The Influence of the Composition of Pulp and the Number of Layers on the Strength Properties of Multi-Layer Papers Intended for the Production of Corrugated Paperboard

Karolina Radomska,* Konrad Olejnik, and Piotr Pospiech

This research investigated the influence of the layered structure of paper on its selected strength properties. Two types of cellulose pulp were used: unbleached kraft pine pulp (UBSK) and unrefined bleached birch kraft pulp (BHK). Multi-ply papers were obtained from layers of appropriate grammage formed separately and bonded in a wet state. Paper layers were formed from primary pulps (UBSK and BHK) or their mixtures (three-ply UBSK-BHK paper and three-ply UBSK-BHK-UBSK paper), from which various variants of laboratory paper samples were made. This work focused on three-layer papers. The obtained laboratory sheets were analysed for changes in tear resistance, tensile strength, bursting strength, short span compression strength (SCT), and corrugating medium test (CMT). In most cases, three-layer structures were characterised by higher strength parameters than single-layer papers. The tear strength and SCT of papers consisting of three layers formed from both mixed pulps were slightly lower than those of solid papers. The results demonstrate the feasibility of producing three-ply paper with significantly reduced variability in parameters such as elongation and bursting strength, which are inherently subject to high variability.

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*Contact information: Centre of Papermaking and Printing, Lodz University of Technology, Wolczanska 221, 93-005 Lodz, Poland; *Corresponding author: karolina.radomska@p.lodz.pl*

INTRODUCTION

Paper production, like many other modern industrial processes, is a complex undertaking, with technological and economic factors both playing an important role. Optimising production costs and tailoring product properties to changing customer needs are important factors that often determine business profitability. The pursuit to enhance the functional properties of the paper web began in the mid-20th century. Initially, multi-layer forming provided a solution to drainage problems associated with the paper web, especially in the case of higher grammage products. However, the true potential of multi-ply forming technology soon became evident, offering manufacturers the flexibility to engineer web structures to meet end-use customer specifications.

Currently, multi-layer forming serves various purposes, including (Attwood and Moore 1994; Odell 1999):

a) Improving surface properties of products.
b) Obtaining new functionality of products.

c) Reducing the use of expensive raw materials.
d) Reducing energy consumption.

Currently, there are two methods of producing multi-layer paper and board used in industry (Attwood and Moore 1994; Reczulski 2019). These methods are presented in Fig. 1.

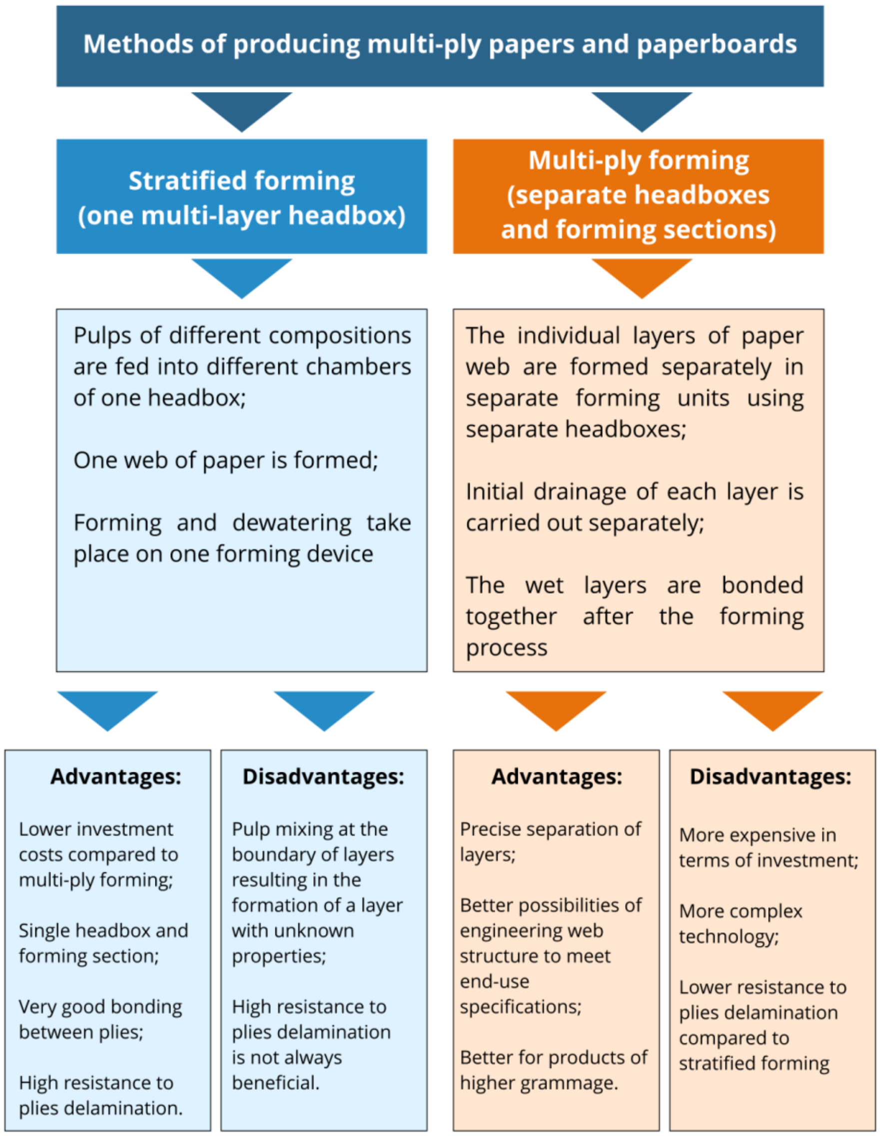

Fig. 1. Advantages and disadvantages of methods of producing multi-ply papers and paperboard

Stratification forming is used to obtain a multi-layer structure of paper using a single headbox. The headbox is equipped with several chambers, each receiving paper pulps with different raw material compositions. As these streams merge upon exiting the headbox nozzle, they create a combined flow (Norman and Söderberg 2001; Söderberg and Lucisano 2005; Reczulski 2019). Stratified forming can be applied to paper grades of any grammage. This technology is widely used in the production of printing papers, two-ply liners, and tissue products. Stratification forming has many advantages over classical, single-layered paper web forming. Page and Hergert (1989) found that when they incorporated 25% of pulp made from mixed waste paper into the middle layer, the bursting strength values were only reduced by 6% compared to a 20% reduction for single-layer paper. Research conducted by Häggblom-Ahnger (1999) also showed that the layered structure of paper facilitates the design of its properties by utilising different cellulose pulps in the middle layer. The strength properties of the paper were modified without changing the properties of the outer layers, which was important in the case of printing papers. On the other hand, Lindberg and Kulachenko (2022) highlighted the importance of layer placement within the paper structure for its subsequent use. They found that a top layer made of pulp with a lower papermaking potential increased the risk of damage to the entire paperboard upon impact. Despite many advantages, one disadvantage of the stratified forming technology is the mixing of adjacent layers of pulps (Söderberg and Lucisano 2005). The mixing of streams occurs in the last phase of pulp flow from the headbox when the streams are no longer separated by lamellas. Although mixing of the layers results in a high degree of bonding, it also leads to a lack of clear boundaries between the layers, resulting in the formation of an additional layer in the paper web with undefined properties or with properties that are very difficult to determine (Attwood and Moore 1994; Söderberg and Lucisano 2005). Unfortunately, this phenomenon is very difficult to eliminate. To minimise this effect, STFI-Packforsk has developed a modification for the stratification headbox, known as ‘Aq-vanes’. This new technology involves injecting a thin, passive layer of liquid between adjacent pulp streams through a narrow hollow channel, thereby preventing interlayer mixing.

