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# **EFFECTS OF THE ENVIRONMENTAL CONDITIONS ON THE MECHANICAL BEHAVIOUR OF THE CORRUGATED CARDBOARD**

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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, in fact the relative humidity (RH), on the mechanical behaviour of a sandwich structure of the corrugated cardboard type. For that, tensile tests were used under various rates of relative humidity. In high rates of moisture, the instrumentation must be adapted. A preliminary comparison of several measurement methods of the mechanical properties was carried out. It made it possible to validate the method of strain measurement using the measurement of the displacement which requires a minimal handling of the specimen. During this study, the effect of the water content on the mechanical properties is presented. Moreover the character viscoelastic coupled with the damage of this material is high lighted.

**KEYWORDS:** Corrugated cardboard – Relative humidity – sandwich –mechanical behavior

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## Introduction

The choice of material for designer, considering performance and competitiveness, becomes more delicate. This choice can be done on the basis of material nomenclature containing their mechanical characteristics which are obtained by mechanical tests. For the case of corrugated cardboard the principal mechanical tests used are 3 points and 4 points bending tests (ASTM C393-62) and shearing tests (ASTM C273-61). These tests make it possible to obtain bending rigidity of corrugated cardboard in both orthotropic directions as well as the shear moduli  $G_{xz}$  and  $G_{yz}$ . Tensile test used to characterize the paperboard (skins) requires special devices (ISO 1924-1 and ISO 1924-2). This test is not extended to the case of the corrugated cardboard because it is regarded as structure. Another approach regarding corrugated cardboard as monolithic material was developed by Aboura and al. [1] and gave satisfaction. Following that, tensile test was adapted for the case of the corrugated cardboard by using strain gage instrumentation [2]. Mechanical tests were carried out under controlled atmosphere (23°C and 50% of relative humidity) as recommended by French standard NFQ 03-010.

Corrugated cardboard is used under various atmospheric conditions. The most severe (around 90% RH) correspond to storage in cold room with forced moisture. A good optimization of the use of this material requires knowledge of its behaviour under this type of atmosphere. It is the goal of this work which proposes to study the effect of the environmental conditions, in fact moisture, on the behaviour of corrugated cardboard. The first part of this study is devoted to the choice of the instrumentation which is important because the material becomes sensitive to any handling during mechanical tests. Tensile test were carried out under various configurations with several type of instrumentation in order to validate one of them making it possible to be used

under severe atmospheric conditions. Thereafter, tensile tests under various relative humidity (RH) were carried out to evaluate the impact of moisture content on the behaviour of corrugated cardboard.

## **Material of the study**

Corrugated cardboard of this study is of type “C “. It’s composed by an upper layer, lower layer and one core which are respectively noted Recto, Verso and Well. All the constituents are composed with 100% cellulosic recycled fibers. The weight of the sandwich is 580g/m<sup>2</sup> and the flute step is P=8mm. The geometrical characteristics illustrated on figure 1 are presented in table 1. MD and CD respectively indicate the machine and the cross direction. Machine direction indicates the direction of manufacture of the paperboard, therefore the orientation of fluting.

## **Validation of measurement methodology**

Tensile tests were carried out under various configurations in order to propose a methodology allowing a valid measurement for tests under an atmosphere with severe moisture. For the paperboard, the standards ISO 1924-1 and ISO 1924-2 purpose to measure the lengthening by using an incremental position sensor. This lengthening makes it possible to express a strain when it is brought back to the working length of the specimen. This configuration was used and then extended to the case of the corrugated cardboard for its validation. The second configuration of the tests is made with specimens instrumented by strain gages. The specimens are instrumented by extensometers in the third configuration. This instrumentation type cannot be

used for the skins because it's likely to damage the specimens considering their flexibility. The last configuration consists of video tensile tests (figure 2). For these tests, we place four circular points on one face of the specimen. These points generate two perpendicular segments (longitudinal direction and transverse direction). A camera makes it possible to digitize the barycentre positions of the points, and to follow their evolutions during the tests. Processing software of data makes it possible to obtain the longitudinal and transverse strains at exit.

