# STRUCTURE OF PAPERS AND NONWOVENS

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**Abstract:** We characterise the structure of fibrous materials: papers and nonwovens by diffraction and transmission of light. This allows the measurement of the fibres orientation distribution of the sample as a whole or for the surfaces using replicas. Applications of the methods are demonstrated in the case of paper for the control of the curl tendency and for two kinds of nonwoven materials, one used in the tailoring of surgical garments and the other used as components of the baby diapers.

**Keywords:** Structure, paper, nonwoven, fibres orientation, optical analysis.

## Introduction

Papers and nonwoven materials are sheets having common physical properties:

- a small calliper in the range of 50 μm to few millimetres,
- a high level of porosity from 50% to 95%, giving a bulky structure to the sheet,
- a porous texture constructed by the interlocked fibres providing an interconnected network of pores opened to the exterior.

The properties required for paper and nonwoven uses are numerous. We will mention: the permeability for liquids and gases, the absorption of liquids (inks and water), the optical properties (opacity, brightness, radiation's filtration), the thermal properties (conductivity and diffusion of heat), the softness or inversely the roughness of the sheet faces, the mechanical properties (resistance to stress, tear, burst, delamination, stiffness) etc.

The properties listen above depends from one part of the physical properties of the components of the papers and the nonwoven materials that is mainly the fibres, natural or synthetic, and another part from the fibres arrangement. Most of the time the structure of papers and nonwovens consist of layers of fibres with a bi-dimensional distribution of the fibres orientation isotropic or anisotropic. Differences in the fibres distribution can exist from one side to the other side due to the process of manufacture. The fibres orientation distribution is an important parameter which influence most of the structure properties and therefore the physical properties of paper [1] and nonwoven materials [2].

In this study we have developed methods for the structure characterisation of the fibrous texture of the sheet with optical analysis based on diffraction and scattering of light.

We have applied these methods to relate some papers and nonwovens physical properties to the parameters of their structure.

## Methods of characterisation

### 1.Replicas Production

To obtain surface replicas of the samples with the highest possible fidelity we used a thermoplastic film, which is placed onto the sample. Then the replica of the surface is obtained by pressing the polymeric film at temperature of about 115ºC, and a pressure of about 350-400 kPa [3]. The equipment used to achieve this is a press, which is shown in figure 1.

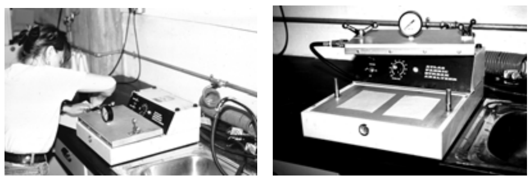


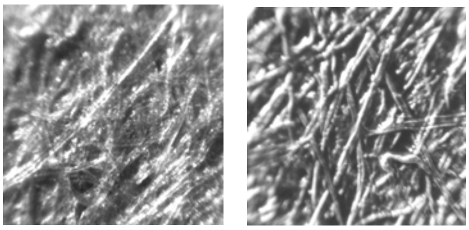
Figure 1. Press for replicas production.

It is constituted by two plates, the bottom one is heated whereas the upper is connected to compressed air. At the end of the process the bottom plate is cooled thanks to a system of water circulation.

We can produce simultaneously, therefore with the same conditions, the replicas of both surfaces of the sample. The quality of the replica was first evaluated by microscopic observations and showed pictures, from which it is difficult to distinguish the surface sample from the replica, even for an skilful expert.

Figure 2(a) present the surface of a paper made of pine fibres, whereas figure 2(b) show the surface of the replica of the same paper sheet.

Even if the location on the paper surface of these two micrographies is not the same, we can certify that the quality of the replica, as shown on the pictures, is as good as that of the paper sample.



(a) (b)

Figure 2. (a) A paper sample micrography and (b) a replica micrography.

## 2.Optical Analysis

### 2.1Light diffraction

In the case of optical diffraction we use an optical bench constituted by a He-Ne laser beam, a spatial filter (*SP*) and a collimating lens ($L_1$) to produce a plane wave front of light (see figure 3).

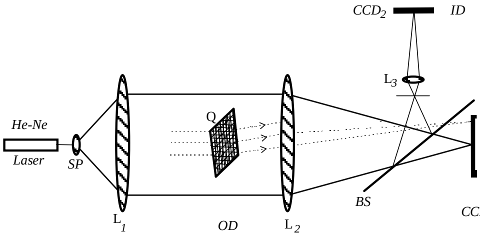



Figure 3. Experimental apparatus for the light diffraction analysis.

