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3D-Oriented Fiber Networks Made of Foam Forming

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ABSTRACT

In industrial applications, such as paper and nonwoven, cellulose fibers are used in the form of a network where the fibers are oriented, more or less, in the sheet-plane direction. However, in many biological systems, *fibers* are oriented, instead, in a three-dimensional (3D) space, creating a wide variety of functionalities. In this paper we have created a 3D-oriented fiber network in a laboratory scale, and have tried to identify some unique features of its structure and mechanical properties. The 3D fiber network (3DFN) sheets were prepared by using foam forming and by modifying consolidation and drying procedures. Fiber orientation and tensile/compression behavior have been determined. Resulted sheets were extremely bulky (above 190 cm³/g) and had extremely low stiffness (or high softness), as compared with reference handsheets. Despite of this high bulk, the sheets retained amazingly good structural integrity. We have found that a 3D-oriented fiber network requires much less fiber-fiber contacts to create a connected (“percolated”) network than a two dimensional (2D) oriented network. The compression behavior in the thickness direction was also unique: it is characterized by extreme compressibility, because of its extreme bulk, and a long initial rise of compression load and high strain recovery after compression, because of its fiber-reorientation during compression.

Keywords: 3D fiber network; Foam forming; Percolation; Compression;

1. INTRODUCTION

Fiber network is a ubiquitous structure that is seen both in industrial materials (paper and nonwoven), and also in biological materials (plant cells and animal tissues). Nature intricately manipulates the network structures by varying density, aggregation, and fiber orientation, to create a variety of functionalities. Fiber orientation, for example, can produce completely different structures made from identical fibers, i.e. two-dimensional (2D) and three-dimensional (3D) fiber networks (Fig. 1). Conventionally normal paper sheet is formed as a highly oriented 2D network (layered structure, Fig. 1a). Therefore, the in-plane mechanical and transport properties are very different from those in out-of-plane direction (ZD). In this regard 3D-oriented fiber networks (3DFN), such as shown in Fig. 1c and d, may offer unique properties not seen in conventional paper products.

40   Foam is a dispersed system of gas and liquid (Exerowa and Kruglyakov 1998)
41   which is extensively used as a suspending medium for producing low density
42   structures from polymers, metals, fibrous materials, ceramic and metal powders.
43   Recently, foam forming was studied extensively to develop the understanding of
44   foam-fiber interactions (Al-Qararah et al. 2012; Al-Qararah et al. 2013;
45   Lappalainen and Lehmonen 2012; Lappalainen et al. 2014; Mira et al. 2014) and
46   also to find the potential applications of this technology in papermaking (Kinnunen
47   et al. 2013; Lehmonen et al. 2013; Poranen et al. 2013), as well as, other specialty
48   products, e.g. filters and insulators (Cervin et al. 2013; Jahangiri et al. 2014). Foam
49   was introduced to the paper industry already in the mid-1960s. Initially foam
50   forming was utilized to improve formation and softness of paper sheets made from
51   long and fine fibers at higher consistencies. Efforts also have been made to produce
52   3D-oriented fiber network structures, but such attempts have largely failed because
53   of the inherent tendency of fibers lying down on the plane (Gatward and Radvan
54   1973; Radvan and Gatward 1972). Radvan and Gatward (Radvan and Gatward
55   1972) and Smith and coworkers (Smith et al. 1974), however, indicated that the
56   foam forming method increases the bulk of the sheets. Poranen and coworkers
57   (Poranen et al. 2013) produced foam-formed bulky structures with the density of
58   13 kg/m³. Madani and coworkers (Madani et al. 2014) found that unrestrained
59   drying of foamed fiber suspension resulted in the sheet density as low as 10 kg/m³.

60   An interesting question may be how the 3D-fiber-orientation is related to the
61   bulk of the sheet. It is expected that they are related in some way, but they may not
62   necessarily have a unique (one-to-one) relationship. Fig. 1 illustrates such examples
63   of bulk-orientation relationship. Normal paper sheet has a highly packed structure
64   with in-plane fiber orientation (Fig. 1a). In the case of Fig. 1b, the sheet is “bulked”
65   up in the thickness direction and loses fiber-fiber contacts but still maintaining in-

plane fiber orientation. However, by creating 3D fiber orientation, in some way, one can have bulky (Fig. 1c) or dense but entangled networks (Fig. 1d).

