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Review

Use of recycled plastics in wood plastic composites – A review

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ABSTRACT

The use of recycled and waste thermoplastics has been recently considered for producing wood plastic composites (WPCs). They have great potential for WPCs manufacturing according to results of some limited researches. This paper presents a detailed review about some essential properties of waste and recycled plastics, important for WPCs production, and of research published on the effect of recycled plastics on the physical and mechanical properties of WPCs.

1. Introduction

Recycled and waste thermoplastics are some of the major components of global municipal solid waste (MSW) and they present a promising raw material source for WPCs, especially because of the large volume and low cost of these materials. Table 1 shows that waste plastics account for 11.2% of the annual 84.2 thousands tons of the municipal waste stream generated in Tehran during 2006 (Ashori, 2008) and 12.4% of 250 million tons in the USA during 2010 (EPA, 2011).

As given in Table 2, high density polyethylene (HDPE), low density polyethylene (LDPE/LLDPE), polypropylene (PP), Polyethylene terephthalate (PET), polystyrene (PS) and polyvinyl chloride (PVC) are the primary constituents of plastics in MSW. The blend of the mixed waste plastics can be changed depending on the regional habits and seasons of a year and on the mode of waste collection, also (Chanda and Roy, 2007). Table 2 also shows that only 7.6% of 31 million tons (12.4% of MSW) of generated waste plastics were recycled.

Reutilizing the post-consumed polymeric materials reduces the environmental impact and the consumption of virgin plastics. 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 (Jayaraman and Bhattacharya, 2004).

Products manufactured from waste plastics for use are increasing, including floor carpets, flower vases, waste paper baskets, park benches, picnic tables (DeWeese, 1998) and plastic lumber (Dutta et al., 1994). Also, recycled plastics can be used in wood plastic composites (WPCs), which use will provide an additional market for recycled plastics. Trex, the largest supplier of wood-plastic composite lumber, purchases an average of over 227,000 kg of plastic scrap each day (Principia Partners, 2002). Winandy et al. (2004) listed some wood plastic composite products using recycled plastics, produced commercially in the USA.

Generally in WPC manufacturing, virgin thermoplastic polymers are widely used. The most prevalent polymers are PE, PP, PVC and PS. The waste and recycled plastics have been used for manufacturing WPCs already in 1990s and the use has significantly increased in the developed and developing countries in recent years. This paper presents a detailed review about waste and recycled plastics and the research published on the effect of recycled plastic on the physical and mechanical properties of WPCs.

2. Properties of waste and recycled plastics

If the recycled plastics are considered as new materials in WPCs production, it is necessary primarily to understand well the elemental and fundamental structure of these materials. By knowing the properties of recycled plastics, the processes for manufacturing WPCs can be well controlled and then the relationship between the properties of recycled plastics and their mechanical aspects can be better understood as well as those of the resulted WPC products.

At the end of the first life cycle of plastic products, or after being re-used several times, plastics can be recycled to yield new polymeric materials or products. Since recycled plastics may be obtained from various sources, having been exposed to different storage and reprocessing conditions, they may therefore exhibit different performance depending on their degradation level. Then the post-consumer plastics waste may contain many grades, colors

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Table 1
Generated materials in the municipal solid waste in Tehran (Iran) in 2006 (Ashori, 2008).

Source	Amount in municipal solid waste	
	Weight ($\times 10^3$ tons)	Percentage
Dried bread	42.1	35.5
Paper and paperboard	22.1	18.6
Miscellaneous inorganic	13.2	11.1
Plastics	11.2	9.4
Metals	9.0	7.6
Glass	1.7	1.4
Textiles	0.7	0.6
Total	84.2	100

Table 2
Types and quantities of plastics in municipal solid waste in the USA in 2010 (EPA, 2011).

Type of plastics	Generation		Recovery	
	10^3 tons	Percent	10^3 tons	Percent of generation
PET	3980	12.8	560	14.1
HDPE	5450	17.6	570	10.5
PVC	910	2.9	–	–
LDPE/LLDPE	7430	23.9	420	5.7
PLA	50	0.2	–	–
PP	7530	24.3	60	0.8
PS	2060	6.6	20	1.0
Other resins	3630	11.7	730	20.1
Total plastics in MSW	31,040	100	2360	7.6%

and contaminants, leading to varying outcomes when these plastics are combined with wood flour/fillers.

