The Recovery, Reprocessing and Reuse of Waste Glass Fibre Fabrics: “Closed-Loop Recycling”

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1 Introduction

The term “closed-loop recycling” is defined here as the recovery, reprocessing and reuse of waste materials (preforms) by the industrial concern that generates the waste. In other words, the waste material that is generated within the organisation is recovered, reprocessed and re-used to manufacture products of commercial value. The current paper is concerned with the recovery, reprocessing and reuse of waste glass fibre preforms (fabric) that are generated during the primary (weaving) and secondary (coating and trimming) fabric production processes. Traditionally, cardboard tubes are used as the mandrel to over-wrap the woven fabric. Although these cardboard mandrels are relatively cheap compared to polymeric or metallic mandrels they have a lifespan, on average, of three cycles (over-wrapping and transport operations). Typical damage modes that are observed with the cardboard tubes during service are shown in Figs. 1 (a and b); the damaged tubes are generally disposed in landfills or incinerated.

Whilst considerable resources continue to be directed to aspects of recycling fibre reinforced composites, comparatively little attention is paid to the recovery and reuse of waste generated in the production of the reinforcing fibres and fabrics. A schematic illustration of typical waste streams for glass fibres and fabrics is presented in Fig. 2; the items numbered 1-7 represent the primary contributors to the waste stream. The sub-categories per waste theme are also listed. A detailed discussion per primary waste stream is outside the scope of the current article. Hence, only the waste stream corresponding to the preforms is discussed here; issues relating to the resin system and productions are discussed in a subsequent section.

With reference to context of the current paper and Fig. 2, the preform of interest is a plain-weave fabric. In general, the starting point is the preparation of the “beam” which involves threading and spooling the required number of “ends” or individual fibre bundles; the waste stream from this operation is minimal. However, during the weaving operation, the edges of the fabric are generally trimmed to obtain the desired width of the fabric; this represents a sizeable waste stream. The woven fabric is then wound or spooled onto cardboard mandrels. The post-processing of the woven fabric is defined here as operations involving specified surface-treatments, recoating, cutting and shaping where significant volumes of off-cuts can be generated.


The global market value and the volume of production for glass fibres in 2012 were estimated to be in the region of US$ 22.2 billion and 9.9 million metric tons respectively [1]. The global glass fibre textile industry is predicted to reach approximately US$ 4 billion in 2017 with a compounded annual growth rate of 7% over the next five years [2], with significant demand being generated by the wind energy industry. It has been estimated that the glass fibre composite materials market will be worth US$
8.4 billion by 2015 [3]. Therefore, with reference to Fig. 2 and the increasing utilisation of composites, appropriate technologies will need to be developed to address each class of waste material that can potentially be generated during the production of fibre reinforced composites.

The aims of the current paper are: (i) to illustrate the procedures that were developed to recover the waste glass fibre fabric produced during the weaving process; (ii) to deploy a recently developed modified wet-filament winding technique (so called Clean filament winding [4]) to manufacture filament wound tubes to replace the cardboard tubes that are used for over-winding the fabric; (iii) to assess the mechanical properties of these tubes; and (iv) to evaluate the long-term performance of the filament wound tubes on-site at the premises of an industrial concern.

2 Experimental

2.1 Materials

Two types of industrially-generated waste E-glass fabrics were used in this study: “direct-loom waste” (DLW) and “waste slittings” (WS). The DLW represents the edges of fabric that are trimmed off during the weaving operation to obtain the required width of the fabric. The trimming of the edges of the fabric is shown in Fig. 3a and a magnified image of the DLW is illustrated in Fig. 3b. With reference to Fig. 3b, the cut edge represents the weft fibres and these fibres are held in position by five rows of cotton stitches. The function of these stitches is to retain spatial configuration of the weft yarns during and after trimming. The generation of the WS is a post-weaving process where a coating is applied to the fabric prior to trimming. The secondary trimming operation where the WS is generated is shown in Fig. 4a and a magnified view is presented in Fig. 4b.

The DLW and the WS were spooled as they were generated using a motorised winder. The general appearance of the two types of spools are shown in Figs. 5 (a and b). It was necessary to wind the waste fabric strips onto spools in order to unwind them in a controlled manner during filament winding.

Two types of resin system were used to manufacture the filament wound tubes: an epoxy/amine (LY3505/XB3403) referred to as the “standard” resin; and a toughened epoxy/amine. The WS and the DLW were used with the LY3505/XB3403 resin system to manufacture filament wound tubes in the laboratory and on-site. The toughened resin system was used with the WS to produce tubes in the laboratory via a pin-winding process.

