**WOOD RESEARCH** doi.org/10.37763/wr.1336-4561/71.2.218232
**e-ISSN 2729-8906**
**71(2): 2026 218-232 pp.**

# THE SYNERGISTIC EFFECT OF PULP BEATING AND POLYMER ADDITIVES ON MECHANICAL PROPERTIES AND ELASTICITY OF PAPER

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(RECEIVED APRIL 2026)

## ABSTRACT

The work investigates the possibilities of increasing the elasticity of paper by combining mechanical beating and the addition of some biopolymers directly to the pulp. The novelty of the approach lies in the volumetric modification of the pulp with biopolymers (gelatine, chitosan, PVA, CMC), which were not applied as a surface treatment, but were incorporated into the pulp suspension. The results confirmed that the increase in beating degree (up to 70°SR) and free drying significantly increase the relative elongation of the paper (an increase of 12.4%). The addition of gelatine increased the elasticity by 2.6%, especially at lower beating levels. The key finding is the synergistic effect of the combination of 1% chitosan and 5% CMC, which was the only combination that ensured a simultaneous increase in elasticity and strength (by 3.9 kN/m). This procedure represents an environmentally sustainable alternative for the production of high-strength and elastic packaging materials.

KEYWORDS: Paper elasticity, mechanical properties, additives, packaging industry.

## INTRODUCTION

The increasing environmental impact and limited recyclability of petroleum-based plastics have intensified the demand for sustainable and biodegradable alternatives in the packaging sector (Petrenko et al. 2024, Daramola et al. 2025). Consequently, current research is focused on replacing synthetic polymers with bio-based materials exhibiting high biodegradability (Abenghal et al. 2025). In papermaking, functional additives are widely applied to modify the physicochemical and mechanical properties of paper, improving strength, elasticity, surface quality and printability (Asta et al. 2024, Chiani et al. 2024, Małachowska 2025, Zhao et al. 2022). In response to the demand for industrial decarbonization, attention is shifting toward biopolymers as functional additives for pulp and paper modification (Małachowska 2025, Adibi et al. 2023). In addition to traditional starch, substances such as carboxymethyl cellulose (CMC), which significantly increases retention of fillers and fine particles and dry strength in the wet part of the process, or polyvinyl alcohol (PVA) and gelatine, used mainly in surface treatments to achieve an excellent barrier against oils and improve print quality (Gusain et al. 2026), are coming to the fore. The synergistic action of these biopolymers with the cellulose matrix allows the production of high-value-added papers that are fully biodegradable and recyclable. Among them, chitosan has gained attention as a multifunctional solution for modern packaging materials due to its unique amphoteric character and antimicrobial properties (Ramakrishnan et al. 2024, Alvarado et al. 2024).

Research has shown that the addition of chitosan to pulp significantly increases the mechanical properties of paper, especially tensile strength and tear resistance (Roy et al. 2024, Todorova et al. 2021, Gal et al. 2023). In addition to mechanical reinforcement, chitosan acts as an effective retention and drainage agent, which directly contributes to the economic efficiency of the process by accelerating drainage on the screen (Chandarana et al. 2025, Małachowska 2025). Furthermore, the conclusions of recent studies highlight its biocidal and barrier effects; paper treated with chitosan shows increased resistance to fat and water penetration, while suppressing the growth of microorganisms, which predestines its use in smart and ecological food packaging (Inthamat et al. 2024, Jahangiri et al. 2024, Roy et al. 2024). In addition, chitosan modifies surface properties of paper, leading to improved smoothness, gloss, and opacity (Gal et al. 2023, Todorova et al. 2021).

In addition to chitosan, CMC is a key biopolymer additive that increases the hydrophilicity of the fibre surface and enhances tensile, breaking, and bending strength as well as surface smoothness, leading to better hydrogen bond formation and consequently higher tear resistance of the paper (Alvardo et al. 2024). PVA is mainly used as a surface coating and binder, improving tensile strength, breaking strength, elasticity, and surface strength (Shen et al. 2021). Studies indicate that PVA forms a continuous barrier on the paper surface that drastically reduces porosity, thereby achieving superior printability and resistance to penetration of organic solvents and fats (Park et al. 2020, Gottberg et al. 2019). Similarly, gelatine is returning to industrial practice, often in modified form or in a mixture with other biopolymers. Recent research shows that the application of gelatin significantly improves the surface strength and smoothness of paper, leading to better print sharpness and reduced surface dustiness (Wojech et al. 2026, Chen et al. 2025). Recent work highlights its ability to act as a natural carrier for active ingredients in smart packaging, thereby improving the mechanical stability of the sheet while maintaining its full compostability. Xu et al. (2025), Aleksandrova et al. (2025) and Fisher et al. (2025) point to the synergy of gelatine with other biopolymers, where gelatine acts as a plasticizer and binder, thus increasing the resistance of paper to oxygen and fat penetration, which are properties essential for ecological substitutes for plastic films (Gül et al. 2025).

