Impact of Core Cell Size on Selected Properties of Honeycomb Paperboard

Gabriela Kmita-Fudalej ,[a,]* Grzegorz Jasiński,[a] and Zbigniew Kołakowski ,[b]

The effect of the cell size of honeycomb paperboard core was studied relative to the grammage (basis weight) and two key strength properties of cellular paperboard: bending stiffness (BS) and flat crush resistance (FCT). The subject of the study was honeycomb paperboard of a different structure, in which single-layer kraftliner paper was used for the flat layers, with a grammage and thickness lower than the paper used for the paperboard core. Five paperboards made of the same fibrous materials of the same thickness and different core cell diameter *D* were tested, equal to 10, 12, 14, 17, and 22 mm, respectively. The research showed a close dependence of the grammage of the paperboard, BS, and the FCT of the honeycomb paperboard on the core cell size. With the increase of the core cell size, the above-mentioned physical properties showed a decreasing trend. For the honeycomb paperboards tested, a linear relationship was obtained between the grammage, BS, FCT of the honeycomb board and the diameter *D* of the hexagonal core cell.

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*Contact information: a: Centre of Papermaking and Printing, Lodz University of Technology, Wólczańska Str. 221, 93-005 Lodz, Poland; b: Department of Strength of Materials, Lodz University of Technology, Stefanowskiego Str. 1/15, Lodz 90-537, Poland; *Corresponding author: gabriela.kmita-fudalej@p.lodz.pl*

INTRODUCTION

In search of sustainable solutions, many industries are increasingly using innovative materials that not only meet the needs of protecting their goods during transportation and storage, but also contribute to environmental protection. One such breakthrough solution in the field of ecological packaging and construction materials is honeycomb paperboard. Cellular paperboard, thanks to its spatial structure, is characterized by low specific weight and good strength properties (Barboutis and Vassiliou 2005; Sam-Brew *et al*. 2011). The low weight redounds into a lower weight of the transported cargo, which entails lower fuel consumption during transportation, thus lowering carbon dioxide emissions. This feature is a significant advantage for companies that want to minimize their carbon footprint. The leading advantages of cellular paperboard are its biodegradability and recycling. Contrary to traditional packaging materials such as plastic or Styrofoam, honeycomb paperboards naturally decompose over time, leaving minimal environmental impact as well as being easily recycled and reused for new packaging materials. The primary indicators used to evaluate paperboard as a packaging material are bending stiffness (BS), edgewise crush test (ECT) and flat crush test (FCT) (Bitzer 1997). In recent years, a great deal of research has been conducted on the properties of cellular paperboards, especially in the context of its application in fields such as packaging and transportation and as a structural material. Wang and Wang (2008) investigated the resistance to static pressure acting perpendicularly to the surface of honeycomb cores and honeycomb paperboards. The subjects of the study were cores and cellular paperboards with different geometric parameters made of different fiber raw materials. They demonstrated that gluing flat layers to a core with a higher grammage than the paper used for the core increases the FCT crush resistance of the paperboard compared to the flat crush resistance of the core alone. In a publication (Yu-Ping and Wang 2010) developed a theoretical model to predict the stresses during unidirectional compression when honeycomb paperboards are crushed flat after crossing the yield point in a region that is characterized by a strong increase in strain with minimal change in force magnitude in various humidity environments. The honeycomb paperboards were made of the same papers, had the same thickness, but had different hexagonal cell sizes. Both calculation and measurement results showed that the value of plateau stress increased as the thickness to length ratio of a single thickness wall of the core cell increased. For the tested paperboards, the plateau stress value decreased with increasing humidity. Other researchers conducted measurements of the static pressure resistance of cellular paperboards and a composite consisting of a paper cellular core filled with polyurethane foam (Wang *et al*. 2015). The cellular paperboards and composite cores were measured. Composites with honeycomb structure achieved higher values of resistance to static pressure than cellular paperboards. The cellular paperboard underwent four times less deformation at maximum force compared to the deformation obtained for the composite.

Previous publications (Smardzewski and Prekrat 2012; Semple *et al*. 2015) described BS test methods for honeycomb paperboards and laminates consisting of a honeycomb core bonded to thin furniture boards. Smardzewski *et al*. (2019) examined furniture boards filled with a paper cell core with two different shapes of the cell of the cores. Rectangular and hexagonal shaped cell core were used. Furniture boards with rectangular cell paper core cells showed higher bending stiffness values of furniture boards in the cross direction and lower bending stiffness values in the machine direction compared to boards with hexagonal core cells. The study of cellular paperboards was conducted by Wen (2012), who compared the results of FCT and ECT index measurements in the machine direction and cross direction for cellular paperboards with a thickness of 5 mm and a mesh size of 4 mm with those of A-wave corrugated paperboards also 5 mm thick. Similar values of ECT edge crush resistance in the cross and machine direction of cellular paperboards were found. The edge crush resistance of corrugated paperboard in the machine direction was almost 3 times lower compared to its ECT in the cross direction. Corrugated paperboard undergoes greater relative deformation at failure than cellular paperboard in both the MD and CD directions. The FCT value for the tested paperboards obtained for cellular paperboard was greater than that obtained for A-wave corrugated paperboards.

Other researchers conducted ECT studies of cellular paperboards in the machine direction and cross direction (Mou *et al*. 2020). The subjects of the study were two groups of cellular paperboards with the same size cell and equal thickness. The flat layers of the paperboard were made of paper of higher grammage and thickness than the core. Different deformation mechanisms were observed in the plastic deformation zone in the MD and CD directions. The work of Samad *et al*. (2018) presented the effect of sample height on the ECT value of cellular paperboard. It was observed that the stress corresponding to the yield stress decreases with increasing specimen height, but no global buckling of the specimens was observed during the measurements.

Guo *et al*. (2010) measured the strength properties of cellular paperboards and laminates formed by gluing cellular paperboard to corrugated paperboard. They studied the resistance of cellular paperboards and laminates to edge crushing. Cellular paperboards with the same mesh diameter and different thicknesses were measured. A paper with a higher grammage and thickness was used for the flat layers compared to the paper used for the core. The results of the ECT measurements showed the effect of the thickness of the cellular paperboard and the corrugated paperboards on the ECT value.

