and shape of fillers, interaction between polymer matrix and filler particles that affect the mechanical and rheological properties of the resulted composite [9] which is valid for WPC as an example of a filled polymer system. Optimizing the process condition of WPCs for the purpose of reducing production cost is one of the major challenges in this industry.

In commercial products, WPCs are produced with relatively high contents of wood, e.g. about 50 and 60 wt%, which is close to its maximum packing content [10]. Such volume fractions of fillers are much higher than that of the inorganic fillers. The main reason is the lower cost of wood that provides the capacity to formulate a cost-effective composite with a higher content of the fillers [11]. The extrusion process of WPCs requires proper knowledge of the flow behaviour especially when they are highly filled. As there is possibility of using various components in WPCs, such as various polymer types and grades and especially various types of woods (species and sizes) and also additives, there exists a wide area of research topics for research and development, both scientifically and industrially so extensive. Works have been carried out to report the effect of wood component on the final properties and rheological behaviour of WPCs [4], [5], [12-18].

A review of literatures shows that the reported rheology studies on the highly filled wood plastic composites are rare. The current works have aimed at understanding the influence of fillers on the composite flow properties. Due to the low contents of wood in the studied composites, little basis is provided for applying their data into commercial process of WPC [10]. There is no clear theoretical basis for the melt flow behaviour of WPCs. Based on the above mentioned conditions, this study in continue of the previous works conducted by the author aimed to investigate the rheological behaviour of the wood plastic composites [13], [14]. Most of research works has been done under laboratory conditions using capillary and rotational rheometers [10], [11], [19-21] and so the main purpose of the current work is to investigate the flow of the WPC's melt in a real extrusion process.

In the way of modelling and analysing the WPC flow behaviour; there is a need to measure the throughput of the extruder versus pressure in empirical or shear stress versus shear rate in rheological experiments. For doing this, it has been tried to assess the rheological behaviour of the WPC in a real production process with a twin screw extruder by conducting an acceptable number of experiments in different conditions. In continue; as it is not possible to examine this composite under the unidirectional shear condition based on previous studies by authors [22] (due to melt breakage or slippage of material between plates) in a rotational rheometer to directly attain the required results, the composites have been studied under oscillatory shear condition same as other research works [11], [14], [20], [23]. At the end, results from the rotational rheometer and the real flow condition in an extruder die have been compared. It shows that although the results of a frequency sweep test by using a rotational rheometer simply can give the required values of parameters in the Bingham plastic model, but these quantities will be different with the empirical experiments results. Moreover, using Mooney techniques for calculating the slip velocity of composite on the wall, which has been reported in some previous works [20], [21], [24], has been assessed in real extrusion process.

2 EXPERIMENTATION

MATERIALS:

Polymers: As it is mentioned, the main polymers commonly used for producing WPC are polypropylene

(PP) and high density polyethylene (HDPE). In this research work, these two types of commercial polymer were selected. Furthermore for inspecting the role of viscosity, two grades of PP were chosen. The characteristics of the experimental polymers used as the matrix are listed in Table 1.

Table 1 Characteristics of different polymer matrices used in the study

Polymer Matrix	Grade	Producer	MFI (g/10 min)
HDPE	ID5620EA	Arak Petrochemical Company	20 (190°C, 2.16 kg)
PP	Moplen Z30S	Arak Petrochemical Company	25 (230°C, 2.16 kg)
PP	Moplen EPD60R	Marun Petrochemical Company	0.35 (230°C, 2.16 kg)

Wood: Wood flour was prepared of Russian fir trees supplied by the local sources and were sieved to obtain particle sizes below 841μm (mesh size< 20). The particle size distribution of the wood flours was measured via seven standard meshing sieves. The standard mesh numbers of these sieves were 20, 30, 40, 50, 60, 80 and 100. By measuring the weight ratio at each level and converting the standard mesh numbers to mesh sizes in micron, the final size distribution was obtained which is given in
Fig. 1. Each column in this diagram shows the weight fraction (in percentage) of each mesh size. Wood flours was dried in a hopper drier at 85°C for 24 hours prior to processing, to minimize moisture content and to avoid porous structure which may result in a low strength product.

