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Mechanical Properties of Auxetic and Conventional Polypropylene Random Short Fibre Reinforced Composites

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Abstract
In this study, prior to the production of composites, auxetic and conventional polypropylene (PP) fibres were produced by the melt spinning technique. The fibres were tested and analysed in terms of Poisson's ratio, linear density, elongation at break and tenacity. The auxetic and conventional PP stable fibre reinforced composites were fabricated by the hand lay up method. Several mechanical properties of the composites were examined, including tensile strength, Young's modulus, elongation at break, energy absorption, impact velocity and damage size. SEM analysis was also conducted to identify microscopic changes to the overall composite structures. It was found that the auxetic fibre reinforced composites (7.5% and 10%) had the highest tensile strength and the auxetic fibre reinforced composite (5%) had the highest Young's modulus. The highest energy absorption was observed for the composite made with 10% auxetic fibre loading.

Key words: *auxetic fibre, polypropylene fibre, composite, tensile impact, smart material.*

Introduction

In fibre reinforced composites, both the fibre and matrix retain their original physical and chemical identities, yet together they produce a combination of mechanical properties that cannot be achieved with either of the constituents acting alone. This is due to the presence of an interface between the two constituents. There are a growing number of uses for fibre reinforced composites in many engineering applications; hence this has made the issue of interphase a major focus of interest in the design and manufacture of composite components. Natural, synthetic and waste textile products have been used extensively as composite reinforcements. Textile reinforced composites have better properties than metal or ceramic based composites; these properties include higher tenacity, superior elasticity and strength, good thermal resistance, low density, and better rigidity [1 - 5]. Polypropylene (PP) is used extensively by the automotive and aircraft industries because of its relative low cost, low density ease of processing and inert nature. In addition, PP can be used as a matrix material because of its low cost and ease of recycling [6 - 8].

Auxetic materials which have a negative Poisson's ratio demonstrate an extraordinary behaviour in that they get fatter when they are stretched, and become thinner when compressed (***Figure 1***). These characteristic materials display properties such as improved strength, acoustic behaviour [9], improved fracture toughness [10], superior energy absorption, damping improvement, and indentation resistance [11-13, 20].

Previous works have shown that auxetic materials can stand up to more than twice the maximum load withstood by conventional materials. This property is important for textile reinforced composites (***Figure 2***) as this creates a stronger adhesion between fibre and matrix.

In this study, prior to the production of composites, auxetic and conventional PP fibres were produced by the melt spinning technique using previous processing parameters. The fibres were then tested and analysed to find the following properties; Poisson's ratio, linear density, elongation at break, and tenacity. Auxetic and conventional PP stable fibre reinforced composites were fabricated by the hand lay technique. Epoxy resin was used as a matrix and the composites were manufactured by using both fibres with three different fibre loading proportions. The mechanical properties of the composites were determined and compared. The tensile behaviour was defined by the tensile strength, Young's modulus and

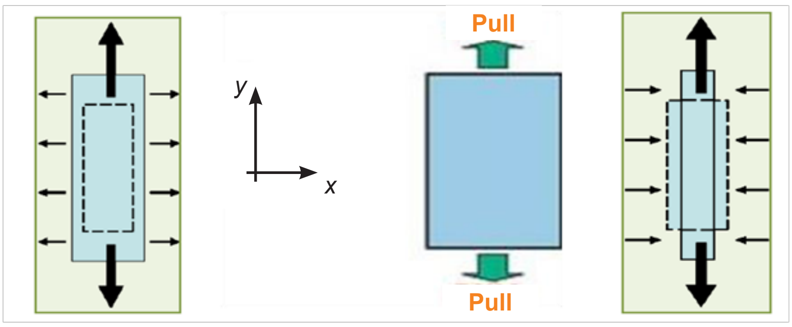

Figure 1. Negative (auxetic) (A) and positive (B) Poisson's ratio behaviours [14].

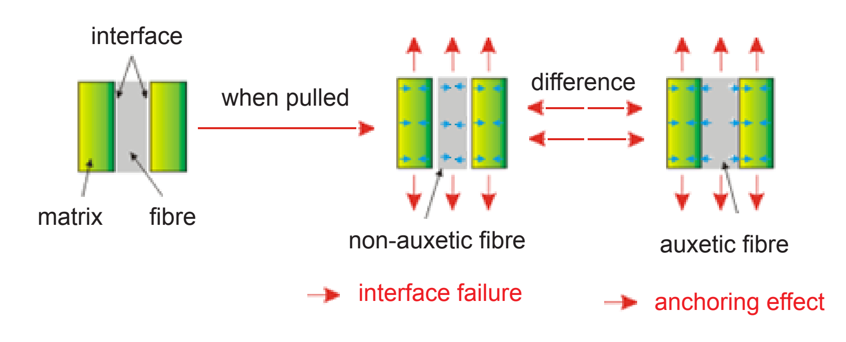

Figure 2. Pullout resistance (anchoring) [14].