The tests of all configurations were carried out, on corrugated cardboard and its components, in conditions of 23°C and 50% RH. The used specimens are receptively inspired from ISO type NF T51-034 and NFQ03-002 and prepared according to the method used by Aboura and al. [1].

## ***Results and discussions***

Tensile tests with various instrumentations highlighted an orthotropic behaviour of the sandwich and its constituents. Young moduli are more significant in the machine direction than in the cross direction (Table 2).

### ***a) Skins***

According to standards ISO 1924-1 and ISO 1924-2, the measurement of the strain is done by the measurement of lengthening on the paperboard. The second method used is video tensile. We note a good correlation between the characteristics of the skins obtained by the measurement of lengthening and those obtained by the video tensile. It should be noted that video tensile measures lengthening between two points of specimen (in our case 10mm). Difference

between the two results obtain by the two instrumentations is with height of the results dispersions (maximum 8% for Well in MD and Recto in CD).

The tests instrumented by a strain gages did not give satisfaction like precedent studies [2]. The materials used for this study are different from those used for the precedent one. It enables us to say that the validity of the results obtained by strain gages instrumentation depends on the nature of treatment undergone by the faces of the material. Table2 shows that the mechanical characteristics obtained, for the skins (upper layer, lower layer and flute), are twice larger than those obtained with the methods of lengthening. We reach an error of almost 240% in the case of the flute (Well) in CD. It is due to a local rigidification of materials caused by the joining of the strain gages which modified the local behaviour of paperboard.

#### ***b) Corrugated cardboard***

The first technique used to measure the strain of corrugated cardboard is video tensile, validated before. The results obtained are illustrated in table 2. The measurement method of strain by lengthening measurement used for the paperboard was extended to the case of corrugated cardboard. Results obtained by the last method are in good correlation with those obtained by video tensile, and that in the two directions (MD and CD). It enables us to say that the methodology of strain measurement by lengthening gives satisfaction on corrugated cardboard.

Extensometer is the third instrumentation used. The moderate tightening of the extensometer on the corrugated cardboard specimens, in order to not damage them, caused its slip. The results of tests were then affected. The errors of the results are about 10% and 30%, respectively in MD and CD, compared to those obtained by lengthening method and video tensile. In the cross direction

the error is higher than in the machine direction. It is due to the fact that the deformation is more significant in the direction CD and the extensometer slips more.

As for the case of the skins, tests instrumented by strain gages did not give satisfaction. Mechanical parameters are obtained with an error around 29% in the machine direction and 33% in the cross direction. The local rigidification generated by the joining of gages did not have as much impact on the corrugated cardboard as it was on the skins. This can be explained by the fact that the sandwich had a structure behaviour what is not the case of the skins.

It will be also noted that in all the cases, errors made on the measures are more significant in CD than in MD. This indicates that the material is more sensitive in this direction.

The results of the strain gages instrumentation and extensometer one have a rather significant dispersion with a maximum of 31%. For the other kinds of instrumentations, the dispersion of the results is lower than 6%.

After these tensile tests, the methodology of strain measurement by lengthening measurement was validated for the case of corrugated cardboard. This method is appropriate for mechanical tests at high relative humidity which will be carried out under climatic chamber. This method requires little handling of the specimens. Video tensile cannot be used under these conditions. It is due to the fact that the presence of the climatic chamber prevents camera from taking the image

## **Moisture equilibrium of the material**

Measurement methodology, validated previously, will be used to measure the strains during tensile tests. These 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.

Tests of conditioning material were carried out to determine the threshold from which the materials of this study reach state of moisture equilibrium. 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, 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 [3]. 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 0.01mg.

Figure 3 shows that moisture equilibrium was achieved after 100 minutes. This state corresponds to moisture content of 8% at 9% for corrugated cardboard and its components. If the dry basis is considered as reference, the moisture content will be 15%.

## **Mechanical tests under various RH**

The mechanical tests are carried out on specimens of corrugated cardboard and its components (Recto, Verso and Well) on tensile testing machine equipped with a climatic



chamber. The chamber is equipped with a thermo-hygrometer which makes it possible to control the rate of RH. His precision is  $\pm 3\%$ . Tests were carried out under various controlled conditions varying from 35% RH to 90% RH. Temperature is fixed at 23°C. For each value of RH, specimens are conditioned in climatic chamber during 24 hours as recommended by French standards NFQ 03-010. After this maintenance, the specimens reach a state of moisture saturation then they are tested.