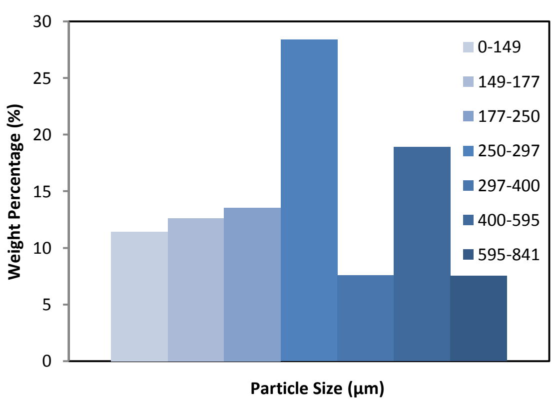

Fig. 1 Particle size distribution of wood

The formulated composites in the experiments are given in Table 2. In order to achieve an accurate composition, two computer-controlled feeders were employed; one for feeding polymer and another one for feeding wood flour.

Table 2 Formulation of different WPC Composites in the study

Composite Code	Polymer (wt%)	Wood (wt%)
HDPE5620-W50	50	50
HDPE5620-W60	40	60
HDPE5620-W70	30	70
PPZ30S-W50	50	50
PPZ30S-W60	40	60
PPZ30S-W70	30	70
PPD60R-W50	50	50
PPD60R-W60	40	60
PPD60R-W70	30	70

EQUIPMENTS:

Extruder: To produce WPC profiles, a laboratory made counter-rotating twin screw extruder was utilized with a screw diameter of 62.5 mm and L/D ratio of 22.4. This extruder was specially designed and manufactured for WPC production with enhanced mixing elements. The barrel consists of four heating zones and also a vent to exhaust the excessive water vapour and other gasses that may be produced during process via any probable decomposition of the wood component. Dies: Four circular extrusion dies were designed to investigate the effect of die dimensions on the quality of final produced profiles. The two principle parameters were selected as: die diameter (D) and die land length-to-diameter ratio (L/D). Fig. 2 and Table 3 illustrate the dimensional characteristics of these dies. Band heaters were used to heat the dies.

Table 3 Dimensional characteristics of different dies utilized in the study

Die Number	D (mm)	L (mm)	L/D (mm)
1	10	50	5
2	10	100	10
3	20	100	5
4	20	200	10

Sensors: As shown in Fig. 2, the temperatures and pressures were simultaneously measured at four locations. The pressure sensors were piezoelectric type, purchased form Sand Company, Model PT131, capable of being connected to a PC using RS232 serial port. The pressure and temperature data could be displayed and saved online in a PC.

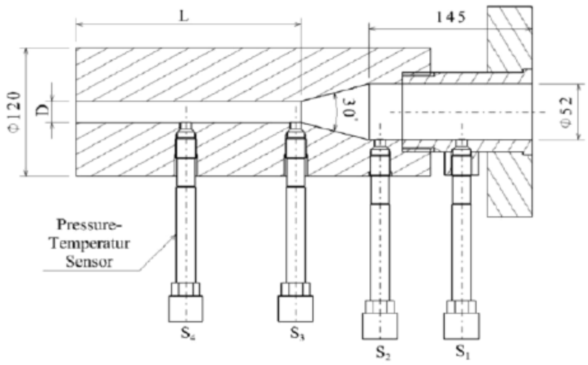

Fig. 2 Schematic picture of the utilized extrusion dies showing the locations of the temperature-pressure sensors (dimensions are in mm)

Rheometer: Rheological measurements were performed on a rotational rheometer, TA Instrument-ARES with parallel plates of 25 mm in diameter. TA Orchestrator software has been utilized in order to plot and analyse the obtained data from the equipment. The maximum shear rate or oscillation frequency level of this instrument was 79.43 Hz (500 rad/s).

3 DESIGN OF EXPERIMENTS

In order to study the effects of material and process parameters on the rheological behaviour of the composite in different conditions, two separate series of experiments were designed; first series for composites with PP as the polymer matrix and the other for those with HDPE. For the case of wood-PP composites there were five variables selected in the experiments: wood content (wt.%), polymer MFI, screw speed, die diameter, length-to-diameter ratio of the die land. For the case of HDPE, one grade of polymer was selected and thus there were four variables for the experiments. The method in designing experiments was full factorial; because it could cover all possibilities that can occur. Considering the levels of each parameter, 72 experiments were designed for wood-PP composites and 36 experiments for HDPE. Table 4 shows the details of the design of experiments for each material. It must be mentioned that the limits of the processing parameters were selected by carrying some primary experiments. For example, in selecting the proper screw speed, above a certain speed, the control of the throughput was too difficult and resulted in a product with poor quality while on the other hand a low speed was not economically viable. Also the processing temperature of 155°C and 175°C were chosen for HDPE and PP matrices respectively.

