

CACTUS-BASED SOLIDS AND BIO-COMPOSITES FOR ENERGY DISSIPATION IN DEFENCE AND BIOMEDICAL APPLICATIONS.

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Abstract

The recyclability, biodegradability and cost effectiveness of natural fibers combined with their high specific mechanical properties and lightweight structure have attracted significant interest. Cactus fibers demonstrate interesting energy dissipation properties under cyclic flexural loading as a fiber composite reinforcement and show a significantly high flexural to axial stiffness ratio of 7:1 and a 4.2-fold increase in the energy dissipation per matrix volume [1]. A multiscale materials characterization methodology [2] for the evaluation of morphological characteristics on a macro, meso, micro and nano scale through various microscopy methods revealed a fractal-like morphology for the cactus fibers. Composite materials were developed using Polypropylene (PP), and cactus fiber powder obtained via ball milling. Under compressive loading a 33% increase in the compressive modulus for PP composites at 0.4% by weight was observed. Morphological data obtained enabled the generation of 3D rendered models and 3D printed analogues of the cactus structure that revealed a high specific bending modulus as compared to their ASTM standard counterparts.

1. Introduction

1.1 Natural & Cactus Fiber Composites

Natural fiber composites have recently been adopted in various industries, including the automotive and aerospace ones because of their low cost, recyclability and biodegradability. Over the past two decades a significant body of research work has been devoted to studying and understanding the potential of various natural fibers to act as reinforcement in composites. Examples of these fibers include flax, hemp and bamboo amongst others [3,4]. It has been demonstrated that natural fibers offer significant advantages in terms of specific properties and can significantly improve the performance of both thermoset and thermoplastic matrices when implemented as a composite reinforcement [4,5]. An interesting natural reinforcement is the fiber obtained from the cathodes of the cacti species of *Opuntia Ficus Indica*. This plant flourishes in various climates, ranging from temperate, subtropical to also cold regions due to its unique crassulacean acid metabolism, leaf tissue and cuticular waxes [6]. Examples of previous composites fabricated with this type of natural fiber are nanocomposites with styrene and butyl acetate, and these materials have shown enhanced matrix bonding capabilities with improved tensile modulus and thermal stability as the concentration of the cactus fibers increased [7]. Composites fabricated with PLA matrix also demonstrated significant improvements in terms of fatigue and toughness characteristics, demonstrating their application potential in various semi-structural scenarios [8]. Previous work carried out in our lab [1] has demonstrated that the use of the unique structure of this type of cacti fibers as a reinforcement for polyester matrices yields materials that exhibit a 4.2 fold increase of the energy dissipation compared to the pure matrix under cyclic load, as well as a significant 7:1 bending to axial stiffness ratio. These are figures of merit that could have significant implications in the fabrication of materials for energy dissipation.

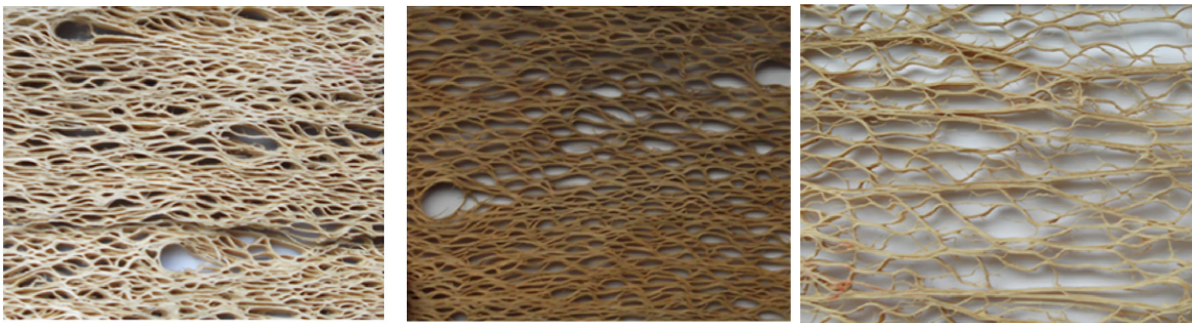


Figure 1. *Opuntia Ficus Indica* Fiber Sheets [1].

The aim of this work is to characterize and understand the structural characteristics of these cactus fibers that enable them to produce these unusual and characteristic properties. Originally it was hypothesized that the properties arise due to the prevalence of a fractal geometry, and a novel methodology was therefore developed [2] to characterize the fractal structure of the cactus fibers. At the same time, thermoplastic composites were also developed using powder-type cactus fibers as inclusions to assess their multiscale reinforcement potential.

