CHEMICAL PROCESSING OF WOOD

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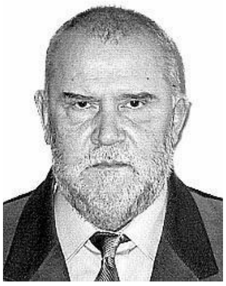


# INFLUENCE OF STRUCTURAL NONUNIFORMITY ON THE STIFFNESS CHARACTERISTICS OF LINERBOARD

Mathematical models are proposed and software is developed for predicting the stiffness characteristics of cardboard based on gap analysis results.

*Keywords*: cardboard, structure, micro- and macrostructure, formation nonuniformity, stiffness, correlation.

Paper and cardboard are considered to be capillary-porous colloid viscoelastic materials with a structure formed by fibres that are stochastically distributed on-plane and through the paper sheet thickness and bonded to one another by interfibre bonds of varying natures [1].

There are two approaches to examining and assessing paper structure, namely micro- and macrostructural. Paper microstructure depends on the specific structure of paper composition elements and the nature of the bonds between its primary components, i.e., fibre and auxiliary materials [2].

The heterogeneity of physical properties, including density variations, in different parts of paper, is directly connected with the fibre distribution pattern and fibre associations within a paper sheet, i.e., it depends on the macrostructure. Indirect methods are used to examine paper macrostructure. These methods are based on an assessment of the variation in the physical properties of the paper or average values of some of its volume and surface characteristics. Optical methods, formation heterogeneity or a poor formation test [5] included are the most popular as the heterogeneity of paper density, just like of many other characteristics, is directly connected with heterogeneous sheet structure. Formation heterogeneity is a connecting link between technology and marketability.

Modern formation analysers enable quantitative assessment of paper and cardboard macrostructure and, consequently, of formation quality. In our study, we used ANFOR 02-2 analyser, which ensures an unbiased quality assessment of sheet formation describing it in figures [6]. The analyser uses light to create a well-lit space on a 150×150 mm paper sample whose transmitted-light image is taken by a digital camera and analysed using specialised software. The analysis is based on the brightness of the light ray that passes through the paper sheet and is captured by a CCD matrix in a pixel grid. The variation in brightness between the pixels reflect the heterogeneity of the structure.

The characteristics measured with ANFOR 02-2 may be divided into three groups: the characteristics of distribution of sample pixel brightness compared to the average value (optical heterogeneity of paper), geometrical characteristics of heterogeneity, characteristics describing the unevenness of pulp distribution in the sample.

The first group of characteristics includes light transmission *T*, formation heterogeneity σ, contrast *K*, and formation index *H*.

Light transmission describes opacity. It is calculated as the ratio between the average brightness of light that has passed through the sample $I_i$ and the brightness of light shining on the sample $I_0$:

$$T = \frac{\frac{1}{n}\sum_{i=1}^{n} I_i}{I_0} 100\%, \qquad (1)$$

where *n* is the number of treated pixels.

When the weight of 1 $m^2$ of paper is increased, the light transmission value traditionally decreases.

Formation heterogeneity σ is calculated as the mean-square deviation of the brightness of all pixels in sample $I_i$ from the average brightness value $I_{mean}$:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(I_i - I_{mean})^2}, \quad (2)$$

where $I_{mean} = \frac{1}{n}\sum_{i=1}^{n} I_i$. (3)

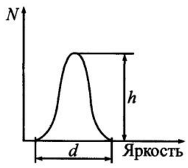
Inferior formation paper samples have higher formation heterogeneity values. In an ideal formation sample, i.e., when the brightness of all pixels in the sample is equal, the formation heterogeneity is zero. In real paper, this parameter traditionally varies between 2 and 10; in cardboard it is much higher.

Contrast *K* is calculated as the ratio of formation heterogeneity to the average brightness value:

$$K = C_1 \frac{\sigma}{I_{mean}}, \quad (4)$$

where $C_1$ is constant.

