

Influence of Pulp Temperature and Convective Drying on Wet Tensile Strength of Towel Papers with Poly(amidoamine epichlorohydrin) Additive

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The influence of the temperature of the paper pulp and drying of towel papers containing polyamidoamine-epichlorohydrin (PAE - 3.5 mg/g ADM) on their wet tensile strength was investigated. The paper was produced from pulp containing 40% pine fibers and 60% eucalyptus bleached kraft fibers, heated to 25 °C, 40 °C, and 50 °C, after which the paper was dried with hot air in the temperature range of 190 to 330 °C. The aim of the research was to determine the influence of the temperature of the paper pulp and drying of the paper formed from it on the degree of PAE bonding with fibers and its self-crosslinking ability. The sheets obtained were tested for wet strength in both the machine direction (MD) and cross direction (CD). The results indicated that the paper drying temperature had a key influence on the increase in its wet strength, while heating the pulp before forming the sheets had a relatively minor effect. The increase in drying temperature to 330 °C allowed the wet tensile index (WTI) to be improved over 100% compared to drying at ambient temperature, with the highest strength demonstrated by samples formed from pulp heated to 50 °C and dried at 330 °C. Paper samples with PAE, tested wet for CD, showed strength at a level of 36 to 44% of the values obtained for MD. The obtained results contribute to the deepening of knowledge on the mechanism of increase in wet strength of PAE-modified towel papers, depending on the temperature conditions used during their production.

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Keywords: Wet strength of tissue paper; Polyamidoamine-epichlorohydrin (PAE); Hot air drying; Curing

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INTRODUCTION

Tissue papers are classified as hygienic and sanitary papers. The key properties of these products are softness, appropriate absorbency resulting from their porosity, low apparent density, and high wet strength. The final paper parameters depend, among others, on the composition of the paper pulp, including the type of cellulose fibers used, chemical additives, and production technology.

A mixture of natural fibers from hardwood and softwood is most often used to produce tissue paper, which provides the product with appropriate strength (long softwood fibers) and softness (short hardwood fibers) (Loebker and Sheehan 2011; de Assis *et al.* 2018, 2019; Fiserova *et al.* 2019). To obtain paper with high bulk (low apparent density), absorbency and softness, eucalyptus cellulose is often added to the paper pulp (Su *et al.*

2012; Fiserova *et al.* 2019; Matos *et al.* 2023, Reczulski *et al.* 2024 and 2025) in an amount of 50 to 80% of the total fiber mass (de Assis *et al.* 2019).

Before forming a web, the fibres are subjected to a refining process that causes internal fibrillation, improving their flexibility, and plasticity as well as water absorption, and external fibrillation, increasing the specific surface area and facilitating access to the carboxyl groups of cellulose. To reduce the loss of paper strength in contact with water, reactive water-soluble polymers are commonly added to the paper pulp, *e.g.*, melamine-formaldehyde (MF), urea-formaldehyde (UF) resins, polyacrylamide-based polymers, polyethylene glycol (PEG), polyethyleneimine (PEI), glyoxal-substituted polyacrylamides, polyvinylamine (PVAm), cationic polymers, modified starch or polyamidoamine-epichlorohydrin (PAE) resins (Linhart 1995; Crisp and Riehle 2009; Francolini *et al.* 2023; Matos *et al.* 2023; Ntifafa *et al.* 2024; Singh *et al.* 2024). Their presence causes the formation of additional chemical bonds of the fibre-polymer and polymer-polymer type, thus increasing the number of connections between fibres and providing protection for existing hydrogen bonds.

The resulting polymer network impedes water penetration into the cellulose fibers, limiting their swelling, which in turn leads to increased paper resistance to moisture (Espy 1995; Häggkvist *et al.* 1998; Lindström *et al.* 2005; Crisp and Riehle 2009; Siqueira 2012; Francolini *et al.* 2023; Ntifafa *et al.* 2024). Hence, the wet strength of paper depends on, among other things, the amount of polymer retained in the paper pulp, the number of chemical bonds formed in the fiber structure, and the degree of polymer cross-linking. One of the resins frequently used in papermaking is PAE, the effect of which on both wet and dry paper strength is widely described in the literature (Espy 1995; Obokata *et al.* 2005; Obokata and Isogai 2007; Crisp and Riehle 2009, 2018; Charani *et al.* 2020; Liang *et al.* 2020; Valencia *et al.* 2020; Korpela *et al.* 2022; Qin *et al.* 2022; Francolini *et al.* 2023; Husić and Botonjić 2023; Singh *et al.* 2024; Reczulski *et al.* 2025).