Plastics degradation is a problem that frequently occurs when a polymer is submitted to a process or service. According to the mode of initiation, the following types of degradation can be distinguished: thermal, chemical, mechanical, and biological. Degradation processes are generally quite complex; often more than one type of degradation is operational, e.g. thermo-oxidative degradation, thermo-mechanical degradation, etc. Degradation usually manifests itself as discoloration, loss of volatile components (smoking) or loss of mechanical properties. Although in some cases the properties of recycled plastic is similar to virgin plastic, mostly the properties of waste and recycled plastics are very different from virgin plastics.

The properties of waste plastics are different in some essential factors which are important in WPCs manufacturing, because the properties of WPCs are a function of the plastic properties. These essential factors are discussed below.

2.1. Melting point

To enable a thermoplastic to flow, it needs to be heated above its melting point. The melting points of common plastics are shown in Table 3. Any recycled plastics which can melt and be processed below the degradation temperature of wood or other lignocellulosic fillers (200 °C) are usually suitable for manufacturing WPCs (Clemons, 2008). Generally, no significant differences were observed in the melting points of virgin and recycled plastics (Achilias et al., 2008; Kazemi-Najafi et al., 2009; Ghahri et al., 2012a), but in some cases the plastic waste (created from commercial products) that contains any impurities and additives may have a melting point above 200 °C.

Melting points are critical when the recycled plastics are a mixed waste of different polymers with a different melting temperature. In such a case, the melting point is not a point but a

Table 3
Melting points of common thermoplastics (Goodship, 2007).

Polyolefin	Melting point (°C)
LDPE	115
LLDPE	123
HDPE	130
Polyethylene (PE)	135
Polypropylene (PP)	170
Polystyrene (PS)	240
Polyethylene terephthalate (PET)	245
Polyamide 6 (PA6)	233

distribution of temperature. The plastics with a lower melting temperature flow faster than those with a higher melting point; thus the final product will be heterogeneous. In case of the plastic wastes mixture of PP and LDPE, if the mixture is processed at a temperature suitable for the LDPE fraction (115 °C), the PP will not melt (170 °C). The un-melted PP would be points of mechanical weakness in the final heterogeneous products. If the mixture is processed above 170 °C (the melting point of PP), both fractions will melt but the temperature is much higher for the LDPE fraction and it may begin to thermally degrade (Goodship, 2007). Degradation of LDPE can cause a considerable loss in the mechanical properties of the plastic and resultant WPCs. The optimum temperature for processing of mixed plastics waste can be obtained by more experiments.

2.2. Immiscibility

Because separation of recycled plastics from each other imposes additional costs, so it is desirable to be able to use these recycled plastics blended together. Generally in plastic industry, polymer blending is a convenient way to overcome the basic disadvantage of a polymer and also a way to decrease the cost of production. For example, the low impact strength of PP is improved by blending it with other polymers (Mehrabzadeh and Ghasemi, 1997).

In addition regarding different melting points (which was discussed earlier), the major problem with mixing plastics is the fact that most polymers are generally immiscible with each other (Table 4).

The poor physical attraction at phase boundaries of immiscible blends can lead to a phase separation under stress, resulting in poor mechanical properties (Chanda and Roy, 2007). The lack of compatibility between the polymers in polymer blends considerably reduces the quality of the products made from mixed plastics such as WPCs. An effective way to improve the compatibility between the plastics is to use compatibilizing agents (compatibilizers), compatiblizer as they improve the interfacial adhesion between the polymers and the dispersion of one component in

Table 4
The miscibility between some polymers (Goodship, 2007).

Polymer	PS	PA	PC	PVC	PP	LDPE	HDPE	PET
Polystyrene (PS)	Y							
Polyamide (PA)	N	Y						
Polycarbonate (PC)	N	N	Y					
Polyvinyl chloride (PVC)	N	N	N	Y				
Polypropylene (PP)	N	N	N	N	Y			
Low density polyethylene (LDPE)	N	N	N	N	N	Y		
High density polyethylene (HDPE)	N	N	N	N	N	N	Y	
Polyethylene terephthalate (PET)	N	N	N	N	N	N	N	Y

Y = miscible; N = immiscible.

another one. Compatibilizers are commercially available for combining a wide range of virgin plastics (Lee et al., 1994; The and Rudin, 1994; Flaris et al., 1995; Bertin and Robin, 2002; Kallel et al., 2003; Krach et al., 2004; Ubonnut et al., 2007) and this technology can also be applied to recyclate blends (Ha et al., 1996, 1999; Fang et al., 2001; Bertin and Robin, 2002). The compatibilizers can be added during reprocessing usually at levels of around 2–5%. The cost of the compatibilizer must be taken into account, but this is offset against the elimination of the cost of separation and the gain in properties and commercial value.

