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EFFECTS OF PROCESSING METHOD AND FIBRE CHARACTERISTICS ON MICROSTRUCTURE AND PROPERTIES OF WOOD-PLASTIC COMPOSITES

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SUMMARY: Processing methods play an important role in the final properties and quality of thermoplastics and reinforced thermoplastic products. Relationships between the material properties and processing of extruded wood-plastic composites (WPC) have been extensively reviewed. However, little research has addressed the comparative properties and microstructures of extruded and injection-moulded (IM) WPC. The objective of this study was to understand the role of processing method and fibre characteristics on WPC properties and microstructure. Three chemo-thermo-mechanical pulp (CTMP) fibre length-to-diameter ratios (L/D) were obtained through mechanical refining and characterized with a fibre quality analyzer (FQA). The rheometer torque properties of high density polyethylene (HDPE) filled with these pulps at different loads were then determined. Variations in fibre load and size resulted in significant variations in melting properties and torque characteristics. Therefore, process parameters should be set accordingly. Composites were manufactured with extrusion and IM processes. IM composites showed better physical and mechanical properties than extruded composites. These differences may be partly explained by the microstructure (fibre alignment) and surface quality.

KEYWORDS: extrusion, injection moulding (IM), torque rheometer, high density polyethylene (HDPE), wood fibres, fibre characteristics, microstructure.

INTRODUCTION

The ability of thermoplastics to melt and re-harden has been exploited in many different processing methods. The most commonly used methods to produce plastics and wood fibre-filled plastic parts are extrusion and injection moulding IM [1,2]. These two different processes follow the same basic steps: melting, shaping and cooling [2]. The effects of extrusion parameters on

WPC material properties have been extensively reviewed. However, little research [1,3] has addressed a comparison of the characteristics of extruded and IM WPC. Further research is needed to understand the relationships between processing method, fibre characteristics and material properties. Thus, the objectives of this study were 1) to determine how variations in fibre load and size affect the torque rheometer characteristics of melted, wood fibre-filled HDPE, and 2) to study how processing method and fibre size affect WPC microstructure and behaviour.

MATERIAL AND METHODS

CTMP fibres were prepared in three fibre length-to-diameter ratio (L/D) classes by mechanical refining and characterized using an FQA. HDPE having a melt index of 0.3 g/10 min, tensile strength at break of 27.3 MPa and flexural modulus of elasticity of 1.276 GPa was used as the matrix. Maleated polyethylene (MAPE) was used as the compatibility agent and OptiPak OP-100 (Honeywell) was used as lubricant. A Haake torque rheometer with a counter-rotating twin-screw mixing chamber was used to mix the CTMP fibres into the HDPE while measuring torque. Three fibre loads for each fibre L/D class were used in the torque mixing chamber: 20, 30, and 40 wt% (weight percent). Tests were conducted at 180ºC and at a screw speed of 50 revolutions per minute (RPM).

In the second part of the study, composites were produced using extrusion and injection moulding, according to the conditions presented in Table 1. All composites were prepared in two stages: compounding for pelletization followed by either extrusion or IM. A 55 mm conical twin-screw extruder was used for compounding. Parameters were adjusted for fibre size to obtain a homogeneous extrudate. The extruded material was cooled and ground to form pellets for use in the final stage, using either a Cincinnati Milacron 35 mm counter-rotating twin-screw extruder (extruded samples) or a Sumitomo 55 US ton SE-DU Series injection moulding machine (IM samples). Physical and mechanical properties of the obtained composites were measured according to standard procedures: ASTM D 1037-99 for moisture tests, ASTM D 2395-93 for specific gravity, ASTM D 790-03 for three-point bending and ASTM D 638-03 for tensile tests. Extruded WPC were machined to specified dimensions for solid material characterization, while IM composites were characterized without modification. Finally, WPC surfaces were analyzed using scanning electron microscopy (SEM).