Su *et al.* (2012) determined that the addition of 1% PAE to bleached eucalyptus pulp increases the wet tensile strength of papers 20% and dry by 15%. However, after exceeding this dose, further increase in wet tensile strength of papers slows down, and their dry strength remains at the same level. Too much polymer added to the paper pulp increases fiber flocculation and limits the increase in wet paper strength. In addition, machine clothing becomes contaminated more quickly (Korpela *et al.* 2022; Francolini *et al.* 2023). The harmful effects of PAE resin on the human body have also been shown (Crisp and Riehle 2018; Seelinger and Biesalski 2023; Singh 2024). There is an EU resolution prohibiting the use of this additive in larger quantities (European Commission (EC) Decision 2019/70 (2019)). According to the Commission Decision, the combined residual monomer content of epichlorohydrin (ECH, CAS No 106-89-8) and its breakdown products 1,3-dichloro-2-propanol (DCP, CAS No 96-23-1) and 3- monochloro-1,2-propanediol (MCPD, CAS No 96-24-2) must not exceed 0.35% (w/w) of the active solids content of the formulation.

For these reasons, it is important to use the right amounts of resin added to the paper pulp to obtain a well-formed product with high wet strength and at the same time safe for the user. In addition to the amount of polymer added, the effectiveness of PAE in enhancing the wet strength of paper depends on the drying conditions and the type of fibers used (Reczulski *et al.* 2025).

The drying conditions of the paper web vary depending on the dryer design and the technology used. The most commonly used drying method is steam-heated cylinders, and in the production of paper towels – the Yankee system with a high-performance hood. The

Yankee system involves usage of a large diameter steam-heated cylinder, and usually the tissue sheet is released from the smooth surface of the cylinder with a creping blade. The drying time and temperature of paper with PAE additives significantly affect the development of their wet strength. Typical laboratory practices, which involve drying sheets in dryers at different temperatures, do not reflect industrial conditions. As has been shown, the drying parameters significantly determine the effectiveness of PAE, but the influence of these factors is still insufficiently described. Additionally, to intensify the resin cross-linking process, the tested samples are subjected to thermal aging and curing (80 to 110 °C, up to 120 min) (Obokata and Isogai 2007), reflecting the natural fixation of the cross-linking structure. The further strengthening of paper with PAE usually occurs within a few or a dozen or so days, depending on the resin used.

The use of a conventional web drying system (DCT - Dry Crepe Tissue) is not an optimal solution to produce porous, large-bulk papers, because the web pressing process increases its apparent density, thus limiting its softness and absorbency (Wang *et al.* 2019; Reczulski *et al.* 2025). To reduce or eliminate the need for mechanical web pressing, only convective drying is used in the production process. This method allows for a higher drying rate (the amount of water evaporated per hour per unit of drying area), and better paper softness and absorbency compared to conventional technology (DCT). It should be noted that DCT technology, in addition to cylinder drying, also uses convective drying. Paper drying with hot air is also used in TAD (Through Air Drying) technology (Sjöstrand *et al.* 2023; Sjöstrand and Bergström 2024; Yan *et al.* 2025). This technology is one of the most used tissue paper drying methods in North America. It involves blowing hot air through the web structure. Depending on the drying system, hot air flows through the paper structure from the inside or the outside of the TAD cylinder. The advantage of this technology is the production of papers characterized by high bulk, softness, and absorbency. Unfortunately, the paper production process using a TAD machine is associated with higher investment costs and higher energy consumption.

Hot air jets are used not only for drying paper in the paper production process. They can also be used for dewatering or heating the paper web (Marchevsky *et al.* 2020). The application of this method leads to high heat and mass transfer coefficients in the region affected by the air jet. In addition, the use of a nozzle system allows for obtaining low apparent paper density. In the production of hygienic paper, technologies are used that use hot air jets to dry or heat paper with various levels of initial moisture (from 10% to 55%) (Chitsazan *et al.* 2021).

The aim of this study was to determine the effects of both the pulp temperature and the drying conditions on the wet tensile strength of tissue paper (kitchen towel) made of a mixture of pine and eucalyptus fibers without crepe, with the addition of the polymer polyamidoamine-epichlorohydrin (PAE). The strength test results of samples with PAE were compared with the results of papers without the addition of resin. Wet strength tests were conducted on the papers in both the machine direction (MD) and cross direction (CD). The motivation for conducting the study was the need to assess the effect of PAE on the mechanical properties of hygiene paper and to determine the optimal conditions for its use to improve the wet tensile strength. It can be expected that the portion of energy in the form of heat will increase the rate of PAE adsorption on fibers and the polymer cross-linking process, which would minimize the natural ageing time and lead to an improvement in the wet tensile strength of the papers. However, two questions call for answers: Can heating the pulp before drying the paper have a significant effect on its WTI index? Is the drying process the most important factor in this case?

