

Enhanced Retention, Drainage, and Strength of Old Corrugated Container Pulp Using Poly(aluminum chloride), Nanofibrillated Cellulose, and Hydrophobic Colloidal Silica Particles

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The performance of the poly(aluminum chloride) (PAC)-nanofibrillated cellulose (NFC)-colloidal silica (SiO₂) system was evaluated relative to the retention and drainage of old corrugated container (OCC) pulp. In this study, OCC pulp was refined to a freeness of 370 ± 10 mL CSF, then different amounts of NFC (0.2, 0.4, and 0.6%) and SiO₂ (0.3, 0.6, and 0.9%) in combination with 1% PAC (constant for all treatments) were added. Finally, from these treatments, standard handsheets were made and their physical and mechanical properties were measured according to TAPPI standards. The results showed that the addition of SiO₂ and NFC in combination with 1% of PAC each separately and independently increased the burst index, tensile index, and Concora medium test (CMT), but the ring crush test (RCT) decreased. The use of different treatments containing PAC, NFC, and SiO₂ also decreased the pulp drainage time and increased their first-pass retention. Also, the use of this system resulted in less water absorption than the control treatment. The use of PAC and NFC in improving the quantitative and qualitative characteristics of OCC fibers can lead to higher first-pass retention, better physical and mechanical properties, while reducing the drainage time.

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INTRODUCTION

Paper recycling is multifaceted in its importance in the world (Ezeudu *et al.* 2019), influencing, for example, people's living conditions, environmental laws, and economic impact. The limited availability of wood resources, particularly in certain regions, adds to the significance of cellulose as a renewable material (Kumar 2021). Paper recycling has many advantages, such as reducing energy consumption, reducing air pollution caused by the pulping and papermaking process, reducing water consumption, reducing virgin cellulose fiber consumption, and reducing paper production costs (Čabalová *et al.* 2011; Deshwal *et al.* 2019). In papermaking, to improve the quality of the produced paper and improve the production process, various materials and chemical compounds are added to the pulp composition (Sixta 2006). Some of these materials, such as drainage and retention aids, are used in the final product to maintain the fines of the fibers and additives in the

product (Hubbe *et al.* 2009; Vishtal *et al.* 2011). These materials increase the retention and drainage from the pulp being formed by creating flocculation between the fibers, fines, and fillers (Hubbe *et al.* 2009).

Some of the most common drainage and retention aid systems use microparticles, which helps promote pulp drainage and retention of fine particles (Brouillette *et al.* 2005; Vishtal *et al.* 2011). These systems include a cationic polymer such as polyacrylamide (Petroudy *et al.* 2014) or cationic starch along with an anionic mineral material such as colloidal silica (Khosravani *et al.* 2010) or bentonite (Darvishzadeh *et al.* 2014). Despite the high cost of microparticle systems, many benefits (high retention) justify their use in the papermaking system. Unlike cellulosic fibers, mineral fibers are not able to form a bond well in the absence of some types of resins (Rojas and Hubbe 2005).

From the point of view of papermaking, one of the limiting factors for the use of recycled paper pulp is its low drainage, especially in high grammage paperboard products (Bhardwaj *et al.* 2005; Vishtal *et al.* 2011). As a result, this problem can be reduced to a great extent with the help of drainage and retention aids (Wang *et al.* 2022). One of the key points in the production of paper, especially from recycled fibers, is the development of methods to improve the bonding between fibers and increase the strength characteristics of the manufactured product (Afra *et al.* 2013; Khosravani and Rahmaninia 2013; Sabazoodkhiz *et al.* 2017; Amiri *et al.* 2019). Despite the economic and environmental benefits of using recycled paper, it should be noted that these types of fibers have relatively different characteristics compared to virgin fibers. In order to compete with virgin types used in papermaking, OCC fibers often require pre-treatments or process changes. The recycling of old corrugated container (OCC) for the production of linerboard and the corrugating medium used in carton making is more popular than the recycling of other grades of paper in Iran, and in the last few years, as well as in the coming months and years, paper production plants have been set up or are about to be launched.

The strength properties of paper obtained from the above-mentioned recycled paper pulp are generally at a lower level compared to paper obtained from virgin pulp. In addition, the presence of materials in brown waste paper, such as adhesives and printing inks, leads to a decrease in the mechanical resistance of the paper. Therefore, there is a need to investigate and promote the most common solutions to improve the strength properties of the manufactured product. Among the suggested solutions are refining, choosing better quality fibers, improving the performance of the wet end section, and using chemical additives. Since the fibers used in papermaking have inherent limitations in refining, the inherent weakening of fibers due to severe mechanical treatments is a limiting issue, especially in weaker recycled fibers. Adding chemicals can be a good solution to overcome the limitations and weaknesses of recycled fibers (Miranda *et al.* 2016; Tajik *et al.* 2021). In the papermaking industry, three characteristics of drainage, retention, and quality of paper formation are of special importance (Hubbe *et al.* 2009).

