<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Polymer testing*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Schneider, C., Kazemahvazi, S., Åkermo, M., Zenkert, D. (2013)

Compression and tensile properties of self-reinforced poly(ethylene terephthalate)-composites.

Polymer testing, 32(2): 221-230

<http://dx.doi.org/10.1016/j.polymertesting.2012.11.002>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-116487>

Compression and Tensile Properties of Self-reinforced Poly (ethylene terephthalate)–Composites

C. Schneider^{†*}, S. Kazemahvazi^{†‡}, M. Åkermo[†] and D. Zenkert[†]

[†]KTH, Department of Aeronautical and Vehicle Engineering, Teknikringen 8, Stockholm, SE-100 44, Sweden

[‡]Arthur D. Little, Kungsgatan 12-14, Stockholm, SE-107 25, Sweden

*Corresponding author: E-mail address: schnei@kth.se (C.Schneider), Telephone number: +46 (0)73 46 12 498

Keywords: A. Fabrics/textiles; B. Mechanical properties; B. Plastic deformation;
B. Mechanical Testing

Abstract

Tensile and compression properties of self-reinforced poly(ethylene terephthalate) (SrPET) composites has been investigated. SrPET composites or all-polymer composites have improved mechanical properties compared to the bulk polymer but with maintained recyclability. In contrast to traditional carbon/glass fibre reinforced composites, the SrPET composites are very ductile resulting in high failure strains without softening or catastrophic failure. In tension, the SrPET composites behave linear elastic until the fibre-matrix interface fails at which point the stiffness starts decreasing. As the material is further strained, strain hardening occurs and the specimen finally fails at a global strain above 10%. In compression, the composite initially fails through fibre yielding and at higher strains through fibre bending. The stress-strain response is reminiscent of an elastic-perfectly plastic material with a high strain to failure (typically over 10%). This indicates that SrPET is not only candidates as structural composites but also as a high efficient energy absorbing materials.

1. Introduction

Improved energy efficiency and reduced fuel consumption has become increasingly important in order to stay competitive in the transport industry. As an example, the commercial truck industry is subject to stringent emission legislations and the aerospace industry sees constant pressure to reduce fuel consumption of aircrafts. Weight reduction has proven to be an efficient way of reducing the fuel consumption of both road and airborne vehicles. To achieve improved weight efficiency of vehicles, the use of lightweight alloys and composite materials has increased significantly during the last decade. A major challenge is however to reduce the weight of structures while reducing costs and improving the recyclability of the structural materials. Traditional composite materials are commonly based on thermoset matrix materials reinforced with carbon or glass fibres. This class of composite materials are generally manufactured using a matrix infusion process followed by a time consuming curing (and cooling) process which results in an overall long manufacturing lead time and consequently high costs. Further, thermoset based composites are generally brittle, have low fracture toughness, low inter-laminar toughness and poor recyclability. In particular, recycling of thermoset matrix based composites has proven to be very costly since no efficient process to separate fibres from the matrix exists [1]. Using thermoplastic matrix materials, new opportunities for cost-efficient manufacturing and improved recyclability are enabled. As an example, thermoplastics can be reheated and rapidly formed using a variety of techniques such as folding, blowing, stretching and stamping. They can also be re-melted and recycled into new structures. In order to improve the mechanical

performance of thermoplastics it is however intuitive to reinforce them with carbon or glass fibres. Doing this will, however, inflict on their recyclability.