2.2 Production of filament wound tubes

(i) Laboratory-based production of tubes: The conventional (resin bath) and the “Clean” filament winding [4] techniques were used to manufacture the tubes for the laboratory-based evaluation and the site trials in industry. Schematic illustrations of the conventional and Clean filament winding techniques are shown in Figs. 6 (a and b) respectively.

The DLW and WS fabric strips were filament wound using a hoop winding pattern on 100 mm diameter mandrels. A “reference” tube was also produced using 4-tows of continuous E-glass fibres (Hybon® 2026, PPG Industries, UK).

(ii) Production of filament wound tubes for on-site trials to replace cardboard: The dimensions of the tubes required for the site trials were: an inner diameter (ID) of 152 mm and length of 1500 mm. Since the filament winding machine that was available in the laboratory was not capable of handling this diameter, and the weight of a 1500 mm steel mandrel, a pragmatic solution was improvised.

A 2-axis filament winding machine (Winding Technology, UK) was modified to extend the axial winding length. The problem associated with handling the weight of a steel mandrel was solved by commissioning the production of cardboard tubes with an outer diameter (OD) of 152 mm, a length of 1500 mm and a wall-thickness of 15 mm. The cardboard tubes were fitted with end-plugs to enable them to be mounted on the filament winding machine. The ends of these tubes were fitted with collars with an array of pins; the function of the pins was to facilitate axial winding. The outer surface of the cardboard tubes was covered with a release-film to prevent the resin system from soaking into it whilst filament winding and curing. Figs. 7 (a and
b) show the spatial orientations of the hoop and axial WS layers in the dry and impregnated states respectively. The following tubes were manufactured: a hoop-wound tube with the standard resin, a hoop-wound tube with the toughened resin and a hoop and axially-wound tube with the standard resin. These tubes were cured using the manufacturer’s recommended processing schedules. After extracting the composite from the cardboard mandrel, the ends of the composite were trimmed and shipped to the industrial concern for the site trials to assess their suitability for replacing the cardboard tubes that are currently used to over-wind the woven fabric.

(iii) Demonstration of on-site filament winding using WS: The aim of this particular aspect of the study was to demonstrate that the WS could be filament wound on-site under typical factory conditions. This was carried on a 2-axis filament winding machine at the premises of an industrial company whose business operation is filament winding. Angle and hoop-wound tubes were manufactured with the standard resin using a mandrel with a 169 mm OD and a 3000 mm length; this was the closest mandrel OD that was available to what was required for the site trials (152 mm OD). A tube each consisting of hoop and axial winding was manufactured as shown in Figs. 8 (a and b) respectively.

2.3 Evaluation of Physical Properties

The physical properties (density, fibre volume fraction (FVF) and void content) of the 100 mm ID filament wound tubes were assessed using the following standards: Density - ASTM D792; FVF - ASTM D2584; and void content - ASTM D2734. Rings of 20 mm widths were cut from the centre portion of the tubes using a water-cooled diamond cutting wheel. With reference to the density measurements, six 20 mm squares were cut from around the ring and the edges were polished using 800-grit abrasive paper. The samples were dried in an air-circulating oven at 40 °C for 1-hour. After density measurements were completed, the samples were dried, re-weighed and prepared for the resin burn-off experiment to determine the FVF. The resin burn-off experiments were carried out in a muffle furnace operating at 565 °C for 6-hours. The procedures stipulated in ASTM D2734 were used to determine the void content.

Sections of the previously mentioned rings were also potted and polished using conventional metallographic procedures.

2.4 Evaluation of Mechanical Properties

The hoop tensile tests were undertaken in accordance with ASTM D2290. Six rings with 25 mm width were obtained from each of the tubes that were produced in the laboratory. These samples were notched and tested as specified in ASTM D2290. The mechanical loading of the notched ring was carried out using a Zwick 1484 mechanical testing machine at a cross-head displacement rate of 2 mm/min.

The lateral compressive strength of the tubes were determined using the method outlined by Gupta and Abbas [5]. Samples of the cardboard tubes that were used on-site for over-wrapping the woven fabrics were also tested. 15 mm wide rings were cut from the composite and the cardboard tubes. Lateral compression tests were carried out on an Instron 5566 at a cross-head displacement rate of 1 mm/min.