The brightness distribution histogram (Fig. 1), with brightness values plotted along the X-axis and the relative number of pixels with this brightness along the Y-axis, is indicative of paper formation quality. A higher, narrower histogram represents better formation and describes formation index *H*, which is calculated as the ratio between histogram height *h* and histogram width *d* (the number of brightness gradations in the sample):




| Рисунок | |
| --- | --- |
| Яркость | Brightness |

Fig. 1 Principle for calculating of the brightness index

$$H = C_2 \frac{h}{d}. \quad (5)$$

Here, $C_2$ is constant.

The calculation of geometrical parameters is illustrated in Fig. 2, which shows the distribution of luminous flux *Φ* that has passed through the sample along the selected line. Scan lines are normally selected length- and crosswise. The average values of lengthwise $l_{length}$ and crosswise $l_{cross}$ heterogeneity are calculated by the same formula, the difference lying in the scanning direction:

$$l_{length}, l_{cross} = \frac{2L}{N}, \quad (6)$$

where *L* is the length of the scan line,

*N* is the number of intersections of the luminous flux chart with its mean value.

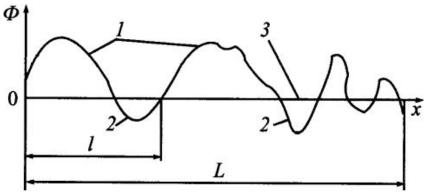



Fig. 2. Calculation principle for paper heterogeneity parameters: Φ – luminous flux, *x* – space coordinate, *L* – scan line length, *l* – heterogeneous space size; *1* – washaways, *2* – floccules, *3* – average luminous flux

The average heterogeneous space size is calculated as the arithmetic mean:

$$d_{mean} = \frac{l_{length}+l_{cross}}{2}. \quad (7)$$

Anisotropy is calculated as the ratio between average heterogeneous space length- and crosswise sizes:

$$A = \frac{l_{length}}{l_{cross}}, \quad (8)$$

The method for calculating parameters describing pulp distribution unevenness within a sample is shown in Fig. 3. Paper (cardboard) is represented as a flat sheet with thickness *s* both surfaces of which have hills (floccules) and pits (washaways). The total volume of floccules (sample mass excess $M_{exc}$) and the total volume of washaways (sample mass deficit $M_{def}$) are calculated in relative units. Their sum is called mass nonuniformity *W*. The higher these values, the poorer the formation quality. Mass distribution ratio is calculated as follows:

$$Q = \frac{M_{exc}}{M_{def}}. \quad (9)$$


| Рисунок | |
|---|---|
| Флокулы | Floccules |
| Промоины | Washaways |

Fig. 3. Principle for calculating parameters describing pulp distribution unevenness within a sample

We have studied the formation quality of liners in 6 cardboard types (weight of 1 m$^2$ – 125, 140 and 150 g): the top liner with bleached top layer (*KTL*), multipurpose cardboard (*KU*), kraft liner of grades K0 (*K*0) and KBC (*KVS*). The collection consisted of 27 to 156 samples, depending on cardboard type.

Formation analyser ANFOR 02-2 was used to obtain the optical characteristics of the different liners. Their statistical characteristics are shown in Table 1. The average values of the optical characteristics of these liners are shown in Fig. 4.

Different producers, composition, quality and weight of 1 m$^2$ of the cardboard make it possible to evaluate the impact of these factors on the optical and stiffness properties of the materials.

