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Mechanical performance of woodfibre–waste plastic composite materials

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Abstract

Plastic products used for packaging are often discarded after a single use resulting in an inexhaustible supply of waste polymeric materials. The stiffness and strength of polymeric materials have been known to improve with the addition of lignocellulosic fibres available in abundance in nature. Hence, composite materials containing natural fibres and waste plastics would result in the reduction of solid wastes and the use of cheap, renewable resources. Composite specimens, consisting of waste plastics obtained from a Kerbside collection (high density polyethylene (HDPE) waste, Janitorial waste, Kerbside waste I and Kerbside waste II) and *Pinus radiata* woodfibres (medium density fibres (MDF)), have been produced through melt blending and injection moulding. The effects of fibre content, matrix type and interfacial bonding on the tensile and flexural properties of these composite materials have been determined through extensive testing at various conditions. The mechanical properties of these composites at room temperature and humidity depend on the amount of woodfibres, the mechanical properties of the waste plastics used and the presence of a suitable coupling agent. The tensile strengths of MDF/waste plastic composites do not generally change with fibre content except for 40% MDF/HDPE waste and 40% MDF/Kerbside waste II (plus 1% Epolene^{TM}) composites, where the tensile strengths increase by about 25% compared to those of the corresponding waste plastics. Flexural strengths of MDF/waste plastic composites increase with the addition of medium density fibres with the exception of MDF/Kerbside waste I composites. The tensile and flexural moduli of MDF/waste plastic composites mostly increase with increasing fibre content.

Keywords: Kerbside waste plastics; Woodfibres; Injection moulding; Woodfibre-reinforced composites; Coupling agent; Tensile modulus and strength; Flexural modulus and strength

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1. Introduction

Plastic bottles and rigid containers make up a substantial volume of the global municipal solid waste (Terrazas, 1995). So, local governments worldwide have focused their efforts on recycling these waste plastics to reduce the volume of material going into landfills. Recycling programmes range from kerbside collection systems to drop off points and a combination of these systems.

Most single polymer plastics made from petroleum are relatively easy to recycle. Therefore, with an efficient collection, separation and recycling system, discarded plastics can be recycled into new products with only the addition of energy. Properties of some waste plastics are similar to those made from virgin materials, with tests indicating only a slight change in mechanical properties of recycled polyethylene (Khattab and El-Zoghby, 1998). Products manufactured from waste plastics are increasing and include floor carpets, flower vases, waste paper baskets, park benches and picnic tables (DeWeese, 1998) and plastic lumber (Datta et al., 1994).

Natural fibres come from renewable resources and are relatively inexpensive. These fibres are now well recognised to impart good reinforcing capability to composites. While their tensile strengths and moduli are generally inferior to those of polymeric fibres, they often exhibit significantly larger elongation giving them better damage tolerance (Chand et al., 1988; Groom et al., 1995; McKenzie, 1978; Mukherjee and Sathyanarayana, 1986).

The collection of plastic packaging materials through recycling programmes is increasing rapidly. Hence, the development of new value added products, to utilise the recovered plastics, is assuming greater importance. The addition of natural fibres, such as woodfibres, flax or sisal, to waste plastics renders the resulting composites viable from both the mechanical properties and the economics points of view.

A relatively large body of published literature (Balatinecz and Woodhams, 1993; Bataille et al., 1989; Beshay et al., 1985; Bhattacharyya et al., 2003; McKenzie and Yuritta, 1979; Raj and Kokta, 1991; Sain et al., 1994a,b; Woodhams et al., 1984; Zadorecki and Mitchell, 1989) in the area of woodfibre-reinforced virgin thermoplastic composites exists. These studies have examined the mechanical properties of the composites and the effects of various coupling agents on the interfacial bonding between the fibres and the polymer. The presence of a suitable coupling agent has been shown to be important for the achievement of significant gains in the mechanical properties of these composites in a recent review by Lu et al. (2000).

