

Review

An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites



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ARTICLE INFO

Article history:

Received 14 February 2014

Accepted 29 April 2014

Available online 14 May 2014

Keywords:

Glass fibre

Recycled mixed plastics

Civil engineering applications

Mechanical properties

Durability

ABSTRACT

In recent years, there has been an increasing interest in seeking the potential applications of recycled mixed plastic wastes in building and construction sectors to relieve the pressure on landfills. This paper presents the recent developments and applications of composite materials made from recycled mixed plastics and glass fibre. Some of the first uses for such composites are as an alternative to non-load bearing applications like park benches and picnic tables. With its inherent resistance to rot and insect attack, these composites can in fact be used as a replacement for chemically treated woods in various larger-scale outdoor applications such as railroad crossties and bridges. However, the properties of the structural components made from recycled mixed plastics are not well understood. Information on the behaviour of such composites under applied loading and at different environmental conditions such as elevated temperature and ultraviolet rays are crucial for the utilisation of recycled mixed plastic materials in construction. This paper presents an overview of the mechanical properties and durability of recycled mixed plastic waste composites. The paper identifies research needs critical in the effective design and utilisation of these composite materials in civil engineering and construction.

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1. Introduction

The combination of three forces has created an opportunity for recycled mixed plastic composites. The first of these is the continuing population explosion, which has created a growing worldwide demand for building materials [1]. The second force is the increased price of the construction materials and decreased availability of quality timber. The third force is the plastic solid waste (PSW) crisis. Ever since the first industrial scale production of synthetic polymers (plastics) took place in the 1940s, the production, consumption and waste generation rate of PSW have increased considerably [2]. The world's annual consumption of plastic materials has increased from around 5 million tons in the 1950s to nearly 100 million tons in 2007 [3]. More and more plastics have been used in packaging, automotive and industrial applications, medical delivery systems, artificial implants, other healthcare applications, water desalination, land/soil conservation, flood

prevention, preservation and distribution of food, housing, communication materials, security systems, and other uses.

With such large and varying applications, plastics contribute to an ever increasing volume in the solid waste stream [4]. Table 1 presents the amount of municipal solid waste (MSW) and PSW generated in Australia, UK and USA. These data shows that the plastic waste comprises 10–16% of MSW by weight. In fact, plastics waste has become one of the largest categories in MSW, particularly in industrialized countries [5]. Due to the lower density of plastics, it contributes to an ever increasing volume in the solid waste stream. Relevant statistics showed that the disposal of plastics would soon become a major problem.

One of the best options to manage the PSW is recycling rather than incineration to decrease the waste volume and reduce environmental issue [6]. Thus, PSW recycling has been a focus of many researchers in the past few decades. Furthermore, the increasing cost and decreasing space of landfills are forcing considerations of alternative options for PSW disposal [7]. Such research is also driven by the changes in social and environmental issues [8]. Although plastics recycling are important, the data shown in Table 1 indicates that only about one-fourth post-consumer plastics waste is recycled around the world while most of them continue to be disposed in landfill and harm the environment.

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Table 1
Plastic waste data.

	MSW generated (million tons)	PSW generated (million tons)	Recycling rate (%)	Reference
Australia in 2008	14	2.3	23	[9]
UK in 2008	32	3.2	24	[10]
USA in 2011	250	32	8.3	[11]

While recycling of plastic products is actively promoted, most of the recycled plastic cannot be used for the same application for reasons of health and environmental protection [12]. One of the efforts to meet this challenge is to convert these plastic wastes into products suitable for housing and construction. Composites manufactured from recycled mixed plastics offer the promise of relieving the pressures on both the landfills and the forests. Recycled mixed plastic extruded in the shape of lumber, generally called 'plastic lumber' is now extensively used in construction [13]. These materials have many advantages including recyclable, natural resistance to rot and insect attack, low energy consumption, low cost, light weight, and good specific mechanical properties [14]. Being lightweight, these materials are easy, fast and economic to install as it requires minimal handling and reduces energy in transportation. More importantly, they offer a totally recyclable material compared to thermoset polymer composites which is now becoming a major environmental hazard in many countries [15]. However, the material properties of the currently available plastic lumber technologies are lower in comparison to solid wood. Their modulus of elasticity is typically one-fourth or less than those of the solid wood which is seen as the main limitation of its usage in civil engineering applications [16]. To expand the available markets for building products manufactured from recycled plastic wastes, the strength and stiffness properties of these materials must be enhanced by adding reinforcement and other chemical additives.

This paper provides an overview on the current research and developments on recycled mixed plastic composites and information on their mechanical properties and durability under different environmental conditions. The effect of fibre reinforcement and chemical additives on the performance of recycled mixed plastic is presented. Critical issues crucial to their effective design and utilisation in civil engineering and construction are also discussed.

2. Current application of recycled mixed plastics composites

New materials and various combinations of recycled materials are constantly being proposed and used in the construction industry. Converting mixed plastic wastes into plastic lumber is considered as an effective alternative to landfilling. Some of the first uses for plastic lumber were in items like park benches and picnic tables as shown in Fig. 1. While the use of plastic lumber to make such small-scale products is completely appropriate, using recycled mixed plastics in load-bearing and structural applications would consume much greater volumes of plastics waste.

Recycled plastics have already been used on several civil engineering materials. Rebeiz, Fowler [18] have studied the behaviour of recycled plastics in polymer concrete where they found that the combination of these materials can provide an economical and technological attractive material system for a variety of engineering applications. Saadeghvaziri, MacBain [19] have presented the design and construction of an innovative dual-purpose screen using recycled plastics that can block headlight glare while having adequate height to deter pedestrian crossover. They found that the strength and stiffness of the recycled plastic materials satisfy the

structural and geometric requirements for the intended application. Babu and Chouksey [20] have used the plastic waste as reinforcement material in soil for ground improvement, sub-bases and subgrade preparation in road construction. They observed that the strength of the soil is improved and the compressibility is reduced significantly with the addition of small percentage of plastic waste to the soil. These studies have focused on using unreinforced thermoplastics in the development of structural products.

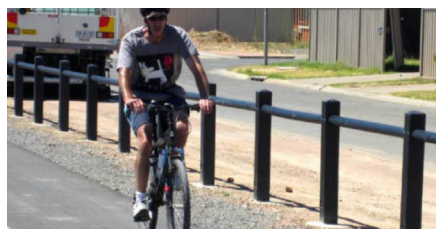
Plastic lumber has in fact been used as a replacement for chemically treated woods in various larger-scale outdoor applications due to its inherent resistance to rot and insect attack. Reinforced with glass fibre, recycled mixed plastic composites have been developed for infrastructure, railroad crossties and bridges. As these composites do not contain toxic preservatives such as chromated copper arsenate that may leak into seawater and cause environmental problems, it can replace the preservative-treated lumber for marine use. This has great potential because the high quality wood for construction is now becoming less available. Some of the bridges built from recycled thermoplastic are shown in Fig. 2. These bridges were made by nearly 100% recycled post-consumer and industrial plastics and were developed by the researchers at Rutgers University, New Jersey and manufactured by Axion International, Inc. [21]. In 1998, the first vehicular bridge made up of polystyrene (PS)/high density polyethylene (HDPE) with a rectangular cross-section was constructed at Fort Leonard Wood, Missouri. The bridge used steel girders to support the plastic section. Although it has high initial cost, there was no maintenance which makes it a cost effective than traditional construction materials. In 2002, a bridge with I beam cross sections was constructed at Wharton State Forest, New Jersey. In 2009, the first bridge in the world made of recycled plastics reinforced with glass fibre was built at Fort Bragg, North Carolina. All bridge components including girders, pier caps, decking, railings and pilings were made from recycled plastics. In 2010, Fort Eustis in Virginia opened the world's first thermoplastic railroad bridges to replace two aged railroad timber bridges. This suggests that it is possible to apply these new generation materials to beam and/or column.

Nosker et al. [22] have discussed about the performance-based approach to the development of a recycled plastic/composite crosstie. It was found that the physical properties of the composite railroad ties exceeded the established targets. The permanent deformation under lateral loads and rail seat compression were both tested in the laboratory and found to sufficiently meet the performance criteria. This resulted in the installation of the first ten plastic ties at Rose Yard in Altoona in October 1995. The ties were non-consecutive and were intermingled with twenty wood crossties. In April 1996, two consecutive ties were placed in a 5-degree curve in the FAST track at the American Association of Railroads (AAR) Transportation Technology Center in Pueblo, Co as shown in Fig. 3. Another six ties were installed in the mainline service on Conrail's Pittsburgh Line in October 1996. The authors mentioned that there is no evidence of tie plate cutting, spike loosening, or any other sign of degradation on these ties suggesting the suitability of recycled plastic materials in this application.