**Table 1**

**Average Values of Optical Characteristics of Liner Samples**

| Cardboard | Weight of 1 $m^2$, g | Characteristic | $H$ | Σ | $K$ | $T$,% | $l_{length}$ (mm) | $l_{cross}$ (mm) | $A$ | $d_{mean}$, mm | $M_{exc}$ | $M_{def}$ | $W$ | $Q$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *KTL* | 125 | $X_{mean}$ | 56.89 | 5.76 | 0.025 | 29.7 | 11.45 | 10.83 | 1.01 | 5.16 | 0.91 | 0.92 | 1.78 | 0.99 |
| | | $X_{min}$ | 42.30 | 4.90 | 0.021 | 28.0 | 10.40 | 9.80 | 0.85 | 4.60 | 0.41 | 0.52 | 0.96 | 0.37 |
| | | $X_{max}$ | 65.90 | 7.60 | 0.030 | 33.0 | 15.60 | 14.90 | 1.13 | 6.80 | 3.05 | 2.00 | 5.05 | 1.72 |
| | | $\sigma_x$ | 3.93 | 0.44 | 0.002 | 1.39 | 0.79 | 0.87 | 0.07 | 0.35 | 0.41 | 0.29 | 0.58 | 0.30 |
| | 140 | $X_{mean}$ | 54.40 | 6.09 | 0.024 | 27.0 | 11.71 | 10.99 | 1.00 | 5.28 | 0.98 | 1.17 | 2.15 | 0.90 |
| | | $X_{min}$ | 44.20 | 5.00 | 0.021 | 26.0 | 10.40 | 10.00 | 0.80 | 4.70 | 0.48 | 0.60 | 1.08 | 0.42 |
| | | $X_{max}$ | 63.10 | 7.70 | 0.029 | 29.0 | 14.60 | 12.10 | 1.12 | 6.00 | 1.44 | 2.45 | 3.64 | 1.70 |
| | | $\sigma_x$ | 4.33 | 0.57 | 0.002 | 0.83 | 0.84 | 0.60 | 0.08 | 0.31 | 0.28 | 0.48 | 0.64 | 0.30 |
| *KU* | 125 | $X_{mean}$ | 19.59 | 19.10 | 0.077 | 26.1 | 12.71 | 12.67 | 0.97 | 6.46 | 8.53 | 16.01 | 24.37 | 0.58 |
| | | $X_{min}$ | 14.70 | 13.00 | 0.006 | 25.0 | 10.70 | 10.10 | 0.72 | 5.00 | 3.18 | 1.03 | 7.74 | 0.23 |
| | | $X_{max}$ | 26.80 | 32.70 | 0.680 | 28.0 | 17.60 | 20.10 | 1.11 | 8.70 | 40.29 | 71.91 | 112.20 | 1.01 |
| | | $\sigma_x$ | 2.71 | 3.17 | 0.050 | 0.34 | 1.22 | 1.58 | 0.07 | 0.70 | 4.16 | 9.94 | 13.34 | 0.14 |
| | 140 | $X_{mean}$ | 19.83 | 18.40 | 0.068 | 26.0 | 14.29 | 14.57 | 0.95 | 7.10 | 8.53 | 15.62 | 23.56 | 0.62 |
| | | $X_{min}$ | 15.70 | 15.00 | 0.008 | 25.0 | 11.50 | 11.00 | 0.67 | 5.80 | 2.35 | 6.00 | 1.56 | 0.32 |
| | | $X_{max}$ | 24.60 | 22.20 | 0.086 | 27.0 | 22.90 | 24.90 | 1.12 | 8.40 | 14.36 | 30.81 | 42.51 | 1.01 |
| | | $\sigma_x$ | 2.19 | 1.94 | 0.013 | 0.35 | 1.94 | 2.57 | 0.10 | 0.69 | 2.66 | 6.25 | 8.14 | 0.17 |
| *K*0 | 150 | $X_{mean}$ | 16.16 | 25.04 | 0.095 | 25.9 | 16.18 | 17.22 | 0.92 | 8.57 | 16.61 | 40.75 | 56.32 | 0.44 |
| | | $X_{min}$ | 13.00 | 17.90 | 0.024 | 24.0 | 13.00 | 13.00 | 0.54 | 0.20 | 6.95 | 12.07 | 19.02 | 0.14 |
| | | $X_{max}$ | 20.60 | 33.20 | 0.122 | 27.0 | 29.10 | 36.00 | 1.17 | 11.40 | 55.38 | 115.80 | 111.46 | 1.03 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\sigma_x$ | 1.73 | 3.08 | 0.013 | 0.56 | 2.43 | 3.92 | 0.13 | 1.16 | 5.88 | 17.16 | 19.19 | 0.13 |
| *KVS* | 150 | $X_{mean}$ | 16.81 | 23.54 | 0.090 | 25.7 | 16.22 | 16.22 | 0.90 | 8.26 | 13.44 | 35.79 | 49.57 | 0.40 |
| | | $X_{min}$ | 14.00 | 18.20 | 0.070 | 23.0 | 11.80 | 12.90 | 0.56 | 6.70 | 7.04 | 13.55 | 20.74 | 0.23 |
| | | $X_{max}$ | 19.80 | 30.90 | 0.118 | 27.0 | 29.60 | 31.30 | 1.07 | 9.80 | 21.37 | 68.40 | 86.72 | 0.59 |
| | | $\sigma_x$ | 1.78 | 3.31 | 0.012 | 0.82 | 3.70 | 3.76 | 0.13 | 0.83 | 4.38 | 12.88 | 16.28 | 0.10 |