### ***Results and discussions***

The conventional normal conditions of tests are 23°C and 50% RH. Corrugated cardboard and its components were tested at 35% RH to measure the effect of the dry conditions on their behaviours.

Figure 4 and figure 5 show that the elastic characteristics do not evolve compared to those of reference (50% RH) in MD. On the other hand they increase of almost 13% in CD. Beyond 50% RH, we note the same tendency in the evolution of elastic properties for corrugated cardboard and its components. Up to 70% RH, the Young moduli evolve little (less than 10%). Thus there is a maximum fall of 10.1% in the case of the upper layer in cross direction.

By increasing the moisture content, water content of material increases appreciably and breaks the bonds between cellulosic fibers. This strongly influences the mechanical behaviour of the material. Thus at rate of 90% RH, the Young moduli of the study materials fall of more than 30% in MD and up to 50% in CD (figure 5).

Moisture content influence is more significant in the cross direction than in the machine direction. This can be explained by the fact that behaviour of the skins in CD, corresponding to the transverse direction of cellulosic fibers orientation, strongly depends on the bonds between

fibers. This phenomenon is extending for the case of corrugated cardboard where MD corresponds to the machine direction but also within the meaning of fibers orientation of its constituents.

Figure 6 and figure 7 present tensile curves of corrugated cardboard under various rates RH, in MD and CD. It is noted that the yield stress decreases with the increase in the moisture content as well as failure stress which is more significant for dry conditions. On the other hand, ultimate strain is proportional to the evolution of the relative humidity.

Thereafter, tensile tests in loads and discharges were carried out to evaluate the effect of damage coupled with the relative humidity on corrugated cardboard. Figure 8 shows various cycles of loads at various levels of stress. We note the appearance of permanent strain beyond elasticity. Moreover loops of hysteresis increase with the level of loading, which can indicate energy dissipation and thus a presence of damage. The kinetics of damage takes a quasi linear form (figure 9). The increase of the damage rate ( $D = 1 - (E_x/E_0)$ ,  $E_x$  is measured in downward phase between 0.85% and 0.25% of the load reached) becomes more marked only towards the end of the tests, before failure. Failure occurs at small values of  $D$ , about 0.20 in MD and 0.40 in CD. Damage curves at different RH have the same pace, but are shifted (figure 9).

We notice that for the same stress intensity, the damage rate increases slightly with increasing relative humidity and this in the two directions. This increase is due to the fact that threshold of damage beginning decreases with the increase in RH. For the value of the damage parameter ( $D$ ) at failure, it also decreases when the rate of RH increases.

The whole of the observations shows that the inelastic behaviour is not only due to the damage but also to viscoelastic behaviour of material. In order to confirm this phenomenon, tensile tests under scanning electron microscopy (SEM) on Recto skins were carried out. Figure 10 shows tensile curve under SEM with maintenance of the load at various levels. It appears that in elastic

phase, the load remains constant at the time of maintenance (point A of figure 10). On the other hand the maintenance in nonlinear phase of curve shows a relaxation of material. Relaxation phenomenon is more pronounced with the high level of load (points B and C of figure 10). On the other hand this phenomenon is not accompanied by damage as shown by fractographies. Damage is perceptible at the end of the loading.

