Enhancing Bulk and Absorbency of Tissue Paper Using Softwood Bleached Chemi-Thermomechanical Pulp

Yahui Lin,[a] Yulong Wang,[a,*] Yishan Kuang,[a] Benping Lin,[a] Defang Li,[a] Rui Yang,[a] and Hongjie Zhang [b]

Softwood bleached chemi-thermomechanical pulp (SW-BCTMP) was added in tissue paper manufacturing, focusing on bulk, absorbency and strength performance. The SW-BCTMP exhibited high fines content (52.4%), elevated polymeric cationic demand (83.0 μeq·L^{-1}), and substantial zeta potential (-93.0 mV), which initially impaired both dynamic drainage performance and first-pass retention of pulp furnishes. The optimal application of polyaluminum chloride (PAC) was found to effectively reduce the cationic demand of pulp furnishes and enhance first-pass retention. The addition of 5.0 to 10.0% SW-BCTMP consistently enhanced the bulk, water absorbency, and air permeability of the handsheets. In the absence of polyamide-epichlorohydrin resin (PAE), dry strength was well maintained or even improved when substituting the bleached hardwood kraft pulp (BHKP), despite a marginal decline upon replacing the bleached softwood kraft pulp (BSKP). However, in PAE-containing systems, a consistent reduction in both dry and wet strength was observed. This detrimental effect was more pronounced when the SW-BCTMP replaced BSKP in the furnishes, which can be attributed to the interference of the SW-BCTMP with the adsorption and effectiveness of the wet-strength resin. The SW-BCTMP showed potential for enhancing bulk and absorbency in tissue products, such as toilet paper, where wet strength agents are not used.

DOI: 10.15376/biores.21.1.1957-1967

Keywords: BCTMP; Tissue paper; Bulk; Absorbency; Wet-end chemistry

Contact information: a: School of Chemistry and Pharmaceutical Engineering, Changsha University of Science and Technology, Changsha, P.O. Box 410114, China; b: National Engineering Lab for Pulp and Paper, China National Pulp and Paper Research Institute Co. Ltd., Beijing, P.O. Box 100102, China;
** Corresponding author: wangyulong_1977@126.com*

INTRODUCTION

As an essential daily commodity, the performance of tissue paper is critically dependent on key physical properties such as bulk and liquid absorbency (Morais *et al*. 2022; Reitbauer *et al*. 2023). Elevated bulk not only imparts a soft and lofty texture but also significantly enhances absorption capacity by increasing internal pore volume (Bytomski *et al*. 2024). Moreover, optimized absorbency ensures effective cleaning performance and user comfort. From a sustainability perspective, higher bulk enables reduced fiber consumption while maintaining equivalent performance, thereby lowering material costs and environmental impact. Consequently, continuous improvement of bulk and absorbency has become a pivotal objective for tissue production to meet consumer demands and advance eco-friendly manufacturing practices.

In current tissue paper production, several technical approaches are employed to improve bulk and absorbency, including: (1) hardwood pulp strategy (minimal or light refining) to increase porosity (Fišerová *et al*. 2019); (2) incorporation of high-yield pulp (HYP) (Stankovská *et al*. 2020); (3) extended-nip press (ENP) with low-pressure dewatering (De Assis *et al*. 2018); (4) high-temperature rapid drying on Yankee cylinders (Reczulski *et al*. 2023), and (5) creping process, and adoption of crescent-former machines (De Assis *et al*. 2018; Qin *et al*. 2023). However, these methods also present certain limitations, for example, the hardwood pulp strategy and creping process often compromise sheet strength; HYP may adversely affect wet-end chemistry; ENP and specialized paper machines entail high capital investment; Yankee drying consumes significant energy and may reduce paper flexibility, leading to brittleness. Therefore, continuous technological innovation is essential to further optimize bulk and absorbency while mitigating these drawbacks.

The bleached chemi-thermomechanical pulp (BCTMP) process represents a well-established and advanced technology. Typically produced from softwood fibers, the BCTMP manufacturing process involves sequential stages of screw pressing of wood chips, chemical pretreatment, high-consistency refining, and bleaching (Pettersson *et al*. 2021; Joelsson *et al*. 2022). The softwood bleached chemi-thermomechanical pulp (SW-BCTMP) exhibits distinctive advantages, including superior fiber length, high rigidity, and competent strength properties. These characteristics facilitate the formation of an open network structure, significantly enhancing paper bulk and liquid absorption capacity. Moreover, SW-BCTMP fibers can offer a favorable combination of bulk development and bonding potential compared to the conventional approach of minimal hardwood pulp refining. This unique property enables simultaneous optimization of bulk and absorbency while maintaining sheet strength performance.

