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EFFECT OF FURNISH COMPOSITION (LONG FIBER, BCTMP, AND FILLER) ON DEWATERING PERFORMANCE AND PAPER QUALITY

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Abstract

This study analyzes the effect of fiber composition and filler type on drainage behavior in papermaking and its relationship with forming dewatering and paper properties. The furnish consisted of Short Fiber (SF), Long Fiber (LF), and Bleached Chemi-Thermomechanical Pulp (BCTMP), while fillers included Ground Calcium Carbonate (GCC) and Precipitated Calcium Carbonate (PCC) at various ratios. Drainage time (s/500 mL) was used as a laboratory indicator and correlated with forming dewatering performance. Results show that increasing BCTMP proportion accelerates drainage, indicated by shorter drainage times and lower forming dewatering values, reflecting faster water removal and a drier web. The fastest drainage time was 15.68 s/500 mL under PCC-dominated conditions (85%). In contrast, increasing LF from 10% to 30% increases flow resistance, resulting in longer drainage times (up to 20.8 s/500 mL) and higher forming dewatering values, indicating slower dewatering and a wetter web. Filler type significantly influences drainage behavior. Higher GCC content, due to its finer particles, increases flow resistance through pore blocking, leading to higher forming dewatering values. Conversely, PCC promotes more stable permeability and faster dewatering. In terms of paper properties, higher BCTMP increases bulk and thickness while slightly reducing density, whereas LF improves strength, with internal bond increasing from 235 to 309 J/m² and tensile strength reaching 4.35 N. These results confirm that furnish composition is critical in balancing dewatering rate and web moisture, which is essential for stable machine operation and consistent paper quality.

Keywords: Dewatering, Drainage, Furnish, Long Fiber, BCTMP, Filler, Paper Quality.

INTRODUCTION

Paper remains an essential material in modern life, supporting education, packaging, sanitation, and communication. As global demand continues to rise to hundreds of millions of tons annually, the pulp and paper industry must not only expand production capacity but also improve operational efficiency and environmental performance. Modern challenges extend beyond achieving high output; they require energy-efficient, stable, and sustainable manufacturing systems. Therefore, optimization at every stage of production has become a key strategy in advancing sustainable engineering practices. PT. XX operates with a production capacity exceeding one million tons per year, supported by Paper Machine YY [34]. The primary raw materials, acacia, eucalyptus, and pine, provide fibers with distinct morphological characteristics that influence sheet formation, drainage behavior, and final paper properties. When pulp enters the paper machine, it contains approximately 99% water. Because thermal evaporation in the dryer section is the largest energy consumer, maximizing mechanical water removal before drying is critical to reducing energy demand.

The forming section is the first stage of dewatering, where fibers interlock to form a web and water is removed through gravity and vacuum. The effectiveness of forming dewatering determines the load on the press and dryer sections. Even a slight increase in dryness after forming can significantly reduce steam consumption downstream. Thus, improving forming performance enhances machine runnability, lowers production costs, and reduces emissions [2]. While technological solutions such as enzymatic treatments or equipment modifications exist, they often require major investment. Furnish optimization offers a more practical approach. By adjusting the composition of short fibers (SF), long fibers (LF), Bleached Chemi-Thermomechanical Pulp (BCTMP), and mineral fillers, mills can control sheet porosity and water flow pathways without significant infrastructure changes. Short fibers contribute to smooth surfaces but may increase water retention due to dense packing. Long fibers create a more open structure, improving permeability and wet-web strength. BCTMP provides cost and yield advantages but contains fines that can hinder drainage if used excessively. Fillers such as GCC and PCC enhance optical properties and reduce costs, yet their particle size and morphology influence pore structure and permeability [15]. The interaction among these components makes furnish optimization both complex and critical. Although freeness provides an initial indication of drainage potential, it does not fully represent forming conditions. Therefore, drainage measurements that simulate web formation are necessary for accurate evaluation. Achieving the proper balance is essential: insufficient dewatering increases energy demand and break risk, while excessive drainage may affect formation quality [31]. From a sustainability perspective, optimizing furnish composition improves mechanical water removal, reduces thermal drying loads, lowers energy consumption, and enhances environmental performance. Early-stage optimization in the forming section thus plays a decisive role in developing stable, economical, and sustainable paper production systems.

METHOD

Process Description of the Forming Section

The forming section is the first stage of sheet consolidation after the headbox, where a highly diluted pulp suspension is transformed into a continuous wet web through gravity drainage followed by vacuum-assisted water removal. In the observed paper machine, the wire speed ranged from 700 to 1350 m/min. The inlet stock consistency was maintained at 1.1–1.3%, while the flow rate from the headbox was typically between 200 and 230 L/s. Dewatering occurred sequentially through forming boards, suction boxes, and high-vacuum elements. Vacuum levels varied from mild suction in the initial drainage zone to intensive extraction in the final unit at the Vacuum Master. These operating conditions were maintained constant during data acquisition in order to isolate the effect of furnish composition on forming performance. The furnish consisted of short fiber (SF), long fiber (LF), BCTMP, and mineral fillers (GCC and PCC). Variations in the relative proportion of these components were suspected to influence mat formation, permeability, and consequently the drainage behavior.

Mill Data Acquisition and Furnish Selection

Operational data were retrieved from the Plant Information (PI) system, which continuously records process parameters from field transmitters. Historical datasets representing stable production and drainage-related disturbances were compared to identify furnish compositions associated with different forming dewatering responses. Selected grade and compositions were then reproduced at laboratory scale using handsheet experiments to verify their influence on drainage under controlled conditions.

Experimental Variables

The study classified variables into control, independent, and dependent parameters.

Control variables

Machine speed, vacuum pressure at each suction element, and pulp sources. These were kept within normal mill operation ranges.

Independent variables

The furnish composition, particularly long fiber ratio, BCTMP ratio, and filler proportion (GCC:PCC balance). Short fiber content was adjusted accordingly to maintain the target total consistency.

The Dependent variable

Drainage time.

Handsheet Preparation

Laboratory validation was conducted using a standard handsheet former. Furnish components (short fiber, long fiber, BCTMP, and filler) were prepared according to the ratios obtained from mill observations. The suspension was mixed at high agitation to ensure homogeneity. A cationic polyacrylamide (CPAM) retention aid was added at a dosage of 0.2 mL, followed by short additional mixing. The slurry was subsequently divided for drainage evaluation and sheet formation. Vacuum was applied to simulate industrial dewatering. Wet sheets were pressed between blotting papers and dried at 105 °C for 15 minutes prior to testing.

Drainage and Freeness Measurement

Drainage performance was evaluated by measuring the time required to collect 500 mL of filtrate through a wired vessel. The result was expressed as HB drainage (s/500 mL). Freeness was determined using the Canadian Standard Freeness (CSF) method, where the total filtrate volume released from the suspension represents the drainage ability of the fiber network.

Statistical Analysis

Several statistical approaches were applied to quantify the relationships among furnish composition, drainage behavior, and paper properties. Linear regression was used to compare laboratory drainage results obtained from HB pulp stock with actual forming dewatering performance in the mill, as well as to examine the relationship between drainage time and forming dewatering. The influence of furnish ratios on forming response was also analyzed using linear regression depending on the observed data trends. In addition, correlations between forming dewatering efficiency and sheet-break incidents were evaluated using bar chart visualization to understand the contribution of drainage stability to machine runnability. Scatter plots were used to visualize the interactions between furnish variables and paper properties in order to identify relationship patterns and trends associated with variations in furnish composition.

RESULTS AND DISCUSSION

Data Analysis of Forming Dewatering

The forming dewatering process in the forming section (Figure 1) is a very crucial initial stage in paper web formation, as it determines fiber distribution, water drainage efficiency, and web stability before entering the drying section[5]. In the forming section, stock with a specific furnish composition and chemical additives enters the wire section, where some of the water is separated by gravity and the rest through vacuum elements from points A to I. The vacuum pressure in each element is kept constant (Table 7) during data collection so that the effect of the furnish on changes in dewatering performance can be observed.

