Int'l Journal of Advances in Agricultural & Environmental Engg. (IJAAEE) Vol. 1, Issue 1(2014) ISSN 2349-1523 EISSN 2349-1531

Structural Characterizations and Models of Fibrous Materials: 1D and 2D Studies

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Abstract--- The mechanical, optical and flow properties of porous materials depend on their structure at different scales. The fabrication process influences the porous structure in the case of industrial products, modifying the bulk and/or the surface of the materials. The first results illustrate the influence of the mean fiber orientation of the bulk on physical properties. The surface is then characterized either in 2D or in 1D. A two parameter model is introduced to synthetize the complex structure at the micro-level to understand the physical properties at the macro-scale of porous materials. An example, concerning paper, illustrates the influence of surface modification (calendaring) on physical properties such as gloss or flow properties which are important for different applications such as printed electronic or microfluidic devices.

Keywords---Anisotropy, fibrous materials, model, physical properties, structure, tomography, topography.

I. INTRODUCTION

THE structure of materials represents a natural link between the industrial elaboration of materials and their physical properties. The industrial process influences both the bulk and the surface of the materials. The characterization of the structure may be carried out either in three dimensions or considering only the surface, depending on the investigated properties. The description of the materials is done classically introducing numerous parameters: more than twenty for the surface characterization. A compromise has to be done between the number of parameters and their efficiency to discriminate different materials. We propose first to illustrate the influence of fiber orientation on physical properties. The fiber orientation is controlled industrially modifying the difference of velocities between the jets of the fiber suspension and the wire. Then, we will focalize on the characterization of surface and introduce the corresponding model. We propose to use different tools to measure topography to prove the efficiency of the proposed model. Finally, we analyze the influence of a unit operation, calendaring, which modifies the surface of paper. A link between surface and physical properties is proposed using the proposed model which is valid independently of the considered scale.

II. MATERIALS AND METHODS

A. Equipment

The mechanical properties were measured following standards on an Instron® equipment.

The 2D measurements of the surface topography were carried out on an industrial device [Altisurf 500 from Altimet®].

The 1D surface analyze used in this work was a Perthometer Mahr® Perthen M4Pi. In stylus type instruments, a small radius tip is pulled across the surface and the vertical position is monitored using appropriate transducers. The radius of its stylus has a U-shape. The maximum scan length was 1.5 mm.

The optical properties were measured on a Lange® Glossmeter.

B. Methods

The proposed model is based on the previous work [1] and is based on quantitative stereology. The number of linear intercepts, $P_L(\theta,\varphi)$, is defined as the number of intercepts between a straight line of direction (θ,φ) and the interfaces of the porous medium, on a unit distance. Considering a two dimensional structure, the numbers of intercepts for the three main directions are measured. The model consists in an ellipsoid characterized by the half-axes (a, b, c) whose projections in 3 main directions correspond to the intercept values. The following relations allow identifying the parameters of the model:

$$P_{LX} = 2\pi\, a.c \quad (1)$$

$$P_{LY} = 2\pi\, b.c \quad (2)$$

$$P_{LZ} = 2\pi\, a.b \quad (3)$$

Consequently, we obtain from (1) to (3):

$$(a/b) = (P_{LX} / P_{LY}) \quad (4)$$

$$(b/c) = (P_{LZ}/P_{LX}) \quad (5)$$

The surface is first measured to obtain a map as exemplified in Fig. 1. A triangulation is then carried out. Finally, the ellipticities are calculated.