2.5 Life Cycle Analysis: Data Acquisition

The life cycle analysis (LCA) was conducted on composite and cardboard tubes. For the composite tubes, the LCA was performed on virgin plain woven and WS tubes. Data for the WS tube were obtained from the resin burn-off experiment (36 % FVF). With reference to the LCA, a comparison is made between tubes manufacture using three classes of materials to manufacture the tubes: (a) virgin plain weave fabric; (b) WS; and (c) cardboard tube. The assumption was made that masses of the virgin fabric and resin used in the production of the tube were similar to that required for the production of the WS tube. The other assumption made was the plain weave fabric and WS composites were manufactured using Clean filament winding and were cured in a 12 kWh oven for 6 hours at 70 °C (259 MJ). The energy used for the filament winding and resin dispensing machines was 6 MJ. The
The volume of acetone that was required to clean the impregnator was 100 cm$^3$.

With reference to the cardboard tube, the thickness and the OD were 15 mm and 152 mm respectively. The density of the cardboard tube was 0.7 g/cm$^3$. The adhesive used in the production of the cardboard tube was Poly(vinyl alcohol). The energy used for winding the cardboard preform on a mandrel was assumed the same as for a composite, namely 3.6 MJ. In order to enable a comparison between the composites (WS and virgin plain weave) and cardboard tubes, three further assumptions were made: firstly, the LCA considered the production of 25 cardboard tubes; and secondly, the life cycle of 25 cardboard tubes was equivalent to one composite tube. Finally, the length of composite and cardboard tubes was assumed to be 1300 mm. The end-of-life issues were not considered in this study. A commercially-available software package, GaBi 5.0 was used for the LCA studies. A summary of the LCA data that were collected is shown in Table 1.

### 3 Results and Discussion

#### 3.1 Filament Winding

**Conventional and Clean filament winding:** A schematic illustration of a typical resin bath-based filament winding process is shown in Fig. 6a. The key components are the fibre creels, tensioning systems, guides to control the trajectory of the fibres, a drum-based resin bath to impregnate the fibres, a traverse-platform and a rotating mandrel. A detailed discussion on the issues associated with the conventional resin bath-based manufacturing process can be found in reference [4]. A brief summary is presented here to demonstrate the relevance of the Clean filament winding technology for processing delicate fabric waste materials. The concerns associated with conventional resin bath-based production of filament wound tubes include: (i) the need to decant, weigh and mix (manually) the resin and hardener where there is a potential for errors in achieving the required stoichiometric ratios. The mixed resin is then poured into the resin bath and re-filled manually; (ii) in some instances, the stoichiometry is adjusted to take into account the ambient operating temperature in the factory (summer, winter, etc); (iii) the primary issue is the mandatory need to use copious volume of solvent to clean every component of the production equipment that comes into contact with the mixed resin/hardener system; (iv) the excess resin in the resin bath has to be transferred to a container and cross-linked. Precautions have to be taken to ensure that this excess waste does not exotherm; and (v) only limited options are available to influence the impregnation process and these are primarily limited to the tension and the fibre haul-off rate.

In the Clean filament winding process, the resin and hardener are stored in separate containers and are pumped on demand, in the required stoichiometric proportions, to a static mixer where they are mixed intimately. The resin dispensing system has integrated sensors to monitor the ambient temperature and to heat the resin or hardener as desired. Thus, it is possible to guarantee the temperature of the two liquids irrespective of the ambient temperature. In the current case, the overall volume of the reservoir in the resin impregnation unit is 30 cm$^3$. The volume of solvent that is required to clean the impregnator at the end of each shift is 100 cm$^3$ and the volume of the residual resin in the impregnation unit, including the static mixer, was 40 cm$^3$. In the case of a 5-litre resin bath, the volume of the residual resin that is retained is 2500 cm$^3$ and the volume of solvent required to clean it was measured to be 1500 cm$^3$. The time required for the cleaning operations for the Clean and resin bath techniques was 5 and 50 minutes respectively. The Clean filament winding technique offers access to a number of parameters to influence the rate and degree of impregnation. For example, the temperature, flow rate and the resin injection pressure can be selected as desired for specified fibres/fabrics.