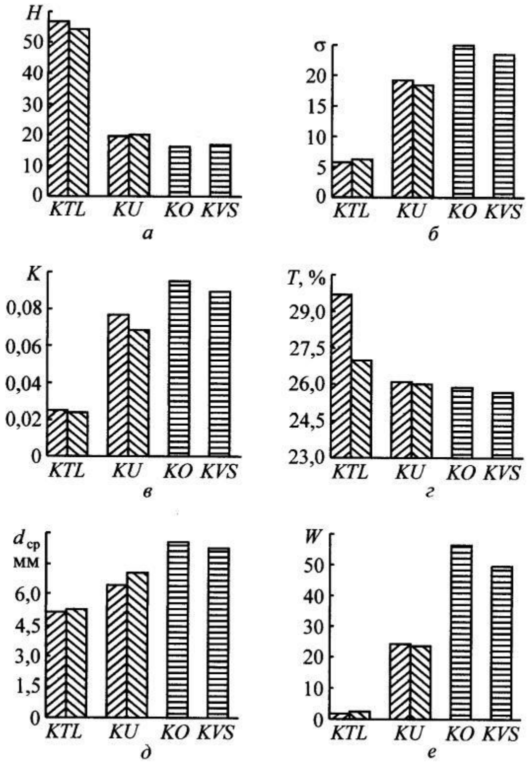



Fig. 4. Average values of optical characteristics of liners: *а* – formation index, *б* – formation heterogeneity, *в* – contrast, *г* – light transmission, *д* – average heterogeneous space size, *е* – pulp distribution unevenness, □ –weight of 1 $m^2$ of 125 g, □ – 140 g, □ – 150 g.

Cardboard with a bleached top layer proved best in terms of formation properties. This cardboard, whose main layer consists of normal-yield unbleached soft- and hardwood pulp, as well as of bleached pulp containing filler within its top layer, is quite thin and very dense. The low formation heterogeneity of this cardboard confirms the good printability of the outer layer.

The least costly material is multipurpose cardboard, whose composition is based on high-yield sulphate pulp and neutral sulphite semichemical hardwood pulp (up to 40–60%). This cardboard has the worst formation properties.

Of all the GOST-certified cardboards, the quality of formation of the KVS cardboard is higher than that of the K0 cardboard, as is confirmed by the formation values obtained. Consequently, by increasing the mechanical properties of the cardboard, the KVS cardboard producers improve the formation quality.

When the weight of 1 $m^2$ was increased, formation heterogeneity increased as well, in all types of cardboard, which can be attributed to worsened formation conditions on the fabric of the cardboard machine (CM). Yet, when the weight of 1 $m^2$ changes, the formation quality changes less than with another type of cardboard.

Consequently, in terms of impact on formation properties, the factors may be arranged in the following line: cardboard type (fibre composition), cardboard grade, weight of 1 $m^2$.