Table 1 WPC formulations and processing conditions

Fibre	**WPC formulation**				**Processing conditions**				
					First stage [1]		Second stage [1]		
L/D	CTMP	HDPE	MAPE	OP-100	Screws	Temp. (°C)	Screws	Temp. (°C)	
class	(wt %)	(wt %)	(wt %)	(wt %)	RPM	B&S[2]	RPM	B&S[2]	Die/Mould
EXTRUSION (conical counter-rotating twin-screw extruder)									
8.3	39	59	2	0	28	197	5	163	171
13.0	39	59	2	0	44	218	5	163	171
21.3	39	59	2	0	44	224	5	163	171
INJECTION MOULDING (injection speed: 8 mm/sec; injection pressure: 167 MPa; injection time: 2 sec)									
8.3	38	57	2	2,7	28	197	-	180	90
13.0	38	57	2	2,7	44	218	-	180	90
21.3	38	57	2	2,7	44	224	-	180	90

[1] First stage: extrusion compounding; Second stage: extrusion or injection moulding. [2] B&S: Barrel and screw.

RESULTS AND DISCUSSION

Torque properties of the wood fibre-plastic blends varied with fibre load and size class (Table 2). The addition of CTMP fibres into the polymer increased torque characteristics. Torque and mechanical mixing energy increased with fibre load and size (Fig. 1). These results are in agreement with previous findings [4, 5], and showed that using different fibre proportions and size has an important impact on WPC processing, such as extrusion and IM. In this study, therefore, compounding parameters of wood fibre-plastic blends were adjusted according to fibre morphology characteristics (Table 1).

Table 2 Properties and standard deviation (in parentheses) of HDPE filled with different CTMP fibre sizes and proportions in a torque rheometer at 180°C and 50 RPM

Fibre load (wt %)	**Stabilized torque (Nm)** L/D class			**Maximum torque (Nm)** L/D class			**Mechanical energy (kJ)** L/D class		
	21.3	13.0	8.3	21.3	13.0	8.3	21.3	13.0	8.3
20	16.3 (0.4)	15.1 (0.3)	13.6 (0.6)	65.5 (2.5)	65.9 (1.3)	60.6 (1.2)	58.0 (1.2)	54.7 (1.0)	49.8 (1.8)
30	18.5 (0.3)	16.5 (1.4)	15.2 (0.4)	67.1 (6.0)	66.0 (1.6)	62.0 (3.0)	66.7 (1.1)	61.7 (7.0)	56.5 (1.0)
40	21.3 (0.1)	17.1 (0.7)	15.5 (0.6)	63.0 (2.6)	63.8 (1.0)	61.0 (1.6)	76.7 (1.7)	65.7 (4.6)	58.1 (1.8)
0		10.2			66.3			38.3	

Electronic micrographs taken on the surface of the WPC samples show major differences in fibre organization within the composites (Fig. 2). With the IM process, fibres were clearly aligned in the main flow direction, while in extruded samples, fibres were more randomly oriented. This result was expected, because structural parameters, like orientation and boundary layers, are generally less distinct in extrusion than in IM [2]. The micrographs enlarged 450 times showed smooth, polymer-rich surfaces in IM samples, whereas surface defects (exposed fibre ends and voids) were seen at the surface of extruded samples (not shown). This result concurs with a previous report [1]. The differences in microstructure suggest that the mechanical and physical behaviour of WPC vary with the processing method.

Physical properties of WPC varied with processing method and fibre size. Density of extruded samples was 5.2% higher than the density of IM samples. Lower fibre L/D ratios resulted in slightly higher WPC density. This could be explained by the fact that longer fibres increase the probability of voids within the composite. A previous study [3] found that the IM process resulted in better physical performance than the extrusion process. After 1000 hours in water immersion, extruded WPC absorbed up to 24% more water and swelled in volume up to 113% more than IM samples (Fig. 3). A similar trend was observed for mass water absorption (not shown). These differences in absorption behaviour could be explained in part by the surface quality of the composites. Exposed fibre ends at the surface of the extruded samples increased water sorption from surface to core, while the hydrophobic, polymer-rich surface of the IM composites reduced water swell. Fibre orientation may also have contributed to the differences in water sorption behaviour. Fibres aligned lengthwise in the IM samples could not diffuse water sideways, thereby reducing water swell compared to the extruded samples. Finally, differences in processing parameters (Table 1) may also have influenced water sorption behaviour.