The second method of producing multi-layer paper and solid paperboard utilises multi-wire and multi-headbox forming units, where each ply of paper is formed separately and is initially dewatered, typically to a dryness of about 10 to 14% (Attwood and Moore 1994). In the next step, the layers are bonded together and the formed paper web is transferred to subsequent sections of the paper machine. Breen (1969) demonstrated that an appropriate moisture content in a single layer is one of the most important technological factors determining the bond strength in the multi-ply paper structure. Furthermore, it was found that the highest delamination strength was achieved when the dryness of each layer did not exceed 20%. Moreover, in the narrow dryness range of 10 to 15%, the delamination strength doubled. If the initial dryness of the layers was too low (below 10%), the fibrous structure was usually insufficiently consolidated. On the other hand, a paper web dryness below 75% is necessary to achieve substantial bonding between the plies (Breen 1969). Experiments conducted by Ryu and Lee (2007) showed that the bonding strength of plies could be improved by spraying the starch onto the formed wet web before it was consolidated into a multi-ply fibrous structure.

High strength properties are most often beneficial; however, it is worth mentioning that very high resistance to layer delamination is not always desirable, *e.g.*, in the case of multi-ply, high-grammage solid paperboard that is intended to be subjected to bending and creasing during further converting. If the ply bond is too strong, the paperboard would not be suitable for creasing, pressing, or bending. As a result, the material may crack during folding (Sharma 1979). Although the multi-wire method is more expensive (in terms of investment and operation) and may cause technological difficulties, it presents additional opportunities to design products with the required functional properties. The achieved effects, including the uniformity of the paper web formation and the desired fiber orientation in each layer, are usually much better compared to the stratification method (Attwood and Moore 1994). Regardless of traditional applications, multi-layer forming can be used to produce advanced products, such as paper-based microfluidic devices (μPAD) and smart packaging (Lisowski and Zarzycki 2013; Wang *et al*. 2022). Economic factors, growing requirements, and emerging new customers' needs mean that a significant proportion of the paper products available on the market are multi-layer papers.

In the latest literature one can find large number of publications relating to the properties and the process production of multi-layer corrugated cardboard. However, the topics related to the properties of multi-layer papers intended for the production of corrugated cardboard are not discussed as often. Moreover, there have been no new publications on multi-ply forming technology and the properties of multi-ply papers, which would take into account, for example, the deteriorating quality of fibrous raw materials. Since improving the functional properties of individual components of multi-layer cardboard is one of the most important factors in optimizing the costs of their production, this topic now seems equally important and interesting. It can therefore be assumed that the importance of this technology will systematically increase, justifying further scientific research on this topic.

The aim of this research was to investigate the influence of the layered structure of paper on its structural and mechanical properties. Single-, double-, and triple-ply structures made in laboratory conditions were tested. Two types of pulps with high and low papermaking potential were used in the experiments to simulate the impact of reducing the price of the raw material on the properties of single- and multi-ply papers. The research included the analysis of two cases that may occur in industrial practice. These cases concerned decisions about choosing the proper technology when:

a) Strength properties are the only priority.
b) Strength properties and cost reduction are equally prioritised, necessitating the addition of cheaper pulp with low papermaking potential.

EXPERIMENTAL

Preparation of Paper Samples

Two types of cellulose pulps of high and low papermaking potential were used in the present work: a) unbleached kraft pulp from *Pinus* sp. (UBSK) refined to 30 °SR (Schopper-Riegler freeness) and b) unrefined bleached birch (*Betula pendula*) kraft pulp (BHK), which was used as a secondary pulp equivalent. The unbleached kraft pine pulp was prepared according to the ISO 5263-1 standard and was refined in the PFI mill according to the TAPPI T 248 standard method. The Schopper–Riegler value of the BHK pulp was 17°SR. The properties of both pulps are presented in Table 1.

Table 1. The Properties of Pulps Used in the Studies

Pulp Grade	Schopper-Riegler Freeness (SR)	Geometric Average Fibre Length (mm)	Internal Bonding Strength (Scott bond) (J/m^2)
UBSK	30	1.49	115.8
BHK	17	0.72	2.4

Eight different types of paper sheets with a final constant grammage of 150 g/m^2 were formed from UBSK and/or BHK pulps. Paper sheets were formed in the Rapid-Köthen machine according to the ISO 5269-2:2005 standard. The samples differed in composition and forming method. The following variants of laboratory paper samples were made:

1) UBSK pulp, one-ply, 150 g/m^2
2) BHK pulp, one-ply, 150 g/m^2
3) UBSK pulp, two-ply, 2 × 75 g/m^2
4) UBSK pulp, three-ply, 3 × 50 g/m^2
5) BHK pulp, three-ply, 3 × 50 g/m^2
6) Mixed pulp (1:1 ratio of UBSK to BHK), one-ply, 150 g/m^2
7) Mixed pulp (1:1 ratio of UBSK to BHK), three-ply, 3 × 50 g/m^2
8) UBSK-BHK-UBSK, three-ply, 3 × 50 g/m^2.

The variants of the paper samples produced are also shown in Fig. 2.

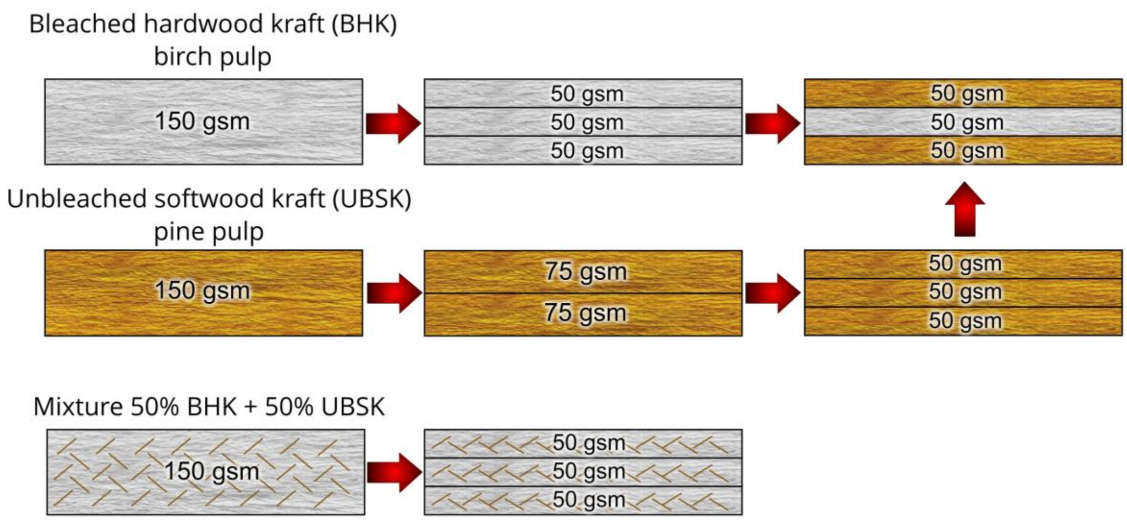

Fig. 2. Variants of paper samples formed and tested in the research

Multi-ply papers were obtained by forming layers of appropriate grammage separately and then bonding them in a wet state. After forming, the handsheets were pressed using a standard 2.8 kg hand roller with a diameter of 140 mm. Pressing was performed under the roller's own weight in such a way that the roller was rolled three times on the sample surface. Drying was carried out at a temperature of 98 °C and a vacuum pressure of 93 kPa. The sheets were clamped to prevent lateral shrinkage during drying. The final grammage of all paper sheets was 150 g/m^2. For instance, in the case of three-ply papers, each ply had a grammage of 50 g/m^2. Prior to measurements, all samples were conditioned in accordance with the ISO 187:1990 standard.