The ECT measurements of cellular paperboard were also dealt with by Hua *et al*. (2017). The purpose of their study was to determine the effect on the ECT of cellular paperboard of the location of the loaded edge of the specimen relative to the walls of the core cell. The authors conducted the study using experimental and numerical methods. The subject of the experimental study was a cellular paperboard of equal thickness and side length of a hexagonal core cell. The results suggest that the location of the edge is one of the factors affecting the edge compression strength of honeycomb paperboard. Chen *et al*. (2014) studied lightweight multilayer panels with a honeycomb core made of paper. The authors described the effect of honeycomb design parameters and the properties of the core and cladding material on the mechanical properties of the laminate.

Borsellino and Di Bella (2009) conducted a study of honeycomb laminates and evaluated the relationship between stresses and strains under uniform compressive static loading. Both Wang (2009) and Gu *et al*. (2020) studied the energy absorption capacity of honeycomb paperboard subjected to compressive loading.

Many papers (Gao and Wang 2012; Wang and Yao 2012; Zhiwei and Zhu 2012; Chen and Ushijima 2013; Utassy and Denes 2013; Wang and Gao 2013; Kadir *et al*. 2017; Wang *et al*. 2018; Czechowski *et al*. 2020; Deng *et al*. 2024) have dealt with the analysis of the strength properties of cellular paperboards using the finite element method. Chen and Yan (2012) conducted a study for honeycomb filled panels made of kraftliner paper determining their elastic modulus. Hao *et al*. (2020) conducted compression properties of wood-based sandwich panels with a novel Taiji honeycomb core.

Although a lot of information can be found in the literature on the study of cellular paperboards, all measurements used laminates and cellular paperboards in which a material of the same or greater thickness than the material used for the cellular core was used for the flat layers. In the present paper, unusual honeycomb paperboards were made under industrial conditions in which single-layer paper of significantly lower grammage and thickness than the two-layer paper used for the core was used for the flat layers. According to the authors, this is a novelty in the proposed work.

EXPERIMENTAL

The subject of the study was honeycomb paperboards. The honeycomb paperboard specimens were composed of a core R, which consists of spatially contiguous hexagonal cells and two flat layers, as shown in Fig. 1.

The paperboards tested were produced from the same papers, for the flat layers of the paperboards a single-layer paper (kraftliner) paper of lower grammage and thickness was used compared to the paper used for the core of the two-layer paper (testliner) (Table 1), which contributes to the unusual structure of the tested paperboards in which usually the flat layers are made of raw material of the same or higher grammage and thickness.

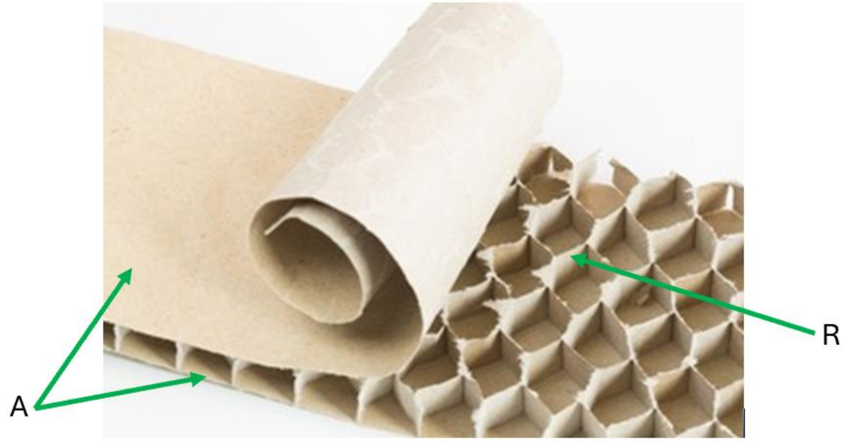


Fig. 1. Construction of honeycomb paperboard: A, flat layers of paperboard, R, paperboard core

Table 1. Papers Used in the Production of Cellular Paperboards

Paper	Grammage (g/m^2)	Thickness (mm)
Kraftliner	75	0.121
Testliner	125	0.190

Figures 2 and 3 show the test materials. Five paperboard versions of the same thickness (H = 12 mm) had different cell sizes (diameter of the circle, D) inscribed in the hexagonal core. The diameter D was equal to 10, 12, 14, 17, or 22 mm.

Prior to testing, honeycomb paperboard samples were conditioned in accordance with PN -EN 20187 (2000) in air with a temperature of 23 ± 1 °C and a relative humidity of 50 ± 2%. Conditioning of the samples was carried out until thermodynamic equilibrium with the surrounding air was reached. The tests were performed in rooms where the conditions were identical to those when the samples were conditioned.

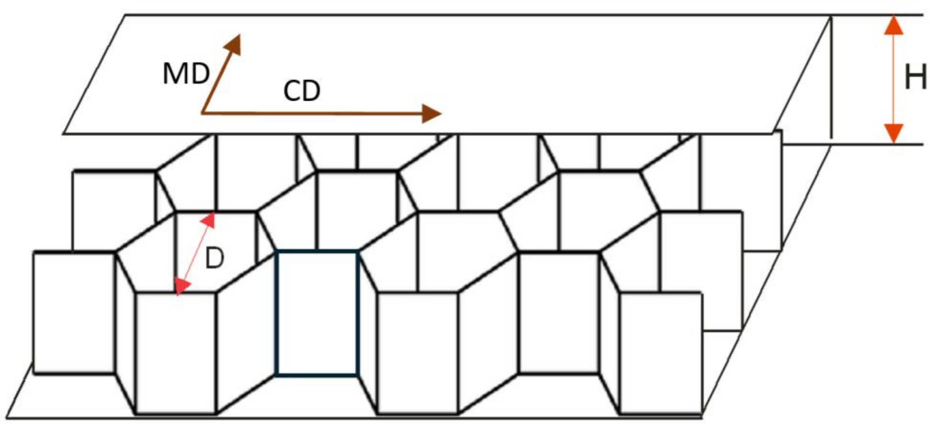


Fig. 2. Cellular paperboard parameters: D – diameter of the circle inscribed in the regular hexagon, defined as the cell mesh size; H – paperboard thickness; MD – machine direction; CD – cross direction