In the paper industry, which is one of the industries that uses nanomaterials, various types of inorganic nanoparticles have been popularized in various fields of the papermaking industry, and drainage–retention aids systems that are based on alum and organic/inorganic nanoparticles are widely used (Khosravani and Rahmaninia 2013). Some of the most common drainage–retention aids systems are based on the use of silica nanoparticles (SiO_2) in combination with starch or polyacrylamide cationic. Silica nanoparticles (SiO_2) are characterized by their nanoscale size, high specific surface area, and reactive surface chemistry, which make them particularly effective in enhancing paper properties. Their selection in this study is grounded in their ability to improve fiber–filler

interactions, promote better retention of fine particles, and reinforce the pulp matrix, thereby contributing to enhanced drainage and mechanical strength. However, the emergence of organic nanoparticles such as nanofibrillated cellulose (NFC) has made research and new approaches available to improve the characteristics of pulp and paper (Afra *et al.* 2013; Yousefhashemi *et al.* 2019; Kaffashsaie *et al.* 2021). Within the system, NFC primarily act as reinforcing additives due to their fibrous morphology and high aspect ratio, forming a three-dimensional network that strengthens the pulp structure. In contrast, colloidal SiO₂ particles serve dual functions as both retention aids and as structural components, facilitating the immobilization of fillers and fines within the fiber network while simultaneously improving the microstructural cohesion of the pulp.

Despite the extensive body of research on the use of aluminum-based chemicals, cellulose nanofiber, and nanosilica particles as individual additives in papermaking, there remains a notable gap in understanding their combined influence on the properties of recycled old corrugated container (OCC) pulp. No prior studies have systematically investigated the synergistic interactions among these three components with retention, drainage, and mechanical performance, particularly within the context of upgrading recycled OCC fibers. Addressing this gap, the present work proposes an integrated approach that harnesses the complementary physicochemical functionalities of alum, cellulose nanofiber, and nanosilica to achieve substantial and simultaneous improvements in OCC pulp quality. By elucidating the cooperative mechanisms underlying these enhancements, this study not only advances the fundamental understanding of multi-additive systems in papermaking but also provides a scalable and industrially viable pathway for enhancing the sustainable reuse of recycled fiber resources.

EXPERIMENTAL

Raw Materials and Chemicals

In this study, to prepare the pulp, 100% OCC pulp was used (Table 1). The prepared OCC was transferred to the laboratory and converted into pieces with dimensions of 5×5 cm. The converted pieces of OCC were mixed with tap water in the tank to suspend the pieces of OCC. To separate the maximum fibers and to minimize the damage to the fibers during the repulping process, the above mixture remained in this state for 48 h, and then the pulp was prepared with a laboratory pulp disintegrator device (Frank PTI, Austria). Table 2 shows the characteristics of additive materials in this study. Deionized water was used to minimize the negative effects of process factors in all stages of the experiments.

Table 1. Characteristics of the OCC

Characteristics	Value
Supplier company	Cheetos (Mashhad, Iran)
Source	Homogeneous mixture of corrugated boxes
Number of recycling times	No recycling operations (virgin cardboard)
Grammage, g/m ²	120 ± 2
Breaking length, km	3.33
Kappa number	30
Brightness, %ISO	52
Opacity, %ISO	78

Table 2. Characteristics of Additives to OCC Pulp

Poly(aluminum chloride (PAC)	Company: Merck (Darmstadt, Germany); purity: >98%; specific gravity: 1.20 g/cm ³ ; insoluble matter: 0.1%; solubility: 450 g/L; and molar mass: 133.5 g/mol.
Silica nanoparticles, SNP (SiO ₂)	Company: Merck (Darmstadt, Germany); purity: 99%; pH: 10-11; specific gravity: 1.10 g/cm ³ ; charge density (0.13 meq/g); specific surface area: 250 m ² /g; and particle size: 2-5 nm.
Cellulose nanofiber (NFC)	Company: Nano Novin Polymer Co. (Iran); pulp source: bleached softwood kraft pulp; production method: super disk grinding; consistency: 2.50%; average diameter: 35 nm; average length: 5 µm; and shape factor: 150.

Experimental Design

The handsheets were made according to TAPPI T 205 sp-95. Control handsheets were made using OCC pulp (without any additives), and other handsheets are described in Table 3. Poly(aluminum chloride) (PAC) at a dosage of 1.0% based on solids was added to the fiber furnish. To prepare handsheets, first, the pulp suspension with a consistency of 0.3% was stirred with a mixer at 1000 rpm for 120 s. Then, the suspension of required materials (PAC, NFC, and SiO₂) was prepared by dispersing the hydrophobic SiO₂ in distilled water using ultrasonication for 10 min before being slowly added to the pulp suspension. After adding these materials, the rotation speed of the stirrer was increased to 1500 rpm and the suspension obtained after stirring for 3 min was poured into the chamber of the handsheet maker. Three handsheets were prepared for each experimental condition.

Table 3. Research Treatments (PAC-NFC-SiO₂ System)

Treatments	PAC (%)	NFC (%)	SiO ₂ (%)
Control	-	-	-
1	1	-	-
2	1	0.2	-
3	1	0.4	-
4	1	0.6	-
5	1	-	0.3
6	1	-	0.6
7	1	-	0.9

First Pass Retention (FPR) and Drainage Time

The drainage time and first pass retention (FPR) were assessed using standard methods to determine the effectiveness of water removal and fiber retention in the papermaking process. The pulp's drainability was evaluated with a Canadian Standard Freeness (CSF) tester following the TAPPI T-261 cm-00 standard. Similarly, the first pass retention (FPR) was analyzed using a dynamic drainage Jar (DDJ) following the TAPPI T-261 cm-00 method.