This has paved way for a new generation of composite materials where the fibres and the matrix are made from the same base material. This class of composites are termed all-polymer composites or self-reinforced polymer (SrP) composites. Some examples of commercially available SrPs include poly (ethylene terephthalat) (PET) [2] and polypropylene (PP) [3] SrPs. SrP are thus an emerging class of composites attributable to the possibility to rapidly manufacture lightweight and recyclable parts with a density well below traditional filled polymers [4, 5]. The fibres used in SrP's have higher molecular orientation which results in improved stiffness and strength compared to the unreinforced matrix materials. The matrix material is commonly amorphous and /or out of a polymer with lower melting temperature. The fibres are much more ductile than the matrix, which is unusual for composite materials, but results in the ability to absorb a high level of energy when (plastically) deformed [6]. SrPs can also be made from commingled fabrics which will eliminate the resin injection process; something that will be described in more detail later in this paper. The material processing is then reduced to heating the commingled material to its melting temperature followed by a cooling process. To date, only a limited number of studies have investigated the mechanical properties of SrP materials. Hine and Ward [7] investigated the mechanical properties of woven PET that was manufactured using a hot compaction process. They found that the SrPET had approximately 2.5 times higher tensile strength and stiffness compared to the isotropic basic material. Yao et al. [2] investigated the mechanical properties of PET fabrics and

films manufactured using a film stacking technique. They showed that tensile strength increases about 2.5 times when the PET matrix is reinforced with PET fibres. Alcock et al. [3] investigated the compression properties of self-reinforced PP made out of co-extruded all-PP tapes. They used an experimental setup where test specimens were end loaded up to failure. It was found that the co-extruded all-PP tapes fail by tape buckling and delamination. The authors further concluded that the drawing mechanism of PP tapes enhances the tensile properties of the polymer structure but does not affect the compression properties. Thus no enhancement of the compression properties was found using drawn all-PP tapes as compared to bulk PP material. This study provides a detailed investigation of the mechanical properties of SrPET composites manufactured from commingled fabrics. The focus is put on understanding the compressive response of the material but the material tensile properties are also presented in order to give a complete picture of the material behaviour. In order to build a clear understanding of the overall stress-strain response of the material coupled to the dominating failure mechanisms, traditional carbon and glass fibre reinforced thermoset and LPET matrix materials have been used for comparisons. The main objective has been to investigate if SrPETs have improved mechanical performance compared to the PET bulk material and if the potential increase of ductility results in improved energy absorption capability.

2. Description of Materials and Method

2.1 Constituent materials and manufacturing methods

SrPET plates were manufactured from fabrics with commingled yarns. In a commingled yarn, matrix fibres and reinforcing fibres are blended. These yarns are woven jointly to form a dry fabric including both the fibres and the matrix. Two types of commingled fabrics were used: The first was a weave with 80% of the fibres in one direction and 20% in the perpendicular direction; this fabric will be denoted UD hereon. The other commingled fabric type was a balanced twill 2/2 weave (denoted Twill). The base matrix material (LPET) has a melting point of around 160 - 180°C. The fibre material is a high tenacity PET (HPET) with a melting point of around 260°C, which is significantly higher than for the LPET. The SrPET plates were manufactured using a vacuum consolidation process with a pressure of 0.95bar under atmospheric pressure. The temperature was increased incrementally up to 220°C for 12min ensuring that the matrix material melts and fully impregnates the HPET fibres leaving minimum amount of voids. The consolidation time of the material is governed by the consolidate pressure and temperature and can be as short as 5 minutes when a pressure of 0.95 bar is applied at 230°C. All Sr-PET plates were manufactured by Comfil® ApS [8]. For reference purpose, two additional types of different materials reinforced with glass or carbon fibres were manufactured. The first reference material was based on the same LPET matrix material as used in the SrPET plates. These plates were reinforced with T300-3K carbon (denoted C) fibres or E-glass (denoted E) fibres. The plates were manufactured from of a balanced, commingled twill 2/2 fabric using the same vacuum consolidation process as for the SrPET plates. These plates were also manufactured by Comfil® ApS [8]. The second reference material was based on Vinyl-Ester Dion® 9102 matrix

