

**THE EFFECT OF PAPERMAKING CONDITIONS ON THE BULK AND
ROUGHNESS OF COATED WOOD-FREE PAPERS CONTAINING
ASPEN HIGH-YIELD PULP**

by

KIERON MOORE

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

Graduate Department of Chemical Engineering and Applied Science, University of Toronto

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ABSTRACT

The effect of partially substituting Aspen high-yield pulp (HYP) for hardwood bleached Kraft pulp (HBKP) on the roughness and bulk of coated paper calendered to a targeted gloss is investigated. The effects of HYP type, HYP content (%), rosin-alum internal size, and precalendering temperature are examined. Controlled amounts of water and coating colour are applied to the paper samples using a modified RNA-52 Printability Tester and a puddle type coater, respectively. There was no significant increase in roughness after coating for up to 20% HYP substituted. In addition, compared to internal sizing, precalendering temperature is the most effective pre-treatment method in reducing roughness after wetting.

There is an interaction effect between internal sizing level and precalendering temperature on the final bulk of coated calendered samples. Moreover, a non-linear relationship exists between precalendering temperature and the final bulk for samples substituted with 30% Aspen HYP.

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LIST OF ACRONYMS

AKD - Alkyl Ketene Dimmer

ASA - Alkenyl Succinic Anhydride

BCTMP – Bleached Chemi-Thermo Mechanical Pulp

HBKP – Hardwood Bleached Kraft Pulp

HSNC - Hot Soft Nip Calendering

HYP - High-Yield Pulp

LWC – Light Weight Coated

PC - Principal Component

PCA- Principal Component Analysis

PLS - Projection to Latent Structures by Partial Least Squares

SBKP - Softwood Bleached Kraft Pulp

SC – Supercalendered

TG - Temperature Gradient

TMP – Thermo Mechanical Pulp

1. CHAPTER 1 – INTRODUCTION

Papermakers are faced with the challenge of producing high quality wood-free coated papers at a lower cost. This challenge cannot be met by simply installing new expensive papermaking technologies [1]. One approach is to utilize the fibre characteristics of the furnish. Wood-free coated papers typically consist of only chemical fibres; however, it is difficult to utilize these fibres. Over the past 20 years, bleached chemi-thermo mechanical pulp (BCTMP) or high-yield pulp (HYP) has been made with the same brightness and strength compared to hardwood bleached Kraft pulp (HBKP). In addition, recent lignin restrictions on these grades have been lifted and HYP is seen as a viable alternative to HBKP in high-quality paper [1,2,3]. HYP is partially substituted up to 30% for HBKP in these grades. It can be specially made from different wood species such as Aspen, birch, maple, and spruce to meet different papermaking requirements [4,5]. Aspen HYP is the main wood species used in wood-free coated papers because it has smoothness and porosity comparable to HBKP. In addition, it is bulkier, has better opacity, and is cheaper compared to HBKP.

However, Aspen HYP or BCTMP is a mechanical pulp and it has been well-documented that it roughens more than chemical pulp when wet. This roughness increase could reduce the gloss of the coated uncalendered sheets and more calendering may be required to achieve the target gloss value of the calendered coated paper samples. However, harsher calendering conditions will reduce the bulk of the paper. Most of the previous literature on roughening has been on light weight coated (LWC) papers, newsprint, and supercalendered (SC) papers with thermo mechanical (TMP) or groundwood pulp at levels >55% mechanical fibres. There is little research on the effect of substituting Aspen HYP which is a BCTMP (closer to a chemical pulp) on the roughness and bulk of coated papers.

In addition, understanding how papermaking parameters can be utilized to preserve the bulk of coated calendered papers at high levels of HYP substitution (up to 30% HYP) is important. Hence there is a need for a comprehensive investigation to better understand how different paper properties affect the bulk of calendered coated papers.

The first objective of this work is to systematically investigate the effect of HYP content, HYP type, internal sizing level, and precalendering temperature on the bulk of coated calendered samples. The second objective is to investigate the impact of these parameters on paper roughness after the application of water and coating colour. Figure 1.1 shows the details of the research approach including the Projection to Latent Structures by Partial Least Squares (PLS) modeling using SIMCA-P to further the understanding between the papermaking conditions and the bulk of coated calendered samples.

This thesis is organized into six chapters. Chapter two provides a link between previous work done on the roughness and bulk of the coated paper samples and the work that still needs to be done. It presents the well-established explanation for the roughening mechanism of mechanical fibres but also highlights the need for more work on Aspen HYP. There is also limited work done on the bulk preservation of coated calendered samples with Aspen HYP. Chapter three investigates the roughening after and during wetting using a RNA-52 Printability Tester. A fundamental understanding of the roughening that occurs due to water absorption by paper without the masking effect of coating is given. In addition, it helps in the understanding of what occurs when the water applied to the paper is equal to the amount of water in contact with the fibres. Chapter four deals with the paper roughening during the coating process and focuses on the bulk preservation of the coated calendered samples. Finally, in chapter five, PLS is used to better understand how the HYP content, HYP type, internal sizing level, precalendering

temperature, and coating weight affect the bulk of coated calendered samples. It includes the non-linear relationship between precalendering temperature and the bulk, and possible interaction between internal sizing and precalendering temperature.

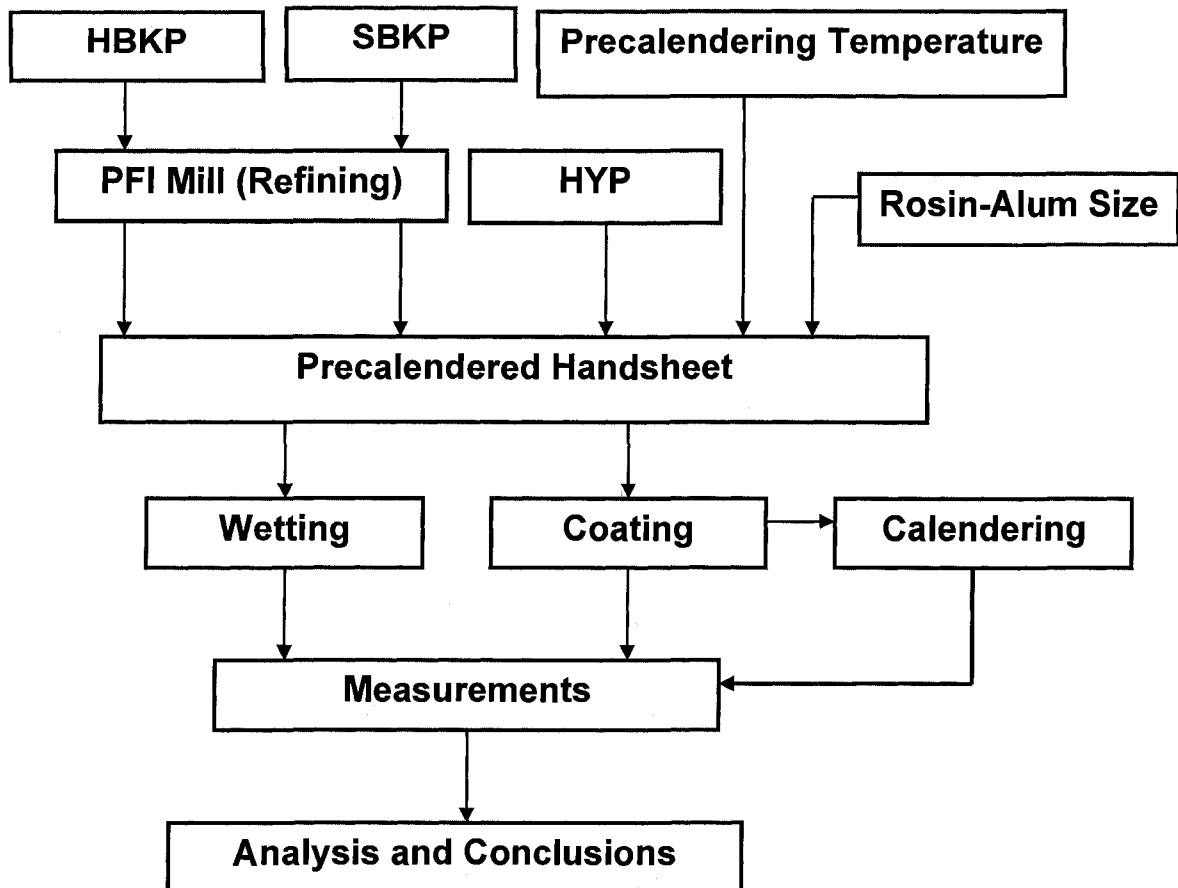


Figure 1.1: Research Approach

2. CHAPTER 2 – LITERATURE REVIEW

This chapter provides a review of previous studies done on the roughness and bulk of coated wood-free papers, and the objectives of this project. It starts with an introduction to wood-free coated paper including its structure and end-use performance. The influence of papermaking and calendering conditions on the paper roughness after coating and on the bulk of coated paper after final calendering are highlighted. In addition, a summary of the previous work related to the bulk and roughness of coated wood-free papers is provided and the statement of the problem for this thesis is given.

2.1. Introduction to Wood-free Coated Papers

Paper is a network of fibres as shown in Figure 2.1. These fibres can be made of three components: cellulose, hemi-cellulose, and lignin. Chemical fibres consist of cellulose and hemi-cellulose, whereas mechanical fibres contain all three components of fibre. For this reason, the yield of mechanical pulping process is higher (~80-90%) compared to chemical pulping process (~50%) [6]. Chemical fibres can be divided into softwood and hardwood pulp. The softwood fibres tend to be longer and have better bonding ability that provides them with superior strength compared to hardwood fibres. However, the hardwood fibres provide better surface smoothness because they are shorter and have a narrower fibre distribution [7].

Wood-free coated papers typically consist of only hardwood and softwood chemical fibres. According to Hu *et al.* [7], wood-free basestock consist of 5-50% softwood fibres and the remainder is hardwood fibres. The composition is dependent on the end-use of the paper. Wood-free grades are used for coated and uncoated printing and writing papers [1].

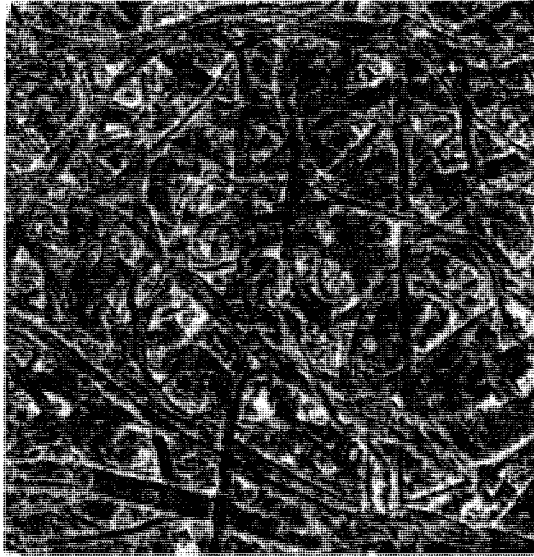


Figure 2.1: Paper Structure Taken from a Confocal Laser Scanning Microscopy and Reconstructed using Image Pro

The market for a high performance, low cost wood-free coated paper has increased in recent years. This has sent papermakers searching for an alternative to the typical hardwood and softwood chemical pulps. The developing demand cannot be met by simply installing new costly papermaking technologies [1]. As highlighted by Zou and Zhou [1], the modification and utilisation of fibre characteristics of different types of furnishes could be employed. Over the past 20 years, high-yield pulp (HYP) has been developed to have similar strength and brightness properties compared to bleached hardwood Kraft pulp. It has proven to be a viable cost-effective partial substitute for hardwood Kraft pulp in traditional high quality ‘wood-free’ papers [1,2,3]. The advantages of HYP made from hardwood over hardwood bleached Kraft pulp are highlighted below [1,8]:

- Higher bulk
- Increased bending stiffness at the same basis weight
- Improved sheet formation and opacity because of shorter fibres and higher fines content

High-yield pulp can be made from various wood species including Aspen, birch, maple and spruce to achieve the desired papermaking product. Each wood species has definite characteristics and are selected to help papermakers meet their target of producing a product with the required end-use performance. As stated by Reis [6], HYP can be customized to meet the papermaker's requirements (see Table 2.1). For example, a HYP mill can produce up to 20 different pulp grades to facilitate the needs of carbonless papers, coated paper, copy paper, ivory board, tissue, or LWC paper producers. Aspen HYP is the main wood species used for wood-free coated grades because it provides low porosity, good smoothness, and good formation [6].

Table 2.1: End-use of Hardwood HYP [6]

Coated Printing and Writing	37%
Uncoated Printing and Writing	33%
Board	15%
Specialties	10%
Tissue/Towel	5%

Although HYP has many advantages, there are inherent disadvantages that need to be addressed. This led Hu *et al.* [7] to propose three major questions concerning the use of HYP as a partial substitute for HBKP:

- Does HYP reduce the strength of the sheet?
- Does HYP lead to greater roughening after coating? If it does, could more calendering be required to achieve the same smoothness?
- Does HYP substitution lead to poor coating coverage and printability?

Throughout this chapter, these questions will be addressed by reviewing relevant literature providing the background objectives of this study.

2.2. Factors Affecting the Roughness and Bulk of Coated Papers

There are numerous factors that affect the bulk and roughness of coated calendered papers including: the papermaking process, furnish, calendering conditions, and coating process [9] as shown in Figure 2.2. Conditions such as wet-pressing, refining, bleaching, calendering temperature, coating pigment type and % coating solids all influence these factors. Although all these conditions are important, this section focuses on the effect of precalendering temperature, internal sizing, and furnish type on the roughness and bulk of paper samples.

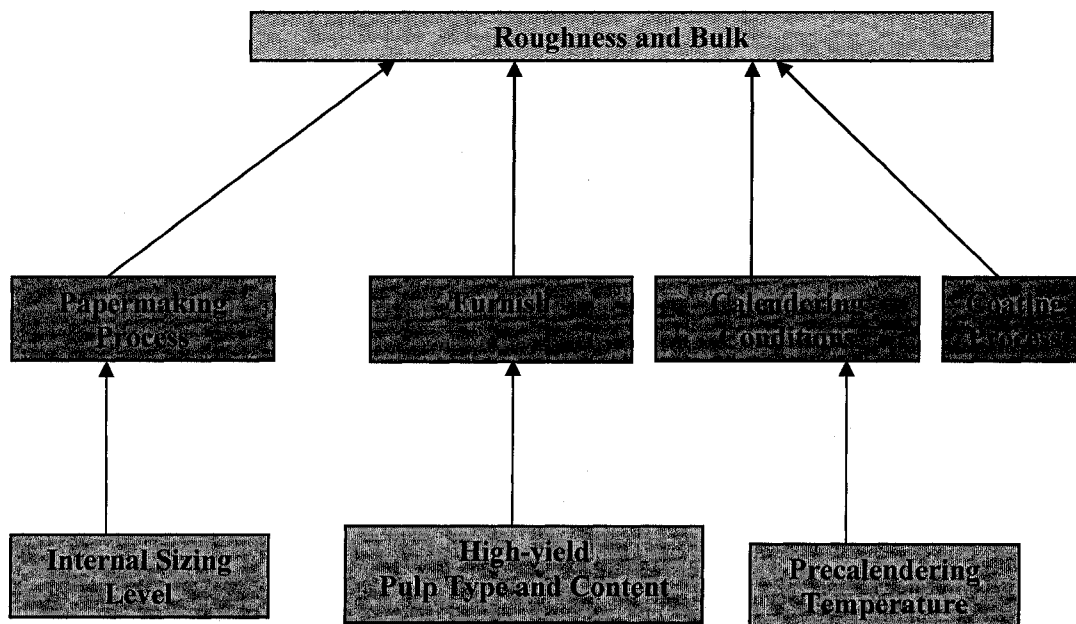


Figure 2.2: Factors Affecting the Roughness and Bulk of Coated Papers

2.2.1. Furnish Type

In this thesis, HYP is substituted up to 30% for HBKP in wood-free coated papers. This could increase the bulk of the final paper product; however, surface roughening during the coating process is more prominent in sheets containing mechanical fibres [10]. The higher surface roughness of samples with mechanical pulp could subject them to harsher calendering conditions

required to achieve a targeted paper gloss. The surface roughening phenomenon has been researched extensively and is generally well-understood.

Prior to coating, paper samples are normally precalendered to improve paper smoothness. This promotes good coating coverage and holdout. The precalendering process also compresses the fibrous structure of paper [11]. The coarse HYP fibres are tubular in shape and are forced to partly collapse. This results in increased levels of internal stress in the fibre network. The chemical fibres, on the other hand, do not contain lignin and hence are well-collapsed during the forming and wet-pressing processes. During coating, a water-based suspension of pigment and binder is applied on paper to improve the optical and topographical properties of the printing surface by filling the surface pores with pigment [12,13,14]. However, the cellulose and hemicellulose components of papermaking fibres are highly hydrophilic and absorb some of the water that is applied on the sheet in the coating process (35-50% of the wet coating volume) [12]. The water is transported quickly into the fibres via capillary pressure (interfibre penetration) and molecular diffusion (intrafibre penetration) [15,16,17]. Subsequently, roughening of the paper surface occurs due to the irreversible swelling, debonding, and internal stress relaxation of the fibres [18]. The mechanical fibres recover their shape prior to precalendering; however, the extent of fibre recovery is smaller for chemical fibres. Hence, coated papers containing HYP could potentially roughen more than wood-free coated papers.

Mechanical fibres have greater volume expansion (lumen opening) compared to chemical fibres [19] after the wetting process. Although more roughening could occur with sheets containing HYP, there could be greater bulk increase during coating. The extent of the bulk increase depends on the fibre wall thickness; fibres with thick walls recover their shape more than thin walled fibres [19]. For supercalendered papers, Forseth *et al.* [10] found that lumen opening

during coating resulted in rough paper samples. In addition, lumen opening increased as fibre wall thickness increased.

Hoc [20] investigated fibre rising in supercalendered magazine, LWC coated grades, and newsprint due to the wetting process. Fibre rising can reduce the gloss of printed images and increase surface roughness of paper. There are three causes of fibre rising: weakening of fibre-fibre bonds, release of the internal stress imposed on the structure of paper, and the swelling of fibres. Hoc measured, counted, and recorded fibre rising using image analysis. It was found that fibre rising was positively correlated to surface roughness and the amount of water applied. However, it decreased with increasing fines content and tensile index (bonding ability). Kartovaara [21] also found that fines played an important role in limiting surface roughening in LWC papers. Fines contributed to opacity, formed strong bonds, and scattered light. Also, the more precalendering a base sheet received, the more severe the roughening that occurred after the coating.

2.2.2. Internal Sizing

Internal sizing provides paper with a degree of resistance to water absorption by fibres and promotes coating holdout [22,23]. Coating holdout is a measure of the paper resistance to coating penetration [12]. The factors affecting coating holdout include the following: pigment type, water retention agents, destabilization of the coating, and pigment binder interactions [24,25,26,27]. In papers with large surface pores, coating pigment may sink into the paper under the application roll or blade pressure, defeating the purpose of coating process: i.e. creating a smooth coating layer on the paper surface. In turn, this could lead to a reduction in the bulk of the coated paper sample.

The type of internal sizing agent used in the paper industry depends on processing conditions in the wet-end of the papermaking process [22]. The most common internal sizing agents are rosin-alum size, alkyl ketene dimmer (AKD), and alkenyl succinic anhydride (ASA). Traditionally, the most common type of sizing agent used in the paper industry was the acid based rosin-alum size. However, papers made under acidic conditions may become yellow, embrittled, cause machine corrosion, and lose their strength [27]. The alkaline sizing agents, AKD and ASA, have been utilized extensively to prevent these problems. However, there is no perfect internal sizing agent: AKD has a slow curing rate and causes problems with on-machine sizing performance and ASA is extremely unstable (~2 hrs) (see Table 2.2). Rosin sizing agents has many advantages including being reliable and economical, and according to Zou *et al.* [23], there has been an effort to switch from acidic to neutral-alkaline pH using rosin sizing agent. This could potentially meet the strength requirements and increase the longevity of archival papers with rosin sizing.