Analytical Methods

The structural and mechanical properties of the paper samples were determined according to ISO standards:

a) Grammage (ISO 536:2019), Lorentzen & Wettre, Sweden.
b) SR value (ISO 5267-1:1999), L&W Schopper–Riegler freeness tester, Sweden.
c) Internal bonding strength, Scott bond (ISO 15754:2009).
d) Tensile index and elongation (ISO 1924-2:2008), Instron 5564, UK.
e) Elmendorf tear resistance (ISO 1974:2012), Lorentzen & Wettre Tearing Tester, Sweden.
f) Bendtsen air permeance (ISO 5636-3:1992), TMI Testing Machines Inc., USA.

g) Bending stiffness, two-point method (ISO 5628:2019), TMI Testing Machines Inc., USA.
h) Bursting strength (ISO 2758:2014), Mullen Burst Machine, Lorentzen & Wettre, Sweden.
i) Compression strength, short span compression test (SCT) (ISO 9895:2008), Haida International Equipment Co., LTD, China.
j) Corrugated medium test, corrugating or Concora medium test (CMT) (ISO 7263-1:2018), Haida International Equipment Co., LTD, China.

Research related to the CMT focused on the 1st peak values. According to the literature (Fürst and Gerards 2016), this first peak or plateau is related to a bending failure that occurs after initial elastic compression. The 1st peak value is more stable because at this point there is no delamination of the paper, which often happens at the end of the measurement. Bending stiffness was calculated according to the formula (1) given by the producer of the testing device,

$$S_b = \frac{60 \cdot F \cdot L^2}{\pi \cdot \beta \cdot B} \quad (1)$$

where S_b is bending stiffness (mN·m), F is bending force (N), L = 50 is test length (mm), π is 3,14159, β = 5 is bending angle (˚), and B = 38 is sample width (mm).

To prepare radar charts, the values of individual parameters were normalised in the range of 0 to 1. The minimum and maximum values of each parameter were determined from the set of all studied cases.

RESULTS AND DISCUSSION

Strong ecological and economic aspects in modern paper production, including the production of corrugated cardboard components, often compel manufacturers to confront the challenge of utilising fibrous raw materials with very low papermaking potential. Such raw materials may not possess the necessary properties to be used as the sole component of fibrous pulp, necessitating their combination with other raw materials with higher papermaking potential. Therefore, this research analysed the properties of one-, two- and three-ply papers made exclusively from UBSK pulp, as well as papers made from a mixture of pulp with high and low papermaking potential. An analysis was also carried out on a sample consisting of external layers made from the pulp with high papermaking potential (UBSK pulp) and an internal layer made from the pulp with low papermaking potential (unrefined BHK pulp). The studies began with a comparison of the general papermaking potential of raw materials used in the research. This assessment was presented in the form of graphs comparing the tear strength as a function of the tensile index (Fig. 3 and Fig. 4). Figure 3 shows the values of the analysed parameters for single-ply papers formed from UBSK pulp (●), BHK pulp (●), and mixed UBSK-BHK pulp (●). UBSK and BHK pulp were mixed in a ratio of 1:1. Using the relationship between the tensile index and tear resistance, it is possible to determine the papermaking potential of the studied pulps, as well as the properties of the paper sheets formed from the fibrous raw materials. The lowest value of the tensile index was observed for single-layer BHK paper (●), while UBSK paper (●) achieved the highest value. Solid papers prepared from a mixture of UBSK-BHK pulps (●) were characterised by a lower tear and tensile strength compared to UBSK papers. The tensile strength was approximately 65% of that obtained for UBSK paper, while the tear strength was approximately 80% of that achieved by UBSK paper. These values exceed what would be expected from a simple calculation based on summing the percentages of individual pulps multiplied by the values of a given parameter for each pulp. This indicates that a 50% addition of pulp with a very low papermaking potential not only allowed for cost savings, but it also resulted in a smaller reduction in the papermaking potential of the final mixture than expected.

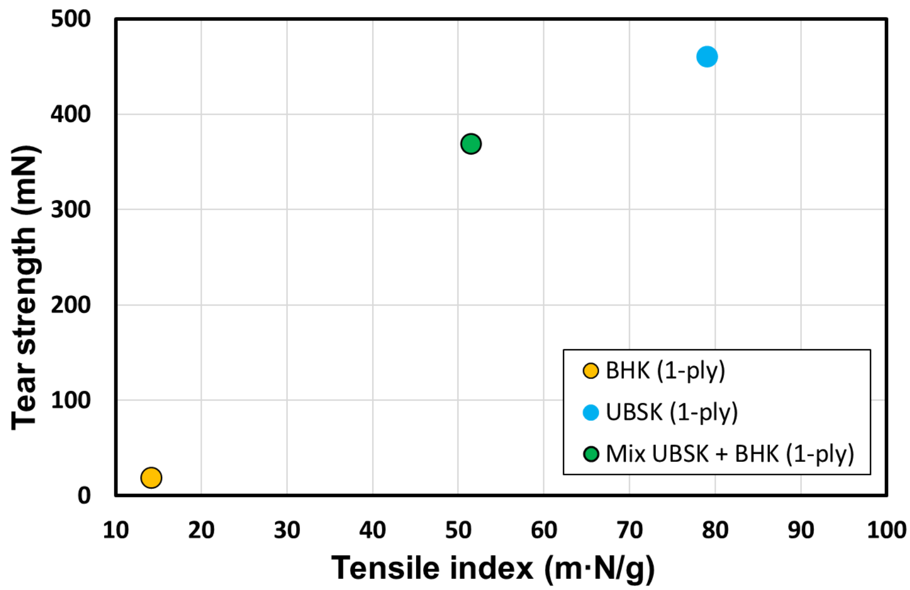

Fig. 3. Comparison of the tear strength as a function of the tensile index of solid (single-ply) papers formed from UBSK (●), BHK (●) or mixed UBSK-BHK pulps (1:1, ●). The grammage of all papers was 150 g/m^2.

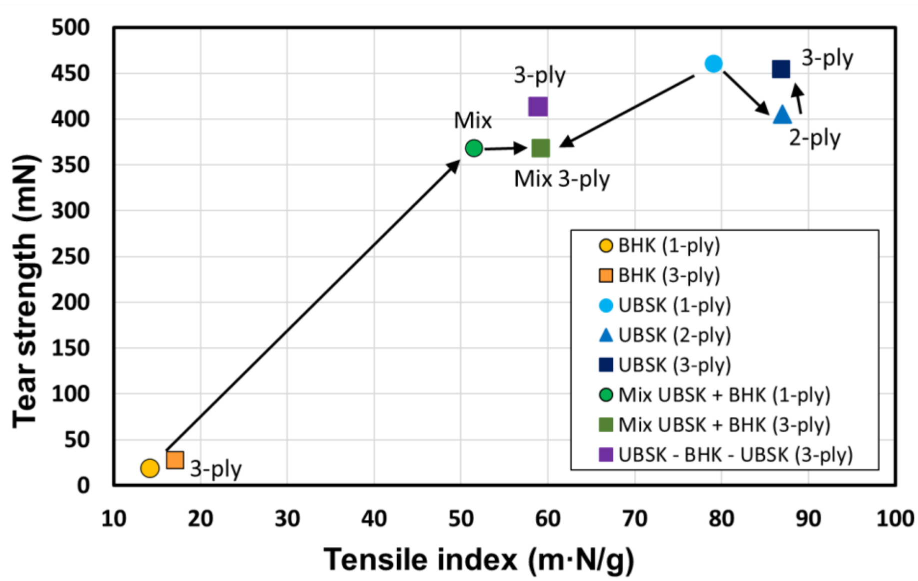

Fig. 4. Comparison of the tear strength as a function of the tensile index of single-ply and multi-ply papers formed from UBSK (● one-ply, ▲two-ply, ■ three-ply), BHK (● one-ply, ■ three-ply) or mixed UBSK-BHK pulps (1:1, ● one-ply, ■ three-ply). Three-ply paper where only the internal layer was formed from BHK pulp has been marked in violet (■). The grammage of all papers was 150 g/m^2.

