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USE OF THE FINITE ELEMENT METHOD IN STUDYING THE INFLUENCE OF DIFFERENT LAYERS ON MECHANICAL CHARACTERISTICS OF CORRUGATED PAPERBOARD

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Original scientific paper

The corrugated paperboard has become a widely used material not only for producing different packages but also for making advertising materials, pieces of art, accessories used for transportation of a number of stock items and many others. With the growing demand for corrugated paperboard comes the need for more detailed knowledge about its mechanical characteristics which would serve for improving the quality and reliability of final products. A model based on the finite element method is used to study how the mechanical characteristics of the layers of the corrugated paperboard affect its complex mechanical characteristics.

Keywords: *analysis, corrugated paperboard, FEM, layered materials, mechanical characteristics*

Korištenje metode konačnih elemenata u proučavanju utjecaja različitih slojeva na mehanička svojstva rebrastog kartona

Izvorni znanstveni članak

Rebrasti karton se sve više traži ne samo za proizvodnju različitih pakovanja već i za izradu promidžbenih materijala, umjetničkih djela, pribora pri prijevozu skladišne robe i mnogo drugih stvari. S porastom potražnje za rebrastim kartonom javlja se i potreba detaljnijeg poznavanja njegovih mehaničkih svojstava kako bi se poboljšala kvaliteta i pouzdanost finalnih proizvoda. Korišten je model zasnovan na metodi konačnih elemenata te su analizirana mehanička svojstva slojeva rebrastog kartona i njihov utjecaj na njegova ukupna mehanička svojstva.

Ključne riječi: *analiza, materijali slojeva, mehanička svojstva, MKE, rebrasti karton*

1 Introduction
Uvod

Corrugated paperboard is a multi layered structure which is widely used in the packaging industry to produce various boxes. In the past few years the demand for this material has grown by hundreds of times worldwide. Apart from packages, designers around the globe are starting to make different products out of it such as pieces of art, advertising products, furniture, shelters, accessories for storing and transportation of goods and many more [1, 4, 5, 8, 9]. With this widening use of the corrugated paperboard comes the need for better knowledge of its mechanical characteristics.

Corrugated paperboard normally consists of three layers – two external layers which are flat and are called "liners" and one internal corrugated layer which is called "flute" (Fig. 1).

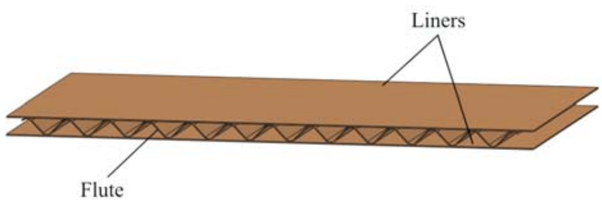

Figure 1 *Structure of the corrugated paperboard*
Slika 1. *Struktura rebrastog kartona*

Since the layers are typically made of paperboard, the complex mechanical characteristics of the corrugated paperboard will be in dependence of the characteristics of the material used for the liners and the flute. During their life cycle most of the corrugated paperboard products are subjected to the influence of different environmental conditions like variable temperatures and relative humidity. It is known that the moisture causes severe changes in the properties of the paper and paperboard [2, 6, 7] This undoubtedly brings changes in the properties of the corrugated paperboard as well. Temperature itself does not bring serious changes but relative humidity does.

Paper and paperboard are hygroscopic materials. If they are transferred from conditions of lower relative humidity to an environment with higher moisture, within a certain period of time they will reach balance with these new conditions absorbing more water [2]. Schematic graphical representation of this process is shown in Fig. 2.

