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# IMPROVING THE COMPRESSIBILITY OF RECYCLED CARBON FIBRE NON-WOVEN MATS

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## Abstract

This paper looks at increasing the fibre volume fraction of composites made of recycled carbon fibres and processed through resin infusion. While the pressure applied on the reinforcement is limited to the difference between atmospheric pressure and the vacuum applied inside the cavity, different methods of increasing the fibre content were investigated, whether before or during composite manufacturing. The most effective method appeared to be through the application of a high loading on the reinforcement before draping the preform in the mould. A change of the non-woven architecture also appeared to enable a significant gain in the composite fibre content, the control of the resin infusion process also enables a gain of a few points of fibre fraction. The influence of the fibre content on the coefficient of thermal extension was also investigated and the improvement of the carbon footprint of the developed composite was estimated through the estimation of energy required to manufacture the raw materials.

## 1. Introduction

Different techniques for recycling carbon fibre composites have been developed that rely on separating the carbon fibre from the matrix [1–3]. While the reclaiming technologies have matured and are able to provide industrial quantities of recycled carbon fibres with remarkably high quality and mechanical properties (up to 99% of the mechanical properties of virgin fibres), these fibres will nonetheless be discontinuous. Some efforts have been engaged towards realigning these recycled discontinuous carbon fibres to make threads or tapes [4,5], however they remain so far at a rather low technology readiness level (TRL). Non-woven mats are so far the most advanced (in term of TRL) use of recycled carbon fibres to make new composite reinforcements and are already commercially available.

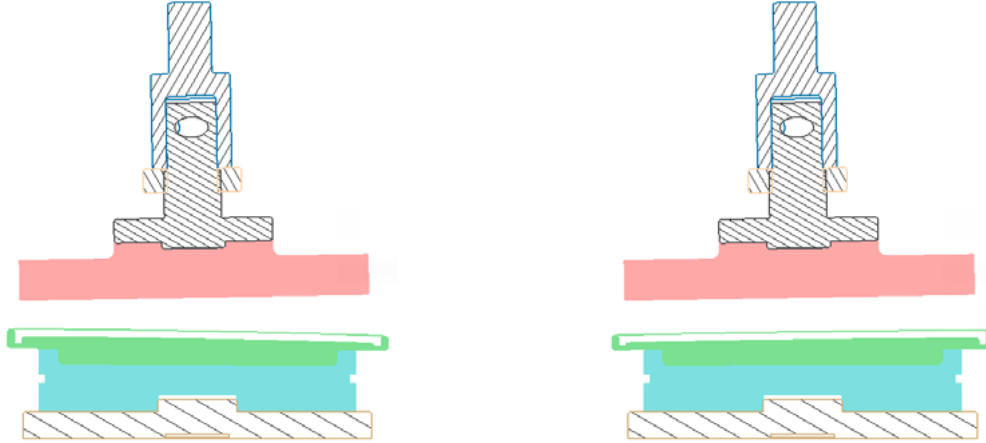
In the boat building industry, it is common practice to manufacture carbon composite moulds through resin infusion to build boats out of carbon/epoxy prepregs. The use of a carbon composite mould enables the tooling to have a small coefficient of thermal expansion (CTE), matching that of the composite part to be manufactured and allowing a better dimensional control. While the moulds are not subjected to high loading, they must be thick enough to remain rigid under bending and provide a good vacuum integrity. This can result in the mould containing more carbon fibre than the actual boat made out of this mould. Using recycled non-woven carbon fibre mats could therefore provide a solution to tremendously reduce the carbon footprint of the boat building industry. However commercially available non-woven carbon fibre mats are usually made through a carding and needling process, leading to high fibre entanglement and a low compressibility. Using resin infusion process, with only vacuum pressure to consolidate the composite leads to low fibre volume fraction (~9-10%), high resin consumption and relatively poor CTE.