This study aims to develop paper with enhanced deformability though targeted physical, mechanical, and chemical modification of the fibre network. The novelty of this work lies in the investigation of the synergistic effect between a high degree of pulp beating (up to 70°SR) and the incorporation of selected biopolymers (gelatine, chitosan, PVA and CMC). In contrast to conventional studies primarily focused on strength properties, this approach seeks to optimize the balance between extensibility, mechanical strength, and barriers performance.

This finding is expected to contribute to the development of fully biodegradable material capable of competing with synthetic polymers in packaging applications.

## MATERIALS AND METHODS

### Starting materials

Standardized pulp RM 8495 Northern Softwood Bleached Kraft Pulp was used as the input raw material. The pulp was supplied by The Procter & Gamble Cellulose Company (Memphis, Tennessee, USA). It is a long-fibre pulp with the following chemical composition: alpha cellulose (83.33%), beta cellulose (2.64%), and gamma cellulose (10.03%).

Porcine skin gelatine (type A, gel strength of 300) was purchased from Merck (Bratislava, Slovakia), as well as chitosan, polyvinyl alcohol (PVA), carboxymethyl cellulose (CMC), and Magnafloc® LT 35. Chitosan (poly(D-glucosamine)) with an average molecular weight (source: BCCL9542) was used, it was prepared by deacetylation of chitin from Merck (Bratislava, Slovakia). PVA in powder form with the chemical composition $[CH_2CH(OH)]_n$ was also obtained from Merck (Bratislava, Slovakia). CMC (Ambergum™ 1221) was supplied by Ashland Industries Europe GmbH (Schaffhausen, Switzerland). As a retention agent, a cationic homopolymer (Magnafloc® LT 35) was used in aqueous solution form with chemical composition 2-propen-1-aminium, N, N-dimethyl-N-2-propenyl chloride polymer, from BASF SE (Ludwigshafen, Germany).

### Preparation of laboratory pulp sheets

*Pulping and beating process*

Pulp suspension was prepared from RM 8495 Northern Softwood Bleached Kraft Pulp. Pulping was performed according to ISO 5263-1. First, 200 g of air-dried pulp was weighted and allowed to swell overnight in water. The prepared test portion was pulped using a laboratory pulper – disintegrator (AG 04, Estanit GmbH, Germany) at a speed of 10.000 rpm for all samples. The suspensions volume was then adjusted to 20 L and checked for the absence of fibre agglomerates.

Beating was carried out according to ISO 5264-1 using a Valley Hollander. Fibers were refined between roller knives and the briquetting die under a lever load of 7.6 kg. Beating was performed for 0, 10, 20, 30, 40, 45, 50 and 55 min. After each beating, a given amount of suspension was taken for its characterization. The degree of beating (°SR) was determined using the Schopper-Riegler method according to ISO 5267-1.

*Forming procedures*

Laboratory sheets were prepared using a manual sheeter UEC-2005-B (Saharanpur, India) according to ISO 5269-1. Sheets were formed from 2 g of air-dried standardized long-fibre pulp. For mechanical modified samples, sheets were produced at different beating times (0-55 min, as listed above), and sets of 10 sheets were prepared for each condition.

For chemical modified samples, additives (chitosan, PVA, and CMC) were introduced after beating to 30°SR. During pulp beating, we prepared additive solutions, with the addition of additives relative to 2 g of air-dried pulp as listed in Tab. 1. Additive solution was prepared by dissolving the required amount of substance in 200 mL of solvent. Subsequently, 1.5 L of pulp was mixed with the solution and stirred for 10 min.