All the light passing through and deviated by the sample replica (*Q*) is collected by the large aperture Fourier lens ($L_2$) which creates a diffraction pattern in the focal point, where a solid state sensor ($CCD_1$) is placed. The beam was splitted in two parts using a beam splitter (*BS*) in order to create on another solid state sensor ($CCD_2$) the image of the paper replica. Both the solid state sensors are connected to a frame grabber, which is installed in a computer, to record these intensity distributions. An application program was written to control the acquisition and recording processes and it also performs all the necessary processing on the recorded data. In figure 4 we can see a general view of the experimental apparatus.

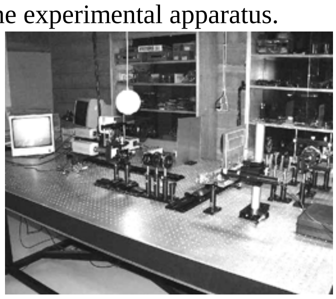
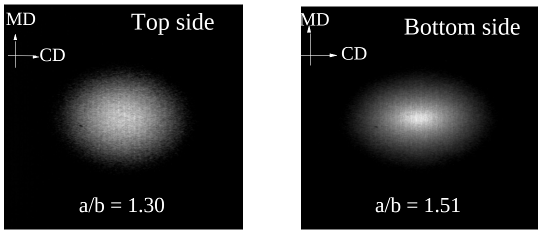


Figure 4. Photograph of the optical bench.

As an example, the following two diffraction patterns (figure 5) have been obtained with the described apparatus, for an unbleached Kraft liner paper (top side and bottom side) which was manufactured by a paper machine with two headboxes.




(a) (b)

Figure 5. Diffraction patterns of a Kraf liner paper; (a) Top side and (b) bottom side.

It has been shown [4] that the density of straight fibres segments orientation in a fibrous network can be expressed by the radius of curvature of an equivalent contour, evolved by fibres in the texture plane, therefore the name of “Equivalent Pore” for this modellisation. The choice of an elliptical contour, figure centro-symmetric because the $\pi$ rad periodicity of the fibres orientation functions, correspond to the features structure which is due to the manufacturing processes.

From the “Equivalent Pore” concept, only two parameters are sufficient to represent the fibre distribution: the ellipticity of the elliptical contour and the direction of its principal axis.

To validate our results, obtained with the optical diffraction analysis, two fibres distributions were generated in a computer to produce their corresponding diffraction patterns (see figure 6).

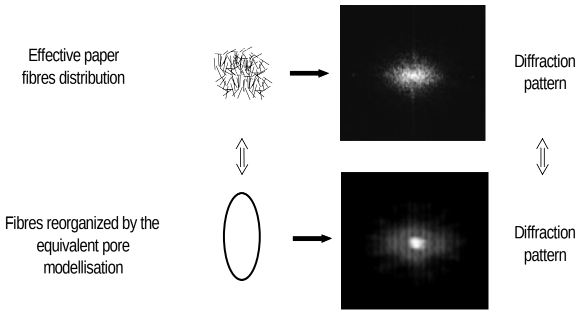



Figure 6. Generated fibre distributions.

On the left, in the upper part, we see an effective fibres distribution in orientation, and on the bottom the same distribution in orientation but, with the fibres reorganised according to the “Equivalent Pore” modellisation. On the right side of the figure is show the corresponding diffraction patterns for these distributions.

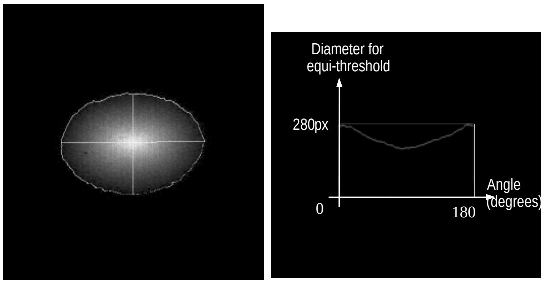
As we can see, both patterns reveal an elliptical shape with the same ellipticity (a/b), rotated by 90º with respect to the main axis of the fibre orientation distribution.

