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REVIEW

Single polymer composites: a review

**K. P. Matabola · A. R. De Vries · F. S. Moolman ·
A. S. Luyt**

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Abstract Increasing concern for the environment has stimulated interest in the research and development of single polymer composite (SPC) materials. These materials are an emerging class of composite materials with mechanical properties comparable to heterogeneous composites. The SPCs are fully recyclable and have specific economic and environmental benefits. The small melting temperature difference between the fiber and the matrix poses a great challenge in the fabrication of SPCs. This article gives an overview of developments in SPCs relating to the materials and fabrication methods used.

Introduction

In the last few decades, the interest in the use of polymers as replacements for other materials such as metals, wood, and ceramics has increased significantly [1]. This is due to the advantages that polymers offer over conventional materials, including ease of processing, productivity, and cost reduction [2]. The polymeric materials have to be reinforced in order to meet the high demands on strength and stiffness for many applications in aerospace, automotive, electrical, microelectronics, infrastructure and construction, medical, and chemical industries [1, 3]. The use of conventional fillers such as glass or carbon fibers has received much academic and commercial attention in the past. Although excellent mechanical properties have been achieved in this way, life cycle assessment does not yield favorable results for traditionally reinforced composites due to limited recyclability [4] and high energy requirements of their end-of-life processes.

Glass fibers are the main component in many plastic products that still cause environmental problems, both in mechanical recycling and end-of-life disposal through incineration (thermal recycling) [5–8]. Current trends toward environmentally friendly composite systems focus on the use of natural fibers as alternatives to glass fibers. Although these fibers do have some ecological advantages over glass fibers (since they are renewable and can be incinerated), natural fiber-based composites are generally not mechanically recyclable. In fact, next to mechanical degradation, the relatively poor thermal stability of these lignocellulosic fibers may lead to severe additional thermal degradation during subsequent recycling or reprocessing steps [9–12].

The heterogeneous composites pose a recycling challenge [10, 13]. Furthermore, heterogeneous composites often have poor matrix–fiber adhesion due to chemical incompatibility of the components [1, 5, 14]. One promising approach to composites recycling is a single polymer composite (SPC) [15] which is an emerging class of materials [16] that has specific economic and ecological advantages [10]. However, the concept of SPCs is not new. SPCs were first introduced by Capiati and Porter [1] about three decades ago. The method used the noticeable difference in melting temperature between the high-density polyethylene (HDPE—crystallized conventionally) matrix and HDPE reinforcement (containing aligned and extended molecular chains) to fabricate an HDPE homocomposite. These materials are often described as one-polymer composites, homocomposites, all (the same) polymer

K. P. Matabola · A. R. De Vries (✉) · F. S. Moolman
Polymers and Composites, Council for Scientific and Industrial Research (CSIR), P.O. Box 395, Pretoria 0001, South Africa
e-mail: adevries@csir.co.za

A. S. Luyt
Department of Chemistry, University of the Free State (Qwaqwa Campus), Private Bag X13, Phuthaditjhaba 9866, South Africa

composites, self-reinforced, or homogeneous composites [17]. Such composites represent the right alternative to traditional fiber-reinforced composites, because both reinforcement and matrix are from the same polymer, therefore recyclability is enhanced [18–20]. Besides recyclability, the interest in the concept of SPCs is based upon the premise that interfacial bonding should improve if matrix and reinforcement are made from the same polymer [1, 5, 12, 15, 21–26].

The growing interest in the recycling of materials is brought about by the desire to preserve the environment as there is limited landfill space due to the large amount of wastes that is being dumped [17]. Furthermore, current environmental legislation and waste management regulations aim to encourage manufacturers of materials and end-products to consider the environmental impact of their products at all stages of their life cycle inclusive of recycling and ultimate disposal [9]. Global warming is also of concern due to the incinerator emissions. These negative impacts can be reduced by recycling the products that would otherwise go into landfills [27–30]. In addition, a strong need to reduce the energy requirements of the recycling process also exists. This has stimulated interest in the development of environmentally friendly materials, including SPC materials [15, 31].

This article gives an overview of the current status in the research and development of SPCs. Firstly, polymer fibers and their production methods are reviewed. This is followed by a review of the reported work on SPCs and their fabrication methods. Finally, the main challenge relating to the development of SPCs is highlighted.