**Filament winding using WS:** The WS material was relatively straightforward to filament wind using the two techniques because of its relative strength and the stability of the WS. However, this was not the case with the DLW and it was only process this waste fabric using the Clean filament winding technique. This is because the intrinsic strength of the DLW was significantly lower since the weft yarns were only held together by five rows of cotton stitches. Unlike the WS tubes, the surface profile of the DLW tubes was highly irregular. This was
primarily because: (i) its intrinsic strength was low and hence, no appreciable tension could be applied; (ii) during the winding process, the application of tension (on the cotton threads) forces the weft fibres upwards. Hence, it was necessary to use an outer layer of peel-ply to control the spatial orientation of the fibres. The relative widths of the DLW were variable from batch-to-batch. Nevertheless, it was demonstrated that the DLW could be used to manufacture tubes using the Clean filament winding technique. It is speculated that the DLW can be used to manufacture pipes where the surface topology is not an issue.

Hoop/Axial Winding: The improvisation associated with the deployment of a 152 mm OD cardboard tube as the mandrel was a necessity as this was the ID that was required for the site trial. The cardboard mandrel was extracted from the composite tube by degrading the cardboard mandrel in water. One end of the tube was sealed with a plastic film to create a reservoir for water. The inner-bore containing the water was permitted to soak into the cardboard tube overnight. The water was decanted and the layers of the cardboard tube were peeled off manually.

On-site winding using the WS: The philosophy behind the Clean filament winding technique is that it is simple to retrofit. In this instance, the traverse arm of the filament winding machine was in close proximity to the mandrel, with the conventional resin-bath being located about two metres behind on a stationary platform. A demountable platform with fibre-guides was present on the traverse arm to control the trajectory of the impregnated fibre bundles before they were directed to the D-eye. Therefore, it was straightforward to mount the Clean filament winding impregnator unit onto this platform. The mixed resin from the resin delivery system was connected to the impregnation unit. Hoop and angle-winding was demonstrated on a three metre, 169 mm OD mandrel. The over-wrapped mandrel was cured in an oven for six hours at 70 °C and then extracted using a hydraulic extraction unit. Fig. 9a shows a photograph of the filament wound tubes. The data presented in Fig. 9b demonstrates that by using appropriate processing conditions, a smooth surface-finish with a uniform wall-thickness can be obtained.

3.2 Physical Properties and Image Analysis

A summary of the results obtained from density measurements and resin burn-off experiments is shown in Table 2. The FVF for the DLW and WS tubes were 26.02% and 40.12% respectively. The FVF for the reference tube (hoop-wound virgin E-glass fibre and epoxy/amine) manufactured via the Clean filament winding technique was 68%. The open architecture of the DLW meant that it could soak up the resin with significant ease. However, it also meant that the propensity for air-entrapment was also significant. On the other hand, the WS had a proprietary coating which was observed to impede the impregnation efficiency. As seen in Fig. 10b, the void contents for the DLW and WS tubes were higher than that observed for the reference tube. These observations are corroborated on inspecting the micrographs presented in Figs. 11 (a and b). In Fig. 11a, the variation in the spatial orientation of the weft fibres in the DLW is readily apparent. Fig. 11b illustrates the presence of resin-rich regions in between the layers of the WS. Close inspection of Fig. 11b also indicates the presence of the proprietary coating that was applied to the fabric.

3.3 Mechanical Properties

Hoop Tensile Strength: Fig. 12a shows the relative performance of the tubes manufactured from the reference (virgin E-glass rovings), WS and DLW. It is apparent from Fig. 12a that the DLW and the WS tubes have a considerably lower hoop tensile strength than the reference glass fibre tubes. A number of reasons can be attributed for this observation. Firstly, on inspecting Fig. 10a, it is seen that the fibre volume fractions are lower when compared to the reference tube. Furthermore, the void content for the DLW and the WS are higher. Secondly, the reference tube was manufactured using continuous glass fibres whereas the DLW consisted of short length of E-glass fibres where their spatial orientation during filament winding could not be controlled as desired. Finally, it was not possible to apply significant tension to the DLW and WS during filament winding. Therefore, it is likely that the degree of impregnation at the mandrel was lower when compared to winding with continuous virgin glass fibres.
**Lateral Compression:** From Fig. 12b it is apparent that all the tubes manufactured from the WS, DLW and the hybrid waste fibre tubes are superior lateral compressive strengths when compared to the cardboard tube. An interesting point to note is that up to approximately 30% of the failure load, the tubes manufactured using the waste fabrics strips showed elastic recovery when the applied load was removed. However, in the case of the cardboard tubes, the deformation was permanent after approximately 15% of the ultimate failure load.