Chtourou et al. (1992), Simpson and Selke (1992) and Yam et al. (1990) have evaluated the mechanical properties of woodfibre–waste plastic composites. Datta et al. (1994) have investigated the use of saw dust–waste thermoplastic composites for guard-rail posts in highways. Miller et al. (1998) have assessed the tensile strength of woodfibre–waste plastic composites with particular emphasis on coupling agents. Results have shown that plastics from the waste stream can be used to make woodfibre-reinforced composite materials with good mechanical properties. However, most of the research in this area has concentrated on the use of either a single plastic from the waste stream or a simulated waste plastic fraction to produce composites reinforced with woodfibres.

The feasibility of post-consumer waste plastics from a kerbside collection reinforced with high temperature mechanical pulp *Pinus radiata* fibres has been investigated in the present study. *Pinus radiata* fibres have been used in this study primarily because of their abundance

in New Zealand. These woodfibres themselves are composites of cellulose microfibrils held together by a lignin and hemicellulose matrix (Walker, 1993). High temperature mechanical pulp *P. radiata* fibres, due to their lignin covered surfaces (Kibblewhite et al., 1980; Lee and McDonald, 2000; Lee et al., 2001), also have advantages as reinforcement in comparison to the highly hydroxylated kraft fibres used for papermaking. These pulp fibres, often loosely categorised as medium density fibres (MDF), are unbonded fibres that have hydrophobic surfaces rather than the hydrophilic surfaces as are present in kraft fibres. They, therefore, possess a greater potential for bonding with the hydrophobic thermoplastic polyolefins. They are slightly weaker than kraft fibres, cheaper to produce and more amenable to surface modification (Beshay et al., 1985; Zadorecki and Mitchell, 1989). Composite specimens of prismatic shapes have been produced through melt blending these woodfibres and waste plastics, followed by injection moulding. The tensile and flexural properties of the specimens have been determined at room temperature and humidity (23 °C and 50% RH, on average), oven-dried (at 80 °C for 36 h) and water-soaked (6 weeks) conditions and low and high temperatures (−50 and 50 °C). The influence of a coupling agent on the tensile and flexural properties of some of the specimens has also been evaluated.

2. Materials

Waste plastic recovered through a kerbside recycling scheme in Auckland consists of a variety of thermoplastic and thermoset materials. Sorting the waste into individual materials is not economically viable except for the separation of easily identifiable materials. As a result, the waste plastics from a kerbside collection considered in this study fell into four categories, namely high density polyethylene (HDPE) waste, Janitorial waste, Kerbside waste I and Kerbside waste II, as shown in Table 1. Maleated polypropylene wax (Eastern Chemicals Epolene E-43) was used as a coupling agent in some of the specimens produced.

The medium density fibres used in this study were commercial fibres supplied by the New Zealand Forest Research Institute in Rotorua. They were light brown in colour with widths varying from 15 to 40 μm, lengths ranging from 1.5 to 5 mm, density of 400 kg/m^3 and a nominal tensile strength and stiffness of 125–150 MPa and 2.5–4 GPa, respectively (Bowis, 1997). It should be noted that these values are very dependent on the source of woodfibres and their fibril angles.

Table 1
Description of the four categories of waste plastics used

Waste plastics	Description
HDPE waste	Consists of plastic milk bottles
Janitorial waste	Consists mainly of cleaning product bottles which are made of different types of polyolefins (polypropylene, polyethylene)
Kerbside waste I	Consists of anything remaining after the HDPE waste, Janitorial waste and soft drink containers (PET) have been separated out
Kerbside waste II	Consists of HDPE waste, Janitorial waste and Kerbside waste I mixed in the ratios found in a typical kerbside recycling collection scheme

3. Production of specimens

HDPE waste, Janitorial waste and Kerbside waste I were melt blended without woodfibres and with 0, 20, 30 and 40% by mass of woodfibres. Compounding was performed in a laboratory sigma blade mixer with a capacity of 50 g. The compounding temperature was standardised at 180 °C and the mixing time at 2 min from the time the full charge was loaded. The compounded materials were melt-pressed between heated stainless steel plates, cut into strips and granulated in a Gretcha D8750 granulator.