These results are in agreement with the optical diffraction theory. It confirms our interpretation of the diffraction pattern of material replicas to characterise the fibres orientation. The ellipticity of

the optical diffraction pattern characterises the fibre orientation anisotropy of the sample surfaces.
The method of characterisation [5] comprises the following steps:

- Create replicas from the sample surfaces,
- Generate the corresponding laser diffraction,
- Find the best of an equi-intensity curve contour, for computing the ellipticity of the diffraction pattern.

In figure 7, we can see the results obtained, with this method, for an unbleached Kraft liner paper replica. The graph shows the changes in diameter through the contour of the equi-intensity curve between 0 and 180º. The ellipticity computed has a value of 1.51. A similar analysis can be done for the other side of the same paper sample, which is less anisotropic with a value of 1.30.




| | | | |
|---|---|---|---|
| Maximum Diameter | 279,5 pixel | at Angle | 179,6 deg. |
| Minimum Diameter | 185.5 pixel | at Angle | 89,6 deg. |
| Angle Difference | 90.0 deg. | | |
| Thereshold | 23 | | |
| Range | 0-180 deg. | | |
| Elipticity: a/b | 1.51 | | |

Figure 7. Results of diffraction analysis for a Kraft liner paper: bottom side.

### 2.2 Light Transmission

In this optical process, the fibres act as light guides spreading the incident light on the paper sheet surface from fibre to fibre. Then the light is transmitted through the fibre structure by scattering and absorption. We observe the light pattern on the opposite surface.
The experimental optical bench, uses a He-Ne laser and a microscope objective ($L_1$) to focus the laser beam on the paper surface (see figure 8).

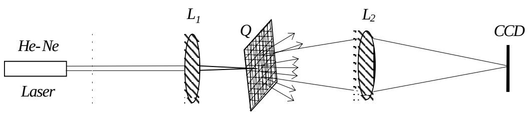



Figure 8. Experimental apparatus for light transmission analysis.

Another lens ($L_2$) and a solid state detector (*CCD*), captures the image on the other side of the sample, and it is acquired and stored on a computer in order to perform the analysis with the same treatment as for diffraction.

The decreasing of the light intensity in any direction for a path according to the axis of the fibre, is proportional to the mean number of fibres crossing by unit length in these direction.
The "Equivalent Pore" theory states that the inverse of the indicatriz of the intercepts by length unity in a fibrous network is the figure of the Equivalent Pore contour. For a determined intensity threshold the location of the light detected give us directly the shape of the Equivalent Pore which enable us to characterise the fibres distribution. The figure 9 show an example of the transmission analysis for a paper made in a dynamic sheet former.
In transmission analysis the main axis of the ellipse as the same direction as the one of the paper maximum fibres orientation. Therefore it do not appear rotated by 90º as for diffraction analysis.
To summarise the light diffraction analysis give us access to the fibres orientation distribution and its anisotropy on the material surfaces and the light transmission analysis reveals the mean fibres orientation of the whole structure.

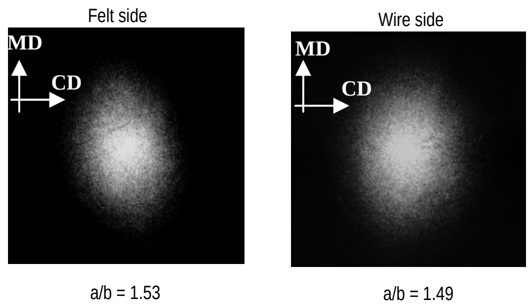
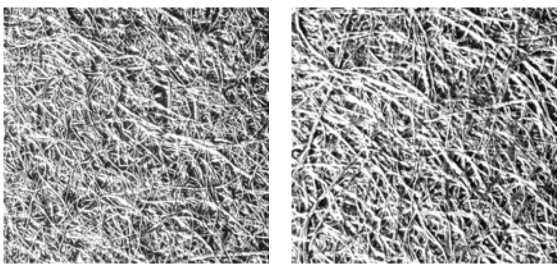



Figure 9. Light transmission patterns of a paper sheet.

## Applications

### 1. Application to paper

The paper is used for printing, converting and packaging uses. In these applications the sheets have to stay flat, without curling, even in different humidities of the ambient air. The curl of paper depend mainly of the pulps quality and of the fibres orientation distribution of the sheet's faces [6].
The figure 10 shows the aspect of the paper faces replicas on the wire and felt sides, in the case of a two layers sheet.



