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Influence of microstructural defects and hydrostatic pressure on water absorption in composite materials for tidal energy

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Abstract

The lifespan and economic viability of tidal energy devices are constrained, in part, by the complex degradation of the tidal turbine blade materials due to prolonged immersion in a hostile sub-sea environment. Seawater penetration is a significant degradation mechanism in composite materials. This work aims to investigate the influence of microstructure and hydrostatic pressure on water absorption in four polymer composites which are candidate materials for use in tidal energy devices. These materials are: a Glass Fibre (GF) powder epoxy, a Carbon Fibre (CF) powder epoxy, GF Ampreg epoxy and a chopped fibre GF Polyether Ether Ketone (PEEK). X-ray CT (computed tomography) is used to characterise the voids, resin-rich areas and other manufacturing defects present in each material. These defects are known to significantly alter the rate of moisture diffusion, as well as the total uptake of water at saturation. The samples are then exposed to accelerated water aging and hydrostatic pressurisation in order to simulate a range of expected sub-sea operating conditions. The
material micro-structure, the matrix material and pressurisation level are shown to strongly influence both the moisture absorption rate and total water uptake. Significant volumetric changes are also noted for all samples, both during and after aging. X-ray CT scans of specimens also provide a unique insight into the role of voids in storing water once a material has reached saturation.

**Key words:** Polymer composites; Tidal turbine blade; Water aging; X-ray CT; Ocean energy; Manufacturing defects; Composite voids.
1. Introduction

Tidal power has the potential to offer a reliable source of low carbon energy across many coastal regions of Ireland, the European Union (EU) and other regions across the globe [1]. Europe has a total capacity of 100 MW of tidal stream projects and currently has 32MW of wave energy projects either in service, under construction and permitted [2]. Ocean Energy Europe estimates that 100 GW of wave and tidal energy capacity can be deployed in Europe by 2050 [3], with the global market for ocean energy at 337 GW of installed capacity by 2050. Today, circa 60% of wave energy companies and 52% of tidal energy companies are based in the EU [2]. Current estimates project that tidal stream power will generate 148 megawatts (MW) worldwide by 2020 [5]. Several prototype commercial turbines are in development, but in order to become commercially viable, these turbines must demonstrate long term reliability and reduce their manufacturing cost per MW generated [1]. It is estimated that in order for tidal turbines to become commercially viable, the capital expenditure per MW must be reduced to below €3 million [6]. At present, the capital cost of prototype projects is significantly higher than this figure, with the MeyGen project having a gross capital expenditure per MW of circa €11 million [7]. Cost effective design, manufacture, and testing of tidal turbine blades remains a major challenge for the tidal turbine industry.

Tidal turbine blades represent a signification proportion of the overall cost of commissioning a tidal turbine system, accounting for up to 15% of the turbine capital expenditure [8]. Repair operations are also costly and typically involve the removal of the turbine to port. Blade failures are being reported and commercial projects are being delayed due to blade issues [8]. As such, reducing the cost of the turbine blades, coupled with improving their reliability, is an important step in reducing the overall cost per MW of tidal power. The structure of tidal turbine blades is broadly comparable to that of wind turbine blades, with Glass Fibre Reinforced Plastic (GFRP) and Carbon Fibre Reinforced Plastics (CFRP) being the most commonly used
materials due to their excellent mechanical properties and corrosion resistance. However, tidal turbines must also operate immersed in a hostile sub-sea environment and withstand significantly higher loading for a given power output [9-16] when compared to wind turbines. While CFRPs can provide the required strength and stiffness for tidal turbine blades, the large quantities of material required for manufacturing [9] would significantly increase the production costs when compared to lower performance GFRP materials. These conflicting requirements have led to research into alternative composite materials and manufacturing methods for tidal turbine blade production [1, 17].

The degradation of polymer composite material properties due to prolonged moisture exposure is a well-researched phenomenon. Significant reductions in strength, stiffness and fatigue life have been reported in both GFRPs and CFRPs, with the severity of property loss often being correlated with both the length of exposure and the total uptake of moisture into the composite [18-25]. Despite this, the precise mechanisms of moisture uptake in composite materials are not fully understood, with manufacturing defects and micro-structural irregularities within laminates complicating the natural diffusion process. In particular, the presence of voids in composites, at both the micro and macro scales, can render moisture uptake prediction methods based on Fick’s Law incomplete, with voids known to influence the rate of absorption and the total water weight in the composite at saturation [26, 27]. The hydrostatic pressure conditions at typical tidal turbine operating depths can also influence the moisture uptake behaviour of composites. Previous studies in this area have yielded conflicting results, with increasing hydrostatic pressure having been shown to both increase and decrease the moisture absorption in composites, depending in part on the void content of the material and the level of pressurisation [28-32]. It has been suggested that the complex relationship between hydrostatic pressure and moisture absorption can be explained by the competing mechanisms of increasing compressive strain reducing the free volume, and hence space, for water to enter the composite
and the increasing chemical potential acting as a driving force for greater water absorption [33, 34].

The wide range of factors, ranging from manufacturing process induced micro-structural defects to turbine operating depth, that influence water uptake in composite tidal turbine blades requires significant further study in order for satisfactory blade lifetime performance predictions to be made. This work provides a detailed comparison of water uptake and volumetric changes under ambient and hydrostatic pressurisation for GF epoxy, CF epoxy and GF PEEK materials proposed for use in tidal turbine blades. The microstructure of the materials is a key focus of this study, with X-Ray Computed Tomography (CT) being used for characterisation of the as-manufactured materials, both before and after water aging. This detailed analysis of the internal composite structure provides a unique insight into the role of voids in storing free water at material saturation as well as offering greater insight into the complexity of the moisture absorption behaviour of multi-phase composite materials.
2. Materials

This work focuses on four polymer composite materials commonly used to construct ocean energy devices. These materials are: a Glass Fibre (GF) powder epoxy, a Carbon Fibre (CF) powder epoxy, GF Ampreg epoxy and a chopped fibre GF Polyether Ether Ketone (PEEK). All materials were subject to identical characterisation and conditioning processes.