1.2 Fractal Geometry

Benoit Mandelbrot, the father and founder of fractal geometry described fractals as ‘beautiful, damn hard, increasingly useful. That’s fractals.’. Fractal geometries were developed to analyze complex non-Euclidean geometries in an effort to correctly estimate the length, area and volume of such unique structures, with coastlines being the most famous example [9,10]. A fractal is a shape that when subdivided into parts each part is a copy of the whole object. This definition implies that fractals are self-similar across scales while being scale invariant, since at all scales the shape of the geometry is

identical. The most common technique used to characterize a fractal geometry is the box counting method, in which a grid of boxes is used to estimate the fractal dimension of the object [9,11]. In the case of natural fractals, it has been proposed to obtain imaging scans at various scales, and then to implement the box counting algorithm to calculate an average estimation of the fractal dimension. This is the approach we have used in the fractal characterization of the cacti fiber described below [12].

1.3 Bio-inspiration & Biomimicry

Nature seems to always have the edge in the design and development of materials and structures that outperform common synthetic materials. Bio-inspiration and biomimicry are therefore approaches used to develop novel materials with unusual and unique characteristics [13,14]. The most famous example of bio-inspiration and biomimicry is nacre [15] that results in strong and tough ceramic materials. There are however other bio-inspired materials with significant potential in this field, like structures originating from living organisms such as fish and fish armor [16,17], as well as cellulose biomimetics [18]. It was hypothesized that the unusual and interesting properties demonstrated by the cactus fibers of the *Opuntia Ficus Indica* are attributed to their unique cellular structure, and that prompted the idea of generating cactus fiber bioinspired solids. Through 3D printing, cactus-based analogues have been generated for further characterization and understanding of the properties of the fiber architecture, as well as to assess the potential of developing new multi-material cactus-based solids.

2. Materials and Methods

2.1 Polypropylene Composite Fabrication

Polypropylene-*graft*-maleic anhydride (PP) was obtained from Sigma Aldrich. The cactus fiber was ball milled with a rotary ball mill using steel balls in a steel vessel to generate the fiber powder at 30 Hz for 15 minutes. The PP pellets were melted in a cylindrical mold at 190°C and cactus-PP composites containing 0.4% wt cactus powder were produced via hand mixing. The disks generated for testing had 40 mm in diameter and 10 mm in thickness.

2.2 Fractal Geometry Analysis

2.2.1 Microscopy

Optical microscopy images were obtained for both the *Opuntia Ficus Indica* (OFI) fiber sheet as well as the processed OFI fiber powders using a Carl Zeiss Microscope at magnifications of: 5x, 10x, 20x, 50x and 100x under Bright Field Light, Dark Field Light and Polarized Light settings. Scanning Electron Microscopy (SEM) images of the fibers with high resolution and at a close magnification were obtained to assess the morphology and fractal order. The fiber fragments were initially silver coated via sputtering to ensure the conductivity of the surfaces for proper imaging.

2.2.2 Fractal Box Counting

The comprehensive description of the algorithm used for the fractal analysis has been previously reported [2]. In brief, all the images obtained via microscopy were binarized via thresholding and the box-counting algorithm was implemented on those images to obtain an estimate of the fractal dimension of the cactus fiber structure.

2.3 Micro CT

A small fragment of the cactus fibers was placed on a Nikon XTH225ST CT Scanner with a 3-micron focal spot size at 35kV. The resulting images were analyzed using the VG Studio MAX software to extract the 3D rendered models of the structures, which were then transferred to MeshLab code to generate the 3D models used for 3D printing of the cactus fiber analogues.

2.4 3D Printing

All samples (cactus & control specimens) were printed on a Raise3D N1 Dual Extruder Printer from the same filament, at 10% infill and all the files were sliced in the opensource software ideaMaker.

2.5 Mechanical Testing

A Shimadzu testing machine fitted with 1kN Load cell was used to carry out the mechanical testing experiments. For compression testing two circular compression platens were used at a rate of 1 mm/min. Three-point bending tests have been carried out at 1 mm/min (ASTM D790 standard).