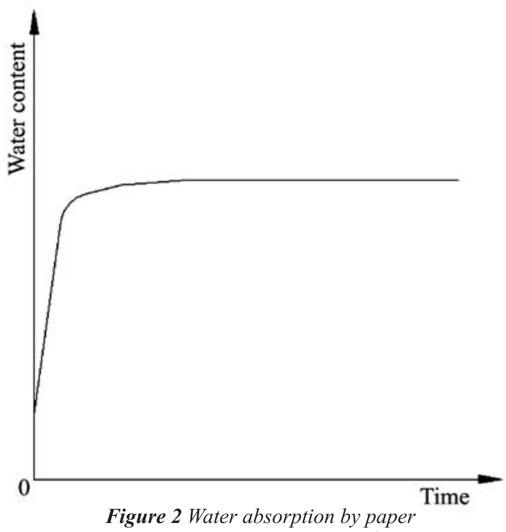

Figure 2 *Water absorption by paper*
Slika 2. *Papir i upijanje vode*

Conducted researches show that the effect of water is smaller in the so called machine direction. [2] This is the direction of the orientation of the cellulosic fibers. The direction perpendicular to it is called cross direction. The stronger effect of the water in this direction is explained by the fact that the mechanical properties are determined mainly by the hydrogen-based bonds between the cellulosic fibers which the water comprises. Since the characteristics in machine direction depend on the mechanical properties of the fibers themselves, the effect of the water in this direction is smaller.

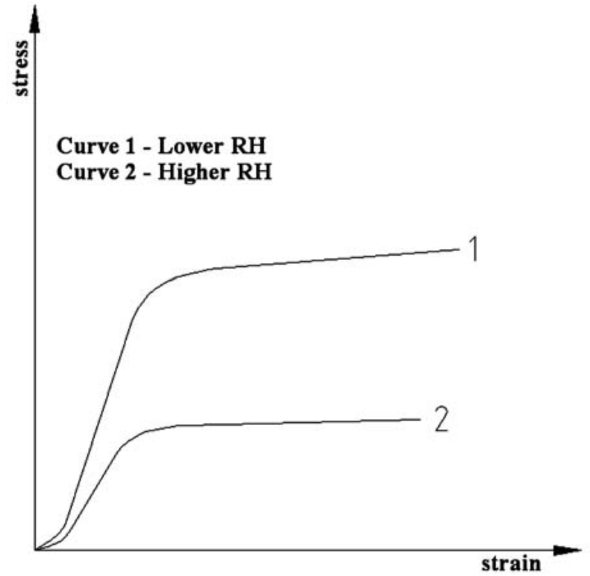

Figure 3 "Stress-strain" curves of paper at different levels of moisture
Slika 3. Krivulje "naprezanje-deformacija" kod papira pri različitim nivoima vlage

Basically, moisture causes lowering of the strength parameters of the paper such as modulus of elasticity, tensile strength, compressive strength, minimal stress which initiates plastic deformation, etc. Until about 70 % RH (relative humidity) these parameters undergo smaller change but it becomes bigger once the relative humidity rises above this level [2]. Fig. 3 schematically shows how the "stress – strain" curves of the paper differ from one another in conditions of lower and higher relative humidity.

In order to study how the changes of the mechanical characteristics of the individual layers of the corrugated paperboard affect its complex mechanical characteristics, a model based on the finite element method (FEM) is used.

2 FEM based model and conducted studies
Model zasnovan na MKE i provedena ispitivanja

The used 3D FEM based model is made of a piece of corrugated paperboard with "C" flute type. This is the most widely used type of flute. The pitch of the flute is 8 mm. and the total thickness is 4,1 mm. Visually these parameters are represented in Fig. 4.

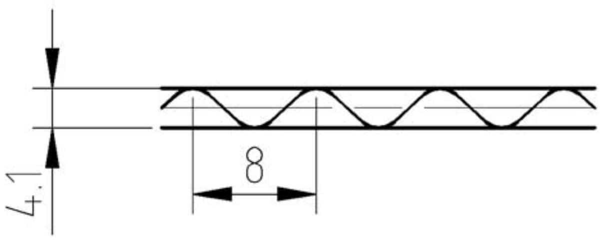

Figure 4 Geometrical parameters of "C" flute type used for the modeling – dimensions are in millimeters
Slika 4. Geometrijski parametri rebara tipa "C"korištenih za modeliranje – dimenzije su u milimetrima

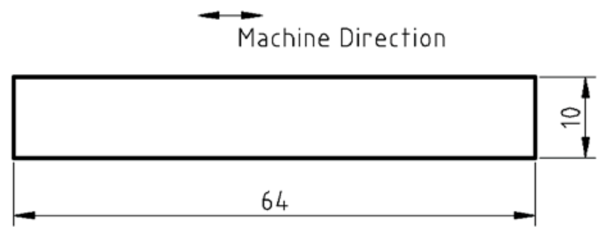

Figure 5 Geometrical parameters of the used model – dimensions are in millimeters
Slika 5. Geometrijski parametri korištenog modela – dimenzije su u milimetrima

The dimensions of the used model are as follows: 10 mm. of width and 64 mm. of length. This is visually represented in Fig. 5.

