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Abstract Corrugated cardboard is very sensitive to atmospheric conditions. The aim of this work is to study the effects of these parameters, especialy the relative humidity (RH), on the mechanical behavior of corrugated cardboard sandwich structure. Tensile and three-point bending tests were used under various rates of relative humidity. An analytical model based on the classical laminate plate theory is used to predict the elastic behavior of the corrugated cardboard under different atmosphere conditions. The model is then extended to predict the inelastic behavior of the corrugated cardboard from the behavior of its components.

Keywords: corrugated cardboard, hygro-mechanical behavior, modeling.

1. INTRODUCTION

Corrugated cardboard pertaining to papers family is one of the most used packing currently. Its employment does not cease increasing each year and covering the various types of packing, such containers and pallets, and extending to other fields such as the dwellings. This success is due to the various virtues of this material: good protection of the product, low cost and can be recycled as well as biodegradable. Biodegradable product are more and more demanding as being a major concern again the protection of the environment and hence respect a durable development.

For a better optimization and diversification of the use of corrugated cardboard, knowledge of its mechanical characteristics and failure, as well as the apprehension of its behavior, is necessary.

The corrugated cardboard is an orthotropic sandwich with the surface plies (facing) providing bending stiffness, separated by a lightweight bending core (fluting) that provides shear stiffness. Two main directions characterize this material. The first noted MD (machine direction) corresponds to the direction

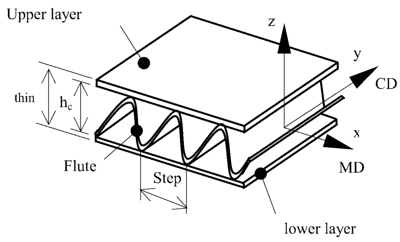


Figure 1. Cardboard panel geometry.

Table 1. Mechanical and geometrical characteristics of the constituent of the corrugated cardboard.

	H (mm)	E_{MD} (Mpa)	E_{CD} (Mpa)	ν_{xy}	ν_{yx}
Upper layer	0.235	4514.53	1895.83	0.282	0.215
Flute	0.19	4458.6	1944.5	0.277	0.115
Lower layer	0.235	4703.75	1854.3	0.353	0.088

of manufacturing of the material. The second noted CD (cross direction) corresponds to the transverse direction and coincides with the y axis (Figure 1).

Aboura at al. have developed an approach regarding corrugated cardboard as monolithic material and have adapted simple's mechanical tests to characterize this material [1,2]. The tests were carried out under a controlled atmosphere (23°C and 50% RH) according to the recommendations of French standard NF Q 03–010. They developed an analytical model to predict elastic and inelastic behavior of the material [1,3]. This model is based on the classical laminate plate theory and was inspired by different studies [4,5,6].

This work purposes to study the effect of the atmosphere conditions, in particular the effect of moisture, on the mechanical behavior of the corrugated cardboard.

First, the study the moisture equilibrium corresponding to the water content in each layer and the sandwich is done. Once the moisture equilibrium achieved, the corrugated cardboard was tested in tensile and three-point bending tests at controlled atmosphere. The relative humidity levels used vary from dry conditions (35% RH) to severe conditions (90% RH). The difficulty at these conditions consists in handling the least possible the specimens. Methodology of measurement developed in a previous study [7] is used. Finally the analytical model developed by Aboura et al. was used to predict the elastic properties of the material at different atmospheres.

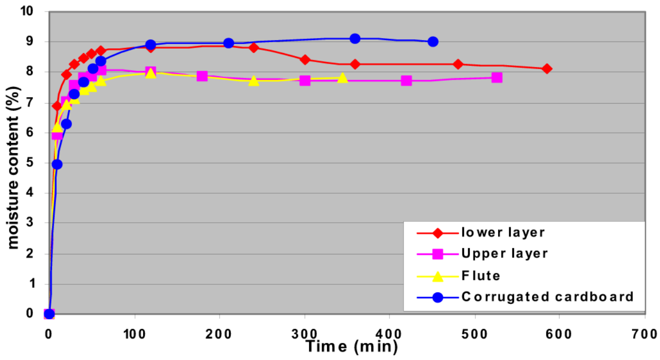


Figure 2. Moisture content at equilibrium for corrugated cardboard and its constituents.