Although several commercial products on glass-fibre reinforced recycled products have appeared in recent years. There is no detailed scientific study and lack of published academic work on glass fibre reinforced recycled mixed plastic wastes. There are also a number of issues on the application of these materials in building and construction which are discussed in the following sections.

3. Properties of plastic solid waste

Most plastics in use today are thermoplastics, which mean that the material can be melted and re-shaped. These plastics have the



Fencing in South Australia



Fence at Sorell Cemetery, Tasmania



Beach Walk at One Mile Beach, Forster



Seating at Xavier College, South Australia

Fig. 1. Non-structural mixed recycled plastic products [17].Fort Leonard Wood,
MissouriWharton State Forest, New
Jersey

Fort Bragg, North Carolina

Fig. 2. Vehicular bridge made of recycled plastics [8].

simplest molecular structure, with chemically independent macro-molecules [23]. This type of plastic is in solid form at ambient temperature and becomes deformable at elevated temperatures, and the process of hardening at low temperatures and softening at high temperatures is reversible. By heating, they are softened or melted, then shaped, formed, welded, and solidified when cooled. Multiple cycles of heating and cooling can be repeated without severe damage, allowing reprocessing and recycling.

In Australia, the largest component of the plastic waste is high density polyethylene (HDPE) at about 22.5%, followed by 16% of

polypropylene (PP), 15.6% of low density polyethylene/linear low density polyethylene (LDPE), 14.4% of polyvinyl chloride (PVC), 8.6% of polyethylene terephthalate (PET) and 22.9% of other types [24]. These five polymer types, together with polystyrene (PS), also dominate the plastic waste stream in the USA [25]. The tensile properties of commonly used virgin and recycled thermoplastics are shown in Table 2. Most studies have shown that the important properties of the thermoplastics are fairly well preserved during recycling. However, some authors have mentioned different results. The mechanical tests conducted by Müller et al. [26] on virgin and recycled PET showed that a great difference exists between

Recycled Plastic Railroad Ties prior to
installationRecycled Plastic Composite Ties being
installed**Fig. 3.** Railroad ties made up of recycled plastic [22].

the virgin and the recycled PET, the former exhibiting a brittle behaviour and the latter a ductile one. This result is a consequence of the difference in crystallinity between the materials which may happen due to the presence of contamination and degradation during processing.

Mølgaard [30] has concluded that recycling of plastic is only environmentally and resource sound if it is separated into its generic plastic types, which makes it possible to produce a recycled plastic with properties comparable to virgin plastic. However PSW is a mixture of several polymers and it is not practically possible to sort the polymers into its generic plastic form. This is due to several factors such as expensive sorting prices and the presence of different polymers in a single product [31]. The production of raw polymeric materials from crude oil is relatively inexpensive. Given the cost of collecting, shipping, sorting, and cleaning recycled polymers, there is little financial incentive for manufacturers of polymer resins to recycle material. Another factor that accounts for the existence of blends is that the articles are constructed from two (or more) different homopolymers. Examples of this include some detergent bottles made with the body of HDPE and cap of PP. A possible strategy to overcome this dilemma is to recycle waste plastics as “commingled or mixed plastics”, which means that the plastics are reprocessed without prior sorting according to plastic type. However the majority of plastic found in mixed plastic waste are immiscible, when melt blended, such plastic form complex dispersed morphologies and often have inferior mechanical properties, poor surface properties [32]. This type of recycling is therefore sometimes referred to as “down-cycling”. Thus, products made of mixed recycled plastics wastes are used for less-demanding, non-load bearing applications, such as outdoor furniture, decking or traffic barriers. This is mainly due to the following phenomena [33]:

3.1. Compatibility

There are many types of polymers which is immiscible and incompatible. When an attempt is made to mould a mixture of two or more polymer types, the different materials form separate phases, and the overall material sample typically has very poor mechanical properties and poor integrity. Even small amounts of an “impurity” polymer can have a negative effect on properties. Given that there are numerous different polymer types, implies that either the waste stream must be very efficiently sorted into its different components, or that a way must be found to compatibilise the various phases.

3.2. Contamination

By their nature, polymers can absorb low molecular weight compounds, which dissolve and migrate into the bulk of the material. Thus, compounds causing discoloration, odour, or toxicity may be incorporated into the material. The remoulding process would not be expected to result in destruction of dissolved contaminants; discoloration by impurities may become worse as a result of the

thermal treatment. Thus, remoulded material may not be usable for the original function, but may need to be employed in a less demanding (typically lower value) application.

3.3. Degradation

Polymers are subject to detrimental changes in their macroscopic properties due to subtle changes in molecular structure that can result from environmental factors: UV light, thermal-oxidative processes that can occur during moulding or even at room temperature, attack by pollutant gasses in urban environments, chemical interaction with liquid contents, and others.

From the above mentioned reasons; a careful separation is performed to obtain polymers as homogeneous as possible. By using the floatation method, generally two fractions are obtained from municipal post-consumer PSW: a light fraction, floating on water, and a heavy fraction. The former is essentially made of low and high density polyethylene and polypropylene – LDPE, HDPE and PP, commonly known as polyolefin, that exhibit of similar density. These polyolefin are the main components beings about 60–70%, other polymers such as PS, PET and PVC make up the remaining part of the composition with possibly minor quantities of polyamide, polycarbonate, acrylic polymers [34]. Polyolefin are that class of thermoplastic polymers synthesised by addition reactions of unsaturated monomers (alkyl-ethylene). HDPE, LDPE and PP differ structurally in the number and length of branches, whose presence tends to reduce the amount and size of crystals, as well as their melting and crystallisation temperatures [35].

Polyethylene (PE) consists of long chains of the monomer ethylene ($\text{CH}_2=\text{CH}_2$) and is produced through polymerization of ethane, and contain small proportions of additives. There are two major categories in PE: high-density polyethylene (HDPE) and low-density polyethylene (LDPE). HDPE is chemically the closest in structure to pure polyethylene. It consists primarily of unbranched molecules with very few flaws to mar its linearity whereas LDPE contain substantial concentrations of branches that hinder the crystallisation process, resulting in relatively low densities. As a result of these branches, HDPE has a high degree of crystallinity (typically 60–80%) and a high melting temperature of 135 °C and high density of 0.94–0.97 g/cm³, while LDPE has lower crystallinity (40–60%) and melting temperature of 125 °C and density of 0.90–0.94 g/cm³ [36]. HDPE is widely used in shampoo and detergent bottles, milk jugs, cosmetics, motor oil, toys, shopping bags, etc. Similarly, LDPE alone is used in shopping bags, six-pack rings, hard drive casings, CD and DVD cases.

Polypropylene (C_3H_6)_x (PP) have a semi-crystalline polymer structure similar to PE and is produced through polymerization of propylene gas. PP has an excellent resistance to stress, low specific gravity, and good mechanical properties such as excellent impact strength. It has a melting point of 160–165 °C, and has low density (0.85 g/cm³ with amorphous, 0.95 g/cm³ with crystalline) and higher stiffness and strength than HDPE. It is used in a wide range of applications, including food packaging, plastic parts and reusable containers of various types [37].

Although the similar chemical nature of the two main components, the mechanical properties of the recycled mixture of PE and PP are quite scare mainly because of the incompatibility and the possible presence of some heterogeneous particles. Polyolefin blends have been studied for many years. There have been many discussions about their miscibility. Liang et al. [38] reported that PP was miscible with LLDPE with blending ratio of 50/50. Li et al. [39] studied the blends containing 20% by mass of PP and LLDPE and found similar results. Bertin and Robin [34] have discussed about the incompatibility between LDPE and PP. In LDPE rich blends, a heterogeneous PP dispersion in the LDPE matrix produces two phases in the melt and the low interfacial adhesion between

Table 2
Tensile properties of virgin/recycled thermoplastics.

	Virgin		Recycled		References
	Tensile strength (MPa)	Tensile modulus (MPa)	Tensile strength (MPa)	Tensile modulus (MPa)	
PET	47	1890	24	1630	[26]
PP	30.1	690	24.1	550	[27]
HDPE	18.7	339	19.1	441	[28]
LDPE	16	180	12	220	[29]

the phases is responsible for a decrease in mechanical properties especially related to its morphology, including impact strength, strain at break and ductile to brittle transition [40]. Shanks, Li [41] have studied different blends of PP, HDPE and LDPE under differential scanning calorimetry and optical microscopy and found that the morphology is distinctly different in each case and the rates of crystallisation show that a phase-separated blend is present.