material from Reichhold (denoted VE) [9]. The VE plates were reinforced with T300-3K carbon (denoted C) or E-glass (denoted G) fibres which are the same as in the reference plates with LPET matrix. The plates were manufactured from a balanced twill 2/2 weave with the same areal weight of fibres as the reference plates based on LPET and approximately the same fibre architecture. These plates were manufactured in-house using a traditional vacuum infusion process with a curing pressure of approximately 1 bar under atmosphere pressure followed by a post curing cycle at 71°C for 4 hours and 82°C for 2 hours. One final reference plate was manufactured out of bulk LPET without any reinforcement. The manufacturing process was the same as for the SrPET plates and the plates were manufactured by Comfil® ApS [8]. Table 1 presents a summary of the physical and geometrical properties of all used materials. The fibre volume fraction of C / LPET and G / LPET is lower than the fibre volume fraction of the C / VE and G / VE composites. This is partly due to the commingled fabrics that were used in the LPET composites and partly due to the difference in the manufacturing process.

In order to evaluate the quality of the laminates, small pieces of the material were embedded in epoxy and mechanically polished using abrasive paper. Optical micrographs were then used to check the quality of the plates (see figure 1). The micrographs show no dry fibre bundles or other defects of significant size. The SrPET-UD plate shows the lowest amount of fibre crimp while the SrPET-Twill plate has a high amount of fibre crimp. The reference plates with carbon or glass fibres had approximately the same level of fibre crimp which is considerably lower than the SrPET-Twill plate.

2.2. Experimental protocol

Tensile tests specimens of SrPET and LPET were manufactured according ASTM D638 [10]. The specimens were tested with an Instron 4045 testing machine equipped with a 100kN load cell to measure the tensile force. All tensile tests were performed at room temperature with a constant cross-head displacement of 2mm/min. The strain was measured using a strain gauge extensometer with a gauge length of 50mm. A minimum of 3 specimens per material configuration were tested. All compression tests were performed with an IITRI test fixture according ASTM D3410 procedure B [11] (see figure 2) at room temperature and at a loading rate of 1.5 mm/min. The specimens were tabbed to assure a safe loading and had a gage length of 12mm and width of 25mm (see figure 2). A minimum of 3 specimens per material configuration were tested. An Instron 4045 testing machine equipped with a 100kN load-cell was used to measure the compression force. For all materials, the true stress and true strain was calculated.

The strain was measured using a digital image correlation technique [12]. A speckled pattern was applied on the side surface of the specimen (thickness direction) and the deformation was recorded before and during displacement. One image per second and the corresponding compression force from the load-cell was recorded simultaneously. The strain field was calculated using the commercial Aramis software code [12]. An area of about 14 x 6.5mm was manually selected for strain calculation and meshed automatically (facet size 15 x 15pixel, facet step size 13pixel). Two measuring points were defined (see figure 2) in the deformation free area, with a gauge length of 12mm. These points were used in the Aramis system as a virtual extensometer to calculate the overall engineering compressive strain.

3. Summary of experimental results

3.1 Tensile behaviour of bulk LPET and SrPET-composites

Figure 3 shows a representative tensile stress-strain response of the LPET, SrPET-Twill and SrPET-UD. The tensile modulus of SrPET-UD and SrPET-Twill is 8.0 ± 0.2 GPa and 5.1 ± 0.2 GPa respectively. This is approximately 2.8 and 1.8 times higher than the tensile modulus of the bulk LPET material which is 2.8 ± 0.1 GPa. The LPET shows a linear stress-strain response up to a stress of 43 ± 3 MPa where it fails in a brittle manner at about 1.5% strain. The SrPET-Twill on the other hand behaves linear up to 40 MPa which correspond to 0.8% global strain. As the global tensile strain further increases, the stiffness starts decreasing. The stiffness however starts to decrease below the strain-to-failure of the matrix material which indicates a fibre-matrix interfacial failure. As the tensile straining progress, strain hardening occurs. Finally, the SrPET-Twill fails at about $16.5 \pm 1\%$ global strain and at a failure stress of 124 ± 2 MPa. The SrPET-UD shows a similar behaviour as the SrPET-Twill. However, in the SrPET-UD composites, the fibre-matrix interface fails at a global strain of about 0.8% but at a higher stress level than in the SrPET-Twill due to the higher fibre volume fraction in the loading direction. The strain hardening exhibited by SrPET-UD is more distinct since the SrPET-UD has lower crimp and the higher volume fraction of fibres in the loading direction. All SrPET-UD tensile specimens failed at the specimen clamping where high stress concentrations appear. This means that the true tensile strength and strain-to-failure is higher than the one displayed in figure 3.

