MECHANICAL PROPERTIES OF RECYCLED PLASTIC FIBRES FOR REINFORCING CONCRETE

YIN Shi [1], TULADHAR Rabin [2], COMBE Mark [3], COLLISTER Tony [4], JACOB Mohan [5], SHANKS A. Robert [6]

Abstract

With the increase in the general awareness of waste management, recycled plastic fibre reinforced concrete has attracted widespread attention. However, the production of recycled plastic with sufficient mechanical properties is still a major challenge. This research focuses on improving the tensile strength and Young's modulus of recycled polypropylene (PP) fibres produced through a hot drawing process. The mechanical properties of the mixture of 50 % recycled PP and 50 % virgin PP were compared with 100 % virgin and 100 % recycled plastic fibres. The 100 % recycled PP fibres achieved tensile strength of 310 MPa and Young's modulus of 620 MPa. The combination of recycled (50 %) and virgin PP (50 %) showed significant improvement in Young's modulus (800 MPa). Tensile strength was found to increase to 360 MPa.

The crystalline structure and crystallinity of the PP fibres were studied to explore the effects of hot drawing process on the mechanical properties of the PP fibres. The hot drawing process increased the crystallinity from around 50 % to over 80 %. Both α- and β-form crystals were found in all the plastic fibres, but recycled PP fibre contained more β-form crystals than the virgin PP fibre, resulting in lower Young's modulus.

Keywords: recycled polypropylene fibre, concrete, mechanical properties, crystallinity degree, crystalline structure

1. Introduction

[1] YIN Shi, School of Engineering and Physical Sciences, James Cook University, QLD 4814 Australia, email: shi.yin@my.jcu.edu.au

[2] TULADHAR Rabin, School of Engineering and Physical Sciences, James Cook University, QLD 4814 Australia, email: rabin.tuladhar@jcu.edu.au

[3] COMBE Mark, Fibercon QLD Australia, email: markc@fibercon.com.au

[4] COLLISTER Tony, Fibercon QLD Australia, email: qcrete@westnet.com.au

[5] JACOB Mohan, School of Engineering and Physical Sciences, James Cook University, QLD 4814 Australia, email: mohan.jacob@jcu.edu.au

[6] SHANKS A. Robert, CRC for Polymers, School of Applied Sciences, RMIT University, Australia, email: robert.shanks@rmit.edu.au

The last few decades have seen considerable growth in the world population, which has led to significant demand for low cost living; this has led to huge production and consumption of plastics. According to Plastics - the Facts 2012 [1], the global annual plastic production from 2010 to 2011 increased by more than 5 % to 280 million tonnes. Around 250 million tonnes of crude oil was consumed annually to manufacture plastics to meet the growing demand [2]. However, the recycling rate of plastic waste during this period was only 7.1 % [3]. More than 90 % of the plastic waste was landfilled or incinerated, which led to severe plastic pollution [4].

On the other hand, concrete is one of the most widely used construction material in the world. According to United States Geological Survey [5], in 2010 alone, a total of 16,500 million tonnes of concrete was manufactured in the world. For such significant production and application, achieving sustainability in concrete industry has become increasingly important, and thus has aroused concerns among researchers and scientists [6].

Researchers are focusing on various ways to improve performance of concrete and reduce environmental impact of plastic and concrete [7-9]. One of the potential ways of producing sustainable concrete structures is to use recycled plastic waste as plastic fibres in concrete [10]. The most common types of recycled plastic fibres are made from recycling polypropylene (PP), poly(ethylene terephthalate) (PET) and high-density polyethylene (HDPE), mainly because they are easier to recycle [11].

Kim et al. [12] prepared straight, crimped and embossed plastic fibres from waste PET bottles, and studied effects of geometry and amount of the fibres on shrinkage cracking of concrete. They melted PET bottles into a roll-type sheet (0.5 mm thick). The sheet was then slit into 1 mm width strands by a slitting machine. A deforming machine was used to produce different geometries, such as crimped and embossed, on the fibres. The plastic fibre produced by this method had tensile strength of around 400 MPa.

In order to reduce manufacturing costs, Oliveira [13] explored producing recycled plastic fibres just by mechanical cutting PET bottles. The remaining bottle necks and the bottom were discarded. However, tensile strength of the fibres thus obtained was only 152 MPa. When 1.5 %·v/v fibres were used to reinforce concrete, the flexural strength of concrete was improved from 1.83 to 2.70 MPa.