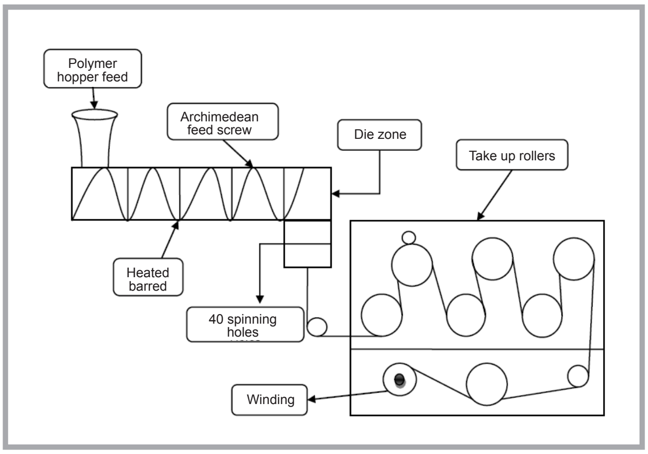

Figure 3. Melt spinning extruder [19].

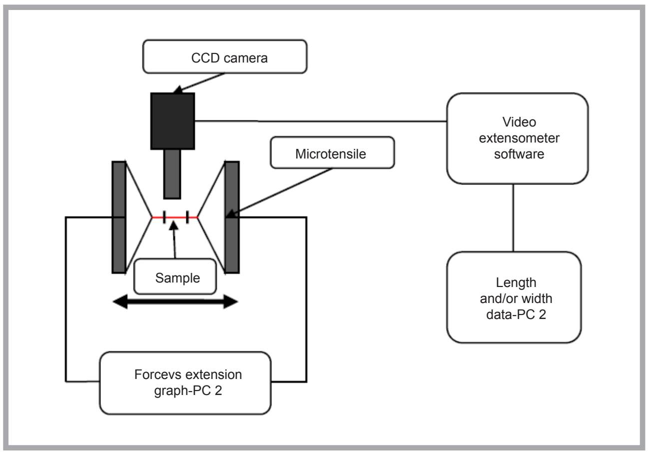

Figure 4. Working principle of videoextensometry.

elongation at break. The impact strength was determined from the energy absorption impact velocity and damage size.

Experimental

Materials

The auxetic and conventional PP fibres were manufactured from Coathylene PB0580 powder, produced by DuPont Polymer Powders (Sarl, Switzerland) and supplied by Univar (Bradford, UK). The PP powder has a rough surface with an average particle size of ~50µm and melting range 159-171°C. The composite matrix is Araldite LY 5052 Resin and Aradur HY 5052 Hardener, supplied by Aeropia Ltd (Sussex, UK).

Fabrication of auxetic and conventional PP fibres

The auxetic and conventional PP fibres were manufactured by the melt spinning technique using previously established processing parameters. A single screw extruder consisting of an Archimedean type screw was used to produce the fibres, being a common type of melt extruder for polymers. The barrel can be heated over a wide temperature range, generally between 150 °C and 300 °C. The melt extruder consists of a hopper, screw and die or spinneret. The extruder screw assists in conveying the material through the extruder, imparting energy to melt the polymer and mix the polymer uniformly [15], which also pumps the molten polymer at a constant rate. The polymer material then passes through the die, which consists of a spinneret. The spinneret has variable thickness and size, being usually circular and made of special stainless steel. The main function of the die is to give the shape required to the extruded polymer. Finally the fibre undergoes orientation and subsequent heat treatment processes before it is taken up by the bobbins, as shown in ***Figure 3*** [16 - 19].