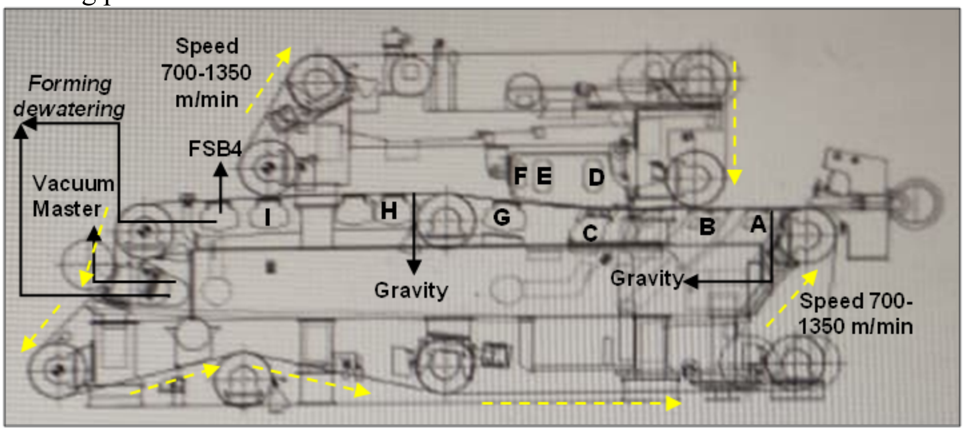

Figure. 1. Forming Section

The water separated from the pulp suspension is then collected as filtrate with a certain consistency level known as White Water Consistency (WWC). The WWC value is an important indicator of solids retention efficiency in the forming section. A high WWC indicates that a large amount of solids are carried into the filtrate, while a low WWC indicates that most of the solids are successfully retained and contribute to the formation of paper sheets [5]. The WWC value can be controlled by adding retention chemicals such as CPAM (Cationic Polyacrylamide) and APAM (Anionic Polyacrylamide), which affect the flocculation level of particles in the pulp suspension [24].

Table 1. Vacuum Pressure in the forming section

Equipment	Pressure (bar)
Vacuum forming board (A)	-0.05 to -0.08
1st Forming board (B)	-0.03 to -0.06
2nd Forming board (B)	-0.04 to -0.07
Wet Suction box (C)	-0.04 to -0.07
Vacuum shoe (D)	-0.03 to -0.06
Top Suction unit 2nd (E)	-0.20 to -0.35
Top Suction unit 3rd (F)	-0.15 to -0.30
Flat suct box 1 (G)	-0.20 to -0.35
Flat suct box 2 (H)	-0.25 to -0.40
Transfer suct box (I)	-0.25 to -0.40
Flat suct box 4 (FSB 4)	-0.30 to -0.45
Vacuum Master	-0.55 to -0.70

At the end of the forming section, there are two main elements, namely FSB4 and Vacuum Master, which are collectively referred to as forming dewatering. A high forming dewatering value indicates that initial drainage in zones A–I has not been optimal, so the drainage load is transferred to the final forming stage. This condition is greatly influenced by the furnish composition, particularly the ratio of short fiber (SF), long fiber (LF), and BCTMP, as well as the type and proportion of fillers used.

Effect of LF, BCTMP, and SF Morphology on Forming Dewatering

Table 2. Morphology of LF, BCTMP, and SF

Variable	LF	BCTMP	SF
Mean length	1.60-1.75 mm	0.75-0.90 mm	0.70-0.85 mm
Mean width	27-32 µm	23-28 µm	16-21 µm
Mean fibril area	8-11 %	2-5 %	1-4 %
Mean fibril perimeter	25-30 %	11-15 %	4-9 %
Mean *fines*	33-38 %	46-51 %	20-25 %

The morphological characteristics of the fibers (Table 2) in each type of pulp have different effects on web formation and dewatering behavior during the forming process. Based on the data in Table 2, long fiber (LF) has the longest fiber length and a relatively large fiber width. In addition, LF also exhibits the highest fibril area and fibril perimeter values compared to other fiber types, indicating a more developed level of external fibrillation. The combination of long fibers, a fibrillated fiber surface, and significant fines content results in a large specific surface area and high water-holding capacity. These conditions enhance inter-fiber interactions through hydrogen bonding and promote water retention on the fiber surface. Consequently, as the proportion of LF increases in the furnish composition, the resulting web structure becomes denser due to increased inter-fiber contact and fines filling the inter-fiber voids. This condition increases hydraulic resistance and reduces permeability within the wet web, thereby slowing water release during the forming stage. This phenomenon explains why an increase in the LF ratio under certain conditions leads to higher forming dewatering values, as water is retained longer within the web structure before being released [27].

This interpretation becomes clearer when compared with the morphological characteristics of BCTMP as shown in Table 2, BCTMP has relatively short fiber lengths, approaching those of SF, but exhibits a larger fiber width and the highest fines content. The dominance of fines in BCTMP originates from the mechanochemical pulping process, which produces numerous fiber fragments and small particles. These fine particles and short fibers tend to disperse easily within the suspension, allowing free water to move more rapidly through the inter-fiber gaps during the early stages of web formation. Additionally, the relatively low fibril area of BCTMP indicates limited external fibrillation, resulting in a lower capacity of the fibers to retain water through capillary mechanisms and hydrogen bonding compared to LF [14]. This combination of characteristics leads to relatively high freeness and promotes faster water release in the initial forming stage. Although high fines content is generally associated with increased flow resistance, under low to moderate BCTMP ratios, the relatively low fibrillation level and the absence of a compact fiber network prevent the formation of a dense pore-blocking structure. As a result, the fiber network remains sufficiently permeable, allowing water to drain more rapidly during the early forming stage. This condition reduces the dewatering load in the final part of the forming section and is reflected in lower forming dewatering values, indicating faster overall water removal during the forming process. Consequently, water release becomes more stable throughout the sheet-forming process [9]. Meanwhile, the morphological characteristics of short fibers (SF) also exhibit a distinct role in influencing web structure and water release mechanisms. Based on Table 2, SF has the shortest fiber length and relatively small fiber width. These small fiber dimensions allow SF to distribute more uniformly within the suspension and effectively fill inter-fiber spaces without forming a dominant load-bearing fiber network. The fines content of SF is at a moderate level, sufficient to partially fill interstitial voids but not high enough to form a dense fines layer that significantly blocks pore structures. In addition, the relatively low fibrillation level indicates a limited capacity of the fibers to retain water through capillary action and hydrogen bonding. As a result, the presence of SF does not significantly increase hydraulic resistance nor drastically alter permeability within the fiber network. Instead, SF contributes to maintaining a more uniform pore structure and stable permeability throughout the forming process. This condition allows water to be released in a more controlled and consistent manner, without causing significant changes in overall drainage behavior or forming dewatering values [8].

Effect of LF Ratio on Forming Dewatering

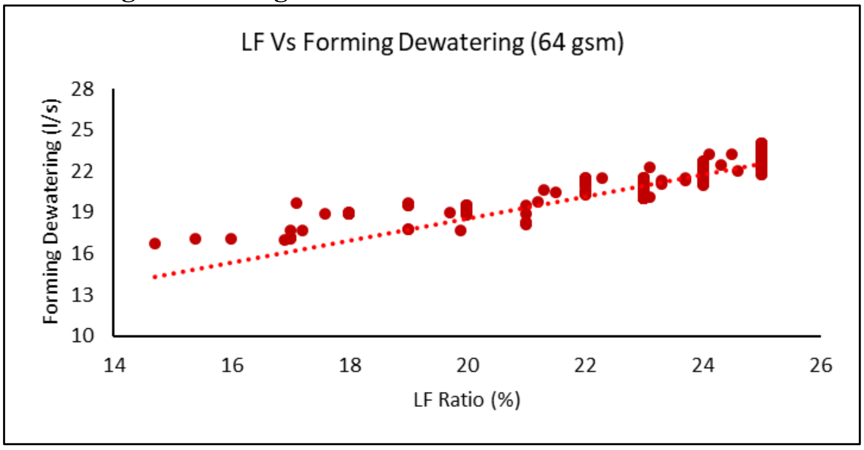

Figure 2. LF ratio vs forming dewatering at 64 gsm

Based on operational data collected from August 2024 to August 2025 for 64 and 60 gsm offset paper grades, variations in the LF ratio show a significant effect on forming dewatering. Under these conditions, the BCTMP ratio was maintained at 11%, filler at 22%, and the composition of GCC and PCC at 70% and 30%, respectively. The SF ratio adjusts for changes in the total fiber ratio. The analysis results in Fig. 2 and Fig. 3 show that every 1% increase in LF causes an increase in forming dewatering of approximately 0.62 l/s and 0.25 l/s. Figures 2 and 3 also show a fairly high coefficient of determination (R^2) of above 0.7. This indicates that the addition of the LF ratio is closely related to forming dewatering.