4. Methods to improve properties of recycled mixed plastics

There are several methods which can improve the material properties of composite materials. Xanthos et al. [42] have suggested that if the recycled composite material is designed correctly, i.e. all the phases present are well mixed and good interfacial adhesion is achieved; key properties for semi-structural applications (such as stiffness and strength) can be fairly independent from the recycled polymer matrix. The compatibility between polyolefin can also be improved by adding a third component such as compatibiliser, fillers and/or other additives.

4.1. Compatibilisation

Compatibiliser refers to an additive used to improve the miscibility and properties of a polymer blend. It can act like solid surfactants, reducing the interfacial tension coefficient, reducing the size of the particles of one polymer dispersed in the other, often improving their dispersion. Others functions of compatibilisers are to stabilise the morphology and to improve the adhesion between the constituents [43]. This has been proven by several researchers. Şirin and Balcan [44] have found that dialkyl peroxide affected the mechanical and the thermal properties of PP and LDPE blend. The morphology improved the interfacial energy between the PP and the LDPE greatly; hence the tensile properties are also improved significantly with a 30% increase in tensile strength. Similarly, Bertin and Robin [34] have incorporated ethylene-propylene copolymer (EPM), ethylene-propylene-diene monomer (EPDM), PE-g-poly (2-methyl-1,3-butadiene) on LDPE/PP blends which have resulted in a sharp effect on properties such as elongation at break and impact resistance. Better mechanical properties were achieved when the graft copolymer was used as shown in Table 3. The authors also observed that using rubbers (EPDM) as additives greatly influences the resilience due to the elastomeric behaviour of these copolymers which act as impact modifiers and influence this property. Penava et al. [45] have observed that the addition of EPDM to PP/LDPE blends improved the mechanical properties, especially the impact strength in LDPE-rich blends. The compatibilising efficiency of EPDM on PP/LDPE blends was confirmed on the improvement of elongation, impact strength and brittleness, morphological and phase structure but no improvement on tensile strength.

4.2. Reinforcement

Generally, the mechanical properties of recycled mixed plastics are markedly improved by adding fibres since fibres have much higher strength and stiffness than those of the matrices as shown in Tables 2 and 4. Mineral fillers and fibres are used frequently in the plastics industry to achieve desired properties.

The interest in natural fibre was generated due to the high material and processing cost, toxicity and specific gravity of the synthetic fibres. However, the efficiency of the wood fibre is less than that expected on the basis of the properties of this material and this is mainly due to the scarce adhesion between the polar filler and the apolar matrix [32]. The presence of hydroxyl and other

Table 3

Comparison of mechanical properties with different compatibilisers [34].

Material	Modulus (MPa)	Tensile strength at yield (MPa)	Elongation at break (%)
Post-consumer material (PCM)	256	10.3	449
PCM + 5% EPM	228	9.1	515
PCM + 5% EPDM	211	8.9	469
PCM + 5% graft copolymer	240	9.5	560

polar groups in natural fibres makes them hydrophilic in nature which results in incompatibility with the hydrophobic non-polar polymer matrices, especially polypropylene and polyethylene [48]. Besides this, natural fibre composites absorb high moisture when immersed in water [49]. The incompatibility between the fibres and polymer matrixes, the tendency to form aggregates during processing, the variation in quality and price and the difficulty in using established manufacturing process lead to the undesirable properties of the composites reinforced with natural fibres [50].

The composites with improved structural properties can be obtained from recycled plastic by the addition of rigid fillers or reinforcement as shown in Fig. 4. This situation was demonstrated better in a number of research works. Dintcheva et al. [51] investigated the effect of three different fillers namely glass fibres, calcium carbonate and wood fibres with the polyolefin recycled plastic and found that glass fibres outperforms others by increasing its tensile modulus from 460 MPa to 935 MPa with 20% glass fibre. However, the reduction of elongation at break was observed. Similar study was done by Putra et al. [52] on the effect of glass fibre, talc, wollastonite and gypsum on the mechanical properties of recycled-plastic composites. Both fillers and reinforcement shows increase in the stiffness of the materials. It was also observed that there is a reduction of tensile strength for gypsum and wollastonite as the fibre percentage increases. Their study found that glass fibres show the best results by improving its tensile and flexural strength by 30% and the significant increase in modulus by 250% with the addition of 30% glass fibre.

The effect of reinforcement is quite similar for tensile strength which shows values similar to those of the unfilled material, whereas the elongation at break is lower. Whereas, the elastic modulus increases with the filler and wood fibre and glass fibres show the best results. The addition of inert fillers strongly improves the rigidity of PSW mixture. These results can be interpreted both on the intrinsic properties and geometry of the reinforcement. Gypsum was not found to improve the properties because the particle size of gypsum is smaller and when no surface coating is present, small particles tend to agglomerate [53]. As

Table 4

Properties of selected natural and synthetic fibres.

Fibre	Density (g/cm ³)	Tensile strength (MPa)	Elastic modulus (GPa)	Yield strain (%)	References
<i>Natural</i>					
Cotton	1.51	400–900	1–12	3–10	[46]
Flax	1.51	800–2000	40–85	3–2.4	[46]
Hemp	1.48	550–900	26–30	1–6	[46]
Jute	1.46	400–800	10–25	1–2	[46]
Sisal	1.33	700	46	2–3	[46]
<i>Synthetic</i>					
E-glass	2.57	3400	72.5	2.5	[47]
S-glass	2.47	4600	88	3.0	[47]
Aramid	1.45	3500	133	2.7	[46]
Carbon	1.7	3700–4800	250	1.2	[47]

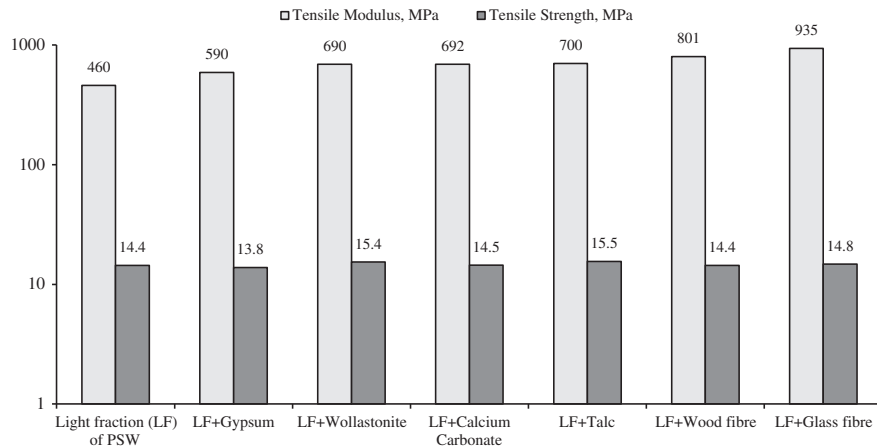


Fig. 4. Tensile properties recycled mixed plastics reinforced with 20% addition of different fibre [51,52].

discussed by Putra et al. [52], the plate-like structure of talc, the acicular structure of wollastonite and spherical particles shape of calcium carbonate exhibit high aspect ratios, which improve wetting with the polymer matrix and hence reduce the number of micro voids between the filler and matrix. Synthetic fibre such as glass fibre has the highest aspect ratio and gives significant and consistent reinforcement [54]. The effect of reinforcing glass fibres to recycled plastics are presented in the next section.

5. Glass fibre reinforcement

Glass fibres are one of the most cost-effective reinforcements for plastic. Short glass fibres can be compounded with recycled thermoplastic to obtain recycled products with improved property sets. They can be easily obtained from a range of manufacturers and their production process is quite energy efficient, so that their use into recycled products does not significantly affect the environmental performance. As discussed on the recent review by Scelsi et al. [55], the main interest in using glass fibres in polymer products is their better and more consistent performance than other fillers and reinforcements. This is due to the high aspect ratio of the fibres (the diameter is in the range of 10–20 μm and final length of 0.5 mm), which translates in an excellent reinforcing ability. The mechanical properties of composites are markedly improved by adding glass fibres to a polymer matrix since fibres have much higher strength and stiffness value than those of the matrices. The increase in material integrity and performance when adding glass fibre to recycled mixed plastic has been interpreted by some authors in terms of physical compatibilisation [56], i.e. binding of dissimilar resin domains through the fibres as shown in Fig. 5. The important parameters that affect the mechanical

properties and durability of recycled mixed plastics reinforced with glass fibres are presented in the succeeding sections.

