Styrofoam or Paper Cup?

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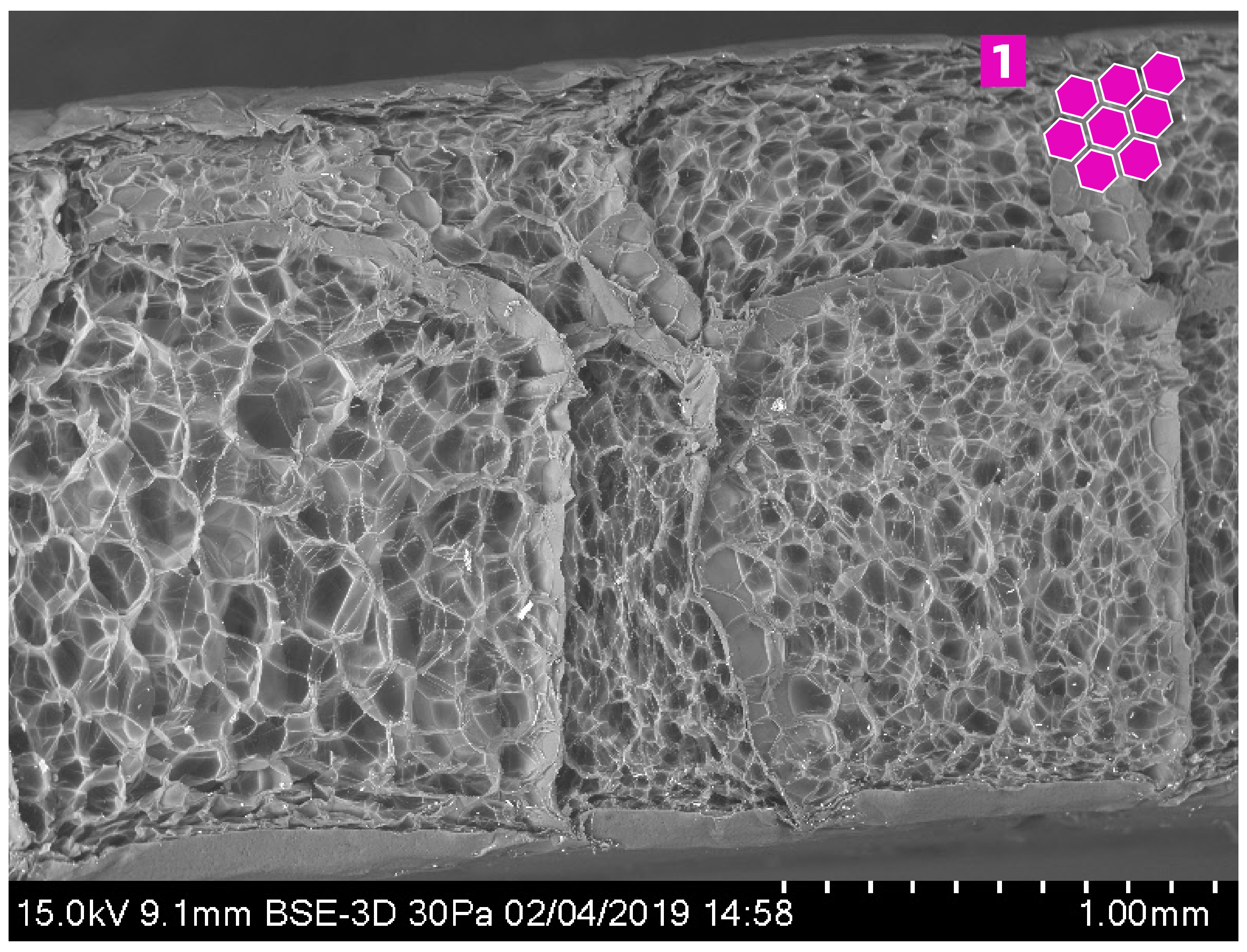