The schematic diagram (Figure 1) explains the mechanism of crack growth restriction in concrete due to the presence of fibres. As shown in Figure 1, fibre rupture (1), pull-out (2) and debonding with matrix (4) can effectively absorb and dissipate energy to stabilize crack propagation in concrete. Fibre bridging the cracks (3) reduces stress intensity factor at the crack tip. In addition, the fibre bridging can decrease crack width, which prevents water and contaminants from entering the concrete matrix and prevents corrosion of reinforcing steel and degradation of concrete. Fibre in the matrix (5) prevents propagation of a crack tip. Consequently, cracks will initiate in other places (6) of the matrix. Fibres with high Young’s modulus and tensile strength can bear higher load in the bridging stage, and thus have a better reinforcing effect.

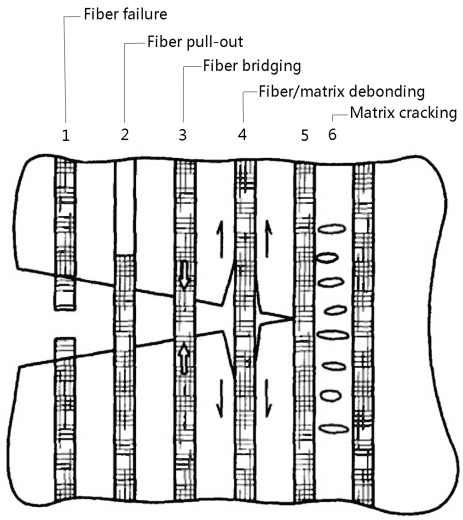

Fig. 1: Mechanism of energy absorption and crack control of fibre in concrete [14]

However, the production of recycled plastics with sufficient mechanical properties is still a major challenge due to their degradation during their service life and heat processing stage. Aim of this research is to improve the tensile strength and Young's modulus of recycled PP fibres produced through a hot drawing process. The mechanical properties of 100 % recycled PP fibre produced by the hot drawing process were presented and compared with those of 100 % virgin PP fibre and the PP fibre with mixture of virgin (50 %) and recycled (50 %). Finally, the mechanism about how the hot drawing process improves the mechanical properties of the plastic fibres was studied through testing crystalline structure and crystallinity of the recycled fibre, virgin fibre and fibre with the mixture of virgin (50 %) and recycled (50 %).

2. Experimental Program

2.1 Material Properties

The virgin PP and the recycled PP used in this study are commercial grade granules. Table 1 presents their characteristics. The materials were extruded at 210-250 °C and hot drawn at 120-150 °C. Further, an indented roller die was used to mark indents on the fibres to increase the bond strength between the fibres and concrete. After indentation, fibres were cut into a length of 47 mm. Although the longer fibres can generate better reinforcement, the longer fibre makes mixing with concrete more difficult. Three kinds of fibres were prepared: 100 % virgin PP fibre, 100 % recycled PP fibre, and 50:50 virgin–recycle fibre that was made by extruding mixed raw materials of 50 % recycled PP and 50 % virgin PP.

Tab.1: Characteristics of raw materials of plastic fibres

Raw material	Virgin PP	Recycled PP
Density	0.90 g/cm³	0.90 - 0.92 g/cm³
Melt flow rate (2.16 kg, at 230 °C)	3.5 g/10min	5 g/10min
Tensile stress at yield	31 MPa	35 MPa
Flexural modulus	1.25 GPa	1.48 GPa
Notched izod impact strength (23 °C, type 1, Notch A)	4.7 kJ/m²	3.5 kJ/m²
Heat deflection temperature B (0.45 MPa)	75 °C	82 °C
Heat deflection temperature A (1.80 MPa)	51 °C	54 °C

2.2 Characterization and Properties

Tests for tensile strength and Young's modulus were performed on the PP fibres according to ASTM C1557-03(2008). The tensile test instrument used for the tests was from United Calibration Corporation and was equipped with a 5 kN load cell and data acquisition software. The displacement was applied at the rate of 50 mm/min in room temperature. Five tensile specimens of each composite were prepared and tested to acquire the mean.