3.2. Compressive behaviour of SrPET and reference materials

In order to enable comparisons and to clearly elucidate the compressive behaviour of the SrPET material it will start by summarizing the findings from the reference material

experiments. Subsequent to this description, the results from the SrPET and bulk LPET material will be described in detail. An overview of the compression test results is shown in table 2. The compression moduli of the materials were determined in the strain range of 0.1-0.5%. Due to their high ductility, the SrPET and LPET specimens did not reach a clearly defined ultimate failure load. The compression strength presented for SrPET and LPET are thus defined as the onset of plastic yielding (will be described in more detail later). For the glass and carbon fibre reinforced specimens the compressive strength is defined at the ultimate failure stress.

3.2.1 Carbon/Glass fibre reinforced Vinyl-Ester Composites

Figure 4 shows a representative compression stress-strain response of the glass- and carbon fibre Vinyl-Ester composites. As expected, the glass fibre reinforced composite has a lower stiffness than the carbon fibre reinforced composite. The compressive strength of the two materials is approximately the same indicating that the failure is governed by plastic instability of the fibres. Although it is difficult to show exactly which mechanism caused the onset of failure, fractographic analysis shows formation of kink-bands and multiple micro-buckled fibres. This agrees well with the established theory of compressive response of brittle polymers reinforced by brittle fibres [13].

3.2.2 Carbon/Glass fibre reinforced LPET Composites

Figure 5 shows a representative compression stress-strain response of the glass- and carbon fibre reinforced LPET composites. It is observed that the stiffness of the two materials are again different, with the carbon fibre composite having significantly higher stiffness. The compressive strength of the materials is however similar and optical micrographs show fibres that have undergone micro buckling failure, see figure 6. Compared to the carbon/glass reinforced Vinyl-Ester composites the compression

strength of the LPET-matrix composites is approximately 30% lower. This reduction in strength is attributable to the lower shear stiffness and strength of the LPET-matrix. According to the theory of micro-buckling, lower stiffness and strength of the matrix material will result in an overall reduction of the strength of the composite; this will be discussed in more detail in subsequent section. The compressive stiffness of the LPET composites is lower than the stiffness of the VE composites which is explained by the higher volume fraction of fibres in the VE composites.

3.2.3 SrPET composites and bulk LPET

Figure 7 shows the compressive stress-strain responses of representative SrPET-UD, SrPET-Twill and LPET samples. The yield point of the material has been defined using the 0.2% offset strain method. Two key characteristic differences can be observed in the stress-strain response of the LPET and the SrPET material. The LPET material shows a, close to, linear stress-strain response up to a peak load of 90 MPa where yielding is initiated and then followed by a softening response. The SrPET material, on the other hand shows a bi-linear type stress-strain response up to the yield point (at about 95 MPa) and almost no softening. The point at which a change in stiffness is observed (resulting in the bi-linear behaviour) will here be referred to as the transition point. The SrPET materials have a transition point at a stress level of approximately 30% of the yield stress level of the LPET. Prior to this transition point the compression modulus of SrPET-UD and SrPET-Twill is $7.9 \pm 0.2 \text{ GPa}$ and $5.3 \pm 0.2 \text{ GPa}$ respectively. This is approximately 2.6 and 1.7 times higher than the compression modulus of the bulk LPET material which is $3 \pm 0.1 \text{ GPa}$. Above the transition point, the compressive modulus of both the SrPET-UD and SrPET-Twill decreases to the same modulus as the bulk LPET. Although both the SrPET-UD and SrPET-Twill show a similar stress-strain response,