*Tab. 1: Addition of additives and solvents in which the solutions were prepared.*

| Additives | Addition relative to 2 g of pulp [%] | Solvents |
|---|---|---|
| Carboxymethyl cellulose (CMC) | 5, 10 and 20 | water |
| Polyvinyl alcohol | 5, 10 and 20 | water |
| Chitosan | 1,5,10 and 20 | 0.1 M acetic acid |

## Gelatine additions

Gelatine was applied at beating degrees of 20, 30**,** and 40°SR. Sheets were prepared in sets of 10. Gelatine was allowed to swell in water for 1 h and then heated to 45°C until clarification occurred. A solution with concentration of 20 g·L$^{-1}$ was obtained. The required dosage was calculated based on oven-dry pulp content. Gelatine was added to the paper pulp at levels of 5%, 10%, 20%, and 30%, always calculated based on the amount of absolutely dry pulp. After addition, the suspension was stirred at 1500 rpm for 30 min to ensure homogenous distribution.

### *Pressing and drying process*

Sheets were pressed according to Chrvalová et al. (2025). Wet sheets were transferred into felts and stacked evenly before pressing. Pressing was carried out at 2 t load using a hand press. Sheets were removed, resulting in wrinkled micro crepe structure. The sheets were dried in an oven at 30°C until dry. This drying method allowed for free shrinkage of the paper. The area of the circular sheets was calculated from the mean diameter of the sheets, which was measured using a measuring device (ruler) for each sheet at least 10 times. Sheets with approximately the same basis weight were selected from each series of sheets.

## Characterization of suspensions of prepared pulps

### *Determination of the degree of beating (°SR)*

The Schopper-Riegler method (ISO 5267-1) was used to determine drainage resistance. The degree of beating fibre swelling and surface modification caused by mechanical treatment (Dienes et al. 2005). With increasing beating, dewaterability decreases due to fibre shortening and increased water retention capacity (Chrvalová 2024, Gharehkami et al. 2015). The determination and expression of the Schopper-Riegler degree (°SR) were based on the procedure described by Chrvalová et al. (2025). The paper shrinkage process was carried out in accordance with the methodology defined in Chrvalová et al. (2025).

### *Monitoring the Zeta potential*

The zeta potential reflects the electrokinetic properties of fibres in aqueous suspension. It is defined by the electric double layer at the fibre-water interface, where the shear plane separates bound and the free water phases (Chrvalová et al. 2025). However, a decrease in these values to the zero level indicates the predominance of attractive forces, leading to unwanted flocculation of the system (Netzer et al. 2024).

Zeta potential was measured using FPA Touch device (AFG Analytic GmbH, 2019b). Electrokinetic properties of additives were measured using CAS Touch (AFG Analytic GmbH, 2019a). Measurement was performed on 10 mL of 1 g/L solution, titrated by oppositely charged standard polyelectrolyte until the isoelectric point was reached. Each measurement was repeated three times. Suspension volume was 500 mL, with concentration ranging from 8.5 to 8.9 $g \cdot L^{-1}$.

*Analysis of the water retention value*

The water retention value (WRV) quantifies the ability of a fibres to retain water under the centrifugal force. It increases with beating due to fibre swelling, internal fibrillation, and pore expansion (Gharehkami et al. 2015). WRV includes several forms of water present in the sample: free water and water bound by hydrogen bonds on surfaces (internal and external), moisture localized in the lumen, capillaries, and pores of the cell walls, and water bound to hydrophilic components adsorbed on the fibre surface (Mayr et al. 2017). The measurement followed ISO 23714. Samples were swollen in deionized water for 30 min, centrifugated, and weighted. Dry mass was obtained after oven drying. Each sample was measured in four repetitions. Information on the exact procedure and calculation was given by Chrvalová et al. (2025).

### Measurement of mechanical properties of laboratory pulp sheets

Mechanical properties were performed at 24.7°C. Sheet thickness and weight were measured using the MTS MI 21 device (Ivry-Sur-Seine Cedex, France) and processed in Instron BlueHill 3 software. Tensile testing was carried out according to ISO 1924-2 using an Instron 3365 laboratory tensile tester (Civest Slovakia, s.r.o.). Strips of width of 15 mm and a length of 100 mm were tested at a clamping length of 100 mm. Evaluated properties included relative elongation, tensile strength, tensile energy absorption, and elastic modulus.