Multi-ply papers, including two- and three-ply papers, were obtained from separate layers bonded in a wet state. As shown in Fig. 4, multi-ply structures in the case of BHK (■) and UBSK pulp (▲ two-ply, ■ three-ply) were characterised by higher strength parameters compared to solid papers with the same total grammage. It was observed that the tensile index of the multi-ply paper made from a mixture of pine and birch pulps (UBSK-BHK, 1:1, ■) was higher by approximately 13% compared to homogeneous sheet paper (●) made from the same pulp mixture.

The tear strength for those two papers was the same. The tear resistance is especially important for sack and wrapping papers, which are typically exposed to physical and tearing stresses. The conducted experiments demonstrate a significant advantage of using multi-ply structures over single-ply papers. It was found that in the case of three-layer papers obtained from mixtures of both pulps (UBSK-BHK), only the tear strength was lower compared to analogous single-layer papers.

Multi-ply sheet papers may contain a different stock mixture in each layer, leading to several benefits from an industrial point of view (*e.g.*, reducing production costs of corrugated board and improving strength properties of final products). In the next stage, the multi-layered sheet papers UBSK (50 g/m^2)-BHK (50 g/m^2)-UBSK (50 g/m^2) were prepared (■). A significant increase in tear strength was observed for UBSK-BHK-UBSK sheets compared to three-layer papers formed from three single-layer mixed UBSK and BHK pulps (■).

The tensile index of both types of multi-ply paper was nearly identical. Analysis of the measurement data for three-layer paper with a middle layer of BHK pulp revealed that, in this instance, the attained value of tear strength were comparable to papers made from UBSK pulp while the tensile index values were similar to those obtained for 3-ply paper made from mixture of UBSK and BHK pulps. This means that by replacing the primary middle layer pulp with BHK pulp, the functional properties of the final paper product can be improved. Moreover, producing such multi-layer structures enables cost savings associated with raw materials and production.

As mentioned before, the obtained results were analysed considering two cases:

a) Strength properties are the only priority.

b) Strength properties and cost reduction are equally prioritised, necessitating the addition of cheaper pulp with low papermaking potential.

Case A: Strength Properties are the Only Priority

When strength properties are the only priority, paper can be produced using only fibrous raw material with high papermaking potential. Normalised values of the tested properties of single- and multi-ply papers made from pulp with high papermaking potential (UBSK pulp) are shown in Fig. 5. The presented radar charts show that an increase in the number of layers in the paper structure improved most of the tested properties. In the analysed situation, the tensile index increased by approximately 9%, elongation by approximately 14%, bursting strength by 17%, SCT by approximately 7%, and CMT (1st peak force) by 6%, while tear resistance showed a decrease of 1% (two-ply paper sample). Additionally, it is worth noting that most of the strength properties of the two-ply paper structure significantly improved. These results show the advantage of a multi-layer structure over a single-layer structure.

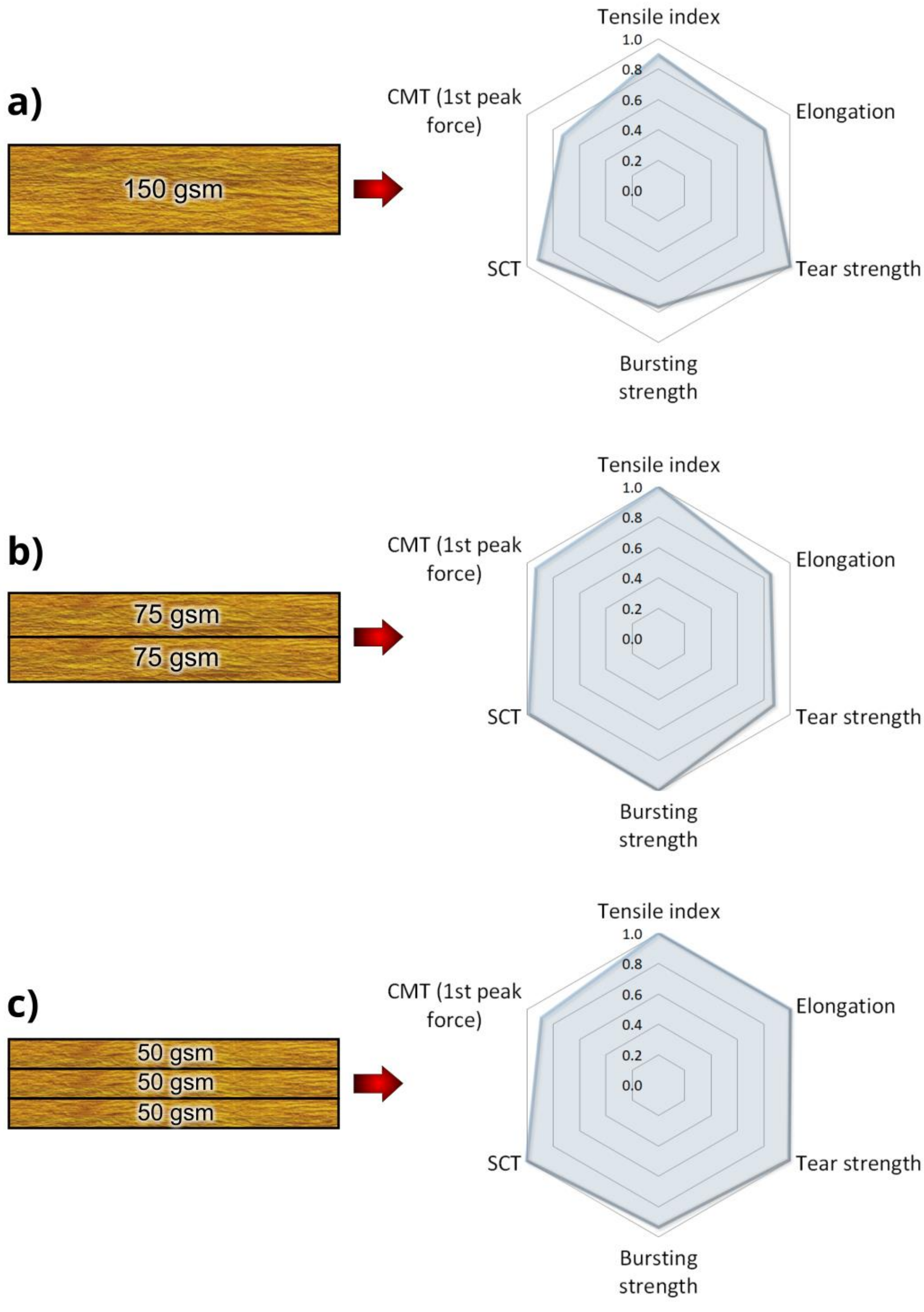

Fig. 5. Changes in the normalised values of the tested properties of single- and multi-ply papers made of pulp with high papermaking potential (UBSK pulp)

Case B: Strength Properties and Cost Reduction are Equally Prioritised

A more difficult but commonly encountered challenge in industrial practice arises when both strength properties and cost reduction are given equal priorities. In such a situation, it is possible to add a low-cost raw material with a lower papermaking potential to the pulp that initially has a high papermaking potential. Alternatively, in the case of multi-ply papers, one or more layers made of a raw material with a high papermaking potential could be replaced with a layer formed from a low-cost raw material with a lower papermaking potential.

