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Permeability of textile fabrics with spherical inclusions

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ABSTRACT

We investigated the effect of rigid spherical inclusions such as microcapsules and fillers on the permeability of fabrics by using glass beads as model inclusions. Beads with a range of diameters (40–800 μm) and volume fractions (2.5–10%) were sieved between layers of woven E-glass fabric targeting a fiber volume fraction of 40%. Permeability measurements were completed by X-ray microtomography to analyze the samples pore structure and estimate their permeability using Computational Fluid Dynamics simulations. Experimental and numerical estimates were also fitted with a Kozeny model accounting for porosity and specific surface of samples. We identified a threshold curve related to bead diameter and volume fraction below which the permeability follows that of a plain packed textile, and above which a strong departure from this trend is observed, induced by strong distortions of the textile. This behavior was closely correlated to the internal features of the textile.

1. Introduction

Fiber-Reinforced Polymer Composites (FRPCs) are extensively used in aerospace, automotive, sports and other applications due to their high strength, stiffness and light weight. These materials traditionally consist of a fibrous reinforcement and a polymer matrix. In some cases, a second solid phase, generally in the form of granular particles, may be introduced. As an example, reactive or non-reactive binders (or tackifiers) are introduced at the preforming stage to ease the handling of multiple layers of reinforcement and improve the efficiency of processing [1,2]. Particles may also be integrated to the polymer matrix to improve the mechanical, thermal and electrical properties of the resulting composite [3–7]. In addition, for composite functionalization, self-healing capsules are sieved between the layers of reinforcement [8,9], hollow microspheres are introduced to improve the buoyancy or to produce lightweight parts [10,11], and powders are added to tailor capillary effects in porous structures [12].

The effect of the presence of a second solid phase on the resulting mechanical properties of FRPCs has been extensively investigated and reported in the literature [2,3,8–10,13–18]. It is also well known that the presence of additional solid phases in FRPCs alter the manufacturing processes. For instance, in Liquid Composite Molding (LCM) processes, where a fibrous preform is compacted in a mold and resin is injected into the preform, the preform should be fully impregnated before resin gelation [19]. Hence, an accurate estimate of the permeability of a fibrous structure is essential to predict the flow kinetics and mold filling time [20–23]. Introducing particles directly in the flowing fluid has been reported to increase its viscosity but also to lead to progressive clogging of the particles during processing which results in spatially varying permeability [24–26]. Flow is either modeled by coupling the resin flow with particle filtration by a retention function [27–30] or by simulating the solid-liquid interaction at individual particle level [31–33].

In the case of functionalization by introducing a second solid phase between the layers of fabric, both in-plane and out-of-plane permeability are influenced. Shih and Lee [34] studied the tackification of carbon fiber woven fabrics and used PT 500 binder from 3 M with various binder sizes between 25 μm and 1000 μm. They noted that smaller powders led to a better coverage of the fabric surface and showed that holding the preforms at temperatures higher than the melting temperature of the binder resulted in an increase of the in-plane permeability. In agreement with Rohatgi and Lee [35], they attributed the increase of permeability by the shrinkage of fiber tows following the penetration of molten binder, resulting in larger channels outside the fiber tows. Both studies showed that if the system was held at low temperatures, the binder stayed between the fiber tows and caused a decrease of permeability at high binder concentrations. Estrada et al. [36] investigated the binder influence by modeling the flow in unit cells obtained from micrographs of cut specimens. The unit cell based

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model showed indeed a different permeability in the principal directions of the anisotropic fabric, but was limited in its predictions as the selected grid was coarse, and the binder distribution was varying a lot. Recently, Becker and Mitschang [37] investigated the influence of preforming technologies (sewing, binder application, shearing and pre-compaction) on the out-of-plane permeability. They reported that the out-of-plane permeability of a glass fiber woven fabric decreased by addition of both activated and non-activated binders. Results showed a lower permeability with activated binder since they caused a more homogenous reduction of available space while non- activated binders hindered nesting, thus leaving some flow channels available. In another study [38], they measured the out-of-plane permeability of preforms manufactured by dry fiber placement, which exhibit one to two orders of magnitude lower out-of-plane permeability than conventional fabrics and they investigated the potential strategies to enhance the out-of-plane permeability of these preforms. They evaluated the effect of binder particle size by sieving three different particle size ranges: medium sized (125–250 μm), coarse (>250 μm) and mixed (in delivery condition) at the same concentration. Highest permeability was observed with the medium sized particles; coarse binders were expected to result in a higher permeability by impeding nesting, but as a lower number of binder particles was introduced to reach the same concentration, the positive effect of sieving large particles was hence reduced. They also studied the influence of binder concentration by sieving different amounts of mixed binders and reported that a slight increase was observed with increasing binder concentration, but positive effects of preserved flow channels were counteracted by blockage of resin flow at high concentrations.