Preliminary testing of these composites showed that the tensile strength and modulus reach maximum values with fibre mass fractions varying between 30 and 40%. So, subsequent melt-blends were made using Kerbside waste II without woodfibres and with 40% woodfibres treated with 1% Epolene^{TM}. It should be noted that during granulation, small pieces of unmelted plastic, believed to be PET, were found dispersed throughout the Kerbside I and Kerbside II blends.

Test specimens were moulded from the different composite materials in a Ray-Ran laboratory injection-moulding machine with the barrel temperature set at 200 °C and the mould set at 30 °C except for 40% MDF/HDPE waste composites which were moulded with a mould temperature of 70 °C. Specimens were produced in two shapes—a 'dog bone' specimen for tensile testing and a rectangular specimen for flexural testing.

4. Testing

The tensile and flexural properties of the MDF/waste plastic composites at room temperature and humidity (23 °C and 50% RH) were determined by following the ASTM standards (ASTM D 638M-93 and ASTM D 790M-93, respectively) in a computer-controlled Instron universal testing machine (Model 5567) using five replicates for each test. These specimens were conditioned at room temperature and humidity for 24 h prior to the tests.

In addition, tensile and flexural tests were carried out on oven-dried and water-soaked specimens and on specimens at temperatures of −50 and +50 °C to simulate dry, wet, winter and summer conditions, respectively. Oven-dried specimens were acquired by drying them in an oven at 80 °C for 36 h and periodically measuring their weights. These specimens were then allowed to cool in a desiccator for 24 h before testing. Water-soaked specimens were acquired by immersing them in distilled water for approximately 6 weeks and weighing them from time to time after wiping their surfaces gently. These specimens were tested directly after removal from the water. The oven-dried and water-soaked specimens were tested at room temperature and humidity.

5. Results and discussion

5.1. Room temperature and humidity

Tensile strengths of MDF/waste plastic composites do not generally change with fibre content except for 40% MDF/HDPE waste and 40% MDF/Kerbside waste II (plus 1%

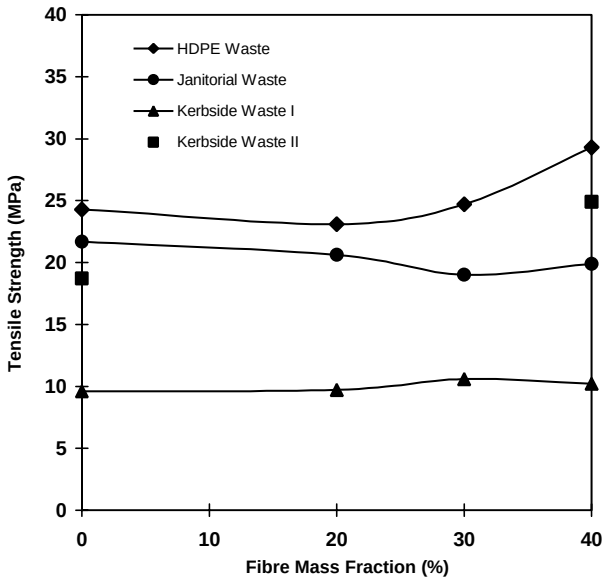

Fig. 1. Tensile strength of MDF/waste plastic composite specimen as a function of fibre mass fraction at room temperature and humidity. The data points shown are mean values with a ±5% error band.