### 3.4 On-site Performance Trials

The three tubes that were manufactured in the laboratory using the WS were subjected to performance trials to assess their fit-for-purpose to replace the cardboard tubes. At the time of writing, the WS tubes had undergone 19-cycles. Typically, shafts, hoists and forklift are used to lift and transport the over-wrapped fabric to specified stations for post-processing. The over-wrapping and the unwinding of the fabric at the end of post-process is defined as one cycle. As indicated previously, the cardboard tubes, on average, only sustain 3-cycles in the factory before being removed from circulation. Fig. 13a shows typical damage inflicted on the WS tubes after 14-cycles in the factory. The damage is limited to the inner-bore and it mainly relates to surface scratches caused by inserting the lifting equipment into the bore. Fig. 13a also shows that the outer-surface of the WS tubes is relatively undamaged. Fig. 13b shows two of the WS tubes with the over-wrapped fabric awaiting shipment.

### 3.5 LCA

**WS versus virgin plain weave fibres:** It is emphasised that the virgin plain weave fabric has been included only as a comparison for the LCA. Although tubes are manufactured using fabrics for specified applications, this was not undertaken in the current study. As expected, Fig. 14 demonstrates that the environmental impact of WS is lower than the of the virgin plain weave composite tubes.

**WS versus Cardboard tubes:** With reference to Figs. 12 (a and b), it is apparent that the tubes manufactured using the WS have significantly higher lateral compressive strength than the cardboard tubes. A detailed visual inspection of the WS tubes, which are currently undergoing site trials, did not indicate the presence of any damage that would impede their continuous deployment as a replacement for cardboard tubes. Since these WS tubes were performing as required after 19 cycles (at the time of writing), it is justifiable to assume that 25 cardboard tubes would be needed to match the length of service of one WS tube in the factory. Fig 14 shows the environmental impact of the WS tubes is much lower than the quantity of cardboard tubes required to match the same service-time as one WS tube. The environmental impact of the composite tubes can be lowered further by: (i) using room temperature curable resin; (ii) using a low-cost lathe to enable to manufacture the WS composites in the factory.

### General Discussion

The concept of “closed-loop recycling” was demonstrated successfully. Here, a waste stream that is generated in the weaving process, namely the WS, was collected and reprocessed to manufacture commercially relevant filament wound tubes with a view to replace the cardboard tubes that are currently used to over-wind the fabric. A visual inspection of the WS tubes (after 19 cycles) indicated the absence of any significant service-induced damage; thus, it can be concluded that the WS tubes can be used for many more cycles in the factory. It is worth reiterating that cardboard tubes, on average, last only 3-cycles. However, this does raise interesting questions about the recyclability and reuse of these tubes. For example, in the current case, if the three WS tubes reach the stage where the scratches on the inner-bore become a source for concern, new repair techniques can be developed.

Accepting the dangers of gross generalisation, current recycling strategies generally require the composite component to be cut down to manageable dimensions prior to re-processing. An alternative approach is to use the composite structure, in its current form, for secondary applications.

### Conclusions

A number of techniques were developed to facilitate the recovery, reprocessing and reuse the DLW and
WS. An existing motorised fibre spooling unit was modified to enable the DLW and the WS to be wound onto bobbins to enable them to be unspooled in a controlled manner for filament winding.

It was demonstrated that the Clean filament winding technique can be used to manufacture filament wound tubes using delicate waste fabric strips. The Clean filament winding technique was retrofitted to an industrial machine and hoop and axial-wound tubes were manufactured on-site. Although the ID of these tubes was inappropriate for the site trials, it did demonstrate conclusively that the WS can be used to manufacture tubes with a good surface-finish.

In order to manufacture the tubes with an ID of 152 mm, it was necessary to improvise a fabrication method in the laboratory. Here, a cardboard mandrel was used in conjunction with an improvised technique to enable the WS to be laid in the axial and hoop directions. The cardboard mandrel was extracted by soaking the inner-bore of the cardboard mandrel in water. The surface-finish of the three tubes that were manufactured was subjected to the rigors on-site. At the time of writing, the three tubes had successfully completed 19-cycles.

Given the fact that the cardboard tubes only last three cycles, the economic and environmental benefits of this closed-loop recycling philosophy using the WS has been vindicated. Although not discussed in this paper, the feasibility of using the WS in pultrusion was also demonstrated successfully.

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References

Figs. 1(a and b): Illustration of typical damage modes observed in the cardboard tubes that are used to over-wind the fabric.
Fig. 2  Schematic illustration indicating the generalised waste streams that can potentially be generated for organic matrix fibre reinforced composites.