one key difference can be observed. The stiffness of the SrPET-UD is higher, simply caused by the higher amount of HPET fibres in the direction of the loading. Figure 8 displays strain maps as measured by digital image correlation for SrPET-UD, SrPET-Twill and LPET specimens. At low levels of global strain ($<2\%$), the strain field across the specimen cross-section of SrPET-Twill and LPET is uniform with minor strain localizations. As the global compressive strain increases, and one reaches the yield point, increasing amount of strain localization is observed. For the SrPET-UD specimens, strain localization start to appear at a low level of global strain ($<1\%$). This means that strain localizations, i.e. localized material deformation, was observed well below the material yield point. For the LPET specimens, strain localizations are focused to one single shear band formation in the $\pm 45^\circ$ direction, indicating of shear yielding in the material. As the compressive straining progresses, the shear band becomes more and more distinct and macroscopic cracks can be observed visually. For the SrPET-Twill specimens, strain localization starts to appear but distributed along the entire height of the test gauge. Further, the intensity of the strain level is less severe than for the bulk LPET case which is an effect from the stabilizing fibre reinforcement. For the SrPET-UD specimens, strain localization start to appear prior reaching the yield point at about 0.4% global strain. The strain localizations are perpendicular to the load direction and appear along the entire height of the test gauge. This strain localizations appear at the transition point, where the stiffness of the laminate changes. The transition point indicates the point at which the individual HPET fibres start to yield. The yielding of the fibres is attributable to the highly aligned molecules that start to collapse (crush) under compressive loading. Fibre crushing of HPET fibres appears at 0.4% global

strain. The critical crush strain of other polymer fibres like Kevlar or PE (Polyethylene) is at 0.5% and 0.08% respectively [14] which is in the same range as for HPET fibres.

In order to investigate the micro failure mechanisms of the specimens, tests were interrupted at different strain levels and micrographs were produced, see figure 9. The optical micrographs of the SrPET-Twill specimen show that the crimp (or curvature) of the fibres increases as the applied strain increased. No kink band formation was observed; instead the fibre crimp of the whole cross section area was increasing uniformly rather than locally. Further, no fibre breakage could be observed. As the applied level of strain increases, a number of cracks starts to grow between the fibre bundles showing clear failure in the interface between the matrix and fibres, see figure 9c. The SrPET-UD specimens show a more localized failure behaviour and a band of kinked fibres can be observed as shown in the micrographs in figure 10. Although the fibres kink, no fibre breakage can be observed which is an effect of the high strain to failure of the fibres.

4 Discussion

In tension, the SrPET composites behave linear elastic until the fibre-matrix interface starts to fail. No bi-linear behaviour could be detected in tension. In tensile loading condition, the fibres have one failure mode less than in compression; fibres or molecules can buckle (or crush) which is not possible under tensile loading [15]. In compression, carbon and glass fibre reinforced LPET and vinyl-ester laminates failed through fibre micro buckling as shown by the kink band formations. Using the Budiansky [16] model for micro buckling of composites, the compression strength of fibre reinforced composites can be calculated using equation 1.

$$\sigma_{ck} = \frac{k}{\gamma_Y + \phi} = \frac{G}{1 + \frac{\phi}{\gamma_Y}} \quad (1)$$

where k and γ_Y are the yield stress and yield strain in longitudinal shear, G is the shear modulus and ϕ the initial fibre misalignment angle, the latter being linked to the fibre crimp. The glass and carbon fibre reinforced laminates have approximately the same compressive strength when using the same matrix material. The compressive strength of the laminates does however change when the matrix material is changed, indicating that the failure mode is matrix dominated, just as the theory of micro buckling assumes.