Analysis of Handsheets

The Cobb test, which is a measure of the amount of water absorbed in a square meter of paper, was determined based on (TAPPI T 441 om-13). Also, burst strength (T 403 om-97), tensile strength (T 404 om-01), RCT (T 818 om-87), and CMT (T 809 om-99) of the handsheets were measured using the TAPPI standard methods.

SEM Analysis

The morphological characteristics of the handsheets were analyzed using a scanning electron microscope (model Hitachi SU3500, Tokyo, Japan). Before imaging, the samples were dried at room temperature and coated with a thin layer of gold using a sputter coater to enhance conductivity. The SEM was operated at an accelerating voltage of 15.0 kV under high-vacuum conditions. Images were captured at different magnifications to evaluate the surface morphology and structural characteristics of the handsheets.

Statistical Analysis

The present research was designed as a completely randomized design. Data analysis was conducted using analysis of variance (ANOVA) with SPSS 16 software (IBM, Chicago). Following ANOVA, Duncan's multiple range test was employed for mean comparison and grouping to identify significant differences among treatments.

RESULTS AND DISCUSSION

Drainage Time

The results of ANOVA showed that there was a significant difference at the 1% level between the pulp drainage time values in the different treatments ($F=79.511$, $P<0.05$). The drainage time of the pulps decreased with the addition of PAC, NFC, and SiO_2 . The control sample had the highest drainage time (30.2 s), while the addition of 1% PAC reduced it to 18.4 s. Incorporating NFC at 0.2% increased the drainage time to 23.0 s, but at 0.4% and 0.6%, the times were 18.8 s and 19.8 s, respectively. In contrast, the addition of SiO_2 led to a continuous reduction in drainage time. At 0.3% SiO_2 , the time decreased to 15.7 s, while at 0.6% and 0.9%, it further decreased to 16.7 s and 14.2 s, respectively (Fig. 1).

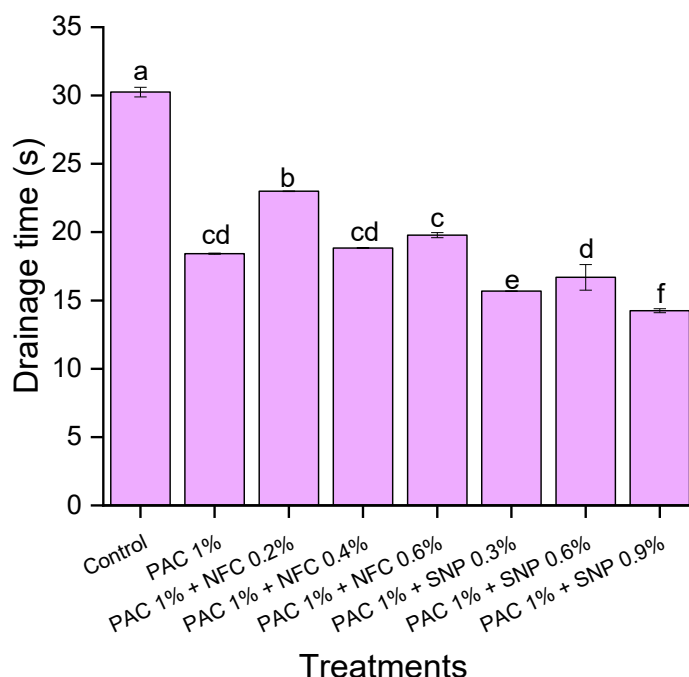


Fig. 1. Effects of PAC, NFC, and SiO_2 on pulp drainage time

The reason for the increase in drainage time in the NFC treatment compared to the SiO₂ treatments may be related to factors such as water holding capacity of the OH groups due to the transformation from micro to nano scale (Yousefi *et al.* 2013). The superior drainage performance of SiO₂ may be related to its ability to increase porosity and reduce water-holding capacity in the fiber network, thereby promoting faster water release. PAC imparts a positive charge to nanocellulose, promoting heterocoagulation with negatively charged colloidal silica particles. This interaction leads to flocculation that decreases the water retention of the system by reducing fiber swelling and porosity, thereby enhancing drainage rates. Additionally, the interaction between PAC and SiO₂ likely improved fiber flocculation and enhanced drainage efficiency. It is well known that the addition of nanoparticles greatly improves retention and drainage by forming micro flocs (Khosravani *et al.* 2010). Further, Khosravani *et al.* (2010) reported that the use of 0.15% of nanosilica and 1.5% of cationic starch increased the drainage of pulp furnish containing 85% of bleached eucalyptus pulp and 15% of bleached pine pulp.

First-Pass Retention (FPR)

The FPR values of pulp samples containing NFC and SiO₂, along with a fixed 1% PAC, exhibited notable variations compared to the control sample ($F=1.842$, $P<0.05$). The control sample showed a retention of 83.3%, while the addition of 1% PAC increased it to 86.5%. Further incorporation of NFC led to a progressive improvement in retention, reaching 88.7% at the highest NFC concentration (0.6%). Conversely, the addition of SiO₂ showed a less consistent trend, with retention values fluctuating between 85.6% and 87.0%, peaking at 0.6% SiO₂ (Fig. 2).