Table 4 Design of experiments' detailed information

Parameters	Wood-PP	Wood-HDPE
Wood Content wt(%)	50, 60, 70	50, 60, 70
Polymer MFI (gr/10min)	0.35, 25	20
Screw Speed RPM(rpm)	5, 15, 25	5, 15, 25
Die Diameter D(mm)	10, 20	10, 20
Die Land Ratio L/D	5, 10	5, 10
Total Experiments:	$3^2\times2^3=72$	$3^2\times2^2=36$

Frequency sweep is a custom experiment among the rotational rheometry tests and that is the observation of the material response to the increasing frequency (rate of sinusoidal deformation) at a constant strain and temperature. Finding the Linear Viscoelastic Region (LVR) was carried out in the earlier tests [25] and according to this knowledge strain of 0.1 was chosen for the frequency sweep tests to make sure that the composite is in its LVR. In this set of tests, the frequency was set to change between 0.1 and 79.43 Hz (0.63 and 500 rad/s). By using full factorial method for design of experiments, 6 experiments for polypropylene matrix and 3 experiments for Polyethylene matrix were conducted on the WPCs.

Table 5 Details of experimental design for frequency sweep tests (Polypropylene matrix)

Parameters	Number of levels	Lower level	Mid	Upper level
Wood Content	3	50	60	70
Polypropylene MFI (gr/10 min)	2	0.35	-	25
Total Experiments:		3 × 2 = 6		

Table 6 Details of experimental design for frequency sweep tests (Polyethylene matrix)

Parameters	Number of levels	Lower level	Mid	Upper level
Wood Content	3	50	60	70
Polyethylene MFI (gr/10 min)	1	20	-	-
Total Experiments:		3		

Table 5 and Table 6 show the details of the design of experiments for frequency sweep tests for each of these matrices respectively.

4 THEORY

In the way of studying flow behaviour of wood plastic composite, there are two points which should be considered carefully. The first one is the slip or non-slip condition of the flow on the die wall for which there are different reports in literature. The second one is finding the most proper constitutive equation for explaining the flow behaviour. The required theories for these issues are discussed in this section. Capillary rheometer normally calculates the apparent shear rate ($\dot{\gamma}_a$) from the volumetric flow rate and die diameter. Utilizing some dies with different diameters give several sets of data which can be used for a slip correction. This is called Mooney technique for calculating slip velocity on the die wall which is shown as Eq. (1) [24]:

$$\dot{\gamma}_a = \dot{\gamma}_T + \frac{4V_s}{R} \quad (1)$$

In which V_s is the slip velocity on the die wall and R is the radius. It is obvious that plotting apparent shear rate ($\dot{\gamma}_a$) against 1/R will give true shear rate ($\dot{\gamma}_T$) and the slope is 4Vs. It is clear that both of these quantities should be positive. Power law has been used as a noticeable equation in explaining WPC flow behaviour [1], [13], [26-28] till now. The general form of its equations for a flow through a pipe can be shown as follow [29]:

$$\tau_{rz} = m\left(-\frac{dv_z}{dr}\right)^n \quad (2)$$

$$Q = \pi\left(\frac{n}{3n+1}\right)\left(\frac{-\Delta P}{2ml}\right)^{\frac{1}{n}} R^{\frac{3n+1}{n}} \quad (3)$$

$$V_z = \left(\frac{n}{n+1}\right)\left(\frac{-\Delta P}{mL}.\frac{R}{2}\right)^{1/n} R\left\{1-\left(\frac{r}{R}\right)^{(n+1)/n}\right\} \quad (4)$$

Eq. (2) to Eq. (4) show the constitutive equation, volumetric flow rate and velocity distribution of a flow in a pipe using power law model, respectively [29]. It has been reported that by increasing the wood content in WPC, the power law index (n) decreases and consistency index (m) increases [28] and the velocity profile shape get close to a plug like flow. Fig. 3 shows the velocity profiles based on different values of n for power law index.
To check availability and make sure about this result for wood plastic composite, some theoretical works had been done by author on some rheometry experiment results with different methods which confirms this report [13]. It means more wood content in the composite will result in lower value for the power law index and higher quantities for consistency index. Although it has also been reported in some research works that by increasing the solid concentration, the power law index falls progressively while the consistency index increases exponentially; it can also be suggested to characterize the flow behaviour by Bingham plastic model with the yield stress and the plastic viscosity which increases with increasing solid concentration [30].