Figure 6 presents changes in the normalised values of the tested properties of one-ply and three-ply papers made from the mixture of pulps with high and low papermaking potential (1:1 ratio of UBSK pulp to BHK pulp). Generally, papers made with the addition of pulp with low papermaking potential were characterised by lower mechanical properties compared to the corresponding properties of papers made solely from UBSK pulp. However, the superiority of three-ply paper over single-ply paper was evident, albeit not across all tested properties. The tensile index increased by approximately 13%, elongation by approximately 10%, and bursting strength by 14%. The tear resistance values remained the same; however, both SCT and CMT decreased by approximately 2%. The decreased SCT value can be explained by the decrease in the average fibre length in the mixture of UBSK and BHK pulps. The influence of this effect was confirmed by Brandberg and Kulachenko (2020), who identified a negative impact of shorter fibres on the SCT value. However, fibre length is not the only factor that affects the SCT value.

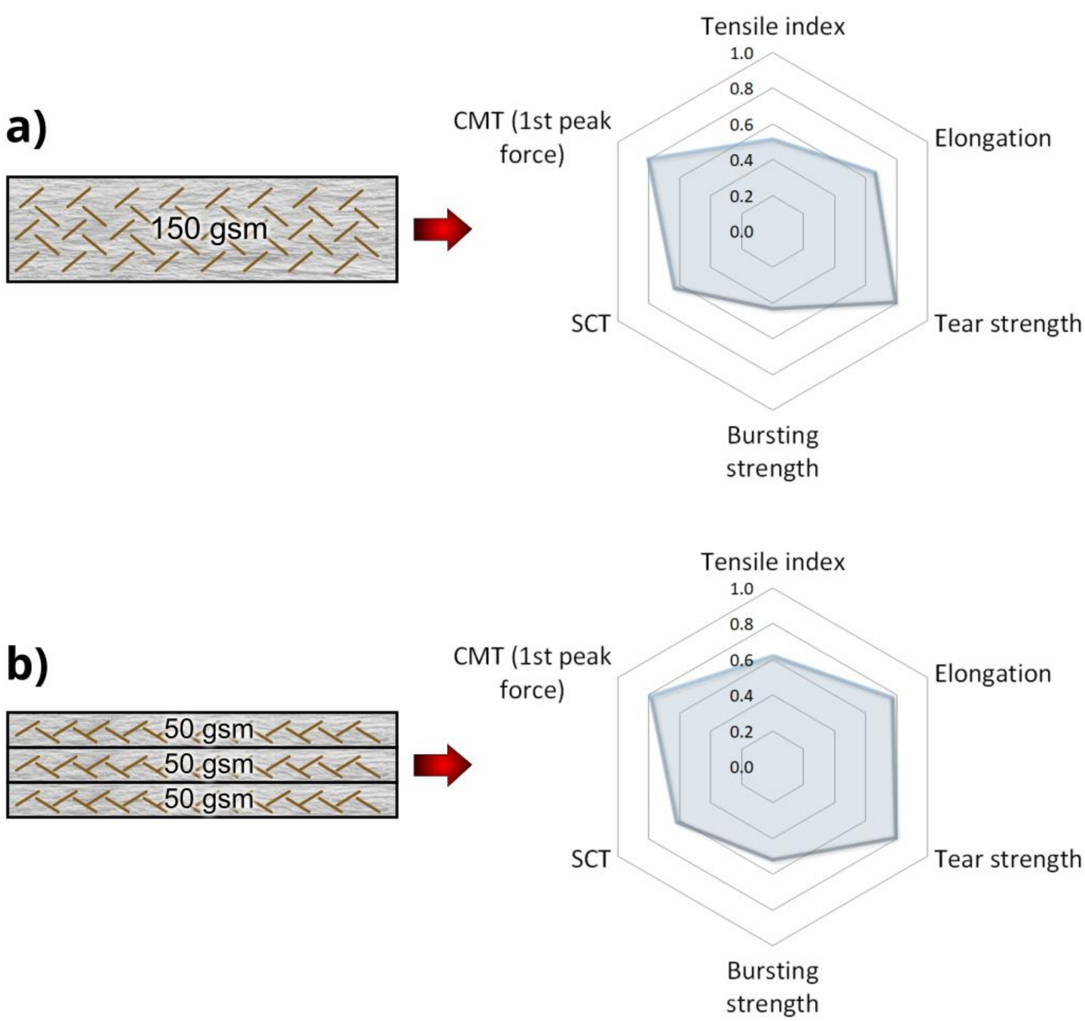

Fig. 6. Changes in the normalised values of the tested properties of single- and three-ply papers made from the mixture of pulps with high and low papermaking potential (1:1 ratio of UBSK pulp to BHK pulp)

Research from Hofbauer *et al*. (2023) indicates that the SCT value increases as the pulp refining process progresses. As the length of the fibres decreases during refining, this suggests that there is contradictory evidence in the literature. Additionally, Hofbauer *et al*. (2023) indicate that the bond strength of the internal paper structure also influences the SCT value. The refining process increases the bonding within the internal structure of the paper, mainly through fibre plasticisation and increased bonded surface area (Page 1989; Hirn and Schennach 2017; Motamedian *et al*. 2019; Hofbauer *et al*. 2023).

For the tested paper samples made from the mixture of pulps with high and low papermaking potential, the value of the Scott bond strength parameter was 50.7 J/m^2 for one-ply paper and 46.4 J/m^2 for 3-ply paper. These values were significantly lower than the Scott bond strength values for paper made only from UBSK pulp (115.8 J/m^2 for one-ply paper and 110.0 J/m^2 for two-ply and three-ply papers).

Interesting results were obtained for the multi-ply paper sample in which the outer layers were made from the pulp of high papermaking potential (UBSK) and the middle layer was made from the pulp of low papermaking potential (BHK). The tensile index value for this sample remained unchanged compared to the three-ply paper made of a mixture of pulps, while it exhibited higher values across all strength properties compared to single- and multi-ply papers made of a mixture of UBSK and BHK pulps. The explanation of this finding lies in the higher amount of low-potential pulp (BHK) in the entire paper structure for papers made from the mixture, as opposed to when only the middle layer was made of BHK pulp. However, upon comparing the strength properties of the discussed sample with the samples made from the pulp of high papermaking potential, it is notable that parameters such as burst resistance and elongation were similar to the values obtained for single-ply paper made solely of UBSK pulp. While the tear resistance was lower, it still surpassed that of two-ply paper made of UBSK.

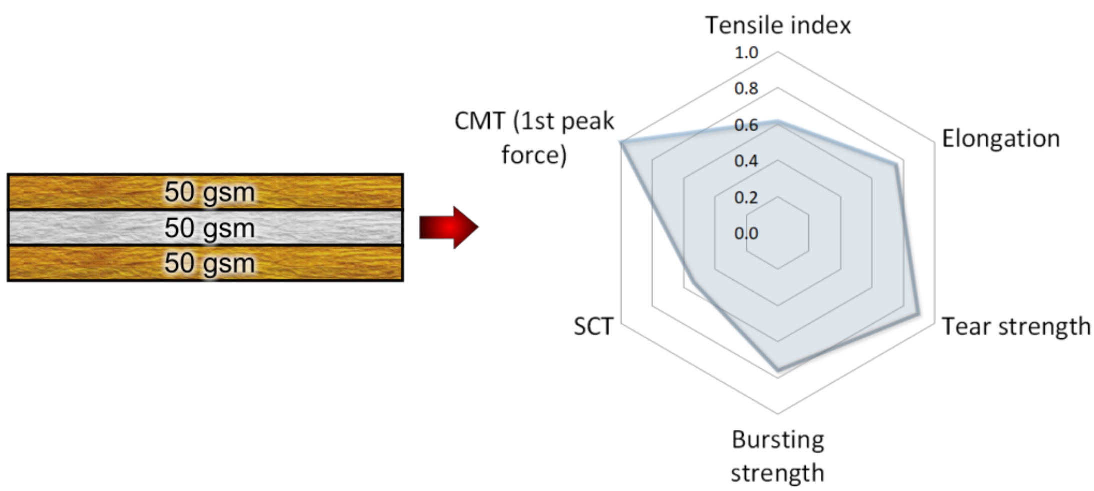

Fig. 7. Changes in the normalised values of the tested properties of three-ply paper; external layers are made from the pulp with high papermaking potential (UBSK pulp) and the internal layer is made from the pulp with low papermaking potential (BHK pulp)

The most surprising result was the CMT value (1st peak) for the sample with a single middle layer made from the pulp of low papermaking potential (BHK). This value was the highest among all tested samples. Explaining this finding based on the papermaking potential of individual pulps is challenging, as the CMT parameter in this case depends on several factors, including the properties of the fibrous pulps and their mutual arrangement in the form of a multi-ply structure. The CMT results are further commented upon in the discussion of Fig. 11.