The model is divided (meshed) into 2399 finite elements while the total number of nodes is 7636. The type of used element is "shell" – quadratic. It has 8 nodes and 6 degrees of freedom is given to each node. Schematic representation of the element is shown in Fig. 6.

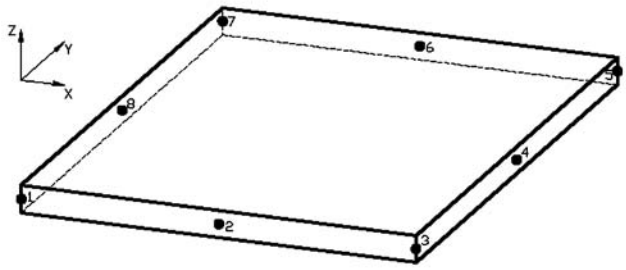

Figure 6 Schematic representation of the used "shell" element
Slika 6. Shematski prikaz upotrebljenog elementa "kvadratića"

The size of the elements on the external layers is 2 mm. each while the ones used for the internal layer are with non constant size. This is because of its rather complex form. The meshed 3D model is shown in Fig. 7.

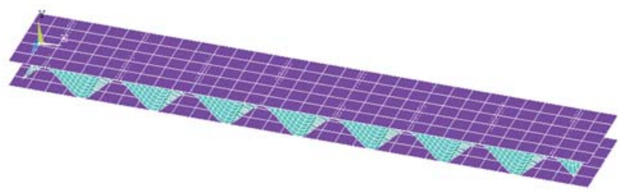

Figure 7 Meshed 3D model with finite "shell" elements
Slika 7. Umreženi 3D model s konačnim elementima "kvadratićima"

The thickness of the liners is 0,26 mm, while the one of the flute is 0,21 mm. These are common thicknesses for paperboard used to make these layers.

The model is subjected to tensile loading. This is due to the fact that normally the mechanical property such as modulus of elasticity, which is a crucial parameter for common FEM simulations used by designers, is determined by conducting tensile tests. On the other hand the experimental "stress – strain" curves which are available for paperboards and corrugated paperboard are also taken by running such an experiment. [3]

The model is loaded using the force which rises from 0 N to 160 N by steps of 8 N each. Visually the applied load and the boundary conditions for the model are shown in Fig. 8.

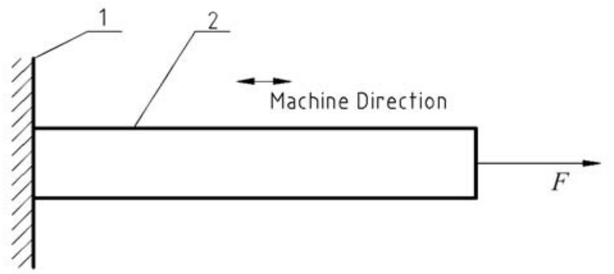

Figure 8 *Applied load (2) and defined boundaries (1)*
Slika 8. *Primijenjeno opterećenje (2) i definirane granice (1)*

The aim of the first conducted study is to examine the reliability of the proposed model. One material is assigned to both external layers and another is assigned to the internal fluted layer. "Stress – strain" curves for these materials are shown in Fig. 9.

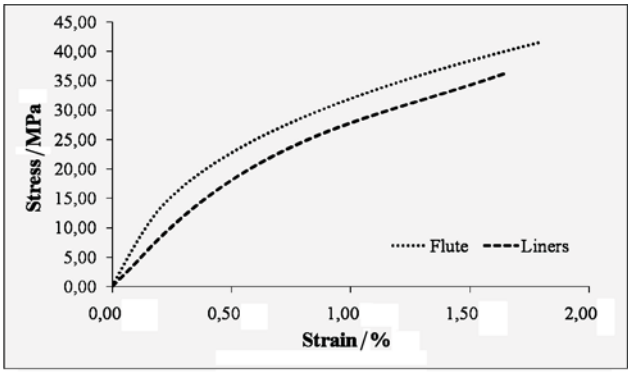

Figure 9 *"Stress – strain" curves used for different layers* [3]
Slika 9. *Krivulje "naprezanje-deformacija" korištene za različite slojeve* [3]

After the calculation procedures have been carried out we examine the stress distribution in the model as well as the strain in different areas of the corrugated paperboard panel. This allows us to see which of its parts undergo elastic deformation and where plastic deformation occurs. [10]

We use the obtained results to create a theoretical complex "stress – strain" curve of the corrugated paperboard panel. We compare this curve to the experimentally determined one. [3] What we see is satisfactorily good coincidence of both curves. Visually this comparison is shown in Fig. 10.