5.1. Effect of reinforcement content

The addition of glass fibre from 10% to 30% by weight results in substantial increase in elastic modulus, accompanied by an increase in strength with reduced ductility [42]. A comparison of the effect of the amount of glass fibre reinforcement based on the results of studies conducted by several researchers is shown in Fig. 6. Since different authors have used different materials, the strength and modulus data were normalised by dividing the strength and stiffness of the specimens reinforced with fibres to that of the unreinforced samples for each author. Thus, Fig. 6(b)–(e) shows the normalised tensile and flexural properties of the composites dealing with the addition of glass fibres. From Fig. 6(a), it can be seen that with the addition of 30% glass fibres, the elongation of break can reduce from 25% to 2%. Fig. 6(b) and (c) shows the normalised tensile strength and flexural strength, respectively and the figures indicate that these properties can be increased by up to 3.5 times with the addition of 30% glass fibre. Fig. 6(d) shows the addition of 30% glass fibre results in the largest improvement in the tensile modulus of up to 5.5 times. This may be attributed primarily to the enhanced interfacial adhesion resulting from the presence of a matrix with increased polarity that may react or interact more favourably with the silane coupling agent present on the glass fibres. As seen from Fig. 6(e), generally the flexural modulus of the composite is lower than the tensile modulus with only an increment of 2.5 times with the addition of 30% glass fibre as reported by many researchers. This might be because the maximum stress in flexural testing occurs at the surface where the filler concentration is relatively lower when compared with that in the core section [52]. It can also be seen that the addition of glass fibre does not produce a linear increment of strength and stiffness properties.

Pegoretti and Penati [57] have reinforced recycled PET with E-glass fibre of 4.5 mm length in 15% and 30% by weight. There was remarkable increase in modulus, tensile strength and impact strength. There was not significant change on the elongation at break. Similar study was done by Rezaeian et al. [58] on the samples of recycled PET with 10–30 wt% of silane-modified short glass fibres (SGF) having an average length of 4.5 mm, diameter of 11 μm , and L/D equal to 409. He discovered that the mechanical properties in glass fibre reinforced composites are governed by morphological characteristics of the composite, such as orientation of short glass fibres (SGF) and extent of interaction

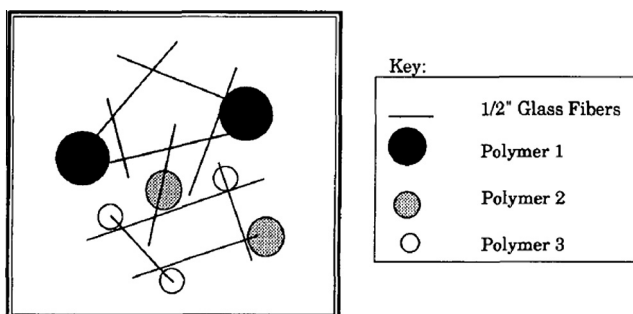


Fig. 5. Schematic diagram of physical compatibilisation [56].

between the glass fibres and matrix. One of the major findings of this study is that the aspect ratio of SGF decreases due to the mixing process from 409 before mixing to about 20 after the mixing which further reduces for higher fibre content as shown in Table 5. Fibre breakage results from fibre–polymer interaction, fibre–fibre interaction, and fibre contact with surfaces of processing equipment which results in fibre length decreasing with the increasing fibre content [62]. This large decrease in the aspect ratio due to the mixing process has a negative effect on the mechanical properties, but it can have a positive impact on flow behaviour. The shorter the fibre, the higher is the possibility for their proper orientation in the matrix. Furthermore, the SEM micrographs indicate that the fracture of the glass fibres is directly proportional to the weight percentage of the glass fibres in the samples. They further observed that due to the fibre breakage, the highest glass content facilitate their orientation in the flow direction. This behaviour was also discussed by La

Table 5
Comparison of SGF dimensions after mixing with r-PET [58].

Aspect ratio (L/D)	Length of modified SGF after mixing (μm)	Sample
19.72	216.96	rPET70/SGF30
20.42	224.62	rPET80/SGF20
22.49	247.42	rPET90/SGF10

Mantia and Ma [59]. They mentioned that the properties of PET/HDPE blends reinforced with 20% GF are increased by about 50% for the modulus, by 110% for tensile strength and are reduced by only about 20% for the elongation at break without impairing processability. The higher contents of glass fibre further improved some properties but impair not only the processability but also the elongation at break.

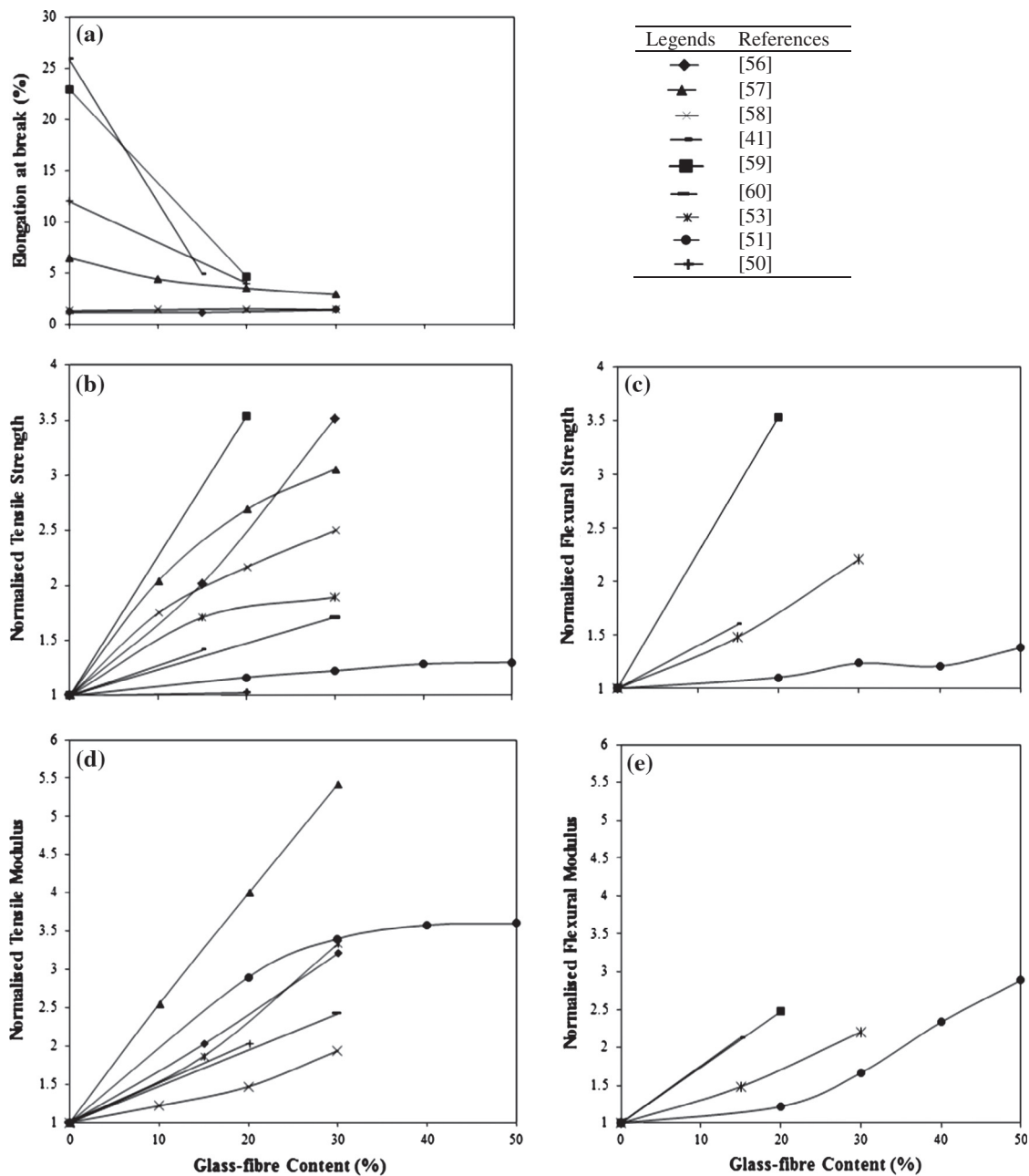


Fig. 6. Mechanical properties of glass-fibre reinforced thermoplastic.