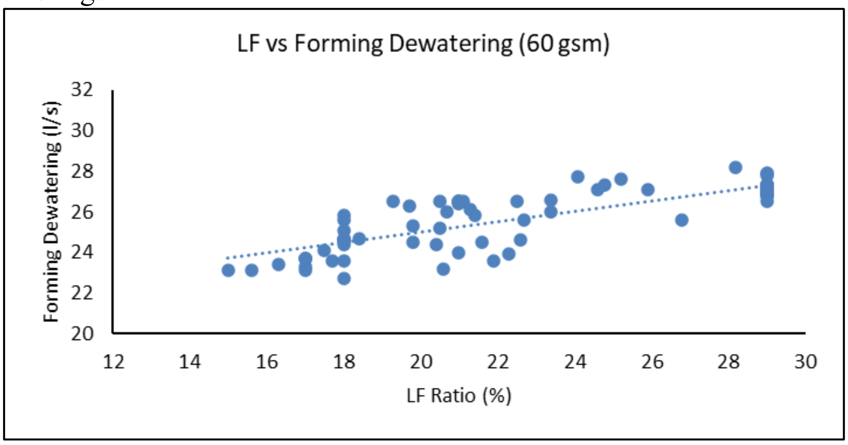

Figure 3. LF ratio vs forming dewatering at 60 gsm

This phenomenon is attributed to the relatively lower freeness of LF compared to the other fiber types. Low freeness indicates a lower drainage ability and higher resistance to water flow, meaning that water is retained longer within the fiber network. As a result, an increase in the proportion of LF tends to slow down water removal and increase the dewatering load toward the end of the forming section (Sjostrand, 2020). The freeness values of each furnish component further support this behavior, with LF at 298–300 mL CSF, SF at 345–348 mL CSF, and BCTMP at 450–455 mL CSF, indicating that LF has the lowest drainage capacity, while BCTMP exhibits the highest.

Effect of BCTMP Ratio on Forming Dewatering

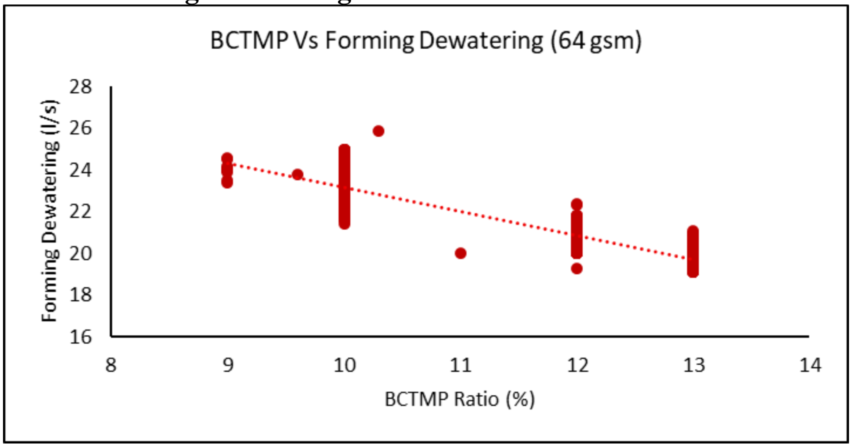

Figure 4. BCTMP ratio vs forming dewatering at 64 gsm

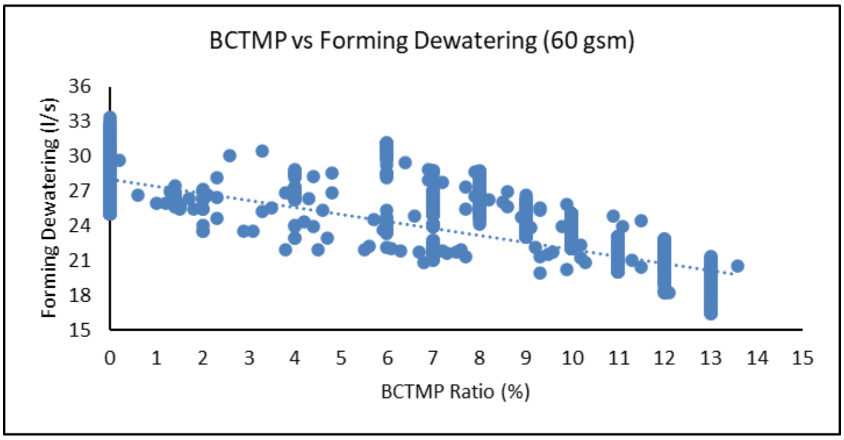

Figure 5. BCTMP ratio vs forming dewatering at 60 gsm

Based on operational data collected for 64 and 60 gsm offset paper grades, variations in the BCTMP ratio show a trend opposite to that of LF. Under conditions of constant LF at 24% and filler at 22%, each 1% increase in BCTMP reduces the forming dewatering value by approximately 1.19 L/s and 0.61 L/s, as shown in Figures 4 and 5. This reduction indicates a faster dewatering rate, resulting in lower water retention within the web during the forming stage. Such conditions lead to a drier web structure, which under excessive conditions may increase the risk of web crushing. This behavior is attributed to the high freeness characteristic of BCTMP, which is the highest among the fiber components, enabling more rapid water release during the early stages of forming. Furthermore, Figures 4 and 5 show relatively high coefficients of determination (R^2) of 0.81 and 0.75, indicating a strong correlation between the BCTMP ratio and forming dewatering behavior.

With an increase in the proportion of BCTMP, water drainage occurs more rapidly in the initial zone of the forming section, thereby reducing the dewatering load in the final part of the forming process. This condition is reflected in lower forming dewatering values, indicating faster overall water removal and a tendency toward a drier web structure. Under excessive conditions, this may increase the risk of web crushing due to insufficient moisture content before entering the drying section. The effect of BCTMP on forming dewatering is primarily interpreted through its freeness value as a macroscopic parameter of drainability. Freeness is widely used as an empirical indicator of a pulp's ability to release water during the forming process, as it reflects the aggregate interaction between fibers, fines fractions, and the resulting web structure [28]. Several studies confirm that freeness remains a relevant process parameter, as it correlates with permeability and flow resistance in pulp suspensions [17]. BCTMP has a relatively short fiber length comparable to SF (mean length 0.791 mm), but with a larger fiber width (24.2 µm) and the highest fines content (48.5%). This morphological combination causes BCTMP to produce a dominant fines fraction and short fiber particles that are easily dispersed, so that free water can be released quickly in the early stages of web formation. In addition, the relatively low fibril area value of BCTMP (2.9%) indicates a limited level of external fibrillation, so that the ability of the fibers to retain water through capillary and hydrogen bonds is relatively smaller than that of LF[14]. These conditions explain why BCTMP exhibits the highest freeness value and is able to increase drainage efficiency in the early zone of the forming section.

Effect of SF Ratio on Forming Dewatering

The short fiber (SF) ratio is not recorded directly at the mill, but rather follows changes in the long fiber (LF) and BCTMP ratios, with the stipulation that the total fiber ratio is always maintained at 100%. Thus, any increase in the LF or BCTMP ratio automatically causes a decrease in the SF ratio, and vice versa. This approach reflects the actual conditions in the paper machine, where the SF ratio acts as a balancing component against other furnish changes. SF has an indirect effect on the forming dewatering value. When the SF ratio increases as a result of a decrease in LF or BCTMP content, the forming dewatering value tends to remain within a more stable range. This behavior is attributed to the characteristics of short fibers, which have shorter lengths and a more homogeneous size distribution, allowing them to distribute more uniformly within the suspension and contribute to a more uniform fiber network structure on the wire section [9].This relatively uniform network structure maintains stable permeability and prevents extreme changes in water flow during the forming stage. As a result, water removal proceeds in a more controlled manner without shifting toward excessively fast or excessively slow dewatering conditions. Unlike LF, which tends to slow down drainage due to low freeness (resulting in higher forming dewatering values and wetter webs), and BCTMP, which accelerates drainage due to high freeness (resulting in lower forming dewatering values and drier webs), SF acts as a balancing component within the drainage system. Therefore, changes in the SF ratio do not exhibit a strong linear relationship with forming dewatering, but instead function as a stabilizing factor in maintaining consistent forming conditions [3].