Contrary to the binders whose effect on permeability and microstructure depends on the degree of melting, particle size and concentration, self-healing capsules are rigid inclusions. Manfredi and Michaud [39] investigated the influence of capsule concentration on in-plane permeability by sieving capsules with a size of 125–250 μm. They reported an increase of permeability by addition of self-healing capsules in comparison to samples with no capsules, but without a correlation between capsule concentration and permeability. In the present work, we propose to address, with the use of a model system, the effect of a rigid dispersed second phase in terms of content and granulometry on both the porous structure topology and permeability to develop general guidelines and constitutive models to optimize flow kinetics, a feature which lacked in the aforementioned studies on composite processing.

We thus introduced spherical glass beads with a range of bead volume fractions and diameters into a woven glass fabric. The 3D porous structure of the reinforcements and the role of the beads were finely characterized using X-ray microtomography. In parallel, the in-plane permeability of the reinforcements was estimated using both in-plane permeability experiments and pore-scale Computational Fluid Dynamics (CFD) simulations using the scanned volumes from microtomography analysis. Guidelines were then provided to assess the effect of inclusion size and inclusion volume fraction on the textile permeability, as a function of the microstructural features of the textile.

2. Materials and methods

2.1. Materials

A 2 × 2 twill weave E-glass fabric (Suter Kunststoffe AG) with a nominal areal weight, $g_f = 390$ g/m^2 and a fiber specific mass, $\rho_f = 2.60$ g/cm^3 was used in this study. The fabric was made of fibers with a diameter of 9 μm and consisted of 6 ends/cm along the warp direction and 6.7 picks/cm along the weft direction with 340 and 272 tex, respectively. Rounded glass beads (Microbeads AG, minimum roundness of 0.90) with specific mass, $\rho_b = 2.45$ g/cm^3 were used as model inclusions. As summarized in Table 1, various bead diameter ranges, d_b, were used (40–70, 70–100, 100–200, 200–300, 300–400, and 400–800 μm), as well as various bead volume fractions, ϕ_b (2.5, 5.0 and 10%). Fig. 1a and b shows two typical micrographs corresponding to the 40–70 and 100–200 μm beads. The bead-diameter distributions in Fig. 1c were calculated from the micrographs using the Matlab function *imfindcircles* (~7600 beads were examined under a microscope for 40–70 μm range, and similarly ~4200 beads for 100–200 μm range).

The samples consisted of $n = 8$ layers of fabrics. During sample preparation, the prescribed mass, m_b, of beads was manually sieved between adjacent layers and the resulting stack was then compacted in a mold of volume V_m and thickness $h = 3$ mm. The volume fractions of fibers ϕ_f, of beads ϕ_b, as well as the porosity ϕ_p of processed samples could thus be estimated as $\phi_f = (ng_f)/(h\rho_f) = 40.0 \pm 0.1\%$, $\phi_b = m_b/(\rho_b V_m)$, and $\phi_p = 1 - \phi_f - \phi_b$ (see Table 1). For the permeability experiments, samples had rectangular in-plane dimensions, *i.e.*, 260 mm along the weft direction (the direction along which the permeability was measured, see below) and 60 mm along the warp direction. For X-ray microtomography analysis (see below), the in-plane shape of samples was circular with a 40 mm diameter.

To characterize the permeability of the samples, a solution of polyethylene glycol (PEG, Sigma Aldrich, 35,000 M) was diluted in distilled water with a concentration of 5.7 mmol l^{-1} to form

Table 1
Experimental, numerical and normalized permeability, and specific surface results.

Sample #	Bead properties		Permeability, K [10^{-11} m^2]		Specific surface, S [10^3 m^{-1}]	Normalized permeability, K^*		
	Bead Diameter, d_b (μm)	Bead Volume Fraction, ϕ_b (%)	Experiment, K_{exp}	Simulation, K_{num}		Experiment, K^*_{exp}	Simulation, K^*_{num}	Semi-analytical, K^*_S
1	0	0	7.92	12.2	6.31	1.00	1.00	1.00
2	40–70	2.5	6.50	11.4	5.98	0.82	0.93	0.98
3		5.0	4.04	5.77	8.05	0.51	0.47	0.47
4		10	1.86	4.29	10.1	0.23	0.35	0.23
5	70–100	5.0	3.71	6.78	7.32	0.47	0.56	0.57
6	100–200	2.5	4.96	9.70	6.20	0.63	0.80	0.91
7		5.0	3.89	7.29	7.01	0.49	0.60	0.62
8		10	3.01	5.40	7.22	0.38	0.44	0.44
9	200–300	5.0	5.65	10.6	6.05	0.71	0.87	0.84
10	300–400	5.0	5.94	10.6	5.67	0.75	0.87	0.95
11	400–800	2.5	6.05	12.2	5.78	0.76	1.00	1.05
12		5.0	6.50	13.3	5.62	0.82	1.09	0.97
13		10	6.84	12.1	5.01	0.86	0.99	0.92