## **Conclusions**

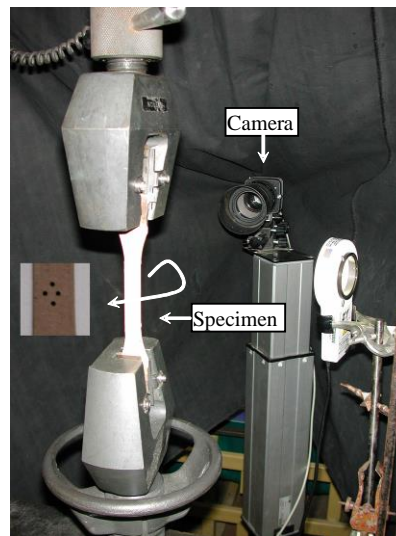
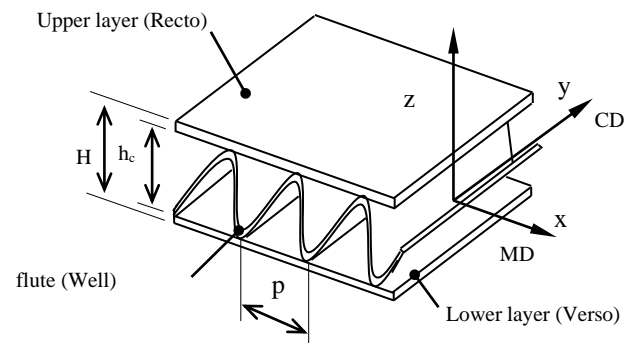
Paperboard is very sensitive material to the environmental conditions, especially moisture, but also with any handling. This study made it possible to show the importance of the choice of instrumentation for mechanical tests. Method of strain measurement via lengthening measurements, used for paperboard, has been extended and validated for corrugated cardboard.

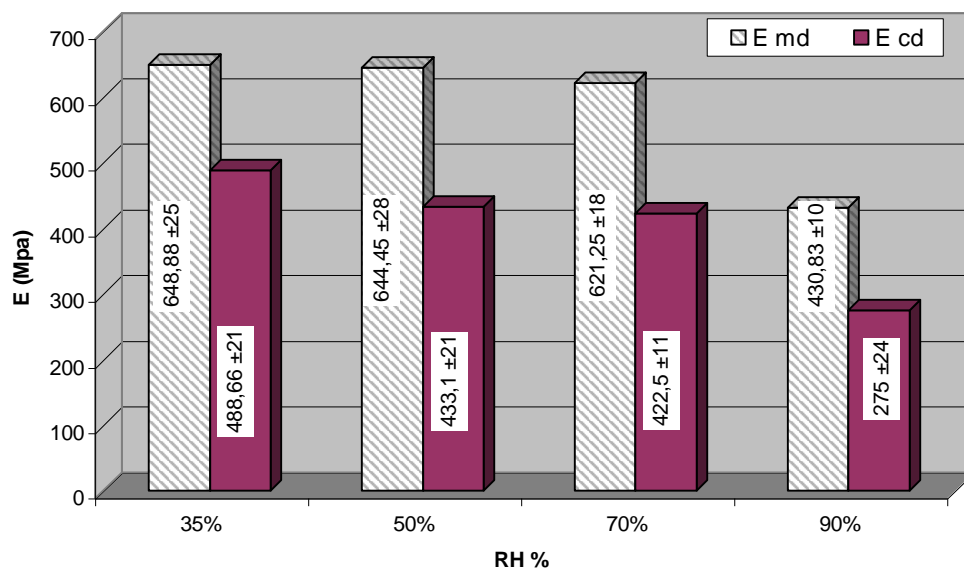
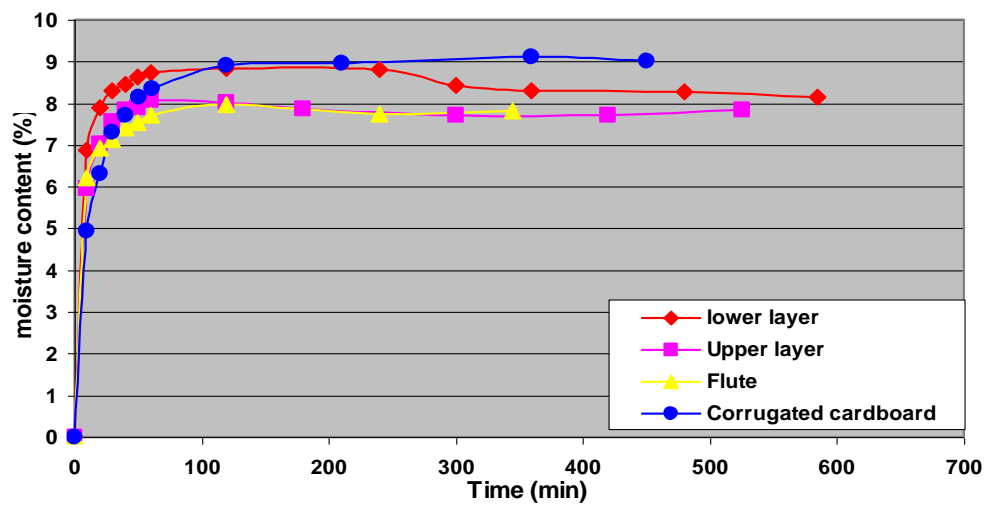
Materials showed sensitivity to the relative humidity of tests environment. Elastic characteristics evolve significantly beyond 70% RH and we reach falls of almost 50% at 90% RH. Failure stress and ultimate strains are even more sensitive to the effect of moisture since their evolutions are noted whatever the rate of RH. The influence of relative humidity in the cross direction is more significant than in machine direction because of privileged orientation of cellulosic fibers.