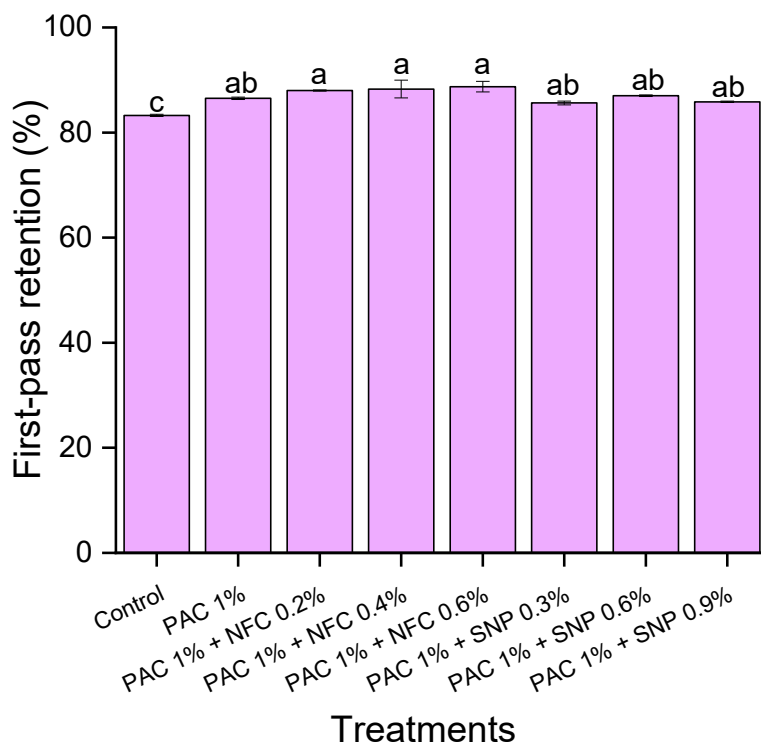


Fig. 2. Effects of PAC, NFC, and SiO₂ on first-pass retention (FPR)

Nanocellulose has a significantly higher surface area compared to regular cellulose fibers. This increased surface area enhances the interaction between nanocellulose and other components in the pulp, leading to improved retention (Korhonen and Laine 2014). These findings align with previous studies highlighting the superior retention performance of nanocellulose in fiber networks (Hubbe *et al.* 2017; Perdoch *et al.* 2022). SiO₂ can bridge between pulp fibers or other fines, forming a network of connections that enhances the retention of larger particles. This bridging effect prevents the passage of fibers through the papermaking system (Sabazoodkhiz *et al.* 2017). Khosravani *et al.* (2010) reported that the use of 0.15% of nanosilica and 1.0% of cationic starch has improved the FPR of pulp furnish containing 85% of bleached eucalyptus pulp and 15% of bleached pulp from pine.

Water Absorption (Cobb Test)

The Cobb test results indicate variations in the water absorption capacity of handsheets containing NFC and SiO₂, with a fixed 1% PAC (F=790.929, P<0.05). The control sample exhibited a Cobb value of 235 g/m², while the addition of PAC increased water absorption to 261 g/m². Further incorporation of NFC led to a progressive rise in Cobb values, reaching a maximum of 297 g/m² at 0.6% NFC. In contrast, SiO₂-containing samples exhibited a different trend, with Cobb values fluctuating and reaching the lowest absorption (218 g/m²) at the highest SiO₂ concentration (0.9%) (Fig. 3).

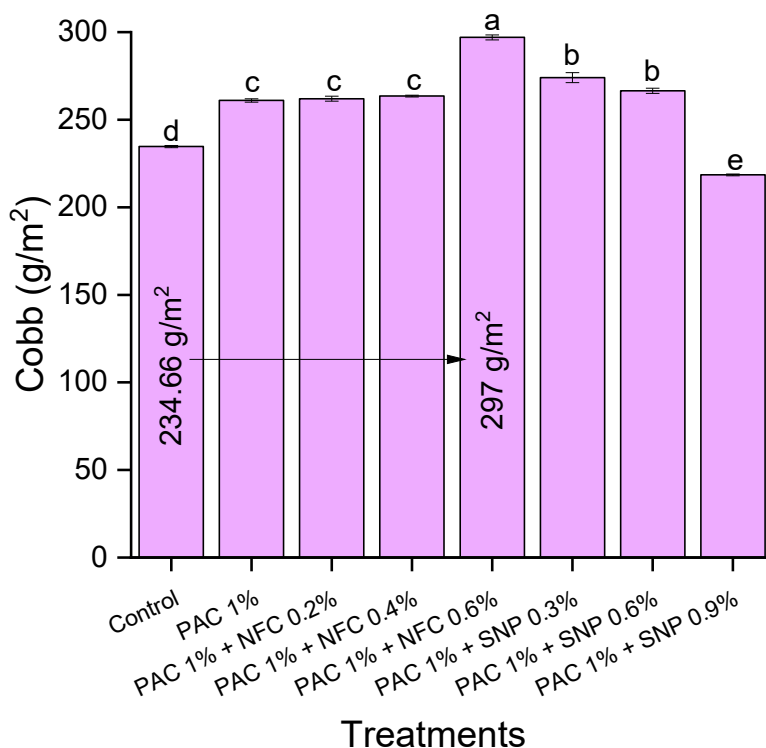


Fig. 3. Effects of PAC, NFC, and SiO₂ on water absorption

This result can be explained by the refining and milling process involved in NFC preparation, which significantly increases the fiber surface area. As a consequence, the capillary forces and the water-holding capacity of hydroxyl (OH) groups also increase. This enhanced water retention leads to greater paper absorbency, as more water is held within the fiber network (Yousefi *et al.* 2013). Conversely, SiO₂ demonstrates a water-repellent effect, particularly at higher concentrations. This behavior is likely due to the