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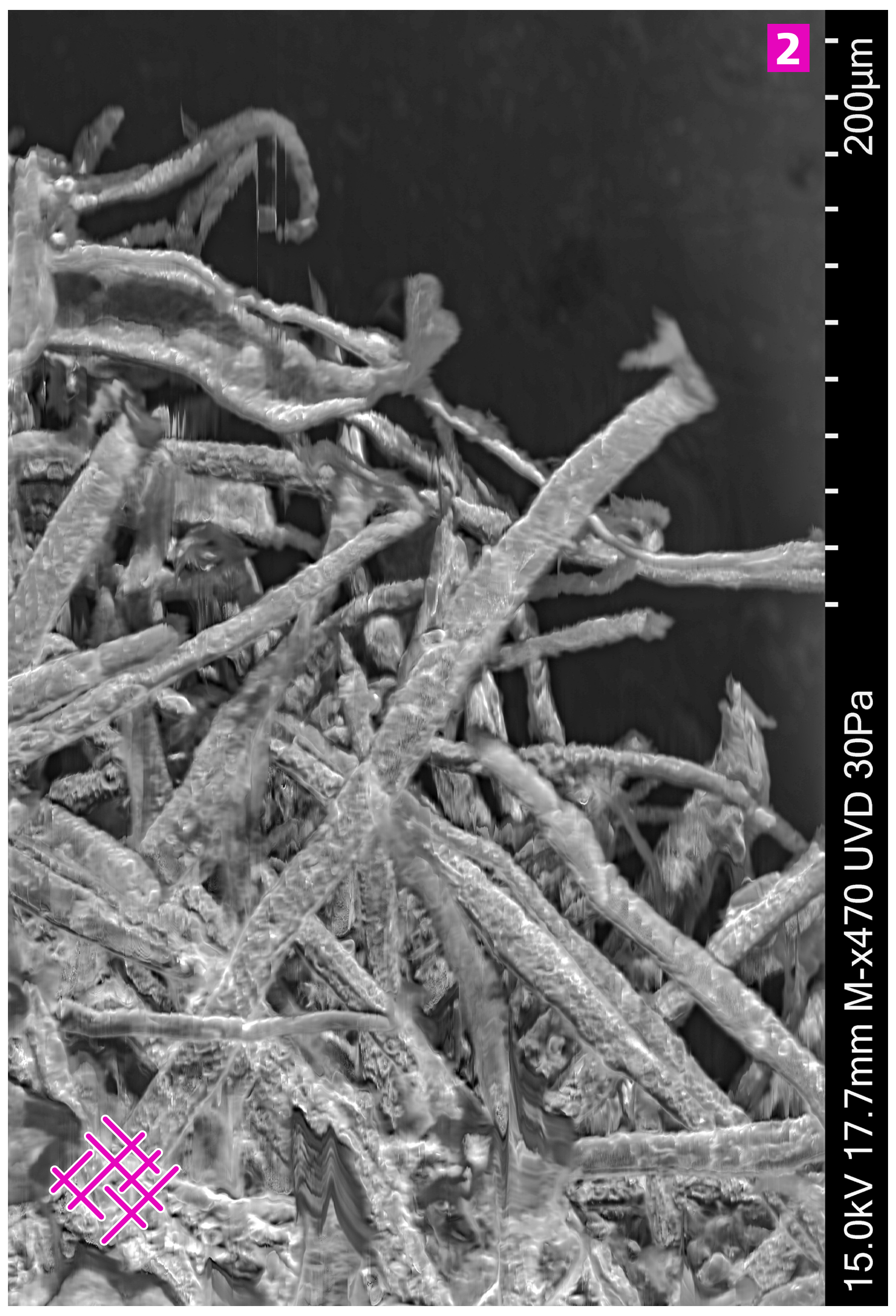