Normalised values of the tested parameters, which are presented in radar charts (Figs. 5 to 7), do not show the actual values of the individual strength properties of tested paper samples. Only the tensile index and tear strength values were previously presented in Figs. 3 and 4. Therefore, the actual values of all other tested properties are shown in Figs. 8 to 11. Figure 8 shows the elongation values of the studied single-, two-, and three-ply papers. The results of these experiments revealed that higher elongation values were observed for multi-ply papers. In the case of solid paper (one-ply, 150 g/m^2) and three-ply paper, both made of BHK pulp, no difference in elongation was observed. These samples were also characterised by the lowest elongation. Three-ply papers formed from mixed UBSK-BHK pulp (three-ply, 3 × 50 g/m^2) and UBSK-BHK-UBSK pulp (three-ply, 3 × 50 g/m^2) showed slightly lower elongation values compared to three-ply papers produced from 100% UBSK pulp.

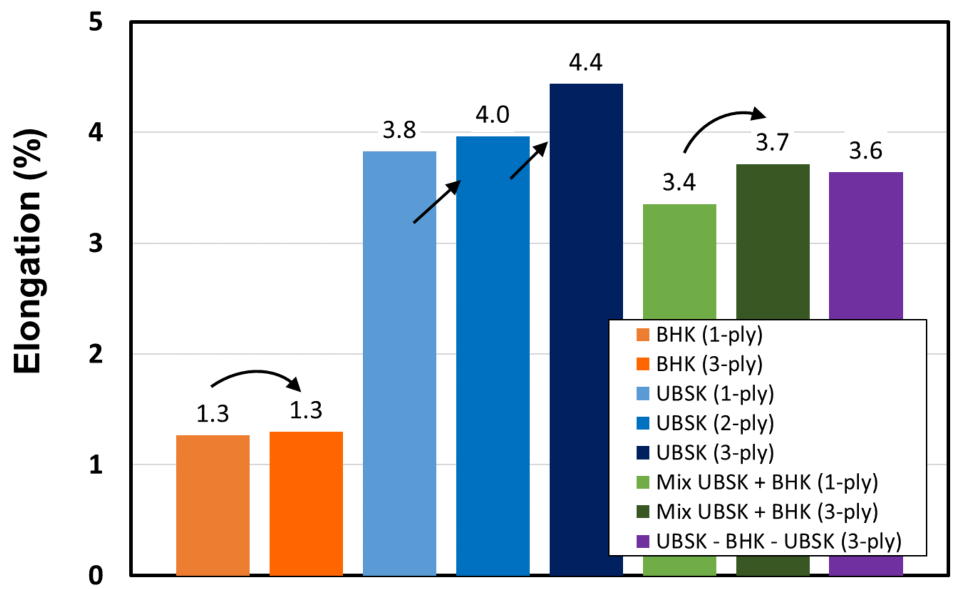

Fig. 8. Comparison of the elongation values for all variants of paper samples (single- and multi-ply papers)

One of the most commonly used strength tests for paperboard and paper is the bursting strength test (Fig. 9). The lowest values of this parameter were observed for papers made from BHK pulp (for both single-ply and three-ply paper). The increased number of plies in the paper structure improved the bursting strength in the case of samples made from UBSK pulp; however, the two-ply paper exhibited higher bursting strength than the three-ply paper. An interesting observation was the considerable increase in the bursting strength value for UBSK-BHK-UBSK papers (three-ply, 3 × 50 g/m^2). The obtained value was essentially equal to the value obtained for one-ply paper made entirely of UBSK pulp. It is evident that the production of layered paper or board structures enables the optimisation of raw materials used in each layer, improving the strength properties of the final paper product. The advantage of the three-ply structure was also evident in the case of samples made from a mixture of both pulps, where the bursting strength of three-ply paper was 578 kPa, while for one-ply paper of the same grammage, this parameter was 497.2 kPa.

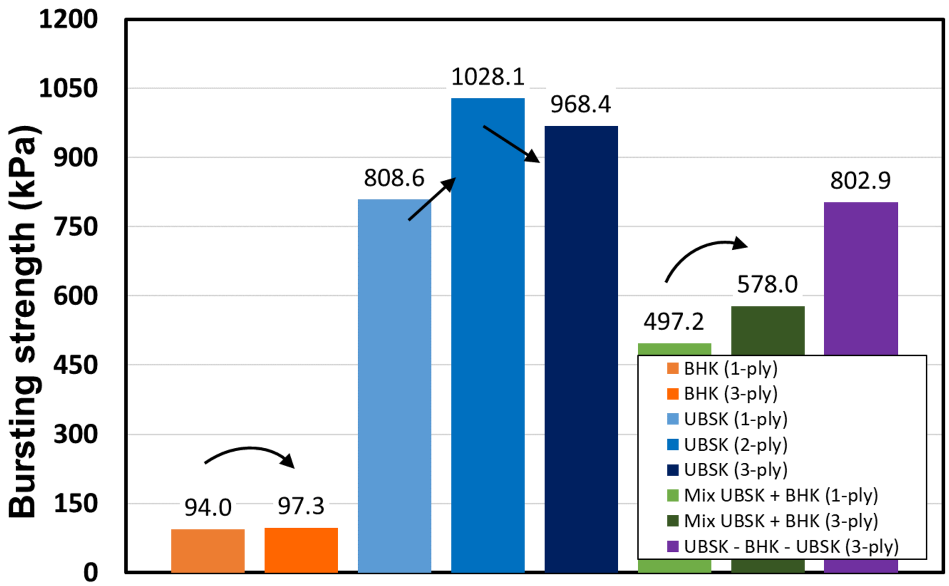

Fig. 9. Comparison of the bursting strength values for all variants of paper samples (single- and multi-ply papers)

Helpful insights regarding the strength properties of multi-ply paper can be obtained by analysing the compression strength parameter. The SCT was performed for all variants of paper samples (Fig. 10).

