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New sustainable materials from waste feathers: properties of hot-pressed feather/cotton/bi-component fibre boards

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ABSTRACT

Feathers from poultry are an abundant, globally available waste. The current beneficial reuse for feathers involves autoclaving them to produce feather meal, an animal feed with low economic value. This paper reports on the production and performance of new feather-derived materials. These have potential to provide a higher value application for waste feathers. Feather fibres, cotton fibres and polyethylene/polypropylene bi-component fibres (blended 55:20:25 by weight) have been air-laid to form 20mm thick non-woven pre-forms with a density of 0.14 g cm$^{-3}$. These were then hot pressed to produce materials with significantly higher density and improved properties. Optimum materials were formed by hot pressing between 150 and 160°C at 6 MPa for 1 minute. Lower temperatures resulted in poor fibre bonding and fibre pull-out during fracture. Higher temperatures caused thermal degradation of the feather fibres. The optimum feather fibre boards with a density of 0.77 g/cm$^3$, corresponding to 31.3% porosity, had tensile strengths of 17.9 MPa a tensile modulus of 1.74 GPa and an elongation at fracture of 5.9%. These samples exhibited fibre fracture during tensile testing. Feather fibre boards have similar tensile strength, density and Young’s modulus to particleboard, organic resin particleboard and flake board. Quantitative estimates of the economic and environmental benefits from using feather fibres to form feather fibre boards are discussed. The research advances sustainability by providing a new potential circular economy outlet for waste feathers and is part of on-going research to develop novel applications that exploit the unique properties of feathers.

Keywords: feathers; hot-pressed; non-woven; air laid; sustainable packaging; automotive.

1. Introduction

Feathers are produced from the significant quantities of poultry that are consumed globally [1]. These are mainly from chicken, although turkey and duck consumption is increasing, with poultry expected to become the most consumed meat by 2022 [2]. Developing new beneficial reuse applications and a circular economy for waste feathers is therefore an increasingly important research area [3–9].

Conventional management waste feathers in the UK involves autoclaving to produce feather meal, a relatively low-value, low-grade protein rich animal feed, that is exported to Eastern Europe and Russia [10]. Specific types of down feathers are suitable for filling duvets, garments and upholstery, but these
applications can only ever use a small percentage of the total feathers that are generated. Waste feathers are normally landfilled or incinerated if suitable autoclaving infrastructure is not available.

The structure of a feather is shown in Figure 1 [11]. The rachis is the central core of the feather that provides stiffness, while the vanes on either side form flat areas with barbs producing a comb-like microstructure. Feathers are strong in tension and are primarily composed of keratin, a tough, insoluble filament-forming protein. The keratin in hair, nails, horns and beaks is predominantly alpha-keratin [12] while feathers contain specialised groups of beta-keratins (FβK) that degrade at relatively low temperatures, but have high strength [13]. Thermal gravimetric analysis (TGA) of chicken feathers indicates that thermal degradation in a N₂ atmosphere occurs at ~180 °C [14]. This limits the use of feather fibres in thermal processes that use high temperatures such as injection moulding.

The development of a circular economy is critical, given the increasing world population and unsustainable levels of resource extraction, materials production and waste generation [15]. In a circular economy materials remain in the economic cycle and by analogy with the natural environment, they add value to the biosphere at end of life. Feather fibres are biodegradable and can provide nutrients to the environment. Products made using feather fibres therefore inherently fit a circular economy model for ecological design. In addition, feather fibres can often be sourced locally and at low-cost.

Textile processing allows precursor materials to be formed with high fibre loadings. These can then be consolidated using processes such as hot pressing and vacuum-assisted-resin-infusion [16]. Various types of cellulose fibres have been processed into boards using different wet filtration techniques [17]. Wet-lay techniques have been used to form boards with good mechanical properties [18]. Kenaf-polypropylene non-wovens produced by carding and needle-punching have also been compression moulded and the mechanical and acoustic properties reported [19]. Board panels have been formed from cat tail-fibres using carding and needle-punching technology [20]. Sunflower stalk fibres have been used to create particle boards using air laid processing combined with spray adhesives [21]. The properties of various natural fibre composites prepared using coir, hemp, jute, banana and sisal fibres have been reviewed, with resin infusion using thermosetting polyesters reported to produce materials with good properties but with relatively low fibre content [22].