EPS-cups are effective and suprisingly green

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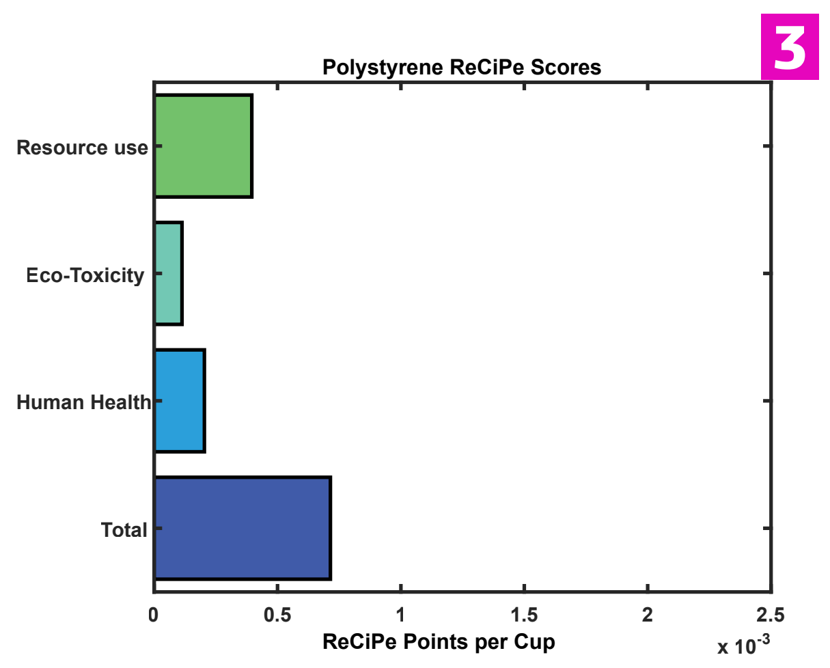

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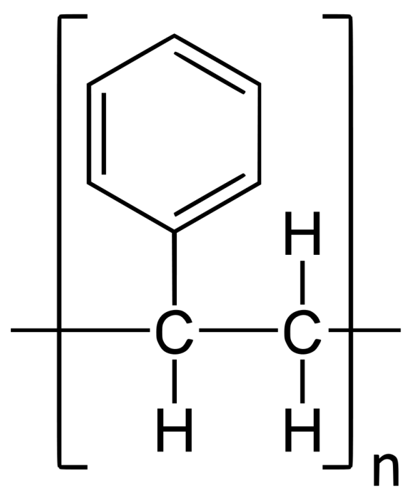

Structure

FTIR analysis of styrofoam cups shows they are made from expanded polystyrene foam (EPS), whose monomer is shown in Figure 4. The EPS is likely atactic[1], which results in an amorphous structure with isotropic properties. The porosity of the foam also has a significant impact on its physical properties.

Properties

The EPS we examined had an extremely low density (0.035 g/cm^3, or about 3.5% polystyrene by volume[3]), which results in very low strength and thus a low Young's modulus. The foam is relatively inert in the temperatures it would see in use (20-100°C), and begins decomposing at higher temperatures.

Environmental Impact

Although EPS is more energy intensive to make per kilogram, the cup only weighs 1.85g, around 20% the weight of the paper cup, meaning it has a lower overall impact. A breakdown of the ReCiPe eco indicator for 1.85g of polystyrene is shown in Figure 3.

Papercups are biodegradable but overbuilt

Structure

FTIR analysis of paper cups shows they are made of cellulose fibers shown in Figure 5; analytical analysis revealed syndiotactic nature. The inner surface of cups is coated with polylactic acid (PLA), which has an atactic structure. This results in an amorphous lattice with isotropic properties.

Properties

The paper we examined is much denser (0.83 g/cm3) than EPS, which results in high tensile strength along the grain, and thus a higher Young's modulus. Surprisingly, we found that paper cups have a structural change in their operating temperature range of 20-60°C, and begins decomposing at above 350°C.

Environmental Impact

Paper as a material has a lower environmental impact than EPS per kg, however, the paper cup we studied weighs as much as five EPS cups, which means the per-cup impact is higher. Figure 6 shows the ReCiPe breakdown for 9.3g.