Fig. 1 Different network structures that are made by varying the fiber orientation and/or network connectivity: (a) 2D structure with in-plane fiber orientation (b) 2D bulky structure with fiber orientation very close to planar direction (c) high-bulk 3D fiber network with low network connectivity and (d) dense 3D fiber network

The objectives of this paper are to investigate a method for producing a 3D fiber network by utilizing foam forming and to examine its unique structures and mechanical properties.

2. EXPERIMENTAL

2.1. Preparation of 3D fiber network

Foam forming method was utilized to create 3DFN structures. As a pulp sample, a refined TMP-reject was obtained from a Swedish paper mill. Table 1 summarizes the properties of the pulp sample (Arithmetic averages were used for the later calculations of network characteristics). Sodium Dodecyl Sulfate (SDS) with 98.5% purity from Sigma Aldrich was used as foaming agent. All foam batches were prepared with approximately 65% air content where the percentage of air content was determined from the ratio of the suspension volume and final foam volume. The SDS concentration was set to be 0.4 g per liter of water.

Table 1 Physical properties of the refined TMP-reject fibers utilized in this study

Property	Unit	Quantity	Source
Arithmetic average fiber length	mm	0.98	FiberLab Measurement
Arithmetic average fiber width	μm	29	FiberLab Measurement
Fiber Coarseness	mg/m	0.19	FiberLab Measurement
Fines content	%	15	FiberLab Measurement
Freeness	ml	~ 150	Reported from the mill

The foam was generated from the fiber suspension of 0.5% fiber consistency with SDS by means of a home-made mixer. To create 3D-oriented fiber network in

the foam, vigorous turbulent flow is needed. However, by increasing the air content of the foam to about 65%, the viscosity of the foamed fiber suspension increases significantly (Punton 1975) and thus the turbulence of the mixing flow decreases. To avoid this, a new mixing container was designed to provide sufficient turbulence even in the highly viscous foam. The basic design was motivated by the earlier work (Al-Qararah et al. 2013). However, the baffles were replaced with a large number of needles positioned in circumferential direction all around the container wall (Fig. 2). As compared with conventional baffles of the same container size, the new baffle system provides a larger surface area (up to three times) which contributes to the creation of more turbulent flow with increased friction force. The new baffle system has the flexibility to use different configurations of baffles in an identical mixing container¹.

Fig. 2 (a) A typical baffle system (b) Modified baffle system in which the baffles are converted into a large number of needles positioned all around the container wall

To create foam, a motor with adjustable rotational speed was adopted. The mixing was carried out at rotational speeds between 500 rpm and 2000 rpm. A home-made foam applicator was utilized for sheet-making (Fig.3). By means of a piston, the foam was transferred to a wire travelling at a low speed (~ 0.1 m/s). The water drainage and foam collapse have to be controlled in order to minimize the in-plane fiber orientation. This may be done by controlled slow drying of the foam. In

¹ Detailed information on the mixer design is available from one of the authors (M. Alimadadi) on request.

113 the foam, water drainage takes place under gravity through plateau borders, i.e. the
 114 borders of bubbles' interfaces. This is also where fibers are contained. In plateau
 115 borders mobility of fibers is limited and fibers would maintain their orientations
 116 until the bubbles collapse at the last stage of drying. However, in a normal fiber
 117 suspension in water, water drainage happens by continuous reduction of the
 118 thickness of the water suspension (thickening). This means that fibers are displaced
 119 continuously in the way to conform to this geometry change of the fiber suspension,
 120 i.e. undergo affine deformation. The consequence is, obviously, that fibers are
 121 oriented strongly in the in-plane direction. In this work the oven drying was started
 122 one hour after sheet forming. The drying was done without restraints in a moderate
 123 temperature of 70°C for, at least, three hours. Fig. 3 schematically shows the foam
 124 forming procedure.

125
 126

127
 128 **Fig. 3** Schematic representation of foam forming procedure

129 For comparison, some reference handsheets were made using Rapid-Köthen
 130 sheet-making machine, in which the handsheets were formed by applying vacuum
 131 with a suction rate of approximately 0.1 l/s. The vacuum at drying was

133 approximately 6 kPa. Part of the handsheets was prepared from a water-suspended
134 pulp (RKWF) and the rest of the handsheets were made from a foam-suspended
135 pulp (RKFF). The fiber consistency for the sheets made by Rapid-Köthen was
136 0.3%. The target grammage for all 3DFN and handsheet samples was 60 g/m².