Thus it can be concluded that the mechanical properties of recycled mixed plastic waste with glass fibre shows better improvement as observed by Xanthos and Narh [60], AlMaadeed et al. [61], Hugo et al. [54], Putra et al. [52], Dintcheva et al. [51]. AlMaadeed et al. [61] have reported that the melt flow index decreased with the increase in the fibre content because of the high weight and the increase in the viscosity of the composite. Similar condition was reported by Hugo et al. [54] who reported that due to the high cost and processing limitations for the recycled composite, the maximum amount of glass fibre which can be incorporated in the product is 30% by weight. With the addition of glass fibre, the effect of reinforcement content in recycled plastic composites can be summarised as in Table 6.

5.2. Effect of coupling agent/compatibiliser

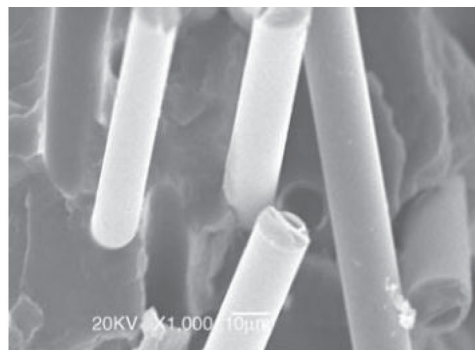
Glass is polar in nature whereas the polymer is nonpolar [32]. These two materials are naturally incompatible and do not form hydrolytically stable bonds. Fillers are often coated with coupling agents to enhance chemical bonding between filler particles and the polymer matrix. Some of the oldest types of coupling agents

are organo-functional silanes. Silane compounds impart a hydrophobic character to the fibre surface and coupling is achieved through compatibility of their organo-functional groups with polymers, whereas the hydroxyl groups bond to the mineral. The increase in interfacial adhesion results in a material with increased mechanical properties. The selection of an appropriate coupling agent involves identification of a suitable group of agents that is compatible with the targeted polymers [63]. Although there is no fundamental rule regarding this relationship, several researchers have reported notable improvements in the stiffness and yield strength of polyolefin composites with the use of methacrylate and amino silanes. Bikiaris et al. [64] have suggested that the fibre/matrix interfacial adhesion was improved with γ -methacryloxypropyltrimethoxy silane (γ -MPS) treatment. The extent of interfacial adhesion is also reflected in the mechanical properties of the material. They further mentioned that the use of functionalized copolymers can be used as adhesion promoters in thermoplastic composites. Of all materials investigated in their study, the best mechanical properties were exhibited by composites coupled with maleic anhydride grafted polypropylene (PP-g-MAH). The tensile strength, modulus and impact strength of the composite increased from 8.54 MPa, 469 MPa and 106 J/m, respectively to 14.46 MPa (69%), 1290 MPa (175%) and 170 J/m (60%), respectively reflecting the strong interfacial adhesion achieved with PE-g-MAH.

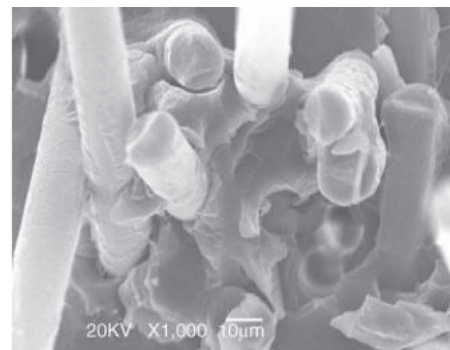
Another way to increase the compatibility between the glass fibre and polyolefin matrix is the use of graft or block polyolefin containing chemical functional groups can react with silanol groups on glass and at the other end the organo-functional group can react with the polymer which lead to the interfacial bond [63]. Compatibilising agents are most often used to improve the interfacial adhesion between the blended polymers. By adding

Table 6
Effect of reinforcement content on composite properties.

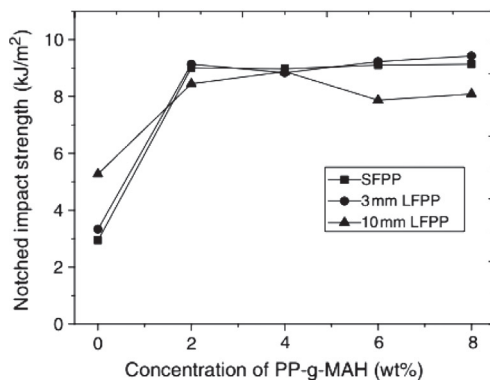
Improvement on	Reduction on
Mechanical strength	Elongation at break
Mechanical modulus	Aspect ratio
Orientation	Melt flow index
Viscosity	Processability



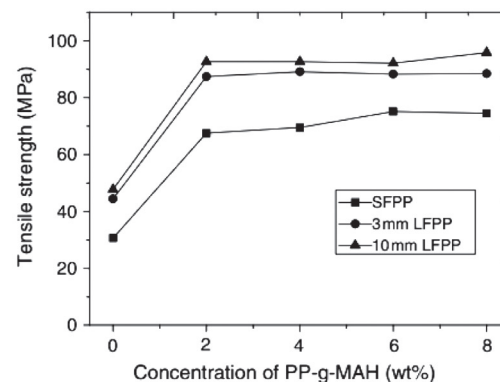
(a) LFPP without PP-g-MAH



(b) LFPP with 6% PP-g-MAH



(c) Notched impact strength for different concentration of PP-g-MAH



(d) Tensile strength for different concentration of PP-g-MAH

Fig. 7. Effect of compatibilisers on adhesion and mechanical properties of glass fibre reinforced polypropylene [67].

compatibilisers with reactive functional groups, it also improves adhesion at the polymer/filler interface which results in more efficient stress transfer and better dispersion [65]. This situation has been validated by many researchers. Yang et al. [66] have investigated the effect of three kinds of compatibilisers (maleic anhydride grafted polypropylene (PP-g-MAH), maleic anhydride grafted polyolefin elastomer (POE-g-MAH) and maleic anhydride grafted ethylene propylene diene monomer (EPDM-g-MAH)) on the mechanical properties of long glass fibre reinforced polyamide and found that the maximum tensile strength is reached for the composites when any of the different compatibilizers are 2.5 wt%. Fu et al. [67] have studied the mechanical properties of short glass fibre-reinforced polypropylene (SFPP) and long glass fibre-reinforced polypropylene (LFPP) with the addition of three different compatibiliser namely octane-ethylene copolymer, maleic anhydride grafted octane-ethylene copolymer and maleic anhydride grafted polypropylene (PP-g-MAH). The results show that the PP-g-MAH outperforms other compatibiliser and improved the adhesion due to chemical coupling. Fig. 7a and b are the scanning electron microscopy (SEM) photomicrographs of the fracture surfaces of glass-fibre reinforced. The figures show that the adhesion between the glass fibre and the matrix is weak without the compatibiliser (Fig. 7a) but were enhanced with the addition of PP-g-MAH (Fig. 7b). Furthermore, Fig. 7c and d show the effect of different concentration of PP-g-MAH on tensile properties which shows that the tensile strength and notched impact strength are greatly improved by the addition of 2 wt% of PP-g-MAH after which the increment of PP-g-MAH concentration does not produce significant improvement.

5.3. Effect of processing conditions

The production of short glass-fibre-reinforced mixed plastics is generally carried out by injection moulding process. Attempts to injection mould glass/polymers blends directly however, can lead to problems of poor surface finish, high differential shrinkage and variable strength due to the presence of undispersed glass bundles in the finished article [68]. It is therefore usual to extrusion-compound a blend of glass fibre and polymer to provide the initial wetting and dispersion of the glass fibres [69]. The resultant extrudate is then pelletized to provide material suitable for injection moulding. This precompounding stage can lead to significant fibre attrition which can have an appreciable effect on the mechanical properties of the final composite. In the case of mixed recycled plastics, this stage can also affect the morphology and crystallisation of the blends which affect the mechanical properties of the blends. The study conducted by Bartlett et al. [70] on HDPE/PP blends found that the extrusion or blending temperature would primarily affect the phase morphology but the strength and modulus were not greatly affected. However, the moulding temperature has a significant effect on crystallisation behaviour which affected on mechanical properties. The higher melt temperature resulted in reduced modulus and strength and a corresponding increase in elongation at break, all of which are consistent with a lower level of crystallinity.