hydrophobic characteristics of the SiO₂, which reduces the paper affinity for water, thereby decreasing Cobb values. The observed trends highlight the contrasting roles of NFC and SiO₂ in modifying the paper's water absorption properties, with NFC enhancing hydrophilicity and SiO₂ decreasing water resistance.

Burst Index

The burst index results reveal the impact of NFC and SiO₂ on the strength properties of paper samples, with a fixed 1% PAC ($F=3.676$, $P<0.01$). The control sample exhibited a burst index of 1.12 kPa.m²/g, which increased to 1.42 kPa.m²/g with the addition of PAC. Further incorporation of NFC enhanced the burst index, reaching a peak value of 1.51 kPa.m²/g at 0.2% and 0.4% NFC, followed by a slight decline at 0.6% NFC. In contrast, SiO₂-containing samples showed lower burst index values, ranging from 1.15 to 1.26 kPa.m²/g, with a gradual increase at higher SiO₂ concentrations (Fig. 4). The observed improvements in burst strength with NFC addition can be attributed to its strong fiber reinforcement capabilities. NFC forms a nanoscale network within the paper matrix, enhancing fiber-fiber bonding and increasing resistance to rupture. However, at higher NFC concentrations (0.6%), excessive nanofiber entanglement may disrupt uniform bonding, leading to a slight reduction in burst strength. On the other hand, SiO₂ exhibited a weaker reinforcement effect due to its particulate nature, which may act as a filler rather than a structural binder. Unlike NFC, SiO₂ does not significantly improve inter-fiber bonding, which explains the lower burst index values observed in SiO₂-treated samples. These findings are consistent with the results obtained by Yousefi *et al.* (2013), Lengowski *et al.* (2019), and Ghaderi *et al.* (2014), who positively evaluated the effect of adding NFC on the mechanical properties of cellulosic film and paper.

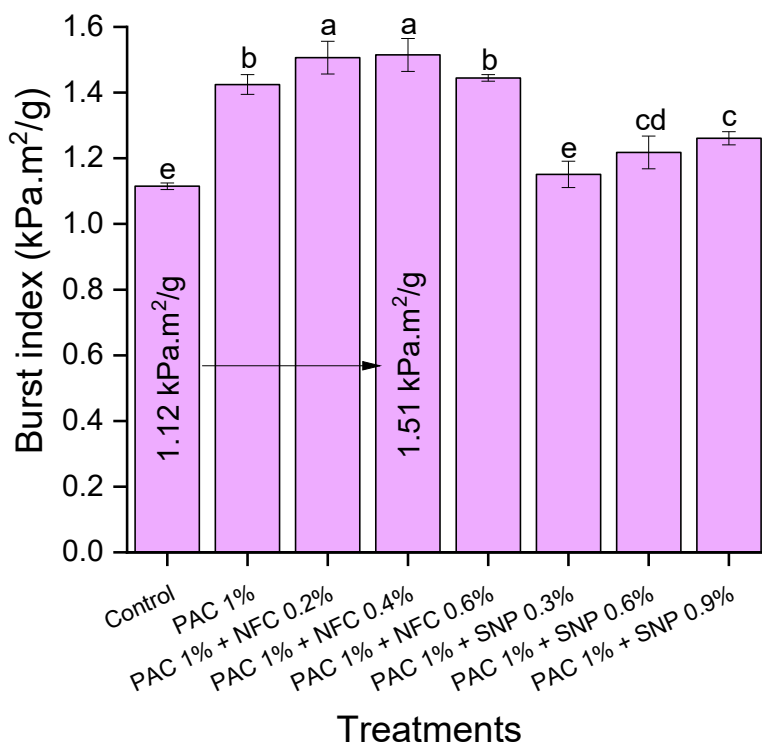


Fig. 4. Effects of PAC, NFC, and SiO₂ on burst index

Tensile Index

The tensile index results demonstrated the influence of NFC and SiO₂ on the tensile strength of paper samples, with a fixed 1% PAC ($F=71.739$, $P<0.01$). The control sample exhibited a tensile index of 82.3 N.m/g, which increased to 92.6 N.m/g with the addition of PAC. The incorporation of NFC led to varying effects, with a slight reduction at 0.2% NFC (81.6 N.m/g), followed by a moderate increase at 0.4% NFC (85.3 N.m/g), and a significant enhancement ($p<0.05$) at 0.6% NFC, reaching 99.4 N.m/g. In contrast, SiO₂-containing samples showed lower tensile index values, ranging from 70.6 N.m/g at 0.3% SiO₂ to 75.2 N.m/g at 0.9% SiO₂, indicating a weaker reinforcement effect (Fig. 5).

