Exploring One-more Dimension of Paper: Properties of 3D-Orieneted Fiber Network

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1 INTRODUCTION

Fiber network is ubiquitous. It is seen not only in industrial materials (paper and nonwoven) but also in biological materials (such as plant cells, animal tissues, etc.). Nature intricately manipulates the network structures, such as density, aggregation, and fiber orientation, to create a variety of functionalities. In this paper, as inspired by nature, we explore 3D fiber network (3DFN) structures. Unlike typical paper where fibers are laid and oriented in-plane, 3DFN has a non-planar fiber orientation that may offer unique properties not seen in conventional papers, e.g. mechanical and mass/heat transport properties.

The objective of this study is to create 3D network from pulp fibers using foam forming process, as recently highlighted by [1]. We have started investigating the properties and characteristics of such network structures.

2 EXPERIMENTAL

Foam (or bubble) as a suspending medium for solid materials is known for many years. It has been introduced to the paper industry since the mid 1960s. Initially the foam forming was utilized in paper industry to improve formation of long and fine fibers at higher consistencies, and then later to enhance bulk and softness characteristics. Efforts also has been made to produce three dimensional network structures, but such attempts largely failed because of the inherent tendency of fibers lying down on the plane [2-3].

In this study a specially prepared foam suspension followed by controlled forming procedure made it possible to retain fibers orienting randomly in 3D space. Refined TMP-rejects with average fiber length of 0.98 mm were used to prepare the networks. Sodium dodecyl sulfate (SDS) with 98.5% purity from Sigma Aldrich was used as foaming agent. Foam generation was done in a home-made mixing container with rotational speed of 500-2000 rpm. A home-made foam applicator was utilized for sheet-making. For comparison, normal handsheets were also prepared by means of Rapid-Köthen sheet making machine. Some of these normal handsheets were produced using water suspension and others were produced from foam suspension.

The 3D structures of foam-formed sheets were evaluated using SEM microscope combined with an image analysis method. The aim was to measure the fiber orientation in the Z-axis direction (sheet thickness direction). To evaluate the fiber orientation we applied the concept developed in [4] with some modifications. The principle of this approach is shown in Figure 1, where the fiber orientation is determined by a pair of angles (θ, ϕ). Consider two fiber cross sections intersected by two parallel planes. The pair angles of fiber are calculated based on in-plane displacement of the cross section $(\sqrt{\delta x^2 + \delta y^2})$ and the distance between two intersecting planes (δz) by

$$\theta = arctan\frac{\sqrt{\delta x^2+\delta y^2}}{\delta z}, \text{ and}$$
$$\phi = arctan\frac{\delta x}{\delta y}.$$

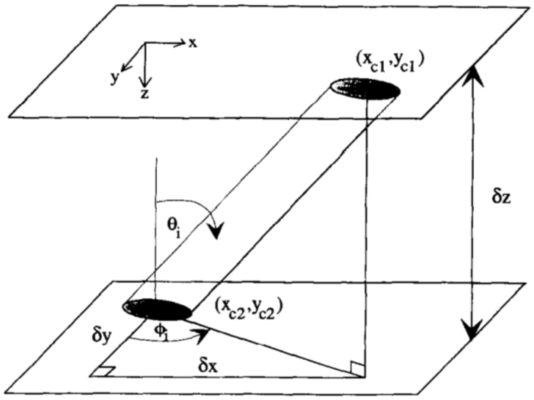

Figure 1. Schematic graph which describes the fiber orientation with pair of angles (θ, ϕ) [4].

The in-plane displacement and the distance between parallel planes were obtained by controlled deep etching, followed by image analyses of SEM cross section. Distribution functions obtained from cross sections always contain a bias associated with the probability of a fiber cut by the cross section plane. We corrected this effect by applying the correction factor obtained in [5]. In-plane and out-of-plane mechanical properties of the foam-formed sheets were determined by an MTS universal testing machine.

3 RESULTS AND DISCUSSION

Table 1 shows the basic physical properties of the 3DFN. The same properties of the normal handsheet samples are also presented. At the same basis weight, there are significant differences in the density and bulk of the 3DFN as compared with normal handsheets. Particularly the density of 3DFN is only 5 kg/m^3, as compared with 400 kg/m^3 (or more) for normal handsheets, and the corresponding bulk is 190 cm^3/g for 3DFN.

Table 1. Physical properties of different samples: RKWF: handsheet of water suspended pulp produced with Rapid-Köthen machine; RKFF: handsheet of foam suspended pulp produced with Rapid-Köthen machine; and 3DFN: 3D fiber network. CoV: Coefficient of Variation

	Thickness (mm)			**Grammage (g/m^2)**			**Density (kg/m^3)**			**Bulk (cm^3/g)**		
Sample	RKWF	RKFF	3DFN	RKWF	RKFF	3DFN	RKWF	RKFF	3DFN	RKWF	RKFF	3DFN
Average	0.127	0.146	11.7	59.56	59.43	59.76	468	409	5	2	2	191
CoV%	3.10	3.16	15.80	1.73	2.41	6.13	2.50	2.69	15.67	2,50	2.69	15.67

Figure 2 shows the tensile stiffness index values for 3DFN and normal handsheet samples. As expected, 3DFN showed extremely low stiffness (or high softness) as compared with the reference sheets. What is interesting is that the relationship between tensile stiffness and density clearly deviates from a linear relation in this very low density range. This suggests changes in the fundamental mechanism in stiffness development, such as 3D fiber orientation effect and percolation effect.