On the other side, the different degradation of polymers during processing and service life can affect the compatibility of the blend components during processing. For example, the compatibility is affected by the presence of carbonyl groups produced by thermo- and photo-oxidation in polymers. The formation of these carbonyl groups in degraded poly-olefin can act as compatibilizer, increasing the phase compatibility in recycled polymer blends (La Mantia and Curto, 1992; Waldman and De Paoli, 1998).

2.3. Rheology

The melt flow index (MFI) is a measure of molecular weight and molecular weight distribution characteristics of plastics in industry. The plastics with higher MFI have shorter chains and therefore lower molecular weight and easier flow (Strong, 2006). The opposite is also true. A low melt index means longer chains and high molecular weight. An increase in molecular weight leads to an increase in melt viscosity and impact strength, but leads to a lower yield strength, lower hardness, lower stiffness and lower softening point. Generally for linear polymers, when MFI is plotted against molecular weight, third order lines are obtained (Tzoganakis et al., 1988; Bremner et al., 1990). An increase in melt flow index of recycled plastics improves the impregnation of plastic on lignocellulosic fillers.

Several authors have investigated the changes of rheological properties of plastics after repetitive extrusion and injection molding (Guerrica-Echevarria et al., 1996; Canevarolo, 2000; Da Costa et al., 2005, 2007; Meran et al., 2008; Kazemi-Najafi et al., 2009). The results showed an important decrease in melt viscosity (increase in MFI) of PP and PE. Generally virgin poly-olefins contain some loaded antioxidants (around 0.1% w/w) (Klyosov, 2007). When the virgin plastics are processed into any products, the initial antioxidant during the processing due to overheating and excessive shear is largely (or completely) depleted. For this reason in the next process, lack (or insufficient amounts) of antioxidants will cause degradation (depolymerization) in polymeric plastics. Kazemi-Najafi et al. (2009) and Canevarolo (2000) showed a significant reduction in the molecular weight in the second round of extrusion during multiple extrusions, which caused a great increase in MFI. This behavior was expected as a result of the polymer chain degradation due to a severe thermal and stress cycle exerted during the extrusion process, leading to a molecular weight reduction. PP is notably less stable than PE, as reflected in the higher concentration of antioxidants and stabilizers required to give it the necessary stability during processing and in service life (Sadrmohaghegh and Scott, 1981). Antioxidants can slow the thermo-mechanical degradation during the reprocessing steps, then avoiding drastic deterioration of the final properties of the recycled plastics (Tzankova Dintcheva and La Mantia, 1999). Lack of antioxidants in the recycled plastic (especially multi-recycled) will be an important factor to accelerate WPC oxidation in presence of temperature and ultraviolet (UV) light. Adding antioxidants aims both at preserving the plastic during the processing at high temperatures and at saving wood/recycled plastic composites from a rapid deterioration under direct sunlight, air oxygen, water, pollutants, and other elements. PPs are more prone to oxidation, hence, requiring significantly higher amounts of antioxidants and UV stabilizers compared to PE (Klyosov, 2007).

MFI values in combination with crystallinity (small value of MFI and high crystallinity % in recycled plastics means that the polymer chains are closely packed with long polymeric chains) would help in deriving meaningful conclusions about the structure of the recycled plastics materials.

2.4. Crosslinking

In general, different methods are used to modify the properties of thermoplastics for special applications by cross linking (Tamboli et al., 2004). The crosslinking reduces the melt flow index, crystallinty, Young modulus and elongation at break, while it improves the impact strength, creep resistance, resistance to slow crack growth and also environmental stress crack resistance.

The crosslinked polymers are used in a wide range of applications such as hot water pipes, packaging and electrically insoluble applications (Ciesielska, 1998; Nalwa, 1999) and for this reason, MSW contains a considerable amount of crosslinked polymers. The degree of crosslinking changes from application to application.