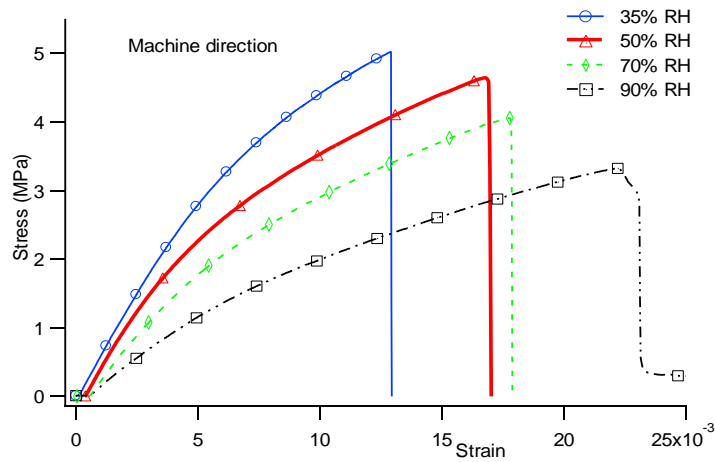
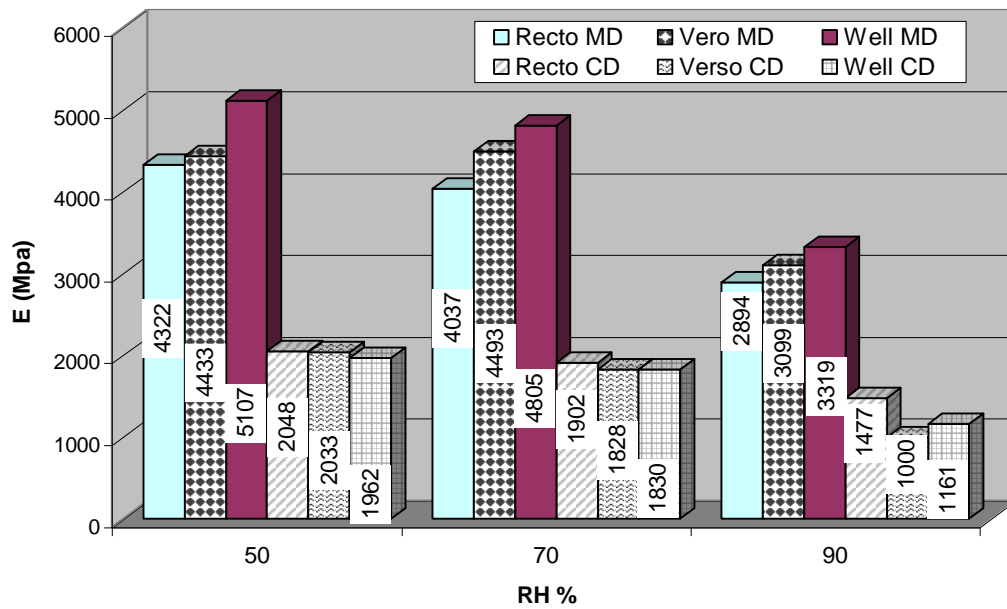
The kinetics of damage showed that inelastic behaviour of corrugated cardboard is not only due to damage but also to viscoelastic behaviour. The purposes of the tensile tests under SEM, in progress, are to better determine phenomena occurring in material. This identification of phenomena will be necessary for installation of macroscopic behaviour law.