EXPERIMENTAL

Materials

In the study, paper sheets were formed from bleached softwood kraft pulp (BSKP) and bleached hardwood eucalyptus kraft pulp (BHKP) mixed in a ratio of 40:60. The sheets produced had a basis weight of 30 g/m².

Both softwood and eucalyptus pulps were refined in a PFI mill, with the pine pulp being refined to 25 °SR and the eucalyptus pulp to 30 °SR. The SR freeness of the pulp was measured according to ISO 5267-1 (1999) (L&W Schopper-Riegler freeness tester, Sweden).

To obtain a product with high wet tensile strength, a PAE resin with the trade name KYMENE 5715 manufactured by Solenis was added to the paper pulp. The decision to choose this resin was justified by its previous use in the production of kitchen towels in one of the Polish paper mills. The diluted resin was added to the paper pulp in the form of a solution at a consistency of 0.036%. Paper samples without the addition of resin were also formed for comparative purposes.

Methods

Preparation of paper samples and their drying process

A forming device from Allimand was used to form wet paper samples. The device allows for forming samples with any selected jet-to-wire speed ratio. It allows for the adjustment of wire (drum) speed and the flow velocity of pulp from the outlet nozzle. The jet-to-wire ratio of 0.95 was used in the tests. Sheets with a basis weight of 30 g/m² were formed from a mixture of pulps without resin and with the addition of PAE. This allowed for determining the increase in the paper's tensile strength in the wet state. The pulp was appropriately prepared before being fed to the forming device. A cationic PAE solution was added to the pulp with a consistency of 0.5% and a specified temperature (25 °C, 40 °C, or 50 °C) in the amount of 3.5 mg/g ADM (the amount was determined based on data obtained from the paper mill). Then the suspension (pulp) was intensively mixed for 5 min. The mixing time was determined based on preliminary analyses. The prepared pulp was used to form paper sheets with dimensions of 220 x 880 mm². The dryness of the samples after forming was 18.5% ± 0.2%. Samples for analysis were cut while wet and kept in conditions of constant air humidity (70%). The dimensions of the samples were limited by the width of the head and the dimensions of the test device's running trolley. Samples were cut in the longitudinal direction (MD) and the cross direction (CD) of the formed sheet. Wet samples cut from the sheet were transferred to the testing device in conditions of constant air humidity (70%) and temperature of 25 °C. The time between forming the sheet, cutting it into samples, and subjecting them to convective drying was several minutes. Pilot studies showed that this time did not affect the increase in the level of paper strength.

For these tests, an experimental stand (Fig. 1) was used, consisting of two main systems, *i.e.*, an adjustable head (No 2 on Fig. 1) supplied with air heated to an appropriate temperature (25 °C, 190 °C, 260 °C, and 330 °C) and a drive system (No. 1 on Fig. 1) with a paper sample placed on it. The head of the device was set at a 90° angle to the moving trolley so that the air jet hit the sample surface perpendicularly. The vertical head adjustment allowed precise determination of the distance between the slot nozzle and the sample surface. A plate with a 3 mm wide slot nozzle, without rounded edges, was installed in the head. The distance from the nozzle to the surface of the paper sample was 10 mm. During the experiments, the parameters of the research stand were controlled, including

the velocity and temperature of the air flowing out of the head, the speed of the trolley, and the tension of the wire. The wet paper sample was placed on a bronze wire on a trolley with adjustable speed. The wire mesh on which the sample was placed was tensioned with a constant force of 4 kN/m using a system of springs. The samples were protected against being blown away during the test. The trolley moved along guides and was driven by a motor with adjustable engine speed. The speed of the trolley was determined by measuring the time taken to travel the distance determined by the motion sensors. Depending on the amount of energy transferred to the sample in the form of heat, the appropriate drying time was selected to obtain the final dryness of paper samples at the level of $93\% \pm 0.5\%$. These tests were preceded by test series, which aimed to determine the optimal drying time of the samples. It was determined that the drying time, depending on the air temperature, would be as follows:

- 25 °C – day in ambient conditions
- 190 °C → 105 s
- 260 °C → 90 s
- 330 °C → 75 s

The velocity of the heated air impingement was the same for all tests – 5 m/s.