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http://dx.doi.org/10.15242/IJCCIE.C0114154

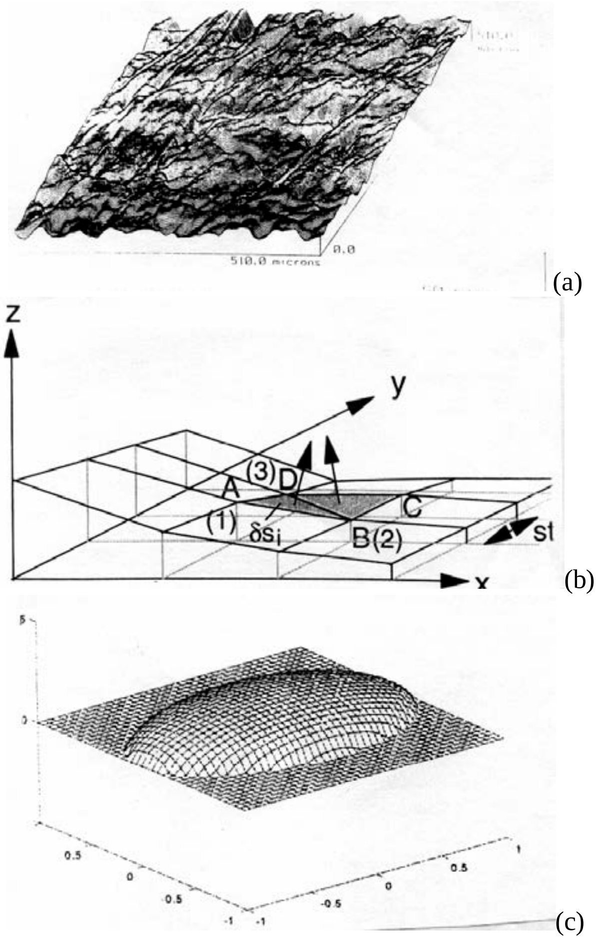

Fig. 1: Measurement of surface (a), triangulation (b) and the ellipsoid model (c)

- The measurement was also carried out in 1D using the stylus equipment. The classical parameters, the average roughness R_a and the quadratic mean R_q, are defined as follow.

$$R_a = \frac{1}{L_T} \sum \left| Z_i - \bar{Z} \right| \qquad (6)$$

$$R_q = \frac{1}{L} \sqrt{\int z^2 \, dx} \qquad (7)$$

Where L is the scan length, x is the position along the profile and z is the vertical coordinate of the profile, measured from the center line of the profile.

The horizontal position (and total length) of the profile are obtained by multiplying the (total) number of sample position by the gap between measured points. A discretization may be carried out on a profile, as schematically illustrate in Fig. 2.

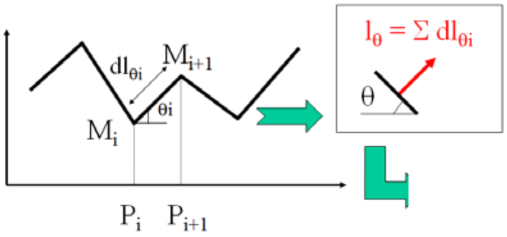

Fig. 2: 1D profile and evaluation of the length l_θ.

III. RESULTS AND DISCUSSIONS

A.- Effects of Fiber Orientation on Mechanical Properties

The first set of data concern paper samples where the fiber orientation was modified by a variation of the difference between the jet and the wire velocities. The main fiber orientation influences the physical properties, as shown in the Table I.

TABLE I
INFLUENCE OF FIBER ORIENTATION ON PHYSICAL PROPERTIES, MD AND CD REPRESENT THE MACHINE AND THE CROSS DIRECTIONS, RESPECTIVELY. THE PAPER 20 CORRESPONDS TO THE ISOTROPIC CASE.

Paper (Label)	18	19	20	16
$V_{jet} - V_{wire}$ [m.min^{-1}]	-29.5	-17.4	-5.7	+8.6
Basis weight [g.m^{-2}]	50.9	48.6	48.5	48.2
$F_{R\,MD} / F_{R\,CD}$	5.7	3.7	1.9	3.5
E_{MD} / E_{CD}	4.7	2.8	2.1	3.3
a/b (*)	5.7	3.7	1.9	3.5

(*) the anisotropy (a/b) represents the fiber anisotropy. The value 1 corresponds to isotropy. E and F_R represent the young modulus and the breaking load, respectively.