Non-isothermal crystallization and melting behaviour of the fibres was studied using a Perkin-Elmer Pyris-1 differential scanning calorimeter (DSC). About 3 mg of the PP was weighted accurately. Samples were heated from 30 °C to 220 °C at the heating rate of 10 K/min to study the melting behaviour of the fibres. The crystallinity and crystalline structure of the PP fibres can be characterised through this heating. The samples were then kept at 220 °C for 3 min to eliminate their thermal history. Subsequently, the samples were cooled to 30 °C to study their crystallization behaviour with temperature; and reheated to 220 °C at the heating rate of 10 K/min to study their melting behaviour with temperature. All measurements were carried out under a nitrogen atmosphere to avoid thermal-oxidative degradation.

Wide-angle X-ray scattering (WAXS) measurements were performed in reflection mode at ambient temperature using an X-ray diffractometer (Bruker D4 Endeavor). The generator was set at 40 kV and 40 mA and the copper Cu-Kα radiation was selected using a graphite crystal monochromator.

3. Results and discussion

3.1 Mechanical properties

As can be seen in Table 2 and Figure 2, Young's modulus of the recycled PP fibre is 619 MPa, which is lower than that of virgin PP fibre by 40 % (868 MPa). However, when 50 % of virgin PP was mixed with 50 % recycled PP, Young's modulus was increased by 30 % to 804 MPa.

The addition of virgin PP only slightly improved the tensile strength and decreased elongation at break of the fibre. Table 2 and Figure 2 show that the tensile strength of the

100 % recycled PP fibre was only 313 MPa, which was lower than that of virgin PP fibre by 40 % (437 MPa). The addition of 50 % virgin PP into recycled PP improved the tensile strength to 364 MPa, which is still lower than the average of 100 % recycled PP fibre and 100 % virgin PP fibre. Moreover, the fibre with mixed raw materials had the lowest elongation at break among the three kinds of fibres, due to a compatibility problem between the virgin and recycled PP.

Tab.2: Tensile properties of PP fibres

Composition	Young's modulus	Tensile strength	Elongation at break
Recycled PP fibre	619 MPa	313 MPa	60.6 %
Virgin PP fibre	868 MPa	437 MPa	74.4 %
50:50 virgin–recycled PP fibre	804 MPa	364 MPa	51.8 %

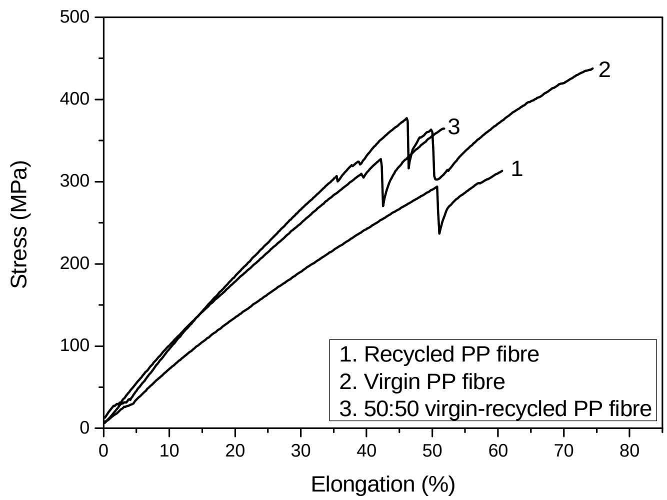

Fig. 2: Tensile properties of different types of PP fibres

3.2 Non-isothermal crystallization and melting behaviour

As shown in Figure 3, the raw material of recycled PP has a broader melting endotherm than that of the virgin PP, which indicates that the recycled PP has more crystals of different sizes, and the virgin PP has more uniform crystal sizes. When the plastic was hot drawn into fibres, a double melting peak was generated at 154 and 170 °C. The peak located at 154 °C is ascribed to the β-form crystals and the other is to the α-form crystals [15].

The α-form crystals have higher tensile strength, higher Young's modulus and lower elongation at break than the β-form crystals [16]. The virgin PP fibre has a large portion of α-form crystals and small amount of β-form crystals, so the virgin PP fibre has the highest tensile strength and Young's modulus among all the fibres. On contrary, the recycled PP fibre has nearly same amount of α- and β-form crystals, thus possessing the lowest tensile strength and Young's modulus. For the fibre containing 50 % of virgin PP and 50 % of recycled PP, a large number of α-form crystals are formed. Therefore, the addition of 50 % virgin PP effectively induces α-form crystals, further generating a high Young's modulus.