Table 2

**Mechanical Properties of Liner Samples**

| Cardboard | Weight of 1 m$^2$, g | $S_b$, N·m | $S_t$, kN/m | *RCT*, N | Number of samples |
|---|---|---|---|---|---|
| *KTL* | 125 | 0.89 | 678 | 180 | 49 |
| *KU* | 125 | 1.30 | 621 | 193 | 156 |
| *KTL* | 140 | 1.22 | 735 | 223 | 30 |
| *KU* | 140 | 1.92 | 696 | 245 | 33 |
| *K0* | 150 | 1.87 | 703 | 254 | 123 |
| *KVS* | 150 | 1.88 | 697 | 257 | 27 |

There is a certain spread in properties associated with formation quality within each cardboard type. The question is to what extent the changes in cardboard formation quality might cause changes in the mechanical properties of same-grade samples.

The consumer properties of corrugated cardboard and boxes depend on the aggregate properties of stock, basically on its tensile, compression and flexural rigidity.

In order to assess the degree of impact of structural heterogeneity on same-grade liner stiffness, flexural rigidity $S_b$ (N·m), tensile rigidity $S_t$ (kN/m) and compression rigidity *RCT* (N) were measured and the mean values of the characteristics were calculated for samples with measured formation characteristics. These values are shown in Table 2.

An analysis of data from Table 2 has shown that cardboard type and weight of 1 m$^2$ selectively affect the tensile, compression and flexural rigidity. Thus, the top liner which has the highest tensile rigidity and sufficient compression rigidity has the lowest flexural rigidity (where the weight of 1 m$^2$ is the same). Multipurpose cardboard has the highest flexural rigidity, while compression rigidity is the highest in K0 and KVS cardboard.

The quantitative assessment of interdependency between formation quality and the mechanical properties of liners was performed using the correlation and regression analyses [3]. The pair correlation coefficients are shown in Table 3.

Unlike data obtained for bank paper [4], the pair correlation analysis of the characteristics of each cardboard type has shown a low correlation ratio, i.e., when the structural properties of the cardboard of a given type are changed, the variations in cardboard stiffness values are less prominent than when there are changes in cardboard composition or weight of 1 m$^2$.

Four out of all structural heterogeneity properties of cardboard were selected for multiple correlation analysis [3]: weight distribution unevenness $W - X_1$, formation heterogeneity $\sigma - X_2$, light transmission index $T - X_3$ included into the list in order to take into account the impact of weight of 1 m$^2$ of cardboard, the average heterogeneous space size $d_{\text{mean}} - X_4$.