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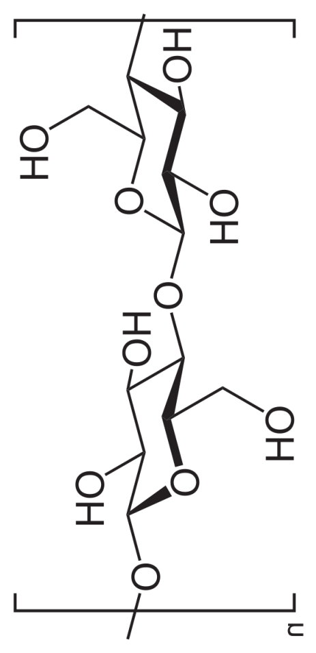

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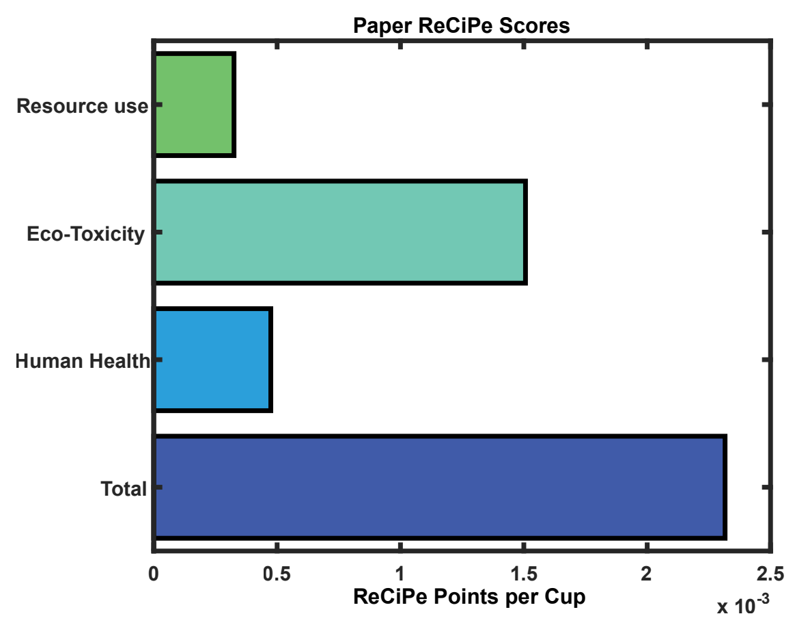

EPS

Paper

Mechanical Testing Data

The EPS was substantially weaker and less stiff, so much so that the two can't be compared easily on the same graph. The stress strain curve for a sample of EPS is shown in Figure 7. The polystyrene lacks a well defined yield point, so we used the 0.2% offset method to find an approximate yield point, which was at 0.21 MPa, much lower than that of paper. Additionally, the Young's modulus (E) is 6.6 MPa, substantially lower than that of the paper. The sample failed with an elongation of about 14%, stretching farther than the paper.

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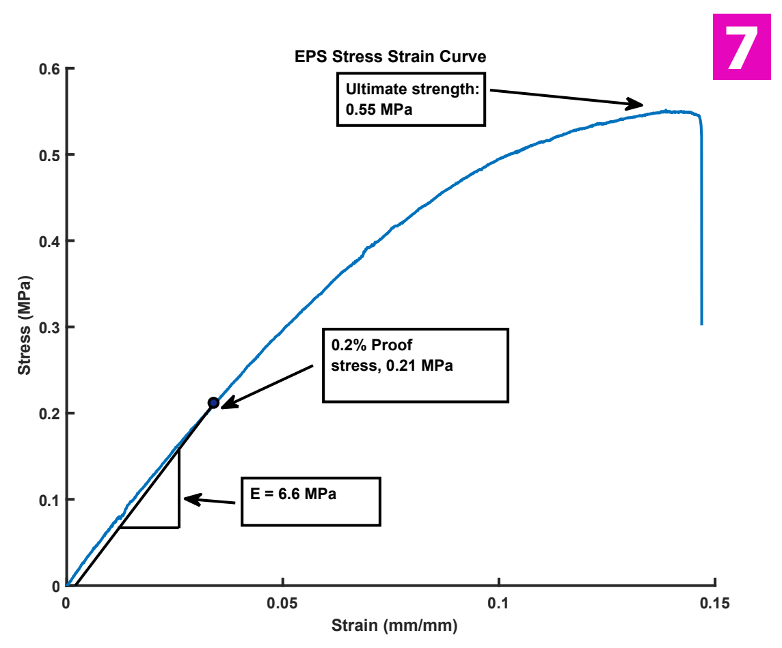