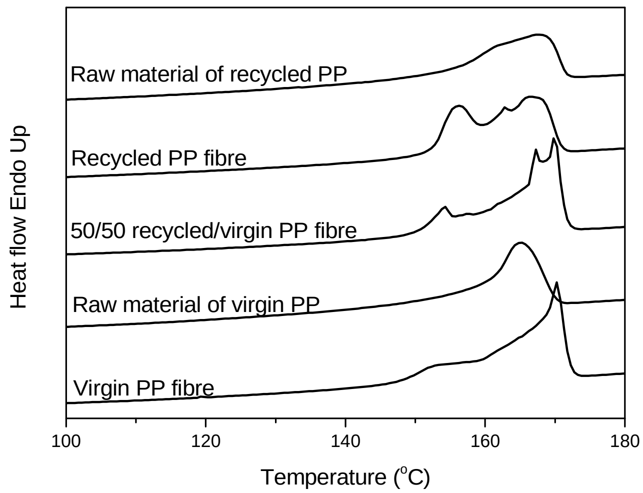

Fig. 3: DSC heating curves of the plastic fibres and their raw materials

After eliminating thermal history of materials by holding the samples at 220 °C for 3 min, the raw materials still have broad peaks as Figure 4(a), which are related to the crystals of three-dimensional crystals known as spherulites and/or rows of lamellae. However, all the fibres have narrow peaks, because the highly chain-extended and the highly oriented crystalline blocks formed fibrils during the hot drawing.

As seen in Figure 4(b), the raw material of recycled PP has lower crystalline temperature than the raw material of virgin PP, indicating that the raw material of recycled PP has lower molecular weight, shorter molecular chains and more defective molecules than the virgin PP, due to the degradation during its service life and heat processing stage. However, after hot drawing, the crystalline temperature of all the fibres improved significantly, because the hot drawing process oriented and aligned the crystal structures. The virgin PP has slightly higher crystalline melting temperature than the other two fibres, suggesting that the virgin PP fibre has more perfect crystals due to higher molecular weight, less molecular defects and higher purity. Because of the more perfect crystals, the virgin PP fibre had the highest tensile strength and Young's modulus among the three fibres tested.

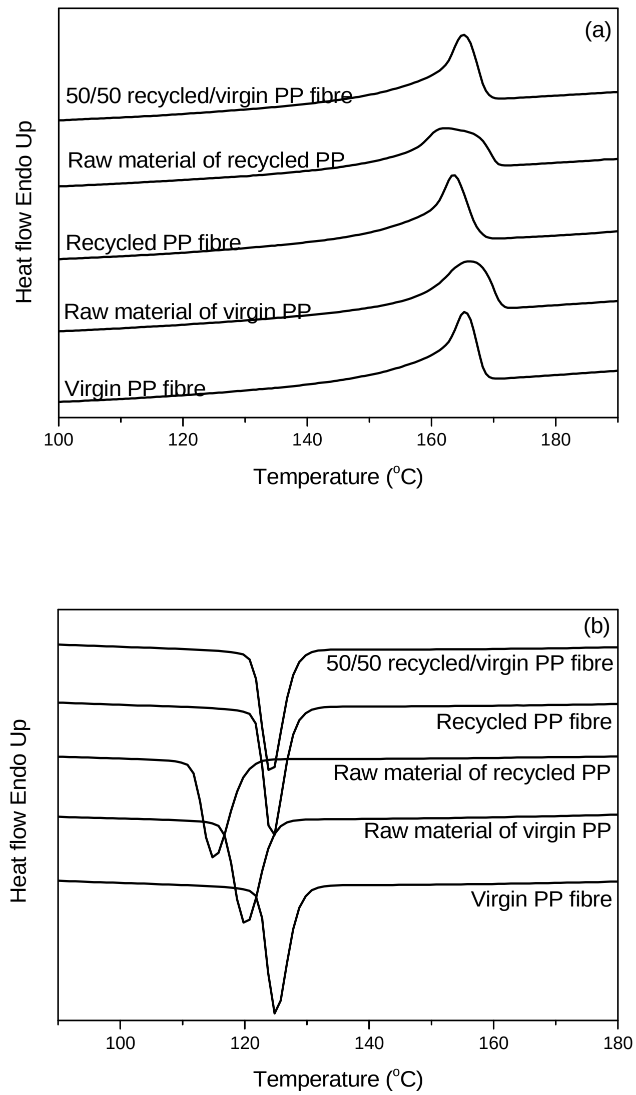

Fig. 4: DSC curve after eliminating thermal history: (a) heating from 30 to 200 °C and (b) cooling from 200 to 30 °C

3.3 WAXS measurements

Table 3 shows that the raw material of recycled PP has slightly higher crystallinity than the raw material of virgin PP, indicating that the raw material of recycled PP has shorter molecular chain, and thus is easier to align and form into crystals than the raw material of virgin PP. However, the hot drawing can considerably improve the crystallinity to more than 80 %. The virgin PP fibre has highest crystallinity, thus generating the highest tensile strength and Young's modulus.