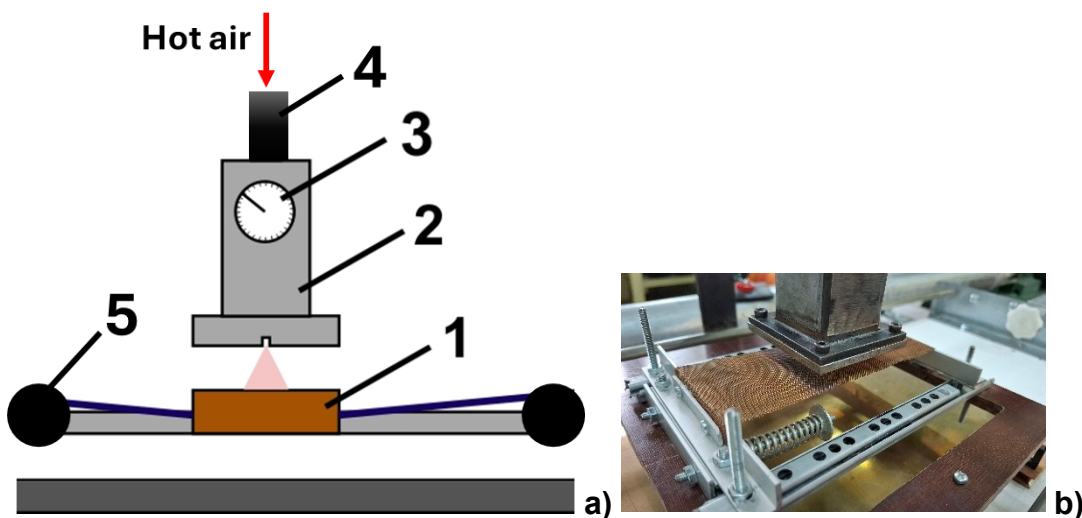


Fig. 1. Research stand: a) scheme of the stand: 1 - trolley with sample, 2 - head, 3 - thermometer, 4 - piping, 5 - drive system; b) view of the head and the trolley

The tensile strength tests of wet samples were divided into four series: A, B, C, and D. In the first series (A), the tests were performed on sheets without the addition of PAE resin. In this case, the pulp was heated to 40 °C; then the samples were formed and dried by impingement hot air at a temperature of 190 °C.

Series B, C, and D differed in the temperature of the pulp from which the sheets were formed, respectively 25, 40, and 50 °C. Each series was divided into 4 variants differing in drying temperatures. The corresponding variants were marked with the following symbols: B/C/D-1 (25 °C); B/C/D-2 (40 °C), B/C/D-3 (50 °C).

In variant 1, the samples were dried with air at ambient temperature, in variant 2 (the second) the drying temperature was 190 °C. In the third and fourth variants, it was 260 and 330 °C, respectively.

In variants 2, 3, and 4, the samples were dried using hot air impingement. The pulp temperature was selected in accordance with industrial practice, where the most common range is 35 to 50 °C. For each variant, 10 samples cut from the formed sheet were tested in the MD and CD directions. All samples were conditioned (natural ageing of paper) in ambient conditions for 10 days before the strength tests.

Strength and Structural Tests

Apparent density was analyzed based on ISO 12625-3 (2014). Roughness determinations were performed according to ISO 8791-2 (2013) (Roughness Tester Bendtsen Method, The TMI Group of Companies, Büchel BV, Veenendaal, Netherlands).

Wet tensile strength tests of samples in the machine direction MD and cross direction CD were performed according to ISO 12625-5 (2024-12).

The measurement results are presented in the form of a wet tensile index (WTI). The wet tensile index for each sample was calculated as the tensile strength (expressed in Newtons per meter) divided by the grammage.

The tests were performed using a standard Zwick Z010 tensile testing machine equipped with a 500 N force measuring head and equipment for testing tissue paper. All measurements were performed in a room with the same climatic conditions as the samples were conditioned. An initial force of 0.1 N and a testing speed of (50 ± 2) mm/min were used. The test span for all measurements was 43.5 ± 0.5 mm. A Finch Cup soaking device was used to test wet tensile strength. The mean value was obtained from 10 valid measurements.

RESULTS AND DISCUSSION

The analysis of apparent density showed a decreasing trend with increasing drying temperature. The highest apparent density values (0.26 to 0.29 g/cm³) were observed for sheets dried at ambient temperature, whereas drying at 330 °C led to a reduction of this parameter to 0.21 to 0.24 g/cm³. This suggests that mild drying conditions minimize structural changes in the paper fiber structure. At high drying temperatures, the internal structure of the paper undergoes substantial deformation. This causes an increase in internal stresses, which promotes the formation of pores and, consequently, a reduction in apparent density. It is worth noting that the changes in apparent density for papers produced from pulp at ambient temperature for all drying temperatures were small. An increase in drying temperature to 330 °C reduced apparent density by only 6.5%. In turn, the apparent density of sheets produced from pulps heated to 40 °C and 50 °C changed considerably depending on the drying temperature. For pulps heated to 50 °C, the apparent density dropped almost 30%. This suggests changes in the degree of polymer cross-linking and its effect on the sheet structure. Changes in the surface topography of sheets due to the drying process were confirmed by the analysis of roughness parameters – with the increase in the hot air-drying temperature, an increase in the surface roughness value is observed. The changes amounted to 40% and are independent of the pulp temperature, which in turn indicates structural changes (stiffness and hornification of fibers on the surface) of the paper under the influence of higher temperatures.

