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Effect of Humidity on Paper and Corrugated Board Strength Parameters

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Abstract
One of the main problems as regards practical utilisation of corrugated board as packaging material is reduced strength followed by the higher humidity of the fibrous materials of which corrugated board is made. Based on the results of laboratory tests, the effect of humidity on the Young's modulus, Poison's ratio and strength properties of fibrous materials used for corrugated and coating layers as well as on the bending stiffness and edge crush strength of corrugated board were determined. Treating fibrous materials as elastic bodies, the stiffness and edge crush strength of the board tested were calculated theoretically. A comparison between calculation and measurement results proved that it is possible to predict changes in the mechanical properties of corrugated board caused by changes in humidity provided we know the effect of humidity on basic properties of the fibrous material of which the corrugated board was made.

Key words: *corrugated board, paper, humidity, bending stiffness, edge crush strength.*

Introduction

Corrugated board is widely used by many industries, not only as packaging material but also in furniture production or as construction elements. Corrugated board is made from renewable materials and after being used it is a source of materials in the form of recovered paper. However, the complicated structure of fibrous materials makes it difficult to predict its strength. Usually the strength of paper products is predicted on the basis of the mechanical properties of paper, which are determined in strictly defined climatic conditions. In practice, paper products are used in different climatic conditions, changing their humidity and mechanical properties.

In order to estimate the loading capacity of paper products used in climatic conditions, different from standardized ones, laboratory tests are performed after conditioning in such conditions.

Despite the fact that changes in the basic mechanical properties of paper caused by those in its humidity have been the subject of various studies, described by cited literature [1 - 6], they are not used to estimate the loading capacity of paper products in variable climatic conditions. Additionally studies on the effect of paper humidity on Poisson's ratio have not been carried out yet.

In practice, it is convenient to estimate humidity in fibrous material assuming that it has reached equilibrium humidity with surrounding air; however, in such a case it is important to know whether the equilibrium has been achieved through adsorption or desorption [7, 8]. To avoid making errors caused by drying hysteresis, this study shows changes in all the tested properties of paper and board in the form of a function of the moisture content given as a relation of the water mass contained in the paper to a unit of the dry substance.

As is well-known, in many cases paper and solid board can be treated as bodies acting according to Hooke's law. It allows to calculate the loading capacity of paper products using simple mathematical relationships based on the basic material constants of paper.

Hitherto knowledge allows to assume a thesis that by knowing the effect the humidity of papers has on their mechanical properties and treating paper as orthotropic elastic material, we can predict changes in the mechanical properties of corrugated board made of those papers caused by various conditioning conditions.

Methods

In order to verify the thesis proposed, tests of Young's moduli, the tensile and compressive strength and Poisson's ratio were carried out for papers after their conditioning in different climatic conditions. Measurements were made for four grades of papers for the production of corrugated board. The papers were marked in the following way:
- P1 – testliner 135 g/m^2,
- P2 – fluting 120 g/m^2,
- P3 – testliner 120 g/m^2,
- P4 – testliner 115 g/m^2.

Additionally edge crush tests (ECT) and the bending stiffness (BS) of double faced corrugated board with flute B, made from the papers tested, were carried out. The boards were marked as T1 and T2, and their weight and thickness were as follows: 445 g/m^2 & 405 g/m^2, 3 mm & 2.9 mm.

The humidity of materials tested was changed as regards the equilibrium humidity obtained in air of 23 °C and relative humidity ranging from 10 to 90%.

Young's moduli and the tensile strength were determined according to PN-EN ISO 1924-2:2010. The compressive strength to the forces in the paper plane were determined using the short-span compressive test according to PN-ISO 9895:2002. To determine Poisson's ratio, the method of the propagation velocity of ultrasonic waves in paper was used [9] with the following relationship:

$$\nu_{MDCD} = \sqrt{\frac{E_{CD}}{E_{MD}}\left(1 - \frac{E_{CD}}{\rho \cdot V_{CD}^2}\right)} \qquad (1)$$

where:
V_{CD} – propagation velocity of ultrasonic waves in CD,
E – Young's modulus (index indicates the direction for which the modulus was determined),