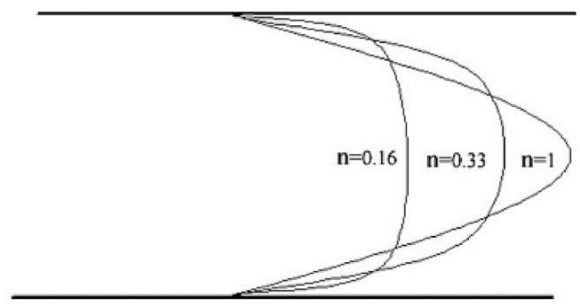

Fig. 3 Velocity profiles for melts with different power law indexes [28]

As it can be seen, in the velocity profile of the composite with higher contents of wood (with lower value for n), the center section will have almost a flat part for which suggesting the Bingham plastic model as the constitutive equation seems completely acceptable. There are also a few researches which suggest this model for WPC [19], [26].

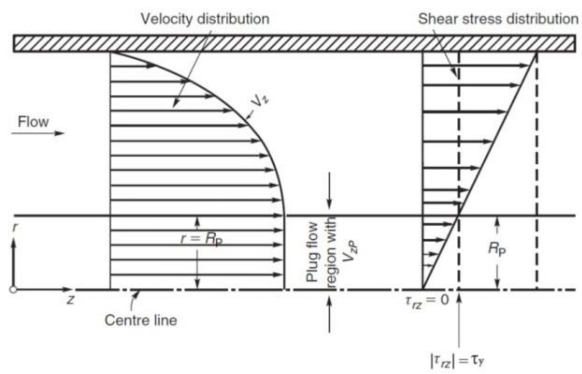

Fig. 4 Schematic velocity distribution for laminar flow of a Bingham plastic fluid in a pipe [29]

Fig. 4 shows the velocity profile and the basic concepts of Bingham plastic. In this theory, a yield stress (τ_y) will be assigned to the fluid and if the applied stress exceeds this critical value; the fluid will start to flow. As it has been mentioned in the picture, there is a plug flow in the center part in which the applied stress is less than τ_y and over this part; the stress will increase up to its maximum value at the wall (τ_w). The radius of the plug, R_p, will depend on the magnitude of the yield and shear stress on the wall as follow [29]:

$$\frac{\tau_y}{\tau_w} = \frac{R_P}{R} \quad (5)$$

Where τ_w is the shear stress at the wall of the pipe.
In annular area, $R_p < r < R$, the shear stress will be expressed by the following equation [29]:

$$\tau_{rz} = \tau_y + \mu[-\frac{dv_z}{dr}] \quad (6)$$

By doing some calculations and simplifications, one can show that the volumetric flow rate will be as follow [29]:

$$Q = \frac{\pi R^4}{8\mu}\left[\frac{-\Delta P}{L}\right]\left[1 - \frac{4}{3}\varphi + \frac{1}{3}\varphi^4\right] \quad (7)$$

Where $\varphi = \frac{\tau_y}{\tau_w}$.
Writing the force balance in a circular channel will result to the following equation for the shear stress on the wall of the pipe [30]:

$$\tau_w = \frac{R}{2}\left(\frac{-d\,P}{d\,z}\right) \quad (8)$$

Rewriting Eq. (7) by substituting φ with its equivalent amount and using Eq. (8) will give the following equation for volumetric flow rate:

$$Q = \frac{\pi R^4}{8\mu}\left[\frac{-\Delta P}{L}\right] - \frac{\pi R^3}{3\mu}\tau_y + \frac{2\pi}{3\mu}\frac{\tau_y{}^4}{\left[\frac{-\Delta P}{L}\right]^3} \quad (9)$$