Currently, the BCTMP finds predominant application in kitchen towel production (Balberčák *et al*. 2022). However, its utilization in premium facial tissues and toilet paper remains scarcely documented in scientific literature, presenting a significant research gap worthy of further investigation. This study focuses on facial tissues and toilet paper as representative tissue products, with the objective of enhancing bulk and absorbency while maintaining other performance through the strategic incorporation of the SW-BCTMP. The fiber characteristics of the SW-BCTMP and its impacts on wet-end chemistry were systematically investigated. Additionally, the bulk, absorbency, and dry/wet strength properties of laboratory handsheets were examined to comprehensively evaluate the feasibility of the SW-BCTMP application in premium tissue paper production.

EXPERIMENTAL

Materials

Softwood bleached chemi-thermomechanical pulp (SW-BCTMP), bleached softwood kraft pulp (BSKP), and bleached hardwood kraft pulp (BHKP) were supplied by Yueyang Paper Co., Ltd. (Yueyang, China). Polyaluminium chloride (PAC) and the wet strength agent polyamidoamine-epichlorohydrin resin (PAE) were obtained from Zhejiang Transfar Chemicals Group Co., Ltd. (Hangzhou, China). All chemicals were used as received without further pretreatment.

Methods

Pulp treatment and experimental design

The SW-BCTMP pulp was refined to 36 degrees Schopper-Riegler (SR), and the BSKP pulp was refined to 42 SR, using a laboratory Hollander beater according to ISO 5264-1 (1979) standard. The BHKP pulp was soaked in water for 4 h and subsequently disintegrated in a standard fiber disintegrator to achieve a beating degree of 15 SR. All prepared pulps were stored for subsequent experiments.

Based on a mill-produced pulp furnish used for premium facial tissue manufacturing (control group comprising 22% BSKP and 78% BHKP), five experimental formulations were designed by substituting 5.0% and 10.0% of BSKP (or BHKP) with SW-BCTMP on an oven-dry weight basis. These substitution levels were chosen to represent a moderate and a substantial replacement scenario, enabling the observation of meaningful trends in property changes while maintaining acceptable processability. The detailed pulp furnish formulations are presented in Table 1.

Table 1. Pulp Formulations with 5.0 to 10.0% SW-BCTMP Substitution for Tissue Paper

Formulation	SW-BCTMP (%)	BSKP (%)	BHKP (%)	Total (%)
Control	0	22	78	100
A	5	17	78	100
B	5	22	73	100
C	10	12	78	100
D	10	22	68	100

Fiber morphology and fiber characteristics

Fiber surface morphology was observed using an Olympus CX34 microscope (Olympus Corporation, Tokyo, Japan). Fiber characteristic parameters were analyzed in accordance with TAPPI T271 om-07 (2007) using a Fiber Analyzer (kajaaniFS300, Metso, Espoo, Finland). The measured parameters included length-weighted average fiber length, number-average fiber length, mean fiber width, fines content, and fiber curl. Test results for each sample were statistically derived from approximately 10,000 fibers.

Polymeric cationic demand (PCD) and zeta potential

The PCD of pulp suspensions was determined using a streaming current detector (Mütek PCD-05, BTG Eclépens S.A., Eclépens, UK). The zeta potential was measured in compliance with ISO/TR 19997 (2018) using a zeta potential analyzer based on the fiber-pad streaming potential principle (Mütek SZP-10, BTG Eclépens S.A., Eclépens, UK).

Dynamic drainage and first-pass retention

The dynamic drainage performance of pulp suspensions was determined using the methodology described by Wang *et al*. (2017). Specifically, 1000 mL of pulp suspension at 1.0% consistency was suspended in the cylinder of a dynamic drainage system (DDJ-2#, equipped with 200-mesh screen, PRM. Inc., Seattle, WA, USA). The suspension was stirred at 400 rpm for 30 s, after which the drainage times required for collecting the first 100 mL and 200 mL of filtrate were recorded. The first-pass retention of the pulp suspension was measured by gravimetric analysis (Fan *et al.* 2023).

Handsheet preparation and physical property evaluation

The pulp suspension was adjusted to 1.0% consistency, followed by sequential addition of 0.3% PAC and 0.25% PAE. Handsheets with a basis weight of 60 g/m^2 were prepared according to TAPPI T 205 sp-20 standard. After conditioning at 23 ± 1 °C and 50 ± 2% relative humidity, the following handsheet properties were evaluated in compliance with ISO standards: bulk (ISO 12625-3 2014), brightness and color coordinates (ISO 2470-1 2016), tensile index (ISO 1924-3 2005), tear index (ISO 4046-5 2016), burst index (ISO 2759 2014), and air permeability (ISO 5636-6 2015). The liquid absorption capacity was assessed *via* capillary rise height measurement (ISO 8787 1986), with the vertical liquid penetration height recorded after 10 ± 0.05 min. All tests were conducted under controlled laboratory conditions with triplicate measurements to ensure data reliability.