2.1 GF and CF powder epoxy

Two powder epoxy NCF (non-crimp fabric) materials, one with GF and the other with CF reinforcement, were tested. NCF materials consist of multiple layers of fabric stitched together. GF and CF powder epoxy materials are widely used in the wind turbine industry as blade materials. Due to their low cost, excellent material properties and ease of manufacture [35], they are also prospective materials for ocean energy applications such as tidal turbine blades. The powder epoxy is a heat activated resin which cures at 180°C. Manufacturing of powder epoxy components proceeds with the lay-up of dry fibres on a flat metal plate, followed by the even distribution of the un-cured powder epoxy throughout the fibres. The entire lay-up is then covered in bagging material and sealed. A vacuum is then applied and the part is heated to the cure temperature.

The development of large, integrally heated, ceramic mould technology has facilitated the cost effective and scalable manufacturing of composite structures using heat activated powder epoxy materials. Figure 1 shows a 13 m GF powder epoxy wind turbine blade and the integrally heated ceramic mould used to cure the blade. Tidal turbine blades of this scale could be manufactured using a similar process and GF powder epoxy material.
These powder epoxy materials offer several advantages over traditional resins. Firstly, there is no significant exothermic heat release during cure. This means that thick composite sections can be manufactured without having to specifically control the cure process to prevent heat build-up. This, in turn, leads to quicker process cycle times [35]. The material itself has no special storage requirements and there are no Volatile Organic Compounds (VOC’s) emitted during manufacture [35]. Finally, composite parts can be formed into solid sub-assemblies without additional polymerisation. This means that for complex parts, such as tidal turbine blades, all parts can be formed into sub-assemblies using low temperature tooling. The components may then be assembled on the integrally heated ceramic tooling for final polymerisation. This results in a final part being manufactured in a one-shot process without the need for gluing sub-assemblies [1].

Tables 1 and 2 provide an overview of the GF and CF powder epoxy specimens used for material characterisation and water aging. The square specimens, of side 25 mm, were extracted from larger laminates, manufactured at ÉireComposites Teo, using a diamond-tipped water-cooled saw in order to prevent damage to the specimen edges. The GF powder epoxy (GFE) specimens have a 6 ply lay-up of the form [45°/-45°/0°]s, with the CF powder epoxy
specimens have a 4 ply unidirectional lay-up [0°]. In addition, 3 GFE specimens (GFE7, GFE8 and GFE9) and 3 CFE specimens (CFE7, CFE8, CFE9) were machined for use in pressurisation tests.

Table 1 Overview of the GF powder epoxy (GFE) test specimens used for material characterisation and water aging. Side 1 and side 2 refer to the length of each side of the square specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Weight (g)</th>
<th>Thickness (mm)</th>
<th>Side 1 (mm)</th>
<th>Side 2 (mm)</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFE1</td>
<td>3.8322</td>
<td>3.12</td>
<td>25.31</td>
<td>25.39</td>
<td>2005</td>
</tr>
<tr>
<td>GFE2</td>
<td>3.9049</td>
<td>3.21</td>
<td>25.30</td>
<td>25.35</td>
<td>2059</td>
</tr>
<tr>
<td>GFE3</td>
<td>3.9709</td>
<td>3.26</td>
<td>25.34</td>
<td>25.30</td>
<td>2090</td>
</tr>
<tr>
<td>GFE4</td>
<td>3.9781</td>
<td>3.27</td>
<td>25.34</td>
<td>25.34</td>
<td>2100</td>
</tr>
<tr>
<td>GFE5</td>
<td>4.0243</td>
<td>3.33</td>
<td>25.32</td>
<td>25.32</td>
<td>2135</td>
</tr>
<tr>
<td>GFE6</td>
<td>4.0100</td>
<td>3.32</td>
<td>25.34</td>
<td>25.32</td>
<td>2130</td>
</tr>
<tr>
<td>Mean value</td>
<td>3.9534</td>
<td>3.25</td>
<td>25.33</td>
<td>25.34</td>
<td>2086</td>
</tr>
</tbody>
</table>

Table 2 Overview of the CF powder epoxy (CFE) test specimens used for material characterisation and water aging. Side 1 and side 2 refer to the length of each side of the square specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Weight (g)</th>
<th>Thickness (mm)</th>
<th>Side 1 (mm)</th>
<th>Side 2 (mm)</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFE1</td>
<td>2.3666</td>
<td>2.45</td>
<td>25.42</td>
<td>25.30</td>
<td>1576</td>
</tr>
<tr>
<td>CFE2</td>
<td>2.3835</td>
<td>2.50</td>
<td>25.38</td>
<td>25.36</td>
<td>1609</td>
</tr>
<tr>
<td>CFE3</td>
<td>2.4055</td>
<td>2.49</td>
<td>25.30</td>
<td>25.28</td>
<td>1593</td>
</tr>
<tr>
<td>CFE4</td>
<td>2.4240</td>
<td>2.58</td>
<td>25.29</td>
<td>25.25</td>
<td>1648</td>
</tr>
<tr>
<td>CFE5</td>
<td>2.4469</td>
<td>2.56</td>
<td>25.30</td>
<td>25.21</td>
<td>1633</td>
</tr>
<tr>
<td>CFE6</td>
<td>2.4686</td>
<td>2.59</td>
<td>25.33</td>
<td>25.34</td>
<td>1662</td>
</tr>
<tr>
<td>Mean value</td>
<td>2.4159</td>
<td>2.53</td>
<td>25.33</td>
<td>25.29</td>
<td>1620</td>
</tr>
</tbody>
</table>

2.2 GF Ampreg epoxy

A GF reinforced composite was manufactured at ÉireComposites Teo for testing, which was prepared using an E-glass bi-axial non-crimp material known as AHLSTROM 62042, with a quasi-isotropic lay-up and utilising Gurit’s Ampreg 22 slow hardening epoxy resin [36]. This epoxy system is designed for use in buildings, wind turbines and in marine applications such
as boat hulls. The laminates were manufactured using Vacuum Assisted Resin Transfer Molding (VARTM). This manufacturing method involves laying a layer of Teflon coated glass fibre on a flat metal plate, then carefully placing a dry fibre lay-up and covering it in a distribution material. This ensures that the vacuum is connected to the entire part and allows the resin to flow into the part. The lay-up is then covered in bagging material and sealed, leaving only an inlet for the resin and a connection for the vacuum pump. A vacuum is applied and de-gassed resin is allowed to flow into the part at 27 °C. This was done to lower its viscosity and ensure it soaked through the fibres before setting. Once the part has been fully infused with resin, the inlet is blocked to avoid air being drawn into the laminate. As the Ampreg epoxy cures, there is an exothermic reaction which generates heat in the laminate. For every 10 °C rise in temperature, the reaction rate doubles, which, in turn, produces more heat [37]. For thin laminates, such as those manufactured for this work, this is not an issue as the heat quickly dissipates. However, for thick sections, this exothermic reaction must be controlled to avoid overheating. Excessive heat build-up can cause damage to the component or damage to the mould on which the component is cured.