### Preparation of the modified laboratory pulp sheets

Pulp was disintegrated and beaten to 30°SR according to ISO 5263-1, ISO 5264-1, and ISO 5267-1. Sheets were prepared from 2 g of absolutely dry pulp using the same procedure as above. Pressed sheets were dried at 30°C between wire grids. Mechanical properties of modified sheets were subsequently evaluated.

## RESULTS AND DISCUSSION

The presented work focused on monitoring the influence of mechanical and chemical modification of pulp, aimed at improving the final properties of laboratory-prepared sheets. Within the framework of the work, we focused on monitoring the influence of biopolymers on the mechanical properties of paper, with a focus on elasticity, using various additions of additives. We mainly focused on pulp beating and the addition of biopolymers to the paper suspension.

### Mechanical modifications

*The effect of beating on pulp properties*

Mechanical modification consisted of beating the pulp to a higher Schopper-Riegler degree to increase the elasticity of the paper and, at the same time, maintain or only minimally reduce the strength properties. Beating, as a mechanical modification of pulp fibres, shortens and fibrillates individual fibers. This fibrillation causes an increase in the surface area of the pulp fibres. The more the specific surface area increases, the more water penetrates the fibre (Chrvalová et al. 2025; Gharehkami et al. 2015). Tab. 2 shows an increase in the beating degree depending on the beating time. At the beginning, we observe a slow increase of the beating degree. In the range of 30 to 55 min, the increase of the beating degree is significantly faster. As we can see, after 55 min we reached a beating degree of 70°SR.

For a more consistent description of the mechanical processing of fibres and further characterization of fibres, we chose the WRV method, which is sensitive to changes in fibres due to mechanical treatment (Mayr et al. 2017). Tab. 2 summarizes the measured WRV values with respect to the degree of pulp beating. WRV values change throughout the papermaking process, increasing during beating due to fibre separation, internal**,** and external fibrillation (Chrvalová 2024). For us, it was important as an additional parameter for monitoring fibre processing. With a longer beating time, we observe an increase in WRV values, as well as when determining the degree of beating. Increased WRV values indicate better fibre fibrillation, which should positively affect the mechanical properties of the resulting paper. Due to beating, the fibres can bind a greater amount of water, which results in increased shrinkage when the sheets are dried (Mayr et al. 2017; Chrvalová et al. 2025).

In the paper industry, measurement of the electrokinetic properties of fibres is important with regard to the subsequent addition of additives. Tab. 2 shows how beating affects the Zeta potential of the prepared pulp. We observe a gradual approach of the Zeta potential values to zero charge, up to a value of –22.86 mV. From 20°SR onward, we observe approximately the same Zeta potential values, which change only minimally. The literature states that the charge affects the swelling of the fibres, the elasticity and adaptability of the fibres, the retention of cationic paper additives, and the flocculation and mechanical properties of the paper. The increase in interactions between ionizable groups and cationic chemicals due to fibre fibrillation during beating leads to the presence of ion exchange as the first mechanism. In the next stage of refining, the carboxyl groups are surrounded by water molecules, which reduces their activity and ion exchange (Netzer et al. 2024; Chrvalová 2024).

*Tab. 2: Degree of beating (°SR) as a function of beating time, WRV values, and Zeta potential of pulp fibres corresponding to a given beating degree.*

| **Time of beating [min]** | **°SR** | **WRV [%]** | **Zeta potential [mV]** |
|---|---|---|---|
| 0 | 10 | 103.1 ± 7.2 | - 29.26 ± 0.95 |
| 20 | 20 | 190.0 ± 11.0 | - 21.60 ± 0.32 |
| 32 | 30 | 234.4 ± 7.2 | - 21.74 ± 0.11 |
| 40 | 40 | 257.4 ± 4.8 | - 21.16 ± 0.30 |
| 55 | 70 | 285.0 ± 15.0 | -21.56 ± 0.26 |

With further beating, the surface area increases due to fibrillation and the formation of fine particles. As a result, adsorption as a second mechanism contributes to an increase in the cationic demand of the suspension. It is clear that during refining there is no significant change in ion exchange; this change is independent of the degree of refining. It has been demonstrated that an increase in the Zeta potential of the fibres can contribute to improving the strength properties of the paper. The closer the Zeta potential approaches zero, the weaker the repulsive charge between the fibres, the better the adhesion of the fibres, and thus the improvement in the strength properties of the paper (Bhardwaj et al. 2004).