2. MOISTURE EQUILIBRIUM OF THE MATERIAL

Two layers and one flute compose the corrugated cardboard used in this study. All the constituents are composed with 100% cellulose recycled fibers. Table 1 shows the constituents geometrical and mechanical characteristics. The thickness of the sandwich is 4.1 mm.

Mechanical tests will be made under various controlled atmospheres. Specimens must be preliminary conditioned to reach a state of moisture equilibrium in these conditions. Standard French norm NFQ 03–010 recommends 24 hours conditioning for any kind of paperboards.

Square specimens of 5 cm of the corrugated cardboard and its components were made. They were conditioned in a climatic chamber under conventional conditions (23°C and 50% RH) during 24 hours. Once the equilibrium is reached, the specimens were weighed and these measurements were used as references. It assumed that the equilibrium at 50% RH corresponds to a moisture content of 6% (dry basis) in each specimen [8]. Then, a rate of 95% RH is imposed followed by a regular weighing of specimens to evaluate the moisture content. The balance used has a precision of 0.01 mg.

After 100 minutes the moisture equilibrium was achieved. This state corresponds to moisture content of 8% at 9% for corrugated cardboard and its components (Figure 2). If the dry basis is considered, the moisture content will be 15%.

3. MECHANICAL TESTS UNDER VARIOUS RH

Tensile and three-points bending tests were carried out on specimens of corrugated cardboard on a tensile testing machine, which is equipped with a climatic chamber. The temperature is fixed at 23°C and the atmospheric conditions vary between 35% to 90% RH.

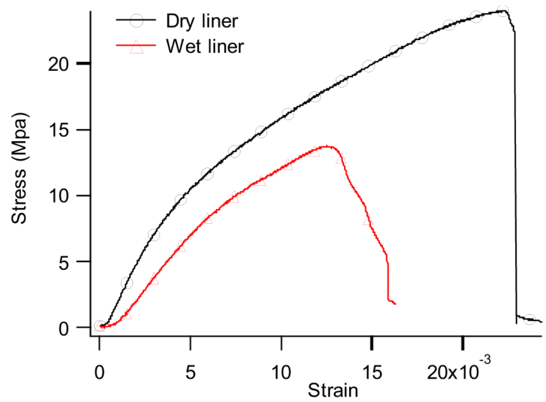


Figure 3. Tensile test of dry layer an wet one at 90% RH (CD).

Before the tests, specimens were conditioned in a climatic chamber under each value of RH, during 24 hours to reach a state of moisture equilibrium. A thermo-hygrometer (precision of ±3% RH) was used to control the rate of humidity.

3.1 Tests conditions

The difficulty of the tests consists in handling the least possible the specimens. For that, the methodology of measurement witch are developed in previous study [7] is used.

A particularly attention is done at high level of moisture. Indeed, a phenomenon of condensation occurs which produce a water drop and then risk to wet the paperboard. This effect is shown on Figure 3. The Young's modulus and the maximum stress and strain are strongly affected by this phenomenon. It is then important at high RH to check before each test that the specimen is not wet.

Another phenomenon is observed during the conditioning of the specimens. By increasing RH, a deformation of the cardboard is observed inducing a curvature. This phenomenon has been modeled for the case of paperboard by Gendron [8]. This phenomenon is more pronounced in the CD.