RESULTS AND DISCUSSION

Fiber Morphology and Fiber Characteristics

Figure 1(a through h) demonstrates the fiber morphology of different pulp samples. As shown, the refined BSKP exhibited pronounced fiber cutting and fibrillation (Fig. 1a), whereas the BHKP subjected only to defiberization maintained smooth fiber surfaces with minimal cutting or fibrillation (Fig. 1b). In contrast, the refined SW-BCTMP contained abundant fiber fragments (Fig. 1c), which are attributable to its high lignin content and inherent brittleness that predisposed it to mechanical degradation during refining. Due to these distinct morphological differences among the three pulp fibers, the addition of 5.0 to 10.0% SW-BCTMP fibers into the control pulp allowed clear identification of BSKP, BHKP, and SW-BCTMP fibers in the blended furnishes (Fig. 1d through h).

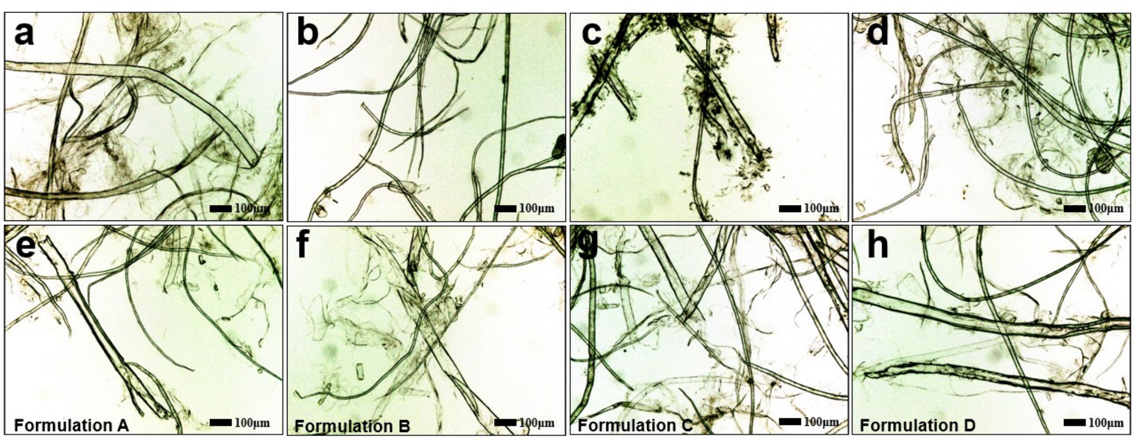

Fig. 1. Fiber morphology of pulp samples: (a) BSKP (42 SR), (b) BHKP (15 SR), (c) SW-BCTMP (36 SR), (d) Control pulp, and (e through h) SW-BCTMP-blended pulp formulations (A through D)

As shown in Table 2, fiber characteristics demonstrate the SW-BCTMP exhibited substantially higher fines content (52.4%) compared to the BSKP (16.8%) and the BHKP (20.7%). Moreover, the SW-BCTMP fibers demonstrated lower fiber curl nature, indicating straighter fiber morphology. This characteristic is also likely associated with the high lignin content that enhances fiber rigidity while reducing plasticity (Wang *et al*. 2019). The addition of 5.0% and 10.0% SW-BCTMP as substitutes for either BSKP or BHKP in the control pulp revealed minimal alterations in fiber length, width, and curl. However, a progressive increase in fines content was observed, directly attributable to the inherently high fines fraction in the SW-BCTMP. High fines content may potentially compromise drainage performance and reduce retention efficiency of the pulp suspension (Taipale *et al*. 2010).