By neglecting the third term in Eq. (9) because of its small value, it can be reduced to:

$$Q = \frac{\pi R^4}{8\mu}\left[\frac{-\Delta P}{L}\right] - \frac{\pi R^3}{3\mu}\tau_y \quad (10)$$

By measuring the extruder output in different production conditions, which has been explained in design of experiments and utilizing the online pressure measurement system and also using Eq. (3) and Eq. (10), the values of n and m for power law model and τ_y and apparent viscosity (μ) for Bingham plastic model can be calculated according to these experimental data.
Also the velocity distribution in $R_p < r < R$, is given by [30]:

$$V_z = \left(\frac{-\Delta P}{L}\right)\frac{R^2}{4\mu}\left(1 - \frac{r^2}{R^2}\right) - \frac{\tau_y}{\mu}R\left(1 - \frac{r}{R}\right) \quad (11)$$

In frequency sweep experiments, the graphs of shear stress vs. strain rate have been plotted and by using the curve fitting module of TA Orchestrator program, the amount of τ_y and μ have been calculated by assuming the Bingham model as the constitutive equation.

5 RESULTS AND DISCUSSION

As it was mentioned before, Mooney technique was used for calculating the slip velocity on the die wall in real extrusion process and diagrams of apparent shear rate versus 1/R were plotted for each set of data. One of these diagrams, for the composite containing HDPE5620 as the polymer matrix and 50wt% of wood content, has been shown in Fig. 5.
As it can be seen, the best lines with its formula have been fitted to these data using linear regression. The most important finding in this diagram is that by assuming the existence of slip velocity on the die wall and using the common Mooney technique for calculating this velocity, the true shear rate will have a negative amount which is completely unacceptable. So it can be claimed that although this method has some satisfactory results for capillary rheometer experiments, but it is not well-matched with the results from real extrusion process and existence of slip velocity is not clear in this condition. One of the most possible reasons for this observation is the big difference of diameters of a capillary die and an extrusion die. The ratio of wood particle size to die diameter is much bigger when they are flowing through a capillary die rather than in an extrusion die. This can change the flow characteristics of the composite melt in these two conditions. It is another reason which shows the importance of flow study in real conditions rather than in laboratory tests.

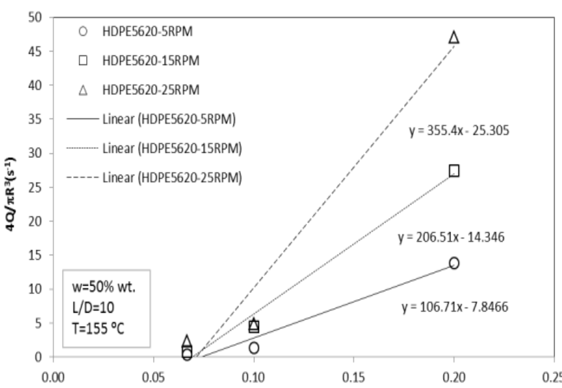

Fig. 5 Apparent shear rate vs. 1/R for the composite containing HDPE5620 as the polymer matrix and 50wt% of wood content (Die temperature: 155°C, L/D: 10)

In continue for evaluating constitutive equations for flow of wood plastic composite melt, similar to previous studies on rheometry experiment results, it was tried to utilize the power law for characterizing the WPC's flow through a circular die in extrusion process. By plotting the volumetric flow rate (Q) vs. $\Delta P/L$ for the experiments with exactly the same material and production conditions but with different RPM for the screw speed, and fitting a power trend line to the results and using Eq. (3), the power law index can be calculated. The power of $\Delta P/L$ in the resulted equation is equal to (1/n). This procedure has been shown in Fig. 6.

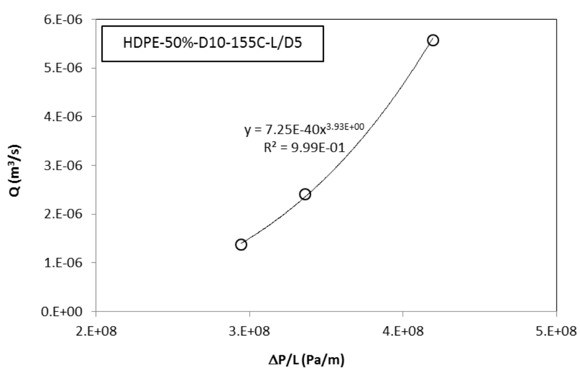

Fig. 6 Volumetric flow rate vs. $\Delta P/L$ for the composite containing HDPE5620 as the polymer matrix and 50wt% of wood content (Die temperature: 155°C, die length to diameter ratio: 5, die diameter: 10mm)

Calculating the consistency index will also be possible by substituting power law index and R values in Eq. (3). Power law and consistency index values for composites having different polymer matrices containing different contents of wood has been shown in Table 7.