It appears clearly that an increase of the orientation in the machine direction increased the mechanical properties (Breaking length and Young modulus) in this direction.

The roughness parameters obtained for the set of oriented papers are presented in Table II, for both sides, called wire and felt sides. The ellipticity (a/b), calculated from the ratios (c/a) and (c/b) proves the effect of the velocities on the main fiber orientation.

TABLE II
SURFACE PARAMETERS FOR THE ORIENTED SHEETS (MEAN OF 10 MEASURES). THE RESULTS ARE COMPARED TO THE VALUES PUBLISHED USING A LASER TRANSMISSION EQUIPMENT [1].

	Paper 18	paper 19	paper 20	paper 16
Wire side	c/a = 0.259	c/a = 0.292	c/a = 0.317	c/a = 0.301
	c/b = 0. 406	c/b = 0.392	c/b = 0.352	c/b = 0.371
	a/b=1.57	a/b=1.34	a/b=1.11	a/b=1.34
Felt side	c/a = 0.276	c/a = 0.289	c/a = 0.324	c/a = 0.291
	c/b = 0.417	c/b = 0.378	c/b = 0.358	c/b = 0.392
	a/b=1.51	a/b=1.31	a/b=1.11	a/b=1.23
$R_{a\,MD}/ R_{a\,CD}$				
Mean	1.44	1.43	1.10	1.45
Wire side	1.41	1.26	1.08	1.40
Felt side	1.48	1.60	1.12	1.50
$R_{q\,MD}/ R_{q\,CD}$				
Mean	1.37	1.32	1.06	1.34
Wire side	1.36	1.23	1.03	1.29
Felt side	1.38	1.42	1.10	1.40
Published Anisotropies [1]	a/b = 1.57	a / b = 1.49	a / b = 1.14	a / b = 1.38

The proposed methodology leads to similar results as the published data, lowering slightly the intermediate values. The obtained values are very close. However, the ranking of the roughness anisotropies using these parameters leads to (16>18>19>20), (18>16>19>20) and (18>19>16>20) using respectively the parameters R_a, R_q and a/b. The last parameter (a/b) leads to the correct ranking.

The model is also valid in the case of a one dimensional measurement. The anisotropy parameters may be calculated as follows:

$$a=\sqrt{\frac{1}{2.\pi}.\frac{L_x.L_z}{L_y}}\quad b=\sqrt{\frac{1}{2.\pi}.\frac{L_y.L_z}{L_x}}\quad c=\sqrt{\frac{1}{2.\pi}.\frac{L_x.L_y}{L_z}}\quad (8)$$

Where L_i represents the intercept number in the i direction

From the expressions of the parameters a, b, and c in (8), the anisotropy parameters are obtained:

$$\frac{a}{c}=\frac{Plz}{Plx}=\frac{\sum \text{projection on x axis}}{\sum \text{projection on z axis}}=\frac{\sum|\Delta X|}{\sum|\Delta Z|}$$
$$=\frac{L_T}{\sum|Z_{i+1}-Z_i|}=\frac{L_T}{\sum|\Delta Z|}\qquad (9)$$

$$\frac{a}{b}=\frac{Ply}{Plx}\qquad (10)$$

We note the difference between the expressions of the ratio (c/a) and the standard parameter Ra. Indeed, the difference of altitudes is considered in reference either to the mean value or to the previous point in the profile.

B.- Effect of Calendaring on Structural Properties

The next series of paper samples were first characterized in terms of basis weight, thickness and bulk as presented in Table III.

TABLE III

STRUCTURAL PROPERTIES OF PAPER SAMPLES FOR THE CALENDARING TESTS

	1	2	3	4	5
Basis weight [g.m^{-2}]	60.3	59.0	58.0	57.3	57.3
Thickness [µm]	88	56	51	46	46
Bulk [cm^3.g^{-1}]	1.5	0.95	0.88	0.80	0.80
Bulk porosity (%)	55	31	26	19	19

The experimental results of roughness and gloss are presented in Table IV. It has to be noted that the gloss as well as the surface measurement have to be carried out on an Equivalent Representative Surface (ERS) [2].