Table 2. Fiber Characteristics of Different Pulp Formulations

Formulation	Length-weighted average Fiber Length (mm)	Number-average Fiber Length (mm)	Fiber Width (μm)	Fines Content (%)	Fiber Curl (%)
100% BSKP	2.12±0.08	0.64±0.12	21.12±1.21	16.85±1.41	12.20±0.83
100% BHKP	1.02±0.02	0.62±0.10	14.71±0.84	20.78±1.94	13.42±1.68
100% SW-BCTMP	1.44±0.14	0.55±0.05	29.31±2.69	52.46±4.91	9.00±1.20
Control	1.04±0.04	0.63±0.03	14.91±1.36	18.65±0.84	13.60±0.62
A	1.03±0.03	0.63±0.11	15.56±0.32	18.39±1.30	13.10±0.99
B	1.04±0.04	0.61±0.07	15.03±0.84	22.93±0.91	13.20±1.47
C	1.04±0.09	0.61±0.13	14.89±1.64	24.29±1.24	13.70±0.66
D	1.02±0.05	0.62±0.09	15.39±0.18	23.43±0.37	13.20±1.71

Cationic Demand and Zeta Potential

The cationic demand and zeta potential are critical parameters for characterizing the colloidal charge properties of pulp furnishes and the surface charge state of particles. These two parameters collectively influence the stability of the wet-end chemical system, thereby affecting the retention of fines, the efficiency of chemical additives, and the final physical properties of the paper. In the experiments, the cationic demand and zeta potential of a series of pulp furnishes were analyzed, and the results are presented in Fig. 2.

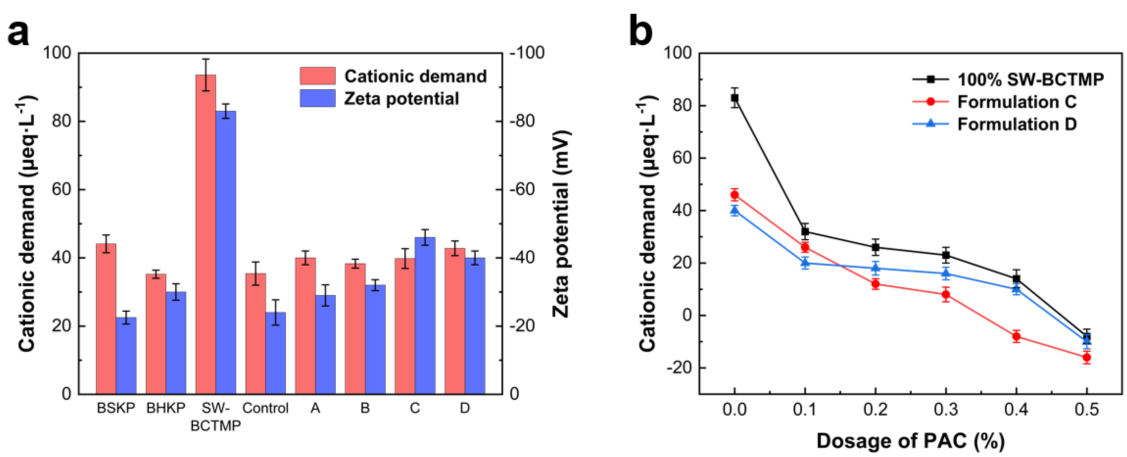

Fig. 2. (a) Cationic demand and zeta potential of different pulp formulations, (b) Effect of PAC dosage on PCD in the SW-BCTMP and SW-BCTMP-blended furnishes (Formulation C and D)

The results indicate that the PCD and zeta potential of the SW-BCTMP were markedly higher than those of BSKP and BHKP (Fig. 2a). This is attributed to the higher content of anionic trash (*e.g.*, lignin, hemicellulose, dissolved organic matter, *etc.*) in the SW-BCTMP, as well as its elevated lignin content of fibers and stronger electronegativity, leading to increased PCD and surface charge density. Excessively high anionic trash may cause several adverse effects, such as increased consumption of cationic additives, impaired drainage performance, deterioration of the white water system, and reduced sheet strength (Wang *et al*. 2016; Sjöstrand and Brolinson 2022).

In this study, the PAC was employed as an anionic trash catcher to regulate the cationic demand of pulp furnishes and maintain wet-end chemical stability. The results showed that the PAC addition effectively reduced the cationic demand (Fig. 2b). When dosed at 3.0 kg per ton of pulp, the PAC rapidly decreased the PCD of SW-BCTMP from 83.0 to 21.0 $\mu eq \cdot L^{-1}$. Similarly, for pulp furnishes containing 10.0% SW-BCTMP (Formulation C and D), the same PAC dosage reduced PCD from 46.0 to 10.0 $\mu eq \cdot L^{-1}$ and from 40.0 to 16.0 $\mu eq \cdot L^{-1}$, respectively. This optimization contributed to stabilizing wet-end chemistry, improving fiber retention and machine runnability, and enhancing final sheet properties.

Dynamic Drainage and First-pass Retention

The BCTMP pulp, characterized by its high fines content and elevated cationic demand, may adversely affect pulp drainage performance and retention efficiency. Experiments were conducted to evaluate the dynamic drainage behavior and first-pass retention of pulp furnishes containing the SW-BCTMP, with results presented in Fig. 3.