3. Results & Discussion

3.1 Cactus Fiber Powder Composites

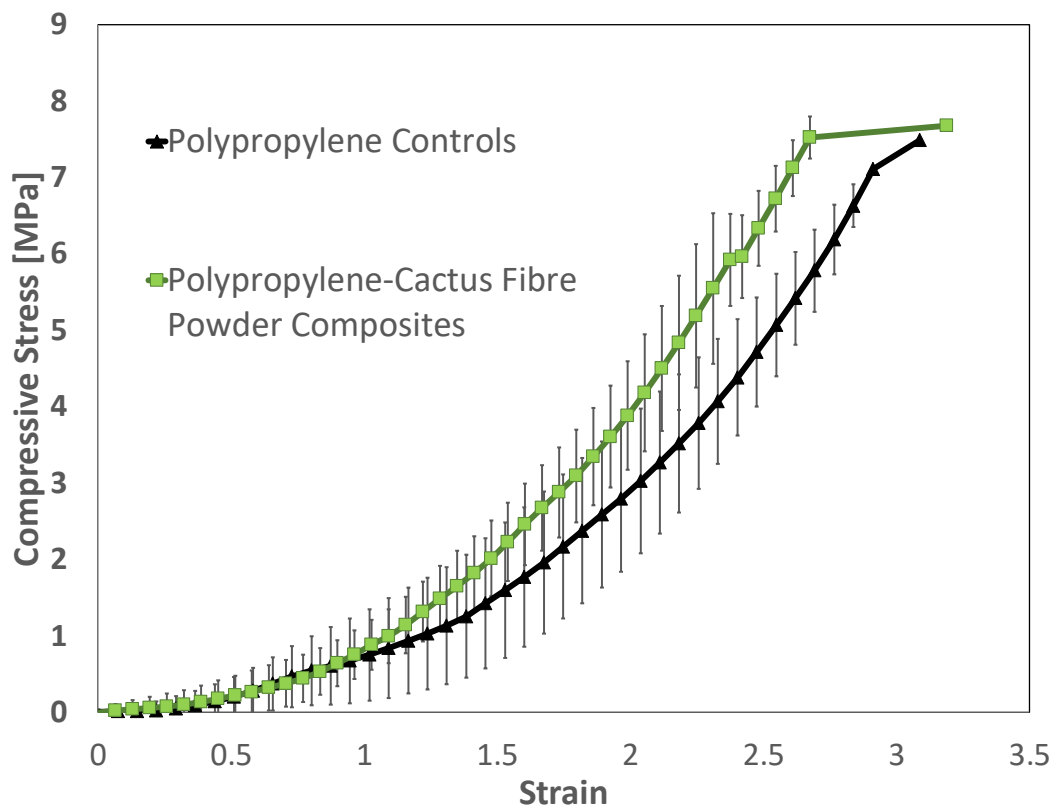


Figure 2. Compression Test to failure of PP specimens and comparison of the Stress–Strain plot between PP controls and PP - cactus fiber composites at 0.4% by weight. The compressive modulus of the PP controls is 2.1 MPa whereas the compressive modules of the cactus-fibre PP Composites is 2.8 MPa.

Via hand mixing only 0.4% by weight of cactus powder with the PP pellets we were able to observe a significant 33% increase in the compressive modulus. This clearly demonstrates the potential of this cactus fiber powder reinforcement in thermoplastic matrices.