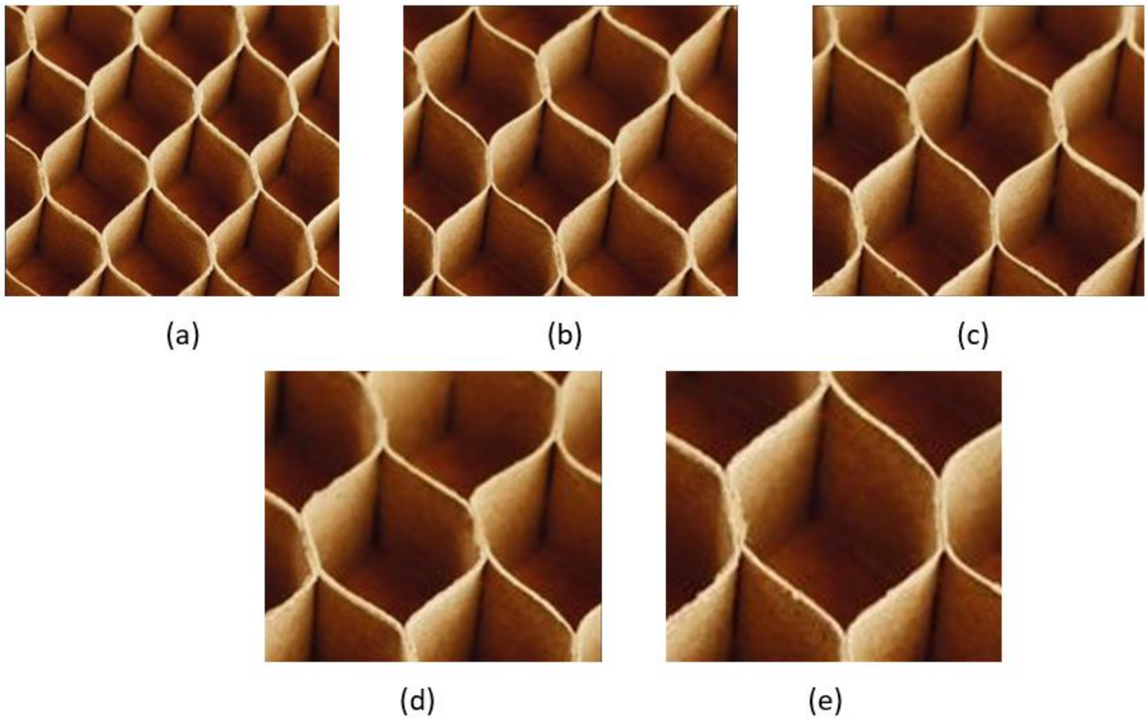


Fig. 3. Cell sizes in the cellular paperboards studied: (a) – D = 10 mm, (b) – D = 12 mm, (c) – D = 1 mm, (d) – D = 17 mm, (e) – D = 22 mm

Measuring the Grammage and Thickness of Cellular Paperboards

The grammage measurement was carried out in accordance with PN-EN ISO 536 (2020). The paperboard samples were weighed on an analytical balance and their surface area was calculated. Twenty rectangular-shaped samples of 500 mm x 100 mm were cut for each type of paperboard. Ten samples in which the MD machine direction of the paperboard was parallel to the longer side of the sample and 10 in which the CD cross direction was parallel to the longer side. The samples were then weighed using an analytical balance to the nearest 0.001 g, and the grammage was calculated as the quotient of weight by area. The average value of the 20 determinations was given as the result.

Thickness measurements were carried out to verify the thickness declared by the manufacturer. An electronic caliper was used to measure the thickness of the paperboards. Twenty thickness measurements were taken for each paperboard. The result was given in mm as the average value of the 20 measurements. During the thickness measurement, the measuring part of the caliper covered at least two double walls of the cellular paperboard core. This way of measuring reduced the effect of too much pressure on the measurement result, since double walls have a much higher stiffness.

FCT Measurement Methodology

FCT flat crush resistance measurements were carried out on 100 mm x 100 mm specimens at a measurement speed of 12 mm/min using a gage with two rigidly fixed plates (Fig. 4) and a Zwick testing machine with a load range of up to 20 kN, designed for quasistatic testing.

Prior to the measurement, the samples were subjected to an initial force. To state the initial force, test measurements were made, in which the initial value of the force was equal to 0 and the force-strain graph was observed, on which was visible in the initial zone the area of fitting of the specimen to the surface of the crush plates of the instrument through the non-linear force-strain relationship. After this stage, a rectilinear crush began, the beginning of which corresponded to different force values, depending on the size of the core cell. To eliminate the influence of the fit of the sample to the instruments, based on the test results, the value of the initial force was selected within the range of 100 to 250 N depending on the compression characteristics of the paperboard with a given cell size. FCT value was calculated from the formula,

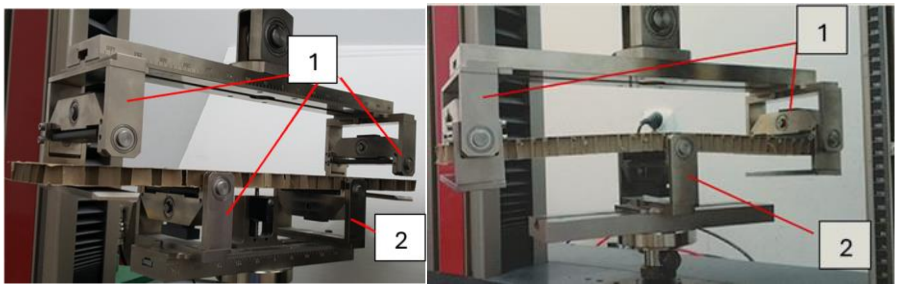
$$FCT = \frac{F_n}{A} \text{ [kPa]} \quad (1)$$

where Fn is value of destructive force (kN), and A is surface area of the test sample (m^2). The result is given as the average value obtained after testing 10 samples.