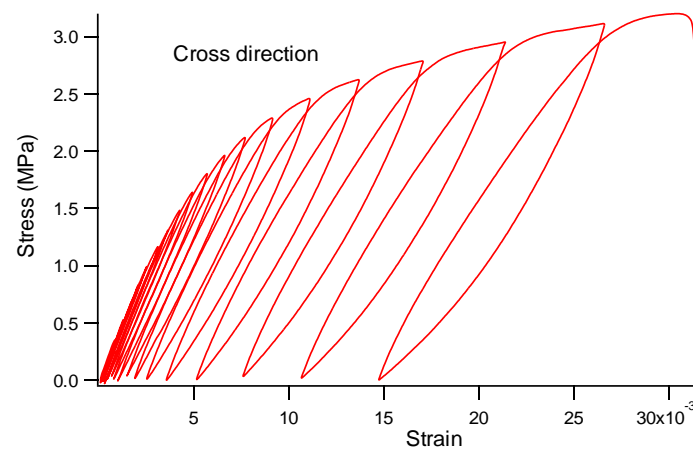
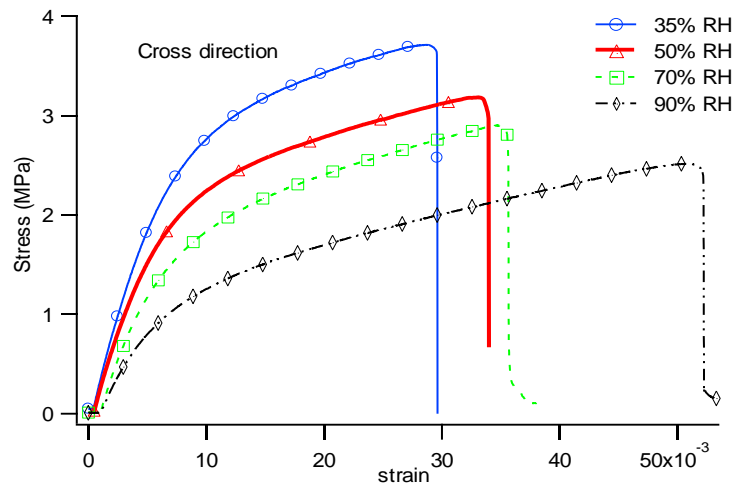
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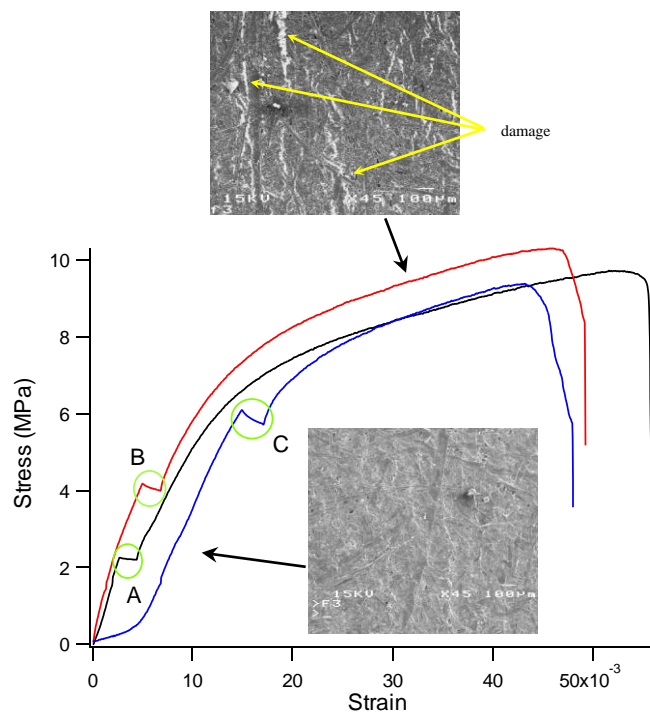
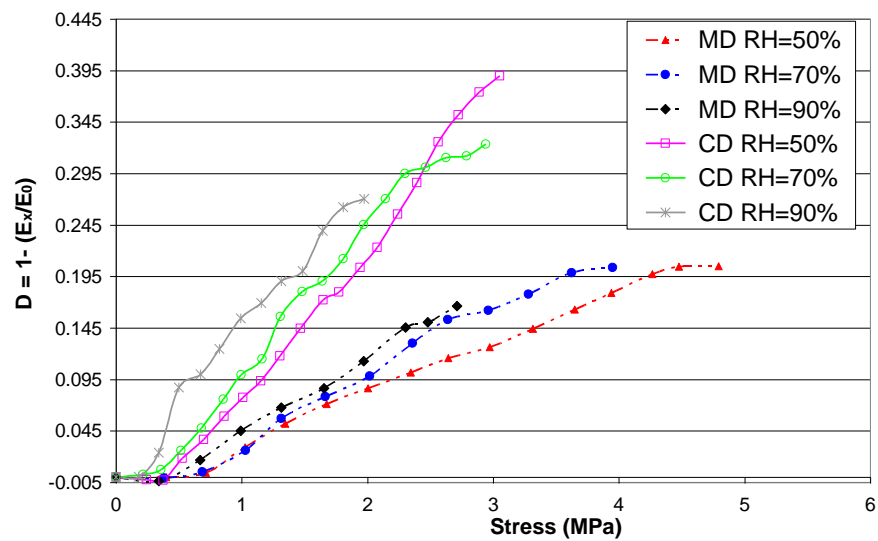