137 **2.2. Fiber orientation measurement**

138 The 3DFN was then subjected to fiber orientation measurements. Among
139 different image analysis techniques for the evaluation of 2D and 3D fibers
140 orientations of fiber-based composites, (Clarke et al. 1995; Eberhardt and Clarke
141 2001; Sander and Barocas 2009; Tsarouchas and Markaki 2011), we used a simple
142 semi-automated method based on the literature (Clarke et al. 1995). This method
143 is suited to the fiber orientation measurements of the very low density fibrous
144 structures, where fiber-fiber overlapping is scarce and individual fibers are easily
145 identified.

146 The spatial fiber orientation is determined by a pair of angles (θ, φ) , which is
147 defined in (Clarke et al. 1995). Consider a fiber intersecting two parallel planes
148 where a fiber cross section is created with each plane (Fig. 4). The pair angles of
149 fiber are calculated based on in-plane displacement of the fiber cross section,
150 $\sqrt{\delta x^2 + \delta y^2}$, and the distance between two intersecting planes, δz , by $\theta =$
151 $\arctan \frac{\sqrt{\delta x^2 + \delta y^2}}{\delta z}$, and $\varphi = \arctan \frac{\delta x}{\delta y}$.

Fig. 4 Schematic representation of the fiber orientation with pair of angles (θ, φ) , redrawn after (Clarke et al. 1995)

A resin-mounted sample of 3DFN was carefully machined into a cube and polished at one desired face which subsequently etched chemically². The etchant dissolves the *resin* and exposes fibers on the surface of the sample (Fig. 5a). The depth of etching, was measured by using an optical stereo microscope. The depth of etching on the surface of sample corresponds to the distance between parallel planes (δz) in Fig. 4. Image analysis of the SEM micrographs was used to evaluate the in-plane displacement ($\sqrt{\delta x^2 + \delta y^2}$) of the fibers' cross-sections. The apparent length of over 650 exposed fibers were measured on a single sample. All the data were processed with a MATLAB code developed for this purpose. In this method there is always a bias associated with the probability of a fiber cut by the cross section plane, which is dependent on the fiber angle. We corrected this effect by applying the correction factor obtained in (Zhu et al. 1997). In our treatment we neglected the edge effect at the angles near 90 degrees. This fiber orientation measurement is based on the assumption that the SEM images are not distorted (i.e. no distortion in the periphery of the images), which is a reasonable assumption for the operating magnification of this work. Another assumption is that the etching

² The utilized etchant in this work was a mixture of methanol, potassium hydroxide and propylene oxide which, in essence, removes the resin and leaves the fibers intact.

172 process erodes the sample surface uniformly to a certain (measureable) depth. Fig.
173 5 shows a typical SEM cross section of 3DFN together with the corresponding
174 processed image.

175

176

(a)

177

(b)

178 **Fig. 5** (a) SEM micrograph of the etched sample surface (b) Corresponding processed image for
179 measuring the apparent fiber length

180

181 **2.3. Mechanical properties**

182 Mechanical properties of handsheets and the 3DFN was measured by using MTS
183 4/ML testing device. In-plane tensile properties were measured for all samples.
184 Moreover, the compression response of the 3DFN in the thickness direction was
185 determined. Handsheets were prepared and tested according to the standard ISO
186 1924-3. The 3DFN was tested according to the standard ISO 12625-1, but due to

187 the soft and very thick structure of the 3DFN, we constructed new grips for tensile
188 measurements.

189 **2.4. Microscopic study of structure deformation**

190 The deformation of the 3DFN under compression was studied by means of
191 microscopic observation. To monitor the deformation behavior of individual fibers
192 under compression, thin cross-sectional slices of two-millimeter-thick were cut
193 from the structure (Fig. 6). To prevent any damages due to the cutting tool, laser
194 cut was used. The cutting speed and applied energy was controlled to avoid the
195 burning of the structure. (However, we found some tiny individual fibers were burnt
196 due to overheating.) A transparent holder was equipped with a pressing bar in order
197 to microscopically study the deformation of the fibers in the network thickness
198 direction. This method of observation also gave a qualitative sense of fiber
199 orientation.

200

201

202 **Fig. 6** The 3DFN and the imaginary two-millimeter-thick slice

203

204 **3. RESULTS AND DISCUSSIONS**

205 **3.1. Structures of 3DFN**

206

207 Fig. 7 shows the cross section of the 3DFN. The most obvious feature of this
208 image is the randomness of fiber orientation, i.e. there is no typical layered structure
209 of fibers, such as seen in paper sheets (however, there is a skin layer in the bottom
210 where fibers are oriented in the in-plane direction. This layer seems to have created

211 during the transfer stage of the foam suspension onto the forming wire. We will
 212 elaborate this point in the subsequent paper.). The presence of some large pores in
 213 the structure may represent the incidence of giant foam bubbles in the foam
 214 suspension.