In addition to crosslinked polymers which exist in MSW, crosslinking may also be induced in polymers during reprocessing and service life. Plastics are widely used for many outdoor applications, exposed to sunlight that causes weathering at long periods. During weathering, polymers are exposed to UV light, heat, and moisture, causing thermo- and/or photo-oxidation to occur. Degradation of some thermoplastics under accelerated and natural weathering have been studied by several researches and the results showed various levels of crosslinking induced in PE (Valadez-Gonzalez et al., 1999; Gulmine et al., 2003; Gulmine and Akcelrud, 2006a,b; Stark and Matuana, 2004; Kazemi-Najafi and Englund, 2013) and PP (Girois et al., 1996). The crosslinking levels depend on light intensity and spectrum, exposure time, temperature, sample thickness, etc. (Girois et al., 1996).

Crosslinking prevents the mobility of molecular chains, causing an interruptive melt-flow behavior that can change the nature of the polymer from a thermoplastic to thermoset (Tamboli et al., 2004). Due to its thermoset nature, the recycling of crosslinked polymers cannot be carried out by melting them, because crosslinked polymers do not melt. Fig. 1 shows the injection mold of virgin HDPE and HDPE exposed to 200 h accelerated weathering at the same processing conditions. Because of considerable crosslinking induction during weathering, the exposed HDPE did not exhibit a thermoplastic melt flow and failed to fill the mold. Fig. 2 shows the image of the flexural and tensile samples of WPCs (containing a different content of highly crosslinked HDPE) prepared by injection molding (Kazemi-Najafi and Englund, 2013). By increasing the crosslinked HDPE content to 20% or higher, the mold could not be filled by the wood flour–HDPE blends. This phenomenon indicates the poor processibility of highly degraded and crosslinked HDPE. The use of crosslinked recycled plastics causes some non-molten regions in the matrix within WPCs (Satoto et al., 1997). These non-molten areas can be the location of stress concentration, which will affect physical and mechanical properties of the composites.

2.5. Crystallinity

Crystallites (crystallinity) promote rigidity, hardness, and heat resistance. On the other hand, amorphous regions give rise to flexibility of polymer chains. In recycled plastics the amount of crystallinity is usually less than that of virgin plastics.

The results of Differential Scanning Calorimetry (DSC) for recycled PP and PE show a decrease in percentage of crystallinity (Valadez-Gonzalez et al., 1999; Baquero et al., 2002; Gulmine

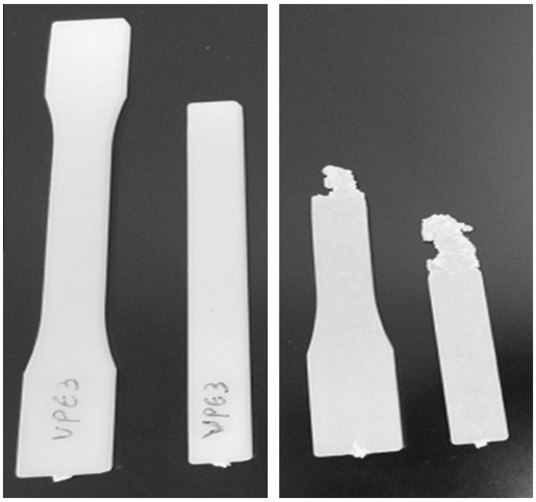

Fig. 1. Injection-molded specimens of virgin HDPE (left) and exposed HDPE after 200 h (right) (Kazemi-Najafi and Englund, 2013).

et al., 2003; Kazemi-Najfi and Englund, 2013). Reduction in crystallinity can be related to crosslinking which takes place in plastics during exposure to thermo- or photo-oxidation, because the crystallinity of the solid polymer decreases with increase in the crosslinking (Tamboli et al., 2004). An increase in mechanical properties like the modulus of recycled PP and PE compared to virgin material can be attributed to crosslinking of the polymer chains by chain scission (NarasimhaMurthy, 2005). The recycled PP and PE contains smaller polymer chains (lower molecular weight) that are formed by chain-scission during the recycling process (may by crosslinking, too). These results show a change in the structure of the recycled plastics.

In contrast to PP and PE, the DSC results show that the recycling of blow molded PET bottles (by extrusion-pelletizing and then injection-molding into tensile specimens), if subjected to thermal cycles of the processes, has a positive effect on crystallization and in turn on mechanical properties (Fann et al., 1996). Avila (2001) and Mancini and Zanin (1999) reported similar results. The reason is that the secondary bonds between chains are attacked when subjected to thermal cycling rather than the chain length of recycled PET decreasing, retaining a less amorphous (more crystalline) structure.

A study on recycled expanded polystyrene (which was extruded and then injection-molded into test specimens), showed that the tensile strength decreases almost linearly with increasing the number of processing cycles. The tensile strength after one cycle was 35.0 MPa while it was reduced to 24.2 MPa after six cycles of injection molding. The impact energy decreased drastically after three times of injection-molding (Ciesielska, 1998).