Tab.3: Crystallinity of the polypropylenes

Composition	Crystallinity (%)
Raw material of recycled PP	51.2
Raw material of virgin PP	47.2
Recycled PP fibre	81.7
Virgin PP fibre	82.7
50:50 recycled–virgin PP fibre	81.9

Wide-angle X-ray scattering measurements in Figure 5 show that the PPs crystallize into the monoclinic α-form via diffractions at 2θ = 14.2°, 17° and 18.8°, associated with the (110), (040) and (130) planes, respectively. At these three faces the diffraction peak position has no change, but there are considerable differences in intensity. The intensity of the diffraction peak reveals the degree of the order in the material, including crystallization and orientation. Therefore, it shows that the hot drawing did not affect the α-form crystal type, but significantly improved the crystallization and orientation of the PP fibres. The peaks of raw materials at 2θ = 21.9°, which represents the α-form crystals, and 2θ = 21.4°, which represents the β-form, disappears after hot drawing. On contrary, new peaks at 2θ = 25.5°, 28.4° are produced, indicating the generation of new β-form crystals.

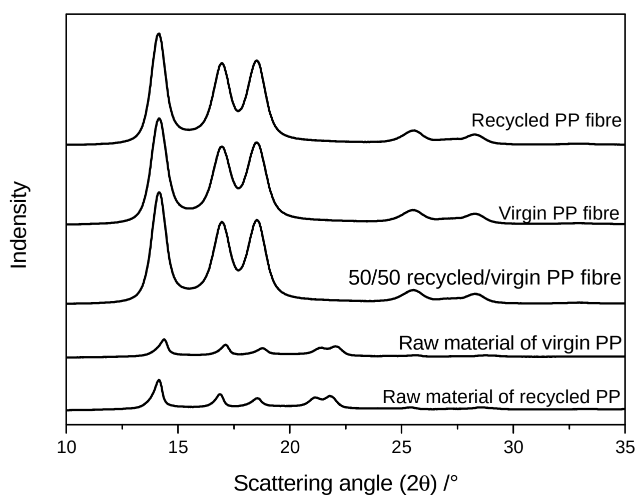

Fig. 5: WAXS profiles of the polypropylenes

4. Conclusions

The fibres with higher Young's modulus and tensile strength can bear higher load in concrete, thus generating better reinforcement. However, the production of recycled plastic with sufficient mechanical properties is still a major challenge due to their degradation during their service life and heat processing stage. In this research the recycled PP fibres were successfully prepared by the extrusion and hot drawing process.

The recycled PP fibre, however, had lower tensile strength and Young's modulus than the virgin PP fibre. When 50 % of virgin PP is mixed with 50 % of recycled PP, the Young's modulus are significantly improved. Both of the 100 % recycled PP fibre and the fibre with mixed 50 % recycled PP and 50 % virgin PP obtained high tensile strength and Young's modulus, which were high enough to reinforce concrete.

From DSC, both α-form and β-form crystals were found in the PP fibres. The recycled PP fibre had more β-form crystals, thus generating lower tensile strength and Young's modulus. On contrary, the virgin PP fibre had more α-form crystals, so it had enhanced mechanical properties. When 50 % of virgin PP was added, the fibre was prone to produce α-form crystals, so the modulus was significantly improved.

After eliminating thermal history, the raw materials were found to contain spherulites and/or rows of lamellae, while the fibres have fibrils formed by highly chain-extended and the highly oriented crystalline blocks. The raw material of recycled PP had lower molecular weight, shorter molecular chain and more defective molecules than that of virgin PP, due to degradation in its service life and heat processing stage. The hot drawing process made the molecule of the fibres highly oriented, thus improving the crystallinity and crystalline melting temperature of fibres.

The raw material PP had very low crystallinity (around 50 %), but the hot drawing process significantly improves the degree to over 80 %, thus generating high tensile strength and Young's modulus. From WAXS profiles, the α-form crystallisation and orientation were considerably improved by the hot drawing process, so increased mechanical properties were obtained.

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