215
 216 **Fig. 7** Cross section of 3DFN in which the randomness of fiber orientation is clearly seen
 217

218 Table 2 shows the bulk values for the sheets made from different methods, i.e.
 219 foam forming and Rapid-Köthen sheet-making. We can clearly see that 3DFN has
 220 distinctively high bulk, close to 100 times higher than the reference handsheets.
 221 This high bulk may be attributed to foam forming and also pressing/drying methods.
 222 However, considering the fact that the reference sheets, either foam-formed or
 223 water-formed, have much lower bulk, it is the pressing and drying processes that
 224 created the large difference in bulk. Smith and coworkers (Smith et al. 1974) also
 225 indicated that the free-drying of the foam-formed handsheets can make the bulk
 226 more than two times higher than those obtained from wet-pressed and press-dried
 227 foam-formed handsheets.

228 **Table 2** Bulk values for RKWF, RKFF and 3DFN sheets; CoV: Coefficient of Variation
 229

	Bulk (cm ³ /g)		
Sample	RKWF	RKFF	3DFN
Average	2.13	2.44	191.20
CoV%	2.50	2.69	15.67

230

231

232 Madani and coworkers (Madani et al. 2014) made foam-formed sheets, and
233 reported about a half of the bulk value of the 3DFN. They found a layered-structure
234 with fibers oriented in the in-plane direction. This in-plane orientation was probably
235 caused by vacuum forming of fiber-foam suspension.

236 Fig. 8 shows the distribution of fiber angles, θ : the angle $\theta = 0$ corresponds to
237 the ZD orientation, and $\theta = 90$ corresponds to the in-plane orientation of the fibers.
238 For the purpose of comparison, the fiber orientation of a commercial nonwoven
239 sample (the core layer of a hygiene pad) was also measured. In the nonwoven
240 sample there is a clear tendency of the fibers oriented in the in-plane direction. It is
241 known that, regardless of air-laid and wet-laid processes, the normal fiber
242 deposition processes creates strong in-plane orientation, and nonwovens and paper
243 are good such examples. However, in the 3DFN, the peak angles are distributed in
244 a broad range of orientation between 0 and 90 degrees, confirming the very high
245 out-of-plane fiber orientation of 3DFN.

246

Fig. 8 Normalized histogram showing the frequency of fiber angles in (a) 3DFN and (b) commercial hygiene pad

3.2. Tensile stiffness and strength

Fig. 9a shows the tensile stiffness index (TSI) values for the 3DFN and the two handsheet samples. The 3DFN shows extremely low stiffness (or high softness) as compared with the reference handsheets. TSI has been known to be linearly related to the density for normal paper sheets (e.g. see (Fellers 2009)). The density value at zero TSI, which is obtained by extrapolation of the linear relation, is called “percolation threshold density”, below which the network is presumed to lose stiffness. In Fig. 9a the TSI-density relation for TMP furnishes is also plotted based on the literature (Fellers 2009). The percolation density is, for example, $\sim 150 \text{ kg/m}^3$ for the literature data, and $\sim 240 \text{ kg/m}^3$ for the pulp used in this work. It is interesting that 3DFN has a much lower density (5 kg/m^3) than the percolation densities of paper sheets, but it still retains significant finite stiffness.

Percolation of fiber networks has been the subject of intense investigation in statistical physics. In this case, percolation refers to *geometrical* percolation, i.e. the point at which the network is geometrically connected by the fibers. The critical number of contacts per fiber at percolation in 2D randomly-oriented networks was obtained by Pike and Seager by Monte Carlo method, and they gave 3.635 with the condition of $l_f \gg D_f$, where l_f and D_f are the fiber length and fiber diameter, respectively (Pike and Seager 1974). In the case of the corresponding randomly-

oriented 3D fiber networks, it was 1.49 (Balberg et al. 1984). It is interesting to note that the 3D fiber network requires much less fiber contacts per fiber to form a connected (percolated) structure. This also explains why the 3DFN still retains finite stiffness even at a very low density.