Effect of Filler Ratio on Forming Dewatering

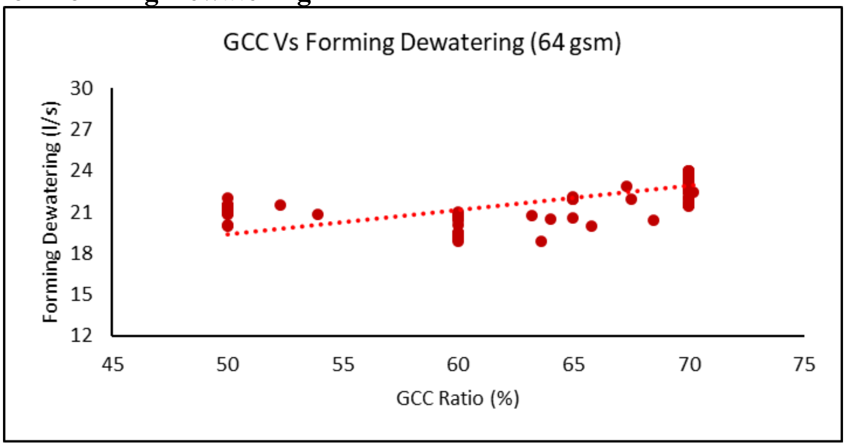

Figure 6. GCC ratio vs forming dewatering at 64 gsm

Under conditions where the long fiber (LF) ratio is maintained at 24% and the BCTMP ratio at 11%, with a total filler content of 22%, the relationship between the GCC (Ground Calcium Carbonate) ratio and forming dewatering shows a tendency for forming dewatering values to increase as the GCC ratio increases. Based on Figures 6 and 7, each 1% increase in the GCC ratio results in an increase in forming dewatering of approximately 0.18 and 0.07 L/s. The coefficients of determination (R^2) shown in Figures 6 and 7 are above 0.5 for both grades, indicating that more than 50% of the variation in forming dewatering can be explained by changes in the GCC ratio. Therefore, this relationship can be categorized as moderate and sufficiently representative in the context of multivariable mill operational data. The positive relationship indicates that increasing the GCC ratio leads to higher forming dewatering values, which reflects slower water removal and greater water retention within the web during the forming stage. This condition may result in a wetter web structure prior to entering the drying section [2].

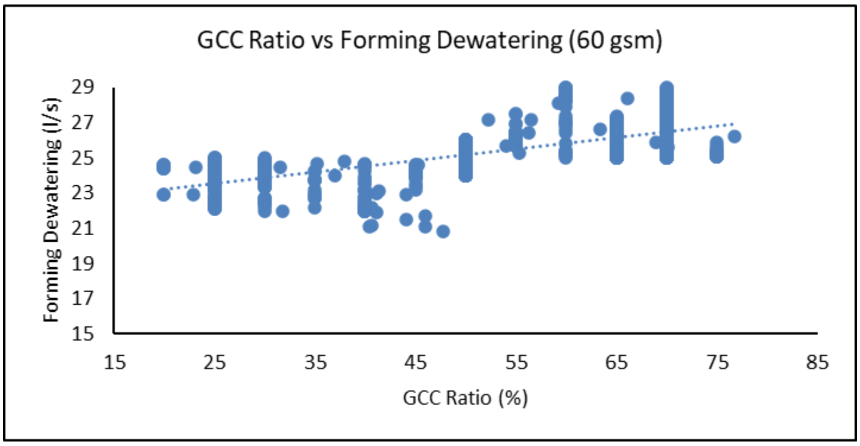

Figure 7. GCC ratio vs forming dewatering at 60 gsm

This behavior may be attributed to the structural effect of GCC particles within the fiber network. Although rigid and granular GCC particles can act as spacers between fibers, their presence, especially when well retained within the web, also contributes to partial pore blockage and increased flow resistance. As GCC content increases, the accumulation of filler particles within the inter-fiber spaces reduces the effective pore size and connectivity, thereby decreasing network permeability in accordance with fluid flow principles in porous media (Darcy's Law). In addition, GCC particles retained with fines can form microaggregates that occupy void spaces within the fiber network, further limiting water flow pathways. As a result, water removal becomes slower, which is reflected in higher forming dewatering values and increased water retention within the web. This mechanism is supported by literature indicating that although fillers may improve structural stability at low concentrations, beyond certain levels they tend to increase hydraulic resistance and reduce drainage efficiency [18].

Grade 64 gsm shows higher sensitivity to changes in GCC ratio compared to 60 gsm. Each 10% increase in GCC at 60 gsm increases forming dewatering by approximately 0.654 L/s, while at 64 gsm the increase reaches approximately 1.787 L/s. This indicates that in thicker sheet structures, the accumulation of filler particles and their influence on flow resistance become more significant. Greater sheet thickness leads to different hydrodynamic pressure gradients during forming, causing variations in structural permeability due to filler addition to have a more pronounced effect on water removal behavior [25]. Meanwhile, an increase in the PCC ratio tends to result in lower and more stable forming dewatering values [2]. This indicates faster water removal during the forming stage and a tendency toward a drier but more controlled web condition.

The distribution of filler particle sizes smaller than 1–4 µm between PCC and GCC can be seen in Table 3, both in terms of target specifications and actual conditions. For PCC, the target fraction of particles < 1–4 µm is set at less than 23–28%, while the actual data shows a value of 4–7%. This relatively low fraction of very fine particles indicates that PCC has a coarser and more uniform particle size distribution. This condition reduces the tendency for fine particle accumulation within micro-pores and minimizes pore blockage within the fiber network. As a result, the web structure remains relatively more permeable, allowing water to be released more easily during the forming stage. Consequently, this behavior contributes to lower forming dewatering values, reflecting faster and more stable water removal during sheet formation. The particle size distribution of fillers smaller than 1–4 µm for PCC and GCC can be seen in Table 3, both in terms of target specifications and actual conditions

Table 3. Filler Particle Size Distribution

Particle Size Distribution (<1-4 microns)		
Filler	Target	Actual
PCC	< 23-28%	4-10%
GCC	50-65%	55-62%

In contrast, GCC has a target particle distribution of <1–4 µm of 50–65%, and the actual data shows a value of 55–62%, which is very close to the target. This confirms that GCC contains a significantly higher fraction of fine particles compared to PCC [38]. The presence of these fine particles leads to increased filling of the inter-fiber voids, forming a denser network structure and reducing effective pore size. As a result, water flow pathways become more restricted, increasing flow resistance within the web. This difference in particle size distribution explains why an increase in the GCC ratio tends to increase the forming dewatering value, indicating slower water removal and higher water retention within the web. In contrast, the lower fine particle fraction in PCC promotes higher permeability, resulting in lower forming dewatering values and faster water release. Therefore, the particle size distribution (<1–4 µm) provides a strong basis for explaining the contrasting effects of GCC and PCC on forming dewatering behavior in the forming section [35]. The increase in forming dewatering observed with the use of GCC in this study is more appropriately interpreted as a consequence of the pore-blocking mechanism within the paper web, rather than a reduction in filler retention in the initial forming zone. This is supported by the GCC particle size distribution data, where the fine fraction (<1–4 µm) reaches approximately 55–62%. These fine particles have a strong tendency to occupy and partially block inter-fiber pores, thereby increasing hydraulic resistance and reducing permeability. Consequently, water removal becomes slower, which is reflected in higher forming dewatering values and a wetter web condition during the forming stage [25].

Meanwhile, the contribution of reduced filler retention in the initial forming zone to increased forming dewatering is considered less dominant in this study. This interpretation is supported by first pass ash retention (FPAR) data, which remains relatively constant in the range of 50–55%, indicating no significant fluctuation in filler retention during the early stages of web formation [35]. In addition, the availability of dewatering profile data for each zone and vacuum element in the forming section shows that variations in dewatering behavior are more strongly correlated with changes in web structure characteristics than with initial filler loss. Therefore, within the limitations of this study, the increase in forming dewatering associated with higher GCC content is more appropriately attributed to the pore-blocking effect of fine GCC particles within the fiber network. This mechanism increases hydraulic resistance and reduces permeability, resulting in slower water removal and higher forming dewatering values, which indicate a wetter web condition during the forming stage. In contrast, the effect of reduced filler retention in the early forming zone was not identified as the primary mechanism influencing dewatering behavior.