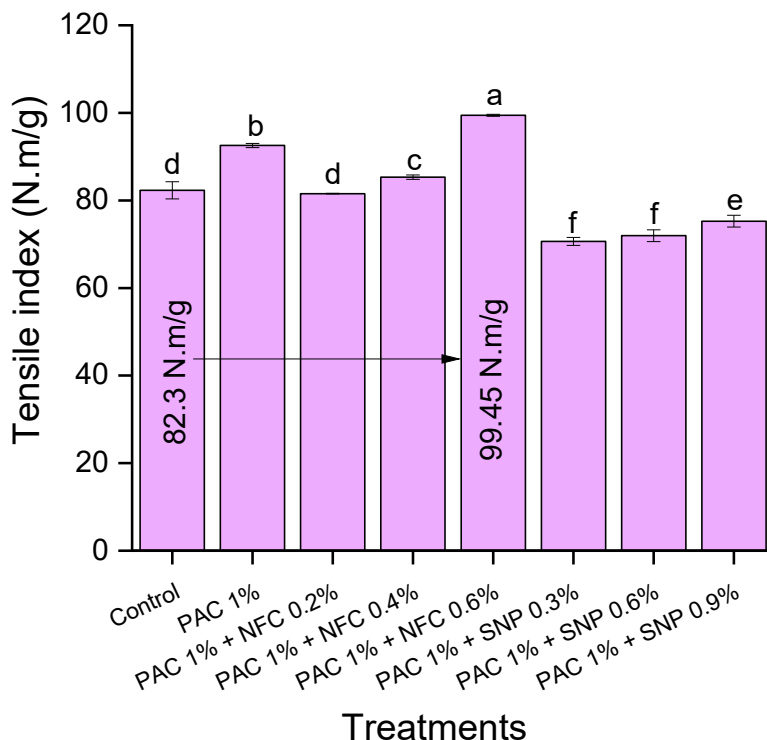


Fig. 5. Effects of PAC, NFC, and SiO₂ on the tensile index

The reason for the increase in the tensile index of handsheets containing NFC can be explained in the way that NFC increases the bonding within the cellulose fibers through entanglement and the bonded surface. Finally, these structures lead to the formation of a more integrated and homogeneous structure, which plays an essential role in improving the tensile strength of paper (Yousefi *et al.* 2013; Lengowski *et al.* 2019; Perdoch *et al.* 2022). By increasing the share of NFC in the paper matrix, increasing behavior in tensile strength is observed. As a result of reducing the dimensions to the nanometer scale, the specific surface of NFC increases. This means that more hydroxyl groups (OH) are placed and available on the surface of nanofibers, which can form hydrogen bonds with the adjacent nanofibers and cause the formation of a network of nanofibers. The entanglement and creation of a network structure of nanofibers per unit volume is more than the expected characteristic of microfibers per unit volume. The entanglement of fibers has a significant effect on the properties of paper, especially the mechanical properties. These findings are consistent with the results obtained by Yousefi *et al.* (2013), Lengowski *et al.* (2019), and Ghaderi *et al.* (2014), who positively evaluated the effect of adding NFC on the mechanical properties of film and paper. In contrast, SiO₂ exhibited a negative impact on tensile

strength, likely due to its particulate nature, which may interfere with fiber bonding rather than reinforcing it. Unlike NFC, SiO₂ does not contribute significantly to network formation and may instead act as a filler, disrupting the fiber bonding in the paper network.

Ring Crush Test (RCT)

The RCT test refers to the resistance to pressure and force applied on the edge of the cardboard and significantly has a direct relationship with CMT strength (Scott *et al.* 1995). The RCT results indicate the compressive strength properties of paper samples containing NFC and SiO₂, with a fixed amount of 1% PAC (F=1.423, P<0.05). The control sample exhibited an RCT value of 136 N, while the addition of PAC resulted in a slight decrease to 133.5 N. In contrast, the incorporation of NFC significantly enhanced the RCT values, achieving a peak of 151.5 N at 0.6% NFC. Conversely, the SiO₂-containing samples showed inconsistent performance, with values ranging from 132 N at 0.6% SiO₂ to 136 N at 0.3% SiO₂, indicating a reduction in compressive strength compared to the control (Fig. 6).