This study will look at the effect of the non-woven manufacturing technologies, the effect of compaction on the dry reinforcement and the control of the resin infusion process to improve the final fibre volume fraction and thermomechanical properties of recycled carbon fibre composites.

## 2. Experimental characterization

### 2.1. Compaction characterization

A custom setup was designed to ensure parallelism of the platens. Rather than being based on a lockable spherical alignment unit, the system is based on two pivoting wedges able to rotate around the z-axis to obtain the parallelism of the two compression platens as schematically presented in **Figure 1**.



**Figure 1:** Compression platen alignment system

The compaction procedure was established to load the reinforcement at a constant loading rate up to a target compaction stress then holding the target load for five minutes before unloading at the same loading rate. Multiple cycles and different target load have been approached. It was decided to perform only dry compression experiments and not take into account the lubrication effect provided by the presence of a fluid.

### 2.2. Composite manufacturing

Composites were manufactured through resin infusion using various filling and post-filling strategies, controlling the inlet pressure and the venting strategy. To compare the properties of the manufactured composites panels they were manufactured to a target fibre areal mass of 3000g/m<sup>2</sup>.

### 2.3. Fibre content determination

Fibre content ( $V_f$ ) was determined through three procedures.

For the compression characterisation as well as the infused part, the  $V_f$  was calculated from the thickness measurement:

$$V_f = \frac{M_a}{\rho * h} \quad (1)$$

With  $M_a$  the areal mass,  $\rho$  the fibre density, and  $h$  the measured thickness.

For plates manufactured through resin infusion, the  $V_f$  was also estimated through weight measurement:

$$M_f = \frac{m_{\text{fibre}}}{m_{\text{composite}}} \quad (1)$$
$$V_f = \frac{M_f}{M_f + \frac{\rho_f}{\rho_m} (1 - M_f)}$$

With,  $m_{\text{fibre}}$  the mass of fibre measured before infusion,  $m_{\text{composite}}$  the mass of the manufactured plate, and  $\rho_f$  and  $\rho_m$  respectively the fibre and matrix density. Samples of composites panels were also tested by Archimedes method and acid digestion to measure the composite properties according to ASTM D3171 and D2734 standards.

#### **2.4. CTE determination**

To perform as a candidate mould material, the recycled composite must have as low a coefficient of thermal expansion (CTE) as possible.

CTE was measured in X, Y and Z direction of the composites through Thermomechanical analysis (TMA). The CTE of a reference composite mould made of virgin fibre and manufactured at Multiplast was also tested for comparison.

### **3. Materials**

#### **3.1. Fibre sourcing**

Recycled carbon fibres were obtained from steam-water thermolysis of CFRP materials by Alpha Recyclage Composites.

#### **3.2. Non-woven manufacturing**

Two different manufacturing methods were compared. A traditional carding and needle punching method and an airlaid and thermally bonded method were used to manufacture non-woven.

### **4. Compressibility of the non-woven**

#### **4.1. Effect of the non-woven architecture**

The web bonding method of the carded mats through needle punching increases the entanglement of the fibre and forces fibre through the thickness direction around the punched sites. The airlaid method uses thermal bonding and presents a more in plane fibre orientation. The later method, reducing the amount of fibre oriented in the through thickness direction allow a better compressibility, the achievable  $V_f$  for as manufactured non-woven under 1 bar compaction, increasing  $V_f$  from 11.9 to 17% respectively for the carded and airlaid mats.