Eucalyptus (Wire side) Pinus (Felt side)

Figure 10. Surfaces of a two layers paper sheet.

The wire side corresponds to the Eucalyptus pulp, whereas the felt one is made from Pine fibres. These replicas are quite fitted for the control of the paper faces in term of the fibres orientation distribution. Moreover we can use it for the characterisation of the porosity by an image analysis process.
In the table 1 we have the results of the fibres orientation analysis in the case of different paper sheets.

Table 1. Paper sheet fibres anisotropy: Ellipticity (a/b)

| **Paper** | **Diffraction analysis (ϕ Laser beam = 10 mm)** | | |
|---|---|---|---|
| | Felt Side | Wire side | Mean |
| MK E 19º SR | 1.10 | 1.12 | 1.11 |
| MK E 54º SR | 1.12 | 1.17 | 1.14 |
| DF E 850 19º SR | 1.52 | 1.14 | 1.33 |
| DF E 850 54º SR | 1.41 | 1.19 | 1.30 |
| DF P 886 19º SR | 1.70 | 1.52 | 1.61 |
| DF P 886 54º SR | 1.67 | 1.50 | 1.59 |
| DF P 1339 54º SR | 1.65 | 1.27 | 1.45 |
| DF 50%E+50%P 54º SR | 1.41 | 1.58 | 1.50 |

DF – *Dynamic Former*
MK – *Isotropic former*

The behaviour of the curl of paper sheets (see figure 11), reveals that the sheets have their concavity in dry air condition toward the face, which is the more anisotropic.

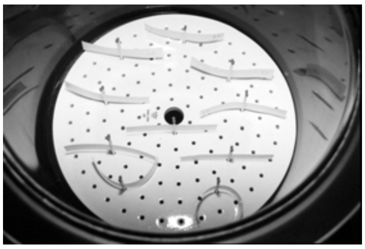


Figure 11. Observations of the curl.

The more is the difference of fibres orientation between the sheet faces, the more is the development of the curl. The curl appears on the opposite side of the paper when the humidity of the air increases (see results in table 2).

Table 2. Results of curl experiments.

| | **MK E 54 ºSR** | | **P 886 54 ºSR** | | **P 1339 54 ºSR** | | **50P(886) + 50E(850) 54 ºSR** | |
|---|---|---|---|---|---|---|---|---|
| **a/b** | W 1,17 | F 1,12 | W 1,50 | F 1,67 | W 1,27 | F 1,65 | W pine 1,58 | F euc. 1,41 |
| **98 % RH** | | + | O | O | O | O | | +++ |
| **20 % RH** | + | | | + | | ++++ | +++ | |

+ Shows the intensity of the curl refereeing to the concave face.
E = Eucalyptus, P = Pine

## 2. Application to nonwovens

The nonwoven materials are used to produce technical textile products. They should resist to mechanical loads, having permeability and filtration properties for fluids, absorption properties, thermal isolation… The control of these properties is intimately related with the structure of the materials.
We analysed a nonwoven material that is used to produce surgical garments. It is composed by a polyester spunlaid (the internal side of the garment) and a cellulosic wetlaid (the external side) consolidated together by hydraulic entanglement.
The figures 12 and 13 show the images of cellulosic and polyester faces of the surgical nonwoven and the figures 14 and 15 show the image of their replicas.

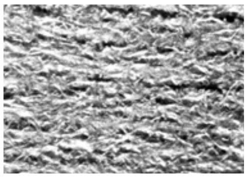


Figure 12.

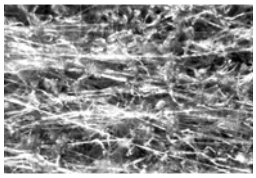


Figure 13.

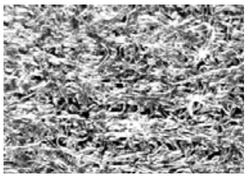


Figure 14.

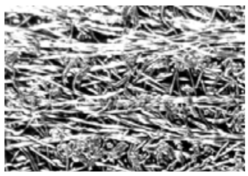


Figure 15.