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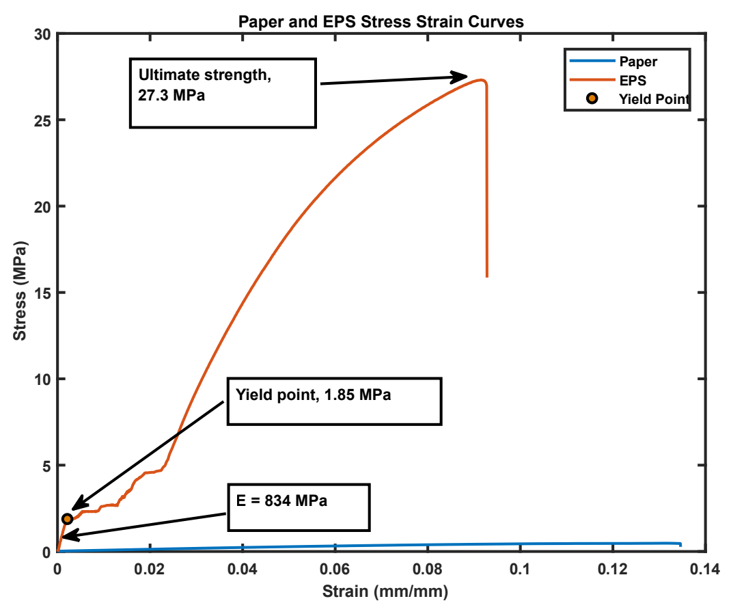

The paper proved to be much stiffer than polystyrene. The stress-strain curve in the Figure 8 shows the behavior of a piece of the paper cup in a tensile test. The short elastic region has a Young's modulus (E) of 834 MPa, much higher than that of EPS. There is a non-uniform region, consistent across multiple trials, which may be due to fibers moving and locking against each other. After that, it takes on a more uniform plastic deformation as the fibers get pulled into alignment and are eventually pulled apart. The yield is clearly defined at 1.85 MPa and the failure at 27.3 MPa. The paper failed at a strain of around 9%, somewhat less than that of EPS.

Scanning Electron Microscope Pictures

The SEM image of the fracture surface of EPS (Figure 9) shows the honeycomb-like structure of EPS. It is a foam within a foam, with small closed cells (shown in Figure 10) (approximately 50μm) contained within much larger cells (more than 500μm) which correspond to the pellets the foam was made from. Figure 9 shows a tendency for the EPS to fail along the boundaries of these larger cells. This structure is the main cause of the relative weakness and very low density of the EPS.

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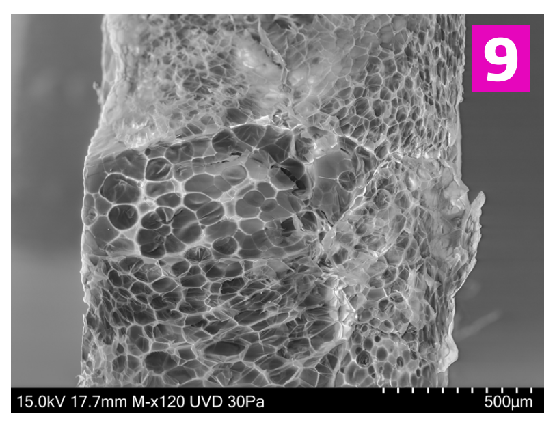