#### **4.2. Effect of cyclic compaction**

Cycling the loading either through multiple compression cycle during compaction characterisation or multiple applications and release of the vacuum before infusion (debulking) allows for a certain level of fibre reorganization and increase of the achievable  $V_f$ . But the gain remains limited to about 1%  $V_f$

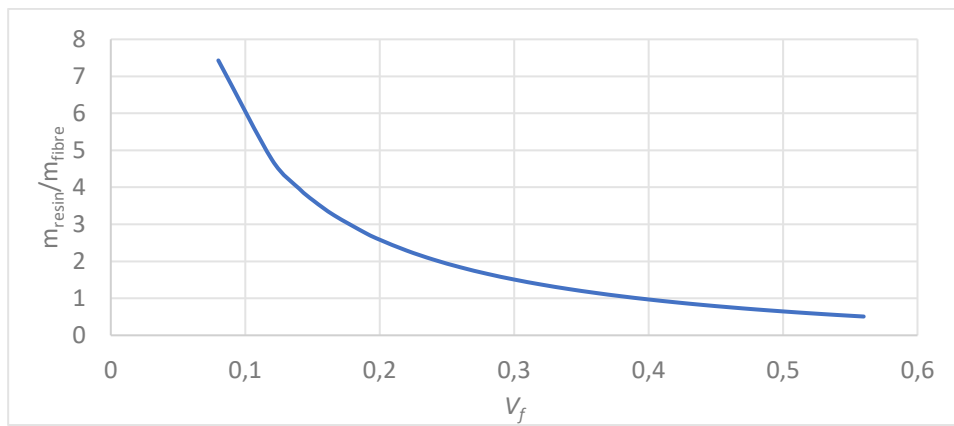
#### **4.3. Effect of higher initial compression**

The compaction response of non-woven displays both an elastic and a permanent deformation response, loading the non-woven to a higher compaction level before infusion could therefore achieve a higher  $V_f$  during a second compaction limited to 0.1MPa as imposed by the resin infusion process. Various levels of initial compression were trialled showing improvement of the compressibility of the non-woven during the second compaction cycle to 0.1MPa. Signs of fibre breakage appeared after loading to 10MPa for the carded non-woven, and 20MPa for the airlaid reinforcement.

Loading to 10 MPa the airlaid non-woven prior to infusion enabled an increase in  $V_f$  from 17% to 29% on a composite pannel.

#### 4.4. Effect of infusion process

During resin infusion, the reinforcement undergoes unloading during the filling stage following Terzaghi's relation [6] as the fluid pressure inside the vacuum bag increases [7,8]. The compaction response of fibrous reinforcement also typically displays a very low rigidity at low compaction stress. Limiting the relaxation by reducing the injection pressure can therefore strongly reduce the resin consumption during the filling stage and limit the amount of excess resin to be drawn from the preform during the post-filling stage. While this is the case for any reinforcement during infusion, the low compressibility and  $V_f$  of the rCF non-woven mats further exacerbate the effect and the quantity of resin able to be saved as illustrated in **Figure 2**. Comparing the two methods on two parallel infusions gave improvement from 15.8 to 18.3% for a carded mat, and from 19.3 to 23% for an airlaid preform.



**Figure 2:** Matrix consumption as a function of  $V_f$

Another process improvement candidate is to convert the inlet into a vent at the end of filling, drawing the excess resin from the most unloaded area of the piece rather than flowing through the length of the part and through the resin break area. While the improvement is somewhat limited when manufacturing small 300x300mm<sup>2</sup> panels, this effect could be more prominent on larger parts.

**Figure 3** summarizes the compressibility testing and resin infusion experiments on the different reinforcement. For compressibility testing the achievable  $V_f$  are presented at 0 bar compaction for fully unloaded reinforcement, at 100 mbar corresponding to the maximum unloading

during infusion at reduced inlet pressure and at 1bar to estimate the maximum achievable  $V_f$  during resin infusion.