Table 1 presents the results of wet tensile strength tests for papers without PAE addition, while Tables 2 and 3, as well as Figs. 2 (Machine Direction) and 3 (Cross Direction), display the results for papers containing PAE.

Table 1. Wet Tensile Strength Test Results of Papers (Series A, Without PAE Additive)

Parameter	Variant A-1
Pulp Temperature, Drying Temperature (°C)	40 190
CD	
Wet Tensile Index, (Standard Deviation) (Nm/g)	0.88 (0.09)
MD	
Wet Tensile Index, (Standard Deviation) (Nm/g)	1.54 (0.12)
CD/MD	
% of Changes	57.1

Table 2. Wet Tensile Strength Test Results for Resin-added Papers for Series B (Pulp at Temperature – 25 °C)

Parameter	Variant B-1	Variant B-2	Variant B-3	Variant B-4	Change from T = 25 °C (%)			Increase by X% TI		
Pulp Temperature, Drying Temperature (°C)	25 25	25 190	25 260	25 330	190	260	330	25→190	190→260	260→330
CD					CD			CD		
Wet Tensile Index, (Standard Deviation) (Nm/g)	6.78 (1.12)	9.78 (0.47)	12.03 (0.68)	14.57 (0.78)	44.1	77.4	114.7	44.1	33.3	37.3
MD					MD			MD		
Wet Tensile Index, (Standard Deviation) (Nm/g)	17.54 (1.02)	24.29 (1.47)	31.18 (0.60)	36.67 (0.97)	38.5	77.8	109.1	38.5	39.3	31.3
CD/MD										
% of Changes	38.7	40.2	38.6	39.7	-			-		

Table 3. Wet Tensile Strength Test Results for Resin-added Papers for Series C (Paper Pulp Heated to 40 °C)

Parameter	Variant C-1	Variant C-2	Variant C-3	Variant C-4	Change from T = 25 °C (%)			Increase by X% TI		
Pulp Temperature, Drying Temperature (°C)	40 25	40 190	40 260	40 330	190	260	330	25→190	190→260	260→330
CD					CD			CD		
Wet Tensile Index, (Standard Deviation) (Nm/g)	7.37 (0.80)	10.16 (2.02)	12.51 (0.91)	14.93 (1.29)	37.9	69.9	102.7	37.9	32.0	32.8
MD					MD			MD		
Wet Tensile Index, (Standard Deviation) (Nm/g)	17.88 (0.98)	23.19 (2.61)	34.08 (1.41)	38.59 (1.59)	29.7	90.6	115.8	29.7	60.9	25.2
CD/MD					-			-		
% of Changes	41.2	43.8	36.7	38.7						

Table 4. Wet Tensile Strength Test Results for Resin-added Papers for Series D (Paper Pulp Heated to 50 °C)

Parameter	Variant D-1	Variant D-2	Variant D-3	Variant D-4	Change from T = 25 °C (%)			Increase by X% TI		
Pulp Temperature, Drying Temperature (°C)	50 25	50 190	50 260	50 330	190	260	330	25→190	190→260	260→330
CD					CD			CD		
Wet Tensile Index, (Standard Deviation) (Nm/g)	8.10 (1.70)	10.54 (1.19)	15.76 (1.75)	17.24 (1.21)	30.1	94.5	112.8	30.1	64.4	18.2
MD					MD			MD		
Wet Tensile Index, (Standard Deviation) (Nm/g)	22.01 (1.93)	27.6 (1.30)	39.98 (1.86)	40.81 (1.78)	25.4	81.6	85.4	25.4	56.2	3.8
CD/MD					-			-		
% of Change	36.8	38.2	39.4	42.2						

In the comparative studies, samples containing PAE and samples formed without resin were analyzed. Sheets without PAE were formed from a pulp heated to 40 °C and dried by hot air at 190 °C. The pulp temperature used corresponds to the typical values used in the paper industry. Papers without PAE had the lowest TI value of all the analyzed

papers. For samples tested in the MD direction, the average TI value was 1.54 Nm/g, while for CD it was 0.88 Nm/g (Table 1, Figs. 2 and 3).

After adding resin to the pulp, the wet tensile strength of the paper samples increased more than 25 times in some variants. Paper samples without PAE, tested wet, achieved strength of 6.6% in the MD direction and 8.7% in the CD direction compared to samples containing PAE (comparison of variants A-1 and C-2, based on average TI values).

In series B, sheets were formed from paper pulp at ambient temperature (25 °C) with the addition of PAE and then dried at the appropriate temperature. A gradual increase in the strength of the samples was observed with increasing drying temperature (from 25 °C to 330 °C), with the highest value recorded at 330 °C. In this variant (B-4), the Wet Tensile Index for the paper tested in the MD direction was 36.67 Nm/g, and in the CD direction it was 14.57 Nm/g (Table 2, Figs. 4 and 5).