Currently, the majority of composite structures used in the renewable energy sector are manufactured using VARTM [1], due to the low material and tooling costs required. In order to use this method to manufacture large, complex parts, such as tidal or wind turbine blades, several parts are manufactured individually, then assembled and glued together to form the final part [1].

Table 3 provides an overview of the GF Ampreg (GFA) epoxy specimens. The square specimens, of side 25 mm, were extracted from a larger laminate using a diamond-tipped water-cooled saw in order to prevent damage to the specimen edges. The specimens have a 16 ply
lay-up in the form of \([45^\circ/-45^\circ/45^\circ/-45^\circ/0^\circ/90^\circ/0^\circ/90^\circ]\)s. In addition, 3 GFA specimens (GFA7, GFA8 and GFA9) were machined for use in pressurisation tests.

Table 3 Overview of the GF Ampreg epoxy (GFA) test specimens used for material characterisation and water aging. Side 1 and side 2 refer to the length of each side of the square specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Weight (g)</th>
<th>Thickness (mm)</th>
<th>Side 1 (mm)</th>
<th>Side 2 (mm)</th>
<th>Volume (mm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFA1</td>
<td>4.8960</td>
<td>4.25</td>
<td>25.21</td>
<td>25.30</td>
<td>2711</td>
</tr>
<tr>
<td>GFA2</td>
<td>4.9195</td>
<td>4.27</td>
<td>25.28</td>
<td>25.26</td>
<td>2727</td>
</tr>
<tr>
<td>GFA3</td>
<td>4.9490</td>
<td>4.28</td>
<td>25.27</td>
<td>25.77</td>
<td>2787</td>
</tr>
<tr>
<td>GFA4</td>
<td>5.0127</td>
<td>4.33</td>
<td>25.30</td>
<td>25.27</td>
<td>2768</td>
</tr>
<tr>
<td>GFA5</td>
<td>5.0231</td>
<td>4.35</td>
<td>25.28</td>
<td>25.54</td>
<td>2809</td>
</tr>
<tr>
<td>GFA6</td>
<td>5.0013</td>
<td>4.36</td>
<td>25.30</td>
<td>25.27</td>
<td>2787</td>
</tr>
<tr>
<td>Mean value</td>
<td>4.9669</td>
<td>4.31</td>
<td>25.27</td>
<td>25.40</td>
<td>2765</td>
</tr>
</tbody>
</table>

2.3 GF PEEK

GF PEEK, a thermoplastic glass fibre composite material sourced from Rochling [38], was also tested. PEEK is a relatively expensive matrix material and is, therefore, unlikely to gain widespread use in larger ocean energy structures. However, due to the low water uptake of PEEK and its excellent mechanical properties in comparison to other matrix materials, the material could find use in sub-sea turbine blade connection points. The composite material also differs from the other materials in this study in that it is a random-fibre composite with a fibre volume fraction of 30\%, in comparison the epoxy-based uni-directional composites. Table 4 provides an overview of the GF PEEK (GFP) specimens. The square specimens, of side 25 mm, were precision machined. In addition, 3 GFP specimens (GFP7, GFP8 and GFP9) were machined for use in pressurisation tests.
Table 4 Overview of the GF PEEK (GFP) test specimens used for material characterisation and water aging. Side 1 and side 2 refer to the length of each side of the square specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Weight (g)</th>
<th>Thickness (mm)</th>
<th>Side 1 (mm)</th>
<th>Side 2 (mm)</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFP1</td>
<td>7.7653</td>
<td>8.03</td>
<td>24.98</td>
<td>24.98</td>
<td>5011</td>
</tr>
<tr>
<td>GFP2</td>
<td>7.7407</td>
<td>7.99</td>
<td>24.98</td>
<td>24.98</td>
<td>4986</td>
</tr>
<tr>
<td>GFP3</td>
<td>7.7453</td>
<td>7.99</td>
<td>24.97</td>
<td>24.99</td>
<td>4986</td>
</tr>
<tr>
<td>GFP4</td>
<td>7.7650</td>
<td>8.00</td>
<td>24.97</td>
<td>24.97</td>
<td>4988</td>
</tr>
<tr>
<td>GFP5</td>
<td>7.7507</td>
<td>7.98</td>
<td>25.00</td>
<td>25.02</td>
<td>4991</td>
</tr>
<tr>
<td>GFP6</td>
<td>7.7539</td>
<td>8.00</td>
<td>24.96</td>
<td>24.94</td>
<td>4980</td>
</tr>
<tr>
<td>Mean value</td>
<td>7.7535</td>
<td>8.00</td>
<td>24.98</td>
<td>24.98</td>
<td>4990</td>
</tr>
</tbody>
</table>
3. Material characterisation

Given the importance of void content to moisture uptake, it is critical to measure the void volume fraction of test specimens prior to commencing water aging. A micro-structural analysis of each of the four materials was performed using 3-D X-ray CT, prior to water aging. The scans were carried out using a 100kV Scanco µCT100 machine with a voxel resolution of 16 μm. A void analysis of the three specimens was carried out using ImageJ Fiji software [39] on the CT scan data. The technique allows the determination of material phases of varying density via the attenuation of X-rays as they pass through a specimen. This facilitates a quantitative characterisation of the void volume content of the specimens, as well as a qualitative investigation of fibre tows, stitching and resin rich areas. Three specimens of each material type were CT scanned prior to conditioning. In addition, the fibre mass and volume fraction of the epoxy-based materials were measured in accordance with ASTM D3171-15 [40]. Characterising the constituent content of the composite materials is important in determining the relative contribution of each material phase by weight to the total composite water uptake.