We evaluate the homogeneity of the fibres distribution in the nonwoven faces doing several diffraction measurements in different locations, using a laser beam with diameter equal to 8 mm, wich is adapted to the level of resolution desired for the physical tests [2]. Examples of the diffraction patterns obtained for polyester and cellulosic faces are respectively shown in figures 16 and 17 where we indicate the machine direction (MD) and the cross direction (CD) of the sample. The interpretation of these patterns is given in table 3, where a/b is the ellipticity, according to the Equivalent Pore, and φ is the angle of the maximum orientation fibres refeering to the machine direction of the nonwoven.

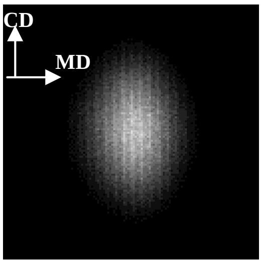



Figure 16.

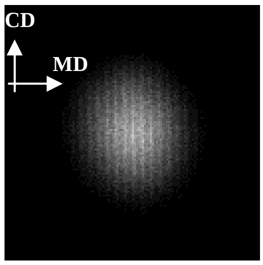



Figure 17.

Table 3.

| | Cellulosic Face | Polyester Face |
|---|---|---|
| a/b | 1.17 | 1.35 |
| $CV_{a/b}$ % | 3.7 | 3.5 |
| φ º | +5.7 | +1.5 |
| $Std.Dev_{\varphi}$ º | 5.4 | 4.0 |
| N | 17 | 13 |

If we compare the bending stiffness of the two faces (see table 4) the most anisotropic face behaves as the most rigid, note however that this result can be also a consequence of the fibrous composition. Both faces are more rigid according to the main direction, close to which the orientation distribution of the fibres reaches its maximum value.

Table 4. Bending Stiffness (Kawabata results) and anisotropy.

| Bending Stiffness ($gfcm^2$/cm) | Faces | |
|---|---|---|
| | Polyester | Cellulosic |
| Machine Direction | 0.406 | 0.219 |
| Cross Direction | 0.051 | 0.031 |
| a/b | 1.35 | 1.17 |

We also analysed some nonwovens used to produce the topsheet and the acquisition layers of baby diapers. The topsheet is in intimate contact with the skin of the baby. It must wet readily and have high fluid permeability. It is a polypropylene spunbonded. The acquisition layer is the component placed below the topsheet and its function is to distribute the liquid through the plane of the layer. It is a carded polyester nonwoven.
The results obtained by diffraction analysis give a fibres orientation anisotropy adequate to the functions of each material the isotropy being in favour of a great permeability and the anisotropy contributing to the spreading of the liquid. Table 5 gives the values of the ellipticity a/b of each component of the diaper.

Table 5.

| | a/b |
|---|---|
| Top Sheet (face in contact with skin) | 1.08 |
| Top Sheet (face in contact with acquisition layer) | 1.26 |
| Acquisition layer (face in contact with top sheet) | 1.31 |

## Conclusions

Making replicas is a simple method to obtain an accurate representation of the surfaces of the fibrous networks as paper and nonwoven materials. By light diffraction the transparent replica of the surface give many informations on the features of the fibrous media namely the fibres orientation distribution a key parameter of the structure. The "Equivalent Pore" model is well fitted to interpret the diffraction pattern of the replica giving a straight forward representation of the fibres distribution and of his anisotropy with the parameter of ellipticity: a/b.
The comparison of these optical methods based on light diffraction and light transmission in respect to an other method, used for fibres orientation measurements with coloured fibres dispersed in the paper sheet have been made. For this we have tested different anisotropics papers made in the laboratory and known as the EFPG series [4]. The agreement of our indirect results with the direct method using coloured fibres is good [3] [6].
The optical method can be done using different incident light beam diameters (see the results of the table 6). The modifications of the resolution give a good evaluation of the uniformity of the paper and nonwoven materials.

Table 6. Diffraction analysis using different light beam diameters.

| Light beam diameter (mm) | | | 5 | 8 | 11 |
|---|---|---|---|---|---|
| Surgical garment nonwoven | External face | a/b | 1.31 | 1.25 | 1.27 |
| | | CV% | 4.6 | 2.1 | 1.6 |
| | | nb of mea | 15 | 18 | 11 |
| | Internal face | a/b | 1.50 | 1.36 | 1.39 |
| | | CV% | 5.8 | 3.5 | 2.4 |
| | | nb of mea | 14 | 12 | 10 |

The optical methods we have presented here are easy to apply. We are working to complete them by image analysis and scattering of light for the determination of porosity and 3D model of the texture.

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