In this study, rosin-alum size was used under acidic conditions. Coated papers could mask the yellowing effect of acidic samples. In addition, rosin-size is stable for up to six months compared to AKD (~ 30 days) and ASA (~2 hrs) and has no sizing development problems. This makes it more user-friendly in a laboratory setting. In conclusion, all internal sizing agents provide water resistance and coating holdout to the paper and hence rosin-alum size was the most appropriate in this work.

Table 2.2: Comparison of the Different Sizing Agents Adapted from [22,27]

Size	Optimal pH	Advantages	Limitations
Rosin-alum	4-7	Reliable, economic, graduated sizing, compatible with other wet end additives	Higher pH, hard sizing, CaCO ₃
ASA	6.5-8.5	Fine papers, CaCO ₃ , on-machine sizing	In-mill emulsion(<2hours), unstable, deposits, no resistance against OH-acids
AKD	7-9	Paper and paperboard, CaCO ₃ , relatively stable emulsion (~30 days)	High filler content, light switch effect, on-machine cure, slippery

The mechanism of rosin-alum size is generally well-established. The carboxyl group (Pulp-COOH) of the pulp forms an ionic bond with the aluminium ions from the aluminium sulphate hydrate and yields the following cationic structures: Pulp-COOAl(OH)⁺ and Pulp-COOAl²⁺. The dispersed rosin emulsion with anionic sites forms ionic bonds with the cationic structures [27,28,29,30,31]. Ohno *et al.* [27] studied the mechanism of size retention for handsheets prepared with rosin-alum systems and confirmed the mechanism for rosin-alum size. They compared samples made from original beaten pulp to carboxyl group-blocked pulp (Pulp-CONHCH₃). The sizing degree of the carboxyl group-blocked pulp was insignificant compared to the original pulp. With the carboxyl group blocked, there was no electrostatic interaction between the pulp and the alum; as a result, there was no sizing.

The degree of sizing is dependent on a number of factors including: rosin-alum ratio, stirring time, and pH. Zou *et al.* [23] found that the optimal sizing ratio was 1g rosin: 1.5 g of alum. The maximum sizing occurs after 4 minutes and plateaus [27]. The degree of sizing is typically measured using a Cobb Tester and Hercules Sizing Tester.

The Cobb Tester measures the mass of water absorbed by 1 m² of paper by a specific time and under specific conditions [32]. The Hercules Sizing Tester uses a solution of formic acid and naphthol green B dye ink that penetrates the sheet. As the solution moves through the sheet, it allows optical detection. The time required for the reflectance of the paper surface not in contact with the dye solution to drop to a predetermined percentage of the original reflectance is measured [33].

2.2.3. Precalendering

Paper is precalendered prior to coating. The precalendering process serves to densify and reduce the number of pores in the sheet [15]. As stated by Lepoutre *et al.* [34], uncalendered samples tend to have a low residual stress and large pores. During the coating process, coating pigment may sink into these pores due to the external pressure of the application roll. This leads to poor surface coverage and coating holdout. Precalendering reduces porosity and improves smoothness. In addition, it helps to prevent coating penetration that can cause poor coating uniformity and coating coverage [35,36,37]. As stated by Koyamoto and Okomori [35], good coating layer uniformity is an important parameter for print quality and helps to prevent mottling in offset printing. Gron [38] found that for LWC papers, coating coverage is 60% with precalendering and 50% without precalendering. In addition to precalendering, coating coverage is improved by using platy kaolin clay, and base paper with a large amount of fines and minimum amount of coarse fibres. Precalendering attaches loose components and fibres to the surface of paper. It improves coater runnability because it limits the detachment of particles that can cause streaks in the coating layer, blade lines and web breaks [39].

Generally, hard nip calendering is used for precalendering and hot soft nip calendering (HSNC) is used for the final calendering. With conventional precalendering, smoothness is negatively correlated to bulk. Kotamoto and Okomori [35] precalendered samples to the same smoothness by adjusting the line load but varying the temperature using a HSNC. High temperature precalendering was more effective in reducing the number of large pores ($>5\text{ }\mu\text{m}$) on the paper surface compared to low temperatures and no precalendering. However, the number of small pores ($<2\text{ }\mu\text{m}$) increased at high temperatures but did not affect the coating coverage. In fact, precalendering at high temperatures led to an increase in coating uniformity equivalent to 1 g/m^2 coating on the surface.

Precalendering at high temperature could lead to the thermoplastic softening of the lignin on the surface of the paper. This temperature is called the glass transition temperature of the fibre component (seen in Table 2.3) and helps to ‘seal’ the surface of paper. All three components of fibre are hydrophilic and the glass transition temperature is moisture dependent [39]. For the paper used in this thesis, the moisture content is approximately 4% and the lignin glass transition temperature would be approximately 100-110°C.

Table 2.3: Glass Transition Temperature of Fibre Components Under Dry Conditions [40,41,42,43,44]

Fibre Component	T _g (°C)
Cellulose	200 to 250
Hemicellulose	150 to 250
Lignin	130 to 200

2.3. Previous Work on Coated Papers with Mechanical Pulp

In this section, previous literature regarding factors that affect the roughness and bulk of papers containing mechanical pulp, such as precalendering temperature and internal sizing, will be discussed.

2.3.1. Previous Literature on the Factors Affecting the Roughness and Bulk of Coated Papers with Mechanical Pulp

Forseth *et al.* [10] studied the surface roughening mechanisms using commercial SC papers containing mechanical pulp. The effect of coarse fibres and fines content on paper surface smoothness after moistening was investigated. The paper samples were subjected to different degrees of moistening in humid air at 97%, 20 °C for 24 hrs or soaked in distilled water for two seconds. Samples with the highest fines content were smoothest prior to and after moistening. It was concluded that fines do not hinder roughening; however, the presence of fines reduced the amount of coarse fibres. The amount of coarse fibres was the main factor in determining the degree of roughening during moistening.

Skowronski [14] focused on the papermaking variables that affect surface roughening of paper due to the coating process. The papermaking properties considered were pulping, bleaching, wet-pressing, conventional calendering (50°C), and temperature gradient (TG) calendering (203°C). Paper samples made from TMP or Kraft pulp with varying papermaking properties were surface treated with water or coating colour using a puddle type and a blade coater. The calendering conditions were 100 m/min, one pass and a hard nip. When the TMP sheets were coated, the paper gloss decrease but the PPS roughness ($10\text{kg}_f/\text{cm}^2$) increased. TMP sheets were roughened

more than Kraft sheets. Also, TG calendered sheets produced glossier and smoother sheets compared to conventional calendering because thermoplastic softening of the surface fibres. TG was most effective in improving gloss that reducing the roughness because it smoothen the individual fibres in contact with the heated roll. In addition, thick fibre cell walls tend to recover their original shape during wetting. However, two key questions remained unanswered: (a) how important is using TG calendering for increasing gloss, and (b) if less calendering is required to achieve the targeted final gloss for these samples.

Forseth and Helle [19] investigated the effect of precalendering, hydrophobic sizing with 0.5%AKD in a hexane immersion, and premix of rosin-alum size on the roughness of paper samples. Newsprint (91%), LWC (55%) and SC (88%) papers; with the % mechanical pulp shown inside the parentheses, were precalendered to various degrees: mild conditions (120 kN/m, 62°C, 2 nips), harsh conditions (150 kN/m, 6 nips, 90°C, 20 m/min), and uncalendered. Water with dissolved LiCl was applied using a laboratory coater (800 m/min) and the mass of water picked up was measured using mass spectrometry. After wetting with water, uncalendered samples showed no change in PPS roughness, while precalendered newsprint exhibited significant increase in roughness (28%). Similar trends were seen for both the LWC and SC papers. Hydrophobic sizing led to a relatively insignificant reduction in surface roughening for precalendered sheets and for uncalendered sheets had no effect on the surface roughness. The experimental plan was too limited to determine the effect of harsh and mild calendering. In addition, the effect of mechanical pulp content <55% was not investigated.

The effect of precalendering and hydrophobic sizing on the coating holdout was investigated by Lepoutre *et al.* [34]. The handsheets made of 60% groundwood and 40% Kraft pulp were prepared with and without 1% hexane solution of ketene dimmer. A film-forming polymer in

solution, CMC, and 6-10 g/m² coating colour were added using a puddle blade coater. The samples were calendered at 16m/min and 10 kN/m. They found that hydrophobic sizing was ineffective in limiting coating penetration because it did not reduce the rate of diffusion of water molecules into the paper sample. Forseth and Helle [19] arrived at a similar conclusion: the smoothness after coating for hydrophobically sized papers was similar to that of the untreated paper, although systematically lower. Precalendering was effective in reducing coating penetration because it limited penetration and the subsequent diffusion of water molecules. It was concluded that high residual roughness is not due to the capillary movement of coating components into the sheet but to the diffusion of water molecules.

Engstrom and Lafaye [36] compared uncalendered basesheets to precalendered basesheets in terms of roughness, thickness, and coating mass distribution. LWC papers containing mechanical pulp: 50 g/m² were precalendered at 4.7 μ m, 100 kN/m, 400 m/min on the felt side, blade coated using a pilot coater at 1000m/min with 11 g/m² of clay, and calendered at 80°C, 300kN/m. The coating layer was more evenly distributed in uncalendered sheets (contrary to what was expected, since the precalendered samples are smoother) because the latex binder was more uniformly dispersed in these sheets. However, the ‘uncalendered’ sample was already machine calendered prior to the precalendering. The precalendered basesheets produced the smoothest sheets after coating but had the greatest change in roughness. In addition, the thickness of the precalendered basesheets doubled during coating compared to the uncalendered sheets.

Skowronski and Lepoutre [13] studied the changes in paper structure that occurs during water-paper interaction in the coating process. Three types of papers including: LWC (36 g/m², 60% double screen groundwood, 40% bleached Kraft), newsprint (88% groundwood, 12% bleached

Kraft) and newsprint (30% TMP, 60% double screen groundwood, 10% bleached Kraft) were examined. The coating color consisted of 15 pph latex, no.1 dispersed clay and 65% solids at a drying temperature of 100°C with a puddle type coater. The roughness and thickness increased by the destructive force of water which acted both on the interfibre (fibre to fibre bond breakage and internal stress redistribution) and intrafibre (swelling) levels. The thickness increase after coating was due to a combination of factors: the destructive action of water and the increase in thickness due to the layer of coating. Papers with more mechanical pulp showed larger structural changes during coating. In addition, sizing delayed the surface structural changes.

2.3.2. Recent Work on Aspen HYP

Recently, there have been numerous studies focusing on the partial substitution of Aspen HYP for HBKP. This section provides a summary of relevant literature.

Hu *et al.* [7] studied the substitution of Aspen HYP for HBKP in LWC wood-free papers. Handsheets were prepared using a dynamic sheet former. The furnish was a mixture of SBKP (557 ml CSF), HBKP (418 ml CSF), and Aspen HYP (344 ml CSF). The softwood composition was fixed at 50% and Aspen HYP was varied from 0, 10, 15, 20, 25 and 30% and remainder was HBKP. The following results were found for basestock samples with up to 30% Aspen HYP:

- The CSF of the furnish was slightly reduced but in LWC sheets a drainage problem was not expected. Tear resistance, burst index, and folding endurance were not affected.
- The basestock bulk increased as the HYP content increased and the top side PPS roughness was unaffected because of the higher fines content.
- There was improved formation which could lead to better strength and structure uniformity of the basestock.

- There was no loss in tensile index or elastic modulus. In addition, the fibre to fibre bonding increased due to the highly fibrillated fibre surface.

These results confirm that up to 30% Aspen HYP substitution for HBKP did not negatively impact the strength of LWC wood-free basestock.

In a subsequent study, Hu *et al.* [45] focused on the impact of HYP substitution on the bulk, surface properties, coating coverage, and printability of coated calendered papers. The experimental parameters were the same as listed in the above paragraph; in addition, the resulting samples (41 g/m²) were coated (9 g/m² per side, 67% coating solids, 80 pph ground calcium carbonate, 20 pph clay, 14 pph binders). The samples were calendered with a laboratory soft-nip calender at 50 m/min with different calendering loads of 140 kN/m and 280 kN/m at 50°C. Even at high calendering loads, the bulk advantage of HYP substitution seen in the basestock was partially preserved for the coated calendered sheets. For 30% HYP substitution, there was a 10% bulk increase compared to 0% HYP at 140 kN/m and 50°C. It was difficult to compare the coated calendered bulk at different calendering loads because samples were not calendered to the same TAPPI gloss.

Up to 15% HYP substitution, there was no negative impact on the roughness of the coated paper samples. This occurred because HYP is a chemically treated mechanical pulp, and substituted for only a portion of HBKP in wood-free basestock. Also, HYP did have an effect of coating coverage; however, from 10-30% HYP, the % of uncovered fibres was unchanged.

Zou and Zhou [1] discussed some of the practical applications of HYP in wood-free coated papers. If HYP content is increased from 5 to 15%, it could avoid a fluting problem because it would improve the bending stiffness. They compared coating holdout of samples with and

without HYP. The reference basestock had equal amount of HBK and SBK pulps: whereas, the other sample had 25% HYP, 25% HBK and 50% SBK. HYP substitution had no effect on the coating holdout 6.79% (0% HYP) to 6.72% (25% HYP). Although the total number of pores increased for the sample with HYP, the number of large pores ($>20\mu\text{m}$) did not increase because the HYP had a higher fines content (2-3 times) compared to the Kraft pulps. In addition, they found that HYP did not significantly affect coating uniformity which is an essential parameter in developing good product quality.

2.4. Conclusions and Statement of Problem

The roughening of mechanical pulp has been well-studied as seen in the literature review. However, most of the research has been on papers containing high levels of groundwood, newsprint and TMP. There is little knowledge of the roughening that occurs at low mechanical pulp content and for BCTMP, specifically Aspen HYP since this type of pulp is widely produced and marketed. It is important to investigate how different papermaking parameters affect the roughening of this type of pulp. In addition, the conditions that control the bulk of coated papers with Aspen BCTMP pulp calendered to a targeted TAPPI gloss has not been studied extensively.

This thesis focuses on the effect of Aspen BCTMP pulp substitution (0-30%), Aspen pulp type, precalendering temperature, and internal sizing on the roughness of paper samples after pigment coating or water application. It also investigates how these parameters affect the coated calendered bulk of paper samples and ranks the important of each parameter on the coated calendered bulk using PLS modeling with SIMCA-P.

3. CHAPTER 3 – THE EFFECT OF PAPERMAKING CONDITIONS ON THE ROUGHNESS OF WOOD-FREE COATED PAPERS CONTAINING ASPEN HIGH- YIELD DUE TO WATER APPLICATION

3.1. Introduction

Paper is a network of fibrous materials and is hygroscopic in nature. As a result, water applied during the coating process causes fibre swelling and irreversible changes in the paper structure [13,46,47,48]. Roughening is the permanent distortion of the fibrous network of paper and results when paper is in contact with water [49,50]. Wood-free paper grades together with sizing are used to reduce the extent of roughening of the paper surface upon contact with water. It is generally accepted that mechanical pulp fibres compared to chemical fibres are more susceptible to roughening. However, there are inherent advantages for using mechanical pulp such as higher bending stiffness, lower cost, increased productivity and environmental friendliness. These advantages fuels interest in using mechanical fibres for printing grades [10,34].

Lepoutre *et al.* [34] acknowledged that the roughening suffered by coated papers containing HYP was severe and a hindrance. These rougher coated sheets required harsh supercalendering conditions to achieve similar gloss levels compared to wood-free grades, which was detrimental to bulk and opacity. The roughening of paper samples with mechanical fibres during the coating process is largely affected by the precalendering of the basesheet. Chemical fibres are ribbon-like and well-collapsed, whereas the mechanical fibres are stiffer and tubular in shape and do not collapse as readily because they contain lignin [49]. Precalendering forces the stiff tubular mechanical fibres to collapse and imposes internal stress on the fibrous network of paper. This is necessary to produce a smoother paper surface prior to coating to improve coating coverage and reduce coating penetration [38]. However, water application during the coating process releases

this internal stress and the fibres recover their shape prior to precalendering causing irreversible changes in the paper structure. Hence, maintaining the smoothness of paper grades with mechanical fibres is difficult [51]. Surface roughening is detrimental to print quality and coating weight distribution [18,52].

Although the surface roughening phenomenon has been well-studied, most of the investigations were carried out on newsprint, SC papers, and LWC papers with mechanical pulp content greater than 55%. However, there has been limited research on the effect of papermaking conditions on the roughening of paper samples containing Aspen HYP at 30% or less addition levels. Further investigation is required to determine how Aspen HYP roughens under different papermaking conditions. This chapter provides a comprehensive investigation of the combined effects of precalendering temperature, HYP type, HYP content, and the level of rosin-alum size on the roughness of wetted paper samples. To investigate the roughening of basesheets during the coating process, controlled amounts of water were applied on precalendered uncoated papers using a RNA-52 Printability Tester with a modified print form. This work provides a fundamental understanding of the effect of HYP on the roughening process during wetting.

3.2. Experimental Plan

The experimental plan used in this study is shown in Table 3.1. The effect of HYP content on the bulk was examined using Aspen 325/85 HB pulp. Four levels of HYP content: 0, 10, 20, and 30% were examined. These experiments were done to quantify the increase in roughness after wetting as the HYP content increased.

The effect of high-yield pulp type was determined by comparing samples made from 30% Aspen 325/85 HB or 30% Aspen 300/85 to samples with no HYP. The characteristics of both high-yield pulps are given in section 3.3.1.

The impact of precalendering temperature was examined at three levels: 23, 80, and 140 °C for paper samples made from 30% Aspen 325/85 HB and 30% Aspen 300/85.

Internal sizing level was examined using rosin-alum size at three levels: 0, 0.10, and 0.15 wt% based on the mass of oven dried pulp. This was done for samples containing either 30% Aspen 325/85 HB or 30% Aspen 300/85.

A total of 19 different conditions were examined as shown in Table 3.2. For each condition, there were four-six samples with different amounts of applied water. The total number of samples prepared and analyzed in this study was 112.

Table 3.1: Experimental Plan for Wetted Paper Samples

Parameter Type	Factor	Component	Levels
Fixed	Base Sheet	Basis weight	1
	Water Application	Print Force	
	Calendering Conditions	Calendering Speed	
		Precalendering Pressure	
	Furnish	Chemical Pulp Type	
Variables	Furnish Content	High-yield Pulp Content	4
	Wood Species	High-yield Pulp Type	2
	Papermaking Process	Internal Sizing Level	3
	Calendering Condition	Precalendering Temperature	3
	Water Application	Print Speed	4

Table 3.2: Experimental Conditions

Condition #	% HYP	HYP Type	Rosin-Alum (wt %)	Precalendering Temp(°C)
1	10	Aspen 325/85 HB	0	80
2	0	Aspen 325/85 HB	0	80
3	30	Aspen 300/85	0	80
4	30	Aspen 325/85 HB	0.1	140
5	30	Aspen 300/85	0.15	80
6	30	Aspen 325/85 HB	0.1	80
7	30	Aspen 325/85 HB	0.15	140
8	30	Aspen 325/85 HB	0	80
9	30	Aspen 300/85	0.1	80
10	30	Aspen 325/85 HB	0.15	80
11	20	Aspen 325/85 HB	0	80
12	30	Aspen 300/85	0	23
13	30	Aspen 325/85 HB	0	23
14	30	Aspen 325/85 HB	0	140
15	30	Aspen 300/85	0	140
16	30	Aspen 300/85	0.1	23
17	30	Aspen 300/85	0.15	23
18	30	Aspen 325/85 HB	0.1	23
19	30	Aspen 325/85 HB	0.15	23

3.3. Sample Preparation

The experimental procedure is shown in Figure 3.1. Handsheets were made from a combination of Eucalyptus hardwood, softwood Kraft and Aspen 325/85 HB or Aspen 300/85. The handsheets were precalendered and water applied to them using a RNA-Printability Tester.