3.1 GF powder epoxy

The CT scans of the GF powder epoxy specimens revealed well-consolidated laminates (Fig. 2). Large resin bands were visible between individual fibre tows. The woven cross-stitching connecting the tows (perpendicular to the main tow direction) was also visible as well as the fibre tow waviness. A void analysis of the specimens resulted in a 0% void volume fraction at the given scan resolution (16 μm). The low void volume can be explained by the relatively thin laminates, which were manufactured specifically for this testing. No other manufacturing defects of note were observed in the specimens. Fig. 2 shows a plan and end view of a scanned GF powder epoxy specimen.
Figure 2 (Top) Plan view of a CT scan of GF powder epoxy specimen (GFE1) at a 0° ply. (Bottom) End view of the same scan. Dimensions shown are the mean value for the GFE specimens. The CT scan resolution shown is 16 µm/voxel.

3.2 CF powder epoxy

Scans of the CF powder epoxy specimens showed well-consolidated unidirectional laminates (Fig. 3). Resin bands were visible in-between the carbon fibre tows. Like the GF powder epoxy, woven cross-stitching connecting the tows is visible, this time with the stitching at an angle of approximately 60° to the main tow direction. The degree of fibre tow waviness can also be detected. A void analysis of the specimens resulted in a 0% void volume fraction at the given scan resolution. Again, this can be attributed to the thin laminates manufactured as well as the unidirectional lay-up of the laminates. No other manufacturing defects of note were observed in the specimens. Fig. 3 shows a plan and end view of a scanned CF powder epoxy specimen.
Figure 3 (Top) Plan view of a CT scan of CF powder epoxy specimen (CFE1). (Bottom) End view of the same scan. Dimensions shown are the mean value for the CFE specimens. The CT scan resolution shown is 16 µm/voxel.

3.3 GF Ampreg epoxy

Like the powder epoxy specimens, the GF Ampreg epoxy specimen scans revealed well-consolidated laminates (Fig. 4). Fibre tows, resin bands and tow stitching were detectable. A notable difference between the materials was the presence of a significant number of small and mid-sized voids in the GF Ampreg laminates. No other manufacturing defects of note were observed in the specimens. Fig. 4 shows a plan and end view of a scanned GF Ampreg epoxy specimen.
A detailed void analysis of the three GFA specimens was carried out, with the average void volume fraction for the specimens was 0.25%, as shown in Table 5. The majority of voids were located within the large resin bands between fibre tows. All specimens also showed bias towards void formation near the bagging side of the laminate. That is, the half of the laminate closest to the surface over which the bagging material was placed. This particular trend in the spatial distribution of voids could have important implications for tidal turbine blade manufacturing, with certain portions of the structure potentially absorbing significantly more moisture over a service life due to a local increase in void volume. Fig. 5 highlights this bias in void formation through CT scans of a GF Ampreg epoxy test specimen.
Table 5 Void volume fraction of GF Ampreg specimens. The void volume on the bagging side of the specimens (50% of the specimen thickness closest to the bagging surface) is also provided.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Total void volume (%)</th>
<th>Void volume bag side (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFA1</td>
<td>0.237</td>
<td>0.259</td>
</tr>
<tr>
<td>GFA2</td>
<td>0.315</td>
<td>0.346</td>
</tr>
<tr>
<td>GFA3</td>
<td>0.184</td>
<td>0.289</td>
</tr>
</tbody>
</table>

Figure 5 A selection of plan view images through the thickness of specimen GFA3 showing the increased tendency for void formation towards the bagging side (top row of images) of the specimen. An end view of the laminate is inset. The CT scan resolution shown is 16 µm/voxel.

3.4 GF PEEK

X-ray CT scans were taken of three separate GF PEEK specimens and the results were consistent in that the scan resolution (16 µm/voxel over a 25 mm square sample) was not sufficient to discern the chopped fibre microstructure of the GF PEEK. The other materials tested in this work were composed of orientated fibres banded together in tightly-packed tows, offering a significant density gradient between fibre and matrix for the given scan resolution,
even at the full specimen scale. Additionally, large air voids were easily discernible due to their favourable aspect ratio and large density difference with the bulk composite. No voids or manufacturing defects were detected in the GF PEEK specimens. Fig. 6 shows a plan and end view of a scanned GF PEEK specimen.

![Plan view and end view of a CT scan of a GF PEEK specimen](image)

*Figure 6 (Top) Plan view of a CT scan of a GF PEEK specimen (GFP1). (Bottom) End view of the same scan. Dimensions shown are the mean value for the GFP specimens. The CT scan resolution shown is 16 µm/voxel.*

### 3.5 Fibre mass and volume fraction measurements

The ASTM standard for measuring the constituent content of composite materials (D3171-15) [40] was used to determine the fibre mass and volume fractions of the composite materials. Given that the fibre phase of the materials (glass and carbon) typically absorb a relatively low proportion of water, knowing the precise fraction of these phases can help in determining the
relative contribution of the matrix towards the total water uptake of the composite. Table 6 displays the fibre mass and volume fractions for the materials tested in this work. Due to the destructive nature of the testing (acid digestion/furnace combustion), specimen off-cuts were used for the fibre volume fraction characterisation. For each material, the fibre mass and volume fraction values quoted are the average of 3 off-cut specimens. Note that the GF PEEK material was not tested using the ASTM standard, instead the fibre volume fraction value is taken directly from the manufacturer data sheet [38].

Table 6 Fibre mass and volume fractions for the composite materials. GFE - GF powder epoxy; CFE - CF powder epoxy; GFA - GF Ampreg epoxy; GFP - GF PEEK.