Effect of Headbox Drainage of Pulp Stock on Forming Dewatering

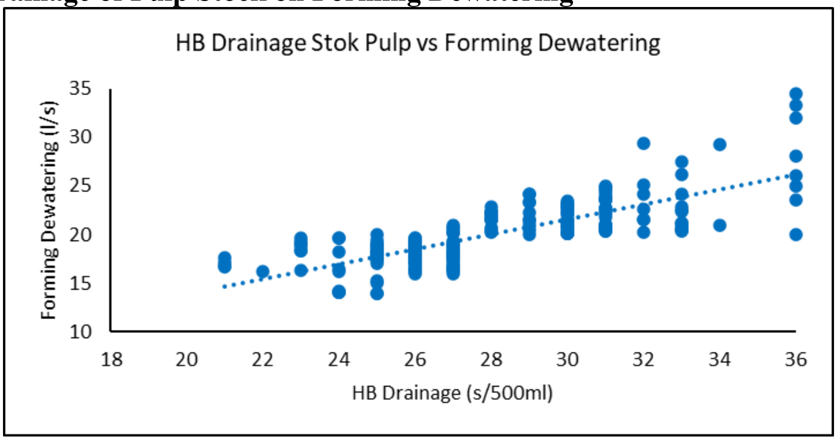

Figure 8. Headbox Drainage of Pulp Stock vs Forming Dewatering

Data used to evaluate the relationship between HB drainage of the pulp stock and forming dewatering were obtained from the mixed grade condition, as shown in Figure 8. Figure 8 shows a positive linear relationship between HB drainage of the pulp stock (s/500 mL) and forming dewatering (L/s), with the regression equation $y = 0.7659x - 1.4113$ and a coefficient of determination $R^2 = 0.6007$. The R^2 value indicates that approximately 60% of the variation in forming dewatering can be explained by variations in HB drainage, which, in the context of industrial process data, represents a fairly strong and practically significant relationship. The positive slope of 0.7659 indicates that every 1-unit increase in HB drainage is followed by an increase in forming dewatering of approximately 0.77 L/s. This relationship reflects that higher HB drainage values, indicating lower drainability and higher resistance to water flow in the pulp suspension, lead to slower water removal in the forming section. Consequently, this results in higher forming dewatering values, which correspond to increased water retention and a wetter web condition prior to entering the drying stage. Therefore, this trend demonstrates consistency between the drainability characteristics of the stock in the headbox and the water release behavior during sheet formation, where increased flow resistance at the suspension level is carried over into the forming process. The increase in HB drainage values is directly proportional to forming dewatering values, as both parameters are governed by the same structural mechanism, namely the hydraulic resistance of the fiber network and the distribution of fine particles in the suspension. Higher HB drainage values indicate lower drainability and greater resistance to water flow, which results in higher forming dewatering values, reflecting slower water removal and a wetter web condition during the forming stage.

Elevated HB drainage values are generally associated with increased fines content, higher fiber fibrillation, and stronger fiber–fiber interactions. These factors increase the specific surface area of the system and reduce effective pore size, leading to greater water retention within the fiber network. When the suspension enters the forming section, these microstructural characteristics are preserved in the developing web, causing the resistance to water flow to persist during the forming dewatering process [21]. This increase in flow resistance can be explained by Darcy's law, where fluid flow through a porous medium is strongly influenced by permeability and specific resistance. Suspensions with high HB drainage tend to form a denser initial sheet structure with narrower flow channels, resulting in reduced permeability. Consequently, water removal becomes slower, which is reflected in higher forming dewatering values. Thus, an increase in HB drainage represents increased resistance at the suspension level that directly translates into slower dewatering behavior in the forming section [31].

Effect of Forming Dewatering on Pre Dryer Break Frequency

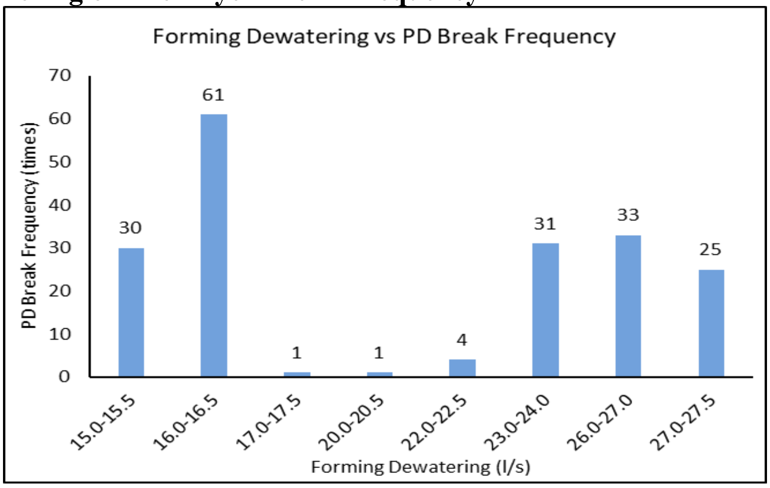

Figure 9. Forming Dewatering vs PD Break

Pre-dryer break is the breaking of the paper web that occurs in the pre-dryer section, which is the initial drying stage after the paper web exits the forming and press section. At this stage, the paper sheet still has a relatively high water content, limited mechanical strength, and is very sensitive to tensile stress, humidity changes, and thermal conditions. Therefore, web stability in the pre-dryer is highly dependent on initial moisture content, fiber structure, and web formation quality in the forming section [9]. The relationship between forming dewatering and total pre-dryer (PD) break shows that there is an optimal operating range. Data used to evaluate the relationship between forming dewatering and pre dryer break frequency were obtained from the mixed grade condition, as shown in Figure 9. Figure 9 shows that a forming dewatering value that is too low (15–16.5) indicates faster dewatering, resulting in a web that becomes too dry and is prone to crushing when entering the pre-dryer. Conversely, excessively high forming dewatering values (23–27.5) indicate slower dewatering, causing the web to remain too wet and more susceptible to breaking. The most ideal forming dewatering range is between 17–22.5, where total PD breaks are at their lowest level. This demonstrates that maintaining a proper balance of web moisture content before initial drying is crucial for stable paper machine operation [17].

Data Analysis of Paper Quality

The analysis of paper characteristics was conducted by processing and evaluating product quality data obtained from the Production Management Information System (PMIS). This data represents the final quality of the paper produced during the manufacturing process. The analysis focused on the relationship between variations in raw material composition within the furnish and changes in the characteristics of the resulting paper. The pulp composition analyzed includes variations in the ratio of Bleached Chemi Thermo Mechanical Pulp (BCTMP), long fiber (LF), and Ground Calcium Carbonate (GCC) filler. Changes in the ratio of each of these components have the potential to affect the fiber network structure within the paper sheet, thereby impacting the characteristics of the final product. The paper characteristics analyzed include weight, thickness, density, roughness, tensile strength, fiber strength, and brightness for paper with basis weights of 60 gsm and 64 gsm. Weight, thickness, density, and roughness represent the physical properties and surface structure of the paper sheet; tensile strength and fiber strength describe the mechanical properties related to the strength of inter-fiber bonds within the paper web; while brightness describes the optical properties of the paper.

Effect of BCTMP on Basis Weight, Thickness, Density, and Roughness

The thickness of the paper in all these conditions was maintained constant at 82 µm. Fig. 10 shows that increasing the BCTMP ratio in paper with basis weights of 64 gsm and 60 gsm tends to result in a slight decrease in basis weight. For 64 gsm paper, increasing the BCTMP ratio from 9% to 13% reduced the basis weight from 64.18 g/m² to 64.10 g/m², while for 60 gsm paper, increasing the BCTMP ratio from 7% to 11% reduced the basis weight from 60.39 g/m² to 60.15 g/m². This is related to the characteristics of BCTMP, which has a higher lignin content, resulting in stiffer fibers and a lower degree of fibrillation compared to chemical pulp. Fibers with low flexibility have limited inter-fiber conformation, causing the resulting fiber network to become more porous [10].

This more open fiber network structure tends to increase sheet thickness because mechanical fibers like BCTMP are not easily compressed and produce higher bulk [14]. Paper thickness is influenced by basis weight and fiber network structure, while density is the ratio of basis weight to sheet thickness. Therefore, an increase in the BCTMP ratio, which results in a more porous sheet structure, generally causes the thickness to increase and the paper density to decrease.