Using the micro-graphs shown previously (see figure 1), the fibre misalignment of the different laminates could be estimated. Vinyl-Ester reinforced with carbon or glass fibre composites had a fibre misalignment of about 5° . Assuming a shear yield strain of $\gamma_y=0.04$ and a shear modulus of 1.2GPa the compressive strength of vinyl-ester based laminates is estimated 377MPa as shown in figure 11. The compressive kink-stress estimation is in the same range as the compression strength of the carbon/glass fibre reinforced Vinyl-Ester composites which further supports that the governing failure mechanism of the laminates was micro buckling. PET has a shear modulus of 1.1GPa and a shear yield strain of 0.025 [17]. Assuming the same fibre misalignment angle of 5° , the compressive strength of the laminate was estimated to 245MPa. Again, this is in good agreement with the experimental observations as shown in figure 11. It is thus reasonable to state that the glass/carbon fibre reinforced LPET composites also fail by micro buckling as the governing failure mode. According to the micro buckling failure theory, the compressive strength of the laminates is independent of the reinforcing fibres. Now, turning to the LPET laminates reinforced by HPET fibres one can observe that the compressive strength is significantly lower than the carbon/glass reinforced

specimens. If the failure mode is to be micro buckling, using equation 1 would require the use of a fibre misalignment angle of 14° in order to predict a strength as low as 100 MPa. Comparing the micro graphs of the SrPET-UD laminates with carbon/glass LPET laminates one can observe that the SrPET-UD even has a lower fibre crimp than carbon/glass LPET laminates. It can thus be concluded that the governing failure mode of Sr-PET laminates is not micro buckling. In figure 10 one can see that fibres in the SrPET-UD laminate appear to be kinked. However, the image in figure 10 is taken at a high compressive strain so the fibres are bent, or rather, the fibre crimp increases as the compressive strain increases. The fibre misalignment angle in the SrPET-Twill was much higher than in the SrPET-UD but no kinked fibres like the one in the SrPET-UD could be detected. SrPET-Twill and SrPET-UD had the same compression yield strength although SrPET-Twill had a higher misalignment angle (higher crimp) of fibres and a lower volume fraction of fibres in load direction (y-direction) (see table 1). This shows that the fibre misalignment angle and volume fraction of fibres had no influence on the compression yield strength. The SrPET-UD had about 2.6 times and the SrPET-Twill about 1.7 times higher compression modulus than the matrix material. Assuming that the fibres perpendicular to the loading direction have the same modulus as the matrix material and using the “rule of mixture”, the compression modulus of the fibres can be calculated. The calculated fibre modulus for SrPET-UD was 15.2GPa and for SrPET-Twill 12.2GPa. This demonstrates that the fibre misalignment, although not affecting the strength, does affect the laminate stiffness.

The LPET failed by shear band formation (see figure 8). The LPET started to shear in 45° bands and then these shear band grew in width as the global strain increased. In the SrPET-Twill, many small shear bands could be detected. It appeared like the shear

bands stopped shearing, locked up, followed by the initiation of a new shear band in another plane. It is believed that the HPET fibres increase the shear resistance of the material in compression. This results in a slightly higher yield compression stress and almost no strain softening after yielding which increased the energy absorption of this material. The energy absorption of a material is equal to the compression strain-energy which is the area under the compression stress-strain diagram (see figure 4, 5 and 7). The specific energy absorption is the absorbed energy per mass. The traditional composites C / Vinyl-Ester can absorb 0.74J/g specific energy during a compression test which is assumed to be 100%. If the fibres are replaced by glass fibres (G / Vinyl-Ester) the specific energy absorption capability increases by 60% to 1.2J/g compared to C / Vinyl-Ester composites. If the matrix is replaced by LPET, the energy absorption decreases. Composites with carbon or glass fibres and LPET matrix can absorb about 0.48J/g and 0.98J/g, respectively. This is approximately 67% and 82% of their counterparts with VE matrix. In compression, the SrPET composites and LPET did not fail and due to that the specific energy absorption was calculated up to 10% strain (which is not the maximum). The non reinforced LPET can absorb 6.4J/g which is 6.7 times more than the C/VE laminate. However, for LPET reinforced with HPET fibres the specific energy absorption increases further: the specific energy absorption of the SrPET-Twill and SrPET-UD is 6.2J/g and 6.4J/g which is about 8.5 and 8.7 times higher than of a C / Vinyl-Ester composite. The high specific energy absorption capability of SrPET is attributable to the difference in mechanical failure mode between the two types of composites. The glass and carbon fibre reinforced composites show a brittle and sudden failure at low strain levels whereas the self-reinforced composites exhibit a ductile and high strain to failure behaviour.