The shrinkage of the paper depends on the method of drying the sheets. Dying without restriction (free drying) or with a small restriction allows the paper to shrink, which increases relative elongation. Based on this assumption, we focused on the shrinkage of sheets during the drying process. In Fig. 1, we can see a graph showing the dependence of shrinkage on the calculated WRV values. The graph shows that with increasing WRV, which increases with increasing degree of beating, there is an increase in sheet shrinkage. Our results confirm that the increase in WRV values also increases the time of dewatering on screens when forming laboratory sheets and also affects the length of sheet drying (Chrvalová et al. 2025).

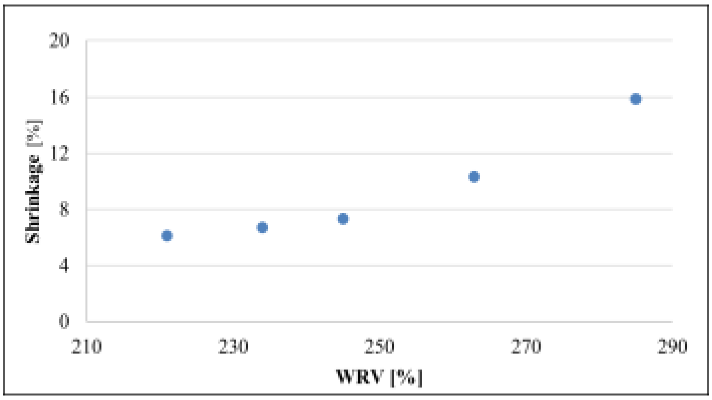

*Fig. 1: Shrinkage vs. WRV of laboratory prepared sheets.*

*Measurement of mechanical properties of pulp sheets*

By measuring the mechanical properties of paper sheets made from pure (chemically unmodified) pulp, we obtained a set of valuable information about the quality of paper without the addition of biopolymers. The measured data are presented in Tab. 3. Pulp processing improves most of the strength properties of paper, which depend on the bonds between the fibres (Das et al. 2025). During beating, the pulp fibres fibrillate, increasing the surface area of the fibres and enhancing the bonding between the fibers in the final product. As a result of beating, the fibres are also shortened, which can reduce their strength. Therefore, it is necessary to ensure that a long beating time does not adversely affect the overall properties and to find a compromise between the positive effects of increased fibrillation and the negative effects of shortening individual fibres (Asta et al. 2024; Inthamat et al. 2024).

However, we observe that with increasing beating degree, the values of the mechanical property parameters increase up to 40°SR, however, as shown in Tab. 3, at 70°SR we observe a decrease in mechanical property values. Since the aim of our work is mainly to influence the elastic properties of paper, the relative elongation becomes an important parameter for us. The results show that with increasing beating degree, the relative elongation of the paper also increases, while the highest value is achieved at a beating degree of 70°SR, namely 21.1%.

Based on the literature, we assumed a decrease in strength properties with increasing elasticity. As we can see, the values of tensile strength do not show a significant decrease as a result of beating. Another parameter we investigated was the absorption of tensile energy. The absorption of tensile energy describes the ability of paper to absorb energy during stretching. As with relative elongation, the absorption of tensile energy also increases with increasing beating degree.

*Tab. 3: Mechanical properties of laboratory prepared pulp sheets without additives.*

| °SR | Tensile strength [kN/m] | Tensile index [Nm/g] | Tensile energy absorption [J/m$^2$] | Tensile energy absorption index [mJ/g] | Modulus of elasticity [MPa] | Tensile length [km] | Elongation [%] |
|---|---|---|---|---|---|---|---|
| **10** | 1.46±0.07 | 13.98±0.67 | 23.0±1.8 | 221±18 | 332±39 | 1.43±0.07 | 2.41±0.09 |
| **20** | 6.57±0.58 | 57.2±5.0 | 245±36 | 2136±311 | 547±74 | 5.83±0.51 | 6.03±0.54 |
| **30** | 7.22±0.34 | 65.0±10 | 365±65 | 3274±581 | 565±166 | 6.60±1.00 | 8.37±0.42 |
| **40** | 8.06±0.68 | 69.8±5.9 | 505±49 | 4373±420 | 470±89 | 7.11±0.60 | 10.52±0.34 |
| **70** | 6.17±0.67 | 38.0±4.3 | 717±178 | 4410±107 | 61±22 | 3.87±0.43 | 21.1±2.9 |