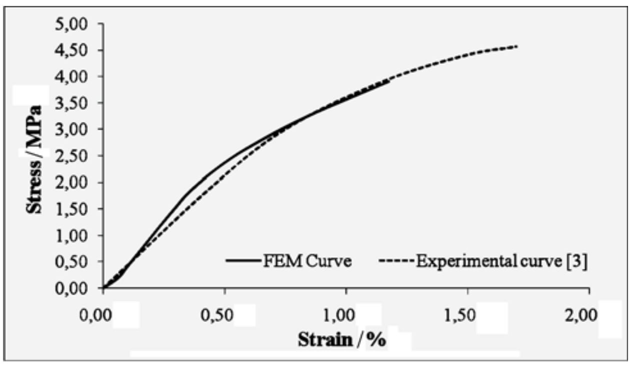

Figure 10 *Comparison between the experimental and FEM complex curves for the corrugated paperboard*
Slika 10. *Usporedba između eksperimentalnih i složenih krivulja MKE rebrastog kartona*

This gives us the opportunity to conclude that the proposed model is reliable enough and can be used to carry out more detailed studies of the corrugated paperboard complex properties.

In order to research how the layers individually affect the complex characteristics of the paperboard we change the properties of their assigned materials by predefining their "stress – strain" curves. At first we change only the curves for the material used for the liners. Each curve is defined by 20 points (excluding the zero point). Each point has two coordinates – the X coordinate for the strain and the Y coordinate for the stress. We multiply the X coordinate of each point by 0,997 and by 0,82 we multiply their Y coordinates. In this way we generate 20 new points (excluding the zero point) which stand for a new curve. By following this procedure we produce 5 additional curves. They are all shown in Fig. 11. All this is done because of two main reasons. The first is that we imitate the changing of mechanical behavior of the paperboard when it absorbs water from the environment. The second is that there are no enough experimental curves available, so we can seek a reliable and accurate enough dependency.

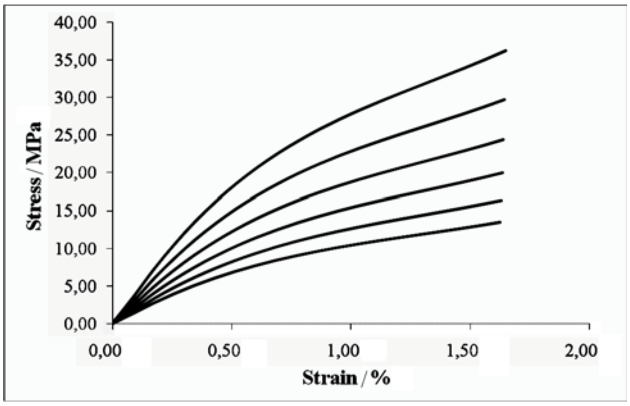

Figure 11 *Used "stress – strain" curves for the liners*
Slika 11. *Korištene krivulje "naprezanje-deformacija" za vanjske slojeve*

Calculation procedures are carried out for each of these 6 materials and the results are examined. Basically we receive 6 different complex "stress – strain" curves for the corrugated paperboard. They are shown in Fig. 12.

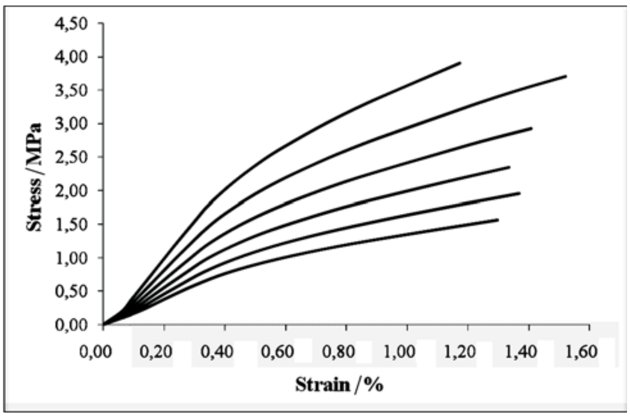

Figure 12 *Resulting "stress – strain" complex curves*
Slika 12. *Dobivene složene krivulje "naprezanje – deformacija"*

First we study how the change of the modulus of elasticity of the material of the liners affects the equivalent modulus of elasticity of the corrugated paperboard panel.