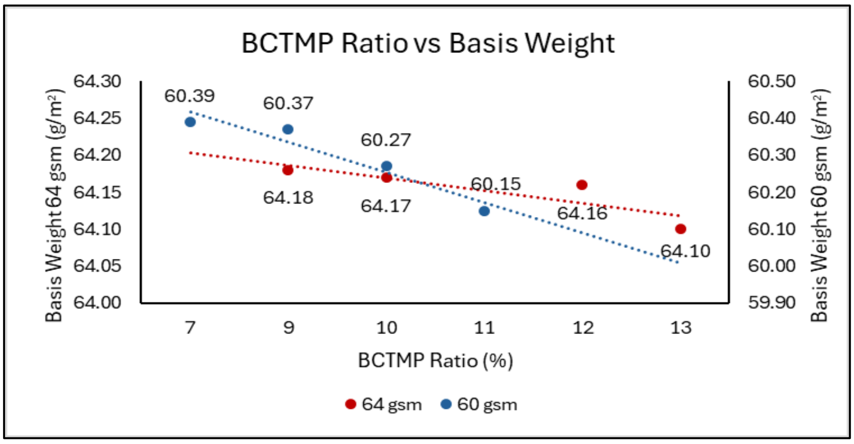

Figure 10. BCTMP Ratio vs Basis Weight

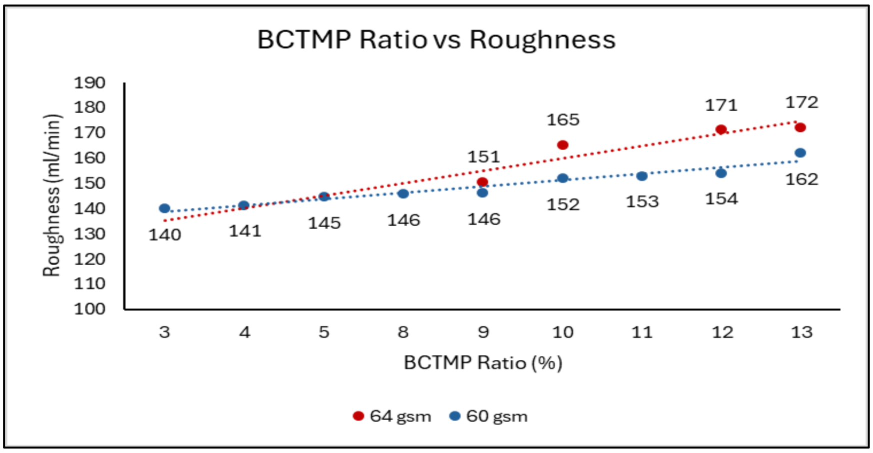

Figure 11. BCTMP Ratio vs Roughness

BCTMP also affects paper roughness, as shown in Fig.11. In 64 gsm paper, increasing the BCTMP ratio from 9% to 13% raised the roughness from 150.65 ml/min to 172.38 ml/min, while in 60 gsm paper, the roughness value increased from 139.93 ml/min to 162.09 ml/min. This increase in surface roughness is related to the characteristics of BCTMP fibers, which have a low degree of fibrillation and are less capable of undergoing plastic deformation during the sheet-forming process. Consequently, the fibers cannot conform optimally to close the inter-fiber voids, resulting in a more porous and bulky network structure. This structure produces micro- and macro-pores on the paper surface, making the sheet surface less smooth, even after undergoing mechanical processes such as the press section and calendering [29]. This condition causes an increase in the roughness value as the BCTMP ratio in the furnish increases.

Effect of LF on Internal Bond and Tensile Strength

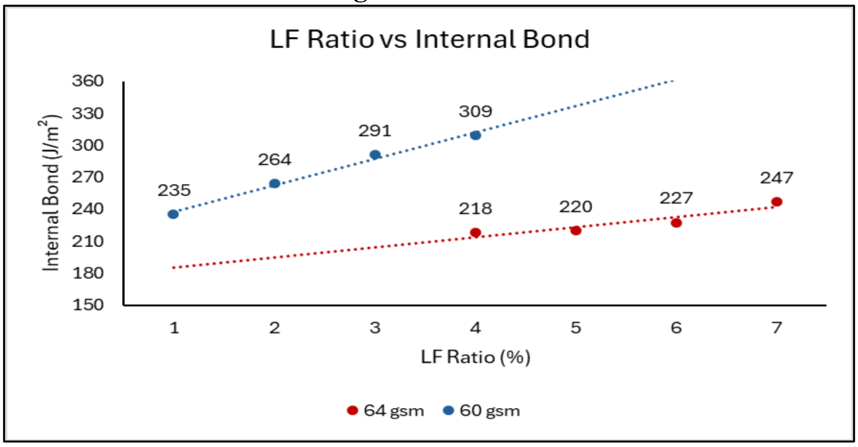

Figure 12. LF Ratio vs Internal Bond

Figure 12 shows that increasing the long fiber (LF) ratio in 60 gsm and 64 gsm paper tends to increase the internal bond value. In 60 gsm paper, an increase in the LF ratio from 14% to 19% raised the internal bond from 235 J/m² to 309 J/m², while in 64 gsm paper, an increase in the LF ratio from 19% to 24% increased the internal bond from 217.93 J/m² to 246.68 J/m². Internal bond describes the strength of the bonds between fiber layers within the paper structure, which is influenced by the number and quality of interfiber bonds [37]. Long fibers have greater fiber length and surface area compared to short fibers, enabling them to form more interfiber hydrogen bonds and enhance interlocking within the fiber network. This strengthens the internal cohesion of the sheet and improves resistance to delamination [24].

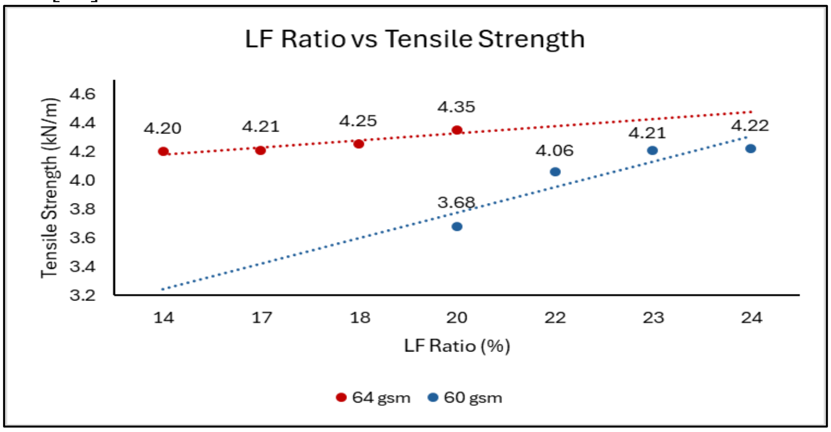

Figure 13. LF Ratio vs Tensile Strength

Increasing the LF ratio also affects the paper's tensile strength, as shown in Fig. 13. In 64 gsm paper, increasing the LF ratio from 14% to 20% increased tensile strength from 4.20 N to 4.35 N, while in 60 gsm paper, increasing the LF ratio from 20% to 24% increased tensile strength from 3.68 N to 4.22 N. Tensile strength is a parameter that describes a paper sheet's ability to withstand tensile force before structural failure occurs [39]. An increase in this value indicates that the presence of long fibers plays a crucial role in strengthening the fiber network, as longer fibers can form a more continuous network structure and increase the number of inter-fiber contact points. More inter-fiber contacts enhance hydrogen bonding, resulting in a more uniform stress distribution within the sheet and improving the paper's resistance to tensile forces [33]. This effect is more pronounced at lower basis weights because the thinner sheet structure makes changes in fiber composition more significant for the paper's mechanical properties.

Effect of GCC Filler on Basis Weight, Density, and Brightness

Figure 14 shows that increasing the Ground Calcium Carbonate (GCC) ratio in both paper weights tends to increase the basis weight. For 64 gsm paper, increasing the GCC ratio from 40% to 75% increased the basis weight from approximately 63.9 g/m² to 64.25 g/m², while for 60 gsm paper, increasing the GCC ratio from 10% to 95% increased the basis weight from 59.97 g/m² to 60.42 g/m². This increase is related to the nature of GCC as a mineral filler with a higher density than cellulose fibers, so that the addition of filler to the furnish increases the mass of the sheet per unit area. In addition to adding mass, GCC particles also fill the inter-fiber voids in the paper network, thereby increasing local density and material retention within the sheet structure. Uniform filler distribution plays a role in forming a more compact paper structure and influences the porosity of the fiber network, which ultimately affects drainage characteristics and water permeability during the sheet-forming process [35].