In the case of free-dried sheets, we observe an increase in tensile energy absorption values as a result of beating. The modulus of elasticity expresses how much the paper deforms under the influence of force. An increase in the degree of beating negatively affected the modulus of elasticity. In Tab. 3, we observe a decrease in the modulus of elasticity of free-dried sheets, and we assume that the shrinkage of free-dried sheets, which increases due to beating, could have caused the low modulus of elasticity.

## Chemical modifications

### *Evaluation of properties of pulp suspension with biopolymer additions*

Another goal of the presented work was the chemical modification of laboratory-prepared sheets using various additives. We assume that by adding additives to the pulp we promote the attachment of additives to the fibre surface, which should lead to an increase in flexibility and elasticity of bonds. As we have already mentioned, we decided to use additives such as chitosan, PVA, CMC**,** and gelatine. We added retention agents to additives with negative Zeta potential to ensure interaction between fibres and additives. By characterizing the properties of pulp suspensions with different degrees of beating and additions of different amounts of biopolymers**,** and by characterizing the mechanical properties of sheets made from these suspensions, we obtained a relatively complete overview of the influence of biopolymers on the elasticity of the resulting papers.

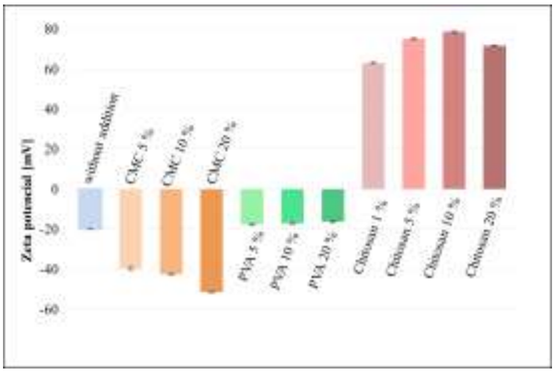

*Fig. 2: Zeta potential of paper pulp without additives and with the addition of CMC, PVA and chitosan.*

In Fig. 2, we can see that the Zeta potential values of the paper pulp without additive are negative. After adding CMC and PVA to the paper pulp, we observe a decrease in the Zeta potential. With increasing addition of CMC, the Zeta potential decreases**,** while in the case of PVA we do not observe large differences with increasing addition. Since the Zeta potential values of the paper pulp with the addition of CMC and PVA decrease, we chose to add retention agents Magnafloc LT 35 and 1% chitosan. We chose retention agents to retain CMC and PVA. The Zeta potential of chitosan added to the paper pulp was the only one that reached positive values; therefore, the addition of a retention agent was not necessary.

Zeta potential of the paper pulp and PVA reached a positive value after the addition of the retention agent. The Zeta potential of the paper pulp and CMC did not reach a positive value, but approached zero, which could enable better fibre binding. Regarding the Zeta potential of pulps after the addition of gelatine, we observe that there is an increase in Zeta potential values, probably because gelatine has a positive Zeta potential and therefore its positively charged particles bind to the negatively charged fibre. We assume that the bonds of gelatine to the fibres may have a positive effect on the mechanical properties of paper.

*Evaluation of mechanical properties of sheets after addition of biopolymers*

When measuring the mechanical properties of the sheets, we focused mainly on evaluating the results of relative elongation and tensile strength. We chose pulp milled at 30°SR to produce sheets with additives, as the pulp milling time was not too high (30 min), but the mechanical properties of the sheets prepared from pure pulp were sufficient to compare sheets with addition of additives.

Tab. 4 shows all the mechanical properties measured from laboratory-prepared sheets, but as mentioned above, we focus on the relative elongation and tensile strength. We observe an increase in relative elongation after adding 1% and 5% chitosan relative to 2 g of air-dried pulp. This was confirmed in accordance with the literature which reports an increase in elasticity after adding 1% chitosan to the paper stock (Fig. 3) (Habibie et al. 2016). The relative elongation value of sheets with 10% chitosan addition was the lowest; the decrease could be due to the formation of a too stiff film with an excessive amount of chitosan.