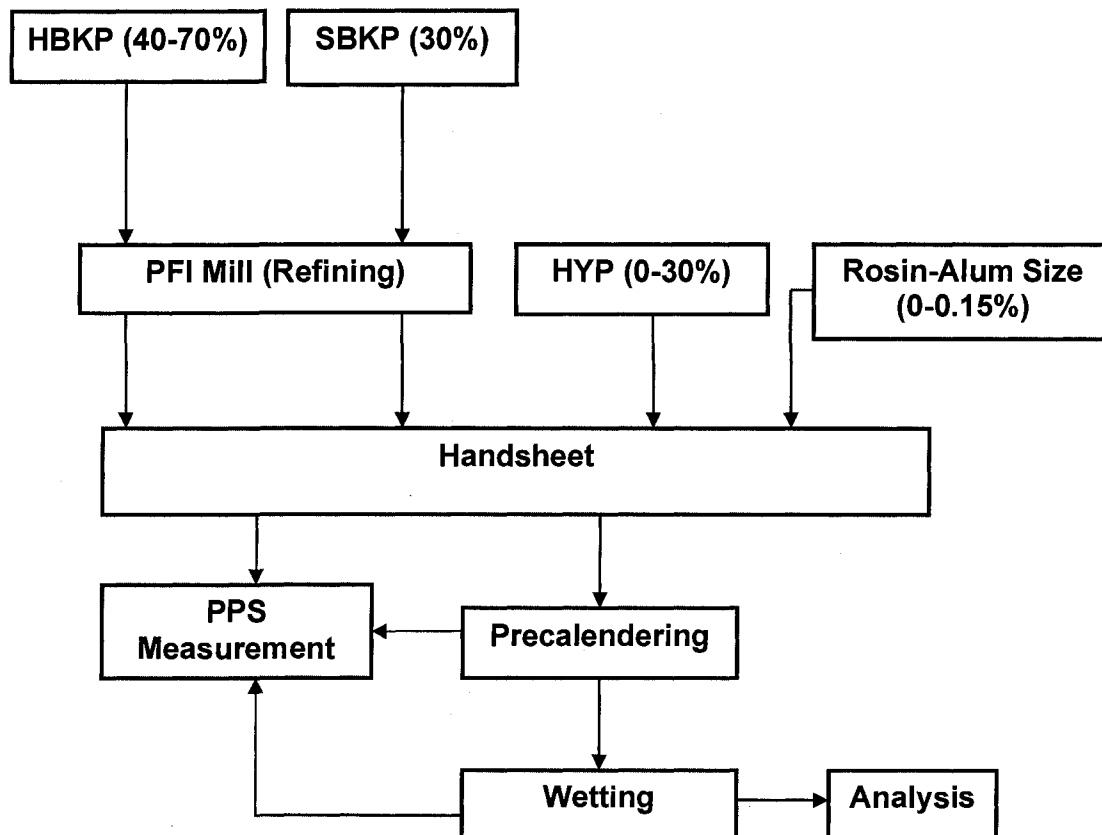


Figure 3.1: Schematic Diagram of Experimental Procedure

3.3.1. Furnishes

The furnish was a mixture of bleached Eucalyptus hardwood, bleached softwood Kraft and high-yield pulp. Two types of high-yield pulps were used in this work, Aspen 325/85 HB and Aspen 300/85. Properties of the pulps are shown in Table 3.3.

Table 3.3: HYP Characteristics [53]

Property	Aspen 325/85 HB	Aspen 300/85
Freeness (ml)	316	309
Bulk (cm ³ /g)	2.3	1.72
Tensile Index (Nm/g)	31.4	46.1
Fines <0.41mm (%)	14.4	21.0

3.3.2. Handsheet Preparation

The moisture content of the different pulps was determined according to TAPPI Test Methods T 412 [54]. The pulp samples were torn, weighed, and placed into an oven at 110°C. It was removed from the oven and weighed every 30 minutes until there was no difference between successive weights. The moisture content was calculated as shown in Equation 3.1. The tabulated values are found below (Table 3.4).

$$M_c (\%) = \frac{m_o(g) - m_{o,d}(g)}{m_o(g)} \times 100\%$$

Where:

M_c = Moisture content Equation 3.1

m_o = Initial mass of pulp

$m_{o,d}$ = Mass of oven dried pulp

Table 3.4: Moisture Content of the Different Pulp Samples

	Softwood	Hardwood	Aspen 325/85 HB	Aspen 300/85
Moisture Content (%)	6.4	7.4	12.6	12.4

Both chemical pulps were soaked overnight in a known volume of water. The saturated hardwood and softwood Kraft pulps were refined separately to typical target CSF values of 404 and 512 ml, respectively using a PFI mill (Figure 3.2). The calibration curve of freeness (ml) against number of revolutions was determined for each chemical pulp (Figure 3.3). The freeness was measured using a Canadian Standard Freeness Tester (Figure 3.2). Both high-yield pulps were left unrefined.

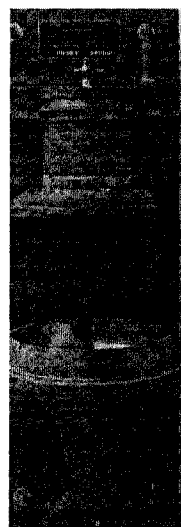
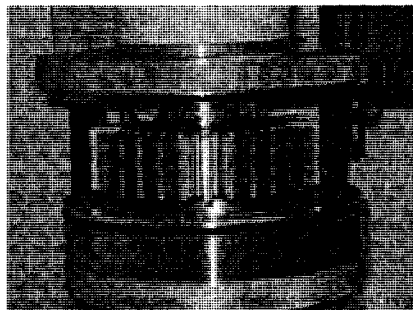


Figure 3.2: PFI Mill (On the Left) and Canadian Standard Freeness Tester (On the Right)

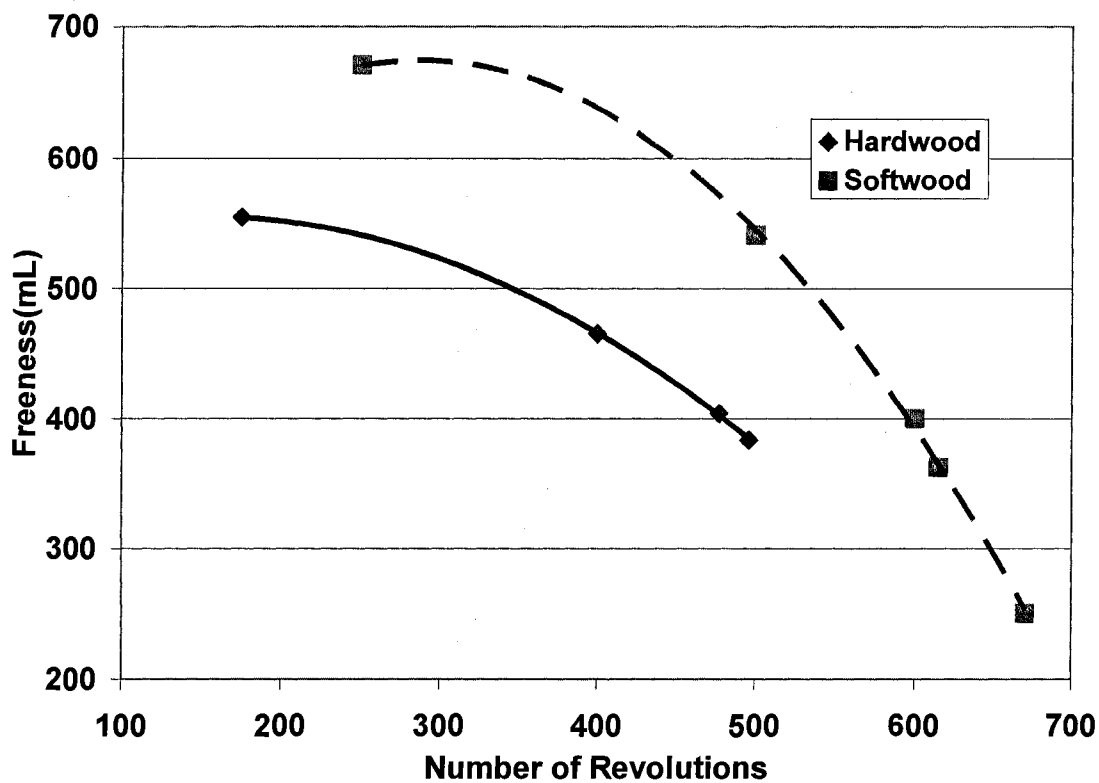


Figure 3.3: Freeness of the Different Chemical Pulps

Basesheets ($56\text{-}64\text{ g/m}^2$) were produced using a standard British handsheet maker. Recirculation was used to maintain the fines in paper samples. The paper samples contained different

proportions of: hardwood Eucalyptus, softwood, Aspen 325/85 HB, or Aspen 300/85. In wood-free samples, the softwood and hardwood made up 30% and 70% of the base sheets, respectively. In samples containing HYP, Aspen 325/85 HB or Aspen 300/85 was substituted for up to 30% for the hardwood Eucalyptus pulp. The handsheets were made according to TAPPI Test Methods T 412 [55].

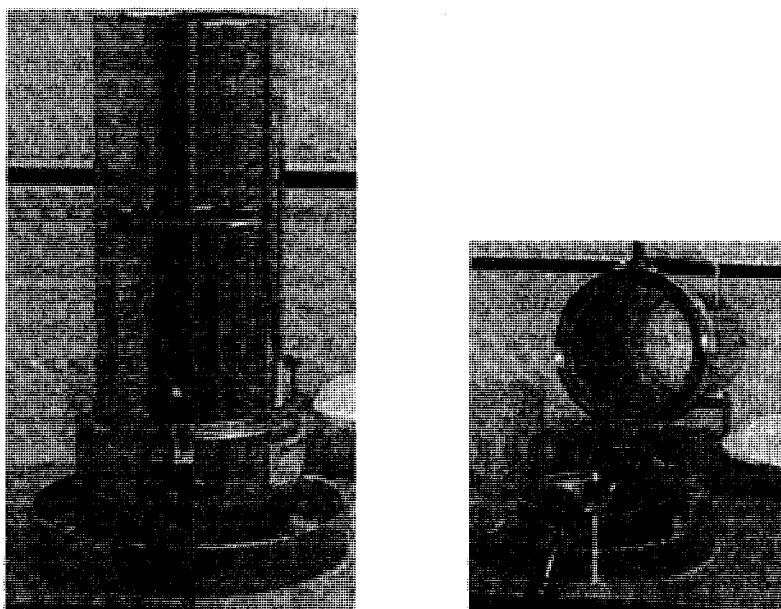


Figure 3.4: Handsheet Making Machine

3.3.3. Rosin + Alum Internal Size

Handsheets were made with and without internal sizing. Emulsions up to 0.15 wt% rosin (Ultraphase, Hercules Inc.) and alum (Aluminium Sulfate Hydrate, 98%, SIGMA-ALDRICH Inc.) based on the mass of oven dried pulp were added to the pulp suspension. The rosin: alum ratio used was 1:1 and the paper samples were left to air dry at 23°C for 24 hours. The experimental procedure and the amount of rosin-alum added are described below.

Table 3.5: Rosin-alum Internal Sizing

Sizing Level (%)	Ratio(Rosin : Alum)	Rosin Required(ml)	Alum Required (ml)
0.05	1:1	1.2	1.2
0.10		2.4	2.4
0.15		3.6	3.6

Rosin and alum solutions with 1 wt% solid content were measured in 250 ml graduated cylinders. The solid content by mass of rosin and alum were 35% and 98%, respectively. The required volume of rosin and alum (shown in Table 3.5) was pipetted into a bucket containing the pulp suspension. A pulp suspension contained 24 grams of pulp on the dry basis. For example, if 0.10% Rosin-alum was required, then 2.4 ml of rosin and alum were placed into the bucket with the pulp suspension. The addition sequence of these materials was kept constant. In the bucket with the mixing pulp suspension, the required volume of rosin was added and 30 seconds later, the required volume of alum was added. They were allowed to mix for at least eight minutes before the handsheets were made.

3.3.4. Precalendering Conditions

The samples were precalendered at 23, 80, and 140°C using a Beloit-Wheeler Supercalender at a speed of 75 m/min shown in Figure 3.5. The number of nips and line load were held constant at two and 62 kN/m, respectively. The felt side of the sample was in contact with the hard heated roll and the wire side touched the soft roll.

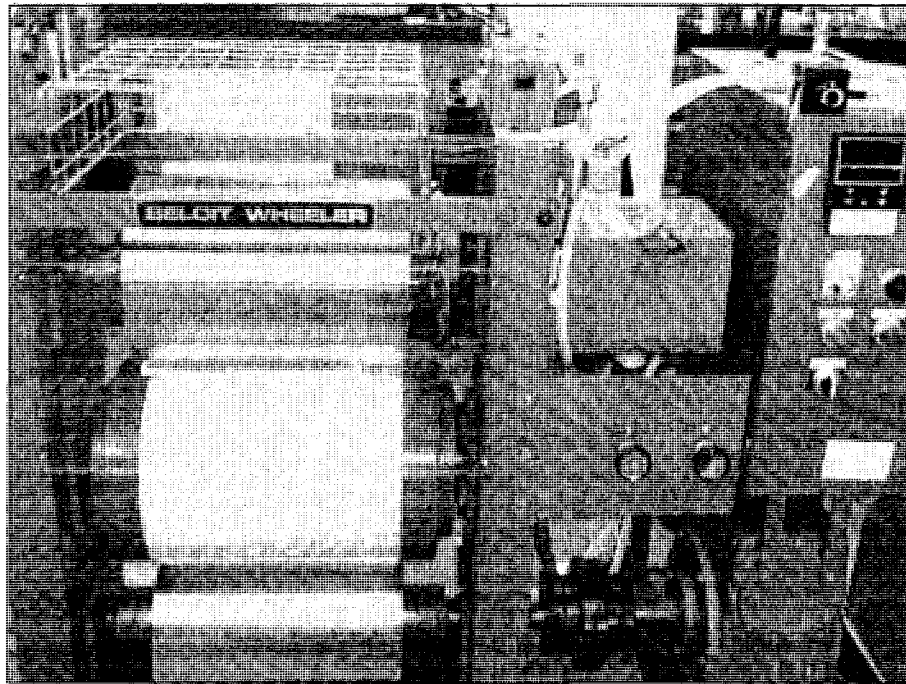


Figure 3.5: Beloit-Wheeler Supercalender

3.3.5. Water Application

The metal print form was modified with a sheet of $\frac{1}{32}$ " polyurethane form which allowed the application of water without additives (Figure 3.6(a)). This form was saturated with water prior to coating in the RNA-32 dampening unit as shown in Figure 3.6(b) to ensure that controlled amounts of water were applied to the paper. For subsequent prints, approximately 1 ml of water was used to re-saturate the form. The samples were mounted on a plastic report cover ($5\text{ cm} \times 10\text{ cm} \times 0.25\text{ mm}$) and attached to the print sector (Figure 3.6(c)). After the water was applied, the sample was immediately covered with a plastic wrapper and allowed to sit for several minutes to prevent evaporation and to ensure all the water got absorbed by the sample. The amount of water applied was then measured gravimetrically. This method of water application was developed by Samsudeen [56] at the Pulp and Paper Centre, University of Toronto.

The amount of water applied to the precalendered paper sample was controlled by the printing speed. The modified RNA-52 Printability Tester at a constant force of 100 N and at four different speeds: 50, 100, 150 and 200 cm/s were used. The lowest printing force of 100 N was used to minimize the smoothening effect caused by the compression of the paper. In addition, a constant low force would minimize errors in the roughness and avoid forced water penetration.

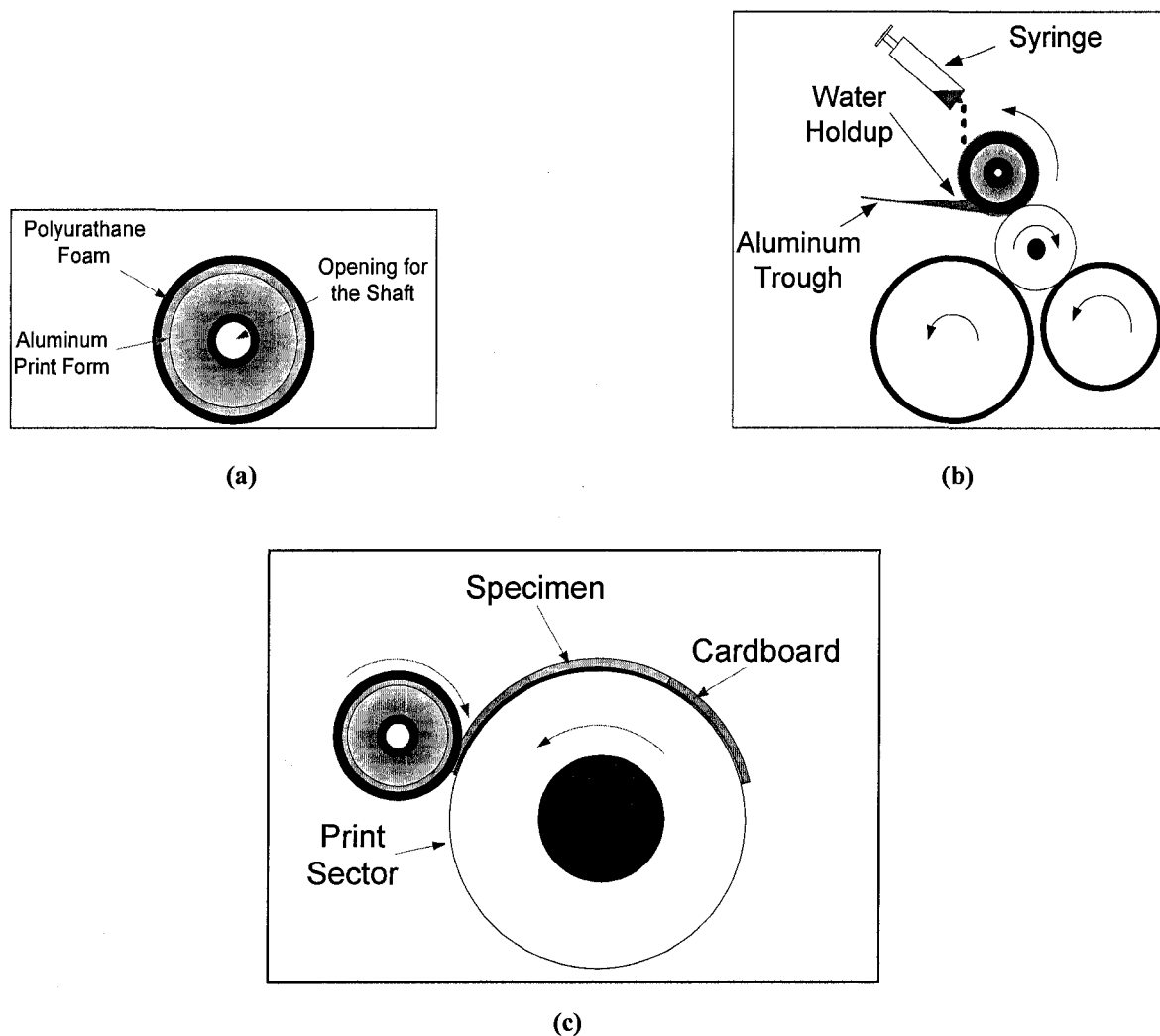


Figure 3.6: Schematic Diagram Showing the RNA-52 Printability Tester Using a Modified Print Form (a) Schematic Diagram of Modified Aluminium Print Form; (b) Schematic Diagram Showing the Water Pick-up by the Modified Print Form; (c) Schematic of the Printing Section of the RNA-52 Printability Tester. (Schematics Taken from Samsudeen [56])

3.3.6. Measurements

The handsheets were circular with a diameter of 15.9 cm. They were cut into squares of length 10 cm and the weight was measured. From this, the basis weight was calculated as shown in equation 3.2.

$$BW\left(\frac{g}{cm^2}\right) = \frac{W(g)}{A(cm^2)}$$

Where :

BW = Basis weight of uncoated uncalendered paper Equation 3.2

W = Weight of uncoated uncalendered paper

A = Area of uncoated uncalendered paper

The roughness of the paper samples was measured after handsheet making, precalendering, and wetting. The roughness for each sample was measured three times at different areas on the sheet and the average roughness was calculated. Roughness was measured using a Parker Print-Surf with a clamping pressure of 20 kg/cm² and a hard backing.