3 Concluding remarks

The compression failure mechanism of self-reinforced PET composites was investigated and compared with composites reinforced with carbon or glass fibre. Composites based on LPET or Vinyl-Ester reinforced with carbon or glass fibre failed by micro buckling which is a catastrophic failure. The compression strength of such composites is matrix dominated and gives the same compression strength for carbon and glass fibre composites. The matrix material LPET failed by shear banding followed by strain-softening. In SrPET laminates, at very low strain, the HPET fibres crushed which reflects in a stiffness reduction. At high strain, the HPET fibres hinder the LPET matrix to shear and due to that no strain-softening or catastrophic failure occurred. This indicates that this class of materials potentially can be used as efficient high energy absorbing materials. In tension, the matrix material LPET is brittle and it had about one-tenth of strain-to-failure of an SrPET composite. The SrPET composites behaved linear elastic until the fibre-matrix interface failed. Due to that, the stiffness reduced. At higher strain, strain hardening occurred.

4 Acknowledgements

This work was performed within the Centre of ECO2 Vehicle Design at the Department of Aeronautical and Vehicle Engineering, Royal Institute of Technology, KTH with financial support from the Swedish Agency for Innovation Systems (VINNOVA). Acknowledged support was also provided by Scania CV and the KTH Production Technology Platform XPRES.

5 References

1. Pinero-Hernanz R, Dodds C, Hyde J, Garcia-Serna J, Poliakov M, Lester E, Cocero M J, Kingman S, Pickering S, Wong K H. Chemical recycling of carbon fibre reinforced composites in nearcritical and supercritical water. *Composites Part A: Applied Science and Manufacturing* 2008; 39(3):454-461.
2. Yao D, Li R, Nagarajan P. Single-Polymer Composites Based on slowly crystallizing Polymers. *Polymer Engineering & Science*, 2006,46:1123-1230.
3. Alcock B, Cabrera N O, Barkoula N M, Spoelstra A B, Loos J, Peijs T. The mechanical properties of woven tape all-polypropylene composites. *Composites Part A* 2007; 55:147-161.
4. Matabola K P, Vris A R, Moolman F S, Luyt A S. Single polymer composite: a review. *Journal of Material Science* 2009; 44:6213-6222.
5. Kmetty A, Barany T, Karger-Kocsis J. Self-reinforced polymeric materials: a review. *Progress in Polymer Science* 2010; 35:1288-1320.
6. Hine P J, Ward I M, Jordan N D, Olley R, Bassett D C. The hot compaction behaviour of woven orientated polypropylene fibres and tapes. 1. Mechanical properties, *Polymer* 2003;44:1117-1131.
7. Hine P J, Ward I M. Hot compaction of woven poly(ethylene terephthalate) Multifilaments. *Journal of Applied Polymer Science* 2003; 91(4):2223-2233.
8. Comfil® ApS. Thermoplastic Composites, DK 8883 Gjer, Denmark, 10.2011, www.comfil.biz.
9. Reichhold AS. Datasheet DION® 9102 Series, Bisphenol-Epoxy Vinyl-Ester Resins, 1.2007.