There has been limited work on using feather fibres to form composite materials. Polybutylene adipate terephthalate (PBAT)-feather composites were formed using an alkali pre-treatment of fibres to allow higher fibre loadings [23]. The biodegradability of bioplastics made by injection moulded polylactic acid (PLA) containing 50 wt.% feather fibres has been reported [4]. The thermal and acoustic properties of epoxy-feather boards have also been evaluated with samples containing 80% feathers found to have the best properties [24].
The original research reported in this paper aimed to develop new materials produced by hot-pressing air-laid non-woven preforms containing high levels of feather fibres. This processing method is different from that used in previous studies and the properties of the materials formed have not previously been reported. Air-laid processing is used to produce wipes, thermal insulation materials and personal hygiene products, but its use for processing waste feathers has been limited [25]. Air laid products are typically soft, non-load bearing and flexible and air laid non-woven feather fibres have been used in thermal and acoustic absorption applications [26]. Hot-pressing air laid feather fibre textiles produces rigid board-type materials with mechanical properties suitable for use in automotive, construction and civil design applications and these are sectors with a strong demand for natural and eco-friendly materials. Non-woven feather fibres have been hot-pressed at a range of temperatures and pressures. The density, tensile strength, tensile modulus, microstructure and fracture mechanisms of the different materials formed are reported.

2. Materials and methods

2.1 Materials

Chicken feathers were obtained from a major UK poultry facility producing ~160 tonnes of wet soiled by-product feathers a week. The as-received feathers were washed in 100g batches using a 5% hydrogen peroxide solution containing an industrial scouring agent (M-SCOUR EF-5, Regency FCB). They were then treated using 1% disinfectant solution (Dupont Virkon S) and dried to form the feathers shown in Figure 2. The dried feathers were shredded using a Rapid 2040 granulator. This processed ~500g batches of feathers using two rotary blade cutters with a 5mm steel mesh and produces feather fibres. The fibres were de-dusted using a 25cm-cyclone system with a filter-sock and this produced homogenous feather fibres containing fibrous feather quill and fibrillated barb-fibres.

2.2 Production of air laid non-woven feather fibre mats

Non-woven feather fibre mats were produced using a mix of 55 wt.% feather fibres, 20 wt.% cotton fibres (32mm recycled cotton, ALTEX) and 25 wt.% bi-component fibres that had a polyethylene (PE) surface and a polypropylene (PP) core (32mm, 2 denier, round cross-section, white, semi-full, LMF-Bico, Fipatec). The cotton fibres acted as a processing aid during the air laid process, as the longer cotton fibres acted as a carrier for the shorter and lighter feather fibres. The bi-component fibre binds the fibres together during the air laid processing and during subsequent hot pressing.
Air laid non-woven feather fibre mats were produced at a commercial pilot plant facility using the process shown in Figure 3. The mixed air laid fibres were heated to 145°C as they move between two moving belts and this produced a 20 mm thick non-woven mat with a density of 0.14 g.cm$^{-2}$ as in Figure 4a.

An AccuPyc II 1340 gas pycnometer (Micromeritics™) using helium was used to determine the average skeletal density of the air laid non-woven preforms. This used 10 purge cycles and made 5 measurements during each run. The value determined was the average of 25 measurements, with calibration performed using standard stainless steel spheres with a volume of 3.1859 cm$^3$.

### 2.3 Hot pressing non-woven feather fibre preforms

The air-laid non-woven feather fibre preforms were cut to 190×55 mm$^2$ samples and these were hot-pressed between two parallel plates (Carver hot press, model 4122CE). Mylar plastic sheets were used on the platens to stop samples sticking to the press. Figure 4b shows a typical hot pressed material. Samples were hot pressed at 6 MPa at temperatures between 130 and 190°C for 60 seconds. The hot-press maintained temperature at ± 2°C. Subsequent experiments varied the pressing pressure applied for 60 seconds at the optimum pressing temperature.

### 2.4 Characterisation of non-woven feather fibre composites

The geometric density of samples was determined from the specimen mass and dimensions. The top and side surfaces of the pre-formed air laid feather fibre mat and hot pressed boards were examined using scanning electron microscopy (SEM, Hitachi TM4000Plus).

Tensile tests to failure were completed in accordance to BS EN ISO 527-4:1997. Samples were laser cut (Denford VLS4.60) to form dog-bone shaped test specimens with dimensions adjusted to provide extended tabs and a shorter neck to make sure that fracture did not occur due to stresses induced by clamping the sample. Test specimens had and overall length of 178 mm, a gauge length of 30 mm and a width of 10 mm and they were tested in tension using a crosshead speed of 2 mm.min$^{-1}$ (Instron model 5984). The specimen strain was determined using an advanced non-contacting video extensometer and all tests were conducted at 21°C and ~45% relative humidity. The tensile modulus was calculated from the gradient of the stress/strain data between strain values of 0.0005 ≤ ε ≤ 0.0025. Average results of 6 test specimens are reported for each material tested. Fracture surfaces were examined using SEM to assess the failure mechanism (Hitachi TM4000Plus).