As shown in Fig. 3(a and b), the addition of 5.0 to 10.0% SW-BCTMP substantially reduced both dynamic drainage performance and first-pass retention of the pulp furnishes. Particularly with 10.0% SW-BCTMP content, the first-pass retention decreased from 81.4% (Control) to 72.0% (Formulation C) and 69.3% (Formulation D), respectively. To improve retention efficiency, 0.3% PAC was introduced into the pulp furnishes, and the resulting changes in first-pass retention are presented in Fig. 3b. The results demonstrated that PAC treatment effectively enhanced the first-pass retention of the SW-BCTMP-containing pulp furnishes. At a dosage of 0.3%, the PAC improved the first-pass retention of 10.0% SW-BCTMP-containing pulp furnishes from 72.0% to 80.3% (Formulation C) and from 69.3% to 77.8% (Formulation D), respectively, effectively mitigating the retention issues caused by the SW-BCTMP. This improvement can be attributed to the dual functions of positively charged hydrated aluminum ions generated by PAC: (1) neutralization of anionic trash components and (2) adsorption onto fine fiber surfaces (Yang *et al*. 2019). These mechanisms add to enhanced furnish retention performance.

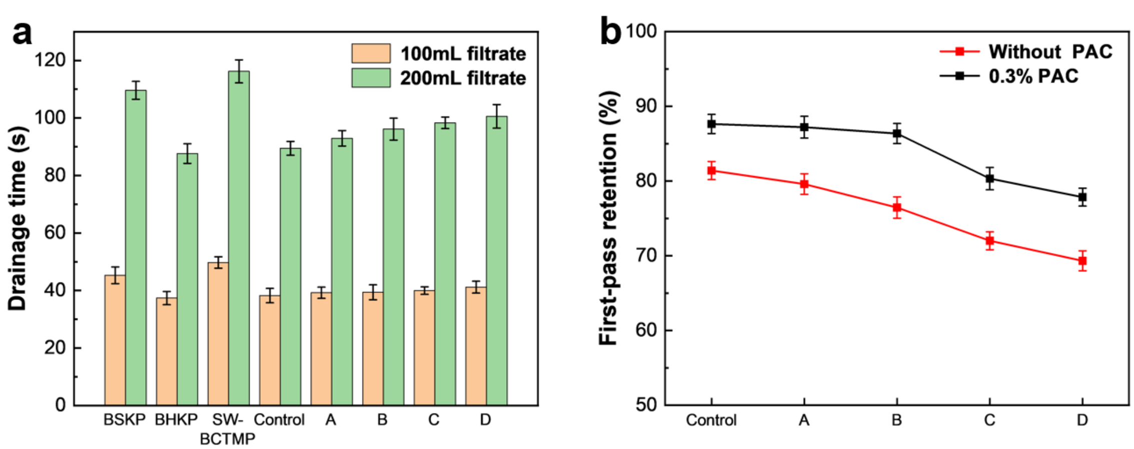

Fig. 3. (a) Dynamic drainage behavior of pulp furnishes, and (b) Effect of PAC (0.3% dosage) on first-pass retention of the SW-BCTMP-blended pulp furnishes

Physical Properties of Handsheets

The common physical properties (bulk, water absorbency, air permeability, and optical performance) and strength properties of handsheets prepared from pulp furnishes containing SW-BCTMP (both without and with PAE) were evaluated. The results are presented in Table 3 (without PAE) and Table 4 (with PAE).

As shown in Table 3, without PAE, the addition of 5.0 to 10.0% SW-BCTMP enhanced the bulk, water absorbency, and air permeability of the handsheets. Specifically, when 5.0 to 10.0% of the BSKP was replaced, the strength properties slightly decreased, while bulk, absorbency, and air permeability increased markedly. In contrast, substitution of 5.0 to 10.0% the BHKP resulted in improved bulk, absorbency, and air permeability, along with enhanced strength performance. These findings suggest that SW-BCTMP holds considerable potential for tissue products that do not require high wet strength, such as toilet paper, where rapid disintegration is desired and wet-strength agents are typically omitted.