Melt extruder set up

Prior to this research, the continuous melt extrusion process had been previously developed to produce the first known auxetic material in fibre form. In this study the melt spinning process was performed using a melt extruder consisting of an Archimedean type screw with a 3:1 compression ratio, 25.4 mm screw diameter, and thermostats for each of the five temperature zones. The PP powder was fed through a hopper into the barrel and fed through the extruder by the action of the screw, with a flat temperature profile of 159 °C in all the zones of the extruder for auxetic PP fibre production. The extruder was operated at a 10 r.p.m. (1.05 rad·s^{-1}) screw speed and 2 r.p.m. (0.03 m·s^{-1}) take-up speed, and a 40 −filament die with each hole of 550 µm diameter was fitted. The extruded fibres were cooled in the air after exiting the die before winding on the rollers. The filament fibres produced were then chopped to form staple fibres. The staple fibres had a various length between 3 and 5 mm [17, 19].

Poisson's ratio determination of fibres (Videoextensometry)

Poisson's ratio characterisation of the fibres was carried out using a MESS-PHYSIK ME 46 video extensometer in combination with a micro tensile testing machine in order to examine the auxetic behaviour of the fibres. A software package was developed by Messphysik GmbH that measures strains and/or extensions on standard specimens. The videoextensometry was used to measure the strains in both the axial and transverse directions, and hence the Poisson's ratio of the fibres was determined (***Figure 4***).

Fabrication of the matrix composites

The composites were fabricated with different fibre loadings (0, 5, 7.5 and 10%). Initially the PP resin and hardener were mixed in a mixer. The matrix materials were prepared with the following proportion: 73% of PP resin and 27% of hardener by volume. Then the fibres were spread into a mould and covered with the matrix. The composites were manufactured using the hand lay up technique with a mould size of 300 mm length × 300 mm width × 20 mm thickness. The composites produced were of 3.5 mm thickness and the mass per square meter of the composites ranged from 2950 to 3100 g/m^2. The composites were kept for 24 hours at room temperature and subsequently put in an oven (8 hours at 80 °) for curing.

Test methods

Tensile properties of the composites were tested using an Instron universal tester. The composite test specimens were prepared in accordance with ASTM D638. The specimens were cut using a standard saw cutter, ready for mechanical testing. The specimens were mounted in the grips of the Instron universal tester, with a 10 mm gauge length.

The low velocity impact behaviour of the control, auxetic and conventional composites was studied. The impact behaviour is defined by energy absorption, impact velocity and damage size. The damage growth process during impact, as the force surged to its maximum value, could be visualised from the static indentation

Table 1. Auxetic and conventional PP fibres properties.

Parameter	Auxetic PP (159 °C)	Conventional PP (170 - 230 °C)
Diameter, tex	40	40
Elongation at break, %	2.17	4.66
Tenacity, cN/tex	3.19	2.32
Poisson's ratio values	-0.70 to -0.40	-0.12 to + 0.35

Table 2. Tensile properties of auxetic and conventional PP fibre reinforced composites; S.D. - Standard Deviation.

Fibre loadings, %	Tensile strength in MPa				Young's modulus in GPa				Breaking elongation in %			
	Auxetic		Conventional		Auxetic		Conventional		Auxetic		Conventional	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0.0	Mean 860		S.D. 0.19		Mean 1.55		S.D. 0.18		Mean 1.55		S.D. 0.18	
5.0	1360	0.05	1180	0.27	1.79	0.14	1.63	0.23	1.57	0.21	1.54	0.04
7.5	1490	0.91	850	0.35	1.41	0.02	1.47	0.25	2.35	0.01	1.01	0.16
10.0	1480	0.08	800	0.22	1.69	0.07	1.12	0.24	1.81	0.05	1.74	0.09

Table 3. Impact properties of auxetic and conventional PP fibres composites.

Fibre loadings, %	Absorbed energy, J		Maximum load, N		Impact velocity, m/s	
	Auxetic	Conventional	Auxetic	Conventional	Auxetic	Conventional
0	0.95		406.4		1.36	
5.0	1.60	1.28	460.1	303.5	1.36	1.36
7.5	2.23	1.90	395.6	444.6	0.98	1.36
10.0	2.57	2.21	449.5	520.4	1.36	1.36