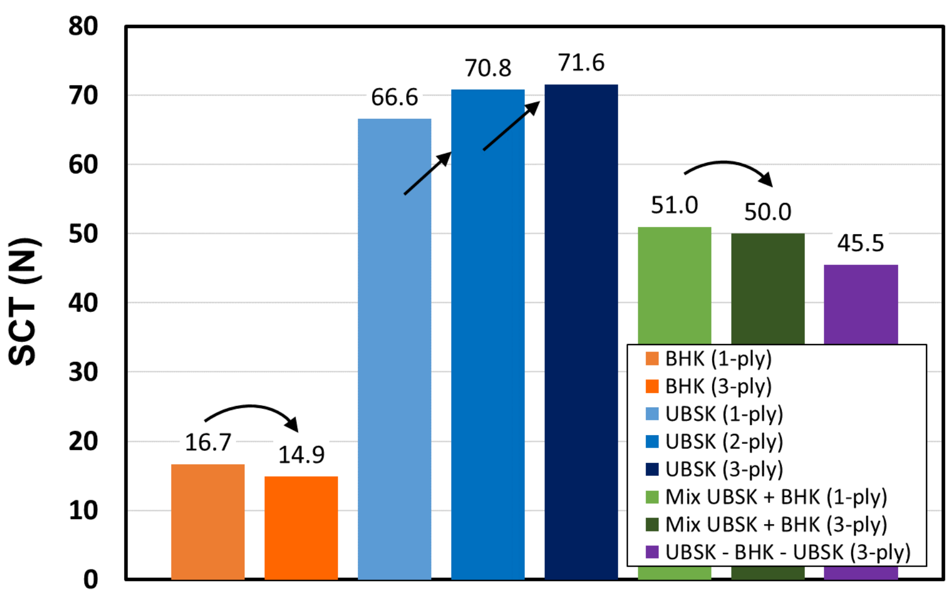

Fig. 10. A comparison of the crushing resistance in the SCT test for all variants of paper samples (single- and multi-ply papers)

In terms of SCT results, it was observed that for two- and three-ply sheets, UBSK was the strongest fibre type. Moreover, the results indicate that the beneficial effect of increasing the number of plies was observed only in the case of paper samples formed from UBSK pulp, which has high papermaking potential. When comparing the single- and three-ply paper from hardwood pulps (BHK), the SCT value was observed to be lower for the three-ply sample. This trend was also observed for samples made from a mixture of both pulps. These results indicate that the SCT parameter depends on the strength of internal bonding within the paper structure and the strength of bonding between layers in the case of multi-ply papers.

The literature (Attwood and Moore 1994) suggests that the bonding strength between the plies is usually lower than the internal ply bonding strength. In the presented research, the Scott bond internal strength values for one-ply paper structures were: 115.8 J/m^2 for paper formed from UBSK pulp only; 2.4 J/m^2 for paper formed from BHK pulp only; and 50.7 J/m^2 for paper formed from the mixture of UBSK and BHK pulp (1:1 ratio).

The CMT provided insights into the properties of the tested samples relevant to fluting production, a crucial component of corrugated board. The CMT measures the crushing resistance of a fluted strip of paper, offering an estimation of the potential flat crush resistance of a sample. Given the low strength of BHK papers, CMT measurements were only conducted for papers containing UBSK and mixed pulp in various configurations (Fig. 11). As already mentioned, two-ply and three-ply structures demonstrate increased resistance to flat crushing compared to one-ply papers. The highest CMT value (199.4 N) was obtained for the sample made from UBSK pulp with an internal layer made of BHK pulp. This unexpectedly high result requires additional comment.

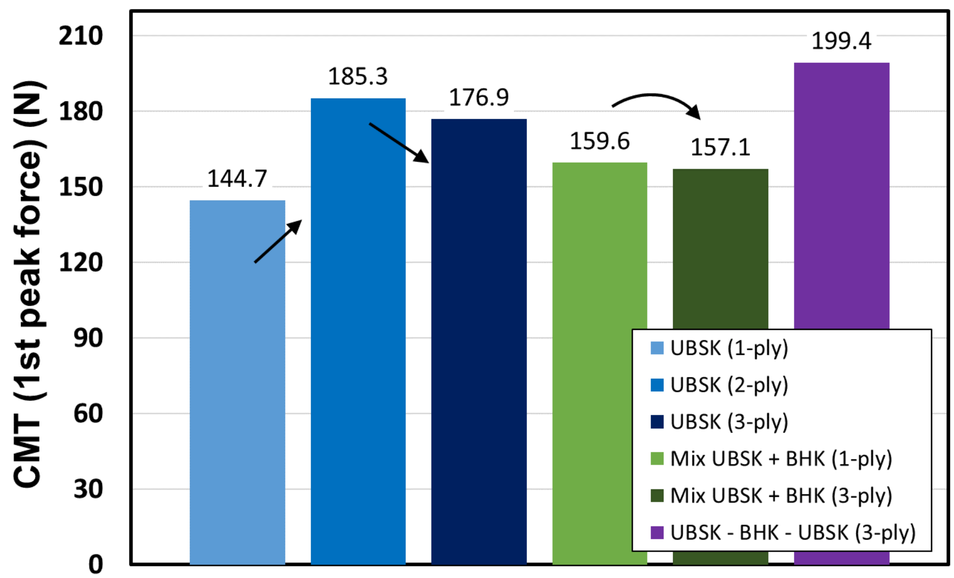

Fig. 11. A comparison of the flat compression strength in the CMT for all variants of paper samples (single- and multi-ply papers)

In the scientific literature, many different parameters have been reported that affect the crushing resistance of corrugated cardboard. This indicates that CMT is a multidimensional parameter, and it is very difficult to describe it mathematically using other paper strength parameters. In industrial conditions, an additional difficulty is the fact, that the shape of a flute wave and its bonding to liner is not perfectly repeatable, which introduces additional, unknown variables. Many researchers indicate that flat crushing resistance of a corrugated medium (CMT) is correlated with parameters such as bursting strength and SCT (Nordstrand 2003; Gigac and Fiserova 2011). Whitsitt and Sprague (1982) reported also that the CMT value depends on the elastic modulus of the tested sheet, a fact that is also confirmed by Savangsrisutikun and Somboon (2019). In the presented research, the elastic modulus for three-ply paper, solely composed of UBSK pulp, was 5.78 MPa, while for three-ply paper with an internal layer of BHK pulp, it was measured as 5.46 MPa. As these results are similar, they cannot fully explain the present observations.

In order to better understand the obtained results, scientific literature on the discussed phenomenon was analyzed. Based on research carried out by, among others, Nordstrand (2003), Jamsari *et al.* (2019, 2020), Park *et al.* (2021), Gajewski *et al.* (2021) and Garbowski *et al.* (2021), it can be concluded that the flute wave crushing process can be divided into several stages. Figure 12 shows the first two stages, which – in the discussed case – seem to be most important for explaining the effects observed. When the wave is crushed, the sides of the wave peak initially bend (Fig. 12a). It can be assumed that – at this stage – the bending stiffness of the material is the most important factor for the strength of the entire structure. In the second stage (Fig. 12b), when the flute wave tops are already flattened, the corrugated medium is further crushed in the direction parallel to the plane of the paper, where the strength of the entire structure is also determined by the compression resistance of the paper. The importance of both of these phenomena and the corresponding paper properties (bending stiffness and SCT) are confirmed by the new S-Test method developed by ABB (Fürst and Gerards, 2016). The principle of this test is to simultaneously subject a paper sample to a bending and compressive force. Taking into account the above information, bending stiffness tests were performed for all variants of the prepared samples. These results are presented in Table 2.