Table 7 Power law and consistency index values for composites containing different polymer matrices and wood contents from 50 to 70 wt% resulted from flow study in extrusion process

Polymer Matrix	Die Diameter (mm)	Wood Content (wt%)	155ºC L/D=5	
			n	m
HDPE5260		50%	0.254	315000
	10	60%	0.090	1244000
		70%	0.070	1739000
Polymer matrix	Die Diameter (mm)	Wood Content (wt%)	175ºC L/D=5	
			n	M
PPZ30S		50%	0.278	185000
	10	60%	0.211	421000
		70%	0.151	512000
PPD60R		50%	0.225	630000
		60%	0.193	827000
		70%	0.159	1092000

It can be seen, there is a good consistency for the resulted n and m values from the experiments. As expected, by increasing the wood content, the power law index value decrease which indicates the existence of a more plug like flow for the composite. As it was mentioned before, this plug like flow is one of the reasons for suggesting the Bingham model for the flow of this composite.
Fig. 7 shows fitting a line to the same results as Fig. 6 and by using Eq. (10), one can calculate the amount of μ and τ_y as follow:

$$3.41\text{E}-14=\frac{\pi R^4}{8\mu}\rightarrow\ \mu=7197\ \text{Pa.S} \tag{12}$$

$$-8.83\text{E}-6=-\frac{\pi R^3}{3\mu}\tau_y\rightarrow\ \tau_y=485496\ \text{Pa} \tag{13}$$

This procedure has been repeated for all experiments and the results have been shown in Table 8 to Table 10 for composites containing different polymer matrices. It should be mentioned that in some experiments, especially the ones with high contents of wood in the composite, producing an intact product with the selected production parameters was not possible and so some cells in these tables are empty.

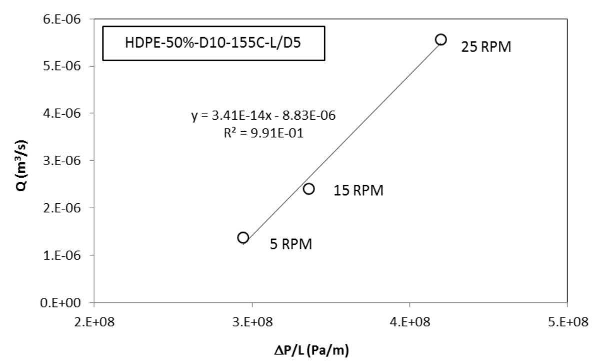

Fig. 7 Volumetric flow rate vs. $\Delta P/L$ for the composite containing HDPE5620 as the polymer matrix and 50wt% of wood content (Die temperature: 155°C, die length to diameter ratio: 5, die diameter: 10mm)

Table 8 shows the estimated values of yield stress and apparent viscosity for composites containing HDPE5620 as the polymer matrix. As it is seen, in a fixed die diameter, increasing the wood content in the composite will cause an increase in yield stress, apparent viscosity and φ. It means having more wood particles in the composite will make it more resistant to start flowing and the flow itself will have a larger plug part in the center. Also by increasing the screw speed, the center plug part of the flow will decrease. The reason for this observation is that increasing the screw speed will cause higher pressure in die and will make higher shear stress at the die wall and so the ratio of yield stress to shear stress at the wall (or φ) will decrease. Another noticeable issue is the effect of length to die diameter ratio (L/D). Increasing L/D value will cause an increase in apparent viscosity and yield stress. The increase in die diameter from 10mm to 20mm will increase the apparent viscosity and decreases the yield stress of the composite. Also it typically causes a slight reduction in φ value. According to $\dot{\gamma} = 4Q/R^3$, increasing the die diameter will cause a decrease in shear rate value and it is a fact that decreasing the shear rate increases the viscosity. Also there is a fact that increasing the die diameter decreases the pressure and based on $\tau_w = (R/2)(\Delta P/L)$ and from the results from the experiments it can be seen that the shear stress at the wall decreases by increasing the diameter. As it was mentioned that the φ value does not change noticeably, so the yield stress should decrease too.