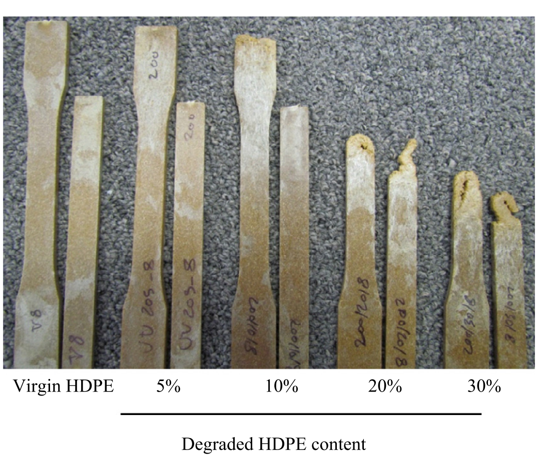

Fig. 2. The flexural and tensile composite samples containing wood flour and virgin and accelerated weathered HDPE (Kazemi-Najafi and Englund, 2013).

2.6. Polarity

In general, PE and PP which are widely used in WPC manufacturing have low polarity and low surface free energy which contributes to highly hydrophobic nature. Surface modification and functionalization is an approach used to modify the surface properties (for some applications) of these polymers without affecting their bulk properties. During modification some polar groups are induced in polymer and the wettability and hydro-philicity of the polymer increases (Cho et al., 2006). This phenomenon will increase the compatibility and interface adhesion between the polymer and hydrophilic natural filler/fibers, the reason the existence of such materials in MSW will be of benefit for recycled plastics on WPC manufacturing.

In addition, the polymeric products during their service life are exposed to UV radiation of solar light. In the presence of oxygen or ozone, oxidation of the polymer will happen. This event significantly shortens the lifetime of plastics. During the oxidation of poly-olefin (thermo-oxidation and photo-oxidation), a considerable amount of chemically bound oxygen is incorporated into the polymer in the form of carbonyl (ketone, aldehyde, carboxyl, ester) and hydroxyl groups (Hoekstra et al., 1995; Girois et al., 1996; Valadez-Gonzalez et al., 1999; Tidjani, 2000; Carrasco et al., 2001; Gulminea et al., 2003; Gulmine and Akcelrud, 2006a; Kazemi-Najafi and Englund, 2013). The number of the various types of carbonyl groups depends upon the chemical and physical structure of the polymer and on experimental conditions such as layer thickness, physical state, temperature, and oxygen concentration (Iring et al., 1980).

The formation of polar groups in recycled plastics (especially in PP and PE) improves compatibility between non-polar plastics and polar lignocellulosic materials. Oxidized polyolefin have been successfully used as compatibilizer for plastics reinforced with talc (Abdouss et al., 2004), organo-clay (Durmus et al., 2007), glass fiber (Dang et al., 2007) and different lignocellulosic fiber/fillers (Lu et al., 2005; Kazemi-Najafi et al., 2011; Raeesi-Nafchi, 2011; Bahrami, 2012). Kazemi-Najafi et al. (2011) showed that oxidized PP is more effective than maleic anhydride-grafted polypropylene (MAPP) as coupling agent in improving the physical and mechanical properties of wood flour–PP composites. It must be noted that sometimes the formation of polar groups are accompanied with crosslinking in photo-oxidized plastics; and as mentioned before, crosslinking has a negative effect on processability of plastics. Li et al. (2011) showed marked improvement in the interfacial interaction of sericite with the matrix for the irradiated HDPE/sericite composites. They indicated that no crosslinking is induced in irradiated (short time UV exposure) HDPE.

3. Use of waste plastic in WPCs

The studies of WPCs based on recycled thermoplastics are limited. Most of the studies have been focused on the use of either a single type of waste plastic (for example, the milk bottle) or a combination of recycled and virgin plastics to produce the WPCs, though some also on using recycled plastic blends. However, the impact of recycled or waste thermoplastics in WPCs is still not fully understood, leaving open research opportunities for the optimization of product properties. There are varying results for the influence of recycled plastics on WPC properties, which are reviewed in 3 categories as shown below.