Graphically this is shown in Fig. 13 depicted with dashed line.

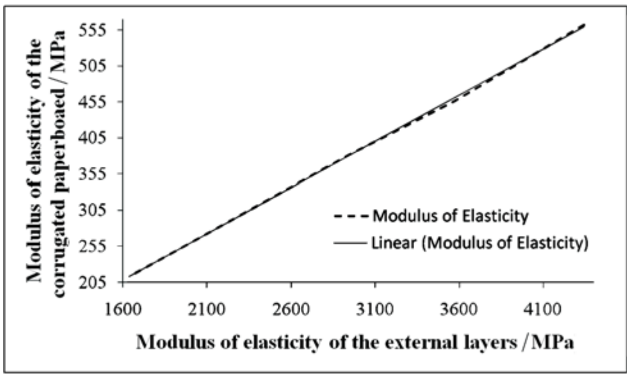

Figure 13 *Effect of "liners" on the modulus of elasticity*
Slika 13. *Djelovanje "vanjskih slojeva" na modul elastičnosti*

We can see from the chart that this is almost a straight line, so we find the linear equation of regression which is written as follows:

$$Y(X) = 0{,}12808 \cdot X + 3{,}11625. \tag{1}$$

The coefficient of regression R^2 for this equation is 0,99949.

The change of the maximal load is also examined. The value for this load is considered to be the magnitude of the force corresponding to the stress value for the last point from the "stress − strain" curve. We determine this load for the material of the liners itself from the 6 charts which are used (Fig. 11) and for the curves obtained for the corrugated paperboard model (Fig. 12). The dependency is graphically represented in Fig. 14. The solid line on this chart depicts the linear equation of regression.

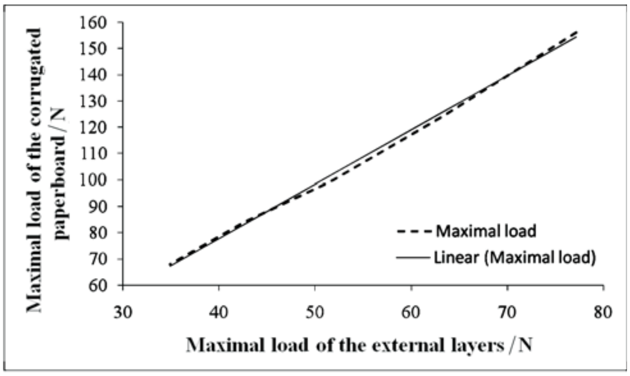

Figure 14 *Changing of the maximal load of the liners and the corrugated paperboard panel*
Slika 14. P*romjena maksimalnog opterećenja vanjskih slojeva i ploče od rebrastog kartona*

The equation of regression for this case is written as follows:

$$Y(X) = 2{,}06114 \cdot X - 4{,}82213. \tag{2}$$

The coefficient of regression for this equation R^2 is 0,99657.

The study continues with the examination of the influence of the internal corrugated layer. Just as in the case with the liners, 6 different "stress − strain" curves are given for the material of the fluted layer while the material for the liners is unchanged this time. These 6 curves, which are shown in Fig. 15, are defined using the same procedure as in the previous case − by multiplying their X coordinates by 0,997 and their Y coordinates by 0,82.