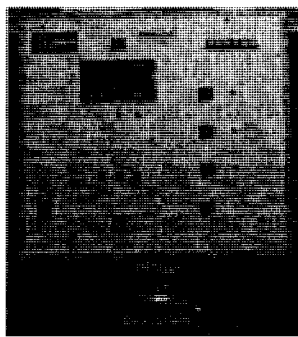


Figure 3.7: Parker Print-Surf Paper Roughness Tester

3.4. Results and Discussion

3.4.1. Summary of Results

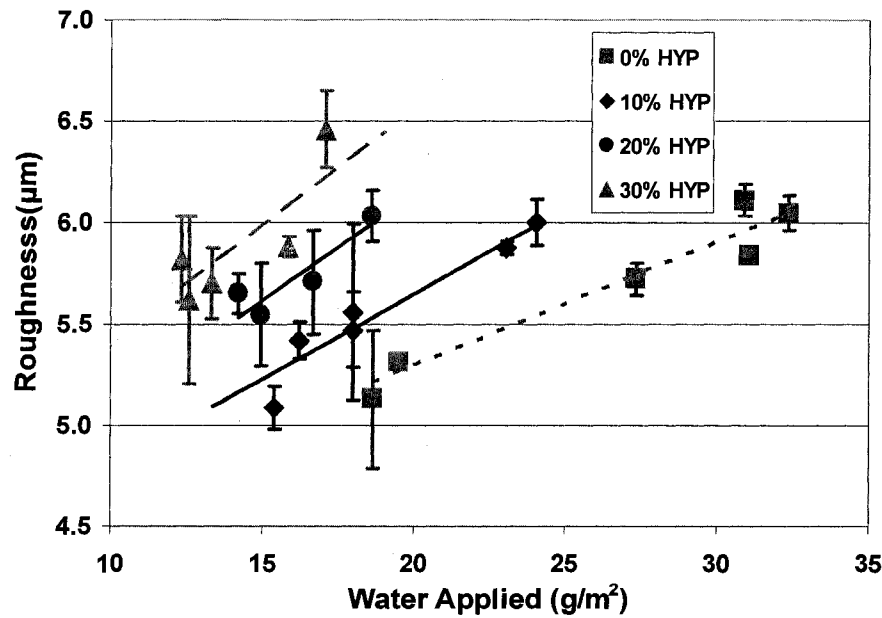
The effect of HYP content, HYP type, precalendering temperature, and rosin-alum size on the roughness of precalendered paper samples are analysed in this section. Table A.1 in Appendix A shows the full experimental results of the experiments including the amount of water transferred to each sample and the corresponding change in roughness.

3.4.2. Effect of High-yield Pulp Content

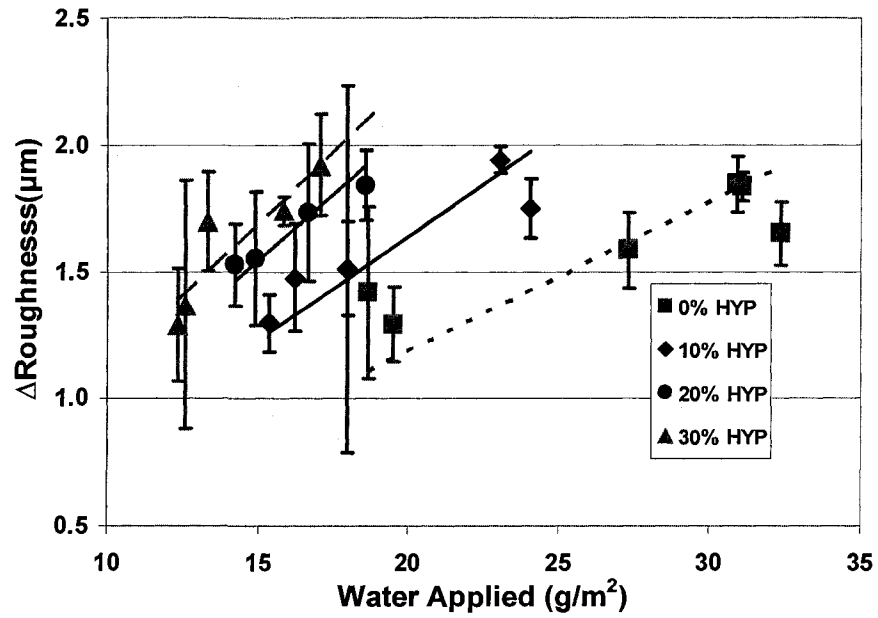
The effect of HYP content on the roughness of the wetted precalendered paper samples is illustrated in Figures 3.8 and 3.9. The samples were precalendered at 80°C, 62 kN/m and two nips. The average roughness of the precalendered samples was $4.1 \pm 0.2 \mu\text{m}$ on the felt side. As expected, the roughness of the precalendered paper samples increased as the amount of applied water applied increased. Figure 3.8 illustrates the negative impact of HYP as a paper furnish. Although the roughness after precalendering was statistically similar for all conditions, it is significantly higher after wetting at higher HYP contents in the sheets. As the HYP content increases, the roughness of the samples after wetting also increases. For example, for an applied water of 10 g/m^2 , the corresponding roughness after wetting were 4.7, 4.8, 5.1, and $5.4 \mu\text{m}$ at 0, 10, 20, and 30% HYP content, respectively. As discussed earlier, this is due to the release of internal stress imposed by the precalendering on the fibrous network and this effect is more severe for HYP compared to Kraft pulp. As a result, an increase in mechanical fibres results in a greater roughening due to water application.

In addition, the slope of the regression lines (Figure 3.8(b)): 0.059, 0.082, 0.103, and 0.113 $\mu\text{m}/(\text{g}/\text{m}^2)$ respectively, increases as the mechanical pulp content increases. This is expected since mechanical fibres are more sensitive to water addition compared to chemical fibres.

As shown in Figure 3.8(b), the increase in roughness due to the HYP content becomes more pronounced as the amount of water applied increases. Note that the amount of water for a coating solution of 15 g/m^2 at 60% solids corresponds to 10 g/m^2 of applied water. However, in a practical coating situation as stated by Skowronski and Lepoutre [57], the actual amount of water in contact with the fibres could be as little as 3 g/m^2 . The remainder of water will be evaporated by the dryers. Figure 3.9 shows extrapolated values for the change in roughness during wetting as a function of water applied and HYP content. It offers a more realistic picture of roughness changes that could occur during the coating process.



(a)



(b)

Figure 3.8: The Effect of Water Application at Various HYP Contents for Samples Precalendered at 80°C , 62 kN/m and Two Nips (a) Roughness of Paper Samples After Wetting; (b) Change in the Roughness of the Paper Samples During Wetting

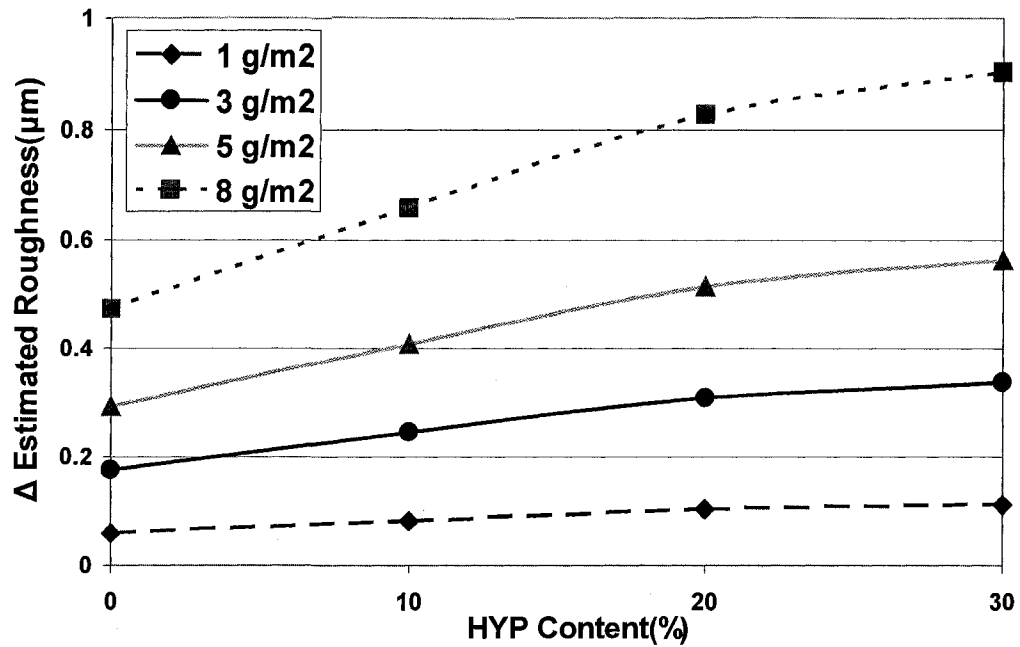


Figure 3.9: The Effect of HYP Content on the Change in Roughness of the Paper Samples at Different Applied Water

3.4.3. Effect of Furnish Type

Figure 3.10 illustrates the effect of high-yield pulp type on paper samples precalendered at 80°C. Both paper samples with 30% HYP roughen after and during wetting to a greater extent when compared to samples with no HYP (Figures 3.10 and 3.11(b)). The degree of roughening experienced by both types of high-yield pulps after wetting is similar. However, as shown by the paper samples precalendered at 23, 80, and 140°C, the change in roughness for Aspen 300/85 is systematically lower compared to Aspen 325/85 HB (Figure 3.11). Aspen 300/85 contains 6.6% more fines than Aspen 325/85 HB. This translates to a 2% increase in fines for paper samples containing 30% Aspen 300/85. This amount is not large enough and can only cause a small decrease in the roughening of paper after the wetting process. However, as suggested by Forseth *et al.* [10], fines play an important role in the roughening of paper samples with mechanical pulp. They do not suppress the roughening mechanism but paper samples may have fewer coarse fibres resulting in less roughening during wetting. In addition, Aspen 325/85 HB fibres are bulkier and have a lower tensile index compared to Aspen 300/85 (Table 3.3); hence, Aspen 325/85 fibres could distort the fibrous network of paper more when wet.

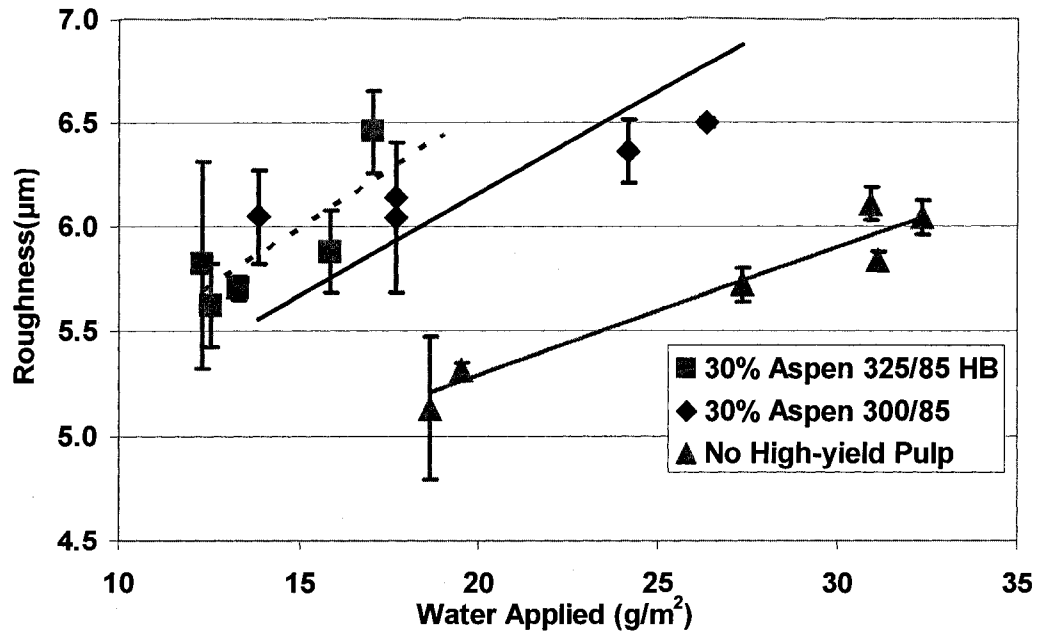
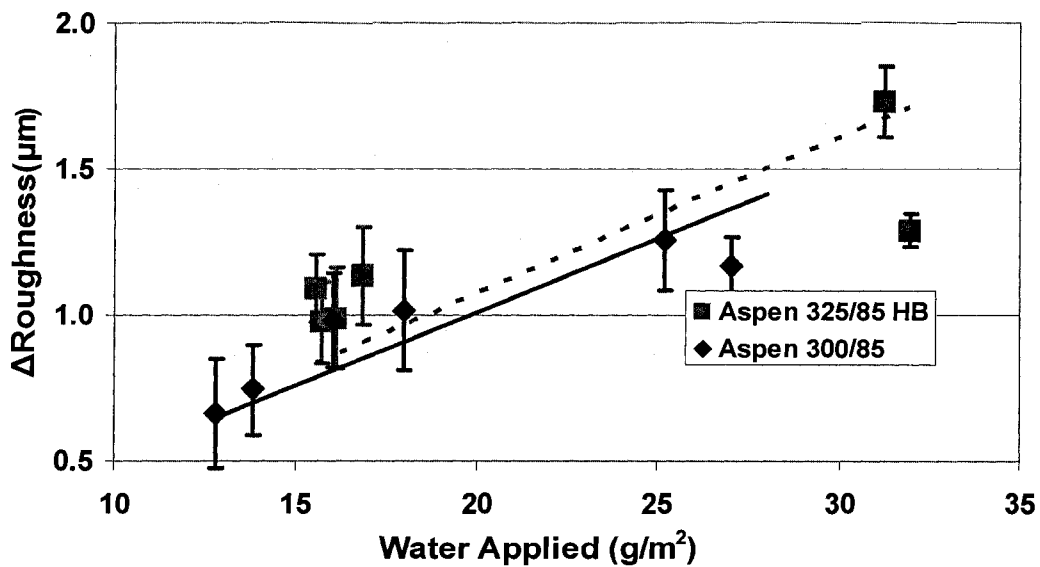
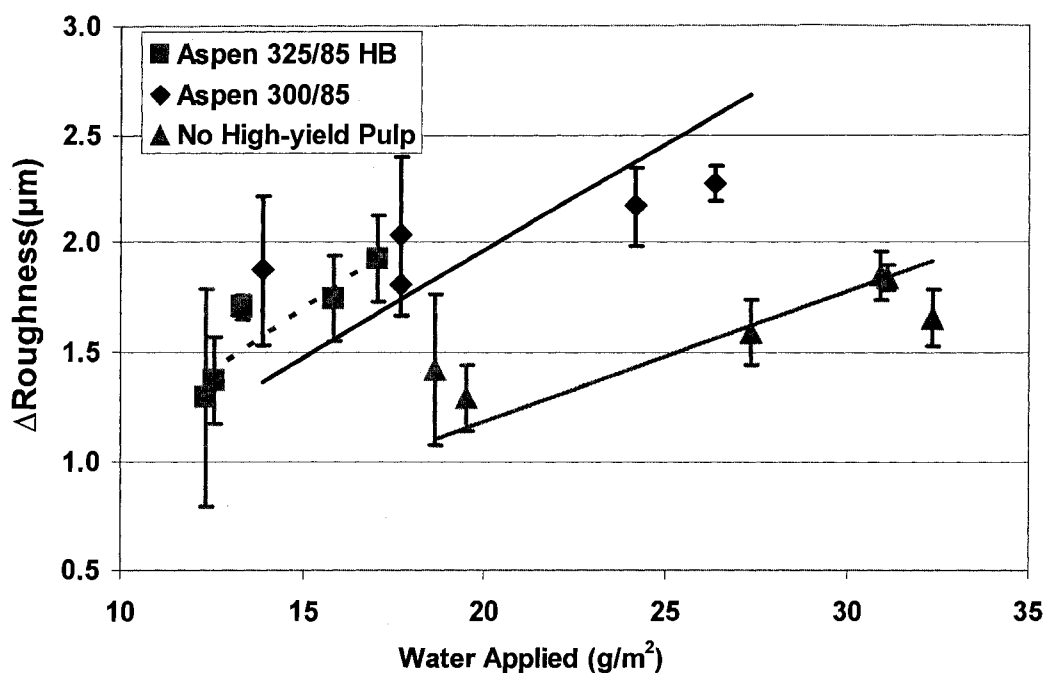


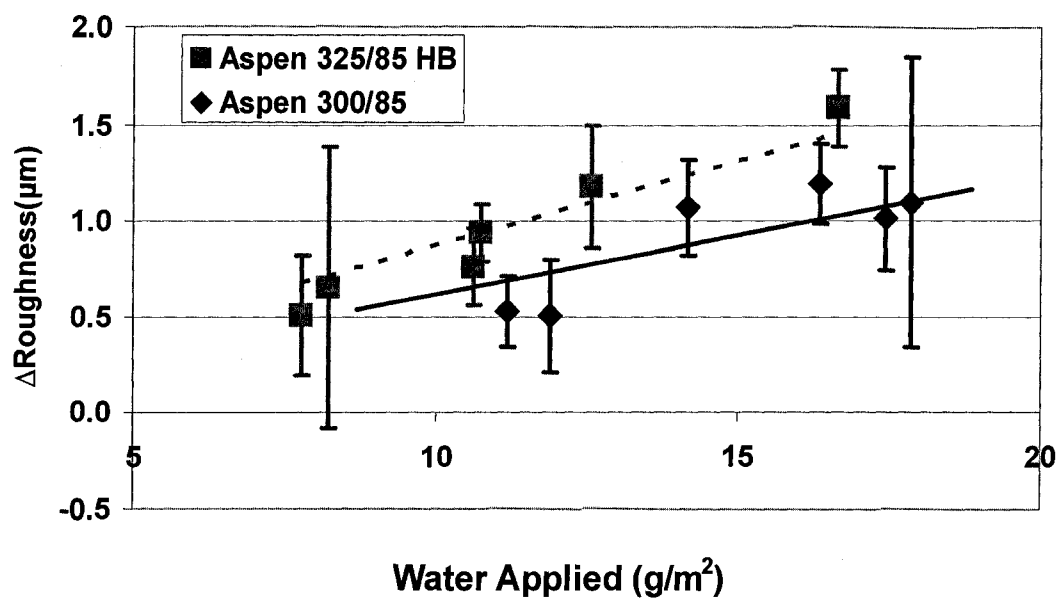
Figure 3.10: The Effect of Furnish Type on the Roughness of Paper Samples Containing Different HYP Content Precalendered at 80°C, 62 kN/m and Two Nips. The Y-Intercept is Set to the Roughness After Precalendering



(a)



(b)



(c)

Figure 3.11: The Effect of Furnish Type on the Roughness of Paper Samples Containing 30% HYP Precalendered at 62 kN/m and Two Nips (a) Paper Samples Precalendered at 23°C; (b) Precalendered at 80°C ;(c) Precalendered at 140°C. The Y-Intercept is Set to Zero

3.4.4. Effect of Precalendering Temperature

The final roughness of paper samples after wetting is dependent on the roughness before wetting and the change in roughness during wetting. The roughness before wetting of the paper samples is affected by the precalendering temperature. After precalendering, the samples had average roughness values of 5.2, 4.3, and 3.7 μm at precalendering temperatures of 23, 80, and 140°C, respectively. As the precalendering temperature increases, the reduction in roughness occurs because the pores on the surface of the paper close as shown by the series of SEM pictures in Figure 4.12 of section 4.3.4. In addition, for temperatures above the glass transition temperature of lignin (100-110), the thermoplastic softening and smoothening of fibre wall occurs [11].