Another study conducted by Dintcheva et al. [51] who processed the light fraction of plastic waste with different number of extrusion steps found that the elongation at break is slightly decreasing with the increasing number of extrusions, whereas the elastic modulus and the tensile strength increase. They further reported that elastic modulus and tensile strength are almost uninfluenced by the processing machine; on the contrary the elongation at break and the impact strength show some dependency on the processing apparatus. In particular, the material recycled in the twin screw compounder shows the best properties with the elongation at break at 12% and impact strength at 66 J/m, whereas

the material recycled in the single screw extruder has an elongation at break at 9.1% and impact strength at 63 J/m. Similar results were observed by Bertin and Robin [34]. Twin-screw extruder, with important shearing and mixing sections, produces LDPE/PP blends with better tensile strength properties and more homogeneity. These improvements are especially observed from stress-strain test in which all the properties are increased. The elongation and tensile strength at break are clearly higher than those obtained by single-screw extrusion, which confirms a more important homogeneity in the blend microstructure. The study conducted by La Mantia and Ma [59] showed that the rate of cooling can also significantly affect the mechanical properties of the composites. They observed that in the case of rapid cooling (500°C/min) of PET/PE composites, the tensile strength rises by 40–90% for the samples with 20% by weight of glass fibre and by 20–80% for the samples without glass fibre; the elongation at break increases by 40–150% and 200–300%, while the modulus decreased by only 5–10% and 10–30% for the samples with and without 20% by weight of glass fibre, as compared with the data obtained under slow cooling conditions (100 °C/min).

The reduction in fibre length during extrusion and injection moulding of glass fibre-reinforced polymers has been studied by many researchers. Gupta et al. [71] have found that the fibre attrition was severe in injection moulding apparently because of the higher shear rates and also because the fibres have to pass through narrow channels. The authors claim that the directly injected-moulded sample and the sample prepared from the once-extruded sample contain regions in which the fibre distribution is not uniform and fibre bundles are present. Samples subjected to further processing history show improved dispersion. Their results further indicate that during extrusion, the breakage of fibres occurs predominately in the melting zone at the solid-melt interface. The cause of fibre breakage during extrusion can be visualized as a two-stage phenomenon

- Firstly, the fibres which are exposed by surface melting of the granules close to the barrel wall of the extruder, interact with the flowing melt and experience a bending moment which can result in fibre breakage.
- Secondly, the broken pieces flow with the polymer melt and can experience further breakage due to post-buckling deformation.

de M Giraldo et al. [72] have investigated the mechanical properties of recycled poly (ethylene terephthalate) (rPET) reinforced with 20% glass fibre, focusing on the influence of two variables involved in the extrusion process: screw speed and torque as shown in Table 7. They found that the screw torque of 60% was the significant factor to increase impact strength of those composites and screw speed of 200 rpm was the significant factor to increase Young's modulus as shown in Fig. 8. The melt flow index (MFI) increased significantly with increase in the screw speed, indicating that reduction in the molecular weight of the chain may have occurred due to shearing effects. A higher screw torque means more material being transported at the same screw speed or the screw channel is being fed with more volume of material, which could affect in some way the fibre aspect ratio.

Table 7
Processing conditions of rPET/GF composite adapted from [72].

rPET/GF	Processing conditions				
	1	2	3	4	5
Rotation (rpm)	100	100	200	200	150
Torque (%)	40	60	40	60	50

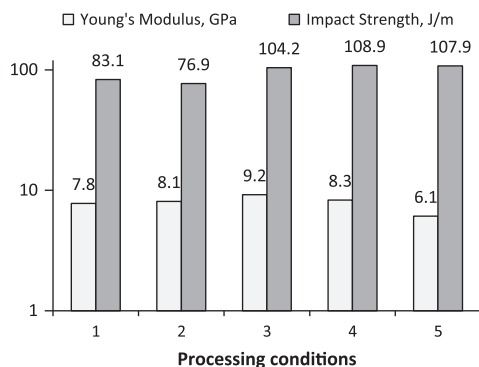


Fig. 8. Mechanical properties of rPET and glass fibre composites with different processing conditions [72].

5.4. Effect of ultra violet degradation

Polyolefin should be impervious to UV degradation and should not absorb the ultra violet (UV) radiation present in sunlight like pure aliphatic hydrocarbons. It is generally assumed that impurities, or chromophores, which absorb UV light, initiate the photooxidation of commercial polyolefin [73]. Most of the commercial organic-based polymers, used in the building and construction industry, undergo photodecomposition (in the absence of oxygen) and photooxidation (presence of oxygen) not only at outdoor by exposure to sunlight but also indoor by exposure to fluorescent light [74]. The polymers contains chromophoric groups, such as carbon-carbon double bonds (C=C) and carbonyl groups (C=O), which are capable of absorbing ultra violet (UV) energy and are involved in the photoreactions that result in the degradation of the polymer. The photodegradation of polyolefins originates from excited polymer-oxygen complexes and is caused mainly by the introduction of catalyst residues, hydroperoxide groups, carbonyl groups, and double bonds during polymer manufacturing. The most likely oxidation reactions caused by UV radiation are represented in Fig. 9a. Even in the absence of a significant amount of UV absorption, small amounts of these impurities can be sufficient to induce polymer degradation [75]. Once initiation has occurred, the long-chain molecule, RH, is converted into a free radical, R^* in the presence of UV light [76]. During the propagation, oxygen usually participates in degradation reactions of polymers as a free radical species [77]. Although an oxidative degradation reaction can occur at normal temperatures and in the absence of UV light, the most common effects result from the combined action of oxidation and thermal degradation or photodegradation. In the second step, RH can be a suitable macromolecule. Because of the chain nature of this reaction, even small concentrations of free radicals can result in significant amounts of oxidative degradation. During branching, the primary oxidation product, the hydroperoxide, ROOH, is thermally and photolytically unstable. It decomposes to produce two radicals, each of which can participate as R^* in the chain process that can abstract hydrogen atoms from the polymer and thus initiate the photooxidation. Thus it can be concluded that the absorbed UV light energy causes the dissociation of bonds (mostly C–C and C–H) in the molecules of one or more of the constituents of a polymeric material by a homolytic process to produce free radicals as the primary photochemical products. This event, with or without the participation of oxygen, can lead subsequently to breaking of the polymer chains, producing radicals and reducing the molecular weight, causing deterioration of mechanical properties and leading to useless materials, after an unpredictable time [78].

Several studies have reported on the effect of UV on the mechanical and chemical properties of polymers. A one year natural

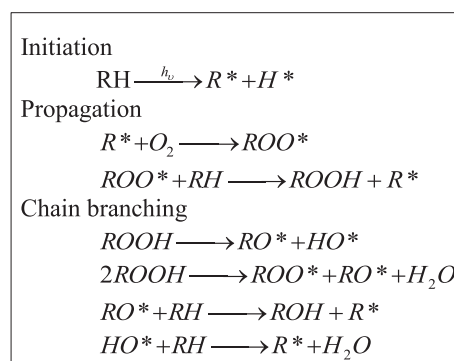


Fig. 9a. Oxidation reactions initiated by UV radiation [76].

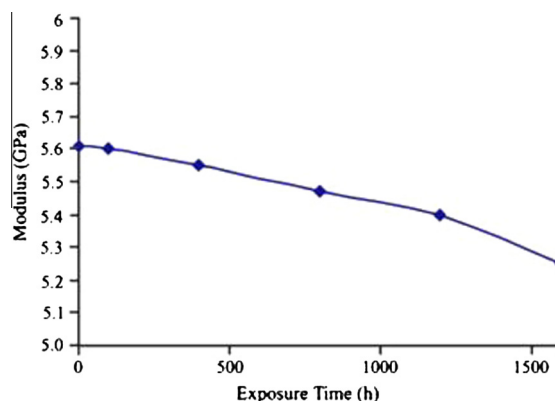


Fig. 9b. Modulus versus UV exposure of glass fibre reinforced PP [83].

weathering study conducted on LDPE by Al-Madfa et al. [79] found that outdoor exposure of LDPE for time intervals of 1–4 months appears to be beneficial to measure strength parameters of the material. However, such exposure deteriorated the ductility of plastics to the extent of total embrittlement. He further mentioned that the cross-linking in LDPE exposed to weather starts to be effective after one week of ageing. Tidjani et al. [80] have exposed low-density polyethylene (LDPE) to both natural and accelerated weathering and examined the elongation at break in conjunction with the formation of carbonyl and vinyl groups after weathering. They determined that in the initial stages of accelerated weathering, the mechanisms of degradation result in a predominance of crosslinking reactions over chain scission. In a later study, Tidjani [81] has expanded on this explanation, concluding that the crosslinking that occurs after accelerated weathering reduces the concentration of radicals that take part in the oxidation process. The author suggested that a relatively high level of oxidation was necessary to overcome crosslinking and decrease elongation. Under accelerated conditions, the polymer retains desirable elongation at the beginning but then it falls dramatically to its lowest value. On the other hand, this decrease in elongation is observed from the very beginning of UV exposure during natural weathering. A complementary explanation came from Jabarin and Lofgren [82], who also examined the structural changes of HDPE after natural and accelerated weathering. They reported an increase in the concentration of carbonyl and vinyl compounds, an increase in crystallinity and a decrease in molecular weight after natural weathering. They determined that as PE undergoes photooxidation during the course of UV exposure, chain scissions occurs, as evidenced by an increase in the concentration of carbonyl and vinyl groups and a decrease in molecular weight. These authors concluded that shorter chains have higher mobility and