### 3. Results
Figure 5 shows the top and side surfaces of the air laid non-woven sample prior to hot pressing. The highly fibrillated and open structure of the feathers is evident and the top and side surfaces of the samples appear to be very similar. Feather fibres appear to be up to 3-4 mm in length and the original vanes of the feather are largely destroyed by the shredding process used to transform feathers into fibres. Although the quills, rachis and barbs of the feathers are evident in the SEM images it is difficult to identify cotton and bi-component fibres. The average skeletal density of the air laid non-woven determined by gas pycnometry was 1.12 g.cm\(^{-3}\) and this represents the maximum possible density of samples containing zero open porosity.

Figure 6a shows the effect of changing the pressing temperature between 130 and 190°C using a pressing pressure of 6 MPa applied for 60 seconds on sample thickness and density. Density increases and thickness decreases for temperatures up to 160°C. At higher temperatures the thickness of pressed samples decreases but this does not correspond to increased density. This is because of thermal degradation of the feathers and this is consistent with thermogravimetric data for feathers [14]. Figure 6b shows the effect of pressing pressure at 154°C applied for 60 seconds. Increasing the pressing pressure reduces the sample thickness and increases sample density.

Figure 7 shows the stress-strain behaviour of different hot pressed air laid non-woven samples. The tensile strength and elongation at fracture vary with pressing temperature and this controls the failure mode.

Figure 8 shows the surfaces of hot pressed samples. The side surface (Figure 8a) shows a tightly layered structure and comparing this image with Figure 5a clearly highlights the increase in fibre packing resulting from hot pressing. Figure 8b is the top pressed surface of the sample and this shows relatively dense packing of randomly orientated fibres with the melted bi-component polymer fibres partially coating the surface, bonding the cotton and feather fibres together.

Figure 9 shows fracture surfaces of tensile test samples hot pressed at 130°C, 150°C and 190°C. The sample hot-pressed at 130°C shows extensive fibre pull-out due to relatively weak and ineffective feather fibre/cotton fibre-binder bonding. This is evident from the stress-strain curve for this sample shown in Figure 7 which shows relatively low load but high elongation at fracture. Hot pressing at 150°C and 6 MPa produced improved bonding of feather and cotton fibres into the material and this results in increased strength, with reduced fibre pull-out and evidence on the fracture surface of fibre fracture. Samples hot pressed at 190°C and 6 MPa were slightly brown indicating thermal degradation of the fibres had occurred. This results in brittle fracture at relatively low stress.
Table 1 summarises the effect of temperature and pressure on the density, tensile strength, Young’s modulus and elongation at fracture of hot pressed feather fibre/cotton fibre/polyethylene/polypropylene bi-component fibreboards. The samples formed have a range of properties with optimum processing occurring in a relatively narrow temperature range between ~150 and 160°C.

4. Discussion

Hot pressing air laid non-woven blends of feather fibre, cotton fibre and polyethylene/polypropylene bi-component fibre produces new materials with potentially exploitable properties. The boards formed have densities ranging from 0.66 to 0.79 g/cm² and exhibit fracture behaviour dependent on the processing conditions. Hot pressing at 130°C does not form strong bonds between the bi-component polymer binder and the feather and cotton fibres, and tensile strength testing causes extensive fibre pull-out and fracture at relatively low loads. Hot-pressing between 150 to 160°C and 6 MPa increases the density and significantly increases feather/cotton fibre/bi-component fibre bonding. Tensile strength is increased, there is reduced fibre pull-out and elongation at fracture is high, with fracture surfaces showing evidence of fibre fracture. Increasing the pressing pressure in this temperature range marginally improves density but does not result in significant increases in Young’s modulus or tensile strength. Hot pressing at 190°C and 6 MPa reduces sample thickness but does not increase sample density due to thermal degradation of the feather fibres, which is associated with discolouration of the specimen surface. The feathers have reduced strength and although the bi-component binder flows extensively during hot pressing the samples have low strength and exhibit brittle fracture with extensive fibre fracture, as shown in Figure 9c.