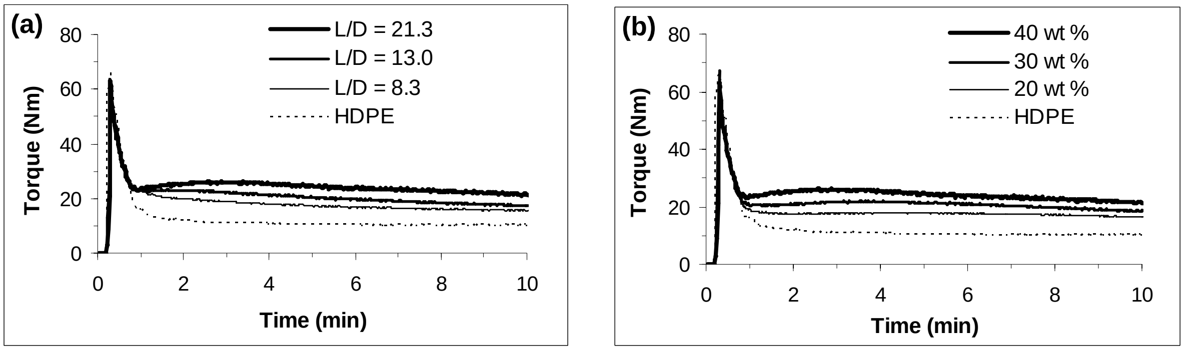

Fig. 1 Torque variation with time for HDPE and HDPE filled with CTMP fibres of different (a) L/D ratios and (b) proportions in a torque rheometer at 180°C and 50 RPM.

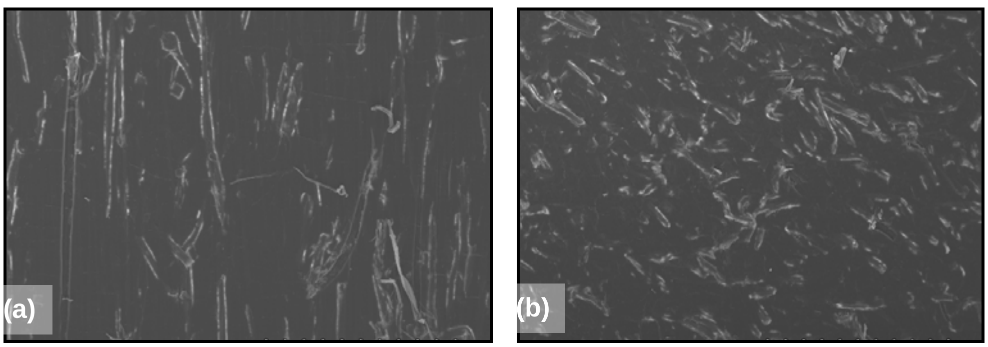

Fig. 2 Electronic micrographs enlarged 100X of (a) aligned fibres in an injection-moulded sample and (b) randomly oriented fibres in an extruded sample.

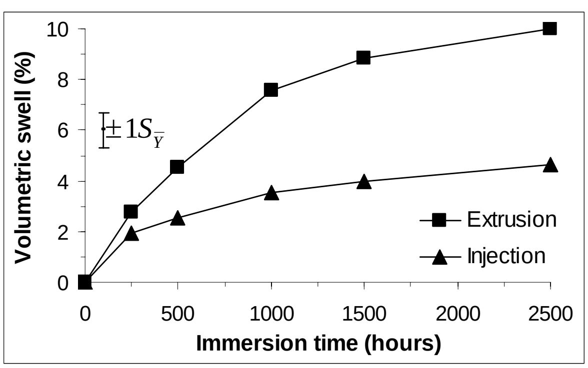

Fig. 3 Volumetric swell with immersion time in water.

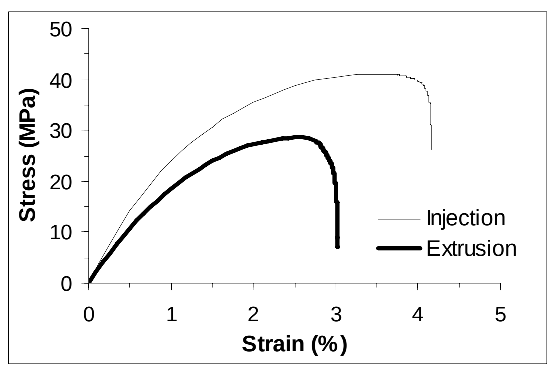

Fig. 4 Typical flexure stress-strain curves of WPC made from HDPE and CTMP fibres.