Epolene^{TM}) composites where the tensile strengths increase by about 25% compared to those of the corresponding waste plastics (Fig. 1). The fibres may act as flaws or fillers at lower fibre mass fractions leading to initial decreases in tensile strengths followed by modest increases with increasing fibre contents. It is interesting to note that both increases (Woodhams et al., 1984; Zadorecki and Mitchell, 1989) and decreases (Bataille et al., 1989; Raj and Kokta, 1991; Sain et al., 1994a,b; Yam et al., 1990) in tensile strength with the increasing fibre content have been reported in the literature, while one researcher has reported mixed results (Chtourou et al., 1992). It appears that the type of woodfibre, the thermoplastic matrix, any additives used and the method of specimen production influence the tensile strength of the resulting composite specimen. Tensile moduli of MDF/waste plastic composites have mostly increased with the increasing fibre content except for 20% MDF/HDPE waste composites (Fig. 2). Most researchers have reported a similar increase in tensile modulus with the increasing fibre content (Bataille et al., 1989; Raj and Kokta, 1991; Sain et al., 1994b; Woodhams et al., 1984; Yam et al., 1990; Zadorecki and Mitchell, 1989), while one has failed to find any definite trend (Chtourou et al., 1992).

Flexural strengths of MDF/waste plastic composites increase with the addition of medium density fibres in all the waste plastic composites except MDF/Kerbside waste I and an increase in the fibre content causes an increase in the flexural modulus of all the waste plastic composites (Figs. 3 and 4). Researchers who have measured flexural properties of woodfibre–thermoplastic composites (Woodhams et al., 1984; Yam et al., 1990; Zadorecki and Mitchell, 1989) have reported similar trends.

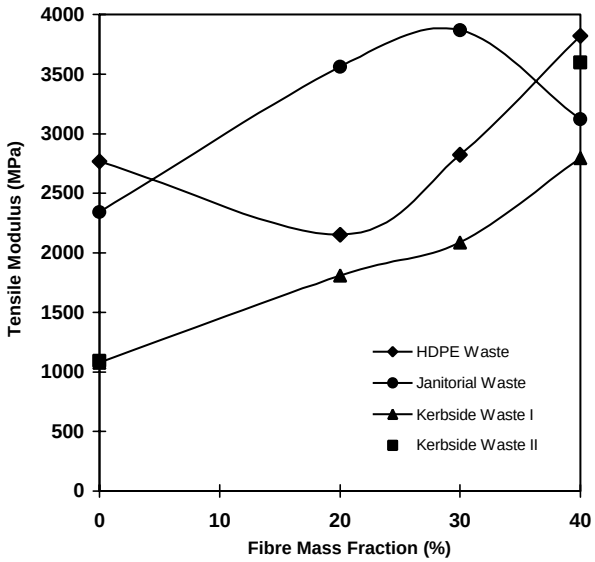

Fig. 2. Tensile modulus of MDF/waste plastic composite specimen as a function of fibre mass fraction at room temperature and humidity. The data points shown are mean values with a ±10% error band.

The addition of 1% Epolene to the 40% MDF/Kerbside waste II composites improves their mechanical performance. It has been hypothesised that the maleic anhydride units in Epolene bond with the lignocellulosic fibres, while the polymer chain (polypropylene) in Epolene entangles with the polymer chains of the plastic matrix leading to the improvement in mechanical properties (Hill, 2000).

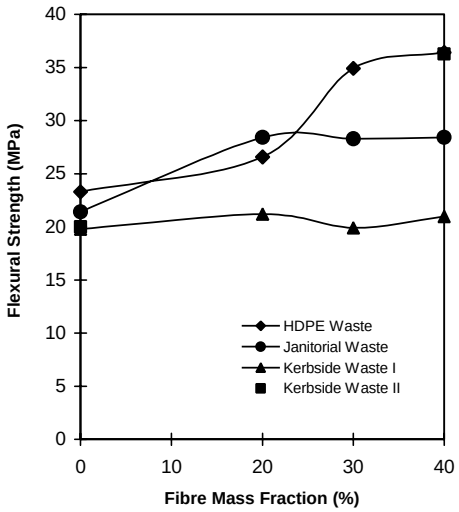

Fig. 3. Flexural strength of MDF/waste plastic composite specimen as a function of fibre mass fraction at room temperature and humidity. The data points shown are mean values with a ±5% error band.