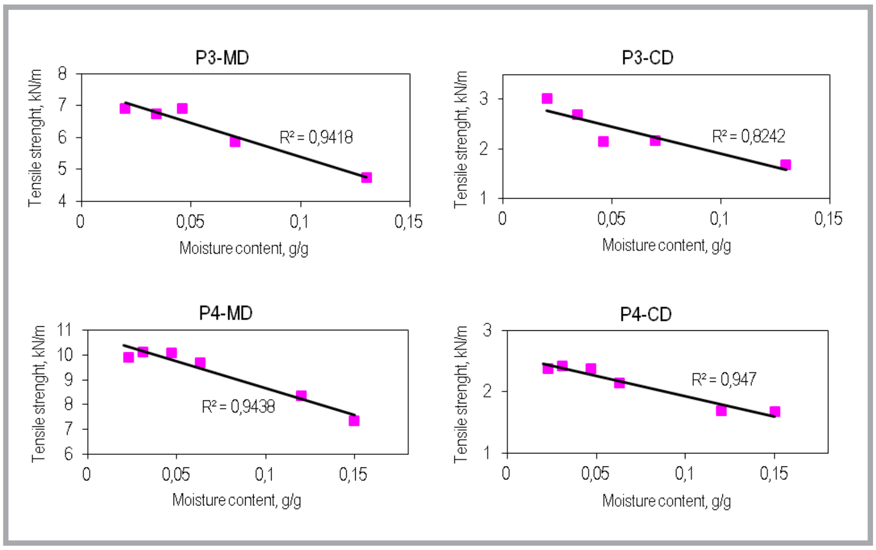

Figure 1. *Tensile strength vs. moisture content (MD – machine direction, CD – cross direction).*

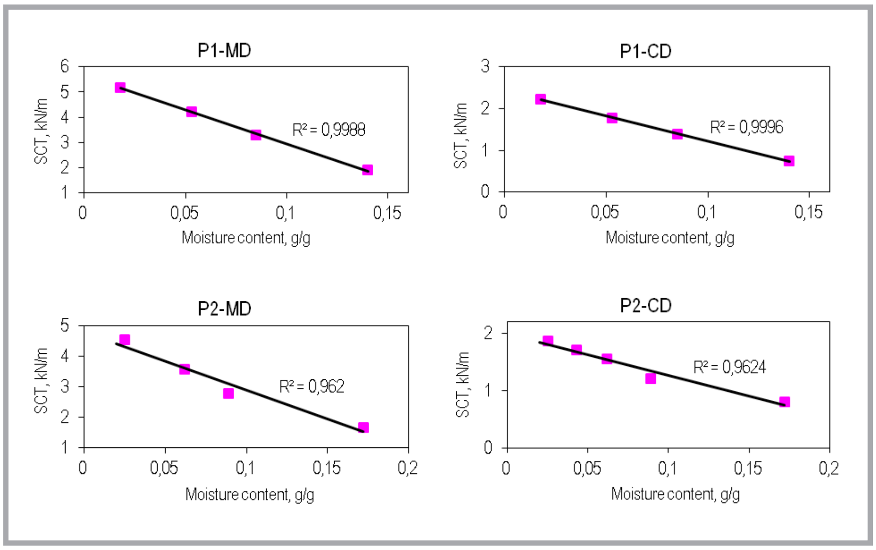

Figure 2. *Short-span compressive strength vs. moisture content (MD – machine direction, CD – cross direction).*