These shapes did not affect the tensile tests. For the three-points bending tests, specimens were tested in two configurations. The load is applied on the convex part of the specimen in the first configuration and on the concave part for the second one. It was found that the elastic behavior is the same one for the two cases. On the other hand the stress and deflexion of collapse are more significant for the specimens tested on the concave part (Figure 4) and this under all the atmospheres. For the follow bending tests, we will alternate

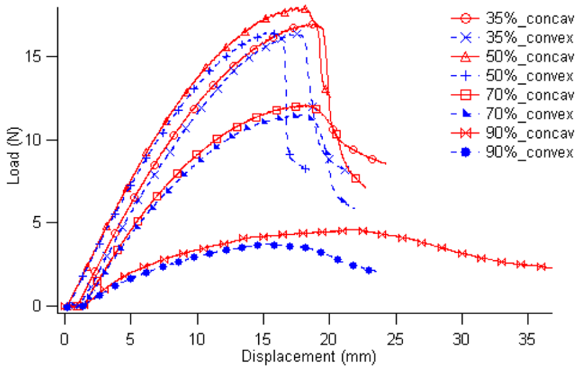


Figure 4. Bending test on convex and concave configuration under different rates of RH (corrugated cardboard in CD).

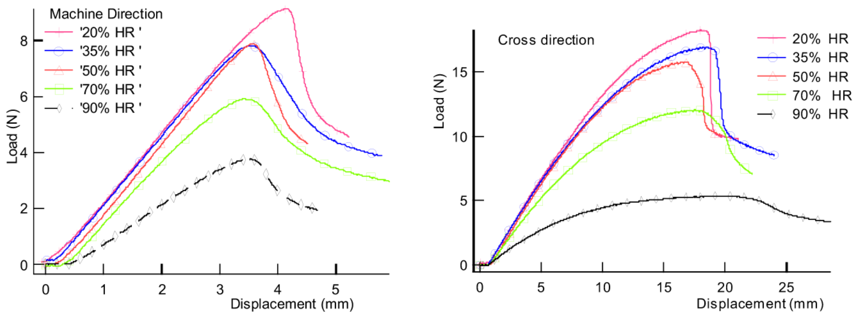
Table 2. Results of tensile and bending tests under different rates of RH.

		Relative Humidity %			
		35	**50**	**70**	**90**
Bending results		**Machine Direction**			
	Rigidity (Mpa)	1283.71	1334.57	1166.62	729.09
	Standard deviation (Mpa)	53.62	95.1	33.88	15.66
	Er (%)	-3.81	0	-12.58	-45.37
		Cross Direction			
	Rigidity (Mpa)	804.9	813.06	682.45	373
	Standard deviation (Mpa)	14.08	29.42	22.76	35.92
	Er (%)	-1.003	0	-16.06	-54.12
Tensile Results		**Machine Direction**			
	Young modulus (Mpa)	648.88	644.45	621.25	430.83
	Standard deviation (Mpa)	25.21	28.15	18.3	9.72
	Er (%)	0.69	0	-3.6	-33.15
		Cross Direction			
	Young modulus (Mpa)	488.66	433.1	422.5	275
	Standard deviation (Mpa)	21.33	21.1	11.09	24.19
	Er (%)	12.83	0	-2.45	-36.5

between the two configurations, and an average of mechanical results will be done.

3.2 Results and discussion

Table 2 shows the results obtained during tensile and bending tests. The conventional conditions (23°C and 50% RH) are used as references. Parameter Er, which is a relative deviation from references conditions, is calculated as



(a) (b)

Figure 5. Three-point bending curves under different rates of RH.

follow:

$$Er = \frac{\text{Elastic properties at RH} - \text{Elastic properties at 50\% RH}}{\text{Elastic properties at 50\% RH}} \times 100 \,.$$

In dry conditions (35% RH), the elastic characteristics do not change and remain in the field of dispersion ($Er < 4\%$), except for the corrugated cardboard in the CD tensile test where $Er = 12,83\%$.