Table 2
Mechanical properties of oven-dried MDF/waste plastic composite specimen

Material	Tensile strength (MPa)		Tensile modulus (MPa)		Flexural strength (MPa)		Flexural modulus (MPa)	
	Range	Average	Range	Average	Range	Average	Range	Average
HDPE waste	24.0–25.2	24.4	1405–1637	1483	22.2–23.8	23.0	946–1113	1019
20% MDF/HDPE waste	22.7–23.9	23.1	1902–2184	2135	26.2–28.4	27.4	1420–1613	1487
30% MDF/HDPE waste	23.9–28.9	27.1	2204–3164	2711	27.9–33.7	32.0	1564–1903	1779
40% MDF/HDPE waste	28.7–31.1	30.0	3773–4291	4141	35.9–41.2	38.8	2386–2454	2429
Janitorial waste	18.6–21.5	20.6	1082–1289	1221	20.1–22.8	21.0	806–915	843
20% MDF/Janitorial waste	20.3–21.9	21.2	1999–2361	2188	28.7–30.4	29.2	1569–1617	1637
30% MDF/Janitorial waste	17.3–19.1	18.2	2243–2458	2348	25.7–28	26.4	1752–1924	1826
40% MDF/Janitorial waste	16.0–21.6	19.7	2420–3667	3209	25.9–29.7	27.9	1901–2421	2189
Kerbside waste I	8.8–11.1	10.2	963–1209	1132	19.1–20.0	19.6	913–1087	988
20% MDF/Kerbside waste I	11.2–13.3	12.2	1856–2214	2094	14.6–21.9	19.1	1047–2143	1578
30% MDF/Kerbside waste I	9.4–12.9	11.1	2063–2691	2376	19.0–23.1	21.6	1753–2235	2052
40% MDF/Kerbside waste I	9.8–12.6	11.4	2808–3568	3053	15.8–23.9	21.1	2216–2571	2478
Kerbside waste II	19.4–20.1	19.7	1127–1272	1194	20.4–28.6	22.6	846–1168	948
40% MDF/Kerbside waste II/1% Epolene	22.1–25.4	23.8	3216–3853	3576	33.1–37.8	35.9	2238–2459	2385

Table 3
Mechanical properties of water-soaked MDF/waste plastic composite specimen

Material	Tensile strength (MPa)		Tensile modulus (MPa)		Flexural strength (MPa)		Flexural modulus (MPa)	
	Range	Average	Range	Average	Range	Average	Range	Average
HDPE waste	22.1–23.8	22.8	1246–1344	1282	23.1–28.8	24.4	929–1441	1113
20% MDF/HDPE waste	20.7–21.7	21.2	1860–2160	2049	23.8–26.8	24.7	1275–1474	1350
30% MDF/HDPE waste	21.7–23.4	22.7	2163–2659	2410	24.1–28.7	26.6	1444–1736	1585
40% MDF/HDPE waste	19.1–22.5	20.6	2081–2644	2400	26.7–29.7	27.7	1582–1829	1703
Janitorial waste	18.3–21.3	20.2	1072–1231	1130	20.1–23.9	21.8	803–1003	853
20% MDF/Janitorial waste	19.4–20.1	19.8	1778–2023	1915	25.5–27.7	26.3	1334–1677	1424
30% MDF/Janitorial waste	15.9–19.9	17.4	1522–2162	1823	22.5–24.3	23.2	1275–1504	1420
40% MDF/Janitorial waste	16.8–18.8	17.9	2110–2554	2376	18.9–26.7	23.0	1154–1828	1495
Kerbside waste I	7.8–9.8	8.9	635–1137	962	17.5–19.7	18.3	862–1076	991
20% MDF/Kerbside waste I	5.5–11.4	9.5	1064–1792	1526	17.1–21.1	19.3	1351–1477	1394
30% MDF/Kerbside waste I	6.4–10.7	8.9	1282–1751	1474	14.0–19.4	17.3	1329–1849	1450
40% MDF/Kerbside waste I	7.1–10.3	9.2	1679–2115	1826	13.8–16.6	15.1	1309–1403	1353
Kerbside waste II	18.4–19.7	19.1	1113–1224	1162	19.8–22.0	21.1	789–923	855
40% MDF/Kerbside waste II/1% Epolene	18.3–21.2	19.4	2330–2847	2528	25.7–28.8	27.6	1466–1676	1616