Polymer fibers

High performance polymeric fibers are one of the essential components of SPCs. In this section, we briefly review some of the polymer fibers that have been used in SPCs and their most commonly used production methods.

The development of high stiffness and strength polymeric fibers are required to impart high mechanical properties on resulting SPCs. These fibers provide some specific features, such as recyclability, ease of production, low cost, low density, and good interfacial bonding without any surface treatment [32]. Increase in mechanical properties of the fibers can be achieved via molecular orientation during spinning and drawing [13]. However, the main difficulty of combining fibers and matrices of similar polymers to create SPCs is to retain the properties of the oriented polymer molecules in the final composite, since molecular relaxation of highly oriented fibers readily occurs during heating [13]. Table 1 shows the mechanical properties of polymer fibers compared with carbon and glass fiber, which are popular reinforcements for polymers. As can be seen from Table 1, the density of the polymer fibers is less than that of the glass and carbon fibers. The high mechanical properties of the fibers induced during drawing are their major advantages in applications where a high strength-to-weight ratio is required.

Three methods are commonly used for the production of polymer fibers. These are solution/gel spinning, melt spinning, and electrospinning [13, 14, 40].

The *solution/gel spinning method* is a special process used to obtain high-strength fibers. The polymer is not in a true liquid state during extrusion. The process can also be described as dry–wet-spinning, since the filaments first pass through air and are then cooled further in a liquid bath [41–45]. Ultra high-molecular-weight polyethylene (UHMWPE) fibers have been produced by this method [25, 30].

In *melt spinning method*, the polymer melt is extruded through small orifices in the spinneret and drawn into thin fibers by a uniaxial drawing process. The spinneret is submerged in the liquid coagulation bath and the emerging

Table 1 Types and mechanical properties of polymer fibers

Fibers	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Strain to failure (%)	Elastic modulus (GPa)	Specific strength ($GPa/g/cm^3$)	Specific modulus ($GPa/g/cm^3$)	References
UHMWPE	0.96	2800	172	4	–	100	–	–	[12, 29, 33–35]
PE	0.96	1000–1500	40–70	4–18	–	–	1–1.5	42–73	[36]
PP	0.9	650	5–20	–	–	–	1.7	6–22	[9, 10, 12]
All-PP tapes	0.732	450	15	–	7	–	–	–	[4, 13, 19, 37, 38]
Vectran M	1.396	–	83.7	–	–	–	–	–	[39]
Vectran HS	1.403	–	88.8	–	–	–	–	–	[39]
Glass	2.54	3000	75	2.5	–	–	1.2	30	[10, 36, 38]
Carbon	1.80	3600	250	1.5	–	–	2.0	139	[36]

UHMWPE ultra high molecular weight polyethylene filaments are coagulated in a precipitating bath or a series of baths of increasing precipitant concentration [46, 47]. Barkoula et al. [3] produced polypropylene (PP), polyamides 6, and poly(ethylene terephthalate) (PET) fibers by the melt spinning method. Li and Yao [15] and Loos et al. [5] produced poly(lactic acid) (PLA) and isotactic PP (iPP) fibers, respectively. Melt spinning is the most commonly used commercial process for production of synthetic polymeric fibers.

In *electrospinning method*, the polymer is deposited from a solution as fibrous material by charging the polymer solution and ejecting it through a nozzle onto an oppositely charged grounded target. The fibers can be spun into non-woven structures which are porous (in the instance where highly volatile solvents are used), but mainly non-porous with sub-micron diameters and high surface areas. This is where electrospinning offers advantages over other conventional processes [48]. Various polymers [e.g., polyethylene (PE), PP, PET, poly(methyl methacrylate) (PMMA), PLA] have been successfully electrospun into fibers of different diameters [49].

Fabrication methods for SPCs

The main challenge in producing a SPC system is to combine fiber and matrix into one composite, as in most instances both constituents will have basically the same chemical structure and hence melting temperature. The main processing routes for SPCs are described below.