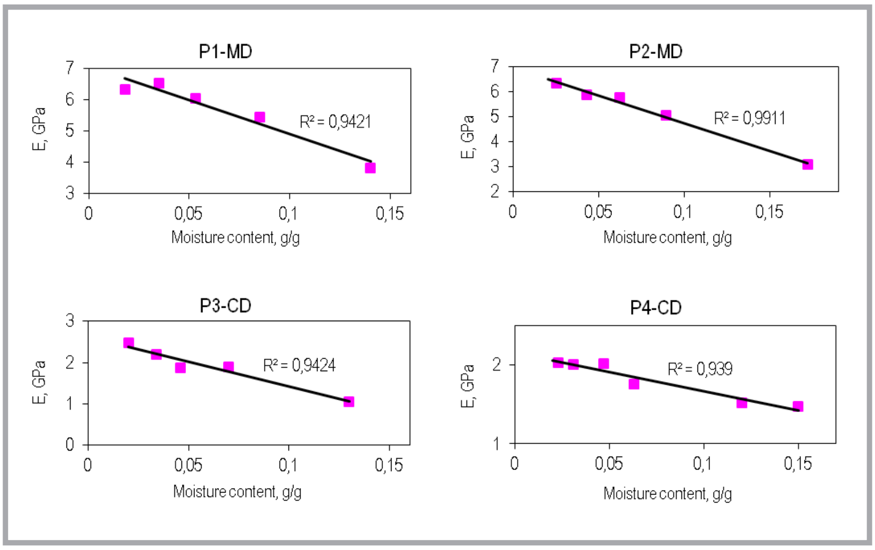

Figure 3. *Young's moduli vs. moisture content (MD – machine direction, CD – cross direction).*

ν – Poisson's ratio (first index shows the direction of transverse strain and the other indicates the stress),
MD – machine direction,
CD – cross direction.

$\nu_{CD\,MD}$ was calculated on the basis of the following relationship:

$$\nu_{CD\,MD} = \frac{E_{MD} \cdot \nu_{MDCD}}{E_{CD}} \quad (2)$$

ECT and BS of the corrugated board were measured according to PN-EN ISO 3037:2009 and PN-ISO 5628:1995.

Theoretical values of the bending stiffness of the corrugated board in the cross direction BS_{CD} were calculated on the basis of the following relationship:

$$BS_{CD} = \frac{1}{l}\left[\frac{E_{CD1} \cdot J_1}{\left(1-\nu_{MD\,CD1} \cdot \nu_{CD\,MD1}\right)} + E_{CD2} \cdot J_2 + \frac{E_{CD3} \cdot J_3}{\left(1-\nu_{MD\,CD3} \cdot \nu_{CD\,MD3}\right)}\right] \quad (3)$$

where:
l – sample width,
J_i – area moment of inertia of a layer (i) in relation to the neutral axis of cross-section of the bent corrugated board,
i – layer designation (respectively: 1 – top layer, 2 – flute, 3 – bottom layer).

The impact of fluting on bending stiffness in the machine direction BS_{MD} is very small, and the value thereof was calculated on the basis of the following relationship:

$$BS_{MD} = \frac{1}{l}\left[\frac{E_{CD1} \cdot J_1}{\left(1-\nu_{MDCD1} \cdot \nu_{CDMD1}\right)} + \frac{E_{CD3} \cdot J_3}{\left(1-\nu_{MDCD3} \cdot \nu_{CDMD3}\right)}\right] \quad (4)$$

The theoretical value of the edge crush strength was determined with the method described by [10] taking into account possible loss of the loading capacity of each layer as a result of crushing or local buckling.

In order to determine stresses $\sigma_{dop\ i}$, causing a loss of the loading capacity of a given layer (i), the following relationship was used:

$$\sigma_{dop\ i} = \min(\sigma_{li}, \sigma_{si}) \quad (5)$$

where:
σ_{li} – compressive stress causing the loss of the loading capacity of a layer (i) as a result of local buckling,

σ_{si} – stress causing the loss of the loading capacity of a layer (i) as a result of exceeding the compressive strength.

The method used allows to determine a range which contains the value of the edge crush strength. The upper value of ECT was estimated by summing up the loading capacity of all the layers. In order to determine the lowest value of ECT, loading transmitted by the board at the moment of loading capacity loss by the first and second layer was calculated. The first and second layer refer to the sequence of destroying, not to that of layers in the board. A higher value of calculated values was taken as the lowest value of ECT.

Results

In both directions tested– machine (MD) and cross (CD), for all papers tested, a similar type of relationship between the compressive and tensile strength and humidity in the papers was found. The results of measurements are presented in ***Figures 1*** and ***2***. Similar to the mechanical strength, Young's moduli for all the papers varied. Measurement results of Young's moduli change depending on the humidity in the paper are presented in ***Figure 3***.