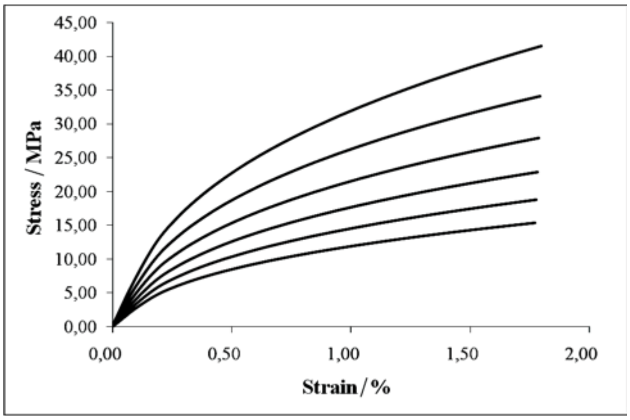

Figure 15 *"Stress – strain" curves used for the flute*
Slika 15. *Krivulje "naprezanje-deformacija" upotrebljene za rebro*

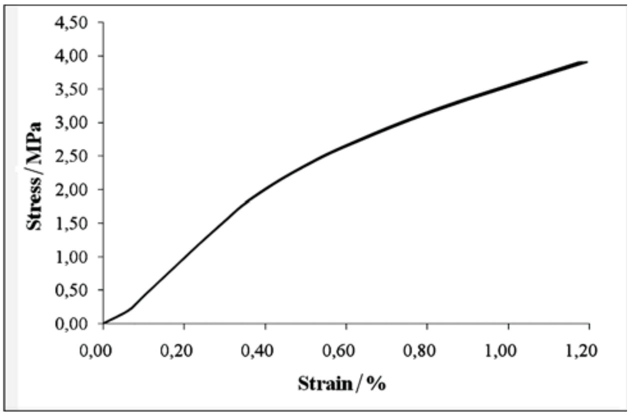

Figure 16 *"Stress – strain" complex curves resulting from the second study*
Slika 16. *Kompleksne krivulje "naprezanje – deformacija" dobivene iz druge analize*

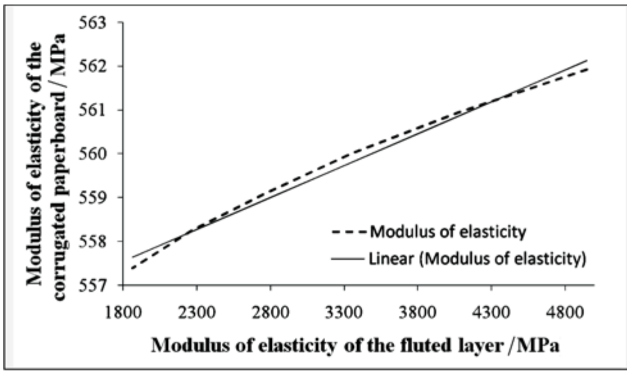

Figure 17 *Effect of the internal layer on the modulus of elasticity*
Slika 17*. Djelovanje unutarnjeg sloja na modul elastičnosti*

After the process of calculation is over we examine the results. We analyze the 6 complex "stress − strain" curves which we have obtained for the corrugated paperboard panel. What we get is almost coincident curves. The average difference between each of the points is 0,22 %. This indicates the insignificant effect of the flute on the complex characteristics of the corrugated paperboard. The curves in question are shown in Fig. 16.

Following the previously used procedure, we examine the change of the equivalent modulus of elasticity for the corrugated paperboard. This change is shown on the chart in Fig. 17.

We determine the linear equation of regression which is depicted with solid line. It is written as follows:

$$Y(X) = 0{,}00146 \cdot X + 554{,}92304. \quad (3)$$

After analyzing the results we notice that the change of the maximal load is so insignificant that it can be ignored. The coefficient of regression R^2 for equation (3) is determined to be 0,98485.

3 Conclusions
Zaključci

1. The FEM based 3D model of the corrugated paperboard has been proposed. The results obtained from this model have been compared to experimentally obtained data [3] and they show good coincidence. This gives us the chance to use the FEM for a more detailed study of the complex properties of the corrugated paperboard and how its parameters, components and geometrical parameters affect its resultant mechanical characteristics.

2. A study has been carried out to investigate how the change of the properties of the materials which are used to make individual layers affects the complex mechanical behavior of the corrugated paperboard. Such changes normally occur in conditions of changing environmental factors such as temperature and relative humidity.

3. The obtained results open the opportunity for the designers of packaging products to predict how the change of the properties of corrugated paperboard would affect the strength of the final products.

4. The investigation shows that the liners affect much stronger the complex characteristics of the corrugated paperboard than the flute, whose influence is almost insignificant. This is clearly seen by analyzing equations (1) and (3). The difference of the slope coefficients (0,12808 for equation (1) and 0,00146 for equation (3)) is approximately 88 times.

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