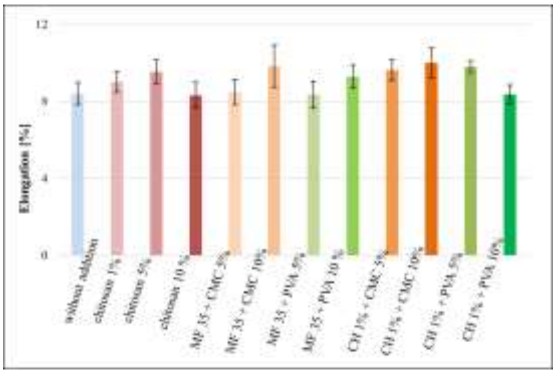

*Fig. 3: Dependence of elongation of sheets from pulp milled at 30°SR on the added polymers.*

Furthermore, we observe that the tensile strength of sheets with 1% chitosan addition increased compared to sheets without the addition. We evaluated the increase in relative elongation together with the increase in tensile strength in the case of 1% chitosan as positive, since increasing relative elongation typically leads to a decrease in strength properties. In the case of the addition of 5% and 10% chitosan, we observe the opposite trend of tensile strength compared to relative elongation.

*Tab. 4: Mechanical properties of laboratory-prepared pulp sheets without additives.*

| Sample | °SR | Tensile strength [kN/m] | Tensile index [Nm/g] | Tensile energy absorption [J/m$^2$] | Tensile energy absorption index [mJ/g] | Modulus of elasticity [MPa] | Elongation [%] |
|---|---|---|---|---|---|---|---|
| without addition | 30 | 6.78±0.62 | 62.9±5.8 | 318±20 | 2950±180 | 687±225 | 8.40±0.57 |
| CMC 5% | 30 | 7.63±0.51 | 71.6±4.8 | 369±28 | 3470±260 | 514±94 | 9.24±0.66 |
| CMC 10% | 30 | 6.43±0.49 | 62.2±4.7 | 299±39 | 2890±380 | 376±136 | 9.17±0.81 |
| CMC 20% | 30 | 6.81±0.94 | 67.2±9.2 | 268±51 | 2640±500 | 785±376 | 7.20±2.00 |
| PVA 5% | 30 | 5.62±0.32 | 57.1±3.3 | 217±33 | 2200±330 | 706±189 | 6.70±1.20 |
| PVA 10% | 30 | 5.80±0.23 | 57.9±2.3 | 253±11 | 2530±110 | 520±105 | 7.95±0.30 |
| PVA 20% | 30 | 5.78±0.32 | 60.7±3.4 | 239±24 | 2510±250 | 493±107 | 7.40±0.71 |
| Chitosan 1% | 30 | 7.30±1.00 | 70.9±9.7 | 344±44 | 3330±430 | 541±137 | 9.01±0.56 |
| Chitosan 5% | 30 | 5.29±0.60 | 57.8±6.6 | 268±20 | 2930±220 | 385±57 | 9.50±0.60 |
| Chitosan 10% | 30 | 7.30±1.00 | 62.5±3.8 | 343±39 | 2950±330 | 683±100 | 8.31±0.67 |
| Gelatine 5% | 30 | 8.22±0.29 | 70.4±2.5 | 422±33 | 3616±279 | 591±96 | 9.18±0.38 |
| Gelatine 10% | 30 | 9.73±0.82 | 81.7±6.9 | 496±42 | 4161±348 | 566±121 | 9.37±0.21 |
| Gelatine 20% | 30 | 9.36±0.46 | 87.8±4.3 | 452±32 | 4241±299 | 639±80 | 8.80±0.32 |
| Gelatine 30% | 30 | 9.63±0.66 | 93.8±6.4 | 491±38 | 4785±368 | 702±74 | 9.34±0.36 |

The next additive we added was CMC. After adding the additive itself, we observed a slight increase in relative elongation for 5% and 10% additions of CMC, and a decrease in relative elongation after a 20% addition of CMC. Since CMC showed negative Zeta potential values, we decided to add retention agents. After adding retention agents - 1% chitosan and Magnafloc LT 35 - we observe an increase in relative elongation, which confirms that the addition of CMC together with a retention agent increases relative elongation values. The combination of 1% chitosan and 10% CMC increase relative elongation by 1%.