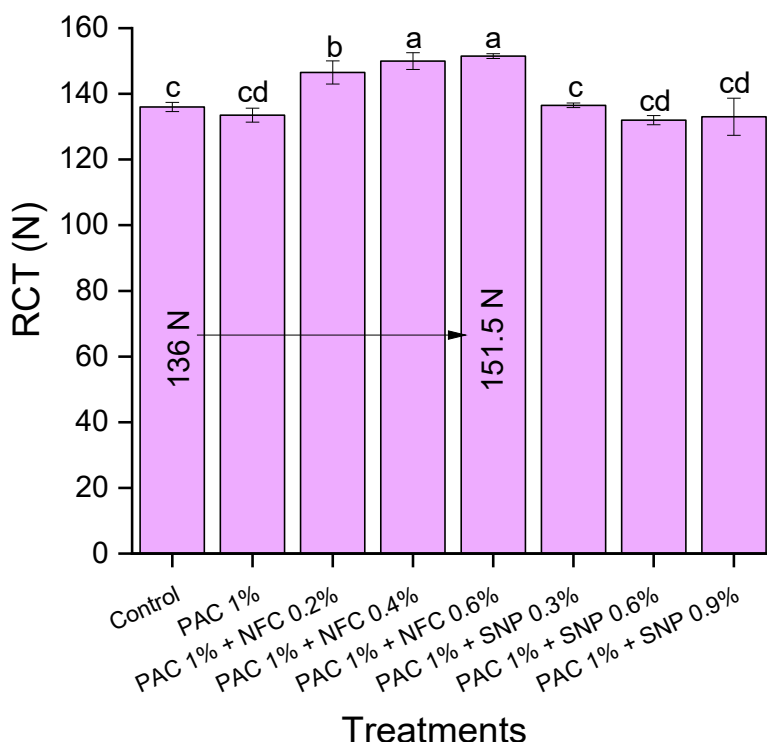


Fig. 6. Effects of PAC, NFC, and SiO₂ on ring crush test (RCT)

The increase in RCT values with NFC addition can be attributed to the nanofiber's ability to improve inter-fiber bonding and structural integrity within the paper network. NFC enhances the mechanical performance through effective hydrogen bonding and the formation of a robust network that distributes applied stress more evenly, increasing resistance to crushing forces. The peak observed at 0.6% NFC suggests that this concentration strikes an optimal balance between reinforcing effects and structural cohesion. Conversely, the lower RCT values associated with SiO₂ may be explained by its particulate nature, which does not contribute significantly to fiber-fiber bonding, potentially leading to weaker compressive strength. The inconsistent results for SiO₂-treated samples highlight the challenges of using nanoparticles as fillers in improving

mechanical properties, as their presence can disrupt the fibrous structure rather than enhance it.

Concora Medium Test (CMT)

The CMT results show the effects of NFC and SiO₂ on the compressive strength of paper samples, with a constant concentration of 1% PAC ($F=9.033$, $P<0.05$). The control sample exhibited a CMT value of 73.5 N, which increased significantly to 97 N with the addition of PAC. Incorporating NFC yielded varied results, with a peak value of 99.5 N at 0.6% NFC, while lower concentrations of NFC (0.2% and 0.4%) showed values of 93 N and 96 N, respectively. On the other hand, the SiO₂-containing samples displayed lower CMT values, ranging from 75 N at 0.3% SiO₂ to 83.67 N at 0.9% SiO₂, indicating a minimal enhancement in compressive strength (Fig. 7). The substantial improvement in CMT values with PAC addition can be attributed to enhanced fiber bonding and increased structural integrity within the paper network. PAC acts as a retention aid, facilitating the interaction between fibers and fillers, which leads to improved mechanical strength. The increase in strength with NFC addition, particularly at 0.6%, suggests that NFC effectively reinforces the paper through its high surface area and ability to form a dense network, enhancing inter-fiber bonding. However, the lower performance of SiO₂-containing samples can be explained by the lack of effective bonding provided by SiO₂. Unlike NFC, which enhances fiber bonding of the paper, SiO₂ may act more as a filler, potentially disrupting the fibrous network and resulting in reduced strength.

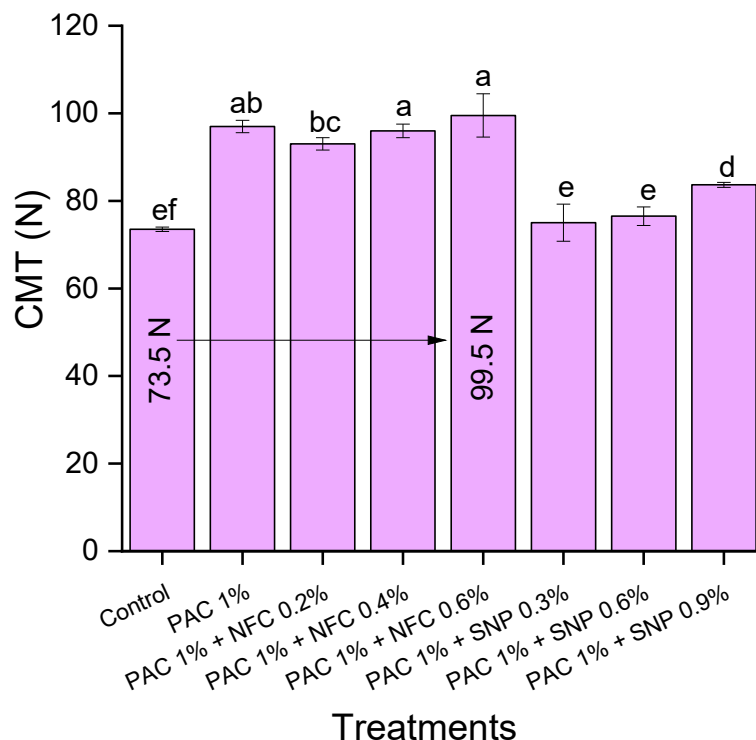


Fig. 7. Effects of PAC, NFC, and SiO₂ on Concora medium test (CMT)