The *traditional melt (solution) or powder impregnation* route entails the impregnation of fiber bundles with a highly viscous polymer resin. Such a process would be very similar to the ones used for manufacturing continuous glass fiber-reinforced PP composites. Impregnation of fiber bundles with highly viscous resins is however one of the main bottlenecks in the cost-effective manufacturing of thermoplastic composites [13]. Low-molecular-weight polymer grades are often used to enhance the impregnation process. The process is relatively slow and costly, because the polymer needs to flow within the fiber bundles in order to fully wet the individual filaments. In addition to the above drawbacks, the reinforcing fibers could also lose their mechanical properties because of partial dissolving or melting during impregnation [9]. The method was used for the development of PE and PP homocomposites [35, 50–53].

In the *hot compaction process*, which is a one-constituent method, oriented polymer fibers are compacted to an oriented polymer sheet under suitable conditions of temperature and pressure. This occurs via partial melting of the fibers so that the molten outer surface of the fibers becomes the matrix after cooling, but the residual fibers continue to fulfill the role of the reinforcement [54–61]. The result is a fully recyclable, self-reinforced polymer material. The challenge in this process is the small processing window, typically about 5 °C or below, between the feasible processing temperature and the melting temperature of the fiber. Within this small temperature window, it is difficult to process the SPC under normal processing conditions without significantly annealing the fibers. Excessive heating results in relaxation and hence a loss of molecular orientation, whereas insufficient heating leads to a poor interfacial bonding between the fibers/tapes. This small temperature processing window reduces the versatility of the processing route. However, the processing window of hot compaction can be enlarged by using fibers produced of the same material, but with different drawing ratios [62]. The main distinction from other processing routes is that the two phases (matrix and reinforcement) of the SPCs are formed from only a single polymer material, assemblies of oriented polymer fibers/tapes [9, 13, 15, 16, 19, 39]. Hot compaction was used to prepare SPCs consisting of liquid crystalline polymer fibers [39], PP [63–67], PE [65, 67–72], poly(ethylene naphthalate) [73], nylon 6,6 [74], and PMMA [75].

With the *overheating method*, the polymer fibers could effectively be overheated above their melting temperature when they are constrained thereby the shrinkage can also be prevented. The oriented polymer fibers are embedded, using this method, in a molten polymer matrix of the same grade. The constraining of the fiber results in the melting temperature shifting to higher values, hence offering a large enough temperature window for the processing of the SPCs [3, 76].

In the *film-stacking method*, the reinforcing textile structure is sandwiched between the matrix films and the composite material is produced by hot pressing. The method has been applied for aramid/nylon [77], PP [12, 18, 78–80], PE [33, 81], UHMWPE [30, 34, 82–85], PLA [15], and iPP fibers [5]. The advantages of the film-stacking method include a wide processing window, freedom of the material selection, and no expensive pre-production.

Co-extrusion technology uses the co-extrusion of two types of polymer tapes (e.g., random PP copolymer/PP homopolymer) of different melting temperatures, cold drawing of the tapes to increase the mechanical properties, and finally consolidation of the tapes. The oriented polymer tapes can be constrained by the molding pressure during consolidation to increase the melting temperature of the oriented core material, and further extend the processing window. The advantages of this process is an enlarged processing window of about 20–40 °C, a high volume fraction of reinforcement (>90%) and an excellent bonding between the tapes due to the co-extrusion process. All-PP composites consisting of highly oriented PP tapes have been prepared by this method by various researchers [4, 9, 10, 13, 19, 20, 37, 38, 86–88].

Reported work on SPCs

Recognizing that the compatibility between reinforcement and matrix is a critical factor that primarily impacts on the mechanical properties of a composite, Capiati and Porter [1] introduced the first example of a SPC of PE. Since then a number of researchers have looked at SPCs of PE and various other polymers. In this section, we give a summary of some of the literature available on PE composites with UHMWPE fibers as reinforcement and UHMWPE, HDPE, and low-density polyethylene (LDPE) as matrices, respectively. We also give an overview of some reported research on SPCs of PP, PET, PLA, and PMMA.

PE/PE composites

Cohen et al. [34] demonstrated a first-of-its-kind fabrication of a homocomposite consisting of UHMWPE fiber and UHMWPE matrix with very good fiber–matrix adhesion without the use of any chemical treatment. The formation of the composite is entirely based on physical interactions between the UHMWPE fibers and matrix. The shear strength (20–25 MPa) and tensile strength (longitudinal: 1.3–1.5 GPa, transversal: 21–25 MPa) of the novel composite material improved as compared to the known fiber composites like UHMWPE fiber/epoxy matrix composites and UHMWPE fiber/HDPE matrix composites. Furthermore, the tensile strength of the UHMWPE fiber/UHMWPE matrix composite is reported to be similar to that of Kevlar fiber/epoxy matrix composites. The improved mechanical properties are attributed to good adhesion between fibers and matrix.