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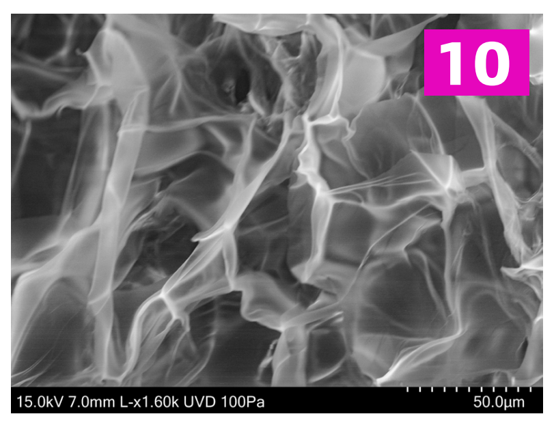

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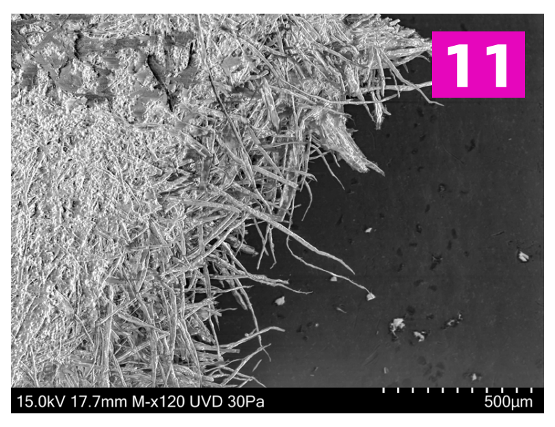

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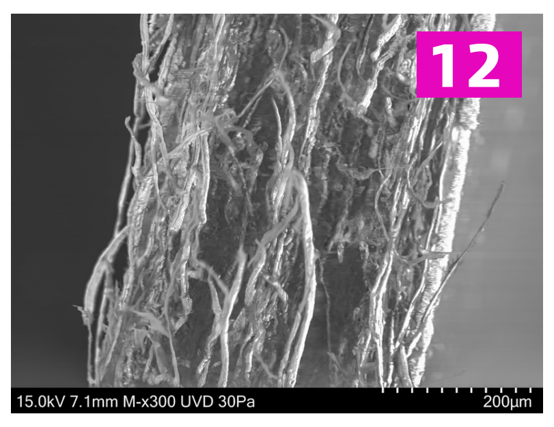

The SEM revealed that paper has fibers randomly oriented in planes parallel to the surface, as seen in the on-edge view (Figure 12). This view also shows the PLA coating on the right, which appears to be around 30μm thick. The first micrograph (Figure 11) hints at some of the paper's mechanical properties, showing the separation and alignment of the fibers around the fracture. The appearance of the ends of the fibers suggests that some broke and some were pulled apart.

Differential Scanning Calorimetry

The EPS cups behaved erratically inside the DSC; the two tests we performed resulted in distinctly different curves. In Figure 13 we analyze the "better" graph, chosen by a somewhat similar pattern to the established DSC curves we saw online.
A small dip is seen at ~105 °C which might correspond to the glass transition temperature of EPS. We could not determine the specific melting point of EPS but our research[7] shows that it should be near ~245 °C, marked by the erratic dip in that region.
At high temperatures, polystyrene decomposes into aromatic hydrocarbon compounds (styrene, ethylbenzene) and aldehydes (acetaldehyde and benzaldehyde)[8].

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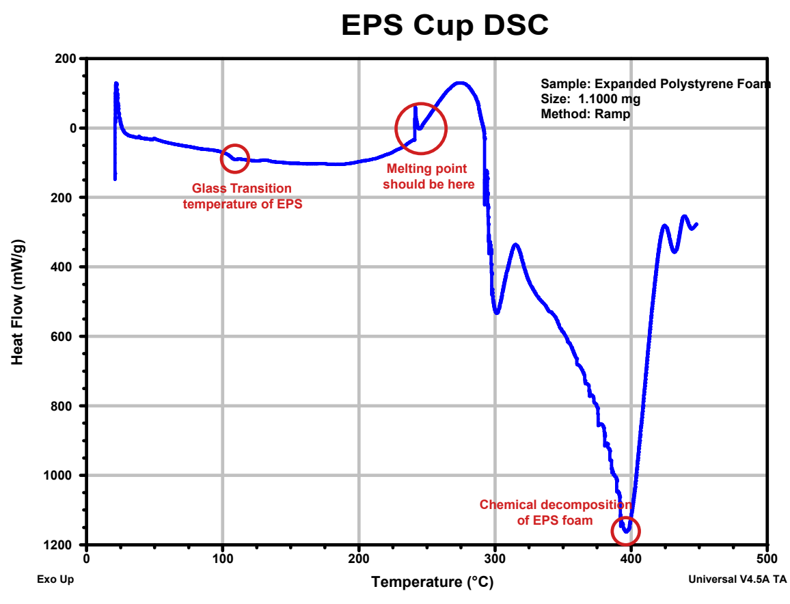