Interestingly, the slope of the regression lines shown in Figure 3.12 indicates that the sensitivity of paper samples to the wetting process is affected by precalendering temperature. It is important to note that the water applied in these experiments refer to the actual amount of water absorbed by fibres. As mentioned earlier, at a typical coating weight of 15 g/m^2 at 60% solids, there are 10 g/m^2 of available water to get in contact with the fibres. Realistically, only 35-50% of this water will be in contact with the fibres because some of the water will be removed by the dryers [12]. Figure 3.14, shows the roughness change at lower amounts of water applied. Paper samples precalendered at 80 and 140°C have a higher change in roughness compared at 23°C. This is due to the high residual stress imposed on the fibrous network of paper at higher calendering temperatures. As a result, water has a larger effect on the roughening during coating at higher precalendering temperatures.

Although samples precalendered at 140°C place more stress on the fibrous network of paper compared to 80°C, they are less susceptible to roughening during water application.

Thermoplastic softening leads to a smoother surface before wetting; however, this hard calendering could cause permanent deform to the fibres. As stated by Reme *et al.* [58], it could potentially cause longitudinal breaks and cracks on the fibres. This hinders their ability to decollapse during wetting. The samples precalendered at 80°C are not subjected to this thermoplastic softening effect; hence, the fibres decollapse when wet.

In a practical situation, the amount of water in contact with the fibres is dependent on the precalendering temperature. It is expected that during the coating process, the amount of water in contact with the fibres will decrease as the precalendering temperature increases. Hence, it is possible that samples precalendered at 23°C could have the highest change in roughness during coating compared to the other precalendering temperatures because its pores are more open and more water seeps into the fibres.

This study provides a fundamental understanding of the effect of precalendering temperature, assuming the water in contact with the fibres were the same. For a typical coating situation, roughness before wetting seems to be more prominent in determining the roughness after wetting compared to the change in roughness during wetting. In general, the difference in roughness before wetting between samples precalendered at different temperatures is greater than the change in roughness due to wetting.

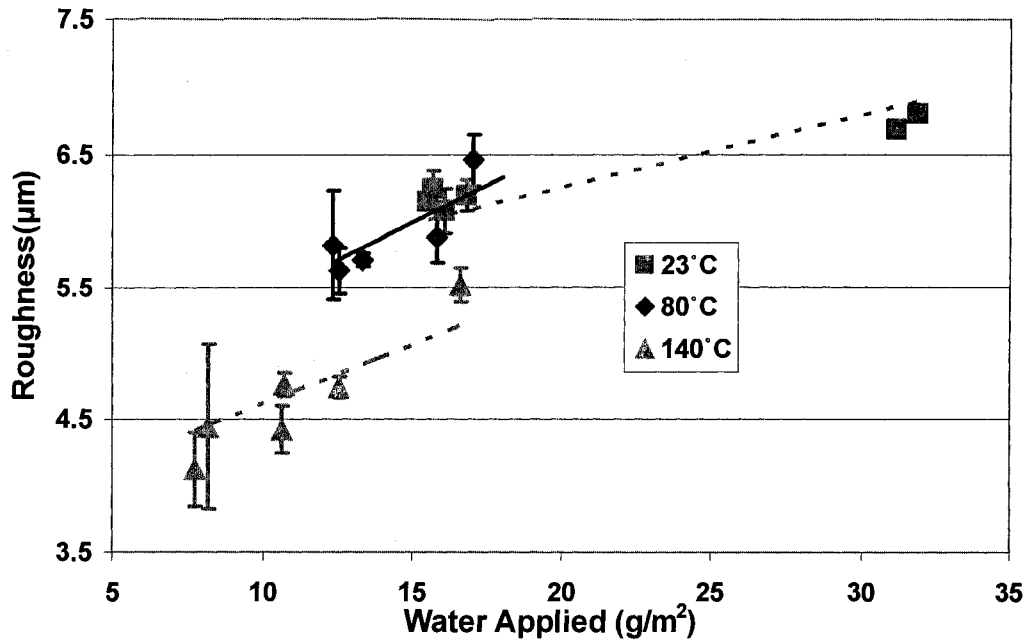


Figure 3.12: The Effect of Precalendering Temperature on the Roughness of Paper Sample Containing 30% HYP at Constant Precalendering Pressure of 62 KN/m. The Y-Intercept is Set to the Roughness After Precalendering

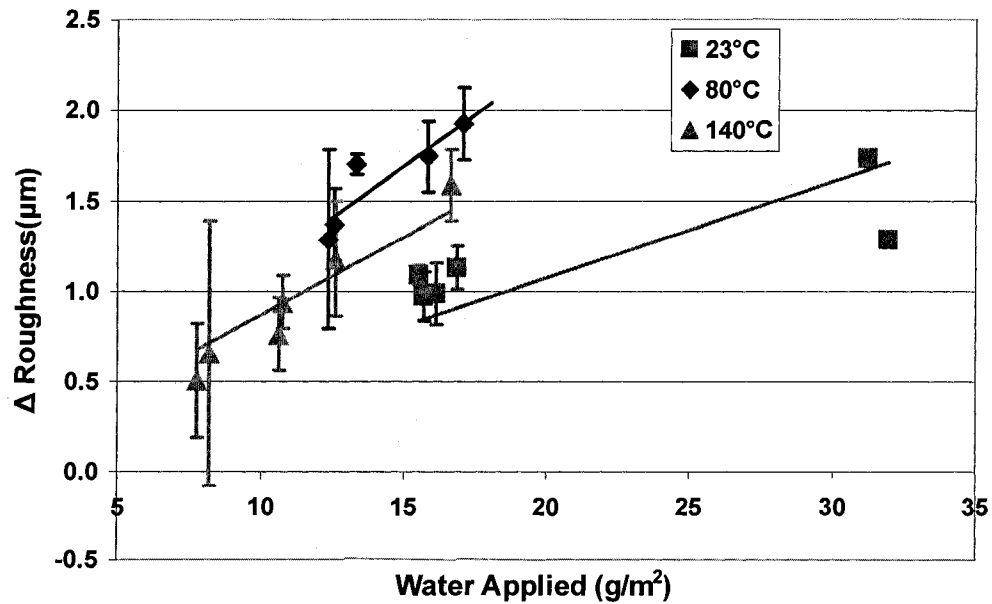


Figure 3.13: The Effect of Precalendering Temperature on the Roughness of Paper Sample Containing 30% HYP at Constant Precalendering Pressure of 62 KN/m. The Y-Intercept is Set to Zero

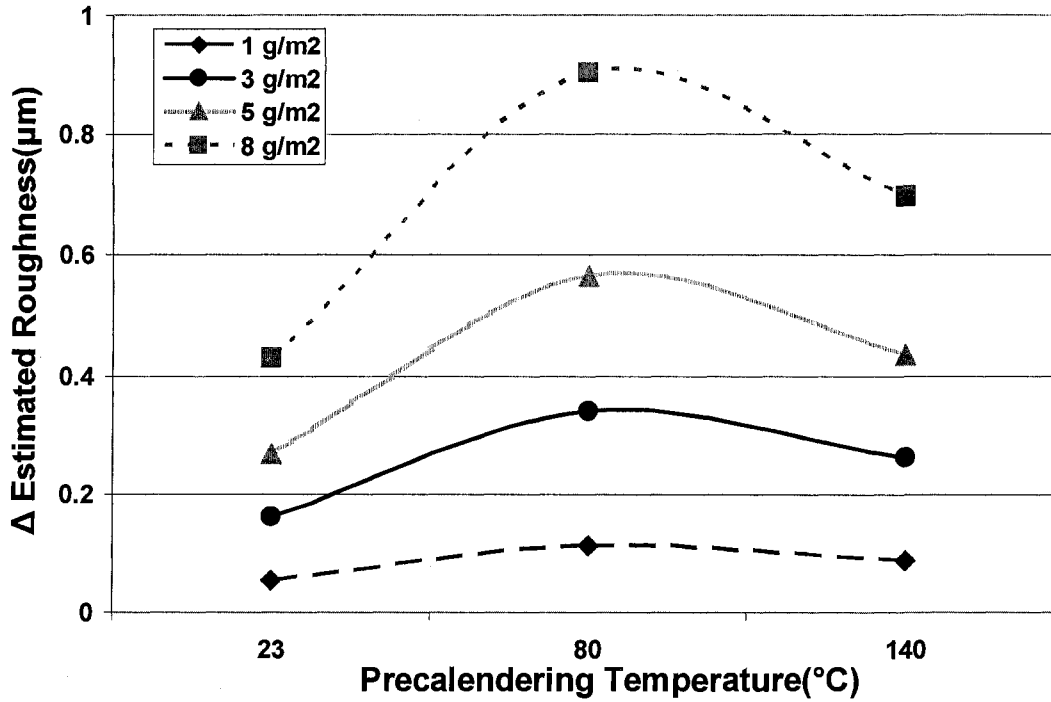
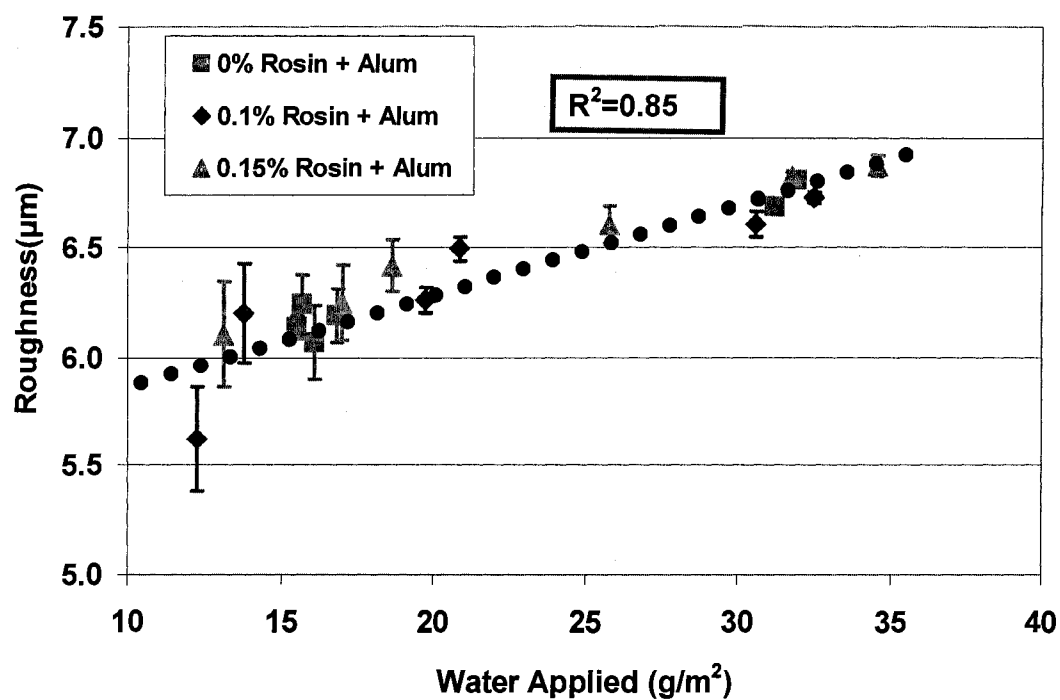


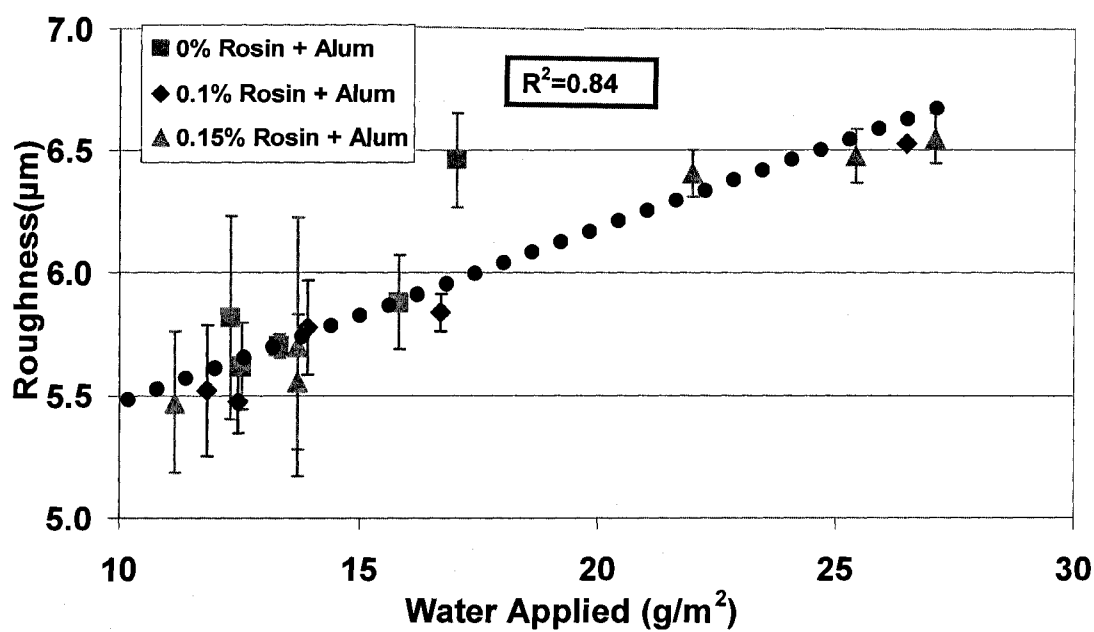
Figure 3.14: The Effect of Precalendering Temperature on the Roughness of Paper Sample Containing 30% HYP at Constant Precalendering Pressure of 62 KN/m

3.4.5. Effect of Rosin + Alum Internal Size

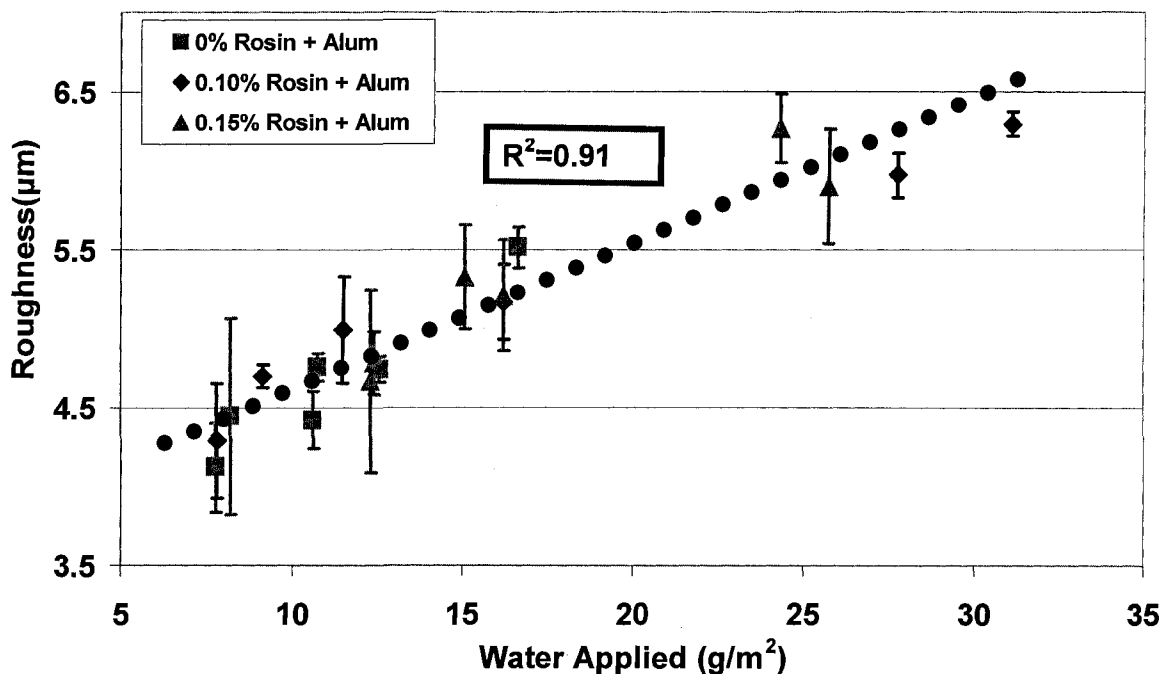
Rosin-alum size provides paper samples with some degree of resistance to coating and water penetration and absorption. Rosin-alum size causes water applied during the coating process to remain on the surface of the paper and subsequently evaporate in the dryers. However, since the samples were wrapped immediately after the wetting process, the amount of water applied corresponds to the actual amount of water absorbed by the fibres. Therefore, the action of the rosin-alum size is rendered ineffective because the mechanism of sizing is suppressed. This is confirmed by Figure 3.15, i.e. in general for the same amount of water applied and absorbed, rosin-alum size has no effect on the roughness of precalendered paper.



(a)



(b)



(c)

Figure 3.15: The Effect of Rosin-alum Size on Samples containing 30% HYP at Three Precalendering Temperatures (a) Paper Samples Precalendered at 23°C; (b) Precalendered at 80°C; (c) Precalendered at 140°C

3.5. Conclusions

The addition of HYP to many traditional wood-free papers could lead to significant financial and environmental benefits. Therefore, it is important to determine the papermaking properties that affect the roughness of samples containing Aspen HYP after wetting process. In this work, the % HYP content, precalendering temperature, and rosin-alum size were investigated and the following conclusions were made:

- As expected, the roughness of paper samples precalendered at the same conditions is dependent on both the HYP content and the amount of applied water.

- Although the roughness of paper samples after the wetting process is dependent on both the roughness before wetting and the change in roughness during wetting, the roughness before wetting had a more significant effect in this study.
- After wetting, the roughness of Aspen 300/85 samples with 2% more fines and less bulky fibres were systematically lower compared to Aspen 325/85 HB. This could be attributed to a more collapsible fibre and a higher fines content for Aspen 300/85 compared to Aspen 325/85 HB.
- At the same amount of applied water, roughening of paper did not depend on the degree of sizing; i.e. sizing does not affect the degree of fibre recovery, it can only reduce the rate of water penetration and absorption.

4. CHAPTER 4 – THE EFFECT OF PAPERMAKING CONDITIONS ON THE BULK OF COATED WOOD-FREE PAPERS

4.1. Introduction

High-yield pulp has become attractive to papermakers in their quest to produce high performance paper products at a low cost. Aspen high-yield pulp (HYP) is often partially substituted for hardwood bleached Kraft pulp (HBKP) in coated wood-free grades because of its relatively good smoothness, low porosity, and good formation [6]. In addition, HYP has better bending stiffness and is more cost-effective compared to HBKP [10,34]. The high-yield pulping process has a higher yield (80-90%) and is more environmentally friendly [6]. The type of wood species, pulping process, furnish, papermaking process, and calendering conditions affect the bulk of calendered coated papers [9]. Therefore, it is important to understand how each of these factors influence the bulk of calendered coated wood-free papers containing Aspen HYP.

Zou [9] investigated improving the bulk and bending stiffness of coated papers through basestock. He found that high-yield pulp or bleached chemi-thermo mechanical pulp (BCTMP) sheets were bulkier than Kraft sheets because the fibres were coarser and did not readily collapse during the papermaking process. To improve and preserve bulk, Zou suggested adjusting pressing and forming conditions, calendering at high temperatures with a minimum load, and lowering the sheet gloss target. He stated that a high sheet gloss did not imply a high print gloss. Unfortunately, Zou only investigated how HYP affected the bulk of basestock. Hu *et al.* [45] examined the impact of substituting up to 30% HYP for HBKP on the bulk of precalendered and uncalendered coated papers at different calendering loads. It was found that the bulk of calendered coated sheets were partially conserved even at higher calendering loads. However,

these studies did not examine the effect of precalendering temperature, sizing or HYP type on the bulk of coated calendered paper samples with Aspen HYP.