At around the same time as Cohen et al., Deng and Shalaby [26] reported on the physical properties of UHMWPE fibers/UHMWPE matrix composites. These composites were prepared from UHMWPE fibers sandwiched between UHMWPE sheets. It was shown that the tensile properties, creep resistance, and impact strength of the self-reinforced UHMWPE composites increased as opposed to the plain UHMWPE. The tensile strength increased as the fiber content increased, a maximum of 70 MPa was reached. The impact strength reached approximately 116 kJ/m^2. Mosleh et al. [25] also studied homocomposites of an UHMWPE matrix and an UHMWPE reinforcing phase. The primary aim was to develop a homocomposite that demonstrates less wear for applications in joint prostheses. The mechanical properties of this composite, such as elastic modulus, tensile strength, and hardness, were improved in a direction parallel to the fiber orientation.

Ogawa et al. [33] studied the mechanical properties of UHMWPE fibers/HDPE composites. An increase in the tensile strength and elastic modulus of the composite compared to the HDPE film was observed for a fiber weight fraction of 0.74. The composites' tensile strength and elastic modulus increased up to 600 MPa and 20 GPa, respectively, almost independent of the molding time. Lacroix et al. [50] reported on the morphology and crystallization behavior of UHMWPE fibers/HDPE composites. Low-voltage scanning electron microscopy revealed a transcrystalline layer at the UHMWPE fiber/HDPE interface (Fig. 1). The presence of a transcrystalline layer gives rise to good interfacial bonding between the matrix and reinforcement, which translates into an improvement in mechanical properties.

A denser and more compact transcrystalline layer was observed by Vaisman et al. [89] when brominated UHMWPE fibers was used as a reinforcement as compared to untreated UHMWPE fibers in a HDPE matrix. The more pronounced transcrystalline layer is ascribed to an increase in the nucleation density of the HDPE matrix on the fiber surface. Lacroix et al. [50] further reported on an alternative way of processing an UHMWPE fiber/HDPE composite by wet powder impregnation as an intermediate step. A HDPE

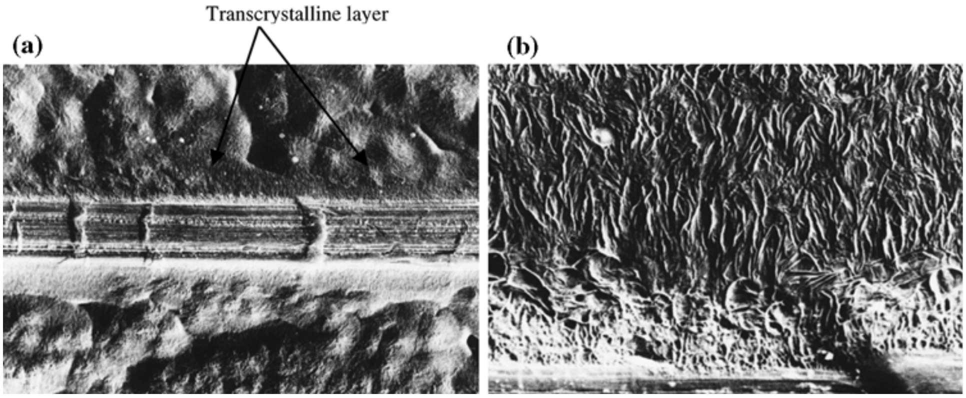

Fig. 1 Low voltage SEM images of **a** UHMWPE fiber/HDPE composite showing the presence of a transcrystalline layer and **b** a close-up of the transcrystalline layer illustrating the presence of lamellae twisting. *Source*: Used with permission [50]