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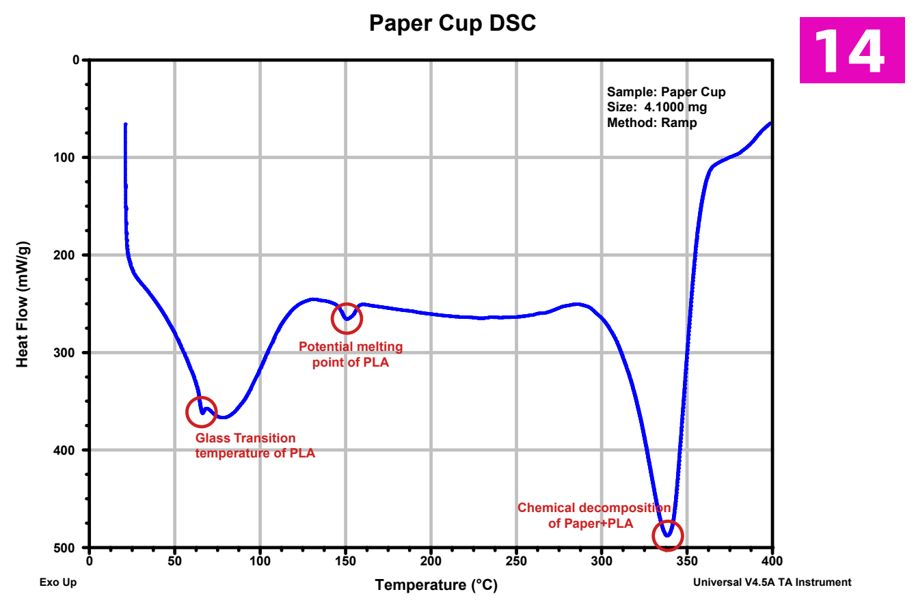

The Heat Flow vs Temperature graph (Figure 14) for paper cups revealed some interesting facts. Our hypothesis about PLA being a part of paper cups was confirmed: we saw a dip at ~150 °C which corresponds to the melting point of PLA. We also observed a relatively smaller dip at ~60 °C, which might reflect the glass transition temperature of PLA.
At higher temperatures, the Paper+PLA decomposes into organic compounds, as seen on the dip near 340 °C. This decomposition results in breakdown of paper, i.e. cellulose, into its monomer glucose, an endothermic reaction that explains the massive dip.

Life Cycle Analysis

Our analysis shows that EPS cups are more environment-friendly than paper cups (unless the paper cups are biodegradable)[4],[5]. Some ReCiPe point totals for polystyrene are shown in Figure 16. Compared to paper cups, manufacturing polystyrene cups requires about 42% less water, 17% less energy, and 22% less petroleum to source materials and ship cups[5]. Additionally, decomposition of EPS cups doesn't produce harmful chemicals likes chlorine dioxide, and doesn't require us to cut down trees. And they cost upto three times less than paper cups.
However, EPS cups take more than a million years to decompose in a landfill. And the low weight-to-volume ratio of polystyrene makes large-scale pickup for recycling impractical[4].