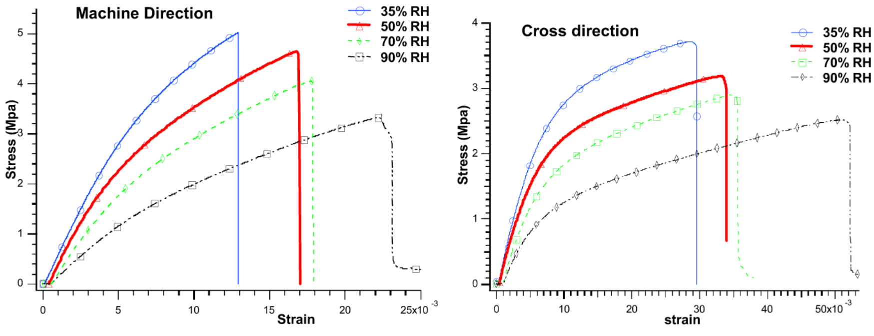
The increase of moisture makes fall the elastic characteristics. This fall is more significant on the bending tests. Indeed, by increasing the moisture content at 70% RH, the Young modulus do not change in the two directions of material. Contrary to tensile tests, the bending stiffness falls under these conditions. The maximum value of fall is 16% in the CD. In the very wet conditions (90% RH), the elastic characteristics break down. The falls of these parameters vary from 33,15% for the Young's modulus in the MD to a maximum of 54% for the bending stiffness in the CD.

The elastic limit and the failure stress change according to the rate of moisture in the cross and machine direction (Figures 5 and 6).

The effect of moisture is more significant in the cross dirsection than in the machine direction. This can be explained by the fact that the behavior of material in the cross direction depends on the hydrogen lies between the cellulose fibers which change when the paperboard was subjected to a change in humidity content.

4. ANALYTICAL MODELING

An analytical model of the elastic behavior of corrugated cardboard was developed [1, 2]. It takes into account mechanical properties and geometrical parameters (core thickness, fluting step, skin thickness) of the components. This model, based on the classical laminate plate theory, was extended to pre-



(a) (b)

Figure 6. Tensile curves under different rates of RH.

Table 3. Mechanical characteristics of the liners and flute under different rates of RH.

		Relative Humidity (%)		
		50	70	90
Upper layer	E_{MD} (Mpa)	4322	4037	2894
	E_{CD} (Mpa)	2048	1902	1477
Flute	E_{MD} (Mpa)	5107	4805	3319
	E_{CD} (Mpa)	1962	1830	1161
lower layer	E_{MD} (Mpa)	4433	4493	3099
	E_{CD} (Mpa)	2033	1828	1000

Table 4. Model results under different rates of RH.

		Relative Humidity (%)		
		50	70	90
E_{MD} model	(Mpa)	**712**	**686.07**	**475.01**
Model / exp.	(%)	10.48	10.43	10.25
E_{CD} model	(Mpa)	**391.47**	**384.55**	**253.98**
Model / exp.	(%)	-9.61	-8.98	-7.65
G_{xy} model	(Mpa)	**200.85**	**195.76**	**131.37**

dict the inelastic behavior of the material [3]. This study purpose to test the validity of this approach under different atmospheres conditions.

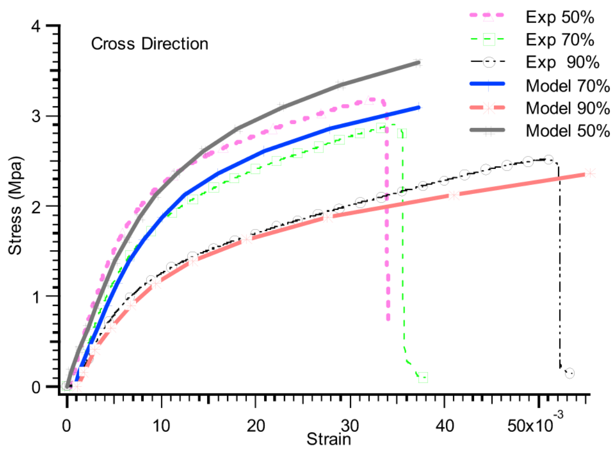


Figure 7. Modeling of the mechanical behavior of the corrugated cardboard under different rates of RH.