As shown in Table 4, with the addition of PAE, the incorporation of 5.0 to 10.0% SW-BCTMP improved the bulk, water absorbency, and air permeability of the handsheets; however, a reduction in strength properties was observed. A consistent trend was identified: replacing 5.0 to 10.0% of either the BSKP or BHKP with the SW-BCTMP increased bulk, absorbency, and air permeability compared to the control. But those changes also resulted in decreased dry and wet strength performance. The strength reduction was more pronounced when substituting 5.0 to 10.0% of BSKP, which contrasts with the trends observed in handsheets prepared without PAE. This phenomenon is likely due to the adverse effect of the SW-BCTMP on the performance of PAE. As a wet-strength resin, PAE enhances both dry and wet strength; however, the SW-BCTMP contains a high level of anionic groups and a substantial amount of fines, which exhibit poor retention. These characteristics reduce the effective adsorption and retention of PAE, thereby diminishing its strengthening effect.

This wet strength reduction may be attributed to the higher fines content and elevated PCD of the SW-BCTMP, which potentially interferes with wet-strength resin (PAE) adsorption on fiber surfaces. Further optimization of the wet-strength resin system, such as adjusting the PAE dosage or employing alternative agents with higher anionic trash tolerance, could be explored to mitigate this reduction.

The addition of SW-BCTMP exhibited a minor impact on the optical properties of handsheets (Table 3). When 10.0% SW-BCTMP was added, the brightness decreased by 1.5 to 2.0% ISO, with slight variations observed in the L, a^*, and b^* color coordinates. These changes primarily resulted from the inherent lower brightness and yellowish hue characteristic of the SW-BCTMP pulp.

Table 3. Physical Properties of Handsheets with Different Pulp Formulations (without PAE)

Formulation	Bulk ($cm^3 \cdot g^{-1}$)	Brightness (%ISO)	*L**	*a**	*b**	Water Absorbency ($mm \cdot 10^{-} min^{-1}$)	Air Permeability ($mL \cdot min^{-1}$)	Dry Tensile Index ($N \cdot m^2 \cdot g^{-1}$)	Tear Index ($mN \cdot g \cdot m^{-2}$)	Burst Index ($kPa \cdot g \cdot m^{-2}$)
Control (without PAE)	2.53 ±0.07	86.68 ±1.39	96.46 ±0.98	-1.36 ±0.04	3.83 ±0.67	88.4 ±3.48	803.6 ±21.68	23.52 ±1.35	2.15 ±0.07	1.56 ±0.04
A	2.76 ±0.04	85.88 ±1.87	96.35 ±1.92	-1.35 ±0.11	4.09 ±1.01	95.3 ±1.39	938.0 ±19.32	23.39 ±0.68	2.11 ±0.04	1.49 ±0.12
B	2.64 ±0.05	85.31 ±1.34	96.30 ±0.62	-1.43 ±0.07	4.38 ±1.34	92.8 ±1.07	844.2 ±46.98	24.12 ±1.01	2.37 ±0.12	1.55 ±0.06
C	2.97 0.08	84.69 ±0.67	96.12 ±1.01	-1.13 ±0.08	4.74 ±1.00	107.8 ±2.47	1004.0 ±17.36	22.21 ±0.59	2.07 ±0.08	1.41 ±0.11
D	2.75 ±0.03	85.17 ±1.08	96.23 ±1.64	-1.91 ±0.14	4.47 ±0.63	96.8 ±0.45	918.9 ±9.14	24.33 ±0.89	2.45 ±0.03	1.54 ±0.18

Table 4. Strength Properties of Handsheets with Different Pulp Formulations (with PAE)

Formulation	Bulk ($cm^3 \cdot g^{-1}$)	Water Absorbency ($mm \cdot 10^{-1} \cdot min^{-1}$)	Air Permeability ($mL \cdot min^{-1}$)	Dry Tensile Index ($N \cdot m^2 \cdot g^{-1}$)	Wet Strength Retention (%)	Tear Index ($mN \cdot g \cdot m^{-2}$)	Burst Index ($kPa \cdot g \cdot m^{-2}$)
Control (with PAE)	2.49 ±0.13	78.4 ±6.14	750.9 ±18.94	25.20 ±1.32	18.49 ±1.68	2.54 ±0.14	1.61 ±0.08
A	2.71 ±0.08	87.3 ±4.36	880.4 ±31.68	23.79 ±0.37	13.24 ±0.41	2.17 ±0.09	1.52 ±0.13
B	2.58 ±0.11	84.3 ±3.83	786.8 ±41.31	24.52 ±1.09	13.78 ±2.14	2.32 ±0.16	1.54 ±0.06
C	2.73 ±0.17	96.3 ±6.91	912.8 ±34.15	23.70 ±0.19	11.52 ±0.19	2.14 ±0.11	1.47 ±0.09
D	2.70 ±0.08	91.3 ±1.25	890.2 ±39.14	24.57 ±1.34	13.35 ±1.33	2.38 ±0.09	1.56 ±0.11