3.1. Effect of recycled plastic on flexural and tensile properties of WPCs

Tensile and flexural properties of wood/recycled plastic composites have been studied by some authors. Yam et al. (1990) studied them on composites made from aspen fibers and recycled HDPE, but they did not compare the results with composites made from virgin HDPE. Youngquist et al. (1994) compared the mechanical properties of the WPCs made from two types of recycled PP and two types of recycled fibers (waste newspaper and old magazines). The WPCs were manufactured by a melt blending method. The materials were compounded in either a single-screw extruder or a K mixer and the test specimens prepared by injection molding. The results showed that with the same filler, substituting recycled PP for virgin PP leads to lower strength and stiffness.

Tzankova Dintcheva and La Mantia (1999) investigated the effect of the addition of wood fibers on recycling of a light fraction sample of MSW (mainly containing PP and PEs). They observed that it led to a remarkable increase of the elastic modulus and the tensile strength remained almost unchanged. The use of functionalized PP samples improved the mechanical properties, in particular at very low concentrations.

Ha et al. (1999) studied the effect of combining cellulose on the properties of virgin and/or recycled commingled plastics with a simulated waste-plastics fraction composed of HDPE, PP, PS, PVC (PE/PP/PS/PVC 57/1/1/1 by weight ratio). The compatibilizing effect of maleic anhydride-grafted styrene–ethylene/butylene–styrene block copolymer (SEBS-g MAH) for the cellulose-reinforced commingled blends was also investigated. It was found that the addition of more than 12.5% cellulose into the commingled blends was effective in enhancing the flexural and tensile strengths of the virgin and recycled blends. The compatibilizer significantly increased the mechanical properties. The composites containing virgin plastics exhibited superior mechanical properties from those containing recycled plastics.

Sellers et al. (2000) demonstrated that for hot-pressed composites of recycled pine wood fibers and recycled PE, these composites have mechanical properties suitable for construction applications. Kamdem et al. (2004) found that the flexural modulus and strength of boards made with virgin HDPE was higher than those made with recycled HDPE. Mali et al. (2003) reported that the tensile strength and modulus of WPCs made from recycled PP are higher than those made from virgin PP. The recycled PP exhibited higher tensile properties compared to virgin PP. Selke and Wichman (2004) produced recycled HDPE (simulated milk gallon)–wood fiber composites using extrusion molding and reported that the composites were at least as good as the composites based on virgin plastic, and in most cases the differences between the recycled and virgin matrix composites were not statistically significant. Jayaraman and Bhattacharyya (2004) investigated the performance of melt blending and injection molding composites made of *Pinus radiata* fibers and different kinds of recycled HDPE and found that the tensile and flexural properties of these composites at room temperature and humidity depend on the mechanical properties of the waste plastics. They did not compare the results to composite made of virgin plastics. They concluded that plastics from the post-consumer waste stream can be successfully utilized to make composite materials with useful mechanical properties. Kazemi-Najafi et al. (2006a) found that the flexural and tensile properties of specimens containing recycled plastics (HDPE and PP) are statistically comparable to those composites made of virgin plastics. The composite containing recycled PE and recycled PP blend exhibited statistically a higher flexural modulus compared to those made of mixed virgin plastics (virgin PE/virgin PP).

Composites based on recycled HDPE and natural fibers were made through melt blending and compression molding by Lei et al. (2007). The effects of the fibers (wood and bagasse) and the coupling agent type/concentration on the composite properties were studied. The results showed that the coupling agents improve the compatibility between the bagasse fiber and recycled HDPE, and that the mechanical properties of the resultant composites are comparable with those of virgin HDPE composites.

Ashori and Nourbakhsh (2009) investigated the tensile and flexural properties of the composites made from recycled plastics and old newspaper fibers. The results indicate that the composites with recycled HDPE provide moderately superior properties as compared to recycled PP samples.

Jayaraman and Halliwell (2009) produced composite specimens and sheets consisting of fibers from the flax plant (Phormium tenax or Harakeke) and waste plastics blends through screwless extrusion followed by injection molding. The proportion of each recycled plastics (PP, HDPE, LDPE and PET) was set in proportion similar to the plastics contained in the household waste stream in New Zealand in order to produce a waste plastics blend. The tensile properties of the composites showed reasonable higher than those made of the waste plastics blend. Also the composites could be thermo-formed into complex shapes.

Adhikary et al. (2008) have shown that the mechanical properties (flexural and tensile properties) of the composites made from post-consumer recycled HDPE are similar to or, in some cases, better than the composites made of the virgin HDPE.