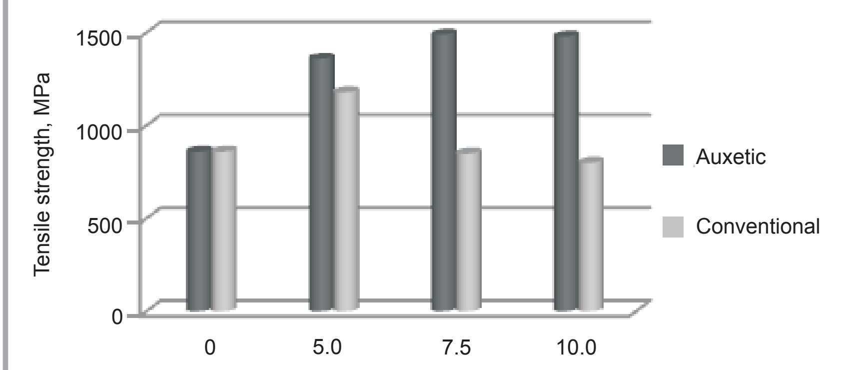

Figure 5. Comparison of tensile strength of control, auxetic, conventional composites.

damage induced at incrementally increased force levels. The impact damage suddenly appeared only when the impact force reached the maximum level. The damage size grew until the fibre damage caused the impact to level off. Images of the composites tested were taken to analyse the damage sizes using Image tool software. The phase morphological characteristics of the specimens were observed by SEM (HITACHI S-3400) in the normal mode. All the composites were fixed on the sample stage using adhesive tape and were coated with gold by a Sputter Coater (SC 7620).

Results and discussions

Auxetic and conventional PP fibre properties

As shown in ***Table 1***, the elongation at break of the auxetic PP fibre (2.17%) was found to be lower than that of the conventional PP fibre (4.66%). The elongation difference between the auxetic and conventional PP fibres was 115%, which is considerable. The auxetic PP fibre showed a higher tenacity (3.19 cN/tex) than the conventional PP fibre (2.32 cN/tex) even though their tex values were same (40 tex). Some significantly different values were recorded in terms of Poisson's ratio. The auxetic PP fibre, which was produced at 159 °C, had negative Poisson's ratio values in the range of -0.70 to -0.40, while that of the conventional PP fibre ranged from -0.12 to +0.35. The Poisson's ratio of the fibres decreased when the temperature of the spinning process decreased. The conventional fibre, which was produced at 230 °C, had the highest Poisson's ratio value in comparison with the rest of the fibres.

Tensile and impact behaviour of composites

Tensile properties of polymer matrix composite

Table 2 presents the tensile strength, Young's modulus and elongation at break. The tensile strength results are depicted in ***Figure 5***. According to the test results, the tensile strength of the control composite was 860 MPa, which is the lowest tensile strength value when compared with the reinforced composites. The tensile strength of the auxetic fibre reinforced composites ranged from 1360 to 1490 MPa while that of the conventional fibre reinforced composites varied from 800 to 1180MPa. The auxetic PP fibre reinforced composites had a 40% higher tensile strength, on average, compared to both the control and conventional PP fibre reinforced composites. The fibre loadings did not affect the tensile strength values of the auxetic fibre reinforced composites significantly.

Noteworthy differences were found between the control, auxetic and conventional composites in terms of elongation at break. It was noted that the elongation at break of the 7.5% auxetic fibre reinforced composite was extensively greater than that of the rest of the composites.

Determination of the impact properties

The damage size of the control composite was 84.8%, which was the largest cracking size compared to the reinforced composites. For 5, 7.5 and 10% auxetic composites the damage sizes were 37.7, 31.2 and 33.1%, respectively, whereas for 5, 7.5 and 10% conventional composites the damage sizes were 50.2, 54.7 and 51.3% respectively. Overall, the characteristic of impact force versus damage size varied with reinforcement materials. There is a significant difference between the auxetic and conventional composite: the auxetic composite damage size (~34%) was narrower and smaller than that of the conventional composite (~52%). The fibre loadings did not affect the damage size appreciably.

A noteworthy difference in the energy performance absorbed was seen when looking at the control, auxetic and conventional composites (***Table 3***). The impact response in both fibre (auxetic and conventional PP) reinforced composites reflects a failure process involving crack initiation and growth in the matrix as well as fibre breakage and pullout. The energy absorption was affected considerably by the fibre loading percentages. 10% auxetic fibre reinforced composites achieved the highest absorption in comparison to the other composites. For all fibre loadings, the auxetic composites had better impact behaviour due to their energy absorption, damping improvement and indentation resistance properties. The auxetic composite's absorption of energy ranged from 1.60 to 2.57 J. The conventional composite demonstrated lower absorption energy levels than the auxetic composite, which ranged from 1.28 to 2.21 J. A significant improvement was noted in that the auxetic reinforced composites showed a 20% higher impact resistance than their conventional counterparts. The impact velocity levels of the composites did not vary (1.36 m/s), with only the 7.5% auxetic composite showing a difference (0.98 m /s).