Fig. 4. Instrumentation for measuring FCT

BS Measurement Methodology

The instrumentation shown in Fig. 5 was used to test the BS of the cellular paperboard. To check the method of loading affects the results of bending stiffness the measurements were carried out using the 4-point and 3-point bending methods. The specimens were bent with a moment lying in a plane perpendicular to the outer plane of the paperboard and parallel to the long side of the specimen.



(a) (b)

Fig. 5. Instrumentation for testing bending stiffness: a) 4-point bending method, b) 3-point bending method, 1 – support with two degrees of freedom, 2 - support with one degree of freedom

The instrument for measuring bending stiffness by the 4-point bending method had four supports (Fig. 5 a). Three of them (two upper supports and one lower) (1) can rotate about two axes parallel to the principal directions in the plane of the cellular paperboard, and the support (2) can only rotate about an axis perpendicular to the plane in which the bending moment acts. The 3-point bending method stiffness instrument (Fig. 5 b) has two upper supports (1) that can rotate about two axes parallel to the principal directions in the plane of the cellular paperboard, and the third lower support (2) has the ability to rotate about an axis perpendicular to the plane in which the bending moment acts. The distribution of forces acting on the specimen is shown in Fig. 6.

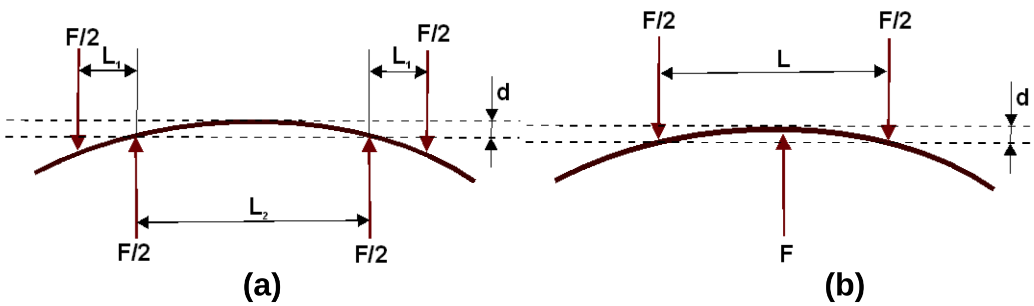


Fig. 6. Loading scheme: a) 4-point bending method, b) 3-point bending method

Using the designations given in Fig. 6, the bending stiffness was calculated from the formulas:

– for 4-point bending method,

$$BS = \frac{F\,L_1 L_2^2}{16db} \text{ [Nm]} \tag{2}$$

– for 3-point bending method,

$$BS = \frac{F\,L^3}{48db} \text{ [Nm]} \tag{3}$$

where F is acting force (N), L, L_1, L_2 is distances between supports (m), d is deflection (m), and b is sample width (m).

For the measurements carried out in this work, for the 3-point bending method, the spacing of the outer supports L equal to 400 mm was used, and for the 4-point bending method, the distance between the inner supports L_2 was 200 mm, and for the distance L_1 of the outer supports from the nearest inner support, the relationship $L_2 = 2L_1$ was used. The test specimens had a dimension of 100 mm x 500 mm. The speed of the moving supports was 10 mm/min for both measuring instruments used, in order to ensure a short test time and avoid permanent deformation of the material. Initial measurements were carried out using different values of initial force on the basis of which the following values of initial force were selected 2 N for paperboards with cell size D = 10 mm, D = 12 mm, 1.5 N for paperboards with cell size D = 14 mm, D = 17 mm, and 1 N for paperboards with cell size D = 22 mm for both devices. The load was increased until the desired deflection arrow was reached, selected in the range of linear dependence of deflection arrow on force. For cellular paperboards with a core cell diameter of D = 10 mm, D = 12 mm, D = 14 mm, the measurement was carried out up to a deflection of 2 mm, while for paperboards with a core cell diameter of D = 17 mm, D = 22 mm up to a deflection of 1 mm.

The measurements were carried out using a Zwick testing machine with a load range of 500 N. The tests were performed on 10 samples in the machine direction MD and cross direction CD from each type of honeycomb paperboard, and the result was given as an average value of ten measurements in each direction.

RESULTS AND DISCUSSION

The average values of the thickness measurement result, the standard deviation, and the maximum and minimum values obtained for the test paperboards are illustrated in Fig. 7. The error bars for the measurement results represent the maximum and minimum thickness values of the paperboards obtained by measurement. Table 2 summarizes the value of thickness measurement errors. The measurement error was calculated as the absolute value from the difference of the thickness measurement value and the thickness value given by the manufacturer related to the measurement value and expressed as a percentage.

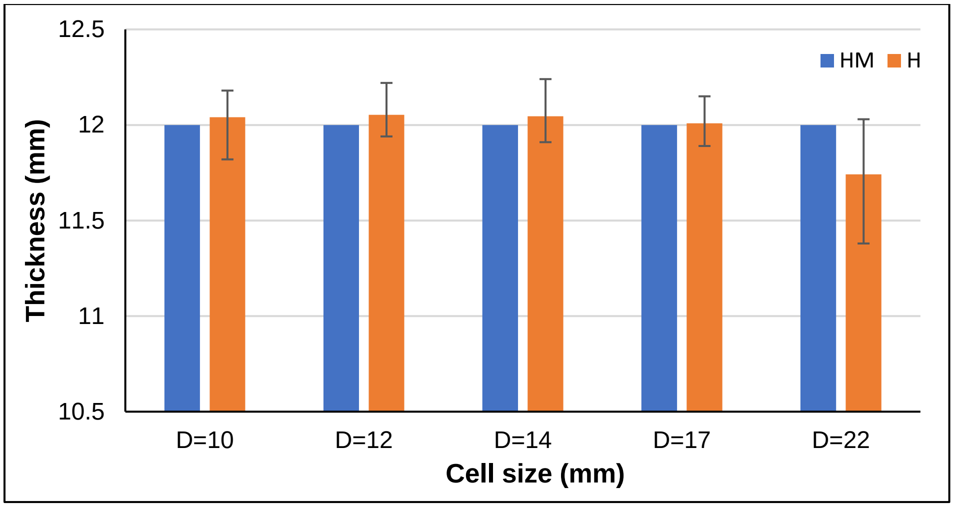


Fig. 7. Comparison of cellular paperboards thicknesses, H_M – thickness declared by the manufacturer, H – thickness measurement