For engineering purposes, it can be assumed that in the range of equilibrium humidity, the changes the papers undergo in their strength and Young's modulus as a result of an exchange of humidity with the air in which they are conditioned are sufficiently well described by a linear relationship. Such an assumption significantly facilitates practical use of the test results of the humidity effect on the mechanical properties of papers for evaluation of corrugated board strength parameters.

Figure 4 illustrates the paper humidity effect on Poisson's ratios $\nu_{MD\ CD}$ for all the papers tested. For all the papers examined, slight differences in the Poisson's ratios obtained for different humidity are contained in the limit of measurement errors, which are in the range of ±10%. On the basis of the measurement results presented, it can be assumed that the Poisson's ratios do not depend on the paper's humidity.

Figure 5 shows ECT measurement and calculation results for both corrugated board grades tested. For both corrugated board grades, the values of edge crush strength measured are contained between the top and bottom limit estimated on the basis of calculations.

Figure 6 shows measurement and calculation results of the board bending stiffness in the machine and cross direction.

Comparing the test results presented in the diagrams, it can be concluded that changes in the bending stiffness in relation to the humidity both in the case of measured and calculated values are similar. The differences between real values and values determined theoretically result from measurement errors.

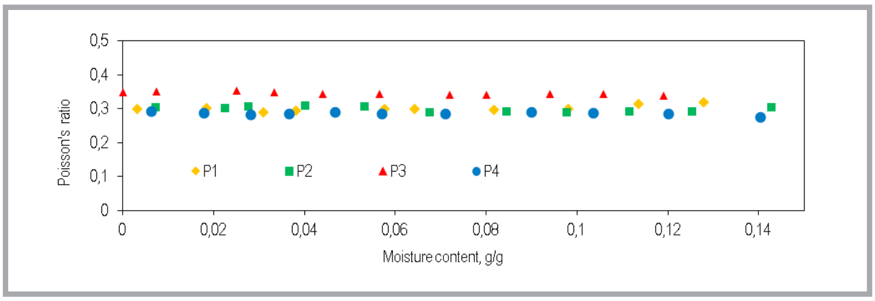

Figure 4. *Changes in Poisson's ratio $\nu_{MD\ CD}$ vs. moisture content.*

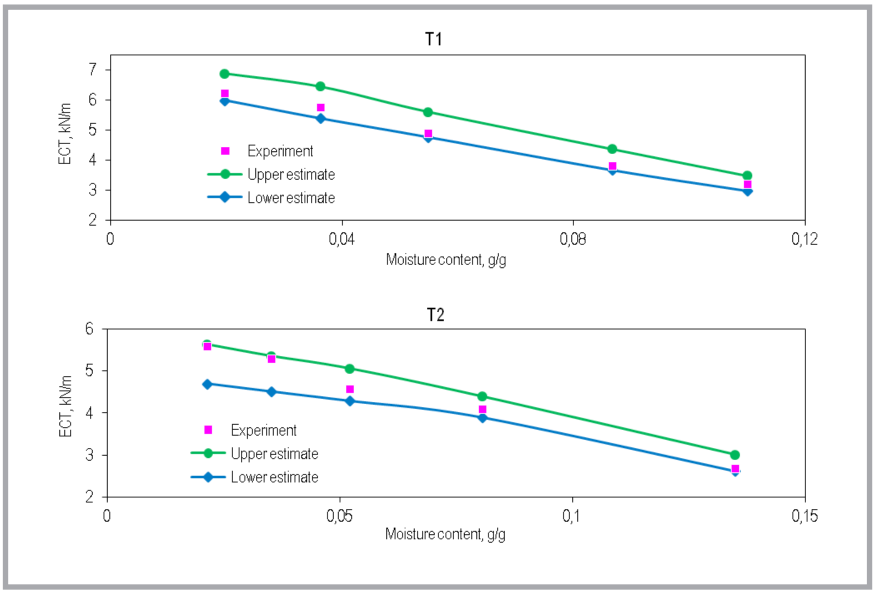

Figure 5. *Changes in ECT vs. moisture content.*

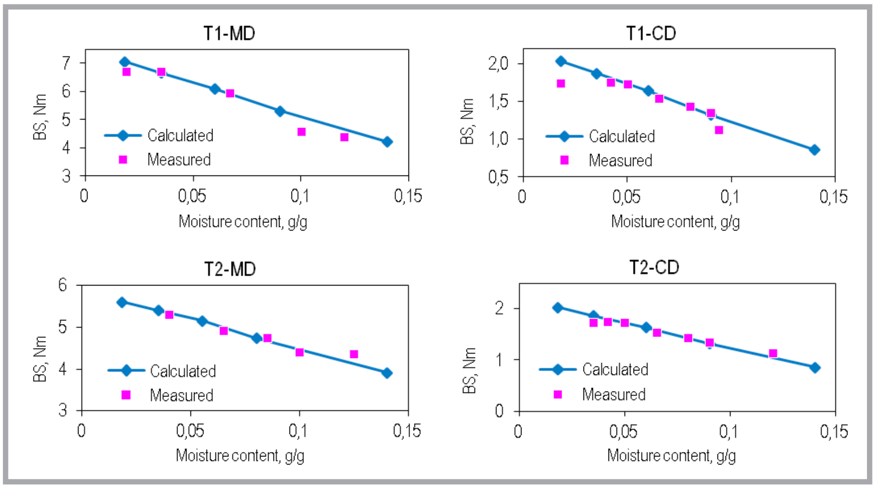

Figure 6. *Changes in board bending stiffness vs. moisture content.*

The test results presented prove the usability of the methods used for ECT and BS corrugated board in the range of changes in the humidity of corrugated board tested.

Conclusions

In the range of humidity obtained as a result of humidity exchange with the surrounding air, changes in the strength parameters of corrugated board can be predicted on the basis of the mechanical properties of paper, treating fibrous material as an elastic body.