A review of the literature shows that the factors that control the bulk of coated calendered paper samples with Aspen HYP is not well-understood. A comprehensive study that considers the effect of various papermaking factors including: wood species, furnish type, papermaking and calendering conditions on the bulk of coated calendered papers does not exist. In this work, the effect of rosin-alum size, precalendering temperature, high-yield pulp type, and high-yield pulp content on the bulk of these samples is investigated. This chapter summarizes the effect of these conditions on the bulk of laboratory coated calendered handsheets.

4.2. Experimental Plan

The experimental plan is shown in Table 4.1. The effect of HYP content on the bulk was examined using Aspen 325/85 HB pulp. Four levels of HYP content: 0, 10, 20, and 30% were considered. A comparison was made with handsheets containing 30% Aspen 325/85 HB or Aspen 300/85 and those containing no HYP to determine the effect of HYP type on the bulk of calendered coated papers. The characteristics of the high-yield pulps are given in section 3.3.1.

The bulk of calendered coated samples precalendered at 23, 50, 80, 110, and 140 °C using 30% Aspen 325/85 HB were also investigated. In addition, samples consisting of 30% Aspen 300 HYP were examined at 23, 80, and 140 °C for similar trends.

Internal sizing level was examined using rosin-alum size at three-four levels: 0, 0.05, 0.10, and 0.15 wt% based on the mass of oven dried pulp at three different precalendering temperatures:

23, 80, and 140°C. This was performed both on Aspen 325/85 HB and on Aspen 300/85 containing samples.

A factorial design of experiment was used to better understand the correlation between internal sizing level and precalendering temperature on the final bulk of calendered coated papers with the aid of the ANOVA function in MS Excel.

Table 4.1: Experimental Plan Showing the Fixed and Variable Experimental Parameters

Parameter Type	Factor	Component	Levels
Fixed	Papermaking Process	Basis Weight	1
		Freeness of Harwood and Softwood Kraft Pulps	
	Coating Conditions	Latex Binder	
		Pigment	
		Solids Content	
		# of Coated Sides	
		Coating Weight	
		# of Coating Layers	
		Drying Temperature	
	Calendering Conditions	Calendering Speed	
		Precalendering Pressure	
		Calendering Pressure	
		Calendering Temperature	
	Furnish	Chemical Pulp Type	
Variables	Furnish Content	High-yield Pulp Content	4
	Wood Species	High-yield Pulp Type	2
	Papermaking Process	Internal Sizing Level	4
	Calendering Condition	Precalendering Temperature	5

4.2.1. Sample Preparation

A schematic diagram of the sample preparation technique is shown below (Figure 4.1). Section 3.3 described the handsheet making and precalendering processes. This chapter describes the coating and calendering processes subsequent to precalendering.

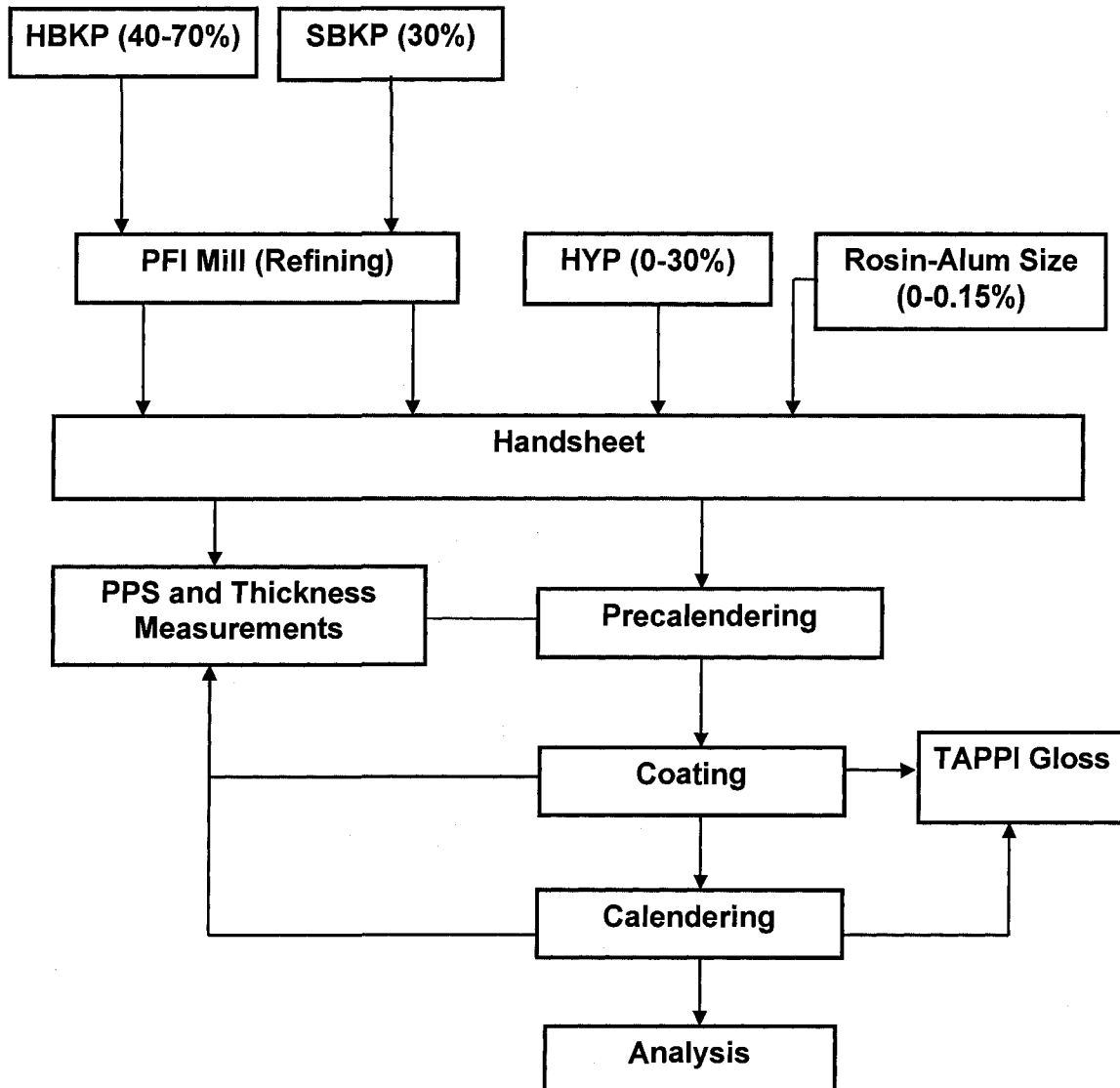


Figure 4.1: Schematic Diagram of Experimental Procedure

4.2.2. Coating Application and Drying

A web-fed puddle type coater (shown in Figure 4.2) was used to apply an average of 7.5 ± 1.5 g/m² of coating colour unto the precalendered paper samples. The brown paper support (Poly coated, Uline) was polycoated on one-side to allow the coating colour to sit on the application roll. A polycoated support prevented coating colour from penetrating it, soaking the sample, and breaking the web. Each paper sample (10 cm × 10 cm) was positioned on the support with the precalendered felt-side facing-up. All four corners of the paper sample were taped to the support to prevent backside penetration of the coating colour.

An appropriate amount of coating colour was placed on the application roll with the nip closed. The amount of coating colour applied to the paper sample was controlled by the nip pressure and the speed of the application roll. The pressure gauge used to adjust the nip pressure is visible in Figure 4.2. The nip pressure and roll speed were chosen by trial and error. Generally, the minimum nip pressure chosen was 20 lbs/inch²(psi). The minimum nip pressure is defined as the minimum pressure that would not allow the coating solution to seep unto the support with the rolls together. The roll speed was adjusted to keep the coating weight of the sample within the acceptable range.

After selecting the appropriate nip pressure and application roll speed, the sample was coated with a coating solution having the composition shown in Table 4.2. The binder was Styronal Latex ($T_g=6^\circ\text{C}$, BN 4606X, BASF, Canada) and the pigment was kaolin clay (Hydragloss 90, HUBER Engineered Materials, Georgia, U.S.A). The coated paper samples were immediately dried using the heated roll dryer directly below the application roll. The drum was heated with

pure silicone fluid (Clearco Products Co., Inc.) at 105°C. The samples were left suspended under the drum for a couple minutes then removed.

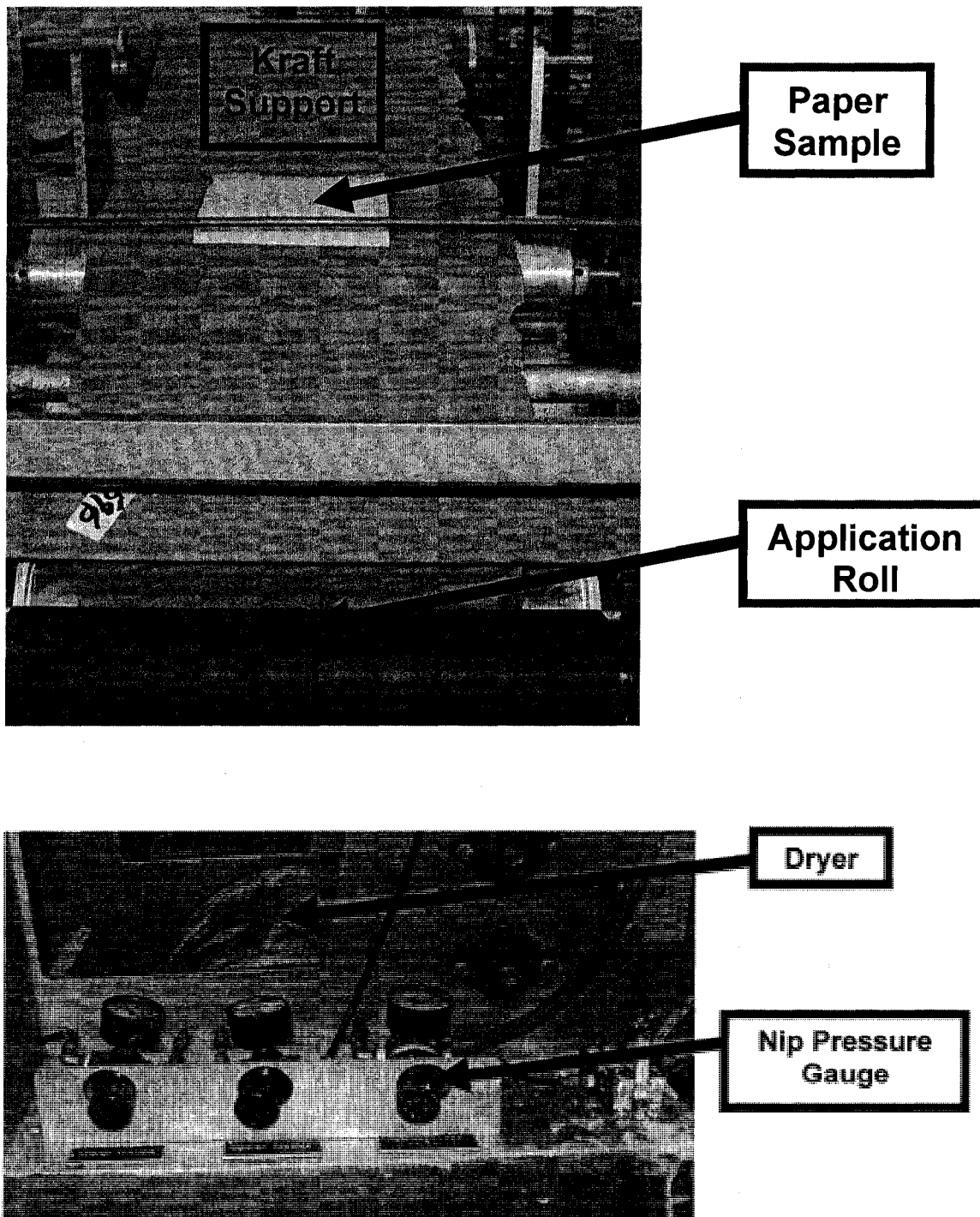


Figure 4.2: Puddle Type Coater

Table 4.2: Coating Formulation

Component	Parts (pph)
Hydragloss 90	100
SB Latex	10
Solids (%)	50

The mass of coating deposited on the paper sample was measured gravimetrically. One cm was removed from each side of the sample prior to weighing to account for the areas covered by the single-sided tape.

$$CW\left(\frac{g}{cm^2}\right) = \frac{C_M(g)}{A(cm^2)} - BW\left(\frac{g}{cm^2}\right) \dots\dots\dots \text{Equation 4.1}$$

Where :

CW = Coating weight

C_M = Mass of coated paper

A = Area of coated paper

BW = Basis weight of uncoated paper

4.2.3. Calendering

As mentioned in section 3.3.4, the calendering was done with a Beloit-Wheeler Supercalender. For final calendaring of coated handsheets, the roll temperature and line load were kept constant at 120°C and 114 kN/m, respectively. The number of nips was varied to achieve a targeted 75° TAPPI gloss of approximately 32 ± 2.

4.2.4. Roughness and Thickness

For each paper specimen, the roughness and thickness were measured after handsheet making, precalendering, coating, and final calendering. The roughness of the specimen reported in section 4.3 is the average of three readings and the thickness is an average of four readings. The thickness was measured using a TMI Precision Micrometer. The bulk was calculated by dividing the average thickness by the basis weight or basis weight + coating weight where applicable.

The bulk of uncoated and coated paper specimens is defined as shown in Equations 4.2 and 4.3:

For uncoated specimens:

$$B \left(\frac{\text{cm}^3}{\text{g}} \right) = \frac{T_a (\text{cm})}{BW \left(\frac{\text{g}}{\text{cm}^2} \right)} \dots\dots\dots \text{Equation 4.2}$$

For coated specimens:

$$B \left(\frac{\text{cm}^3}{\text{g}} \right) = \frac{T_a (\text{cm})}{BW \left(\frac{\text{g}}{\text{cm}^2} \right) + CW \left(\frac{\text{g}}{\text{cm}^2} \right)} \dots\dots\dots \text{Equation 4.3}$$

Where :

B = Bulk of specimen

T_a = Average thickness of specimen

B.W = Basis weight of uncoated uncalendered paper

C.W = Coating weight

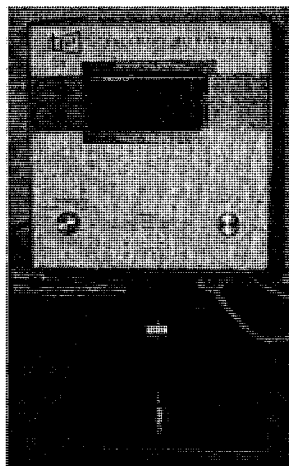


Figure 4.3: TMI Precision Micrometer

4.2.5. Gloss

The 75° gloss was measured using a conventional gloss meter (NOVO-GLOSS™) according to TAPPI T480 [59]. The TAPPI gloss was measured for uncalendered coated samples and calendered coated specimens. For uncalendered coated samples, the gloss was measured three times and five times for the calendered samples.

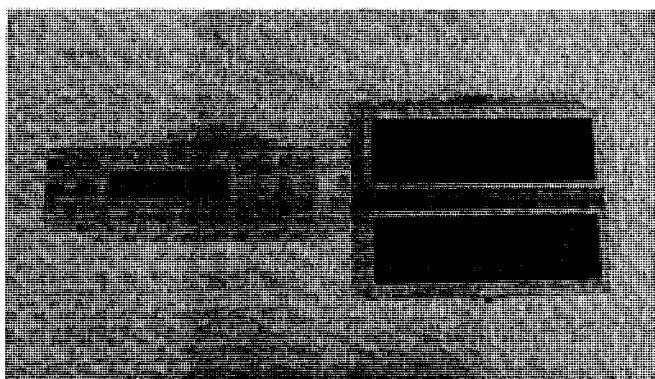


Figure 4.4 Conventional Gloss-meter (NOVO-GLOSS™)

4.2.6. SEM Sample Preparation

Paper samples were loaded into a compression spring. It was then embedded in a resin block and left for 48 hrs in an oven at 60°C to solidify. The sample was ground and polished to expose the paper cross-section. Carbon coating was applied to the surface of the resin block to increase the conductivity of the sample. The images were viewed using back-scattered electrons (BSE) at 500X and 15 kV. The SEM is a JEOL, JSM-840 Model.

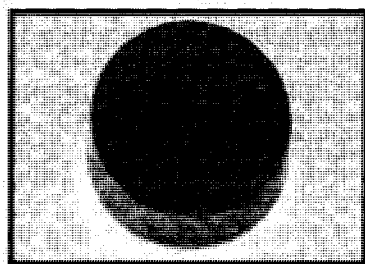


Figure 4.5: Picture of Sample Preparation

4.3. Results and Discussion

4.3.1. Summary of Results

This section summarizes the main findings of Chapter 4. It analyses how HYP content, HYP type, precalendering temperature, and internal sizing affect the bulk of calendered coated paper samples. Table B.1 in Appendix B shows the full experimental results. There were 26 different conditions examined in this study. For each condition, there were three-five replicates. The total number of samples examined was 122.

4.3.2. Effect of High-yield Content

Figure 4.5 shows handsheets containing 0, 10, 20, and 30% Aspen 325/85 HB HYP. They were subjected to the following conditions: precalendered at 80°C, 62 kN/m and 2 nips, single-coated to $7.0 \pm 0.9 \text{ g/m}^2$ on the felt side, and calendered to a target 75° TAPPI gloss of approximately 31 ± 2 . As expected, HYP content did not affect the surface roughness of the uncalendered handsheets [1]. Similarly, after precalendering, all the samples had statistically similar roughness. After coating, there was no significant increase in roughness up to 20% HYP which is similar to the findings by Zou and Zhou [1]. This indicates that at 20% HYP, the amount of mechanical pulp in the sheet may not be large enough to affect the roughness after coating. This result is consistent with Figure 3.9, i.e. at low amounts of applied water; there is little change in roughness of HYP even at 20% HYP content. In comparison to paper samples with 0% HYP, as shown by the ‘wetted’ samples (see Figure 3.9), the theoretical change in roughness during wetting is $0.1 \text{ } \mu\text{m}$ at 3 g/m^2 applied water, which is within the experimental error (Figure 4.5). Moreover, the coating layer could mask this small roughening effect.

According to the pair-wise test (Table 4.3), there is a statistically significant increase in roughness after coating with 30% HYP samples compared to those with 0% HYP. As stated in Section 3.4.2, HYP fibres are forced to collapse during the precalendering process. Water from the coating colour releases the internal stress imposed on paper structure and the fibres decollapse, i.e. recover their shape prior to precalendering. As a result, sheets with 30% HYP roughen more compare to samples with only well-collapsed chemical fibres.

Table 4.3: Statistical Analysis of the Roughness and Bulk of the Paper Samples Represented in Figures 4.6 and 4.7

Comparison	Confidence Level (%)	
	Roughness After Coating	Bulk After Calendering
0-10	26	10
0-20	29	98
0-30	99	100
10-20	57	91
10-30	98	100
20-30	100	99

- Pair-wise t-test between two samples assuming equal variances
- "0-10" indicates a statistical comparison between paper samples containing 0% HYP and 10% HYP
- Confidence Level > 90% shows a statistical significant difference between the pairs and <85% shows statistical insignificance difference.