Table 2. Error in Thickness Measurement

Thickness Measurement Error (%)					
D (mm)	10	12	14	17	22
Error (%)	0.34	0.44	0.38	0.08	2.15
Standard deviation (mm)	0.092	0.083	0.084	0.071	0.185

For most of the tested honeycomb paperboards, the measured thickness values were higher than the manufacturer's stated value. Only for the paperboard with the largest cell D = 22 mm, lower measurement values were obtained with respect to the nominal value. This paperboard had the largest standard deviation and the largest measurement error of 2.15% with respect to the measured value. This may indicate that it is difficult to maintain a precise thickness value with a larger mesh size for honey-comb paperboard. The smallest scatter of thickness values was characterized by the paperboard with cell size D = 17 mm, for which the lowest standard deviation and measurement error values were obtained, which were 0.071 mm and 0.08%, respectively. Paperboards with a cell size of D = 10 mm and D = 14 mm had similar error values, despite the slightly higher standard deviation values for paperboard with a mesh of D = 10 mm.

Figure 8 compares the grammages of honeycomb paperboards according to cell size. The error bars represent the maximum and minimum values. The results show that the grammage of cellular paperboard decreased with an increase in the cell size. The decrease in grammage with an increase in the size of the cell diameter of the core *D* is due to a decrease in the number of cells on a given area of paperboard, which entails a lower consumption of paper for the paperboard core, that is, a decrease in the weight of the cellular core.

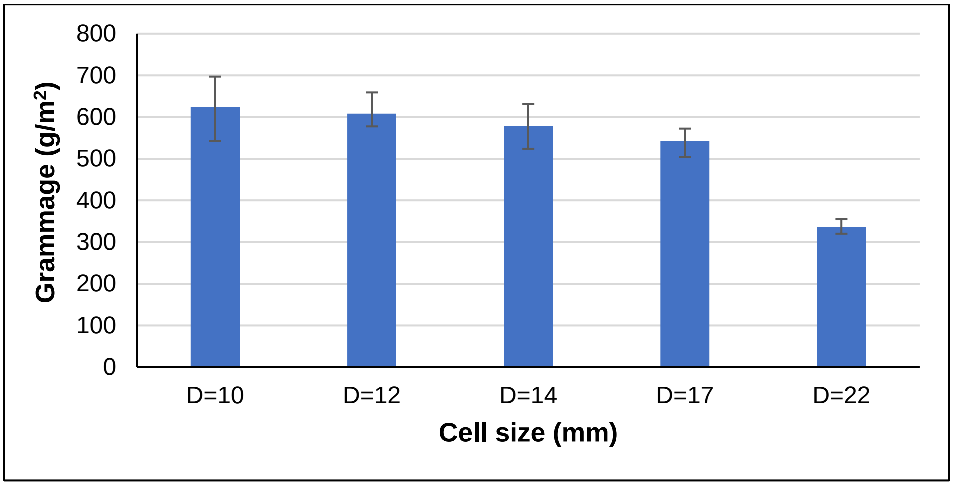


Fig. 8. The grammage of the tested honeycomb paperboards

The standard deviation of the grammage measurement was the largest for the honeycomb paperboard with the smallest cell, while it was the smallest for the paperboard with the largest cell. The largest scatter of results between the maximum and minimum measurement values was obtained for paperboards with a cell diameter of *D* = 10 mm and *D* = 14 mm, which indicates a large heterogeneity in the structure of cellular paperboard probably caused by the irregularity of the cell size in the tested samples. The regularity of the mesh depends on the cellular paperboard production process, which was carried out correctly, and is influenced by two factors: the correct stretching of the cellular paperboard core and the widths of the adhesive band applied to the paper webs during the production of the cell core. The irregularity of the cell caused by inaccurate stretching of the core resulted in a concentration of the structure and an increase in the grammage of the cellular paperboard.

The dependence of the grammage of honeycomb paperboard on the diameter of the core cell *D* could be described by a linear function equation, as a linear approximation of the measurement results Fig. 9. The linear approximation equation gave a good representation of the results as evidenced by the value of the coefficient of determination R^2 = 0.9032.

Table 3 shows the results of grammage calculations based on linear approximation for the cellular paperboards tested, as well as the calculation error as a modulus of the difference between the calculated value and the measured value related to the measured value and expressed in %.

The differences in the measured values of grammage and grammage calculated using the equation of the linear function of the dependence of grammage on the core cell diameter *D* ranged from 0.95 to 51.63 g/m^2. For honeycomb paperboards with a cell diameter of 10, 12, or 22 mm, higher calculated values were obtained than the measured values. In the case of honeycomb paperboards with a cell diameter of 14 or 17 mm, lower calculation results were obtained than measured results. However, these differences were small, with a relative error of 0.16% to 10.6%.

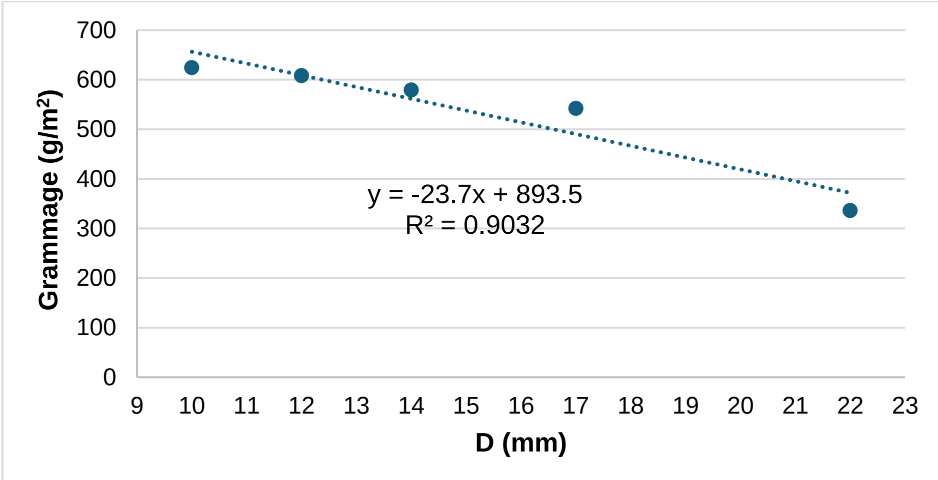


Fig. 9. Linear approximation of the dependence of grammage on cell size

Table 3. Grammage Calculation Based on Linear Approximation

Grammage (g/m^2)					
D (mm)	10	12	14	17	22
Calculation	656.38	608.95	561.52	490.37	371.79
Error (%)	5.19	0.16	3.02	9.53	10.65

Figure 10 compares the FCT values of the tested paperboards. The error bars represent the maximum and minimum values of the results obtained during the measurements.