The highest tensile strength values were observed after adding 5% CMC together with retention agents. In the case of the Magnafloc LT 35 retention aid, the tensile strength reaches values higher than those achieved with 1% chitosan. The tensile strength of the sheets with 5% CMC and Magnafloc LT 35 increased by almost 4% (Fig. 4).

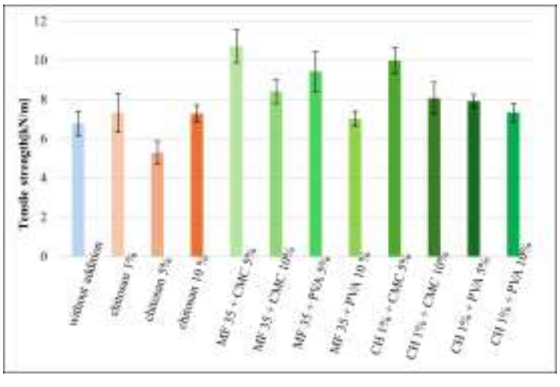

*Fig. 4: Dependence of the tensile strength of sheets from pulp milled at 30°SR on the added biopolymers.*

The penultimate additive we chose was PVA. Sheets with the addition of PVA had lower values of relative elongation compared to sheets without the addition. An increase in relative elongation was observed after the addition of PVA and the retention aid in sheets with the combination of additives Magnafloc LT 35 + 10% PVA and 1% chitosan + 5% PVA. The highest increase was recorded in the combination of 5% PVA and 1% chitosan addition. The relative elongation value of sheets with 1% chitosan + 5% PVA compared to the relative elongation of sheets without additions increased by 1.4%. At a lower addition of PVA (5% PVA), we observe higher values of tensile strength compared to a higher addition (10% PVA). The highest tensile strength value was achieved by sheets with the addition of Magnafloc LT 35 in combination with 5% PVA. The tensile strength value increased by 2.6% compared to sheets without additives.

## CONCLUSIONS

The study focused on improving the elastic properties of paper through mechanical pulp modification combined with the addition of selected additives (gelatine, chitosan, PVA, and CMC) incorporated directly into the paper composition prior to sheet formation. This approach enabled us to modify the internal structure of the paper network and the interactions between fibres already during their formation.

As part of mechanical preparation, it was confirmed that pulp beating is a basic prerequisite for the development of elasticity. The beating process led to intense fibre fibrillation, which was shown by an increase in the degree of beating according to Schopper-Riegler and an increase in the WRV of the fibres. When the electrokinetic properties were measured, it was shown that with an increase in the degree of beating, the negative Zeta potential of the fibres approached zero. These changes in the morphology and physicochemical state of the fibres had a direct impact on the mechanical properties: with increasing beating degree, the value of relative elongation increased, while at a degree of 70°SR an increase in elasticity of 12.4% was recorded compared to 30°SR.

In the field of chemical modification, the influence of biopolymers was investigated. When gelatine was applied, a positive effect on extensibility was observed, especially at lower and medium beating degrees (20–30°SR), where relative elongation increased by 1–2.6%. However, at a high beating degree (40°SR), the effect of gelatine was no longer significantly evident, which indicates the existence of a saturation point in mechanical processing. When other additives (CMC, PVA) were tested, the necessity of using retention agents was shown because of their negative charge. The key solution proved to be the combination with chitosan, which functions not only as an additive enhancing elasticity but also as an effective retention agent.

The final comparison of all modifications showed that while most additives increasing elasticity cause a simultaneous decrease in strength, the combination of 1% chitosan and 5% CMC is an exception. This synergy enabled us to achieve a high degree of elasticity while maintaining, or rather achieving a slight, improvement in strength properties (increase in tensile strength by 3.9 kN/m). The results of the work thus indicate that targeted modification of paper pulp in the bulk phase using biodegradable polymers represents a sustainable and ecological path to the production of highly elastic paper materials, particularly suitable for the modern packaging industry.

## ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency under Contracts Nos. APVV-22-0277 and VEGA grant 1/0651/23. This work was supported by the Slovak Research and Development Agency under the contracts Nos. APVV-22-0034, APVV-22-0388, and VEGA Grant 1/0743/24.

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