Comparing drying at ambient temperature (variant B-1) with drying at 330 °C (variant B-4), a substantial increase in the strength of the samples was observed. The Wet Tensile Index value for the mentioned variants increased 109% in the MD direction and 115% in the CD direction, which confirms the considerable effect of high drying temperature on improving the mechanical properties of the paper. In the remaining variants, the WTI increased approximately 20% to 30% with the increase in drying temperature. This applies to both samples cut in the MD and CD direction (Tables 3 and 4).

In series C, the paper pulp was heated to 40 °C, resin was added, and then sheets were formed, which were dried at temperatures of 25, 190, 260, and 330 °C. Analysis of the results showed that heating the paper pulp to 40 °C had no noticeable effect on the Wet Tensile Index compared to samples formed from pulp at 25 °C (Table 3, Figs. 2 and 3). For the CD direction, the increase is at the level of 10% (except for C-3) and for the MD direction, only for variants C-3 and C-4 a slight increase in WTI was observed (17% and 7%, respectively). After drying at ambient temperature, the strength increased from 17.54 to 17.88 Nm/g for the MD direction and from 6.78 to 7.37 Nm/g for the CD direction, which is an increase of 1.94% and 8.70%, respectively (average WTI values). In the subsequent variants of the C series, the increase in the hot air-drying temperature caused a further increase in the WTI index. Increasing the temperature from 190 to 260 °C caused a 46.9% increase in strength in the MD direction and 23.1% in the CD direction, while a further increase in temperature to 330 °C resulted in an increase of 13.2% (MD) and 23.1% (CD), respectively (Table 3).

The obtained results clearly indicate that the high-temperature drying process has a key impact on improving the mechanical properties of paper, and the highest effectiveness was achieved at 330 °C.

In series D, the paper sheet preparation process included heating the pulp to 50 °C, adding resin and forming sheets, which, similarly to the other samples, were dried at ambient temperature of 25 °C and an air jet at temperatures of 190, 260, and 330 °C.

Raising the temperature of the paper pulp to 50 °C before forming the sheets clearly increased the strength WTI of the tested samples, compared to those made from pulp at a temperature of 25 °C (Figs. 2 and 3). The results obtained in series D, compared to the results from series B, showed an increase in the WTI in all tested sample variants, in all directions, in the range from 8% to 31% (assuming average WTI values). It is worth noting that in series C the increase in WTI compared to series B was small, remaining below 10% in all tested variants for the same drying temperatures. Similarly to the previous series, also in this one (series D), the increase in drying temperature contributed to the increase in wet

tensile strength of the paper in both MD and CD directions. After drying the samples at 190 °C the WTI of the tested papers increased 25.4% in the MD direction and 30.1% in the CD direction, compared to the samples dried at ambient temperature. The increase in drying temperature to 260 °C compared to ambient temperature contributed to the 81.6% increase in WTI in the MD direction and 94.5% in the CD direction. At 330 °C it was 85.4% and 112.8%, respectively (assuming average WTI values) (Table 4).

It was observed that in all series, papers dried at 330 °C achieved higher wet tensile strength compared to the other variants tested. The increase in this strength in the case of PAE papers can be attributed, among others, to the increased level of resin cross-linking in the paper structure. In addition, drying in such conditions promotes an increase in fiber plasticization. In these cases, the flow of heat energy to the paper was the highest compared to the other variants tested. In variants with hot air drying, increasing the temperature from 190 to 260 °C led to an increase in the Wet Tensile Index by 45% to 50%, regardless of the sample orientation (MD and CD). Increasing the drying temperature another 70 °C (Series D, increasing the temperature from 260 °C to 330 °C) caused the Wet Tensile Index to increase 2.08% in the MD direction and 9.38% in the CD direction. It is worth noting the exceptionally low increase in the WTI value in the MD direction, amounting to only 2.0% compared to the other results. The increase in the WTI value was small, close to the measurement error (Figs. 4 and 5). The average WTI values indicate that the PAE paper samples, tested wet in the CD direction, achieved strength of 36% to 43% compared to the results obtained in the MD direction.