Table 3

**Pair Correlation Coefficients of Structural and Mechanical Properties of Liner Samples**

| Cardboard | Weight of 1 $m^2$, g | *Y* | *H* | σ | *K* | *T* | $l_{length}$ | $l_{cross}$ | *A* | $d_{mean}$ | $M_{exc}$ | $M_{def}$ | *W* | *Q* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KTL | 125 | $S_b$, N·m | −0.297 | 0.250 | 0.109 | −0.118 | 0.118 | 0.278 | −0.205 | 0.108 | 0.289 | −0.119 | 0.152 | **0.469** |
| | | $S_t$, kN/m | −0.118 | 0.058 | −0.234 | −0.367 | 0.111 | 0.128 | −0.383 | 0.069 | 0.269 | −0.183 | 0.013 | 0.318 |
| | | *RCT*, N | 0.052 | −0.076 | −0.412 | −0.362 | 0.025 | −0.037 | 0.020 | −0.107 | 0.089 | −0.295 | −0.132 | 0.309 |
| | 140 | $S_b$, N·m | **−0.574** | **0.543** | 0.410 | **−0.620** | 0.230 | 0.199 | −0.058 | 0.331 | **0.561** | 0.310 | 0.482 | 0.024 |
| | | $S_t$, kN/m | 0.197 | −0.175 | −0.282 | −0.263 | −0.001 | −0.425 | −0.019 | −0.332 | −0.182 | −0.041 | −0.109 | −0.195 |
| | | *RCT*, N | −0.079 | 0.129 | 0.003 | −0.260 | −0.028 | −0.042 | 0.310 | −0.095 | 0.307 | 0.074 | 0.193 | 0.001 |
| KU | 125 | $S_b$, N·m | −0.087 | 0.110 | 0.003 | −0.052 | −0.007 | −0.014 | 0.001 | 0.042 | 0.040 | 0.076 | 0.071 | −0.064 |
| | | $S_t$, kN/m | **0.248** | −0.198 | −0.093 | −0.128 | −0.016 | −0.118 | −0.019 | −0.132 | −0.212 | −0.200 | −0.205 | 0.047 |
| | | *RCT*, N | −0.185 | 0.171 | 0.052 | 0.116 | 0.111 | 0.167 | 0.080 | 0.185 | 0.127 | 0.169 | 0.154 | 0.012 |
| | 140 | $S_b$, N·m | −0.222 | 0.172 | −0.008 | −0.175 | 0.018 | 0.248 | −0.095 | 0.141 | −0.055 | 0.082 | 0.119 | −0.171 |
| | | $S_t$, kN/m | 0.210 | −0.206 | −0.212 | −0.026 | −0.016 | 0.129 | −0.088 | −0.113 | −0.330 | −0.068 | −0.149 | −0.070 |
| | | *RCT*, N | 0.167 | −0.125 | −0.308 | 0.060 | 0.124 | 0.282 | −0.295 | −0.021 | −0.156 | −0.080 | 0.008 | 0.049 |
| K0 | 150 | $S_b$, N·m | **0.308** | **−0.430** | **−0.426** | −0.165 | −0.046 | 0.284 | **−0.304** | −0.028 | −0.224 | **−0.331** | **−0.325** | **0.310** |
| | | $S_t$, kN/m | 0.221 | **−0.320** | −0.221 | −0.112 | −0.182 | 0.150 | −0.117 | −0.080 | −0.182 | −0.256 | −0.285 | 0.221 |
| | | *RCT*, N | 0.142 | −0.224 | −0.159 | 0.104 | −0.200 | 0.016 | −0.030 | −0.073 | −0.127 | −0.136 | −0.198 | 0.077 |
| KVS | 150 | $S_b$, N·m | 0.265 | −0.461 | −0.449 | −0.156 | −0.069 | 0.010 | −0.135 | −0.311 | −0.448 | −0.313 | −0.367 | −0.088 |
| | | $S_t$, kN/m | 0.262 | −0.321 | −0.329 | −0.195 | 0.030 | −0.011 | −0.014 | −0.064 | −0.182 | −0.168 | −0.186 | 0.035 |
| | | *RCT*, N | 0.204 | −0.171 | −0.147 | 0.175 | 0.114 | −0.040 | 0.084 | −0.027 | −0.026 | −0.081 | −0.063 | 0.220 |

Note: Important correlation coefficients are highlighted in bold.