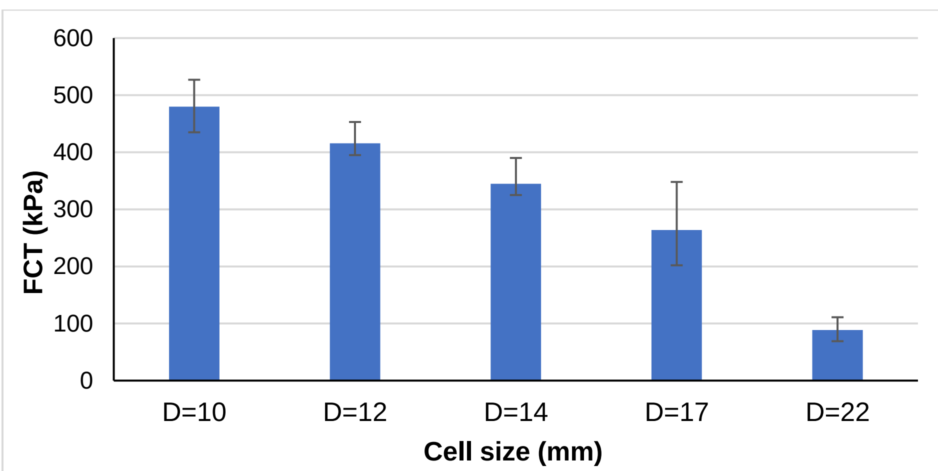


Fig. 10. Results of FCT measurement of tested honeycomb paperboards

The results of FCT measurements for the tested paperboards show the dependence of FCT on the cell size of the core. As the cell diameter increases, the FCT value of paperboards made from the same fiber raw materials and of the same thickness decreased.

For paperboards with a cell size of *D* = 10 mm, the FCT value was 5.4 times higher than for a cell size of *D* = 22 mm. A linear approximation of the results of FCT measurements for the tested paperboards was also performed (Fig. 11).

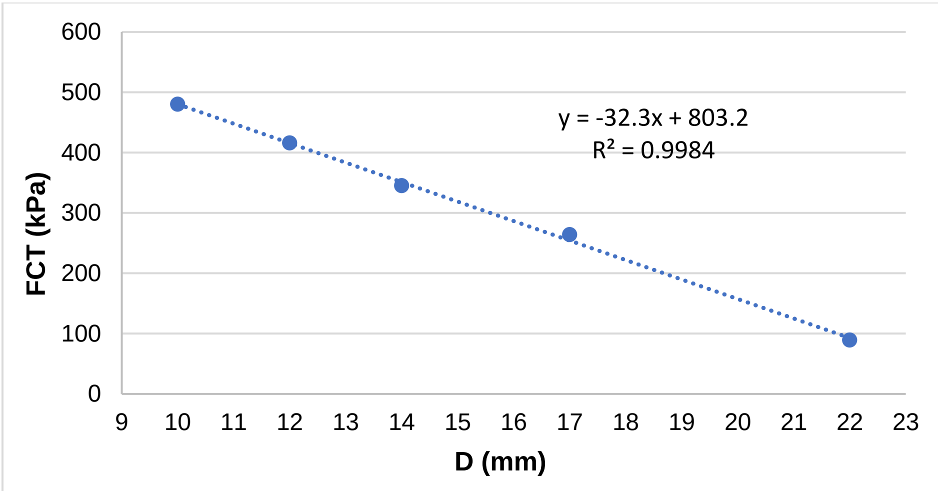


Fig. 11. Linear approximation of the relationship of FCT value to cell size

The dependence of FCT on cell size can be described by a linear function with a coefficient of determination R^2 close to 1, which indicates a very good fit of the straight line to the measurement results. Table 4 shows the results of FCT calculations based on linear approximation for the tested cellular paperboards and the calculation error as a modulus of the difference between the calculated value and the measured value related to the measured value and expressed in %. The calculation error ranged from 0.06% to 4.2% and had an increasing trend with increasing cell size. The average calculation error was 1.96%.

Table 4. FCT Calculation based on Linear Approximation

FCT (kPa)					
D (mm)	10	12	14	17	22
Calculation	480.28	415.69	351.1	254.215	92.74
Error (%)	0.06	0.07	1.77	3.71	4.20

Based on the linear function equation, it was possible to predict the FCT value with high accuracy for honeycomb paperboards made of the same fibrous raw materials and of the same thickness with different mesh sizes, as evidenced by the relative calculation error ranging from 0.06% to 4.2%.

The following graphs compare the results of measurements made using the 3-point and 4-point bending methods for bending stiffness in the machine direction and cross direction (Figs. 12, 13). The error bars represent the maximum and minimum values of the results obtained during the measurements.