Kazemi-Najafi et al. (2009) studied the influence of twice extruded PP on the mechanical properties of wood flour/PP composites. The results showed that the flexural modulus and the strength of PP are significantly increased by extrusion and re-extrusion of virgin PP. The composites containing recycled PP exhibited higher flexural properties and hardness than those containing virgin PP. MAPP significantly increased the mechanical properties of the composites made of both virgin and recycled PP. Similar results were found by Ghahri et al. (2012a).

The influence of highly degraded HDPE on the physical, rheological and mechanical properties of wood flour–HDPE composites was studied by Kazemi-Najafi and Englund (2013). For this purpose, virgin HDPE was subjected to accelerated weathering. The virgin and exposed HDPE and pine wood flour were compounded to produce wood flour–HFPE composites. Accelerated weathering degraded HDPE highly and created extensive crosslinking in HDPE and consequently poor processibility. Only a small part (10%) of the virgin HDPE could be replaced by highly degraded HDPE for wood flour–HDPE composite manufacturing. The tensile and flexural properties of the composites containing highly degraded HDPEs were similar to the composites with virgin HDPE and exhibited superior properties in some cases.

3.2. Effect of recycled plastic on hygroscopic properties of WPCs

Water absorption and the consequent thickness swelling are the most important characteristics of WPCs exposed to environmental conditions, determining their end-use applications. Therefore, the hygroscopic characteristics have to be taken into account in the design of WPCs for their final application as limiting parameters. For this reason, considerable research has been conducted on water absorption of WPCs made of virgin plastics. The hygroscopic properties of wood/recycled plastics have also been studied in limited researches.

Kazemi-Najafi et al. (2006b) found that the maximum water absorption and diffusion coefficients of WPCs of recycled plastics (PP or HDPE) are higher than those made of virgin plastics. WPCs made of the mixture of recycled PP and recycled HDPE exhibited the highest water absorption and diffusion coefficients. Water absorption of the composites was proved to follow the kinetics of a Fickian diffusion process.

Short-term water absorption of wood plastic composites (WPCs) produced from sawdust and virgin and recycled plastic (HDPE and PP) was studied by Kazemi-Najafi et al. (2007). The results showed that water absorption of WPCs made of recycled plastics is higher than those made of virgin plastics and those made of a mixture of recycled PP and recycled HDPE exhibit the highest water absorption (Fig. 3).

Adhikary et al. (2007) showed that the composites made from the recycled plastics (PP and HDPE) show comparable water absorption and thickness swelling to the composites made of the virgin plastics. However, the water uptake and thickness of swelling can be reduced significantly with the incorporation of the coupling agent (MAPP) in the composite formulation. Adhikary et al. (2008) also showed that the wood plastic composites containing 50% by weight of recycled HDPE have lower water absorption and thickness swelling compared to those made of 50% virgin HDPE.

Kazemi-Najafi et al. (2008) have studied also long term thickness swelling of composites made of recycled plastics immersed in water. The results showed that the maximum thickness swelling of composite made of virgin and recycled plastics (PP and HDPE) are the same, but by increasing the recycled plastics content, the swelling parameter rate considerably increases. The composites containing a mixture of recycled HDPE and PP exhibit the highest swelling parameter rate.

The influence of thermo-mechanically degraded PP on water absorption and thickness swelling of beech wood flour–PP composites was studied by Kazemi-Najafi et al. (2010b). According to the results, the composites containing recycled PP exhibit higher water absorption and thickness swelling. They also concluded that the degradation of PP may influence MAPP performance of decreasing these parameters for wood flour–PP composites.

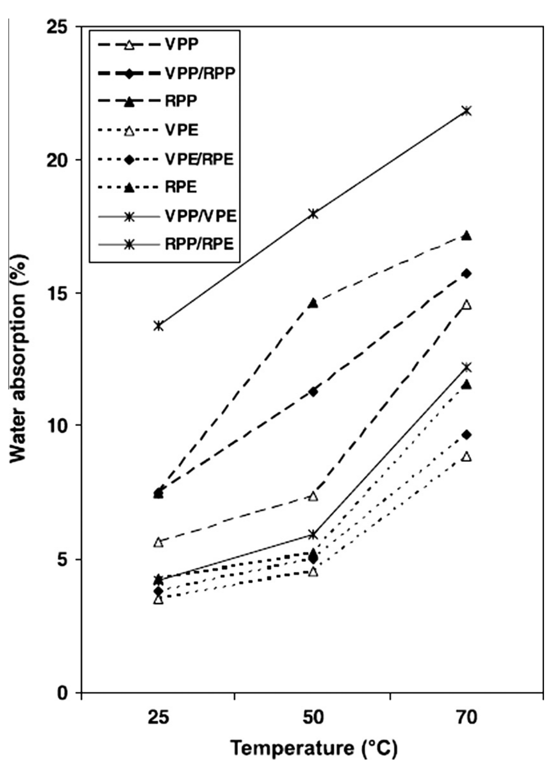

Fig. 3. Water absorption of composites after 24 h immersion in water at different temperatures (V = virgin and R = Recycled) (Kazemi-Najafi et al., 2007).