<table>
<thead>
<tr>
<th>Material</th>
<th>Fibre content by mass (%)</th>
<th>Fibre content by volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFE</td>
<td>67</td>
<td>49</td>
</tr>
<tr>
<td>CFE</td>
<td>58</td>
<td>48</td>
</tr>
<tr>
<td>GFA</td>
<td>63</td>
<td>44</td>
</tr>
<tr>
<td>GFP</td>
<td>N/A</td>
<td>30</td>
</tr>
</tbody>
</table>

4. Accelerated water aging and hydrostatic pressurisation

4.1 Methodology

The accelerated aging was carried out in accordance with the ASTM standard for moisture absorption of polymer matrix composites (D5229/D5229M – 14) [41]. In order to accelerate
the rate of moisture uptake, a water temperature of 50 °C (±3 °C) was chosen for aging. Increasing the water temperature acts to increase the rate of diffusion without significantly altering the saturation point of the specimens, within a given temperature range for a material [42, 43]. Care must be taken not to induce extra damage in a specimen due to excessively high water temperature. It is recommended to age composites below the material glass transition temperature (T_g) in order to prevent unwanted changes to the material properties [44]. An Arrhenius law-based relation can be used to estimate the degree of aging acceleration achieved at a given aging temperature [44]:

\[
F_{H,L} = e^{\frac{-E}{R \left( \frac{1}{T_H} - \frac{1}{T_L} \right)}}
\]  

(1)

where \( F \) is the acceleration factor at the higher aging temperature \( T_H \) over the reference temperature \( T_L \), \( E \) is the activation energy and \( R \) is the universal gas constant. The acceleration factor is strongly dependent on the activation energy for the material, which can lead to difficulty in calibrating the precise aging time endured by test specimens. A doubling of activation energy can lead to an order of magnitude increase in acceleration factor for a given aging temperature. Values reported for E-glass epoxy average 93 kJ mol\(^{-1}\) [44] and with a value of 59 kJ mol\(^{-1}\) being taken for CF epoxy [45]. Fig. 7 shows the variation of acceleration factor for GF and CF epoxy materials for a range of reference temperatures and an aging temperature of 50 °C. This information is useful in linking the accelerated aging test results in this work to the actual aging experienced by turbine blade materials over the expected operational life of a tidal energy device immersed in water temperatures between 4 °C and 24 °C.
Figure 7 Plot of acceleration factor against reference temperature for an aging temperature of 50 °C. The graphs plots curves for GF and CF epoxy materials, based on activation energy values obtained from the literature [44, 45].

Based on a reference temperature of 12 °C, estimated as the operating temperature of a tidal turbine device off the coast of Ireland [46], an acceleration factor of 101 is estimated for GF epoxy and 16 for CF epoxy. In this work, accelerated aging took place over 17 weeks, corresponding to an aging period of 33 years for GF epoxy, and 5 years for CF epoxy. It should be noted that these acceleration factors should only be considered as a general reference due to the high variation in activation energy values for both GF epoxy and CF epoxy reported in the literature. Detailed activation energy values were not obtained for GF PEEK, however the activation energy for diffusion of neat PEEK was found to be in the order of 42 kJ mol⁻¹ [47].

The first 6 specimens of each material type (ID from 1 to 6) underwent aging at ambient pressure, immersed at a water depth of approximately 0.3 m. In order to simulate the hydrostatic pressure that an operating tidal turbine blade could be exposed to [11], pressurised water immersion at 6 bar and 50 °C was also conducted on the remaining specimens for each material.
type (ID from 7 to 9). A pressure of 6 bar corresponds to a water column of approximately 60 m and is selected to represent the operating depth of a large tidal turbine. An overview of the characterisation and aging test programme is provided in Table 7.

Table 7 Overview of the material characterisation and water aging test programme for this work. GFE - GF powder epoxy; CFE - CF powder epoxy; GFA - GF Amreg epoxy; GFP - GF PEEK.

<table>
<thead>
<tr>
<th>Material</th>
<th>GFE Specimen ID</th>
<th>CFE Specimen ID</th>
<th>GFA Specimen ID</th>
<th>GFP Specimen ID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-3</td>
<td>1-3</td>
<td>1-3</td>
<td>1-3</td>
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<tr>
<td></td>
<td>1-6</td>
<td>1-6</td>
<td>1-6</td>
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<tr>
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<td>7-9</td>
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<td>7-9</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>1-3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1-9</td>
<td>1-9</td>
<td>4-9</td>
<td>1-9</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>1-3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1-6</td>
<td>1-6</td>
<td>4-6</td>
<td>1-6</td>
</tr>
</tbody>
</table>

Prior to aging, the specimens were dried in an oven at 50°C for 24 hours to remove any residual moisture, before being weighed and measured (See Tables 1 to 4). The specimens under ambient pressure were conditioned in a tap water-filled bath, shown in Fig. 8. Distilled water and tap water are commonly used in place of seawater for laboratory aging experiments. Studies have shown seawater is slower to diffuse into composites compared to distilled water [48, 49], although testing comparing seawater, distilled water and tap water absorption rates have also shown no significant differences between the media [50]. The specimens under
hydrostatic pressure were conditioned in a custom-built pressure pot, immersed in an aging tank, as shown in Fig. 8.

![Temperature control](image1)
![Stirrer](image2)
![Specimens](image3)

**Figure 3 (Left)** Water bath used for the accelerated aging of the test specimens. A cover is placed over the bath during aging to limit evaporation and prevent foreign matter entering the bath. (Right) Pressurised test setup using an accelerated curing tank 12 kW 3 phase with a pressure pot resting in the accelerated curing tank.

The specimens were removed from their respective aging baths and weighed every 7 days in order to monitor the rate of water uptake. At each time interval, in accordance with ASTM D5229/D5229M – 14, the specimens were placed in a sealable bag once removed from the aging bath. A time period of approximately 10 minutes was given to allow stabilisation of the temperature of the specimens. Subsequently, the surfaces of each specimen were wiped with lint-free cloth to remove remaining surface water. In total, the specimens were never outside of the aging bath for more than 30 minutes for any given time interval. Towards the end of the experiment, weigh intervals were increased to 14 days. Prior to weighing, the surface of the specimens was wiped with non-linting absorbent cloth. An enclosed scales with an accuracy of ± 0.0001 g was used to weigh the specimens.
4.2 Water aging results

The weight gain for each individual specimen of the four materials, for both ambient aging (17 weeks) and pressurised aging (15 weeks) at 50 °C are shown in Figs. 10 to 13. In this work, weight gain refers to the moisture uptake of the composite by weight and is calculated by:

\[
Weight\ gain\ \% = \frac{W_t - W_0}{W_0} \times 100
\]

where \( W_t \) is the weight of the specimen at time \( t \) and \( W_0 \) is the initial weight of the specimen, after drying.

Before presenting the results of the composite aging tests, the moisture uptake of the neat matrix of each material system (at, or close to, saturation) is shown in Table 8.