Table 4

**Multiple Correlation Coefficients ($W - X_1$, $\sigma - X_2$, $T - X_3$, $d_{mean} - X_4$)**

| Cardboard | Weight of 1 m$^2$, g | *Y* | $r_{y,12}$ | $r_{y,13}$ | $r_{y,14}$ | $r_{y,23}$ | $r_{y,24}$ | $r_{y,34}$ | $r_{y,123}$ | $r_{y,124}$ | $r_{y,234}$ | $r_{y,134}$ | $r_{y,1234}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KTL | 125 | $S_b$, N·m | 0.26 | 0.18 | 0.15 | 0.25 | 0.27 | 0.15 | 0.26 | 0.27 | 0.27 | 0.18 | 0.27 |
| | | $S_t$, kN/m | 0.08 | 0.37 | 0.10 | 0.38 | 0.07 | 0.37 | 0.38 | 0.11 | 0.40 | 0.38 | 0.40 |
| | | *RCT*, N | 0.14 | 0.42 | 0.13 | 0.44 | 0.11 | 0.40 | 0.44 | 0.14 | 0.44 | 0.42 | 0.44 |
| | 140 | $S_b$, N·m | 0.54 | 0.67 | 0.48 | 0.70 | 0.56 | 0.64 | 0.70 | 0.56 | 0.71 | 0.67 | 0.71 |
| | | $S_t$, kN/m | 0.19 | 0.35 | 0.39 | 0.40 | 0.35 | 0.50 | 0.40 | 0.39 | 0.50 | 0.51 | 0.52 |
| | | *RCT*, N | 0.21 | 0.28 | 0.40 | 0.26 | 0.32 | 0.32 | 0.29 | 0.40 | 0.39 | 0.45 | 0.45 |
| KU | 125 | $S_b$, N·m | 0.13 | 0.09 | 0.08 | 0.12 | 0.14 | 0.07 | 0.13 | 0.14 | 0.15 | 0.10 | 0.15 |
| | | $S_t$, kN/m | 0.21 | 0.23 | 0.21 | 0.23 | 0.20 | 0.18 | 0.24 | 0.22 | 0.24 | 0.24 | 0.24 |
| | | *RCT*, N | 0.29 | 0.24 | 0.26 | 0.29 | 0.38 | 0.11 | 0.30 | 0.38 | 0.39 | 0.29 | 0.39 |
| | 140 | $S_b$, N·m | 0.19 | 0.20 | 0.14 | 0.23 | 0.17 | 0.22 | 0.25 | 0.20 | 0.23 | 0.22 | 0.26 |
| | | $S_t$, kN/m | 0.22 | 0.16 | 0.15 | 0.21 | 0.21 | 0.12 | 0.23 | 0.22 | 0.22 | 0.16 | 0.23 |
| | | *RCT*, N | 0.30 | 0.06 | 0.04 | 0.13 | 0.16 | 0.06 | 0.30 | 0.30 | 0.17 | 0.08 | 0.31 |
| K0 | 150 | $S_b$, N·m | 0.43 | 0.35 | 0.36 | 0.45 | 0.46 | 0.17 | 0.45 | 0.46 | 0.48 | 0.39 | 0.48 |
| | | $S_t$, kN/m | 0.32 | 0.30 | 0.29 | 0.33 | 0.32 | 0.13 | 0.34 | 0.33 | 0.34 | 0.31 | 0.34 |
| | | *RCT*, N | 0.23 | 0.23 | 0.20 | 0.25 | 0.22 | 0.13 | 0.26 | 0.23 | 0.25 | 0.23 | 0.26 |
| KVS | 150 | $S_b$, N·m | 0.22 | 0.23 | 0.22 | 0.20 | 0.17 | 0.17 | 0.25 | 0.24 | 0.22 | 0.24 | 0.26 |
| | | $S_t$, kN/m | 0.28 | 0.23 | 0.26 | 0.23 | 0.26 | 0.14 | 0.29 | 0.31 | 0.26 | 0.27 | 0.32 |
| | | *RCT*, N | 0.20 | 0.08 | 0.12 | 0.17 | 0.21 | 0.11 | 0.20 | 0.23 | 0.21 | 0.13 | 0.23 |

Table 5

**Coefficients of Equation of Regression $b_i$ and Approximation Accuracy Evaluation ($r$, δ) with an Equation of the Form $Y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4$**