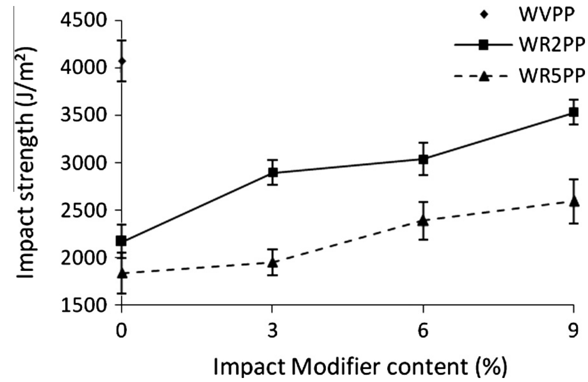

Fig. 4. Effect of impact modifier (EVA) on impact strength of WPCs (W = wood flour, V = virgin, R2 = twice recycled, R5 = five times recycled) (Ghahri et al., 2012a).

3.3. Effect of recycled plastic on impact strength of WPCs

In contrast to flexural, tensile and hygroscopic properties, almost all of the researches showed lower values of impact strength for WPCs made of recycled plastics than for those containing virgin plastics. Youngquist et al. (1994) showed that with the same filler, substituting recycled PP for virgin PP leads to lower un-notched impact energy. Kamdem et al. (2004) showed that the composite of virgin HDPE exhibite significantly higher un-notched impact strength. Kazemi-Najafi et al. (2006a) reported no significant difference between the impact strengths of composites containing virgin PP and recycled PP, but for HDPE composites, the impact strength decreased (about 20%) significantly when the recycled HDPE fraction increased to 50%. In this research, the impact strength of composite made of mixed recycled plastics was significantly lower (22%) than that made of virgin plastics.

Kazemi-Najafi et al. (2010a) reported that by replacing 50% of virgin PP by thermo-mechanically degraded PP, the impact strength of wood flour–PP composites decreases. Kazemi-Najafi et al. (2009) also showed that the impact strength of WPCs made of twice-extruded PP is significantly lower than of those made of virgin PP. Similar results were reported by Ghahri et al. (2012a) for two and five times extruded PPs.

Some attempts were made to improve the impact strength of the composites made of recycled plastics. The influence of ethylene–vinyl-acetate (EVA) and ethylene-propylene-diene monomer (EPDM) on the impact strength of sawdust-recycled PP composites was evaluated by Ghahri et al. (2012b). Both impact modifiers improved the impact strength of the composites, but the addition EVA gave the greatest improvement. Ghahri et al., 2012a also showed that by increasing the EVA content up to 9%, the impact strength of the composites containing recycled PP increases significantly but is still lower than the impact strength of composites containing virgin PP (Fig. 4). EVA decreases the flexural strength and modulus of wood flour–recycled PP composites.

Sharifi et al. (2012) investigated the improvement of the impact strength of composites made of wood flour and recycled PP by using nano-clay. The use of nano-clay increased significantly the notched and un-notched impact strength, the flexural and tensile modulus and strength, and decreased the water absorption and thickness swelling of the wood flour–recycled PP composites.

4. Conclusion

It has been shown that recycled thermoplastics have great potential for WPCs manufacturing. Because recycled plastics are probably obtained from various sources, exposed to different storage and reprocessing conditions, they may show different performance depending on their degradation level. The degradation of plastics due to repeated processing cycles and environmental exposure complicates recycling, so focused researches are required. Therefore, the effect of the degradation level of recycled plastics on mechanical properties and performance of WPCs needs to be identified to obtain an acceptable level of physical and mechanical properties of the final product. Such an analysis has not been addressed so far in the literature but should be considered. On the other hand, because the separation of recycled plastics imposes additional costs, it is required that these recycled plastic blends be used together. Thus more research is needed on WPCs produced from recycled plastic blends (or MPW).

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