Table 9 shows estimated values of yield stress and apparent viscosity for composites containing PPZ30S as the polymer matrix in their composition. Again the trends in this table are similar to Table 8, except that the apparent viscosity and yield stress values are mainly less than the results for HDPE5620 which is expectable because of the lower viscosity of the PPZ30S.

Table 8 Calculated values of yield stress and apparent viscosity for composites containing HDPE5620 as the polymer matrix, resulted from flow study in extrusion process

Die Diameter (mm)	Wood Content (wt%)	155 ^{0}C			
		L/D=5		L/D=10	
		μ (Pa.s)	τ_y (Mpa)	μ (Pa.s)	τ_y (Mpa)
10	50%	7,197	0.486	9,158	0.826
	60%	7,304	1.278	9,977	1.570
	70%	8,828	2.057		
20	50%	10,788	0.149	33,852	0.202
	60%	34,192	0.890	70,011	0.936
	70%	70,882	1.533	148,183	1.783

Table 9 Calculated values of yield stress and apparent viscosity for composites containing PPZ30S as the polymer matrix, resulted from flow study in extrusion process

Die Diameter (mm)	Wood Content (wt%)	175 ^{0}C			
		L/D=5		L/D=10	
		μ (Pa.s)	τ_y (Mpa)	μ (Pa.s)	τ_y (Mpa)
10	50%	5,957	0.242	5,278	0.516
	60%	6,459	0.412	7,994	0.837
	70%	7,176	0.609		
20	50%	29,525	0.094	32,724	0.406
	60%	30,207	0.811	33,563	0.699
	70%	36,360	0.757	-	-

Table 10 shows estimated values of yield stress and apparent viscosity for composites containing PPD60R as the polymer matrix. Again the trends are similar to previous tables but the higher viscosity of the matrix makes the apparent viscosity and yield stress values of the resulted composites higher than the others. The only deviation from this trend is that for composites having HDPE matrix with high contents of wood with 20mm diameter, the apparent viscosity will increase more rapidly in the way that it even reaches to higher values than PPD60R.

Table 10 Calculated values of yield stress and apparent viscosity for composites containing PPD60R as the polymer matrix, resulted from flow study in extrusion process

Die Diameter (mm)	Wood Content (wt%)	175 ^{0}C			
		L/D=5		L/D=10	
		μ (Pa.s)	τ_y (Mpa)	μ (Pa.s)	τ_y (Mpa)
10	50%	14,965	0.812	28,538	1.365
	60%	17,406	0.934	31,028	1.548
	70%	18,046	1.129		
20	50%	39,746	0.934	80,140	1.125
	60%	41,554	0.671	98,418	1.306
	70%	50,866	1.054	-	-

Fig. 8 shows the difference between velocity distributions suggested by power law and Bingham plastic models for a composite containing HDPE5620 as the polymer matrix and 50 wt% of wood content. As it is shown, the velocity profiles are close to each other but Bingham plastic model suggest an obvious plug section in the center of flow which also matches with the results from other studies on this composite [19, 28].

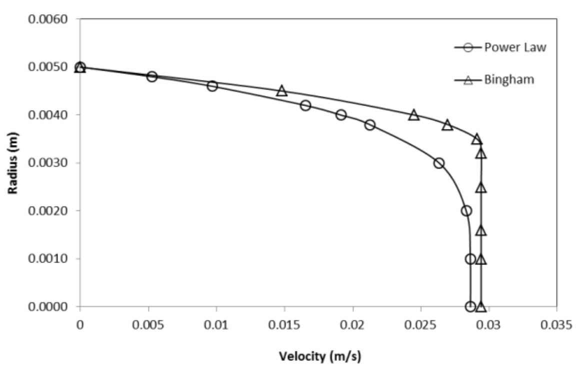

Fig. 8 Suggested velocity distributions for wood plastic composite with HDPE5620 as the polymer matrix and 50 wt% wood content, based on Power law and Bingham plastic models

As it was explained in design of experiments, rheometry tests were performed on composites having

different polymer matrices and wood contents using rotational parallel plate rheometer to study the flow behaviour of its melt. This study can be done by the results from either unidirectional or oscillatory shear (frequency sweep) modes. Similar to previous observations by authors [14] it was again confirmed that the composite does not behave properly in unidirectional shear tests and so only the results from frequency sweep were analysed.
Shear stress vs. shear rate from the results of rheometry experiments were plotted and by fitting the best curve to this data using Bingham model by TA Orchestrator program, yield stress and apparent viscosity of the composites have been calculated. The values of these parameters have been reported in Table 11 for the composites having different polymer matrices and wood contents from 50 to 70 wt%.