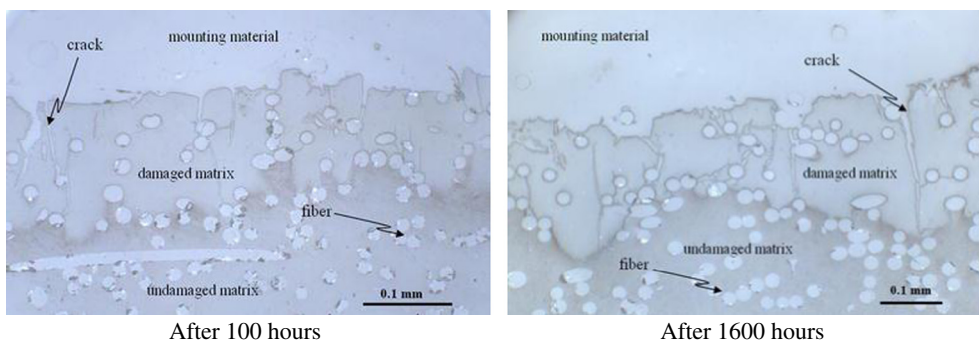


Fig. 10. Polished cross section of glass fibre reinforced PP exposed to UV [83].

crystallize readily, resulting in an apparent increase in crystallinity. As UV exposure continues, chain scission continues to affect molecular weight and crystallinity, which leads to the embrittlement of the PE, which corresponds with a decreased elongation at break.

Goel et al. [83] have studied the effect of UV exposure on the mechanical properties of long fibre thermoplastic composites. He mentioned that in the case of glass fibre reinforced polymer, more chromophores are added in the form of functional groups present in the sizing applied to the glass fibres for better bonding with the polymers. These chromophores accelerate the photo-oxidation of polymer and hence more damage is seen in the surface layer of the composites in terms of greater change in crystallinity and modulus as shown in Fig. 9b.

The explanation for the reduction of the mechanical properties has been shown by optical microscopy images of the polished cross section of the UV exposed LFT at different stages of exposure which shows the progression of damage. At 100 h, the cracks appear to start at the surface and propagate inward. After 1600 h of exposure, the material shows more cracks and the distinct contrast between the damaged and the undamaged layer as shown in Fig. 10. Furthermore, the scanning electron microscopy micrographs in Fig. 11 showed the degradation of the surface after UV exposure. For the unexposed LFT specimen, the glass fibres are well bonded to the matrix. After UV exposure, the damage in the matrix in the form of cracks as well as debonded fibre was observed. Most of the matrix in the surface region was disappeared and fibre was exposed to the surface.

5.5. Effect of elevated temperature

A critical technical barrier for widespread use of fibre reinforced polymer (FRP) in structural engineering application is the influence of temperature on the material [84]. The influence of temperature

on polymers can be separated into two effects, namely short term and long term. The short-term effect is generally physical and is reversible when the temperature returns to its original state, whereas the long-term effect is generally dominated by chemical change is not reversible. When FRP composite materials are exposed to high temperature (300–500 °C) the polymer matrix will decompose and will release heat and toxic volatiles. When heated to lower temperatures in the region of 100–200 °C, FRP composites will soften, creep and distort, and this degradation of the mechanical properties often leads to buckling failure mechanisms of load-bearing composite structures [85]. This has been validated by many researchers. A study performed on the plastic lumber made up of recycled plastic and sawdust by Carroll, Stone [86] at -23.3 °C to simulate winter conditions and 40.6 °C to simulate summer conditions also suggests that the high temperature strength and stiffness was lower than at low temperature as shown in Table 8, so the high temperature values would determine the allowable strength and stiffness for design. They further report that the plastic lumber have properties comparable to wooden lumber during winter however during summer it would have much less strength than wooden lumber.

Table 9 presents the study conducted by Gupta et al. [87] on the effect of elevated temperature on the tensile properties of unreinforced and reinforced PP. They found that at low temperatures, both shows brittle behaviour whereas at higher temperature, it shows ductile behaviour. It further indicates that there is reduction of more than 50% tensile strength for the rise in temperature from 20 °C to 55 °C for both reinforced and unreinforced samples. However, with the introduction of glass fibre, the reduction in both tensile strength and modulus at elevated temperature is lower than that of unreinforced samples as shown in Table 8 and Fig. 12. The authors further noted that with an increase in test temperature, the interfacial shear strength decreases for all composite

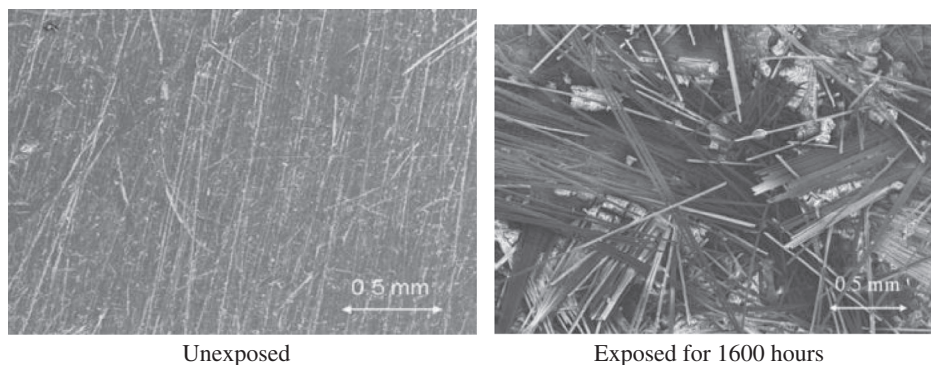


Fig. 11. SEM of glass fibre reinforced PP exposed to UV radiation [83].

Table 8
Results of mechanical test simulating winter and summer conditions [86].

Material property	Cold test at −23.3 °C	Hot test at 40.6 °C
Compression strength	37.3 MPa	16.8 MPa
Compression modulus	22.5 GPa	5.79 GPa
Flexure strength	37.7 MPa	12.0 MPa
Flexure modulus	4.52 GPa	1.03 GPa
Tensile strength	7.52 MPa	1.45 MPa
Tensile modulus	3.59 GPa	1.12 GPa
Shear strength	11.7 MPa	5.31 MPa

Table 9
Effect of temperature on the tensile strength of unreinforced and glass fibre reinforced PP [87].

Temperature (°C)	Tensile strength (MPa)		Reduction in strength (%)	
	PP	PP + 30% GF	PP	PP + 30% GF
−43	73.9	121.8	–	–
20	35.7	65.6	52	46
55	18.2	45.6	75	63
90	12.6	29.6	83	76

samples which can arise either from a weakening of the chemical bond or from the relaxation of thermal stresses and the decrease of bond strength at the fibre–matrix interface.

5.6. Effect of stabilisers

The intrinsic resistance of polyolefin materials to oxidative degradation is extremely low and, therefore the use of processing, heat and light stabilizers is necessary to ensure high durability of polymer performance. The addition of stabilizers can produce a significant improvement in the lifetime of a polymer. Mixtures of hindered phenols and amine stabilizers are widely used for processing stabilizers for polyolefin compounds. Hindered phenols have also shown to be very effective long-term heat stabilizers [88], however some of the transformation products of phenolic antioxidants can lead to a discolouration of the polymer during service [89]. On the other hand, hindered amine light stabilisers (HALS) have proved to be very effective than hindered phenols, especially with polyolefins [90]. High molecular weight hindered amine stabilisers (HAS), which are well known as UV-stabilisers, have been promoted as long-term heat stabilisers for polymers, especially for polyolefins [88]. The results of Kartalis, Papaspyrides [91] have illustrated that the restabilization is mandatory for improving the light stability of unfilled postconsumer plastic. Photostabilizers are compounds developed to combat UV degradation. They used Recyclossorb 550, a combination of processing and light stabilisers, especially developed for recycling of polyolefin for outdoor applications. The tensile impact strength for control and weathered for 2000 h is shown in Fig. 13. The addition of

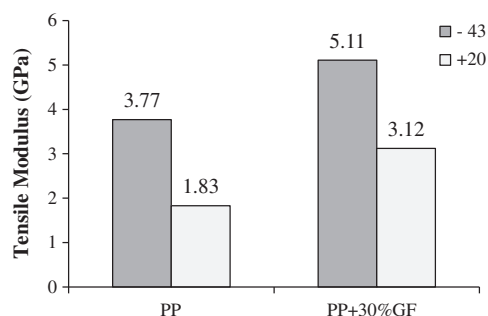


Fig. 12. Effect of temperature on the tensile modulus of unreinforced and glass fibre reinforced PP [87].

restabilisation system improves the light stability, resulting in excellent retention of the tensile impact strength. The SEM graphs shows that restabilisation effectively eliminates the crack formation on the surface of the recycled material and even significantly reduces bleaching and discoloration.