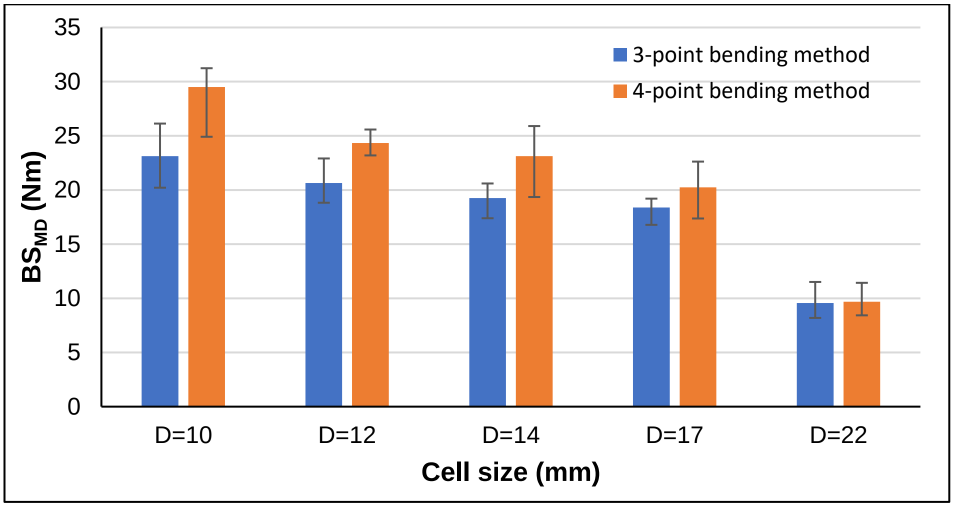


Fig. 12. BS_{MD} measurements results for honeycomb paperboards using 3-point and 4-point bending

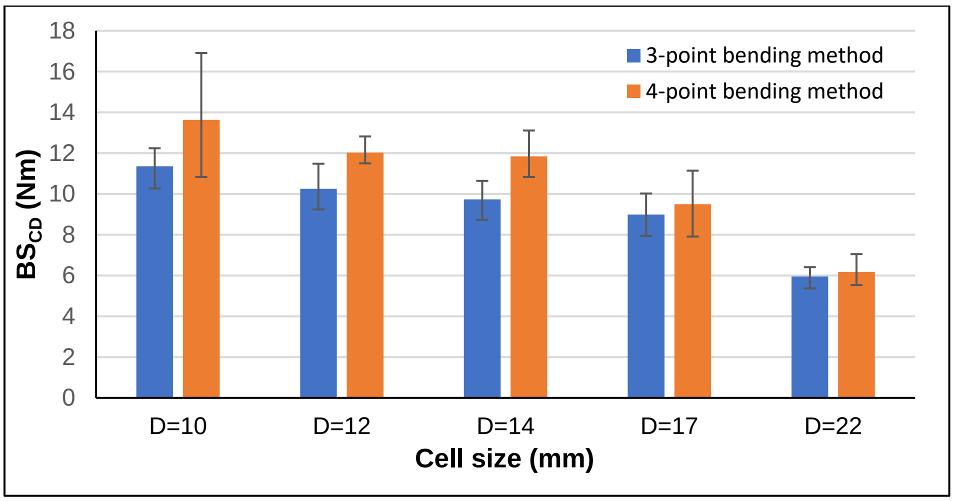


Fig. 13. BS_{CD} measurements results for honeycomb paperboards using 3-point and 4-point bending

The results show that as the cell size increased, the BS values decreased regardless of the measurement method used. For both main directions in MD and CD cellular paperboard, the average values of BS measurements using the 4-point bending method were higher than the results of measurements obtained using the 3-point bending method. For BS_{MD}, the differences ranged from 0.12 to 6.38 Nm, while for BS_{CD} they ranged from 0.22 to 2.27 Nm. The reason for the lower BS values in the 3-point bending method was the shear forces on the measuring section, which were eliminated in the case of the 4-point method. For all the honeycomb paperboards tested and both measuring instruments used, the BS_{MD} values were about twice the BS_{CD} values. For example, the average BS_{MD} value for honeycomb paperboard with a cell diameter of D = 10 mm was 2 times greater than the BS_{CD} value using the 3-point bending method, while the value was 2.1 times greater using the 4-point bending method. For paperboard with a cell of D = 22 mm, the smallest scatter of measurement results was obtained in both main directions in the plane of the paperboard and for both measuring instruments, as evidenced by the smallest value of the standard deviation and the difference between the maximum and minimum values obtained during measurement. The largest scatter of measurement results was observed for paperboards with a cell of *D* = 10 mm and *D* = 14 mm. The reason for the large scatter of results for the above paperboards could be the irregular shape of the mesh that was observed in some of the honeycomb paperboard samples tested. The smallest difference between BS_{MD} and BS_{CD} was obtained for paperboard with a cell size of *D* = 22 mm, and the largest by paperboard with a cell size for *D* = 10 mm. The larger the cell diameter, the difference in bending stiffness values in the MD and CD directions for both instruments used decreases.

A linear approximation of the BS_{MD} and BS_{CD} measurement results were also performed (Figs. 14, 15).

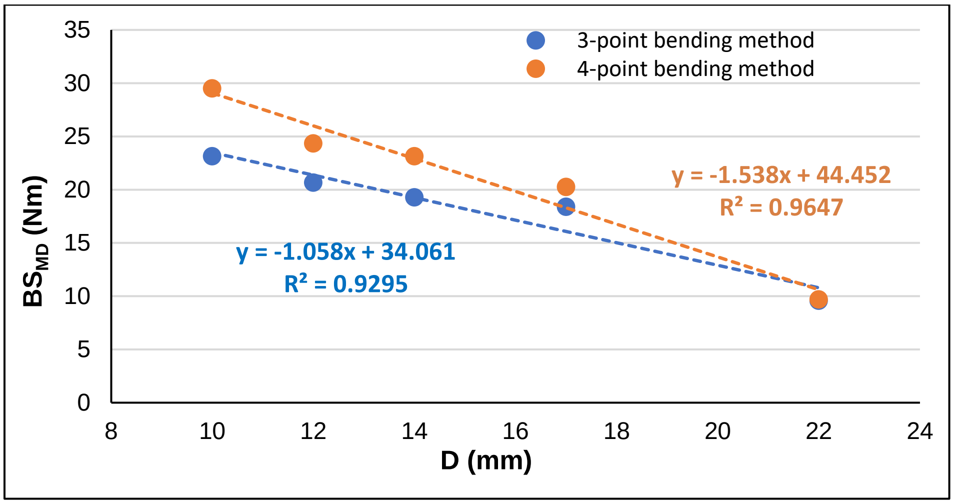


Fig. 14. Linear approximation of BS_{MD} dependence on cell size for 3-point and 4-point methods