A process envelope therefore exists that produces feather fibreboard materials with the highest performance across these properties. Pressing between ~150 and 160°C at a pressure of 6 MPa produces optimal materials which have a density of 0.77 g/cm³, corresponding to a porosity of 31.3%, tensile strength of 17.9 MPa, tensile modulus of 1.74 GPa and an elongation at fracture of 5.9%. All samples have been pressed for 60 seconds and pressing for longer may produce improved materials. Feather fibres are highly insulating (0.028-0.034 W m² K⁻¹) and this is likely to limit the sample thickness that can be effectively hot pressed. Excessively thick samples will have limited heat flow into the centre of air laid feather fibre preforms, causing poor bi-component melting and inhomogeneity in the resulting microstructure, although the production of laminated samples is possible to increase thickness.

The feather/cotton/bi-component boards formed have been benchmarked against plastics, foams, composites and natural materials as shown in Figure 10 (CES EduPack 2018, Granta Design Ltd.). This shows that these materials have similar tensile strength, tensile modulus and density to particleboard,
organic resin particleboard and flake board. They have lower density, similar modulus but lower strengths than most plastics.

Feathers are inherently biodegradable and this is becoming increasingly important in material selection for some uses. Fully bio-derived boards could be formed using biodegradable bi-component fibres to replace the plastic bi-component fibres used in this work. New materials that are inherently biodegradable fit with a circular economy model, with products mimicking nature at end of life by providing nutrients back into the eco-system. Further processing and characterisation studies are required to fully understand the performance, feasibility and potential opportunities associated with new materials manufactured by hot pressing air laid non-woven materials containing feather fibres.

There are economic and environmental benefits associated with producing feather fibreboards. Clean and disinfected waste feathers suitable for processing into low cost feather fibres can be obtained in Europe. The normal outlet for these is the rendering industry which produces feather meal, a relatively low-grade protein rich animal feed, formed by partially grinding feathers under conditions of elevated heat and pressure followed by additional grinding and drying. This costs the poultry industry up to ~200 € per tonne of feather. Feather meal has a value of between 0 and ~150 € per tonne depending on demand and location. The production of feather fibres is estimated to cost ~400 € per tonne and this compares favourably with the costs of other natural fibres such as flax, hemp and cotton, which typically range in price from 880 to 3,360 € per tonne [27]. The carbon footprint for flax fibres (798 kg CO$_2$-eq/tonne) and hemp fibres (682 - 835 kg CO$_2$-eq/tonne) have been reported [28]. Cotton is well known to have a large carbon footprint of ~7,000 kg CO$_2$-eq/tonne [29]. This highlights the negative environmental effects associated with using fibres derived from specifically cultivated crops. The carbon emissions associated with feather fibre production depend on the source of feathers, but for clean by-product feathers these relate to the energy used in shredding/granulation, which is relatively minimal. There are therefore significant inherent environmental advantages in using appropriate supplies of waste feather fibres in new materials, as reported in this research.

The carbon footprint of the air laid processing is estimated to be ~600 kg CO$_2$-eq/tonne and therefore the feather boards produced can be considered low-carbon sustainable materials. We envisage that feather boards can be hot-pressed into different profiles and used to manufacture parts for automotive interiors such as door panels and shelves, as this is an industry where there is a legal requirement to increase the use of bio-derived materials. We also believe that low-cost low-carbon feather fibres have potential to be used as new sustainable packaging materials, another sector where alternative bio-derived materials are in high demand.
The poultry industry in the UK recognises there is a need to develop more sustainable and preferably commercially viable alternative applications for waste feathers. This research reports, for the first time, the development of new materials manufactured from feathers using new processing methods. The work therefore advances sustainability and is part of an on-going programme of research to develop novel sustainable materials derived from waste feathers.

5. Conclusions

Developing a circular economy for feathers is a major challenge that requires innovative research. Feather fibres combined with cotton and bi-component fibres have been air laid and hot pressed to produce new materials. The pressing temperature is critical to develop optimum properties. These are achieved at temperatures between 150 and 160°C. The failure mechanism changes with pressing temperature. Fibre pull out occurs at low temperatures due to poor fibre bonding. Fibre fracture and strong bonding occurs under optimum pressing conditions. Brittle fracture occurs at processing temperatures >170°C due to thermal degradation of feather fibres. The feather fibre boards formed have similar density, strength and Young’s modulus to particleboard, organic resin particleboard and flake board. Feather fibres are low-cost if appropriately sourced and the embodied carbon is low in comparison to fibres obtained from cultivated crops. The materials produced have potential to be used in automotive and sustainable packaging applications where they can replace less sustainable alternatives. Further research will investigate the use of biodegradable bi-component fibres as part of on-going research to develop sustainable materials from waste feathers.