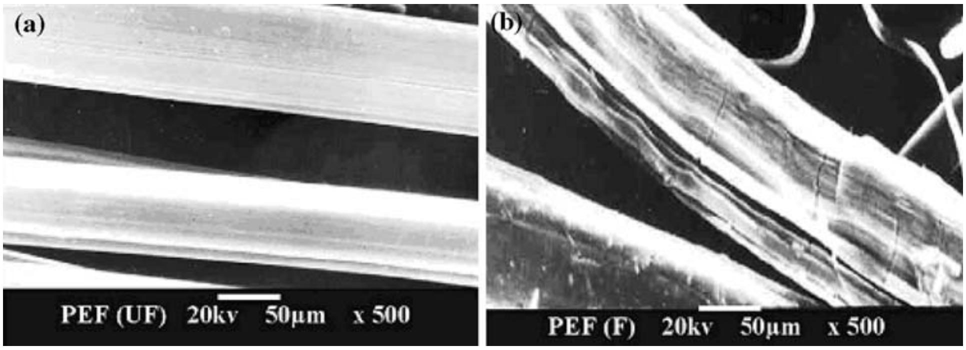

Fig. 2 SEM micrographs of **a** unmodified and **b** modified UHMWPE fibers. *Source*: Used with permission [92]

powder in propanol suspension was used for this purpose. This method was suggested as another option to solution and dry powder impregnation. Young's moduli and tensile strengths of the composites were reported to be high in the fiber direction, whereas the compressive strengths were low. The mechanical properties were generally poor perpendicular to the fiber direction. Pegoretti et al. [90] used the filament-winding process to manufacture UHMWPE fiber/HDPE composites with untreated HDPE and temperature-treated HDPE as matrices. The influence of the winding angle of the fibers on the dynamic properties (storage and loss moduli) of the composites was investigated. A decrease in the storage modulus with increasing winding angle was observed for both the untreated and treated HDPE, with the untreated HDPE showing a steeper decrease in the storage modulus. A similar trend was observed for the loss modulus, but with no significant difference between the untreated and treated HDPE.

Hinrichsen et al. [35] prepared UHMWPE fiber/LDPE composites by aqueous powder and dry powder impregnation. The mechanical properties of UHMWPE fiber/LDPE composites were studied. Good mechanical properties with increasing fiber content were reported (tensile strength: 460–1100 MPa, elastic modulus: 11–22 GPa, and elongation at break: 4.9–8.3%). Lacroix et al. [51] introduced the novel solution impregnation method as an intermediate process in the preparation of SPCs of UHMWPE fibers/LDPE matrix. The process entailed the immersion of the UHMWPE fibers in an LDPE/xylene solution. The influence of immersion time on the impregnation of the fibers and the effect of the processing temperature on the mechanical properties of the composites were investigated. A high Young's modulus and tensile strength were reported, but an increase in processing temperature resulted in a decrease in these properties. This was ascribed to fiber shrinkage and damage at the higher processing temperatures. Ogawa et al. [33] reported on the morphology, thermal behavior, and mechanical properties of UHMWPE fiber/LDPE matrix SPCs. Minor voids were observed in the composites and significant fiber agglomeration was absent. Furthermore, a maximum tensile strength and elastic modulus of 660 MPa and 14 GPa, respectively, were observed for the LDPE composites. These results compare well with that obtained by Hinrichsen et al. The increased fiber–matrix adhesion was reported to be responsible for the improvement in the mechanical properties, especially the tensile strength. More recently, the use of chemically modified UHMWPE fibers as reinforcement in an LDPE matrix have been reported by Maity et al. [91, 92]. The surface of the UHMWPE fibers was modified by direct fluorination. SEM images of the unmodified and modified fibers illustrate the difference in the surface roughness of the fibers (Fig. 2). Composites were prepared with the modified and unmodified fibers. The modified fiber composites showed an increase in mechanical properties and thermal stability compared to that of the unmodified fiber composites. Better adhesion between the modified UHMWPE fiber and the LDPE matrix is cited as one of the main reasons for the improved properties. In addition, surface energy analysis showed an increase in the surface energy for the fluorinated samples.