Scanning electron microscopy studies

SEM images of the composites are demonstrated in ***Figure 6***. It was observed that the adhesion between the fibre and matrix is strong, but there are some pull-outs and de-bonding. The auxetic fibre reinforced composite exhibits a ductile appearance with minimum plastic deformation. The conventional PP fibre reinforced composite has a rough surface, which may be caused by fibre and matrix interactions. According to the SEM images, there was not a remarkable difference between the auxetic and conventional fibre reinforced composites.

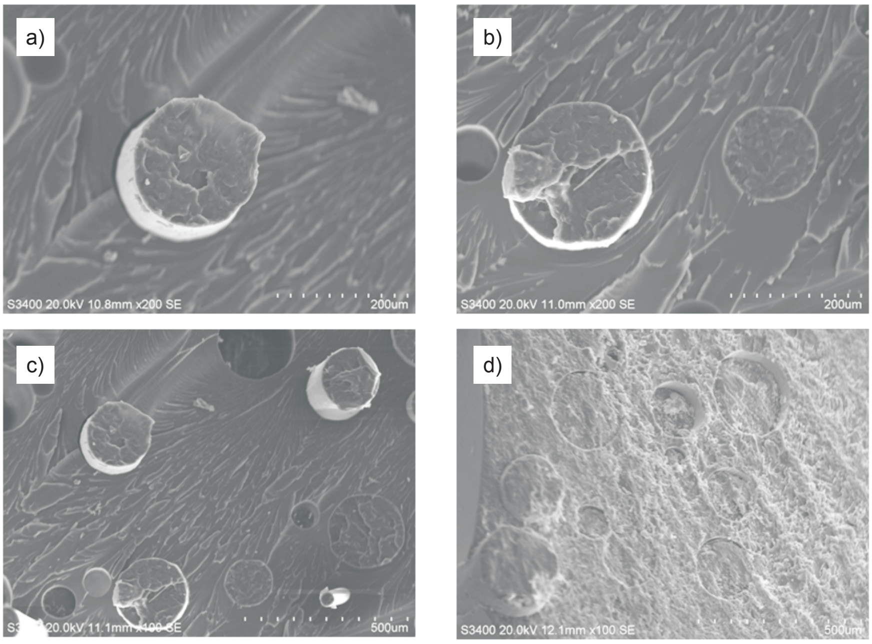

Figure 6. *SEM images of auxetic and conventional PP composite surfaces (×200 and ×500); a) Auxetic PP reinforced composite, b) Conventional PP reinforced composite, c) Auxetic PP reinforced composite, d) Conventional PP reinforced composite.*

Conclusions

This study evaluated the processing and testing of auxetic and conventional PP fibres and their composites. The aim was to enhance the mechanical properties of the composite by employing unique auxetic PP fibre. It was shown that auxetic behaviour has some promising advantages for engineering applications such as composites and textiles. The composites reinforced with auxetic PP fibre show better mechanical properties than the conventional PP fibre reinforced composites. It was observed that the impact properties of the composites can be improved by using auxetic PP fibre.

From the test results the following conclusions can be drawn:

- The elongation at break of the auxetic PP fibre (2.17%) is lower than the conventional PP fibre (4.66%).
- The tenacity of auxetic PP fibre is found to be higher than conventional PP fibre (27% stronger). The PP fibre produced at 159 °C has lower Poisson's ratio values than the PP fibre processed at 230 °C. The increase in production temperature causes a higher Poisson's ratio value.
- The auxetic PP fibre reinforced composite has 40% superior tensile strength than both the control and conventional fibre reinforced composites. The fibre loadings did not affect the tensile strength properties considerably.
- There is a considerable difference between the control, auxetic and conventional composites in terms of elongation at break features.
- The damage size of the auxetic composites (~34%) was narrower than that of the conventional composite (~52%). The fibre loadings did not affect the damage size notably. An important improvement is found in that the auxetic fibre reinforced composites have higher impact resistance than their conventional counterparts.

However, further research needs to be conducted on the subject of interactions between the auxetic PP fibre and composite structure. The parameters of composite production, such as the fibre length and fibre loading proportion, which possibly affect auxetic behaviour, should also be highlighted. These are important further studies that must be undertaken to achieve the optimum auxetic effect. Structural auxetic materials (from textile fabrics not from fibre) could also be investigated to achieve the maximum beneficial results for auxetic behaviour for textile based composite applications.

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