Process–Structure–Property Modelling of Recycled Carbon Fibre Needlepunched Nonwovens for Sustainable Composite Applications

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Abstract

Recycled carbon fibre (rCF) needlepunched nonwovens provide a sustainable pathway for transforming high-performance carbon fibre waste into lightweight and functional composites, including bipolar plates for fuel cells and flow batteries. However, their highly stochastic three-dimensional (3D) fibrous architecture presents significant challenges in predicting their mechanical behaviour, which is essential for the rational design of subsequent composite materials. Here, we present a comprehensive theoretical framework for predicting the elastic modulus of rCF-based needlepunched nonwovens by establishing a process–structure–property relationship. The framework integrates the intrinsic properties of the constituent rCFs, 3D morphological descriptors of the nonwoven obtained using X-ray micro-computed tomography (microCT), and the proportion of fibre length oriented in the thru-thickness direction predicted from needlepunching parameters. By extending the classical "Paper Physics" approach into 3D through orientation averaging, the model accounts for the structural anisotropy inherent to needlepunched nonwovens. The framework was validated using two structurally distinct rCF nonwovens, rCF-NP100 and rCF-NP300, characterized using scanning electron microscopy and X-ray microCT. The predicted elastic moduli showed good agreement with experimental measurements in both the machine and cross-machine directions. The model further captured the contrasting architectures of the two nonwovens, with rCF-NP100 exhibiting greater planarity and preferential fibre alignment and rCF-NP300 displaying a comparatively quasi-random fibre architecture. Importantly, the framework predicts elastic moduli in the tens of megapascals, revealing a three-to-four-order reduction from the constituent carbon fibres to the resulting nonwoven network. By quantitatively linking needlepunching parameters, fibre anisotropy, and constituent properties to macroscopic elastic behaviour, this work provides a mechanistic basis for tailoring rCF needlepunched

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nonwoven architectures. The developed framework also establishes a foundation for predictive modelling and design of rCF-based composites, supporting the sustainable deployment of recycled carbon fibres in advanced structural and functional engineering applications.

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