		Corrugated	Upper layer	Lower layer	Fluting		
		cardboard (H)	(Recto)	(Verso)	(Well)		
Thickness (mm)		4.1	0.264	0.26	0.21		
		instrumentations					
Material	Direction		Position	Video tensile	Strain gages	Extensometer	
			sensor				
Corrugated	cardboard	E (MPa)	<b>644.45</b>	<b>656</b>	<b>830.67</b>	<b>715.75</b>	
		MD	Dispersion (%)	4.37	6.39	9.46	23.77
		E (MPa)	<b>433.10</b>	<b>412.38</b>	<b>577.07</b>	<b>548.02</b>	
		CD	Dispersion (%)	4.87	6.14	8.34	31.34
Recto		E (MPa)	<b>4322.20</b>	<b>4514.53</b>	<b>8054.65</b>		
		MD	Dispersion (%)	13.12	5.68	8.11	
		E (MPa)	<b>2048.27</b>	<b>1895.83</b>	<b>3983.33</b>		
		CD	Dispersion (%)	3.59	3.72	17.53	
Verso		E (MPa)	<b>4433.48</b>	<b>4458.60</b>	<b>8279.66</b>		
		MD	Dispersion (%)	9.11	6.21	2.51	
		E (MPa)	<b>2032.91</b>	<b>1944.50</b>	<b>3780.51</b>		
		CD	Dispersion (%)	9.02	3.34	0.35	
Well		E (MPa)	<b>5106.67</b>	<b>4703.75</b>	<b>7348.83</b>		
		MD	Dispersion (%)	4.45	4.72	0.86	
		E (MPa)	<b>1962.35</b>	<b>1854.30</b>	<b>6342.44</b>		
		CD	Dispersion (%)	5.66	4.34	25.26	

**Figure 1:** Corrugated cardboard geometry

**Figure 2:** Video tensile test

**Figure 3:** Moisture content at equilibrium for corrugated cardboard and its constituents

**Figure 4:** Evolution of the Young moduli of the corrugated cardboard according to RH

**Figure 5:** Evolution of the Young moduli of the skins according to RH

**Figure 6:** tensile curves of the corrugated cardboard in MD according to RH

**Figure 7:** tensile curves of the corrugated cardboard in CD according to RH

**Figure 8:** Load and discharge curve of corrugated cardboard in CD

**Figure 9:** Kinetics of damage of corrugated cardboard according to RH.

**Figure 10:** tensile curve with load maintenance. Layer Recto in cross direction

**Table 1:** *Geometric characteristics of the corrugated cardboard and his constituents*

**Table 2:** *Tests results of the validation of the measurement methods*