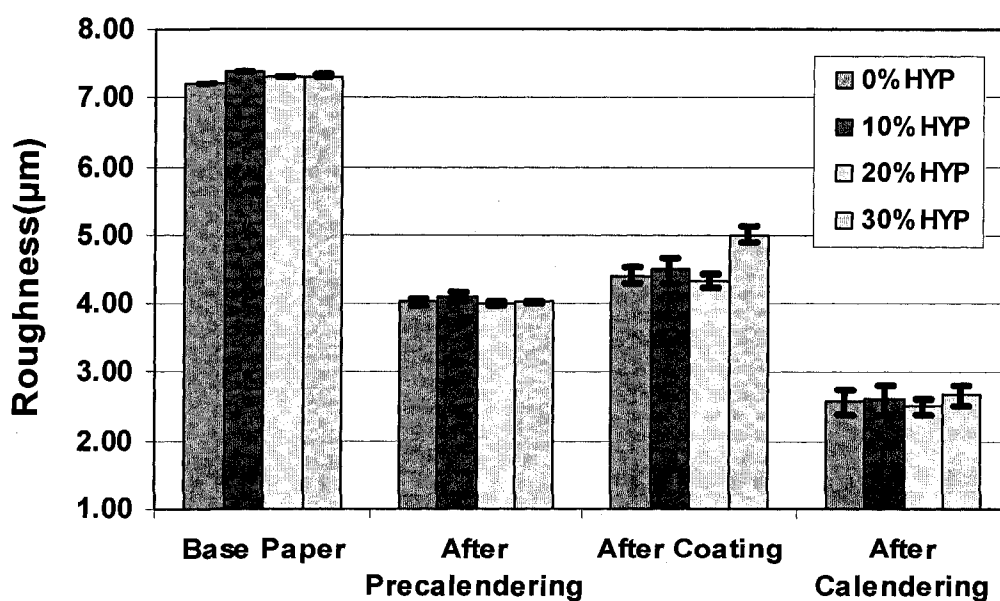


Figure 4.6: The Effect of HYP Content on the Roughness of Paper Samples Precalendered at 80°C , 62 kN/m, and Two Nips

The roughness increase after coating gained by using 30% HYP paper samples yields an important question: does this increase in roughness lead to a lower gloss after coating and is additional calendering required to achieve the targeted final gloss? Table 4.4 shows that the higher roughness for coated handsheets containing 30% HYP does not translate to a lower gloss compared to the sample with no HYP. As discussed by Caner *et al.* [60], the relationship between roughness and gloss after coating is exponential (Equation 4.4). Since the coating process leads to rough samples regardless of the HYP content, it implies that a change in roughness for a ‘rough’ specimen results in a relatively small change in gloss. On the other hand, if the samples were ‘smooth’ as in the case of the calendered coated samples, the same roughness change could have a more significant impact on the gloss. This becomes important to maintain bulk because the specimens with 30% HYP did not need more severe calendering to achieve the same gloss target.

Table 4.4: Effect on Gloss of Various Sheets with Difference HYP Content after Coating

HYP Content (%)	Coated Roughness(μm)	Calendered Coated Roughness(μm)	Coated TAPPI Gloss	Calendered Coated TAPPI Gloss	# of Nips
0	4.4 ± 0.4	2.6 ± 0.2	11 ± 1	32 ± 1	3.1
10	4.5 ± 0.4	2.6 ± 0.2	10 ± 1	31 ± 2	2
20	4.4 ± 0.2	2.5 ± 0.2	10 ± 1	30 ± 1	2
30	5.0 ± 0.3	2.7 ± 0.1	10 ± 1	32 ± 3	2.1

$$G_T = A \times e^{-K \times R}$$

where :

G_T = Tappi Gloss (G.U) Equation 4.4

A, K = Constants

R = PPS Roughness (μm)

As expected, the bulk of the base paper increases with HYP content because they contain more tubular, coarse HYP fibres. Figure 4.6 also shows that the specimens with 30% HYP had a higher increase in bulk during coating. The coated bulk of a specimen is altered via two mechanisms: volume expansion of the fibres and the thickness of the coating layer [14,52]. Since all the samples had similar coating weights ($7.0 \pm 0.9 \text{ g/m}^2$), the difference in bulk is mostly due to the volume expansion. As the HYP content increased from 0 to 30%, the average bulk increased from 1.10 to 1.21 cm^3/g . As suggested earlier, HYP fibres have a tendency to decollapse upon wetting and the well-collapsed chemical fibres do not. This resulted in a higher bulk increase during coating for the specimens with 30% HYP.

The gloss after coating of the sample with 30% HYP is comparable to those with 0% HYP samples. Consequently, there was no need to calender those samples more severely to achieve the targeted 75° TAPPI gloss value. A similar trend is seen in the bulk after calendering, i.e. a bulkier coated uncalendered sample results in a bulkier coated calendered sample. However, the 10% bulk advantage for samples with 30% HYP after coating is only partially preserved after calendering. This occurred because HYP fibres are more compressible compared to chemical fibres. As a result, this led to a 6% bulk advantage compared to 0% HYP after final calendering. The sample with 10% and 20% HYP had a bulk advantage compared to 0% HYP of 0 and 2%, respectively. This implies that a significant bulk advantage is seen at substitution levels above 20% HYP.

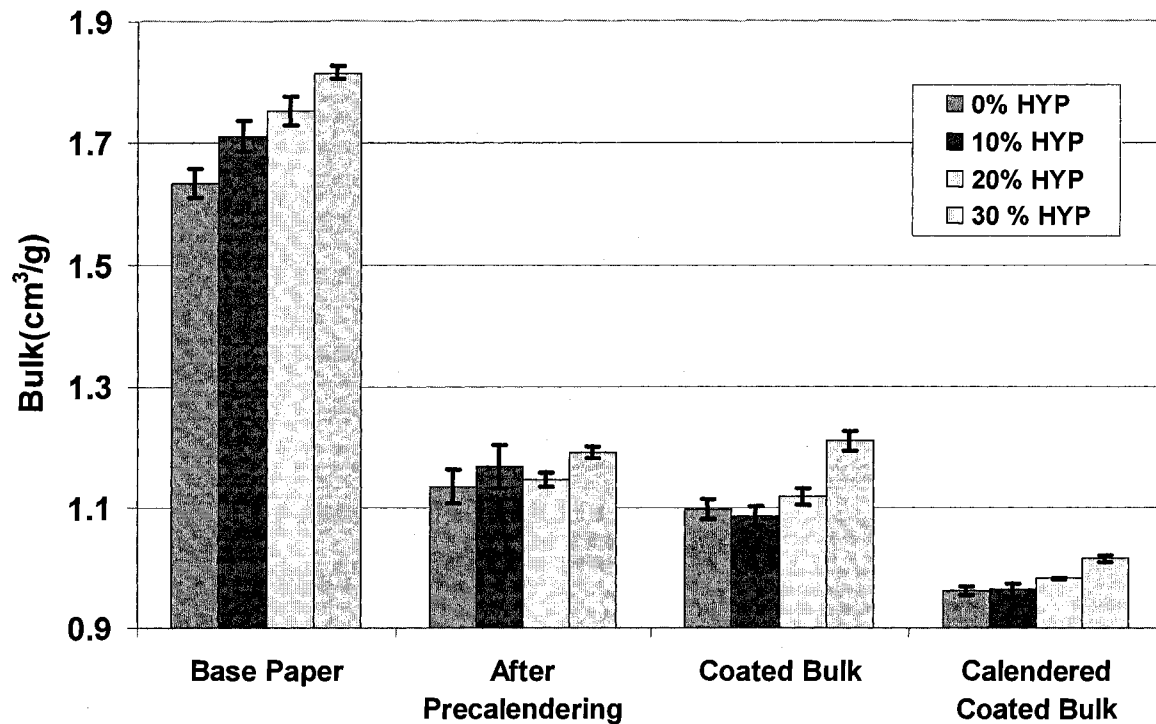


Figure 4.7: The Effect of HYP Content on the Bulk of Paper Samples Precalendered at 80°C and 62 kN/m

In an attempt to account for a slight difference in the final gloss of the coated calendered samples, an exponential plot of gloss vs. bulk can be used to estimate the bulk of all the samples at a TAPPI gloss of 32. This is achieved by interpolation using Equation 4.4. This allows for a better comparison between bulk of coated calendered papers shown in Table 4.5. The experimental bulk values are similar to the calculated values and illustrate an important trend for papermakers: for samples up to 30% HYP content, increasing the HYP content will improve the bulk of the final calendered coated sample. This confirms that the initial bulk advantage due to HYP substitution is partially preserved even after final calendaring.

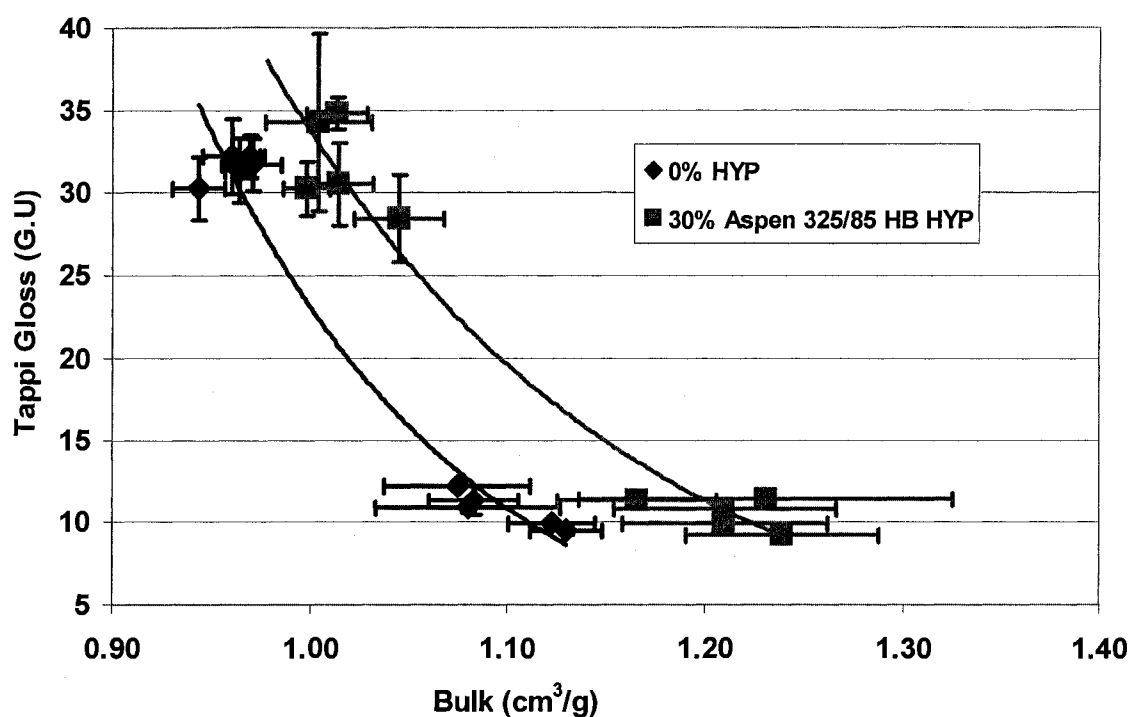


Figure 4.8: The Effect of HYP Content on the Bulk of Paper Samples Precalendered at 80°C and 62 kN/m

Table 4.5: Corrected Bulk Increase (Decrease) by Using HYP with Respect to Wood-free Samples

HYP Content (%)	Basestock Bulk Advantage ¹ (%)	Coated Calendered Bulk Advantage (%)	Corrected Bulk Advantage (%)
10	5	0	(1.0)
20	7	2	2
30	11	6	6

$$^1 \text{ bulk advantage} = \frac{\text{bulk of HYP samples} - \text{bulk of wood - free samples}}{\text{bulk of wood - free samples}}$$

4.3.3. Effect of Furnish Type

Aspen 325/85 HB and Aspen 300/85 samples both contained 30% HYP. The samples were precalendered at 80 °C, 62 kN/m, and 2 nips with similar coating weights. The HYP type is an important factor in determining the roughness after coating. Samples with Aspen 325/85 HB had a higher roughness after coating. The Aspen 325/85 HB fibres are bulkier and could distort the fibrous network of paper more during the coating process. Furthermore, the high fines content of Aspen 300/85 could lead to a smoother sample after coating (Figure 4.8). This is consistent with the finding of both Kartovaara [21] and Forseth *et al.* [10], who found that increasing the proportion of fines reduced the roughening after coating. As stated by Forseth *et al.* [10], fines do not suppress the roughening mechanism; however, more fines means that fewer coarse fibres are present in the sheet. As stated in Section 3.4.3, this roughness decrease is relatively small because the sheets with Aspen 300/85 contain only 2% more fines.

The final bulk of calendered coated paper samples depend on the high-yield pulp type (Figure 4.10). The Aspen 325/85 HB samples were bulkier than Aspen 300/85 in the basestock while statistically there is no significant difference in the roughness of these samples (Figure 4.9). This provides papermakers with an important consideration: a bulkier HYP results in a bulkier final sample. The bulk advantage for Aspen 325/85 HB and Aspen 300/85 compared to samples made from 0% HYP were 6% and 2%, respectively.

Table 4.6: Statistical Analysis of the Pulp Type on the Roughness and Bulk of the Paper Samples

Comparison	Confidence Level (%)	
	Roughness After Coating	Bulk After Calendering
Aspen 325 - 300	100	99
Aspen 325 – 0% HYP	99	100
Aspen 300 – 0% HYP	52	100

- Pair-wise t-test between two samples assuming equal variances
- “Aspen 325-300” indicates a comparison between paper samples containing Aspen 325/85 HB and Aspen 300/85
- Confidence Level > 90% shows a statistical significant difference between the pairs and <85% shows statistical insignificance difference.

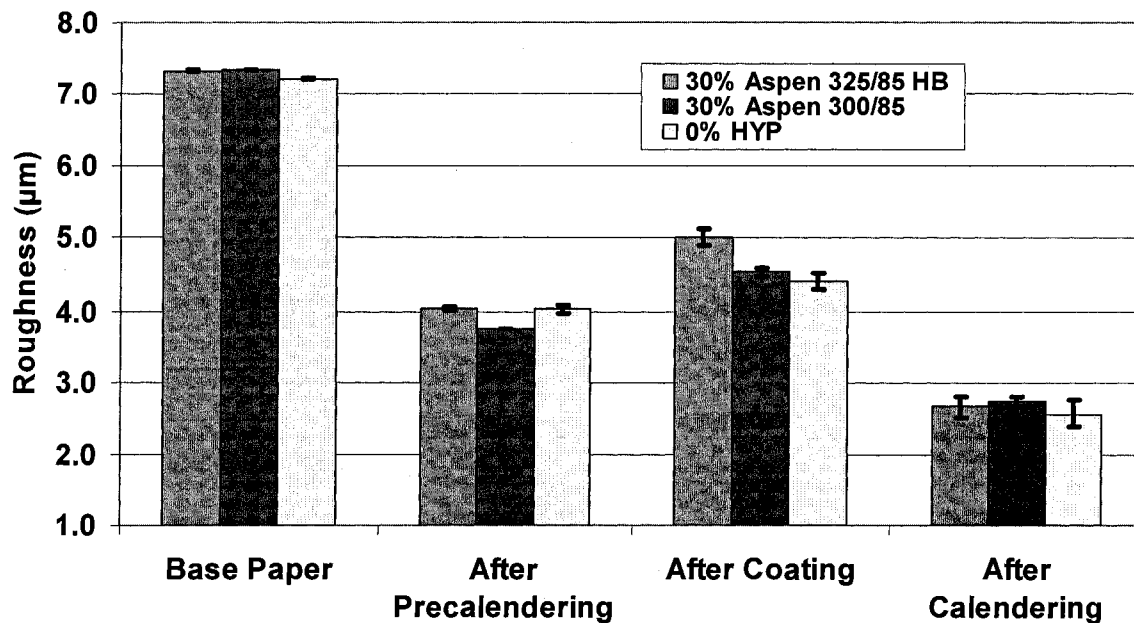


Figure 4.9: The Effect of Pulp Type on the Roughness of Paper Samples. All samples were Precalendered at 80°C, 62 kN/m, and Two Nips

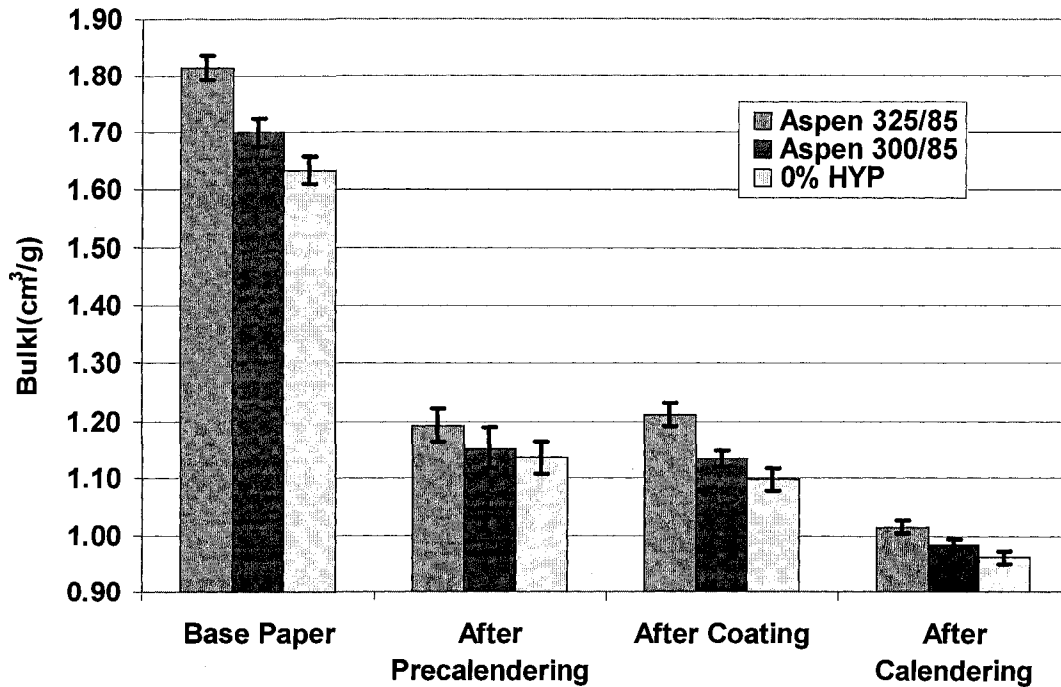


Figure 4.10: The Effect of Pulp Type on the Bulk of Paper Samples. All samples were Precalendered at 80°C, 62 kN/m and Two Nips

4.3.4. Effect of Precalendering Temperature

As the precalendering temperature increases, the samples with 30% HYP became smoother after precalendering (Figure 4.10). In general, smoother samples prior to coating resulted in smoother sheets after coating. This supports the argument made in section 3.4.4: the roughness before wetting of the base sheet plays an important role in the roughness change during coating. All of the samples made with 30% HYP roughened more during coating compared to 0% HYP. As the precalendering temperature increased from 23°C to 80°C to 140°C, the roughness change during coating increased by 1.25, 0.98, and 0.60 μm , respectively. This could suggest that precalendering temperature affects the amount of fibres that decollapse during the coating process by slowing down water penetration into the sheet and subsequent absorption by fibres.

Therefore, samples precalendered at 140°C had the least amount of water absorbed by the fibres, and hence were roughened less than samples precalendered at 23 and 80°C. Another possible reason is that precalendering at 140°C could permanently deform the fibres and limit their ability to decollapse during coating.

Table 4.7: Statistical Analysis of the Effect of Precalendering Temperature on the Roughness and Bulk of the Paper Samples

Comparison	Confidence Level (%)	
	Roughness After Coating	Bulk After Calendering
23-0%HYP	100	97
80-0%HYP	99	100
140-0%HYP	100	97
23-80	100	97
23-140	100	10
80-140	100	97

- Pair-wise t-test between two samples assuming equal variances
- "23-80" indicates a comparison between paper samples containing 30% HYP precalendered at 23 and 80°C
- Confidence Level > 90% shows a statistical significant difference between the pairs and <85% shows statistical insignificance difference.