Table 8 Moisture uptake of the neat matrix materials for each of the composite materials tested in this study.

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture uptake by weight (%)</th>
<th>Test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder epoxy</td>
<td>2.16</td>
<td>90 days @ 50 °C</td>
</tr>
<tr>
<td>Ampreg 22 [36]</td>
<td>1.41</td>
<td>N/A</td>
</tr>
<tr>
<td>PEEK [38]</td>
<td>0.50</td>
<td>N/A</td>
</tr>
</tbody>
</table>

As there was no published data available for the water uptake behaviour of the powder epoxy material, the material was tested separately at The University of Edinburgh under similar aging conditions (50 °C, artificial seawater). Fig. 9 shows the water uptake response of the powder epoxy material (average response of 5 specimens).
Figure 9 Weight gain plot for the neat powder epoxy material. The curve plotted is an average response of 5 specimens tested at an aging temperature of 50 °C in artificial seawater.

The powder epoxy specimens exhibited a consistent weight gain response with little variation in weight gain from specimen to specimen. Although the rate of weight gain substantially slowed after 12 weeks aging time, final saturation of the specimens was not attained within the aging time-frame.
Figure 10 Weight gain plot for the 6 GF powder epoxy specimens (GFE ID from 1 to 6), aged at ambient pressure over 17 weeks and the 3 pressurised specimens (PGFE ID 7 to 9), aged at a pressure of 6 bar over 15 weeks, at a water aging temperature of 50 °C.

The GFE specimens were found to be substantially saturated (weight change < 0.02% per week) after 12 weeks, although final saturation was not attained within the test time-frame for either the ambient or pressurised specimens. Similar to the neat powder epoxy specimens, the GFE specimens registered consistent weight gain profiles over the course of aging, with little spread in the weight measurements between specimens. Over a similar time-frame, the GFE specimens experienced a total weight gain of approximately half that of the neat powder epoxy. This is expected, as the glass fibre phase (approximately 50% by volume) is expected to absorb relatively little moisture by weight. The pressurised specimens were observed to have an increased initial weight gain rate when compared to the ambient specimens, although by week 15 the difference in water uptake between the two groups of specimens was minimal.
Figure 11 Weight gain plot for the 6 CF powder epoxy specimens (CFE ID from 1 to 6), aged at ambient pressure over 17 weeks and the 3 pressurised specimens (PCFE ID 7 to 9), aged at a pressure of 6 bar over 15 weeks, at a water aging temperature of 50 °C.

The CF powder epoxy (CFE) specimens followed a similar weight gain profile to the neat powder epoxy and GFE specimens, although the average weight gain was approximately 40% higher for the CFE specimens compared to the GFE specimens at the end of aging. This difference in final weight gain between the CF and GF powder epoxy materials can be partially explained by the difference in fibre weights for each composite. Although the materials have similar fibre volume fractions, the mass fraction of the glass fibres is 67% for the GFE specimens compared to 58% for the CFE specimens. Thus, for equivalent water uptake in the matrix phase of each composite, the relative weight gain would be less for the GFE specimens, assuming low levels of moisture absorption in the respective fibre phases. The rate of weight gain slowed significantly for the CFE specimens over the course of the test, however, like the GFE specimens, full saturation was deemed not to have been achieved. The pressurised
specimens were noted to have both a higher initial rate of weight gain and a higher final weight uptake when compared to the ambient specimens.

![Weight gain plot](image)

**Figure 12** Weight gain plot for the 6 GF Ampreg specimens (GFA ID from 1 to 6), aged at ambient pressure over 17 weeks and the 3 pressurised specimens (PGFA ID 7 to 9), aged at a pressure of 6 bar over 15 weeks, at a water aging temperature of 50 °C. Note: ambient specimens GFA1, GFA2 and GFA3 were removed from the test after 15 weeks for X-ray CT characterisation.

The GF Ampreg epoxy (GFA) specimens exhibited a notably different weight gain profile compared to the powder epoxy materials. The initial rate of weight gain was higher than the other materials tested, with all specimens having reached saturation after 11 weeks. The average weight gain at saturation for the GFA specimens (1.26%) was similar to, although slightly lower than, the reported moisture saturation weight of the Ampreg 22 resin [36] (1.41% by weight). Given that the GFA specimens contain 63% GF by weight, this indicates that the manufactured composite absorbs more water than its constituent materials would suggest. Free water stored in voids likely contributes to the greater than expected weight gain for the GFA
specimens, with CT scans showing an average void volume content of 0.25%. Significant scatter in weight measurements was observed, with many specimens also showing weight loss shortly after reaching saturation. This weight loss is discussed further in Section 4.3. Once again, the pressurised specimens were shown to have an increased initial weight gain rate, however no significant difference in final weight was observed between the pressurised and ambient specimens.

Figure 13 Weight gain plot for the 6 GF PEEK specimens (GFP ID from 1 to 6), aged at ambient pressure over 17 weeks and the 3 pressurised specimens (PGFP ID 7 to 9), aged at a pressure of 6 bar over 15 weeks, at a water aging temperature of 50 °C.

As expected, the thermoplastic-based GF PEEK (GFP) specimens registered the lowest weight gain among the materials, saturating after week 12. PEEK is widely known for its resistance to solvents and low moisture absorption. In general, thermoplastic composites are known to absorb significantly less moisture when compared to thermoset composites [51]. The neat PEEK saturation level is 0.5% as reported by the manufacturer [38], with the saturation level of the GF PEEK composite being 0.3%, similar to the measured values in Fig. 13. A reduction in weight gain between the neat PEEK matrix and the composite is expected due to the presence
of GF phase. The specimens displayed consistent weight gain profiles during aging, with little deviation from the mean. Notable for the GFP material was the significantly increased initial weight gain rate for the pressurised specimens when compared to the ambient specimens, as well as a final weight gain almost 75% higher for the pressurised specimens. It is unclear why the GFP specimens specifically were more sensitive to aging under hydrostatic pressure compared to the epoxy-based specimens. It is possible that due to the lower relative contribution of the fibre phase by weight, and the low weight gain of the specimens in general, that any sensitivity of the matrix phase of the GFP specimens to aging under hydrostatic pressure would be more noticeable than in the case of the other composites tested. The water aging results are summarised in Table 9, with Fig. 14 providing a comparison of the averaged weight gain response (average of each curve set shown in Figs. 10 to 13) between the materials for both ambient and pressurised conditions.