Morphology

The SEM micrographs in Fig. 8 illustrate the surface morphology of paper under four different conditions. Figure 8a corresponds to the control sample, where cellulose fibers are visible, and the overall structure appears relatively uniform without any

additional coating. In Fig. 8b, representing paper containing 1% PAC leading to increased fiber adhesion and reduced porosity compared to the control. Figure 8c, which includes 1% PAC along with 0.6% NFC, shows a denser network between fibers, potentially enhancing mechanical strength and reducing porosity. No apparent differences in surface appearance were observed among the 1% PAC + 0.6% NFC (Fig. 8c) and 1% PAC + 0.9% SiO₂ (Fig. 8d) treatments, indicating that the applied treatments did not induce visible morphological alterations. It is important to note that certain chemical components, such as PAC, exist at the molecular scale and therefore cannot be directly visualized in SEM micrographs. Accordingly, these images are presented as supplementary visual evidence to illustrate the general surface characteristics rather than to demonstrate the chemical modifications themselves.

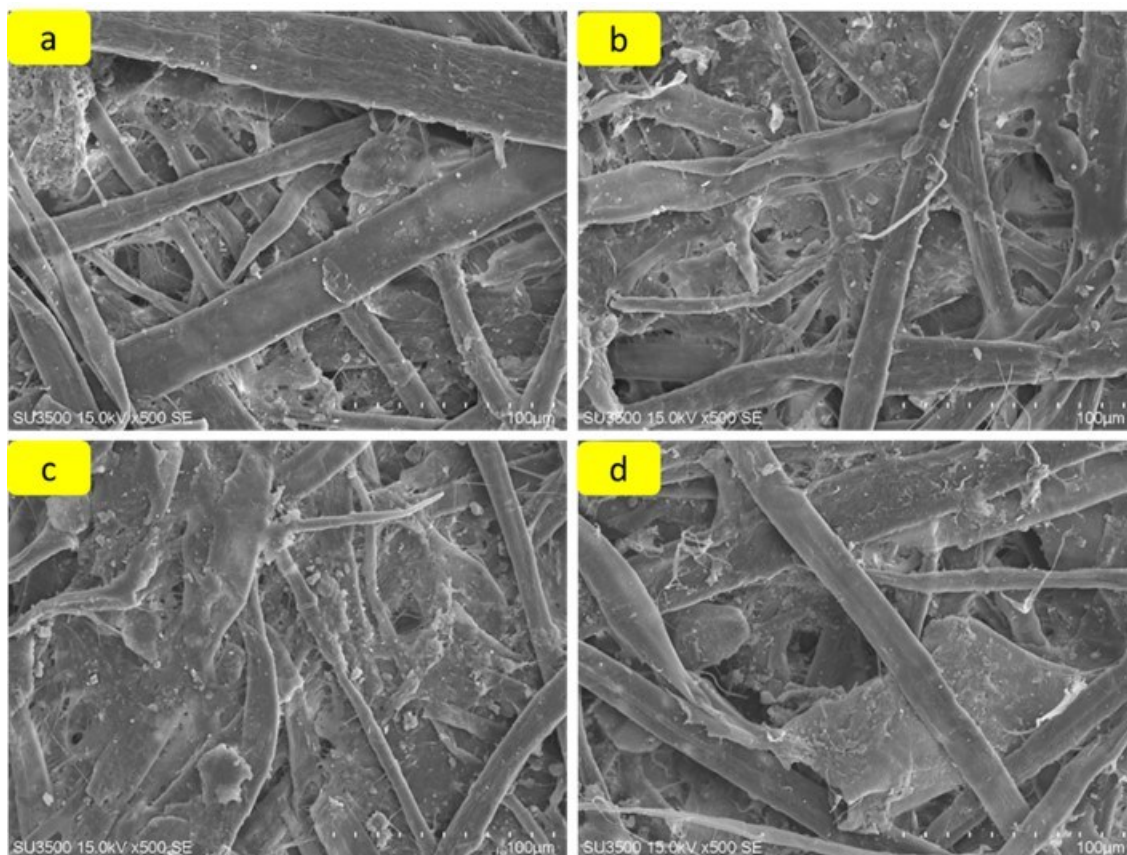


Fig. 8. The morphology of paper surface: a) control, b) 1% PAC, c) 1% PAC + 0.6% NFC, and d) 1% PAC + 0.9% SiO₂

CONCLUSIONS

1. This study was conducted to compare the effect of poly(aluminum chloride) (PAC), nanofibrillated cellulose (NFC), and colloidal silica (SiO₂) on the drainage and retention of pulp and the strength of recycled paper made from old corrugated container (OCC) pulp.
2. The addition of PAC and NFC each separately and independently improved the mechanical strengths (burst index, tensile index, and Concora medium test, CMT). The

results showed that there was no significant difference between the RCT mean values of the treatments in this study.

3. The application of PAC with the NFC resulted in a reduction in drainage time. First-pass retention also increased significantly with the application of PAC and NFC.
4. The hydrophobic SiO₂ effectively decreased water absorption in the paper sheets, as confirmed by the Cobb test, indicating improved barrier properties.
5. The addition of PAC and NFC improved the mechanical properties of recycled paper without significantly affecting the RCT. Furthermore, the improved first pass retention and reduced dewatering time underline the potential of these additives to optimize the papermaking process.

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