Komori and Makishima (Komori and Makishima 1977) calculated the average number of contacts per fiber in a general fiber network which is given by:

$$\bar{n} = \frac{2D_f N l_f^2}{V} I \quad (\text{Eq. 1})$$

where l_f and D_f are the fiber length and fiber diameter, respectively, I is the parameter that is dependent on the degree of fiber orientation which is $2/\pi$ for a random 2D network and $\pi/4$ for a random 3D network, and N is the total number of fibers in the volume V . Based on Eq. 1 and fiber characteristics measured in this work (Table 1), we obtained the estimates of $\bar{n}_{2D} = 0.95$ and $\bar{n}_{3D} = 1.17$ at a network density of 5 kg/m^3 , i.e. the density of 3DFN. First it is interesting to observe that the 3D fiber orientation creates more contacts per fiber than the 2D orientation case at the *same apparent density*. This also gives, again, an advantage to the 3D fiber network in terms of the integrity of the network in a low density range. It should be noted, however, that these estimates are clearly lower than the estimates from the Monte Carlo simulations. This may be understandable because the analysis by Komori and Makishita didn't explicitly include the finite length effect of fiber, and our experimental evaluation of the fiber diameter may yield a lower estimate than the reality since some fibers formed bundles in the suspensions.

In Fig. 9b, the ratio of tensile strength index of in-plane direction and thickness direction (MD/ZD ratio) of the 3DFN is plotted together with the results for the other handsheets. The MD/ZD ratio of tensile strength is a measure of mechanical anisotropy, and in the case of a 3D isotropic sheet, the ratio takes unity. The very low ratio (approximately 5) of the 3DFN, as compared with those for handsheets,

295 i.e. about 60 for RKFF and RKWF, is a clear indication of more fiber orientation in
 296 the out-of-plane direction.

298 **Fig. 9** Comparison of mechanical properties between 3DFN and normal handsheets (a) Tensile
 299 stiffness index. The Ref. TMP curve represents TMP furnish from the literature (Fellers 2009) and
 300 (b) MD/ZD tensile strength index ratio
 301

302 3.3. ZD-compression response

303 The deformation characteristics of the 3DFN were observed under optical
 304 microscope by using the conditions described earlier. As seen in Fig. 10, a
 305 considerable volume (in 2D images it is an area) of the structure is occupied by
 306 giant pores. Successive images of the compression sequences showed that the
 307 deformation starts mainly by bending of the fibers that surround the giant pores.
 308 The bending of the fibers with low θ , i.e. the fibers oriented close to the thickness
 309 direction, is evident. The fibers which are oriented horizontally or very close to the
 310 horizontal orientation experienced almost no bending but were only displaced to
 311 new positions. Within the resolution of optical microscope, no obvious slippage and
 312 fracture were detected in fiber-fiber bonds.

Fig. 10 2-mm-thick slice of the 3DFN under compression: (a), (b), (c) loading sequences, and (d) unloading

The behavior of the 3DFN under cyclic compression loads is shown in Fig. 11. A pre-load of 0.1 N was applied to the samples. The samples were compressed to 80% of their thickness and then unloaded (to 0.1 N) and this cycle was repeated 5 times. 20 samples were tested for two successive days, except one that was tested for three successive days (with a 24-hour rest time between each two tests). In Fig. 11a we plotted the compression curve of as received sample (i.e. never compressed before), exhibiting the typical three deformation types, i.e. nonlinear elastic recovery, time-dependent recovery (indicated by arrows), and irreversible deformation. When comparing the cyclic-loading behavior of the same sample on different days (Fig. 11b), we found that after the first day, the second- and third-day responses became similar, i.e. the structures are stabilized after the first compression loading cycles.

(a)

(b)

Fig. 11 Cyclic compression response of a typical sample of 3DFN: (a) Compression test arrows represent schematically the extent of deformation recovery few minutes after removing the load (right arrow – red in color version) and after 24 hours (left arrow – green in color version) (b) Compression test on the same sample in three successive days

Compression behavior of fiber networks, particularly textile fiber assemblies, have been investigated for many years both theoretically and experimentally. As reviewed by van Wyk (van Wyk 1946), M. and J. Eggert pioneered an analytical formulation of compression behavior, followed by van Wyk, Carnaby and Pan (Carnaby and Pan 1989), Komori and Itoh (Komori and Itoh 1991) and Komori and coworkers (Komori et al. 1992) who developed a series of models that take into account fiber bending, fiber-fiber contacts by compression and fiber re-orientation during compression. Perhaps the most general form of the relationship between pressure and compression deformation is the one which was originally given by Eggert but later re-examined by Komori and coworkers and Matsuo (Komori et al. 1992):