All-PP composites

Initial studies on the hot compaction of PP fibers to form an all-PP composite was undertaken by Abo El Maaty et al. [93]. The selective melting of the fibers was not achieved and hence good bonding between the fibers was absent, which resulted in a weak composite. Hine et al. [94] extended the initial PP hot compaction work to woven PP tapes. The effect of the compaction temperature on the properties of the PP SPCs was investigated. The PP sheet obtained at an optimum compaction temperature of 182 °C was reported to be homogeneous and well bonded. A significant amount of annealing was observed at the optimum compaction temperature (as much as a 20% increase in crystallinity). The good mechanical properties obtained were attributed to the formation of a transcrystalline layer between the PP tapes and tape bundles. Furthermore, Hine et al. [54] also investigated the parameters that influence the hot compaction behavior of woven-oriented PP fibers and tapes. It was reported that the molecular weight and the crystallinity of the base polymer and the geometry and weave style of the reinforcement significantly affect the mechanical properties of the final composite. Loos et al. [5] studied the morphology of an SPC consisting of highly drawn and constrained iPP fibers embedded in an iPP matrix. Once again, the formation of transcrystalline layers showed an improvement in the interfacial adhesion between the matrix and reinforcing material.

A few studies on SPCs of PP, where the matrix consisted of a propylene–ethylene (PPE) copolymer, have been reported. Houshyar et al. [12, 53, 95–98] successfully prepared an SPC consisting of a PPE random copolymer matrix reinforced with PP fibers. The effect of PP fibers with different fiber diameters on the structure, thermal and mechanical behaviors of thermoplastic composites based on PP was studied. Figure 3 illustrates the effect of the different fiber diameters on the various moduli. Incorporation of the fibers resulted in an increase in the static and storage moduli. However, only for the static modulus was a significant difference observed for the different fiber diameters. In addition, Houshyar et al. [32] studied the effect of fiber concentration on the mechanical and thermal properties of fiber-reinforced PP composites, consisting of PP fibers in a PPE random copolymer matrix. The increase in the fiber concentration resulted in an increase in the tensile, flexural, and storage moduli. Kitayama et al. [99] studied the interfacial properties of PPE/PP composites consisting of iPP fibers and a PPE random copolymer matrix. The formation of a transcrystalline layer was found to increase the interfacial strength.

All-PP tapes, i.e., two types of PP tapes (PP homopolymer—core; random PP copolymer—skin), coextruded into tapes of different melting temperatures have been described by Cabrera et al. [9]. It was found that the all-PP composites can compete with or even out-perform glass mat-reinforced thermoplastics or natural fiber mat-reinforced thermoplastics for structural and impact applications, owing to their good mechanical properties combined with a low density. Alcock et al. [13, 19, 20, 37, 38] prepared all-PP composites from highly oriented PP tapes, and the response of these composites to mechanical loading at a range of temperatures and strain rates, the impact performance, as well as the interfacial and mechanical properties, were investigated. These composites exhibited excellent resistance to falling weight penetration, and the excellent mechanical properties of the oriented tapes were retained in the resulting composites, despite the high temperatures involved in the compaction process. The specific mechanical properties were comparable to those reported for a commercial unidirectional glass fiber-reinforced PP. The compaction conditions were found to influence the interfacial properties of the composite materials.

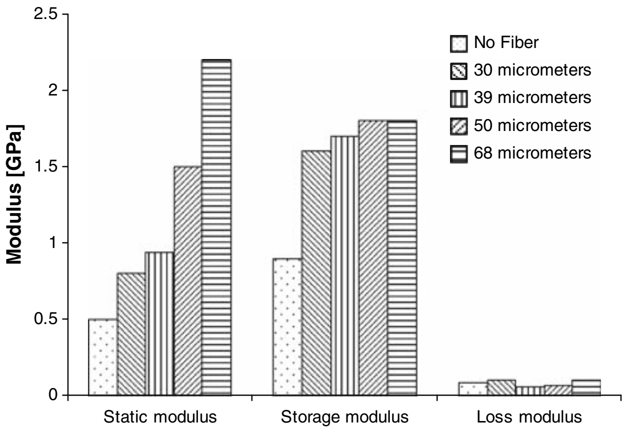

Fig. 3 Effect of different fiber diameters on the moduli of the PPE matrix/PP fibers composites

Barany et al. prepared and characterized self-reinforced PP composites. The film-stacking method was used. They studied the correlation between the consolidation temperature and holding time and the mechanical and morphological properties. In their studies, random PP copolymer [80, 100] and beta polymorph of PP [18, 79, 101] were used as matrix material and carded mat [18, 79, 80, 100] and woven fabric [101] of alpha polymorph of PP as reinforcement. The increase in the processing temperature gave rise to an increase in the tensile properties, but a decrease in the perforation impact energy. An increase in the holding time did not cause any large change in tensile properties, whereas the perforation energy slightly improved.