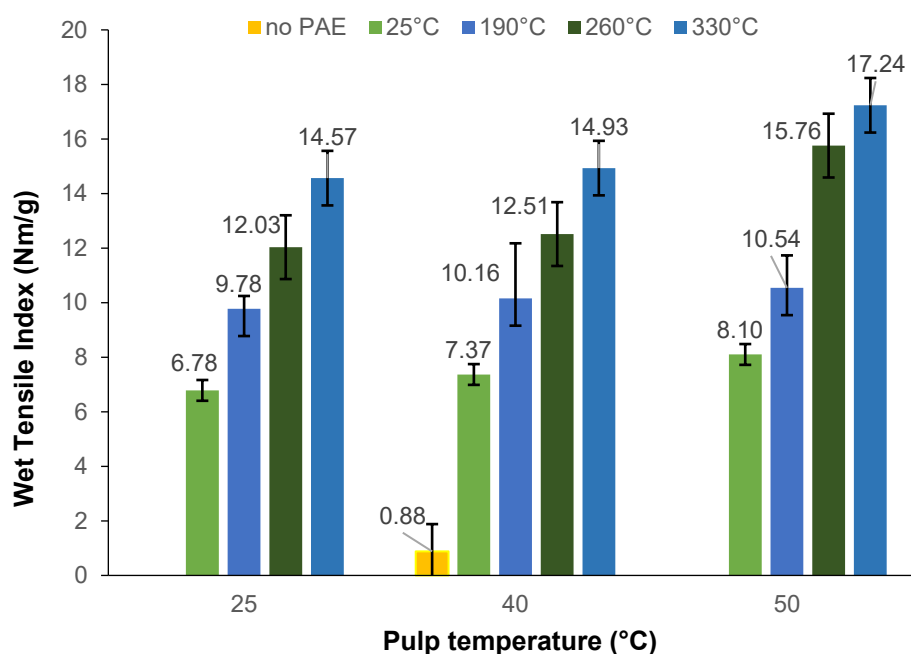


Fig. 2. Changes of wet tensile index according to pulp and drying temperature in cross direction

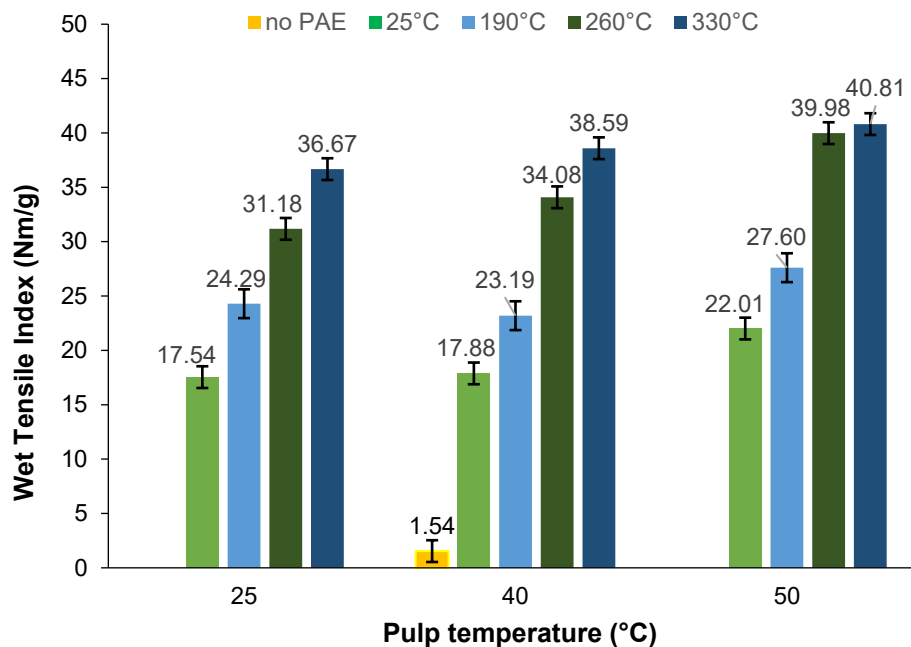


Fig. 3. changes of wet tensile index according to pulp and drying temperature in machine direction