CONCLUSIONS

1. The softwood bleached chemithermomechanical pulp (SW-BCTMP) exhibited high fines content (52.4%), elevated cationic demand (83.0 μeq·L^{-1}), and substantial zeta potential (-93.0 mV), which collectively impaired both dynamic drainage performance and first-pass retention of pulp furnishes. The application of polyaluminum chloride (PAC) was demonstrated to effectively reduce the cationic demand of SW-BCTMP-containing pulp furnishes while improving first-pass retention.
2. In the absence of PAE, the addition of 5.0 to 10.0% SW-BCTMP effectively enhanced the bulk, water absorbency, and air permeability of the handsheets. When the SW-BCTMP replaced the BSKP, the dry strength saw a marginal decline, whereas its substitution for the BHKP led to a concurrent improvement in both the bulk-absorbency properties and the dry strength performance.
3. In PAE-containing systems, the addition of 5.0 to 10.0% SW-BCTMP sustained the improvements in bulk, water absorbency, and air permeability; however, a consistent reduction in both dry and wet strength was observed. This detrimental effect was more pronounced when the BSKP was replaced. The effect was attributed to the interference of the SW-BCTMP with the adsorption and effectiveness of the wet-strength resin.

Based on these findings, the SW-BCTMP demonstrated considerable potential for enhancing bulk and absorbency in tissue paper manufacturing, particularly for tissue products, such as toilet paper, where wet strength requirements are non-critical.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the Natural Science Foundation of Hunan Province (Grant No. 2023JJ30012).

REFERENCES CITED

Balberčák, J., Kuňa, V., Boháček, Š., Celulózy, V. Ú. P. A., and Ihnát, V. (2022). "Reduction of the softwood long fibre pulp addition in tissue production. Case study," *Wood Res.* 67(3), 447-459. https://doi.org/10.37763/wr.1336-4561/67.3.447459

Bytomski, E., Velciu, J., Dasyam, P., Saengerlaub, S., and Zollner-Croll, H. (2024). "Water absorption of commercial and laboratory tissue sheets," *BioResources* 19(4), 8296-8311. https://doi.org/10.15376/biores.19.4.8296-8311

De Assis, T., Reisinger, L. W., Pal, L., Pawlak, J., Jameel, H., and Gonzalez, R. W. (2018). "Understanding the effect of machine technology and cellulosic fibers on tissue properties – A review," *BioResources* 13(2), 4593-4629. https://doi.org/10.15376/biores.13.2.deassis

Fan, Z., Li, Z., Qi, W., Zhao, S., Zhou, B., Liu, S., and Tian, Y. (2023). "Preparation of *in-situ* modified diatomite and its application in papermaking," *Colloid Surf. A-Physicochem. Eng. Asp.* 657, article 130582. https://doi.org/10.1016/j.colsurfa.2022.130582