TABLE IV

STRUCTURAL CHARACTERIZATION AND MAIN ANISOTROPIES OF PAPER SAMPLES (PROFILOMETER MAHR (1D), 2D AND GLOSS LANGE (20, 60 AND 85°))

Sample	1		2		3		4	
	Felt	Wire	Felt	Wire	Felt	Wire	Felt	Wire
R_q 1D (µm)	6.1	5.5	2.1	2.3	1.5	1.8	1.1	1.2
R_a 2D (µm)	3.9	4.1	2.4	2.0	2.0	1.6	0.5	0.9
R_q 2D (µm)	4.8	5.2	3.1	2.5	2	2.1	0.8	1.2
Gloss (20°)	1.2	1.2	1.5	1.4	1.9	1.8	3.6	2.9
Gloss (60°)	3.3	3.0	6.8	5.9	11	9.4	22	18
Gloss (85°)	1.5	1.8	14	14	27	24	51	44

The parameters (a, b and c) of the model were evaluated for both sides of the samples, called Felt and Wire sides, respectively. The results are presented in table V.

TABLE V

STRUCTURAL CHARACTERIZATION AND MAIN ANISOTROPIES OF PAPER SAMPLES

Paper	1		2		3		4	
Side	Felt	Wire	Felt	Wire	Felt	Wire	Felt	Wire
a	4.16	4.50	4.23	4.69	4.45	4.93	4.80	4.88
b	3.88	3.57	3.85	3.47	3.72	3.35	3.41	3.36
c	0.73	0.89	0.60	0.53	0.16	0.26	0.40	0.41
c / b	0.19	0.25	0.16	0.15	0.04	0.08	0.12	0.12
c / a	0.18	0.20	0.14	0.11	0.04	0.05	0.08	0.08
a / b	1.07	1.26	1.10	1.35	1.20	1.47	1.41	1.45

The evolution of gloss may then be correlated to the model parameters, as presented in Fig. 3.

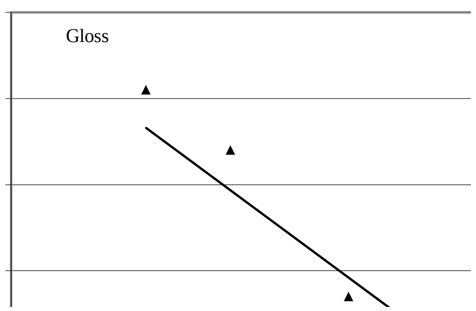

Fig. 3: Evolution of gloss (20, 60, 85°) vs. the model parameter, c

- The last series of samples consist in a paper (REF.) calendared in different conditions as presented in the table VI.

TABLE VI

STRUCTURAL CHARACTERIZATION USING THE (A, B AND C) PARAMETERS OF PAPER SURFACES MODIFIED BY DIFFERENT CONDITIONS OF CALENDARING (N TIMES X LOAD)

FELT SIDE	PAPER REF.	1 x 30 kN.m^{-1}	2 x 30 kN.m^{-1}	1 x 60 kN.m^{-1}	2 x 60 kN.m^{-1}
a/c	3.19	3.25	3.25	3.32	3.54
b/c	2.58	2.65	2.69	2.81	2.84
a/b	1.21	1.23	1.21	1.18	1.24

As the parameter (a/b) is constant, we may conclude that there is no modification of the fiber orientation is the plane, as expected. The parameter c (or the ratios a/c or b/c) decreases as expected.

IV. CONCLUSIONS AND PERSPECTIVES

The model of the ellipsoid characterized by its half-axes (a, b and c) may be used to characterize surface, and its anisotropy, as exemplified with the flattening of the surface due to calendaring. Obviously, it does not reflect all the characteristic of the surface as it does not reflect the multi-scale aspect of the surface, but remains a useful single parameter. We note that the evaluation of the surface parameter does not depend on the size measured.

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