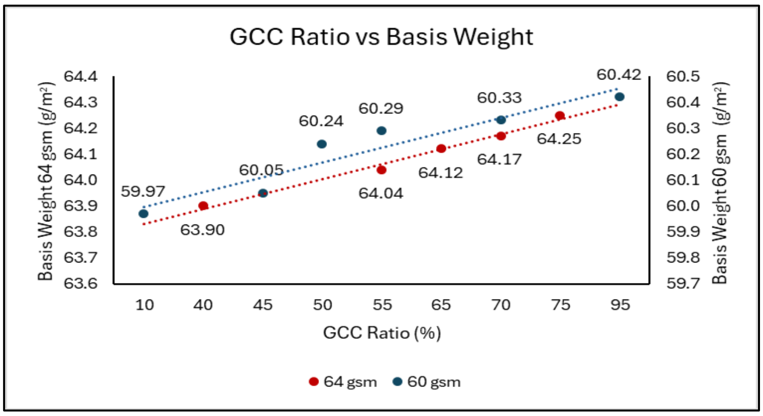

Figure 14. GCC Ratio vs Basis Weight

Ground Calcium Carbonate (GCC) is a mineral filler capable of enhancing optical properties, particularly brightness. GCC particles have a higher refractive index than cellulose fibers, thereby increasing light scattering within the sheet structure [18]. The presence of filler particles within the fiber network increases the total light-reflecting surface area and enhances light reflection efficiency from the paper surface; thus, theoretically, increasing the GCC ratio in the furnish can contribute to higher brightness values. However, in paper production practice, sheet brightness is influenced not only by mineral fillers but also by optical additives such as Optical Brightening Agents (OBAs), which operate via a fluorescence mechanism by converting ultraviolet radiation into blue light, thereby enhancing the perceived brightness of the paper [3]. Since this study focuses on variations in furnish composition, particularly the fiber-to-filler ratio, the influence of OBAs is not analyzed in depth. Therefore, the observed changes in brightness are primarily attributed to the contribution of GCC fillers and the optical characteristics of the fiber network, although under industrial operating conditions, the use of OBAs can also significantly affect paper brightness levels.

Research Results

Table 4. LF, BCTMP, and SF Freeness

Freeness (ml CSF)	
Long Fiber	309
BCTMP	478
Short Fiber	340

Table 5. Drainage Research Results

Variation	SF (%)	LF (%)	BCTMP (%)	GCC (%)	PCC (%)	Drainage (s/500ml)
A1				15	85	16.69
A2	80	10	10	50	50	18.37
A3				85	15	19.94
B1				15	85	16.54
B2	75	10	15	50	50	17.34
B3				85	15	19.11
C1				15	85	16.49
C2	70	10	20	50	50	17.25
C3				85	15	18.25
D1				15	85	16.47
D2	65	10	25	50	50	17.16
D3				85	15	17.98
E1				15	85	15.68
E2	60	10	30	50	50	16.42
E3				85	15	17.58
F1				15	85	17.31
F2	75	15	10	50	50	17.85
F3				85	15	18.66
G1				15	85	17.36
G2	70	20	10	50	50	18.32
G3				85	15	19.54
H1				15	85	18.13
H2	65	25	10	50	50	18.72
H3				85	15	19.96
I1				15	85	18.79
I2	60	30	10	50	50	19.25
I3				85	15	20.80

Freeness Analysis

The freeness values in Table 4 show that BCTMP has the highest freeness (478 mL CSF), followed by short fiber (340 mL CSF), while long fiber has the lowest freeness (309 mL CSF). Theoretically, a higher CSF value indicates faster drainage and lower filtration resistance in the suspension. This is consistent with the morphological characteristics of each fiber type. BCTMP, which contains relatively higher lignin, has a stiffer structure, thicker cell walls, and a lower degree of fibrillation, resulting in a more open and permeable network. In contrast, long fiber chemical pulp exhibits higher flexibility and fibrillation, forming a denser network with greater inter-fiber contact area, leading to increased flow resistance and lower freeness values [19].

The results of this study are consistent with these characteristics. Increasing the proportion of BCTMP in the furnish leads to faster drainage, as indicated by shorter drainage times and lower forming dewatering values. This reflects reduced flow resistance and higher permeability within the fiber network, resulting in a drier web condition during the forming stage. Conversely, increasing the proportion of long fiber leads to slower drainage, as indicated by longer drainage times and higher forming dewatering values. This behavior is attributed to the ability of long fibers to form a more compact and highly interconnected fiber network, increasing tortuosity and reducing effective permeability. As a result, water removal becomes more difficult, leading to higher water retention and a wetter web condition.

Freeness (CSF) represents the drainability of individual pulp suspensions under simplified laboratory conditions without complex interactions between furnish components [28]. In real mixed systems containing multiple fiber fractions and fillers, drainage behavior is governed not only by individual fiber properties but also by interactions such as fines retention, pore structure development, and fiber network formation. When BCTMP content is increased, its stiff and bulky fibers promote the formation of a more open network structure, enhancing permeability and facilitating water flow. In contrast, increasing long fiber content enhances inter-fiber bonding and network compactness, which increases hydraulic resistance. Therefore, the observed drainage behavior in mixed furnish systems remains consistent with the fundamental relationship between freeness, permeability, and flow resistance, where BCTMP promotes faster dewatering while long fibers contribute to slower water removal.

Drainage Analysis

Effect of BCTMP on Drainage

Based on the data in Table 5 and Figure 10, when the BCTMP ratio is increased from 10% to 30% with LF maintained at 10%, the drainage time decreases consistently across all filler compositions. For the 85:15 filler ratio, drainage decreases from 19.94 s (BCTMP 10%) to 17.58 s (BCTMP 30%). For the 50:50 filler ratio, the value decreases from 18.37 s to 16.42 s, and for the 15:85 filler ratio, it decreases from 16.69 s to 15.68 s. This trend indicates faster drainage behavior, which is consistent with mill data showing that increasing the BCTMP ratio leads to lower forming dewatering values. Lower forming dewatering values reflect faster water removal during the forming stage, resulting in a drier web condition. Under excessive conditions, this may increase the risk of web crushing prior to the drying section.

From a structural perspective, this behavior can be explained by the morphological characteristics of BCTMP, which tend to form a relatively more open and porous fiber network. This structure increases permeability and reduces flow resistance, allowing water to move more easily through the web [31]. Thus, although BCTMP has high individual freeness, in a mixed furnish system its dominant effect is to increase inter-fiber spacing, facilitating water flow and accelerating the dewatering process.

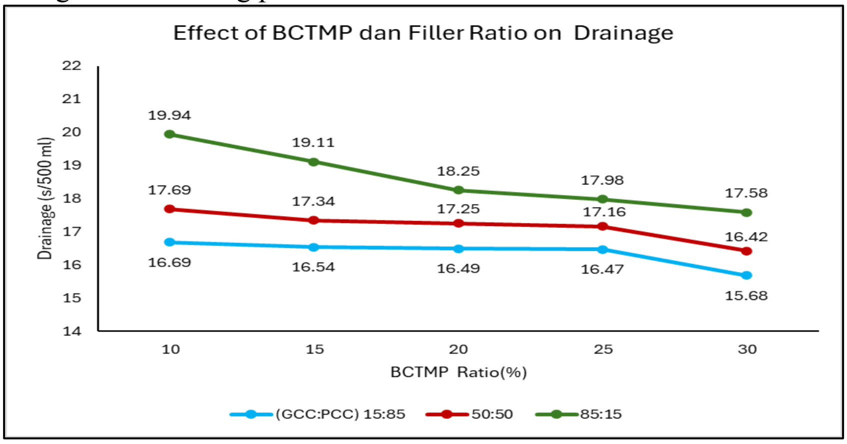

Figure 10. BCTMP and Filler Ratio vs Drainage

Effect of LF on Drainage

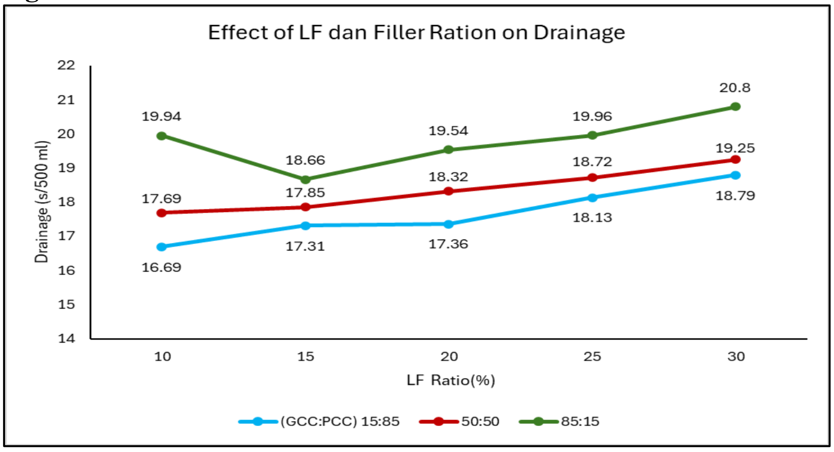

Figure 11. LF and Filler Ratio vs Drainage

Based on the data in Table 5 and Figure 11, when the LF ratio is increased from 10% to 30% with BCTMP maintained at 10%, the drainage time (s/500 mL) generally increases across all filler ratios, with an increase of up to approximately ±2 seconds under certain conditions. This trend indicates slower drainage behavior, which is consistent with mill data showing that increasing the LF ratio results in higher forming dewatering values. Higher forming dewatering values reflect slower water removal during the forming stage, leading to greater water retention and a wetter web condition. This behavior can be explained by changes in the fiber network structure. Long fibers have a high length-to-diameter ratio, promoting stronger inter-fiber interlocking and bridging. This structure increases flow path tortuosity, making water pathways more complex and reducing effective permeability in accordance with Darcy's law [25]. As a result, flow resistance increases, making water more difficult to remove and leading to longer drainage times.