Table 4
Mechanical properties of MDF/waste plastic composite specimen at −50 °C

Material	Tensile strength (MPa)		Tensile modulus (MPa)		Flexural strength (MPa)		Flexural modulus (MPa)	
	Range	Average	Range	Average	Range	Average	Range	Average
HDPE waste	40.6–45.4	43.0	1602–1726	1664	66.0–69.9	67.7	2368–2526	2475
20% MDF/HDPE waste	1.9–43.6	42.7	2949–3544	3247	63.7–68.4	66.5	2714–3114	2967
30% MDF/HDPE waste	35.3–47.4	40.7	2708–4326	3517	67.0–71.8	69.4	3508–3731	3630
40% MDF/HDPE waste	41.3–55.5	48.4	5241–5259	5250	57.6–68.2	64.9	4026–4509	4282
Janitorial waste	28.7–41.6	35.2	3387–4085	3736	61.5–81.3	69.1	2327–2770	2614
20% MDF/Janitorial waste	40.8–42.3	41.6	3088–4738	3913	64.2–75.9	69.5	3374–3625	3460
30% MDF/Janitorial waste	38.3–38.9	38.6	4285–4462	4374	58.8–64.1	60.9	3043–3654	3445
40% MDF/Janitorial waste	31.2–36.4	33.8	4604–5382	4993	52.6–61.3	58.1	4080–4490	4268
Kerbside waste I	21.2–25.5	23.3	2767–2785	2776	45.3–52.1	47.9	2277–2924	2586
20% MDF/Kerbside waste I	23.8–26.0	24.9	3893–4446	4170	17.6–20.9	19.7	3033–3438	3280
30% MDF/Kerbside waste I	23.7–24.6	24.1	5256–5473	5365	39.1–54.8	44.0	1526–4240	3089
40% MDF/Kerbside waste I	21.8–24.2	23.0	5821–6595	6208	38.9–50.4	45.9	3754–4730	4425
Kerbside waste II	44.7–45.6	45.2	2561–3811	3186	67.7–71.3	69.4	2400–2499	2458
40% MDF/Kerbside waste II/1% Epolene	44.6–48.5	46.8	5488–6708	6194	74.4–98.1	70.3	4127–4654	4384