3.2 Fractal Geometry Analysis

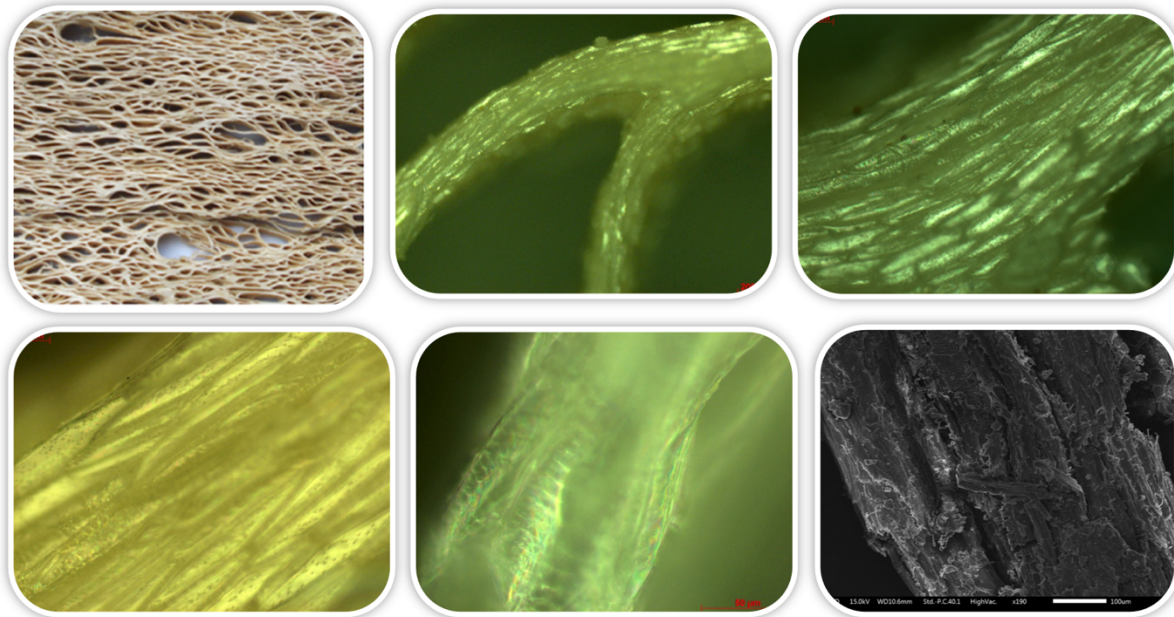


Figure 3. Optical microscopy and SEM images used for morphological evaluation and fractal order estimation.

The optical images obtained at different magnifications and scales were used in order to determine the fractal characteristics of the cactus fiber structure. Through the box counting characterization it was determined that a fractal dimension of 1.8 is maintained across scales, which serves to prove our hypothesis of the fractal geometry. It is also observed in the images themselves that the fibrils do maintain a self-similarity as the magnification increases. There is some validity in using fractal geometry for the morphological analysis of the cactus fibers, and similar approaches could be used for the characterization of other types of natural fibers.

3.3 Bio-inspired 3D Printed analogues

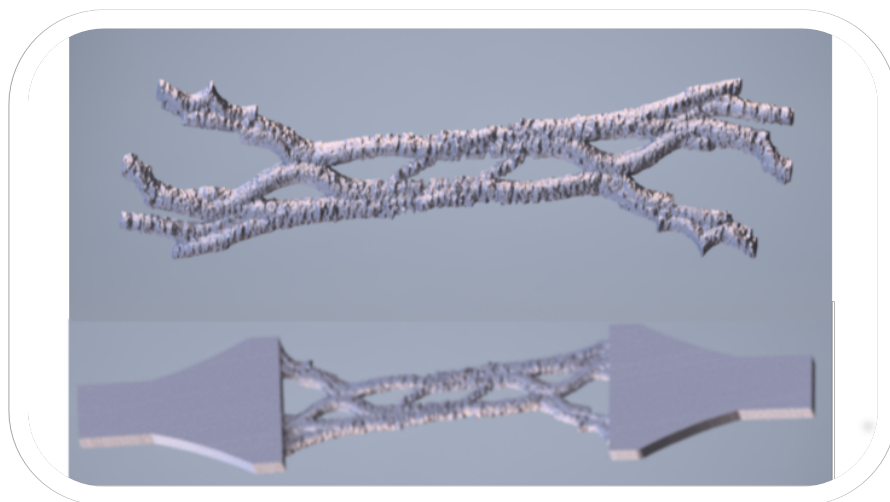


Figure 4. 3D Rendered models of the cactus fibers architecture for mechanical and structural evaluation.

Through the use of Micro-CT imaging we were able to reconstruct one structural unit of the cactus fibers in order to be able to perform future mechanical simulations on this cellular structure and develop a simulation model to replicate the properties observed in nature. The ability to have a 3D model of the structure however prompted the idea of developing 3D printed cactus analogues for experimental testing under bending conditions in order to determine the mechanical properties of the architecture, irrespective of the material composition. Thus, we tested the 3D printed analogues according to the ASTM D790 standard and compared them to the solid beams controls using the same filament material.