Fišerová, M., Gigac, J., Stankovska, M., and Opalena, E. (2019). "Influence of bleached softwood and hardwood kraft pulps on tissue paper properties," *Cell Chem. Technol.* 53(5-6), 469-477. https://doi.org/10.35812/cellulosechemtechnol.2019.53.47
ISO 1924-3 (2005). "Paper and board – Determination of tensile properties – Part 3: Constant rate of elongation method (100 mm/min)," International Organization for Standardization, Geneva, Switzerland.
ISO 2470-1 (2016). "Paper, board and pulps – Measurement of diffuse blue reflectance factor-Part 1: Indoor daylight conditions (ISO brightness)," International Organization for Standardization, Geneva, Switzerland.
ISO 2759 (2014). "Board – Determination of bursting strength," International Organization for Standardization, Geneva, Switzerland.
ISO 4046-5 (2016). "Paper, board, pulps and related terms – Vocabulary – Part 5: Properties of pulp, paper and board," International Organization for Standardization, Geneva, Switzerland.
ISO 5264-1 (1979). "Pulps-Laboratory beating – Part 1: Valley beater method," International Organization for Standardization, Geneva, Switzerland.
ISO 5636-6 (2015). "Paper and board-Determination of air permeance (medium range) – Part 6: Oken method," International Organization for Standardization, Geneva, Switzerland.
ISO 8787 (1986). "Paper and board – Determination of capillary rise – Klemm method," International Organization for Standardization, Geneva, Switzerland.
ISO 12625-3 (2014). "Tissue paper and tissue products – Part 3: Determination of thickness, bulking thickness and apparent bulk density and bulk," International Organization for Standardization, Geneva, Switzerland.
ISO/TR 19997 (2018). "Guidelines for good practices in zeta-potential measurement," International Organization for Standardization, Geneva, Switzerland.
Joelsson, T., Persson, E., Pettersson, G., Norgren, S., Svedberg, A., and Engstrand, P. (2022). "The impact of sulphonation and hot-pressing on low-energy high-temperature chemi-thermomechanical pulp," *Holzforschung* 76(5), 463-472. https://doi.org/10.1515/hf-2021-0109
Morais, F. P., Vieira, J. C., Mendes, A. O., Carta, A. M., Costa, A. P., Fiadeiro, P. T., Curto, J. M., and Amaral, M. E. (2022). "Characterization of absorbency properties on tissue paper materials with and without "deco" and "micro" embossing patterns," *Cellulose* 29(1), 541-555. https://doi.org/10.1007/s10570-021-04328-1
Pettersson, G., Norgren, S., Engstrand, P., Rundlöf, M., and Höglund, H. (2021). "Aspects on bond strength in sheet structures from TMP and CTMP – A review," *Nord. Pulp Paper Res. J.* 36(2), 177-213. https://doi.org/10.1515/npprj-2021-0009
Qin, T., Liu, L., Cao, H., Nie, S., Lu, B., Cheng, Z., Liu, H., and An, X. (2023). "Creping technology and its factors for tissue paper production: A review," *Eur. J. Wood Wood Prod.* 81(5), 1075-1091. https://doi.org/10.1007/s00107-023-01947-2
Reczulski, M., Szewczyk, W., and Kuczkowski, M. (2023). "Possibilities of reducing the heat energy consumption in a tissue paper machine—case study," *Energies* 16(9), article 3738. https://doi.org/10.3390/en16093738
Reitbauer, J., Machado Charry, E., Eckhart, R., Sözeri, C., and Bauer, W. (2023). "Bulk characterization of highly structured tissue paper based on 2D and 3D evaluation methods," *Cellulose* 30(12), 7923-7938. https://doi.org/10.1007/s10570-023-05314-5

Sjöstrand, B., and Brolinson, A. (2022). "Addition of polyvinylamine in chemi-thermomechanical pulp and kraft pulp and the effects on dewatering, strength, and air permeance," *BioResources* 17(3), 4098-4115. https://doi.org/10.15376/biores.17.3.4098-4115

Stankovská, M., Fišerová, M., Gigac, J., and Opálená, E. (2020). "Blending impact of hardwood pulps with softwood pulp on tissue paper properties," *Wood Res.* 65, 447-458. https://doi.org/10.37763/WR.1336-4561/65.3.447458

Taipale, T., Österberg, M., Nykänen, A., Ruokolainen, J., and Laine, J. (2010). "Effect of microfibrillated cellulose and fines on the drainage of kraft pulp suspension and paper strength," *Cellulose* 17(5), 1005-1020. https://doi.org/10.1007/s10570-010-9431-9

TAPPI T 205 sp-20 (2002). "Forming handsheets for physical tests of pulp," TAPPI Press, Atlanta, GA, USA.

TAPPI T271 om-07 (2007). "Fiber length of pulp and paper by automated optical analyzer using polarized light," TAPPI Press, Atlanta, GA, USA.

Wang, C. J., Chen, C., Ren, H., Yang, Y. Q., and Dai, H. Q. (2016). "Polyethyleneimine addition for control of dissolved and colloidal substances: Effects on wet-end chemistry," *BioResources* 11(4), 9756-9770. https://doi.org/10.15376/biores.11.4.9756-9770

Wang, Q., Xiao, S., Shi, S. Q., and Cai, L. (2019). "Mechanical property enhancement of self-bonded natural fiber material *via* controlling cell wall plasticity and structure," *Mater. Des.* 172, article 107763. https://doi.org/10.1016/j.matdes.2019.107763

Wang, Y., Tang, C., Liu, Y., Wang, Y., Lin, B., Zhu, H. and Liu, C. (2017). "Improved bleached chemical reed pulp properties using atmospheric high consistency refining," *BioResources* 12(2), 3331-3339. https://doi.org/10.15376/biores.12.2.3331-3339

Yang, S., Li, W., Zhang, H., Wen, Y., and Ni, Y. (2019). "Treatment of paper mill wastewater using a composite inorganic coagulant prepared from steel mill waste pickling liquor," *Sep. Purif. Technol.* 209, 238-245. https://doi.org/10.1016/j.seppur.2018.07.049

Article submitted: July 22, 2025; Peer review completed: October 5, 2025; Revised version received and accepted: January 3, 2025; Published: January 15, 2026.
DOI: 10.15376/biores.21.1.1957-1967