10. ASTM D638-10 Standard Test Method for Tensile Properties of Plastics. DOI: 10.1520/D0638-10.
11. ASTM D3410/F3410M-03(Reapproved 2008). Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear loading. DIO:10.1520/D3410_D3410M-03R08.
12. GOM mbh. User Manual: Aramis v5.3.0, Braunschweig, Germany <http://www.gom.com>.
13. Fleck N A. Compression failure of fiber Composites, *Advances in Applied Mechanics*. 1997; 3: 43-117.
14. DeTeresa S J, Porter R S, Farris R J. Experimental verification of microbuckling model for the axial compressive failure of high performance polymer fibres. *Journal of Materials Science*, 1988; 23:1886-1894.
15. Hosford W F. *Mechanical Behavior of Materials* – 2nd ed. Cambridge University Press, 2010. p.356.
16. Budiansky B. *Micromechanics*. *Computer & Structures* 1983; 16:3-12.
17. Baltussen J J M, Northolt M G. A model for the tensile curve with yield of a polymer fibre. *Polymer Bulletin* 1996; 36:125-131.

Figure 1: Optical micrographs of the composites. The magnification level is the same in all figures (displayed in figure f): a) SrPET-UD, b) SrPET-Twill, c) C / LPET, d) G / LPET, e) C / VE, f) G / VE

Figure 2: IITRI compression test fixture with test specimen, geometry of the compression test specimen (Gage length: 12mm, Width: 25mm) displayed with the measuring points for strain measurement

Figure 3: Tensile stress-strain diagram for LPET, SrPET-Twill and SrPET-UD

Figure 4: Compression stress-strain diagram of G / Vinyl-Ester and C / Vinyl-Ester

Figure 5: Compression stress-strain diagram of G / LPET and C / LPET

Figure 6: Optical micrographs of the compression failure of C / LPET (figure a) and G / LPET (figure b)

Figure 7: Compression stress - strain diagram for SrPET-UD, SrPET-Twill and LPET

Figure 8: Compression strain of LPET, SrPET-Twill, and SrPET-UD in Y direction and shear displayed by digital image correlation technique.

Figure 9: Optical micrographs of the compressed SrPET-Twill specimens.
The magnification is the same in all figures
(displayed in figure c): a) 6% strain, b) 17% strain, c) 23% strain

Figure 10: Optical micrographs of the compressed SrPET-UD specimen, 8% strain with kinked fibres

Figure 11: Compression strength σ_c [MPa]: C/LPET, C / Vinyl-Ester, G / LPET, G / Vinyl-Ester, SrPET-UD, SrPET-Twill, LPET at yield point. The dashed lines show the calculated kinking stress for a 5° misalignment angle of the fibres

Table1: Physical and geometrical properties of the used materials

	Plate Thickness [mm]	Fabric Type	Area weight fabric [g/m ²]	Weight fraction fibre [%]	Volume fraction fibre	Density [g/cm ³]
SrPET-UD	5.2	UD 4/1	555	50	0.50	1.38
SrPET-Twill	5.7	Twill 2/2	750	50	0.50	1.38
C / LPET	5.1	Twill 2/2	500	54	0.48	1.60
G / LPET	5.2	Twill 2/2	750	57	0.42	2.10
C / VE	3.3	Twill 2/2	196	68	0.58	1.60
G / VE	3.3	Twill 2/2	396	73	0.54	2.10
LPET	6.8	-	-	100	0	1.38

Table 2: Summary of compression test results of all tested materials

	Compression	Compression	Strain to	Tensile
	Modulus	Strength	failure [%]	Modulus
	[GPa]	[MPa]		[GPa]
C / VE	57.5 ± 2.5	365.5 ± 38.3	0.7 ± 0.1	57.1 ± 1.0
G / VE	31.2 ± 1.2	392.5 ± 20.0	1.4 ± 0.2	27.1 ± 0.6
C / LPET	48.9 ± 3.3	285.3 ± 9.1	0.6 ± 0.05	50.0 ± 2.0
G / LPET	20 ± 1.2	239.2 ± 8.2	1.3 ± 0.1	17.2 ± 1.1
SrPET-UD	7.9 ± 0.2	101.0 ± 1.1	>15	8.0 ± 0.2
SrPET-Twill	5.3 ± 0.2	94.7 ± 0.7	>15	5.1 ± 0.1
LPET	3.0 ± 0.1	89.3 ± 1.0	>15	2.8 ± 0.2