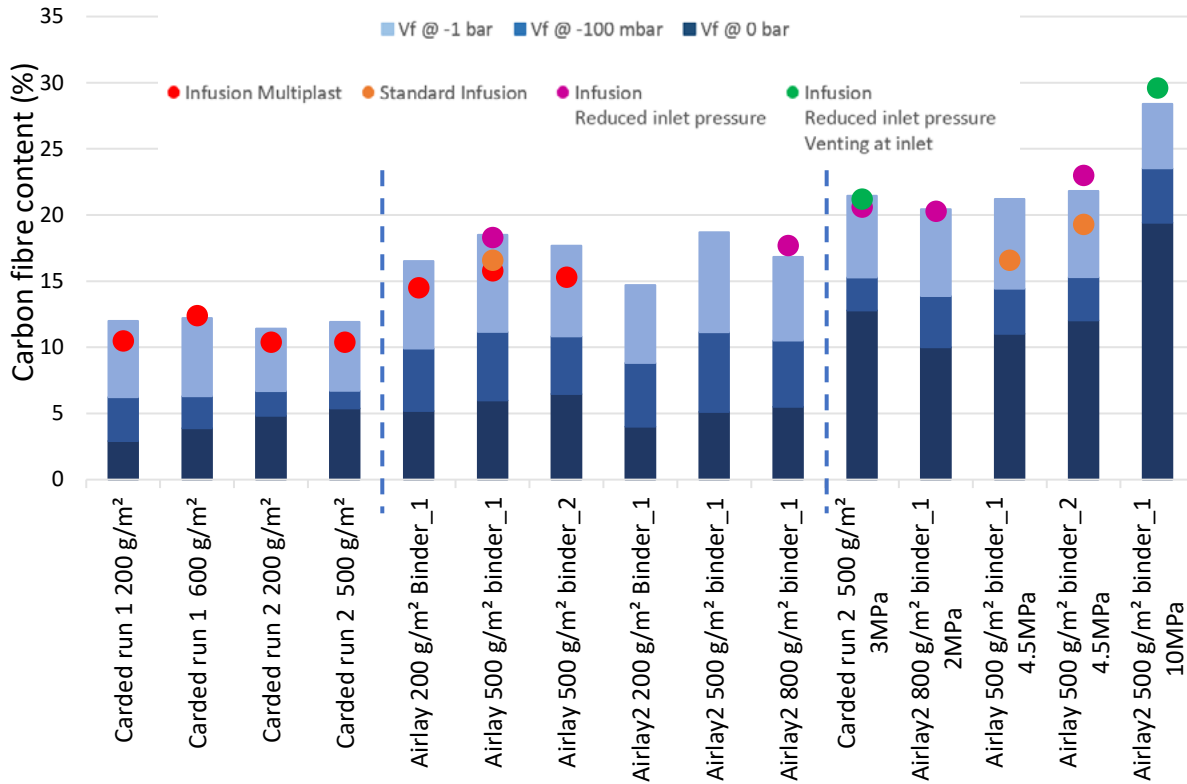


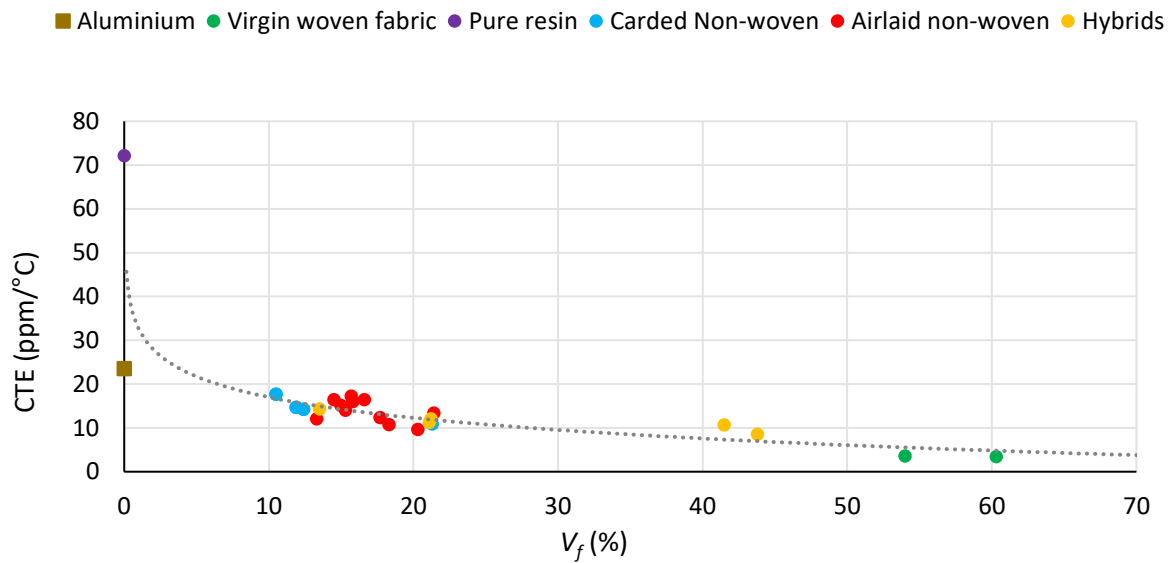
Figure 3: summary of compressibility testing