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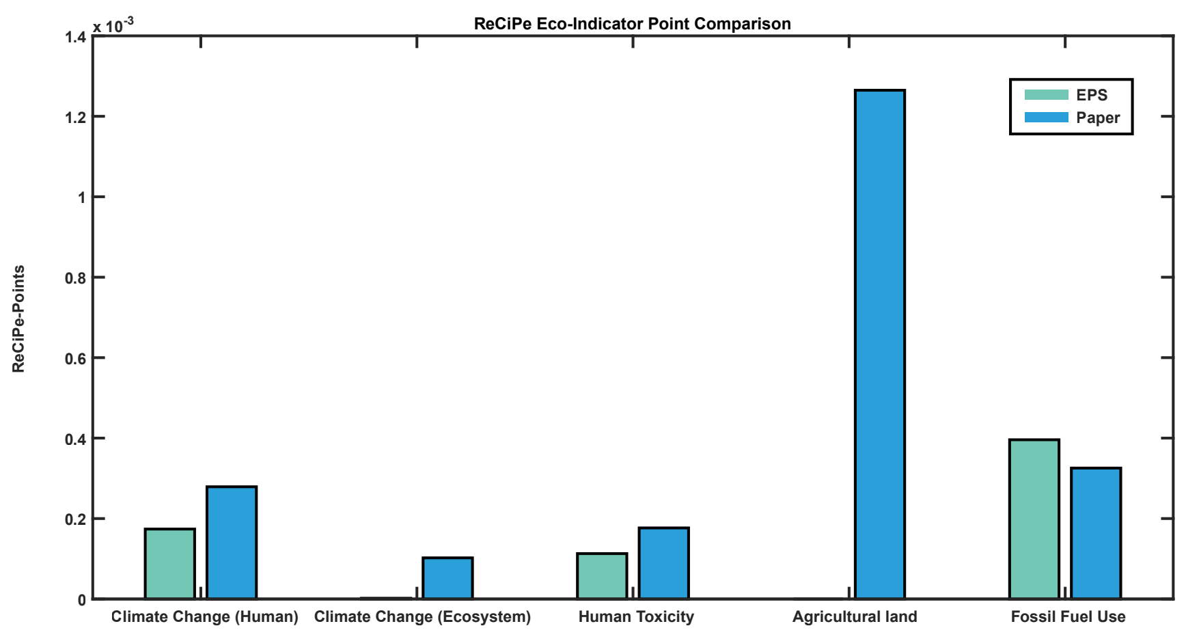

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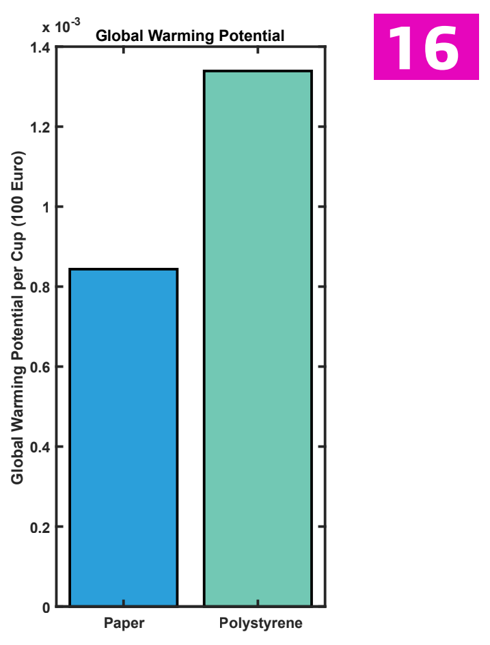

The ReCiPe point totals for several categories of paper are shown in Figure 16. The highest impact from paper in the ReCiPe breakdown comes from the land use for sourcing wood. The human toxicity score is surprising high as well, possibly due to byproducts. Additionally, they require more water and energy to produce. However, the paper cups are biodegradable while the EPS cups essentially never biodegrade[4].
Compared to polystyrene cups, paper cups produce about 28% fewer greenhouse gases, only take 20 years to decompose in a landfill and just a few days in water[5]. Paper cups are also far easier to recycle, and thus are recycled at a much higher rate[4].

Sources

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