PET homocomposites

One of the first successfully prepared homocomposites of PET was reported by Rasburn et al. [102] using the hot compaction technique. The mechanical properties and the structure of the compacted samples were studied. They found that a high percentage of the original properties of the fibers was retained under suitable conditions. The concept of constraining of fibers for the manufacturing of SPCs was investigated by Barkoula et al. [3]. PET was one of the polar polymers that were studied. It was shown that a difference of about 10.0 °C in the crystalline melting point could be obtained between the constrained and unconstrained PET fibers (Fig. 4). This small difference in the crystalline melting points is ascribed to the limited drawability of the PET. Post-drawing processes were recommended for further small increases in the crystalline melting point.

Rojanapitayakorn et al. [103] studied the effect of various hot compaction temperatures on the crystallinity and molecular orientation of PET SPCs. The PET SPCs were prepared using a simplified one-step hot compaction

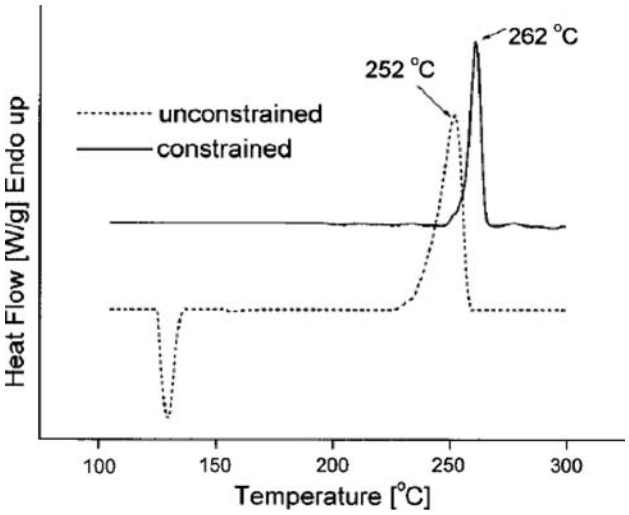

Fig. 4 DSC curves showing the effect of constraining on the crystalline melting point of a PET fiber [3]

process. Furthermore, the influence of the processing conditions on the mechanical properties of the composites, such as flexural strength, flexural modulus, and impact strength, was assessed. The most significant improvement was observed in the impact strength of the composites compared to the isotropic PET samples, as much as 5–7 times higher. Nagarajan and Yao [104] prepared PET homocomposites consisting of PET woven fabric, meshes, and an amorphous film. A reliance of the interfacial adhesion on temperature and pressure in the PET homocomposite was observed. A significant increase in the strength of the fabric-reinforced PET homocomposite compared to the non-reinforced PET was reported. Yao et al. [105] successfully prepared a PET SPC consisting of an amorphous PET film and highly crystalline PET fabrics. A substantial improvement in the mechanical properties compared to non-reinforced PET was reported. The consolidation conditions (heating temperature, heating rate, and the holding time) influenced the mechanical properties of the PET SPCs.

PMMA single polymer composites

Some work on PMMA SPCs has been reported by Wright-Charlesworth et al. and other researchers [75, 106–108]. For example, a self-reinforced PMMA composite consisting of high-strength PMMA fibers and PMMA matrix was described by Wright-Charlesworth et al. [107]. It was observed that the ultimate stress (MPa), elastic modulus (GPa), and percentage elongation (%) were 68.50, 2.51, and 8.55, respectively. Furthermore, Wright-Charlesworth et al. [107] undertook a systematic study of a hot-compacted PMMA SPC. The influence of processing temperature and time on the fracture toughness and morphology and the thermal properties of the composite were investigated. It was found that the consolidation of the composite, the fracture mechanism, and the orientation of the fibers were influenced by the processing parameters. In addition, the exothermic and endothermic events of the PMMA SPC as measured by DSC were shown to be affected by the processing temperature and time.

PLA single polymer composites

PLA SPCs consisting of amorphous sheets as matrix and highly crystalline fibers, yarns, and fabrics were prepared by Li and Yao [15]. A significant improvement in tensile strength to 58.6 MPa and a Young's modulus of 3.7 GPa have been reported.