We have also measured a spring-back tendency in ZD-compression of this network. The sample was compressed down to 10% of its initial thickness, retained for 30 seconds, unloaded, and after 10 seconds, the residual deformation was measured. The result showed approximately 75% recovery of the applied deformation.

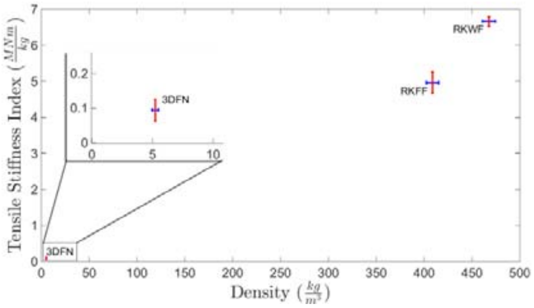

Figure 2. Tensile stiffness index vs. density for 3DFN and normal handsheets.

To further understand the behavior of 3DFN under compression, the deformation process of 3DFN cross sections with 2 mm thickness was observed under the optical microscope (Figure 3). It was evident that there was no obvious failure of fiber-fiber bondings during loading/unloading cycle in compression. Fibers seem to undergo a large elastic bending deformation. This may explain the large spring-back of compression deformation.

The same figure also shows that a substantial number of fibers are oriented in out-of-plane (ZD), unlike typical paper sheets where fibers are layered and oriented preferentially in the in-plane direction.

Figure 4 shows the probability density function of fiber angle in the Z-axis direction (θ). The angle $\theta = 0$ corresponds to ZD orientation of fibers and $\pi/2$ corresponds to the in-plane orientation. It is clear that more fibers are oriented in the out-of-plane direction.

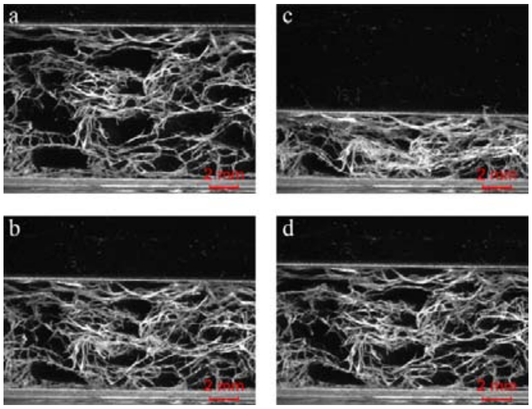

Figure 3. 3DFN of 2 mm slice under compression: (a), (b), (c) loading sequence, and (d) unloading.

In Figure 5, the in-plane (MD)/out-plane (ZD) ratio of tensile strength index of different samples are compared. The ratio for 3DFN drastically decreased; this also confirms the out-of-plane fiber orientation.

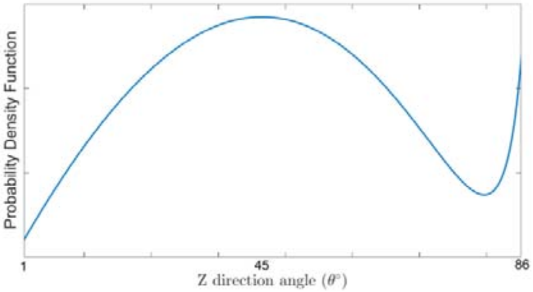

Figure 4. Probability density function of the fiber orientation in 3DFN structure. Probability density function is not normalized.

4 CONCLUSION

The 3DFN has unique structures, which are not seen in normal sheets. Extreme high bulk and 3D fiber orientation may offer special mechanical properties and mass transport properties suited for a class of hygiene products and composite materials. For example, in the area of short-fiber-reinforced composites, dispersing individual fibers uniformly is the most challenging task in order to ensure the reinforcement effect of fibers. Pre-forms made of this 3DFN may be a way to make fiber-reinforced polymer composites without flocculating fibers within the composites. High spring-back property may offer additional comfort of, for example, bed cover and adult hygiene.

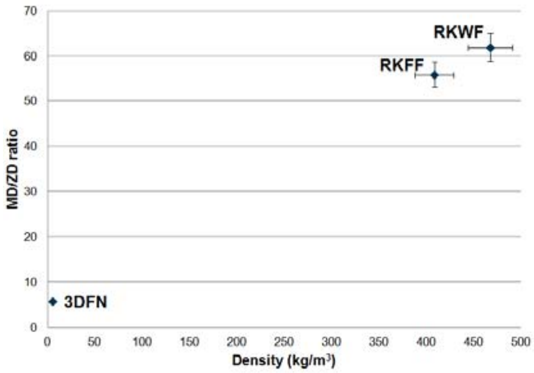

Figure 5. MD/ZD tensile strength index ratio of 3DFN and normal paper samples.

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