4.1 Elastic properties

The model need as input the elastic properties of the skins an flute obtained by tensile tests under different rates of 50%, 70% and 90% of RH (Table 3). The predicted properties at each rate of RH are compared to the experimental results (Table 4).

At 50% HR, the model estimates the Young modulus with an error of 10% compared to the experiment. This error is caused by the fact that the model does not take account of the effect of the manufacture process. During this process the skins lose some of their rigidity.

The model results at each rate of RH compared to the experimental ones gives practically the same error. This error is about 10% in the MD. In the CD we note a light fall of the error in estimation of the elastic characteristics. However this fall remains in the field of dispersion (2%). From that we deduce that the interface between the skins and flute does not affect the behavior of corrugated cardboard. We note that the model predict correctly the elastic properties.

4.2 Inelastic behavior

To predict the inelastic behavior of the corrugated cardboard, the model requires the knowledge of the behavior laws of the components of corrugated cardboard [3]. Considering the assumption of iso-strain, in a first approach, the model will be fed by the experimental results of tests carried out on the skins and flute under different atmospheric conditions. The inelastic predict behavior of the model in the MD is shown on the Figure 7.

On the whole of the rates of humidity, a good correlation between the results of the model and experimental ones is noted. At 50% RH, and 70% RH the inelastic predicted behavior over estimate the experiment one contrary at 90% HR. This is probably due to the effect of the interfaces which are not taking into account on the model.

The prospect for this study is to develop a macro-micro law of the behavior of cellulose fibers. This law will make it possible to predict the behavior of the skins and thereafter that of the corrugated cardboard.

5. CONCLUSION

The paperboard is a very sensitive material to the environmental conditions, especially moisture, but also with any handling. The corrugated cardboard showed sensitivity to the relative humidity of the environment tests. A particular attention must be made during these tests in order to not perturb the results.

Concerning elastic properties, they change significantly beyond 70% RH. This effect is more perceptible on bending characteristics than the tensile ones. Thus bending stiffness falls by 54% when the RH reaches 90%.

For the behavior beyond elastic phase, it has been shown that the failure characteristics, stress and strain failure, are even more sensitive to the effect of moisture.

The effect of the moisture in the cross direction is more significant than in the machine direction because of privileged orientation of the cellulose fibers.

An analytical model developed in previous study was applied to predict the behavior of the corrugated cardboard under atmospheric conditions. It has been found that this approach can predict correctly the elastic an inelastic behavior.

REFERENCES

[1] Aboura Z., Talbi N., Allaoui S. and Benzeggagh M.L. "Elastic behavior of corrugated cardboard: Experiments and Modeling" Composite Structures, 2004, 63, 53–62.

[2] Aboura Z., Allaoui S. and Benzeggagh M.L. "Etude et modélisation du comportement èlastique d'une structure sandwich de type carton ondulé", JNC 13, Strasbourg 2003, 1027–1036.

[3] Allaoui S., Aboura Z. & Benzeggagh M.L. "Elastic and inelastic modeling of corrugated cardboard", ICCM 15, Durban South Africa, 2005.

[4] Ishikawa T, Chou TW. "Stiffness and strength behavior of woven fabric composites". Journal of Material Science. 1982, 17, 3211–3220.

[5] Aboura, Z., Chouchaoui, C.S. and Benzeggagh, M.L., "Analytical model of woven composite laminate. Superposition effect of two plies" ECCM 6, 1993, Bordeaux.

[6] Scida D., Aboura Z., Benzeggagh M.L. and Bocherens, E., "Prediction of elastic behavior of hybrid and non-hybrid woven composite" Composites science and technology. 1997, 57, 1727–1740.

[7] Allaoui S., Aboura Z. & Benzeggagh M.L. "Effets des conditions environnementales sur le comportement mécanique de structures sandwich de type carton ondulé", JNC14, Compiègne 2005, 1165–1174.

[8] Gendron G., Dano M.L. and Cloutier A. "A numerical study of the hygro-mechanical deformation of two cardboard layups" Composite Sc. and techn., 2004, 64, 619–627.