| Cardboard | Weight of 1 $m^2$, g | $Y$ | $b_0$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $r$ | $\delta$ |
|---|---|---|---|---|---|---|---|---|---|
| KTL | 125 | $S_b$, N·m | 0.733 | −0.0047 | 0.047 | 0.0004 | −0.021 | 0.27 | 4.31 |
| | | $S_t$, kN/m | 974 | −3.81 | −16.08 | −10.05 | 19.88 | 0.40 | 3.25 |
| | | *RCT*, N | 401 | −2.37 | −9.88 | −5.90 | 3.14 | 0.44 | 7.65 |
| | 140 | $S_b$, N·m | 2.24 | −0.0028 | 0.067 | −0.045 | −0.043 | 0.71 | 3.24 |
| | | $S_t$, kN/m | 1,210 | 8.68 | −6.03 | −9.89 | −35.97 | 0.52 | 1.92 |
| | | *RCT*, N | 569 | 17.96 | 1.81 | −6.41 | −42.22 | 0.45 | 8.52 |
| KU | 125 | $S_b$, N·m | 1.85 | −0.0008 | 0.013 | −0.023 | −0.025 | 0.15 | 6.91 |
| | | $S_t$, kN/m | 963 | −0.41 | −1.88 | −12.80 | 5.87 | 0.24 | 5.02 |
| | | *RCT*, N | 46.51 | 0.0034 | −3.59 | 5.50 | 11.07 | 0.39 | 7.07 |
| | 140 | $S_b$, N·m | 3.44 | −0.005 | 0.026 | −0.079 | 0.024 | 0.26 | 6.71 |
| | | $S_t$, kN/m | 982 | 0.781 | −8.68 | −6.54 | 3.62 | 0.23 | 4.63 |
| | | *RCT*, N | 233 | 1.30 | −6.07 | 3.42 | 0.54 | 0.31 | 5.31 |
| K0 | 150 | $S_b$, N·m | 3.94 | −0.0002 | −0.034 | −0.058 | 0.035 | 0.48 | 8.37 |
| | | $S_t$, kN/m | 968 | −0.257 | −3.58 | −7.29 | 3.29 | 0.34 | 4.67 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| KVS | 150 | *RCT*, N | 157 | −0.087 | −1.45 | 5.14 | 0.57 | 0.26 | 7.42 |
| | | $S_b$, N·m | 5.50 | −0.00001 | −0.028 | −0.112 | 0.0053 | 0.60 | 9.39 |
| | | $S_t$, kN/m | 609 | −0.603 | −1.71 | 9.40 | −11.27 | 0.32 | 5.67 |
| | | *RCT*, N | 207 | −0.131 | 0.70 | 1.85 | −3.76 | 0.23 | 6.17 |

Multiple correlation coefficients that reflect the combined effect of two $r_{Y,12}$, three $r_{Y,123}$ and four $r_{Y,1234}$ factors were calculated. Multiple correlation coefficients have slightly higher values than pair coefficients (Table 4). Multiple correlation coefficients grow as the number of recordable factors increases. Consequently, a multiple correlation analysis provides a more reliable assessment of correlation relationship as, when technological factors vary, different optical characteristics vary synchronically, though to a varying extent.

In order to predict the stiffness of the cardboard based on its optical characteristics, linear equations were obtained as a result of multiple regression analysis (Table 5). The same formation characteristics were used as input parameters as in multiple correlation analysis. For most cardboard types, the error of the regression equations ranges from 2% to 9%. Consequently, these equations have a high predictive power in relation to tensile, compression and flexural rigidity.

## *Conclusions*

1. We obtained experimental data on the heterogeneity of liner structure and the correlation of structural and physico-mechanical characteristics.

2. An analysis of structural heterogeneity of several liner types showed that, in terms of impact on formation properties, the factors may be arranged in the following order: cardboard type (fibre composition), cardboard grade, weight of 1 $m^2$. At the same time, there is a certain spread in the properties associated with formation quality within each cardboard type.

3. We generated regression equations and created software that help obtain predictive estimates for tensile, compression and flexural rigidity of different liners with an error not exceeding 2–9% as a result of non-destructive testing with an ANFOR 02-2 formation analyser.

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**Influence of Structural Nonuniformity on the Stiffness Characteristics of Linerboard**

Mathematical models are proposed and software is developed for predicting the stiffness characteristics of cardboard based on gap analysis results.