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References


[18] R. Arévalo, T. Peijs, Binderless all-cellulose fibreboard from microfibrillated lignocellulosic


Table 1. Properties of the feather fibre boards produced using different hot pressing conditions.

<table>
<thead>
<tr>
<th>Pressing conditions</th>
<th>Temperature °C</th>
<th>Pressure MPa</th>
<th>Time s</th>
<th>Density g.cm⁻³</th>
<th>Porosity %</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tensile strength MPa</td>
</tr>
<tr>
<td>130</td>
<td>6</td>
<td>60</td>
<td>0.66</td>
<td>41.1</td>
<td>8.0</td>
<td>0.50</td>
</tr>
<tr>
<td>140</td>
<td>6</td>
<td>60</td>
<td>0.71</td>
<td>36.6</td>
<td>14.5</td>
<td>1.28</td>
</tr>
<tr>
<td>150</td>
<td>6</td>
<td>60</td>
<td>0.73</td>
<td>34.8</td>
<td>17.3</td>
<td>1.44</td>
</tr>
<tr>
<td>160</td>
<td>6</td>
<td>60</td>
<td>0.74</td>
<td>33.9</td>
<td>16.8</td>
<td>1.52</td>
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<tr>
<td>170</td>
<td>6</td>
<td>60</td>
<td>0.68</td>
<td>39.3</td>
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<tr>
<td>180</td>
<td>6</td>
<td>60</td>
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<td>1.36</td>
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<tr>
<td>190</td>
<td>6</td>
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<td>1.46</td>
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<td>2</td>
<td>60</td>
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<td>37.5</td>
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<td>154</td>
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<tr>
<td>154</td>
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<tr>
<td>154</td>
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<td>60</td>
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<td>1.73</td>
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<tr>
<td>154</td>
<td>10</td>
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<td>0.79</td>
<td>29.5</td>
<td>16.0</td>
<td>1.66</td>
</tr>
</tbody>
</table>

Note: the original air laid non-woven preform had a density of 0.14 g cm⁻³, corresponding to 87.5% porosity.
Fig. 1. The structural features of a typical flight feather.
Fig. 2. Washed disinfected and dried chicken feathers used to form hot pressed feather fibre boards.
Fig. 3. Schematic diagram showing a typical air-laid non-woven manufacturing process.
Fig. 4 a) Air-laid non-woven feather fibre sample with dimensions of 190mm x 55mm x 20mm used in the hot pressing trials. b) The board feather fibre material manufactured by hot-pressing the air laid non-woven sample in a) at 6 MPa and 154 °C for 60 seconds. This hot-pressed feather fibre sample had a tensile strength of 17.7 MPa and a tensile modulus of 1.74 GPa.
Fig. 5. Scanning electron microscope images of the air laid non-woven feather fibres prior to hot pressing (the sample shown in Figure 4a). The bi-component fibres bind the feather and cotton fibres together during the heating stage in the air-laid process to form a low-density network of fibres: a) side surface of sample; b) top surface of sample.
Fig. 6. Effect of pressing temperature, pressure and time on the thickness and density of hot pressed feather fibre boards a) effect of pressing temperature maintaining the pressing pressure at 6 MPa and the pressing time at 60 second; b) effect of pressing pressure keeping the pressing temperature at 154 °C and the pressing time constant at 60 seconds.
Fig. 7. Typical stress-strain data for samples tested in tension that were pressed at 6 MPa for 60 seconds at a range of temperatures between 130 and 190°C.
Fig. 8. Scanning electron microscope images of the air laid non-woven sample after hot pressing at 6 MPa and 154°C for 60 seconds. This is the sample shown in Figure 4b. a) side surface of sample; b) top (pressed) surface of sample.
Fig. 9. Fracture surfaces of samples tested in tension: a) hot-pressed at 130°C and 6 MPa showing extensive fibre pull out during fracture due to relatively weak feather fibre-binder bonding; b) hot-pressed at 150°C and 6 MPa showing improved feather fibre-binder bonding resulting in increased strength and reduced fibre pull-out; c) hot pressed at 190°C and 6 MPa. The feather fibres are thermally
degraded at this temperature and this results in extensive fibre fracture and a more brittle fracture surface.
Fig. 10. Young’s modulus, tensile strength and density of hot pressed air-laid non-woven feather fibre boards compared to a range of other materials (Charts created using CES EduPack 2018, Granta Design Ltd.).