$$P - P_I = C[(V_I/V)^g - 1] \quad (\text{Eq. 2})$$

where V is the volume of fiber mass under applied pressure P ; V_I is an initial volume under a small initial pressure P_I ; C and g are the semi-empirical material parameters, but Komori and coworkers obtained an explicit expression for C . The parameter C depends on fiber diameter, fiber elastic modulus, network density (total fiber length per unit volume), and initial fiber orientation before compression. The parameter g represents a structural deformation of the network, such as due to fiber contacts and fiber re-orientation (Komori et al. 1992). Table 3 shows the estimates of C and g obtained for two of the 3DFN samples, together with Matsuo's data on the piled card webs made of polymeric fibers. First, the parameter C of the 3DFN shows distinctively high values as compared with those of other samples. Among the fiber properties affecting C , Komori suggested the initial fiber orientation that makes the most significant difference in the compression behavior (Komori et al. 1992). In fact this is very likely the case for the 3DFN. The parameter g was also different between the 3DFN and other samples, suggesting the difference in the deformation mechanisms. It is likely that, as the 3DFN is a bonded fiber network, fiber re-orientation and new fiber contacts during compression take place more slowly than the counterpart. Lower g values for the 3DFN means slower (relative) pressure rises at a given deformation.

Table 3 Coefficient values for the 3DFN samples and polymeric piled card webs from Matsuo's work

Network	Sample	C (Pa)	g	R^2
Random 3D fiber network	3DFN-1	1813	1.12	0.9964
	3DFN-2	606	1.23	0.9945
Piled card web	Polypropylene	67	1.87	NA
	Polyester	99	1.68	NA

Table 4 shows a general comparison of compression properties for various fibrous materials including 3DFN. The data of other materials were obtained from

various literature sources. In Table 4, the porosity is defined as $\Phi = 100(1 - \rho_b/\rho_f)$, where ρ_b is the bulk density of the network and ρ_f is the density of the constituent fibers, for which the values were obtained from the literature. (For 3DFN, $\rho_b = 5 \text{ kg/m}^3$ and we assumed $\rho_f = 1000 \text{ kg/m}^3$.) The compressibility is the percentage of deformation at the pressure given in the table. The recovery is the percentage of recovered deformation, and the pressure is the maximum pressure applied.

Table 4 Summary of the response of different fiber networks under compression

Material	Thickness (mm)	Grammage (g/m ²)	Porosity (%)	Compressibility (%)	Recovery (%)	Pressure (kPa)	Ref.
Cotton (Knitted)	1.163	387	79	30	13	256	(Stankovic 2008)
Acrylic (Knitted)	1.181	376	73	33	17		
Viscose (Knitted)	1.048	367	77	23	9		
Hemp (Knitted)	0.916	360	73	20	7		
Paper	0.165	110	33	40	17	15000	(Rättö 2005)
Paper	1.42	1050	26	28	11		
Paper	0.184	60	67	60 ^a	8	9000	(Ting et al. 2000)
Paper	0.081	60	26	30 ^b	10		
3DFN	11.7	60	99.5	80	25	8	-

^{a, b} The maximum compressibility is obtained from a slightly different loading history (Ting et al. 2000) as compared with other samples.

We can easily see the distinct features of 3DFN: the extremely high porosity, 99.5 %, and extremely high compressibility 80% at only an 8 kPa pressure. In addition the recoverable deformation is also highest, i.e. a soft and springy network.

4. CONCLUSION

Foam forming was used to create the networks of 3D fiber orientation (3DFN). The resulted sheets have extreme high bulk of more than 190 cm³/g, or extreme low density of 5 kg/m³. This super high bulk or super low density of the 3DFN is a result

391 of ZD fiber orientation (out-of-plane orientation) in the fiber network. The key to
392 produce the 3D fiber orientation is, first, to create the 3D fiber orientation in the
393 foam suspension, and, secondly, to maintain the orientation during forming,
394 pressing, and drying stages.

395 The unique properties of 3DFN are that it is extremely porous and soft, but still
396 retains good structural integrity. The latter is due to the 3D-oriented fiber network
397 structure, in which percolation takes place at a much lower density than in the 2D
398 fiber networks. The nonlinear compression stress-strain relationships are also
399 unique as compared with other fibrous systems, such as nonwoven and paper.

400 Therefore, 3DFN may be regarded as a potential material platform for polymer-
401 impregnated composites, acquisition layers of absorbent products, and thermal
402 insulators, for example. The most obvious challenge is an industrially applicable
403 manufacturing process, which is the subject of our subsequent studies.

404

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