In the range of paper humidity tested for engineering purposes, it can be assumed that Young's moduli as well as the compressive and tensile strength change linearly along with the change in paper humidity, whereas the value of Poisson's ratio does not depend on the paper's humidity.

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E-MRS 2014 FALL MEETING

Symposium M: ‘Functional Textiles – from Research and Development to Innovations and Industrial Uptake’

15 - 19 September 2014, Warsaw University of Technology, Poland

Symposium Organisers:

- Prof. **Rimvydas Milašius** Ph.D., D.Sc., Department of Materials Engineering, Kaunas University of Technology, Lithuania
- Prof. **Paul Kiekens** Ph.D., D.Sc., Department of Textiles, Gent University, Belgium
- Prof. **Francesco Branda** Ph.D., D.Sc., Department of Materials and Production Engineering,University “Federico II Napoli”, Italy

Functional textiles are one of the most important fields in textile industry and textile materials science. They include breathable, heat and cold resistant materials, ultra strong fabrics (e.g. as reinforcement for composites), new flame retardant fabrics (e.g. intumescent materials), optimisation of textile fabrics for acoustic properties.

This symposium will provide a forum for presentation and discussion of the latest scientific achievements, developments and innovations in the field of functional textiles as well as the possibilities for their industrial applications.

The symposium will bring together all innovation actors in the field fostering a multidisciplinary approach between universities, research institutes, SMEs (in textiles 95% of the companies are SMEs) and sector associations.

The symposium will be organized in conjunction with the Coordination Action 2BFUNTEX and supported by members of the COST Action MP1105 FLARETEX and COST Action MP1206 “Electrospun Nano-fibres for bio inspired composite materials and innovative industrial applications”

Hot topics to be covered by the symposium

- **Functional fibres**
- **Textile composites**
- **Protective textiles**
- **Technical textiles**
- **Textile membranes**
- **Combination of novel materials (ceramics, metal, glass powders) into structural textile based materials**
- **Industrial needs in the field of functional textiles**
- **Health & medical textiles**
- **Nanotextiles**
- **Flame retardant textiles**
- **Smart and interactive textiles**
- **Surface functionalisation and coating of textile based materials**
- **Industrial applications of functional textiles**

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