Table 9 Comparison of peak weight gain for specimens under ambient pressure aging and hydrostatic pressurisation at 6 bar.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ambient peak weight gain % (mean ID 1 to 6)</th>
<th>6 bar peak weight gain % (mean ID 7 to 9)</th>
<th>% difference in weight gain for 6 bar over ambient pressure (week 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFE</td>
<td>0.90</td>
<td>0.85</td>
<td>-3.6</td>
</tr>
<tr>
<td>CFE</td>
<td>1.20</td>
<td>1.30</td>
<td>8.6</td>
</tr>
<tr>
<td>GFA</td>
<td>1.26</td>
<td>1.26</td>
<td>1.7</td>
</tr>
<tr>
<td>GFP</td>
<td>0.23</td>
<td>0.40</td>
<td>75.4</td>
</tr>
</tbody>
</table>
Figure 14 Plot of the average weight gain response (average of each curve set shown in Figs. 9 to 12) for the 4 materials under ambient (GFE, CFE, GFA & GFP) and 6 bar hydrostatic pressure (PGFE, PCFE, PGFA & PGFP) at a water aging temperature of 50 °C.

As expected, all specimens for each material and aging condition recorded a high initial rate of moisture uptake, with the rate slowing noticeably after approximately 3 weeks aging. Major trends include a significantly higher weight gain for the epoxy-based materials compared to the PEEK material and an increase in weight gain rate for pressurised specimens over those aged at ambient pressure. In terms of the influence of hydrostatic pressure on total water uptake, the trend is less clear. The epoxy-based materials show relatively little change in moisture uptake, with only the GFP material showing a definite and substantial relation between pressurised and ambient aging. Another trend of note is the difference in water uptake between the GFE and CFE specimens, despite having the same powder epoxy matrix material. This can be explained in part by the difference in fibre mass fraction for the GFE and CFE specimens, with an equivalent mass of water absorbed into the matrix of each material having a comparatively greater contribution to the overall percentage weight gain of the less dense CF
material. In addition, differences fibre bonding in the materials could lead to differing moisture absorption behaviour. The GFA is the first material to reach saturation, as well as the only material to exhibit weight loss during the test time-frame.

### 4.3 Moisture absorption and specimen volume changes

In addition to weight measurements, the specimen dimensions were also noted during and after aging in order to track the volume change of the specimens as they absorbed water. After week 17, the ambient pressure specimens were removed from the aging bath and dried at 50 °C for 24 hours to remove all absorbed moisture. This allowed comparison of the changes in average specimen volumes and weights, with respect to initial measurements, during and after aging as shown in Figs. 15 and 16.

![Figure 15](image)

*Figure 15 Plot of the average volume change, with respect to initial (dry) volume, for each material under ambient pressure aging after week 8, 17 and final dry volume. GFE - GF powder epoxy, CFE - CF powder epoxy, GFA - GF Ampreg epoxy, GFP - GF PEEK.*
Despite the significant spread of measurements, it is clear from Fig. 15 that there is an increase in specimen volume for all materials during aging and that the relative change in percentage volume is greater than the change in specimen weight. This volumetric change could have significant implications for tidal turbine blade design, including at the interface points between the blades and the main turbine structure where relative changes in blade volume during immersion in seawater may dictate design tolerances at the connection points. It is generally accepted that when composite materials absorb water, there is a resulting swelling of the polymer matrix which would lead to an increase in the specimen volume. Given that the density of water is generally less than half the density of the composites tested here, the relative contribution by weight of the water can be expected to be less than the volumetric contribution, without considering the material microstructure. Interestingly, after final drying, the average
specimen volume and weight for the GFE, CFE and GFP specimens was higher than before aging. This may indicate that the drying period of 24 hours at 50 °C is not enough time to ensure complete moisture desorption from the polymer phase of the specimens. Other studies have also noted residual weight gain for specimens after drying [52], with reasons given including plasticisation of the resin leading to a quantity of water being fixed within the polymer. For this work, it is unlikely that any significant quantity of free water remained within voids, as CT scans of the dry GFA specimens indicated complete moisture desorption from the internal voids after 24 hours drying. Alternatively, it suggests that moisture absorption alone does not account for the volume and weight changes during aging. A build-up of foreign matter on the surface of the specimens (fouling) can contribute to both the increased volume and weight measurements after final drying. A change in specimen colour, notably for the GFE and GFA materials after aging may be indicative that some form of fouling, or alternatively chemical change within the polymer phase [53, 54], had occurred during the aging process. Fig. 17 shows the change in colour observed between un-aged and aged GFA and GFE specimens.
Figure 17 Change in colour observed for the GF Ampreg (GFA) and the GF powder epoxy (GFE) specimens before aging (dry) and after aging. Both materials exhibited a 'lightening' in colour, possibly indicative of surface fouling or a chemical change undergone during the water aging.

On the contrary, the GFA specimens exhibit noticeable weight loss after final drying, with specimens averaging 1% below the initial specimen weight despite maintaining an increased volume. A possible explanation for this weight loss is the leaching of soluble aspects of the resin into the water, a commonly reported phenomenon which is often exacerbated by higher aging temperatures [55, 56].

4.4 Void saturation

In order to investigate the influence of voids on water uptake during aging, three GF Ampreg specimens (GFA ID 1 to 3) were removed from the aging bath after 15 weeks for X-ray CT characterisation. GF Ampreg specimens were chosen as they were the only laminates in this study with a measurable void content. The specimens were kept immersed in water during the
scanning process in order to prevent premature loss of moisture. As before, the scans were carried out using a voxel resolution of 16 μm, with the subsequent void analysis of the three specimens being performed with ImageJ Fiji software. This allows direct comparison of the specimen void content before aging and after 15 weeks, as shown in Fig. 18.

Figure 18 X-ray CT scans comparing dry and saturated void volume contents for GF Ampreg epoxy specimens GFA1, GFA2, GFA3. The images are taken from the same point through the laminate thickness for each specimen. The majority of voids are observed to completely fill with water during the aging test. The CT scan resolution shown is 16 μm/voxel.
For each of the specimens shown in Fig. 18, the void content is shown to decrease at saturation, with only the largest voids spaces still containing air. Due to the similar densities of water and the epoxy resin, a distinct water phase is not distinguishable in the scan outputs. A quantitative comparison of the void volume of the specimens before aging and after saturation is provided in Table 10.