Figs. 3 (a and b): (a) Illustration of the generation of the DLW; and (b) magnified view of the DLW showing the stitched weft yarns being secured in position by the cotton-stitches.

Figs. 4 (a and b): (a) Photograph showing the slitting operation where the edge of the fabric is trimmed and this waste is referred to as the waste slitting; and (b) magnified view of the waste slitting.
Figs. 5 (a and b): Photographs showing a bobbing of the: (a) DLW; and (b) WS.

Figs. 6 (a and b): (a) Conventional resin bath-based filament winding. The coded items A–F are as follows: A-creels; B-fibre guides and tensioning devices; C-traverse platform; D-rotating mandrel; E-pin or drum-based resin bath; F-impregnated fibre bundles.

(b) Clean filament winding. Items A, B, C, D and F are identical to those cited in Fig. 6(a). Here, item E represents a custom-designed resin impregnator that is mounted on the traverse-platform (C).

Figs. 7 (a and b) Photograph showing the spatial orientations of the hoop and axial WS layers in: (a) dry WS and (b) impregnated WS.
Figs. 8 (a and b) Industrial winding with WS using the Clean filament winding technique to produce: (a) hoop-wound tube on a 169 mm OD mandrel; and (b) angle-wound tube on a 169 mm OD mandrel. The length of the mandrel was 3 m.

<table>
<thead>
<tr>
<th>Composite Tubes</th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Tubes</td>
<td>Epoxy resin (kg)</td>
<td>Plain weave fabric (kg)</td>
<td>WS (kg)</td>
<td>Power consumption for filament winding process (MJ)</td>
<td>Power consumption for curing (MJ)</td>
<td>Acetone for cleaning (kg)</td>
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<td>Plain weave tube</td>
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<td>6.8</td>
<td>-</td>
<td>5.9</td>
<td>259</td>
<td>0.1</td>
</tr>
<tr>
<td>WS Tube</td>
<td>4.8</td>
<td>-</td>
<td>6.8</td>
<td>5.9</td>
<td>259</td>
<td>0.1</td>
</tr>
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</table>

Table 1 Summary of the data collected for the LCA input.

Figs. 9 (a and b): (a) Photograph showing the three tubes produced for industrial site trials; and (b) Graph demonstrating the uniform wall-thickness of one of the hoop wound tubes.
Table 2 Summary of the results obtained from density measurements and resin burn-off experiments.

<table>
<thead>
<tr>
<th>Property</th>
<th>Virgin E-glass: Clean filament winding</th>
<th>Waste slitting: Clean filament winding</th>
<th>Direct loom waste: Clean filament winding</th>
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</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.108 ± 0.04</td>
<td>1.69 ± 0.004</td>
<td>1.51 ± 0.004</td>
</tr>
<tr>
<td>Fiber volume fraction (%)</td>
<td>68.10 ± 2.57</td>
<td>40.12 ± 2.77</td>
<td>26.01 ± 1.47</td>
</tr>
<tr>
<td>Void content (%)</td>
<td>0.50 ± 0.04</td>
<td>3.05 ± 0.93</td>
<td>1.04 ± 0.11</td>
</tr>
</tbody>
</table>

Figs. 10 (a and b) Graphs showing: (a) FVF of tubes produced in-house; and (b) void content of tubes produced in-house. CFW=clean filament winding. WS=waste slitting. DLM=direct-loom waste.

Figs. 11 (a and b): (a) Micrograph of a DLW sample showing significant variations in the orientation of the weft fibres. The presence of large resin-rich areas is readily apparent along with the presence of voids. (b) Micrograph showing the impregnated warp and weft fibres in the multi-layered WS composite. The inter-layers consist of a proprietary coating that was applied to the fabric at the time of production and the epoxy/amine layer.
Fig. 12 (a and b) (a) Hoop tensile strength of waste glass fabric compared to virgin glass rovings. (b) The lateral compression strength of filament wound tubes compared to cardboard tubes. The term “hybrid” represents the case where skin/core sandwich composite tubes were manufactured with the DLW acting as the core and the WS as the inner and outer-skins.

Figs 13 (a and b): (a) Photograph showing the typical damage inflicted on the WS tubes after 14 cycles in the factory. (b) Photograph showing two WS tubes with the over-wrapped fabric awaiting shipment.

Fig. 14 Environmental impact produced from manufacturing composite and cardboard tubes. The data have been normalised to the production of 25 cardboard tubes.