However, at a filler ratio of 85:15 (GCC:PCC), a non-linear behavior is observed. When LF increases from 10% to 15%, drainage time initially decreases from 19.94 s to 18.66 s before increasing again at LF ≥ 20%. This initial decrease can be interpreted as a structural transition phase. At low LF levels, the system is still dominated by short fibers and BCTMP, with fillers occupying inter-fiber voids and limiting permeability. A slight increase in LF begins to form a supporting fiber framework that improves pore connectivity and creates more continuous flow channels, temporarily increasing permeability and accelerating drainage.

Beyond this threshold, the interlocking effect of long fibers and increased tortuosity become dominant, leading to higher flow resistance, reduced permeability, and slower water removal. Consequently, forming dewatering values increase again, indicating a shift toward wetter web conditions. This behavior demonstrates the presence of two competing mechanisms: improved pore connectivity at low LF levels and increased network compactness at higher LF levels, resulting in a non-linear drainage response [26].

Effect of Filler on Drainage

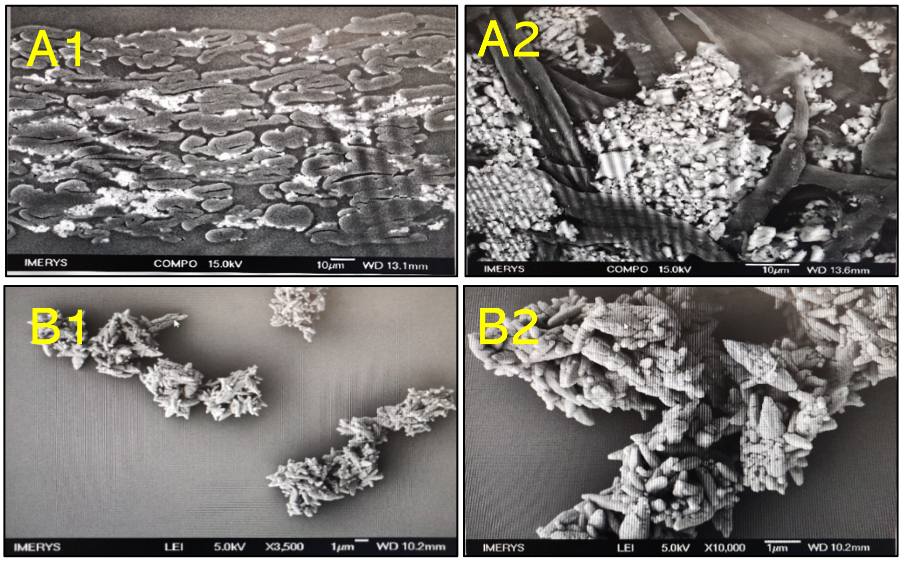

Figure 12. SEM Analysis of GCC (A1 and A2) and PCC (B1 and B2)

SEM analysis in Figure 12 shows significant morphological differences between GCC and PCC, which directly influence drainage behavior. GCC exhibits irregular, angular to sub-angular particle shapes with a relatively wide particle size distribution, including a substantial fraction of fine particles. Its surface appears rough, and these particles tend to accumulate within the inter-fiber spaces, contributing to partial pore filling and reduced pore connectivity. In contrast, PCC displays a more regular crystalline morphology, typically rhombohedral or scalenohedral, with a more uniform particle size distribution and a lower fraction of very fine particles. It is important to note that the filler particle sizes used in the laboratory tests are comparable to those applied in the mill, ensuring that the observed morphological effects are representative of actual industrial conditions.

These morphological differences lead to distinct pore structure characteristics within the sheet. The higher fine particle fraction in GCC promotes filling and partial blockage of inter-fiber pores, reducing effective pore size and connectivity. As a result, hydraulic resistance increases and permeability decreases, leading to slower water removal during forming. Conversely, the more uniform and relatively coarser PCC particles reduce the tendency for pore blockage, allowing the fiber network to maintain more stable permeability and facilitating faster water release. This behavior is reflected in lower forming dewatering values for PCC-rich systems and higher values for GCC-rich systems [18]. This trend is consistent with the drainage data shown in Table 5, Figure 10, and Figure 11, where increasing the GCC ratio from 15% to 85% results in higher drainage times across all fiber combinations. For example, at LF 10% and BCTMP 10%, drainage time increases from 16.69 s (15:85) to 19.94 s (85:15). Longer drainage times indicate slower water removal, which corresponds to higher forming dewatering values and greater water retention within the web. This confirms that GCC, particularly its fine particle fraction, contributes to increased flow resistance through pore-blocking mechanisms, consistent with the concept of specific cake resistance in suspension filtration [18]. At a grammage of 64 gsm, which has a relatively thinner fiber network, the influence of filler morphology becomes more pronounced, as small changes in microporosity can significantly affect permeability and water flow resistance. In this context, PCC contributes to more stable drainage behavior due to its more uniform particle distribution, while GCC tends to increase resistance and slow down dewatering. Therefore, an appropriate balance between GCC and PCC is required to achieve optimal forming conditions, ensuring sufficient water removal without causing excessive wetness or instability in the web prior to drying.

CONCLUSION

This study investigated the effect of furnish composition, including Long Fiber (LF), Bleached Chemi-Thermomechanical Pulp (BCTMP), and mineral fillers, on dewatering performance and paper quality in the papermaking process. The results demonstrate that variations in furnish composition significantly influence drainage behavior during sheet formation, which is directly reflected in forming dewatering performance and the resulting paper characteristics. An increase in BCTMP proportion enhances dewatering by promoting faster water removal, as indicated by shorter drainage times and lower forming dewatering values. This behavior is attributed to the relatively stiff and bulky fiber structure of BCTMP, which forms a more open and permeable network. However, excessive dewatering may result in a drier web condition, increasing the risk of web crushing prior to the drying section. In contrast, increasing the LF ratio increases flow resistance due to stronger inter-fiber bonding and higher tortuosity, leading to longer drainage times and higher forming dewatering values. This condition results in slower dewatering and a wetter web structure, although it contributes positively to paper strength, as reflected in higher internal bond and tensile strength.

The effect of fillers further reinforces this behavior. Higher GCC content, characterized by a larger fraction of fine particles, increases flow resistance through pore-blocking mechanisms, resulting in higher forming dewatering values and slower water removal. Conversely, PCC, with a more uniform and relatively coarser particle distribution, maintains more stable permeability and promotes faster dewatering, reflected in lower forming dewatering values. The fastest drainage condition was observed in PCC-dominated furnish, reaching 15.68 s/500 mL. Overall, the findings indicate that furnish composition plays a critical role in controlling the balance between dewatering rate and web moisture condition. Optimal forming dewatering must be maintained within a specific range to avoid excessively dry or excessively wet web conditions, both of which can negatively affect runnability and increase the risk of pre-dryer breaks. Therefore, proper optimization of fiber and filler ratios is essential to achieve stable machine operation, efficient water removal, and the desired mechanical and physical properties of paper.

Further studies are recommended to investigate the interaction between furnish composition and other process variables in the papermaking system. Future research may include the effects of refining intensity, fines content, and chemical additives such as retention aids and optical brightening agents on drainage behavior and forming dewatering performance. In addition, more detailed analysis using pilot-scale or industrial machine data would provide deeper insight into the relationship between laboratory drainage measurements and actual forming conditions. Expanding the study to include sheet formation quality, retention efficiency, and drying energy consumption would also support a more comprehensive approach to furnish optimization for sustainable papermaking processes.

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