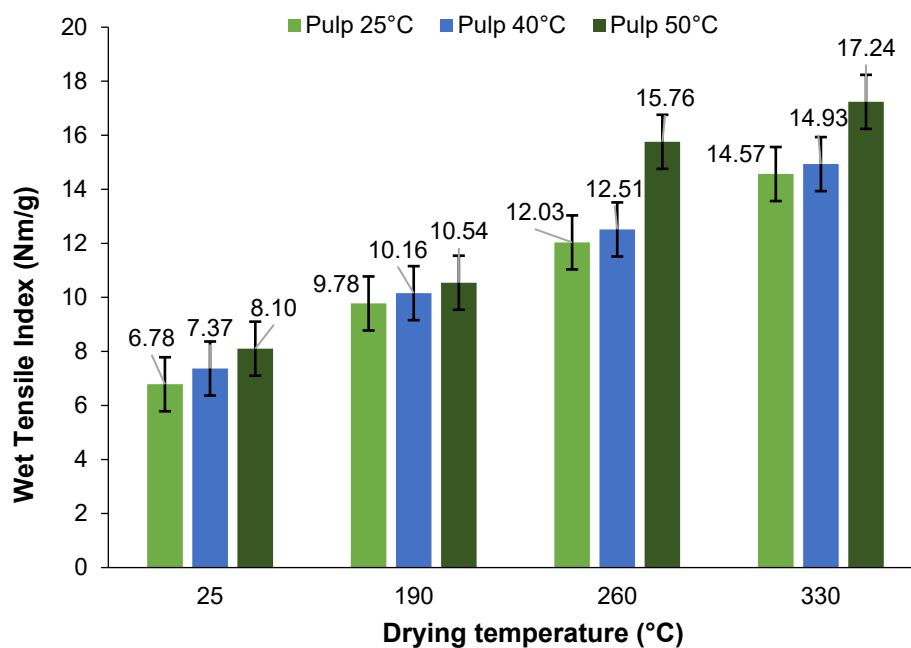


Fig. 4. Changes of wet tensile index according to pulp and drying temperature in cross direction

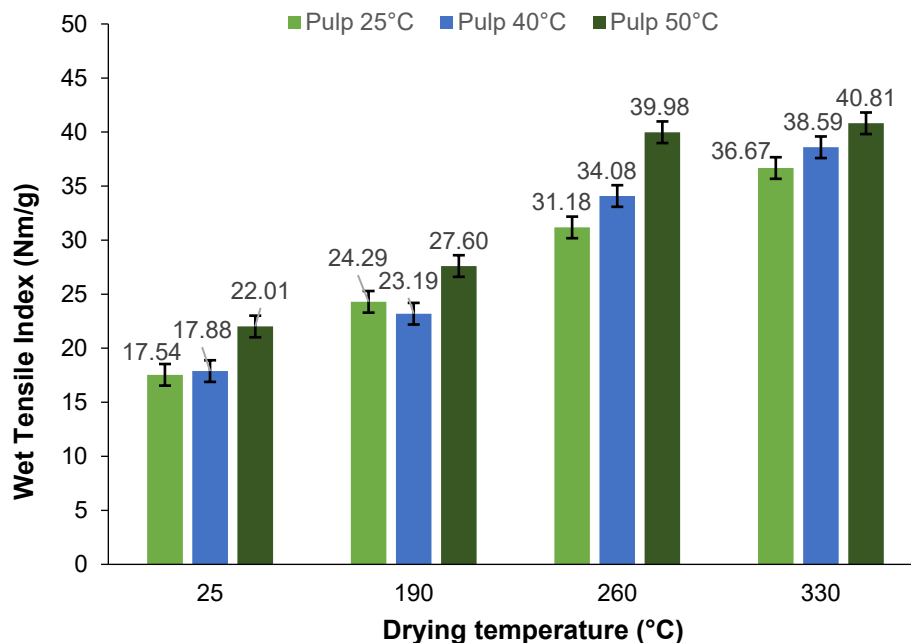


Fig. 5. Changes of wet tensile index according to pulp and drying temperature in machine direction

CONCLUSIONS

1. The increased wet strength of paper samples treated with poly(amidoamine epichlorohydrin) resin (PAE) results from the formation of permanent ester bonds between the azetidine groups of PAE and the carboxyl groups of cellulose, as well as the self-crosslinking processes. The key role is played by heat treatment, which intensifies the number of intermolecular bonds and the rate of their formation. Analysis of the effect of the paper pulp temperature and the drying process showed that the increase in the temperature of the paper pulp with PAE resulted in an increase in the wet tensile index value in both tested directions (MD and CD). The increase in temperature to 40 °C resulted in an improvement in strength of less than 10%, while heating to 50 °C resulted in an increase in the range of 10% to 20%. This phenomenon was observed regardless of the drying variants used.
2. The most important factor determining wet strength was the drying temperature of the samples. An increase in the drying temperature in the range of 25 to 330 °C resulted in an increase in the wet tensile index by over 100%. This means that the more heat energy was supplied to the paper structure, the more its resistance to wet tensile strength increased. The highest strength was demonstrated by papers made from pulp heated to 50 °C and dried at 330 °C. The increase in the drying temperature was also associated with a decrease in the time of contact of the sample with the hot air, which indicates that an increase in temperature increases the rate of bond formation and their number. It was noted that the WTI for papers containing PAE was even 25 times higher than for papers without added resin, regardless of the fiber orientation and the drying conditions used.

3. In all analyzed series, it was observed that the wet strength of the tested samples also depended on the fiber orientation in the paper structure. The PAE paper samples, tested wet in the CD direction, achieved strength at the level of 36% to 43% compared to the results obtained in the MD direction. Continuous improvement of technologies aimed at increasing paper resistance to moisture is a major challenge for the paper industry. Sometimes even minor modifications of production parameters can visibly improve the properties of the final product. Each action in this area should consider both economic efficiency and the ecological aspect.

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