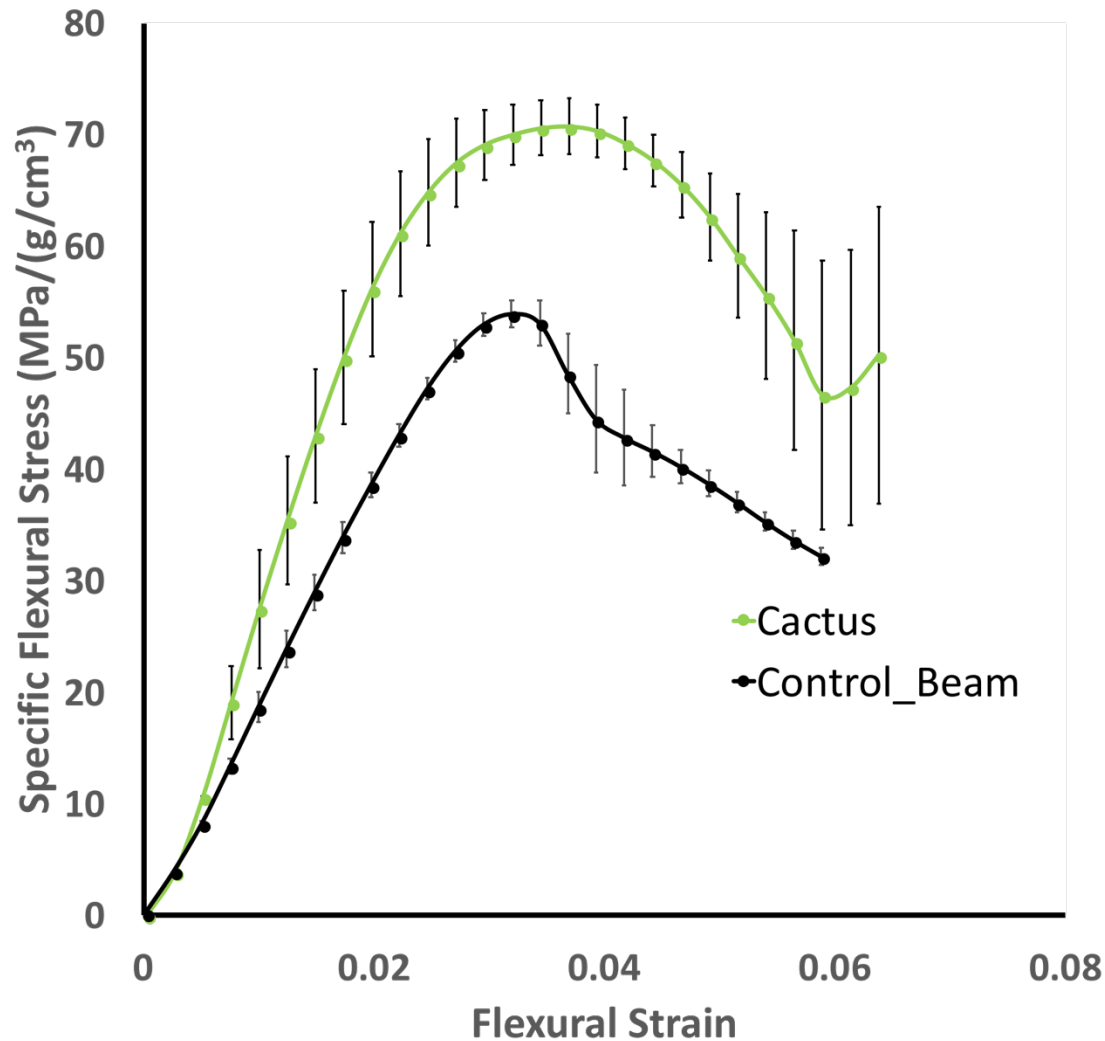


Figure 5. Bending Test to failure of 3D printed PLA specimens and comparison between controls and cactus fiber analogues. The specific Bending modulus of the controls is 1959 MPa/(g/cm³) and the specific bending modulus of the cactus analogues is 2831 MPa/(g/cm³). ASTM D790

It was observed that the bending modulus of the cactus analogues as normalized by density is significantly higher than the controls (1.7 times). The cactus analogues demonstrate high bending properties as it is expected from their behavior in nature [1], and its unique fractal architecture seems a clear indicator of this unusual behavior.

4. Conclusion

Natural fibers have shown significant promise to generate novel lightweight bio-composite materials with significant reinforcement potential in thermoset and thermoplastic matrices. Bio-inspired designs have given rise to new material paradigms with interesting and unusual properties. In this work we present novel cactus fiber powder bio-composites that achieve a 33% increase of the compressive stiffness of the PP matrix with 0.4% by weight, while demonstrating some unique fractal geometry characteristics. Their biomimetic 3D-printed equivalents exhibit a significantly high specific bending modulus. These novel cactus-based solids have significant potential for applications in energy dissipation and mitigation of impact effects.

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