Table 5
Mechanical properties of MDF/waste plastic composite specimen at 50 °C

Material	Tensile strength (MPa)		Tensile modulus (MPa)		Flexural strength (MPa)		Flexural modulus (MPa)	
	Range	Average	Range	Average	Range	Average	Range	Average
HDPE waste	12.5–13.6	13.2	562–627	599	10.8–11.6	11.3	421–472	447
20% MDF/HDPE waste	12.1–13.3	12.9	885–1135	1026	13.3–14.2	13.9	694–776	739
30% MDF/HDPE waste	14.8–16.4	15.4	1330–1527	1379	16.6–19.1	17.6	980–1049	1018
40% MDF/HDPE waste	17.1–22.7	19.9	1851–2783	2356	20.2–23.4	21.8	1354–1458	1403
Janitorial waste	11.7–12.6	12.2	599–633	612	10.0–11.9	11.0	370–480	423
20% MDF/Janitorial waste	11.9–13.2	12.7	925–1192	1059	16.0–17.6	16.5	927–1029	980
30% MDF/Janitorial waste	10.8–13.0	11.5	999–1597	1171	15.0–17.2	15.8	762–1160	998
40% MDF/Janitorial waste	12.5–14.0	13.0	2024–2710	2289	15.7–18.3	17.1	1195–1458	1321
Kerbside waste I	4.9–6.8	6.0	461–586	534	10.8–12.0	11.3	471–580	533
20% MDF/Kerbside waste I	4.0–7.9	6.4	857–1299	977	17.6–20.9	19.7	856–1054	962
30% MDF/Kerbside waste I	5.6–7.2	6.3	1029–1643	1306	9.9–13.6	11.8	793–1393	1148
40% MDF/Kerbside waste I	6.9–8.7	7.4	1711–2870	2007	10.5–15.2	12.6	1362–1854	1567
Kerbside waste II	9.4–11.4	10.8	510–591	554	10.4–12.2	11.2	390–418	418
40% MDF/Kerbside waste II/1% Epolene	13.6–19.0	16.8	2266–2703	2448	21.1–25.0	23.6	1363–1640	1545

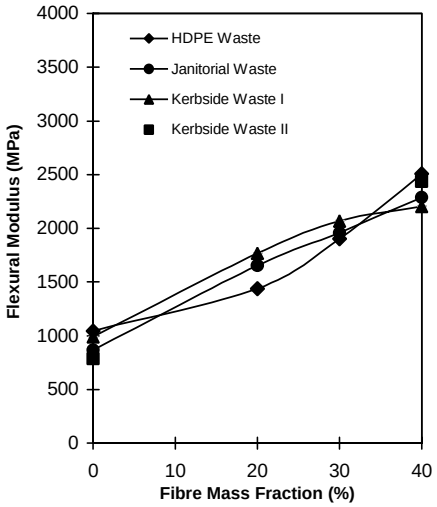

Fig. 4. Flexural modulus of MDF/waste plastic composite specimen as a function of fibre mass fraction at room temperature and humidity. The data points shown are mean values with a ±10% error band.

5.2. Oven-dried and water-soaked conditions

The mechanical properties of the oven-dried composite specimens generally vary very little from the properties displayed at room temperature and humidity conditions, while the water-soaked specimens show a degradation in mechanical properties (Tables 2 and 3). While the tensile modulus of the fibres tends to decrease with an increased moisture content, tensile strength either remains constant or may even increase slightly (McKenzie and Yuritta, 1979). Therefore, the effect of high moisture content on the tensile and flexural properties of the water-soaked composite specimens may be attributed to the poor bonding at the fibre/matrix interface due to the presence of moisture.

5.3. Low and high temperature conditions

The mechanical properties of all the specimens show a significant improvement at low temperature and degradation at high temperature (Tables 4 and 5). This is again expected as an increase in temperature lowers the mechanical properties of both the plastic (Osswald and Menges, 1996) and the woodfibre (Dinwoodie, 1989) constituents.

6. Concluding remarks

The present study has shown that plastics from the post-consumer waste stream can be successfully utilised to make composite materials with useful mechanical properties. Higher fibre content generally improves the mechanical properties of all the waste plastics composites reinforced by medium density fibres. The mechanical properties of MDF/HDPE waste

composites are generally the greatest, closely followed by MDF/Janitorial waste composites and MDF/Kerbside waste I composites. In most cases MDF/Kerbside waste I composites have inferior mechanical properties of all the MDF/waste plastic composites tested along with a substantial amount of voids and unmelted inclusions. The properties of 40% MDF/Kerbside waste II composites are only slightly lower than those of the MDF/HDPE waste composites due to the addition of 1% Epolene which may have improved interfacial bonding. The MDF/Kerbside waste II composites also have the advantage of lower cost because the waste plastics used would require the least amount sorting after collection.

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