Table 11 Calculated values of yield stress and apparent viscosity for composites containing different polymer matrices and wood contents from 50 to 70 wt%, resulted from curve fitting of frequency sweep test with Bingham model

Polymer matrix	Wood Content (wt%)	Gap Size (mm)	Strain=0.1% 155 °C	
			μ (Pa.s)	τ_y (Mpa)
HDPE5620	50%	1	43,572	0.587
	60%		46,702	0.850
	70%		49,597	0.768
Polymer matrix	**Wood Content (wt%)**	**Gap Size (mm)**	**Strain=0.1% 175 °C**	
			μ (Pa.s)	τ_y (Mpa)
PPZ30S	50%	1	19,488	0.420
	60%		23,473	0.915
	70%		-	-
PPD60R	50%		54,622	0.644
	60%		64,110	0.843
	70%		-	-

Similar to results from the extrusion experiments and also as expected, increasing the wood content in the composite will cause an increase in apparent viscosity and yield stress of the flow. The reason is that by increasing the wood particles in the composition, the composite melt will need more driving force for start flowing which will be seen as a more rigid liquid that has a higher apparent viscosity and yield stress. Another point as expected is that the composite with higher viscos polymer matrix has higher apparent viscosity and yield stress.
Comparing the results from frequency sweep test and extrusion process shows that the same trend exists in both geometries but the values differ from each other. Some reasons can be expressed such as different shear rates and geometries in these two conditions which can affect the results noticeably. But the most important finding from this comparison is that although the results of a frequency sweep test can give the required values for parameters in the Bingham plastic model, but these quantities will be different with those from empirical experiments. So it cannot be expected that these parameters can be achieved just by doing some simple rheological experiments.

6 CONCLUSION

In this study, a wide range of WPC rod shaped profiles were produced with different materials and process conditions to evaluate the effect of various parameters on flow behaviour of the WPC's melt. Moreover, frequency sweep experiments were performed on the selected composites using rotational plate rheometer. The results concluded the followings:
Mooney technique, which had been reported as a good method for calculating the slip velocity on the die wall in capillary rheometer, has been evaluated in real extrusion process and it was seen that this equation does not well-matched with results. It can be concluded that although there are some reports which shows the compatibility of this equation for capillary rheometer results, it cannot be extended to real conditions in an extruder.
Although both power law equation and Bingham plastic model can describe the flow characteristics of the WPC's melt through a circular die in extrusion process satisfactorily, according to other reports and visual observation by author, Bingham plastic model with its center plug flow concept seems to be more proper for characterizing the flow of this composite.
There is a similarity between the reported trends in results from the circular die in extrusion process and rotational rheometer. But the reported values are different with each other which can be explained based on either different geometry in these experimental methods or different processing conditions such as different shear rate or flow regime.
It can be concluded, although the results of a frequency sweep test by using a rotational rheometer simply can give the required values in the Bingham plastic model for wood plastic composite, these quantities will be different with the values resulted from the empirical experiments and may not be used for analysing real conditions. Further investigation is required for finding a possible relation between the results of them.

7 NOMENCLATURE

L	Die land length (mm)
D	Die diameter (mm)
L/D	Die land length-to-diameter ratio
T	Temperature of die or melt (C)
RPM	Speed of screws (RPM)
M	Polymer melt flow index (gr/10min)
MFI	Melt Flow Index (gr/10min)
W	Weight percentage of wood
LVR	Linear Viscoelastic Region
WPC	Wood Plastic Composite
n	Power Law Index
m	Consistency Index
μ	Apparent Viscosity
τ_y	Yield stress
τ_w	Shear stress at wall
φ	Ratio of $\frac{\tau_y}{\tau_w}$

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