Similar results were discussed by Kaci et al. [92] who found that the presence of HALS in the LDPE film reduces significantly the rate of decline of the elongation at break. This is probably due to the role of HALS to retard a chain scission mechanism. The SEM micrograph for unstabilised and stabilised LDPE film is shown in Fig. 14 which shows that the surface damage caused by weathering is less severe for the stabilised film. Furthermore, a dispersion of microvoids is observed whose number and sizes are reduced.

6. Opportunities for research and development

Recycled mixed plastic are now being used as substitute for timber in several construction applications, mainly in outdoor applications such as park benches, fences because they are more resistant to moisture and biological attacks than wood. While useful as an early replacement for wood in such basic applications, suitable end uses seems constrained by a number of fundamental limitations in materials properties. The lower modulus of elasticity (<20% of timber value) and strength properties, compared to low strength timber as per AS/NZS 2878 [93], limits their use in structural applications. In an attempt to expand the potential use of mixed plastic wastes in structural applications, many researchers have investigated the effect of different fillers/fibres and found that glass fibre improves the mechanical properties of recycled mixed plastic waste. However, the mechanical properties of glass-fibre reinforced thermoplastics extracted from literature reviews presented in Fig. 8 shows significant variation thus characterisation of recycled mixed plastic composites is necessary. It is also clear that the engineering properties of polyolefin composites vary depending on the processing conditions and the compatibilisers used in manufacturing. The differences in engineering properties of polyolefin produced by different manufacturer's highlights the need for the development of a grading system for differentiating the structural properties.

Despite the preceding findings, a gap remains in understanding the other important properties such as compressive and shear behaviour of the glass fibre reinforced mixed plastic composites (GMPC) which are important properties to be investigated for civil engineering materials. In addition, currently there are currently no standards and design guidance for the use of mixed plastic composites in design. Most of the infrastructures built from mixed recycled plastics were based from the existing design guidelines developed for other traditional materials such as timber and steel. For example, the bridge at Fort Eustis Project was designed and constructed following the AREMA Manual and Virginia Department of Transportation (VDOT) specifications [21]. The short span highway bridge at Ohio was also designed to load and resistance

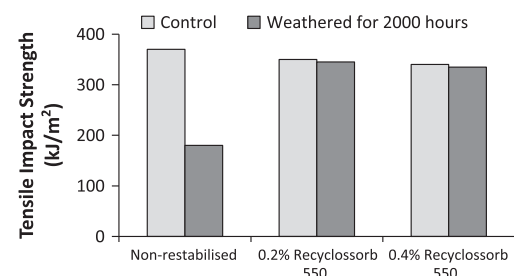


Fig. 13. Tensile impact strength of control and weathered HDPE with and without restabilisation [91].

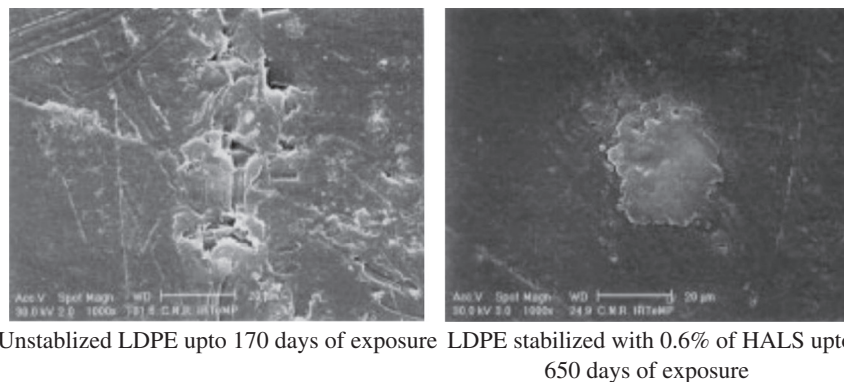


Fig. 14. SEM micrographs of LDPE samples exposed to natural weathering [92].

factor design (LRFD) specifications. On the other hand, the railroad plastic/composite crosstie discussed by Nosker et al. [22] was developed based on the standard hardwood tie specification. Hence, there is a need to establish materials specifications and design guidance for GMPC to effectively utilise their distinct mechanical properties in appropriate engineering applications.

Due to high cost and processing limitations for the recycled composite, the maximum amount of glass fibre which can be incorporated in the product is 30% by weight. Thus to further increase the strength and stiffness of the composites, compatibilisers in appropriate amount can be incorporated in the fabrication of GMPC to increase the adhesion between different polymers as well as glass fibre which results in the increment of mechanical properties. The effect of these compatibilisers on the mechanical properties and durability of GMPC shall be examined for recycled mixed plastic composites.

The mechanical properties of GMPC on different environmental conditions such as elevated temperature and UV radiation on GMPC are crucial for the utilization of recycled plastic materials in construction. However most of the studies of degradation mechanisms of polymeric material have concentrated largely on the chemical reactions that are involved. As a consequence, the understanding of the chemical mechanism of degradation is quite advanced. The improvement in polymer lifetime made possible by stabilisers, many of them commercially available and in widespread use, bears testimony to this. It is evident, however, that some of the engineering aspects of weathering-related failure of polymers are not as well understood as the chemical mechanisms of degradation. Also the photo-degradation of polyolefin has been studied extensively, however majority of these are made of virgin material ([80,79]). Thus it seems that to be able to predict lifetimes of GMPC a more comprehensive appreciation of the engineering aspects of failure is required and that more insight is needed into the relationship between chemical and mechanical degradation [76].

For higher durability of polymer composites, stabilisers are incorporated into polymer during manufacturing [84]. Photostabilisers are compounds developed to combat UV degradation. However, much of the available information on photostabilisers covers solely the photostabilisation of unfilled plastic [75]. Thus, the future research should focus in the development of an understanding of how elevated temperature and UV degradation affects the properties of GMPC and also the effect of photostabilisers on the properties of GMPC after weathering.

7. Conclusion

An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites was

presented in this article. This includes current state of problem, recent developments and applications of these composites, properties of plastic waste and its limitation for construction application, methods to improve its properties and the effect of different parameters on the mechanical strength and durability of composites. The conclusions that are drawn from this study are as follows:

- Recycling of plastics wastes has drawn much attention due to the increasing cost and decreasing space of landfills. However, only about one-fourth PSW is recycled around the world. This can be increased by converting these plastic wastes into products suitable for housing and construction.
- The use of these recycled mixed plastics is limited to small-scale products such as park benches and picnic tables due to their low stiffness and strength properties. Reinforcing the recycled mixed plastics with glass fibre will make them suitable for infrastructure applications.
- The addition of compatibilisers and fillers improves the mechanical properties of recycled mixed plastics composites. Compatibilisers such as EPM, EPDM and graft polymer have shown positive effects on the properties of composites such as elongation at break and impact resistance.
- Glass fibres show the best potential and most cost-effective reinforcement for recycled mixed plastic composites. When compounded with recycled thermoplastics, composites with improved mechanical properties and durability can be achieved.
- The effectiveness of glass fibre as a reinforcement to recycled plastic composites is affected by the reinforcement content and length, fibre adhesion and processing conditions.

Several issues and recommended solutions for the widespread application of glass fibre reinforced recycled mixed plastics composites to civil engineering and construction are identified in this paper. A complete understanding on the mechanical properties of these new generation materials including compression and shear are also warranted. Similarly, the effect of elevated temperature and UV radiation and also the effect of light and thermal stabiliser on the durability of GMPC shall be studied to improve the future markets of these composites on the construction industry.

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