SPCs based on liquid-crystalline fibers

Pegoretti et al. [39] prepared SPCs based on liquid-crystalline fibers (Vectran M and Vectran HS). The fibers have the same chemical composition, but different physical properties. It was shown that the consolidation temperature is the key variable in the production of single polymer liquid-crystalline composites. A decrease in tensile strength from 920 to 480 MPa was observed as the consolidation temperature increased.

The reported work on SPCs is summarized in Table 2.

Main challenge in the development of SPCs

Proximity in melting temperatures of matrix and reinforcement

In spite of the advantages of SPCs over traditionally reinforced composites in terms of chemical compatibility and recyclability, the small difference in melting temperature between the fibers and the matrix poses a big challenge during fabrication, as both constituents have basically the same chemical structure and hence melting temperatures [104, 105]. The major challenge is to find a processing window that is large enough to maintain the integrity of the fibers after consolidation [10]. A clear difference in the melting temperatures of the fibers and the matrix is required for manufacturing SPCs [1, 3]. For instance, the melting temperature for a HDPE matrix and fibers reported by Mead et al. [21] were 132 and 139 °C, respectively. With this small temperature window, it is difficult to process the resultant homocomposites under normal processing conditions without annealing the fibers. In the case of UHMWPE, the difference in melting temperature between the fibers and the matrix is in the range of 5–9 °C. It is known that PE fibers, annealed at a temperature close to its

Table 2 A summary of reported work on SPCs

Fiber	Matrix	References
HDPE	HDPE	[1]
UHMWPE	HDPE	[33, 50–52, 89, 90]
UHMWPE	UHMWPE	[25, 30, 34, 65, 67–72]
UHMWPE	LDPE	[33, 35, 51, 91, 92]
PP	PP	[5, 12, 18, 37, 38, 54, 63–67, 79, 80, 93, 94, 101]
PP	PPE random copolymer	[4, 9, 10, 12, 13, 19, 20, 32, 37, 38, 53, 79, 80, 85–88, 95–100]
PET	PET	[3, 102–105]
PMMA	PMMA	[75, 106–108]
PLA	PLA	[15]
Poly(ethylene naphthalate)	Poly(ethylene naphthalate)	[73]
Nylon 6,6	Nylon 6,6	[74]
Vectran HS	Vectran M	[39]

melting temperature, have a much reduced modulus compared to the modulus of 1 GPa of bulk HDPE [25, 104, 105].

The processing window is enlarged by using polymers with the same chemical composition, but with different chemical structures [15, 51, 81, 104, 109, 110]. Examples are a HDPE matrix reinforced by UHMWPE fibers [51, 81] and an LDPE matrix reinforced by HDPE fibers [25]. In both cases, a processing window of about 20 °C exists. When LDPE is reinforced by UHMWPE fibers, the processing window can be further enlarged to about 40 °C [109]. Apart from different molecular weights, HDPE, LDPE, and UHMWPE also have different chain configurations. The compatibility and miscibility of different grades of PE are affected by the difference in chain configurations (e.g., the length of the branched chains) [111].

Tsuji et al. [112] electrospun PLA stereocomplex nanofibers and found that the stereocomplex resulted in an increase in melting temperature to about 220 °C as compared to 178 °C for the pure polylactides of PLLA and PDLA. A 40 °C higher melting temperature was observed for the PLA blend. The PLA stereocomplex can thus be used to increase the processing window. However, the fiber form of the PLLA/PDLA blend has not yet been reported as reinforcement in a PDLLA matrix for the preparation of an SPC.

Barany et al. [18, 79, 101] successfully exploited the polymorphism of PP as a possibility for enlarging the processing window in all-PP composites. A temperature difference of up to 25 °C between the α-PP and the β-PP has been reported with the α-PP having the higher melting point. These composites were primarily prepared by the film-stacking method. Abraham et al. [113] reported on the dynamic mechanical properties of all-PP composites where the β and α polymorphic forms of PP were used in the preparation of the composites. Alpha-PP tapes served as the reinforcement in a β-PP matrix.

Concluding remarks

SPCs are recyclable materials first prepared and reported in 1975 by Capiati and Porter. These materials are being developed with a view to reducing growing global environmental problems such as limited landfill space, littering, and disposal problems. There is increasing interest in SPCs due to the need for environmentally friendly composite materials. The future of SPCs looks promising due to continuing improvement in their preparation and properties, their market growth, and their recyclability.

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