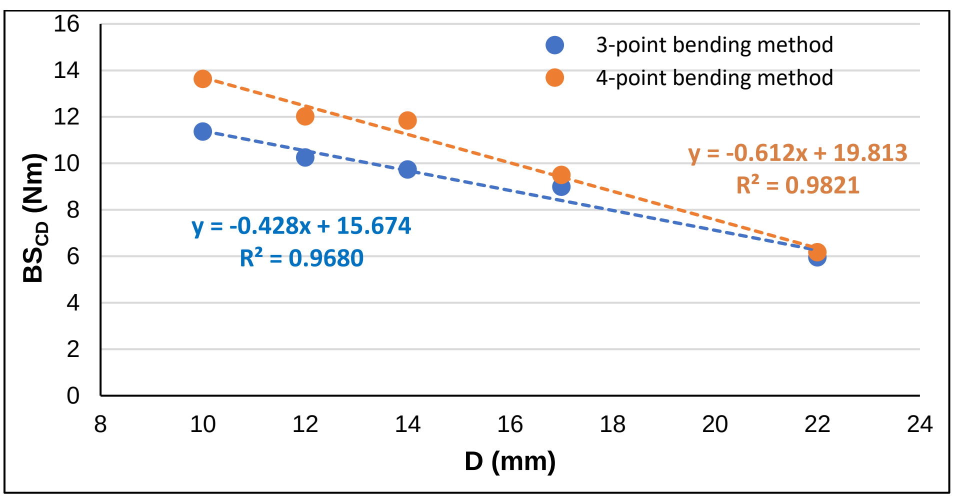


Fig. 15. Linear approximation of BS_{CD} dependence on cell size for 3-point and 4-point methods

Analyzing the dependence of BS values for both measurement methods and both MD and CD bending directions on cell size for honeycomb paperboards made from the same papers and of the same thickness (Figs. 14, 15), a linear relationship was obtained. Comparing the coefficient of determination R^2, a better fit of the straight line to the measurement points for both BS_{CD} and BS_{MD} was obtained for measurements made using the 4-point bending method. The R^2 values for the 4-point bending method in the CD and

MD directions were 0.9821 and 0.9647, respectively. For the 3-point bending method, the R^2 values, for BS_{CD} and BS_{MD}, were lower, at 0.9680 and 0.9295 respectively.

Tables 5 and 6 show the results of calculating BS_{MD} and BS_{CD} values based on linear approximation.

Table 5. BS_{MD} Calculated from a Linear Approximation and Calculation Error

BS_{MD} (Nm)										
	3-point bending method					4-point bending method				
D (mm)	10	12	14	17	22	10	12	14	17	22
Measure-ment	23.12	20.64	19.26	18.38	9.56	29.5	24.33	23.13	20.24	9.68
Calculated	23.48	21.37	19.25	16.08	10.79	29.07	25.99	22.91	18.30	10.61
Error (%)	1.57	3.52	0.05	12.53	12.82	1.47	6.82	0.93	9.59	9.58

Table 6. BS_{CD} Calculated from a Linear Approximation and Calculation Error

BS_{CD} (Nm)										
	3-point bending method					4-point bending method				
D (mm)	10	12	14	17	22	10	12	14	17	22
Measure-ment	11.36	10.25	9.73	8.99	5.95	13.63	12.02	11.84	9.50	6.17
Calculated	11.40	10.54	9.68	8.40	13.69	12.47	11.24	9.41	6.34	10.61
Error (%)	0.32	2.83	0.46	6.55	0.44	3.71	5.05	1.00	2.83	9.58

The calculation error for BS_{MD} for the 3-point bending method ranged from 0.05% to 12.8%, whereas for the 4-point method the values ranged from 0.93% to 9.59% relative to the measurement value, and the average error was 6.1% and 5.68% relative to the measurement value, respectively. The calculation error for BS_{CD} for the 3-point bending method ranged from 0.32% to 6.55%, whereas for the 4-point method it ranged from 1% to 9.58% relative to the measurement value. The average error was 3.8% and 2.61% relative to the measurement value, respectively. Based on the linear approximation, one can predict the bending stiffness values for both MD and CD directions of honeycomb paperboards made from the same fiber raw materials and of the same thickness with different cell sizes with high accuracy.

The ability to predict the grammage, FCT and BS of honeycomb paperboards made from the same fiber raw materials and with the same thickness, but different cell sizes contribute to the ability to match the cell size to the required properties at the honeycomb paperboard design stage. The honeycomb paperboard produced will meet the customer's requirements and will be economical to manufacture. Manufacturers of honeycomb paperboards make hexagonal shaped honeycomb structures with a certain degree of accuracy. The proposed approach allows these imperfections to be considered.

CONCLUSIONS

1. The size of the core cell was found to affect the grammage (basis weight) of the honeycomb paperboard. As the cell size increased, the grammage of cellular paperboard decreased. This is because as the cell size was increased, the number of cells on a given area of paperboard decreased, which resulted in less paper being used for the paperboard core, *i.e.* the weight of the honeycomb core decreased.
2. The results of flat crush test (FCT) measurements for the tested honeycomb paperboards show that as the cell diameter of the paperboard core increased, flat crush resistance decreased. This can be attributed to a decrease in the number of cells on a given paperboard surface, which entails a decrease in core strength. The dependence of FCT on cell size can be described by a linear function, based on which it is possible to predict with high accuracy the FCT values of paperboards for any cell size made of the same fiber raw materials and of the same thickness.
3. The bending stiffnesses of all paperboards tested in both the machine and cross directions obtained using the 3-point bending method were lower than those obtained using the 4-point bending method. The reason for the lower values in the 3-point bending method is the action of shear forces on the measuring section, which are eliminated in the case of the 4-point method.
4. The study showed a close dependence of bending stiffness (BS) on cell size for paperboards made from the same fiber raw materials and of the same thickness. As the cell size increased, BS values in both the machine and cross directions decreased regardless of the measurement method used. For all the honeycomb paperboards tested and both measuring instruments used, the BS_{MD} values were about twice as large as the BS_{CD} values.
5. A large influence of the shape of the core cell on the strength properties of the paperboard was observed. Honeycomb paperboard core cell irregularities arose at the core production stage because of improperly applied glue strips on the paper webs or improper stretching of the core contributed to large scatterings in the measurement results.

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