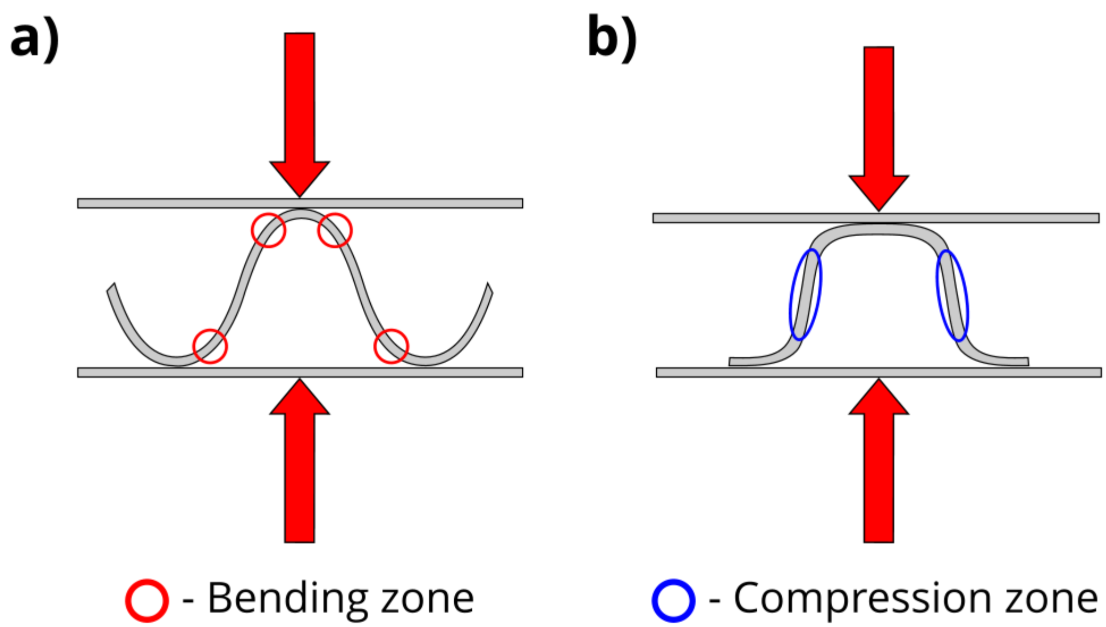

Fig. 12. The scheme representing two steps of corrugated cardboard crushing a) initial geometry b) partially crushed geometry

Among the tested samples, paper with a single middle layer made from the pulp of low papermaking potential (BHK) was characterized by the highest stiffness. In this case, the outer layers of UBSK pulp acted as a kind of "shell" that sandwiched the layer made from shorter and stiffer fibers. It resulted in high material stiffness which, together with high bursting strength (see Fig. 9) and average SCT value, (see Fig. 10) provided the highest CMT value. This result confirms the advantage of multi-ply paper structures over single-ply ones.

Table 2. Bending Stiffness Values Obtained for all Tested Samples and the Corresponding Coefficients of Variation

Sample Name	Bending Stiffness (mN·m)	COV, %
BHK (1-ply)	7.2	12.3
BHK (3-ply)	11.4	1.3
UBSK (1-ply)	9.2	10.7
UBSK (2-ply)	10.6	5.1
UBSK (3-ply)	11.3	6.6
Mix UBSK+BHK (1-ply)	10.5	10.4
Mix UBSK+BHK (3-ply)	10.9	6.0
UBSK-BHK-UBSK (3-ply)	11.6	2.6

The highest values of individual parameters obtained for all types of papers tested are presented in Table 3. The results indicate that, when strength properties are the only priority, the best results were usually obtained for papers made from pulp with the highest papermaking potential, regardless of the number of plies. However, the increasing number of plies has a positive effect on most of the strength properties, which are also important for the production of corrugated board. When the priority is both strength and the lowest possible process costs, the best results were obtained for three-layer papers containing a middle layer made of pulp with low papermaking potential. This can be observed in Table 4, where the highest values of individual parameters were exclusively observed for papers containing pulp with low papermaking potential.

Table 3. The Highest Values of Individual Parameters Obtained for All Types of Papers Tested

	Pulp of high papermaking potential (UBSK)			Pulp of low papermaking potential (BHK)		Mixture of pulps (low and high papermaking potential)		External plies—pulp of high potential, middle ply—pulp of low potential
No. of plies	**I**	**II**	**III**	**I**	**III**	**I**	**III**	**III**
Tensile index	**3**	**1**	**2**					
T.E.A.	**3**	**2**	**1**					
Elongation	**3**	**2**	**1**					
Tear strength	**1**		**2**					**3**
Bursting strength		**1**	**2**					**3**
SCT	**3**	**2**	**1**					
CMT (1st peak)	**3**	**2**						**1**

Note: 1—highest value, 2—second-highest value, and 3—third-highest value

Table 4. The Highest Values of Individual Parameters Obtained for Those Papers Containing Pulp with Low Papermaking Potential

	Pulp of low papermaking potential (BHK)		Mixture of pulps (low and high papermaking potential)		External plies—pulp of high potential, middle ply—pulp of low potential
No. of plies	**I**	**III**	**I**	**III**	**III**
Tensile index			**3**	**1**	**2**
T.E.A.			**3**	**2**	**1**
Elongation			**1**	**2**	**3**
Tear strength			**2**	**3**	**1**
Bursting strength			**3**	**2**	**1**
SCT			**1**	**2**	**3**
CMT (1st peak)			**3**	**1**	**2**

Note: 1—highest value, 2—second-highest value, and 3—third-highest value

Table 5. Comparison of the Coefficients of Variation (COV) of All Tested Paper Samples

	Pulp of high papermaking potential			Pulp of low papermaking potential		Mixture of pulps (low and high papermaking potential)		External plies – pulp of high potential, middle ply – pulp of low potential
No. of plies	I	II	III	I	III	I	III	III
Tensile index	4.3%	4.3%	3.9%	6.2%	4.0%	6.6%	3.3%	3.4%
T.E.A.	12.8%	11.7%	10.9%	17,0%	15.9%	**22.2%**	10.3%	9.5%
Elongation	8.2%	7.1%	6.7%	8,0%	9.9%	**15.0%**	5.7%	5.7%
Tear strength	10.6%	8.3%	4.2%	35.4%	**43.3%**	8.9%	5.7%	4.1%
Bursting strength	9.7%	4.5%	2.6%	7.4%	3.4%	6.5%	3.9%	**35.9%**
SCT	3.8%	8.15%	7.3%	7.5%	7.8%	**8.9%**	3.9%	4.05%
CMT(1st peak)	13.3%	1.52%	2.4%	-	-	**57.6%**	0.6%	23.94%
Sum of COVs:	63%	46%	38%	82%	84%	126%	33%	87%

Note: Red colour indicates the lowest (best) values for a given parameter, while black-bold indicates the highest (worst) values

The advantages and disadvantages of one-ply and multi-ply paper structures can be also revealed by analysing the coefficients of variation for all tested parameters (Table 5). Notably, the greatest variability in strength properties was observed for paper samples containing pulp with low papermaking potential. To draw more general conclusions, a simplified analysis of the overall quality of the tested structures was conducted by summing up all the coefficients of variation for each type of paper. It was assumed that the risk of a potential complaint would increase with the increasing number of deviations. It could be concluded that by using multi-ply forming, it was possible to significantly reduce the overall variability of the strength properties of the tested samples. However, this improvement was primarily observed in papers where cellulose pulp with high papermaking potential was used as either the sole or partial raw material. In the case of specimens containing only cellulose pulp with very low papermaking potential, the number of layers was of little importance.

CONCLUSIONS

1. This study examined how the composition of pulp and the number of layers influenced the strength properties of multi-layer papers. The conducted experiments indicate a significant advantage of multi-ply structures over solid papers (one-ply paper sheets), with only the tear resistance measured to be higher for one-ply paper.
2. When high strength properties were the only priority, three-ply paper made entirely from refined kraft softwood pulp demonstrated the largest number of indices with the highest values. However, if the priority was to obtain a product with high strength properties and reduced production costs, three-ply paper made from a mixture of both pulps and three-ply paper with an internal layer made of unrefined bleached hardwood kraft (BHK) pulp proved effective.
3. Interestingly, paper with a middle layer made of pulp with low papermaking potential exhibited higher strength properties compared to paper with all plies made from a mixture of pulps with high and low papermaking potential. It was found that in the examined case, the high values of bending stiffness and bursting strength had a greater impact on the high corrugating medium test (CMT) value than the short-span compression strength (SCT) parameter.
4. It was also found that multi-ply papers often had lower coefficient of variation (COV) values for strength properties compared to one-ply papers. However, the addition of pulp with low papermaking potential may also cause an increase in the unevenness of the paper structure and lower internal bonding strength, leading to an increase in the COV value of some strength parameters. It is also worth emphasizing that combining pulps of high papermaking potential with pulps with low papermaking potential increases the risk of greater variability in the produced papers.

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