Significant differences in mechanical properties were observed with processing method and fibre size. Typical flexure stress-strain curves for the two processes studied are shown in Fig. 4. For all formulations studied, the addition of wood fibres into HDPE increased stiffness (Fig. 5), whereas an increase in resistance was obtained only with the IM process (Fig. 6). When using the IM process and fibres with a high L/D ratio, the resistance of neat HDPE was improved up to 34%.

Compared to extruded composites, IM composites had up to 50% higher modulus of elasticity (MOE) and up to 44% higher modulus of rupture (MOR). These results are in agreement with previous findings [1]. The differences in mechanical behaviour with processing method could be explained in part by the microstructure (fibre alignment) of the composites. According to the classical theory of mechanics, load applied to a fibre-reinforced composite material is transferred from the matrix to the fibres by shear stresses along the fibre-matrix interface. Transfer efficiency increases with increasing fibre L/D ratio and is optimal when fibres are aligned in the load direction. Thus, in this study, oriented fibres in IM composites (Fig. 2) resulted in better mechanical characteristics than randomly oriented fibres in extruded composites (Fig. 4 to 6). Mechanical properties also increased with increasing fibre L/D ratio (Fig. 5 and 6). SEM micrographs showed surface defects on extruded samples, whereas the IM surface was smooth and polymer-rich. According to the classical theory of mechanics of materials, these imperfections resulted in stress concentration and consequently a decrease in strength. Moreover, IM composites were tested without modification, whereas extruded samples were machined. However, according to Stark and al. [1], planed WPC are stiffer and more resistant than non-machined WPC. Finally, processing conditions, such as temperature (Table 1), residence time, pressure, cooling rate, shear rate and shear stress, varied with the processing method and could have had an impact on the mechanical properties of the finished fibre-filled thermoplastic composites [2].

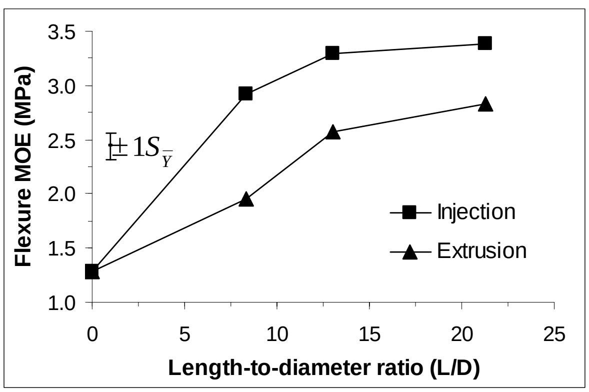

Fig. 5 Flexure MOE with increasing fibre L/D ratio for the two processing methods.

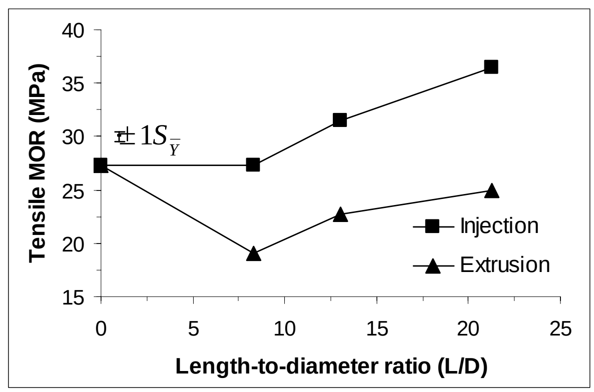

Fig. 6 Tensile MOR with increasing fibre L/D ratio for the two processing methods.

CONCLUSIONS

This study led to the following conclusions:

- Rheometer torque properties increased with increasing fibre proportion and L/D ratio. Consequently, using different fibre sizes and proportions would have a significant impact on processing parameters.
- Composite material behaviour varied with processing method. The injection moulding process resulted in better mechanical and physical performance than extrusion.
- The differences in behaviour with processing method may be partly explained by the microstructure (fibre alignment) and surface quality of the composites.
- Mechanical performance of WPC increased with wood fibre L/D ratio.

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