## 5. Effect of $V_f$ on composite properties

### 5.1. CTE

The main desired performance for a tooling material for prepreg moulding, is to have a low coefficient of thermal expansion, matching that of the composite to be moulded. While the reference mould material has a CTE of  $3.5 \times 10^{-6}/^{\circ}C$  the initial non-woven materials had a CTE close to  $20 \times 10^{-6}/^{\circ}C$ .

While the carbon fibres have a very low or even slightly negative CTE, the tooling resin used has a CTE of  $72.1 \times 10^{-6}/^{\circ}C$ , therefore increasing the  $V_f$  is necessary to reduce the CTE of the composite. Hybridizing the composites by mixing recycled non-woven layers with woven virgin fibre layers permits also more freedom in tailoring the CTE of the tooling material. **Figure 4** presents the averaged in plane CTE for various composites manufactured during the project. While the carded non-woven displayed an orthotropic behaviour with an anisotropic ratio of nearly 2, the airlaid non-woven display very isotropic in-plane properties.



**Figure 4:** Average in plane CTE of the manufactured composites

## 5.2. Estimation of LCA improvement

The LCA improvement was estimated through the energetic consumption of producing the raw materials (carbon fibre and resin), and of the reclaiming process of carbon fibre through steam thermolysis, using literature data [9,10] data the impact of the textile manufacturing process was unavailable, and the composite manufacturing process being unchanged, its impact has not been accounted to perform the comparison. While the impact of recycled fibre is of course lower than that of the virgin fibre, the effect of a lower  $V_f$  and thus higher resin consumption should be taken into account. The calculated measures are presented in **Table 1**, a higher  $V_f$  for recycled carbon fibre will lead to lower energy cost for the materials but at the expense of an increase energy need for the thermocompression step in the non-woven densification step.

**Table 1:** Embodied energy in material sourcing for raw materials and composites

|                         | Virgin carbon fibre[9] | Recycled carbon fibre[9] | Epoxy resin[9] | Virgin fibre composite 50% $V_f$ | Recycled fibre composite 10% $V_f$ |
|-------------------------|------------------------|--------------------------|----------------|----------------------------------|------------------------------------|
| Embodied energy (MJ/kg) | 350                    | 45                       | 80             | 244                              | 75                                 |

## 6. Conclusions

In order to prove a viable solution for manufacturing composite moulds for high performance boats, the compressibility of recycled carbon fibre non-woven reinforcement had to be improved. The effect of different parameters on the compaction of non-woven reinforcement was considered. The most effective improvements were through applying a higher compaction load on the reinforcement during manufacture of the non-woven or prior to draping in in the mould. Changing the non-woven architecture also permitted large gains. Applying different infusion strategy appeared also quite effective while the cyclic debulking of the reinforcement didn't bring much gain.

The influence of the non-woven properties on the CTE of the composites was also evaluated as the key performance indicator for use as a mould material. While a full life cycle analysis was not performed, studying the energy cost of the different materials showed great potential for reducing the carbon footprint of composite moulds by using recycled fibrous reinforcements.

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