Table 10 Void volume fraction of GF Ampreg specimens. The initial void volume was measured from X-ray CT scans of dry specimens. The saturated void volume was measured from CT scans of specimens immersed in water after 15 weeks of accelerated aging.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Void volume (initial) (%)</th>
<th>Void volume (saturated) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFA1</td>
<td>0.237</td>
<td>0.028</td>
</tr>
<tr>
<td>GFA2</td>
<td>0.315</td>
<td>0.097</td>
</tr>
<tr>
<td>GFA3</td>
<td>0.184</td>
<td>0.017</td>
</tr>
</tbody>
</table>

The significant decline in observed void volume content at saturation for each specimen indicates the role of the air voids in storing water during aging. Although the precise mechanisms of moisture transport to the internal voids in the GF Ampreg laminates cannot be determined from the X-ray CT scans alone, there exist a number of possibilities for the presence of water in a liquid phase in the voids, including:

- Direct entry of liquid water into internal voids in the composite via a connected network of microcracks, surface voids and interfacial debonds, which could be aided by capillary action [27].

- Moisture which has been absorbed into the matrix collects at internal voids and condenses into a liquid form. If water vapour were to exist within the internal voids, the pressure in the voids would have to be significant and, therefore, would likely damage the surrounding composite. This topic has been of interest to the microelectronics industry where pressure models have been developed suggesting the
presence of water in a liquid phase in voids in polymer materials for this very reason [57, 58].

This stored water weight constitutes a noticeable proportion of the total water uptake weight for the specimens and represents water uptake distinct from the primary polymer moisture absorption mechanism. The complex water storage behaviour via voids shown here can make predictive methodologies for moisture diffusion based on Fick's Law redundant for high void content composites. This is the case even when the bulk composite, with low void content, shows Fickian behaviour. Multi-phase microstructures, the presence of voids, leaching and permanent volume and mass changes all likely contribute to the observed complex diffusion behaviour. Fitting traditional Fickian diffusion models to these materials is likely to give misleading water uptake predictions, meaning physical testing of the materials is essential to determining in-service moisture absorption. In addition, given the relatively low void content of the specimens in this study, due to the carefully controlled manufacturing process, the role of voids in total water uptake is expected to be even greater for large structures such as tidal turbine blades. These structures may have void volume contents of several percent due to the substantially thicker laminates, as well as more complex void distributions such as those observed in the GF Ampreg laminates, shown in Section 3.3. Another implication of the presence of water stored internally in voids is the possibility of damage, such as matrix microcracking, occurring within the composite due to freeze-thaw action. Tidal turbine blades could potentially be exposed to this freeze-thaw action during transport or repair operations above the water-line. Although a previous investigation has shown little effect on load bearing capacity of composite laminates due to freeze-thaw action [59], it should be noted that this study involved samples with a negligible void content. The current work suggests that the effect of freeze-thaw action on composites with fully saturated voids and void contents representative
of actual blade structures (estimated to be in the range of 5% to 20% for composite wind turbine blades [60]) may warrant further study.

5. Conclusions

A detailed study of the water uptake behaviour of four prospective tidal turbine blade materials, GF and CF powder epoxy, GF Epoxy (Ampreg) and GF PEEK, under ambient and 6 bar hydrostatic pressure has been conducted. The role of material microstructure on the moisture absorption behaviour has also been investigated through the use of 3-D X-ray CT. The primary conclusions of the study are:

- Hydrostatic pressurisation was found to universally increase the initial rate of water uptake for the materials. However, the final water uptake of the specimens was not affected by pressurisation, except for the GF PEEK material where, on average, the 6 bar pressure led to a 75% increase in final water uptake weight over the ambient pressure aged specimens.

- The thermoset epoxy-based materials registered a significantly higher weight gain compared to the thermoplastic-based GF PEEK material. However, the benefits of this favourable moisture absorption behaviour is unlikely to offset the higher costs associated with PEEK-based materials. The powder epoxy materials did not saturate during the time-frame of the experiment despite the accelerated water aging at 50 °C. For the aging time-frame studied here, the carbon fibre-based powder epoxy samples registered, on average, a 40% greater weight gain compared to the glass fibre-based powder epoxy samples. This can be explained, in part, by the higher mass fraction of the glass fibre composite compared to the carbon fibre composite.
• X-ray CT scans of the GF Ampreg specimens before aging and at saturation were used to quantify the contribution of the void volume of the specimens in storing free water. The role of voids in storing water is likely to significantly influence the moisture uptake behaviour of large composite structures which may have higher void volume contents. It is, therefore, important to accurately measure the void volume content of any composite material prior to water aging.

• In general, specimens registered volume, as well as mass increases, during and after the aging tests. The mass and volume changes were maintained after aging and drying, indicating permanent deformation of the specimens and possible fouling and/or chemical change at the exposed specimen surfaces. These volumetric changes could have significant implications for tidal turbine blade design, particularly at interface points to the main turbine structure. The GF epoxy (Ampreg) displayed mass loss during the test, likely indicating leaching of the polymer matrix. These mass changes were often on the same order as the perceived water uptake of the specimens, which casts doubt on the precise percentage contribution of moisture to the weight change of the specimens. CT scans of the GF Ampreg specimens after drying showed that liquid water was no longer present in the internal voids.

• The void volume content of small, well-made test specimens is likely unrepresentative of, and may significantly underestimate, the void content and spatial distribution of defects in large scale composite structures. As measured by X-ray CT scans, three of the materials had 0% void volume content with the GF epoxy (Ampreg) material having a void content of 0.25%.

• Due to the complex water uptake response observed for the specimens, physical testing of multi-phase composite materials is essential to determining moisture absorption behaviour.
• Future work will include the aging of thick composite sections more representative of a tidal turbine blade structure in terms of void content and additional manufacturing defects. In addition, a finite element modelling methodology for moisture diffusion in multi-phase composites based on X-ray CT scan input, based on existing methods developed at NUI Galway [61, 62], is envisaged.
Acknowledgments

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References