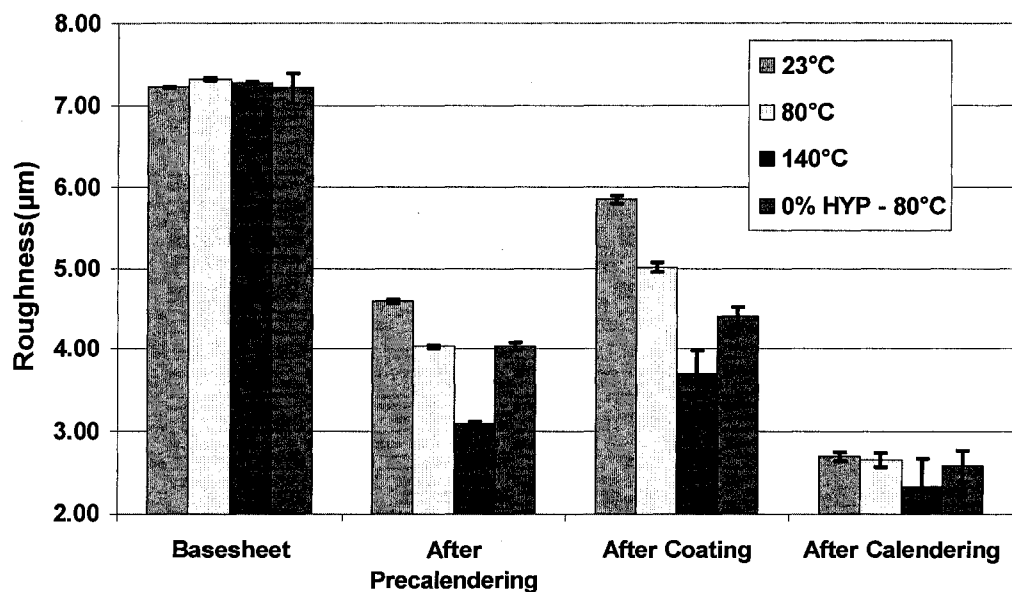


Figure 4.11: The Effect of Precalendering Temperature on the Roughness of Paper Samples

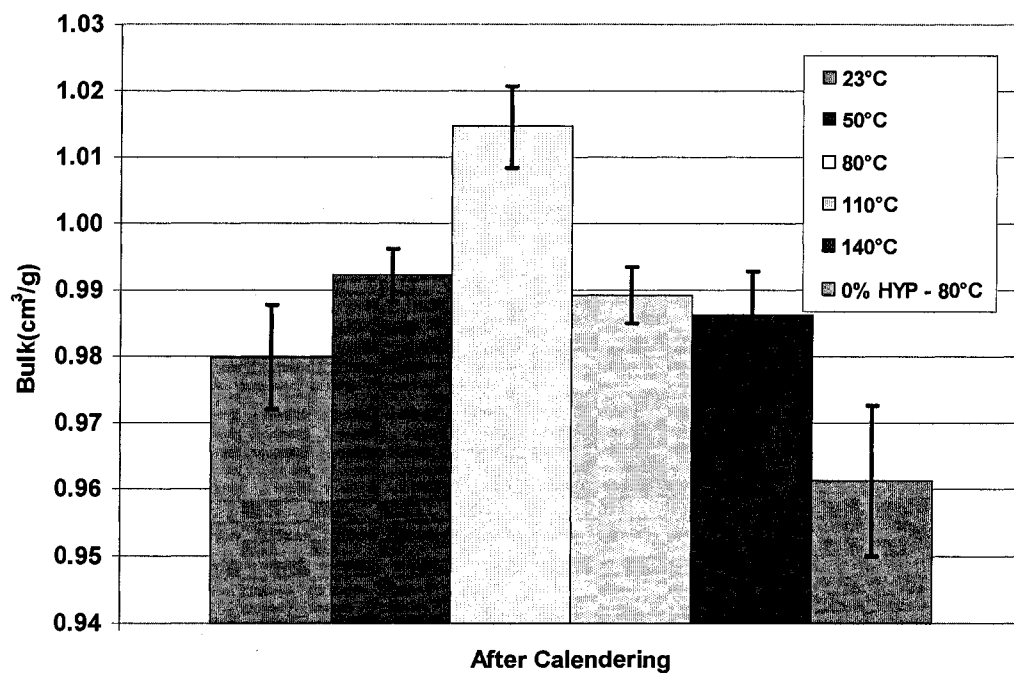
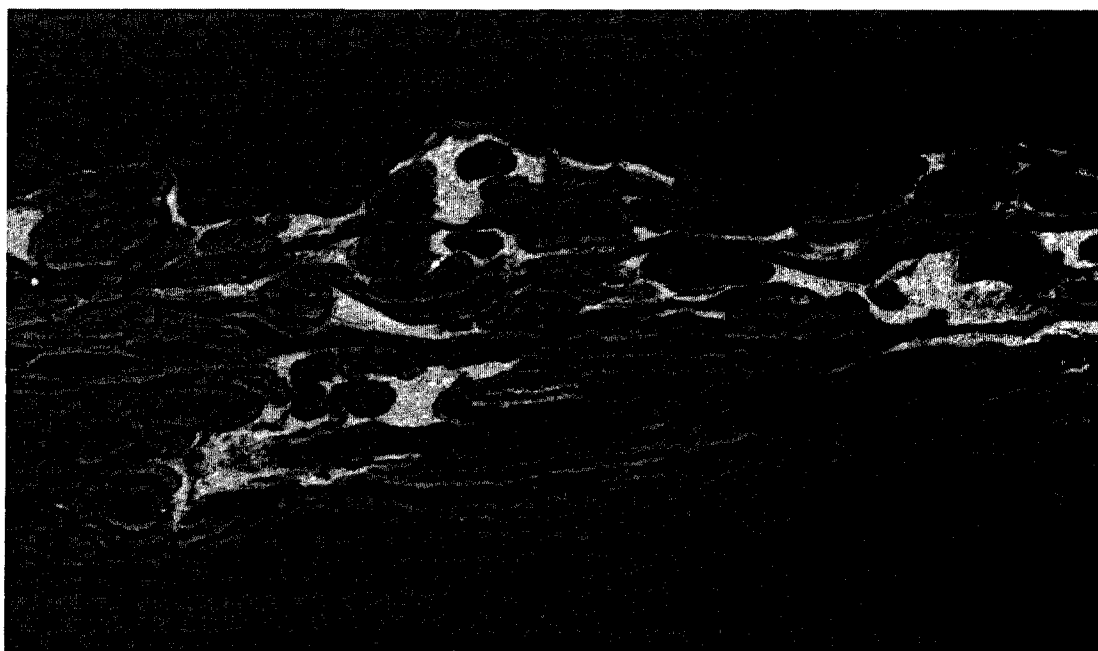


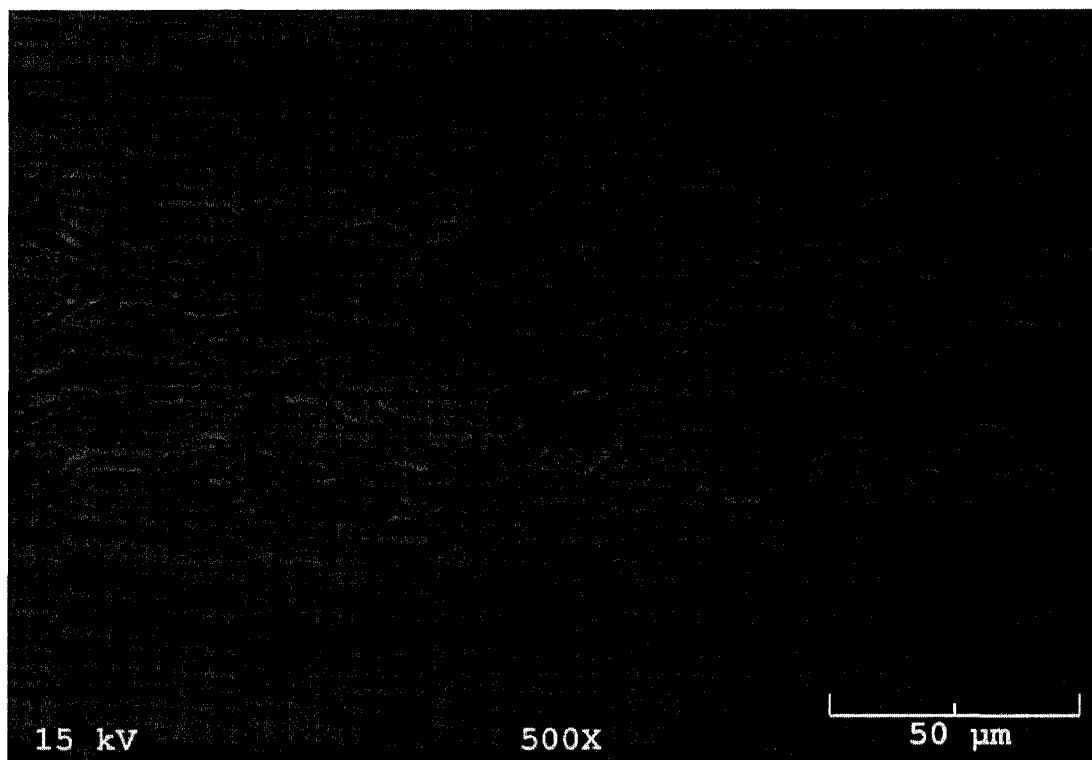
Figure 4.12: The Effect of Precalendering Temperature on the Bulk of Paper Samples after Calendering. All Samples were Precalendered at a Constant Pressure of 62 kN/m. The Average Coating Weight was 6.9 ± 1.1 g/m²



(a)



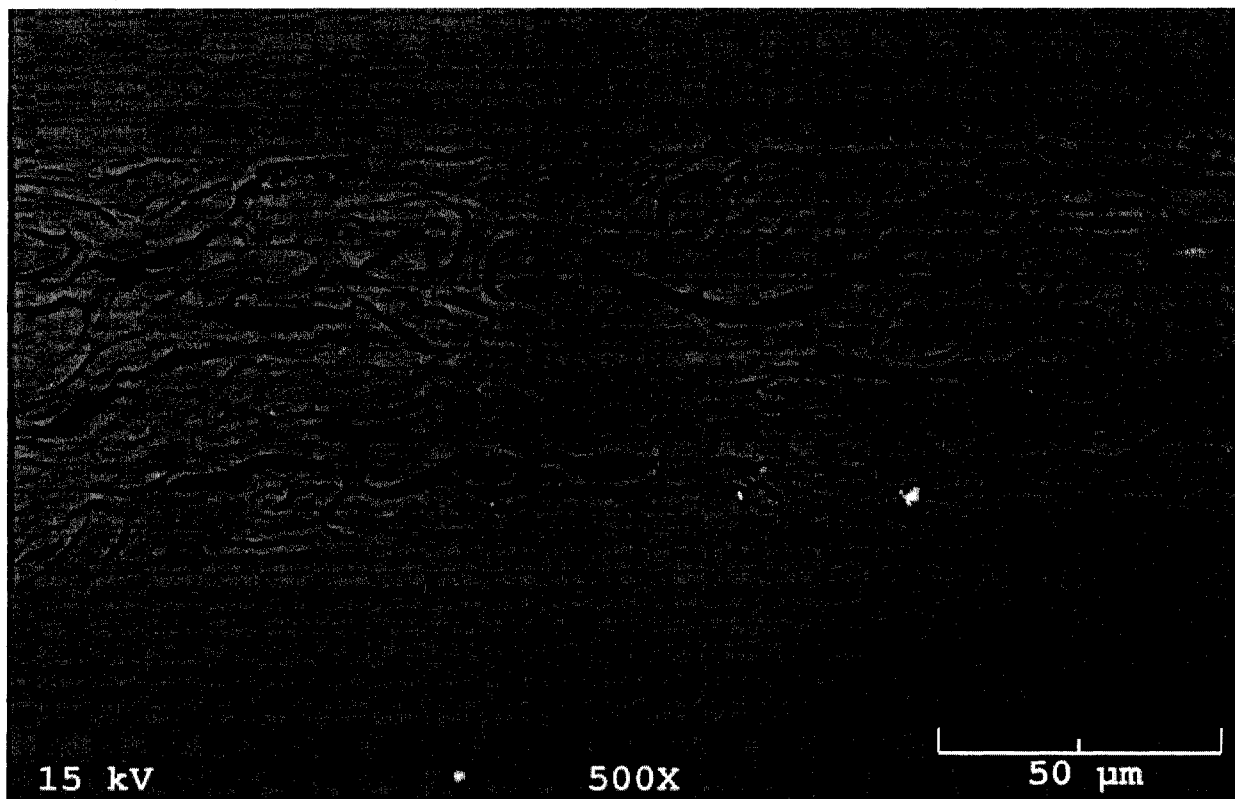
(b)



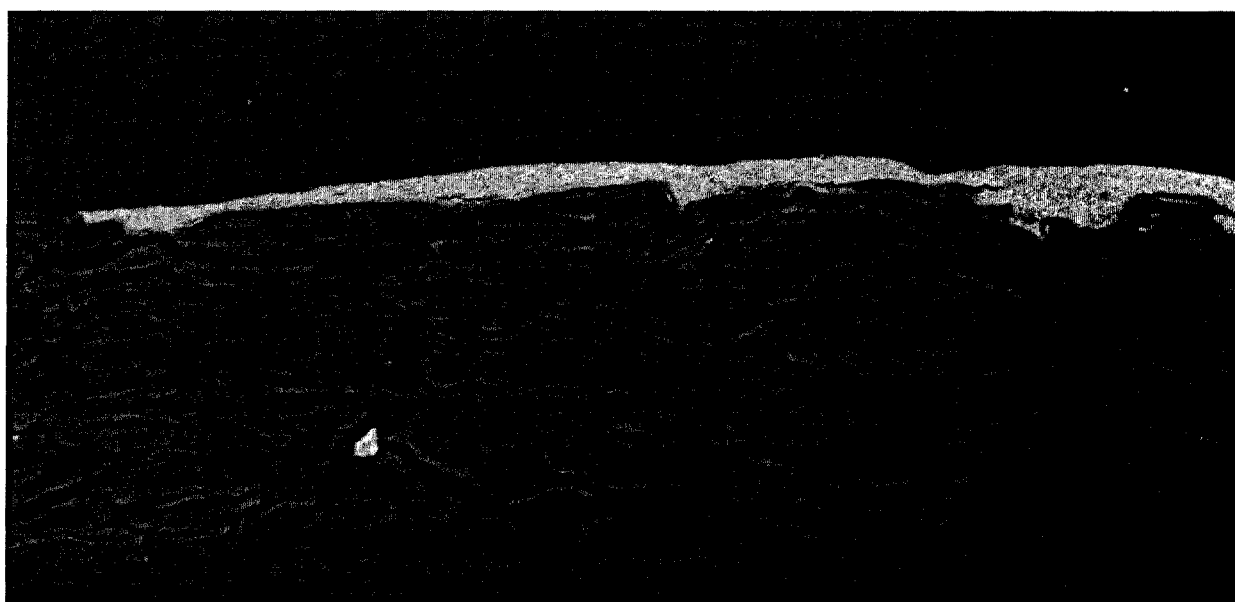
(c)



(d)



(e)



(f)

Figure 4.13: SEM Images of 30% Aspen 325/85 HB Paper Samples at Different Precalendering Temperatures and Coating Holdout (a) Precalendered at 23°C; (b) Coated and Precalendered at 23°C; (c) Precalendered at 80°C; (d) Coated at 80°C; (e) Precalendered at 140°C; (f) Coated and Precalendered at 140°C. Images Viewed under Back Scattered Electron at 500 X, 15 kV

For all of the precalendering conditions, the bulk of calendered coated samples with 30% HYP samples is higher compared to those with 0% HYP. The highest bulk advantage is seen at 80°C and falls sharply above and below this temperature. In Table 4.7, a pair-wise comparison between the temperatures is given. This analysis shows that higher bulk of coated calendered papers at 80°C is statistically significant.

The bulk of calendered coated paper depends on the thickness of the paper and the coating layer, as stated earlier. The difference in bulk for sample calendered at the 23, 50 and 80°C could be due to coating holdout as shown by the SEM pictures in Figure 4.12. For samples precalendered at 23°C, the pores are quite large and coating could sink into them leaving the surface bare of coating. This defeats the purpose of coating because the coating gets into the paper via pressure in the application roll [12]. However, at 80°C the pores would be sufficiently close to prevent such penetration. According to Lepoutre *et al.* [34], surfaces with high residual stress are rough and have large pores that coating will be forced into by the pressure in the application roll. They suggested that calendering could be beneficial for coating holdout. Consequently, the higher bulk for samples precalendered at 80°C could be due to improvements in coating holdout.

All coated calendered samples precalendered from 80 to 140°C should have relatively good coating coverage because they have smooth surfaces. In fact, samples precalendered at 140°C should have the least coating penetration, and therefore the thickest coating layer due to the higher precalendering temperature. However, the bulk of these samples is 0.98 cm³/g compared to 1.01 cm³/g for the samples precalendered at 80°C. Precalendering at 110 and 140°C could be considered hard calendering and as suggested by Reme *et al.* [58] could crush the fibres promoting longitudinal breaks and cracks in the fibre wall. This could hinder the amount of fibres that decollapse during wetting. The temperature gradient softening of lignin ranges from

100-110 °C for paper samples with 4% moisture content [39]. The fibres in the paper could be permanently crushed leading to a reduction in bulk. In addition, a seal surface could reduce the amount of water in contact with the fibres; hence, limiting the volume expansion of the paper.

If the paper is assumed to be a semi-infinite medium and the calender is a constant heat source, then Equations 4.5 and 4.6 could be used to determine the depth into the paper where the temperature is above the T_g [61].

$$\frac{T_s - T}{T_s - T_o} = \text{erf} \left[\frac{x}{2\alpha t} \right] \dots\dots\dots \text{Equation 4.5}$$

T = Glass Transition Temperature of Lignin

T_s = Roll Temperature

T_o = Room Temperature

t = Residence Time of Paper in the Calender

α = Thermal Diffusivity of Paper

x = Distance into paper with temperature $> T$

$$t = \frac{w}{s} \dots\dots\dots \text{Equation 4.6}$$

w = Nip Width

s = Calender Speed

Table 4.8: Distance into the Paper Samples with $T_s > T_g$

$T_s(^{\circ}\text{C})$	$T_o(^{\circ}\text{C})$	$T(^{\circ}\text{C})$	$\alpha^1 (\text{m}^2/\text{s})$	$t^2 (\text{ms})$	$x(\mu\text{m})$
23-80	100	23	6.65×10^{-8}	5	0
110					5
140					14

⁻¹Taken from Basmadijan and Farnood [61]

⁻² Estimated dwell time in the laboratory Supercalender

As shown in Table 4.8, thermoplastic softening of the fibres increased as the precalendering temperature increases above the approximate T_g . This could lead to the destruction of the fibres for the samples precalendered at 110 and 140°C. The values in Table 4.8 would suggest that samples precalendered at 140°C should have a lower bulk than 110°C, however, their bulks are similar. The difference in coating weight between 110 and 140°C of 5.5 to 7.2 g/m² could explain why this occurs. Since the coating layer is denser compared to the paper fibres (1.8 g/cm³ [21] to 0.9 g/cm³), a lower coating weight could over estimate the bulk. Another possible reason could be that samples precalendered at high temperatures have less water in contact with the fibres because the surface is well sealed. Hence, volume expansion could be less for samples precalendered at high temperatures.

The precalendering temperature affects thermoplastic softening of fibres, coating holdout, and the amount of water absorbed by the fibres. All of these factors play an important role in determining the bulk of coated calendered samples. Ideally, samples should be precalendered at elevated temperatures to provide sufficient coating holdout and good paper smoothness; however, this temperature should not be excessive in order to avoid crushing of the fibres and to allow adequate volume expansion.

A similar trend for precalendering temperature is seen with Aspen 300/85 (Figure 4.14). The precalendering temperature trend seems to be independent of HYP type. The Aspen 325/85 HB has higher bulk at all temperatures for the reasons described in the previous section.

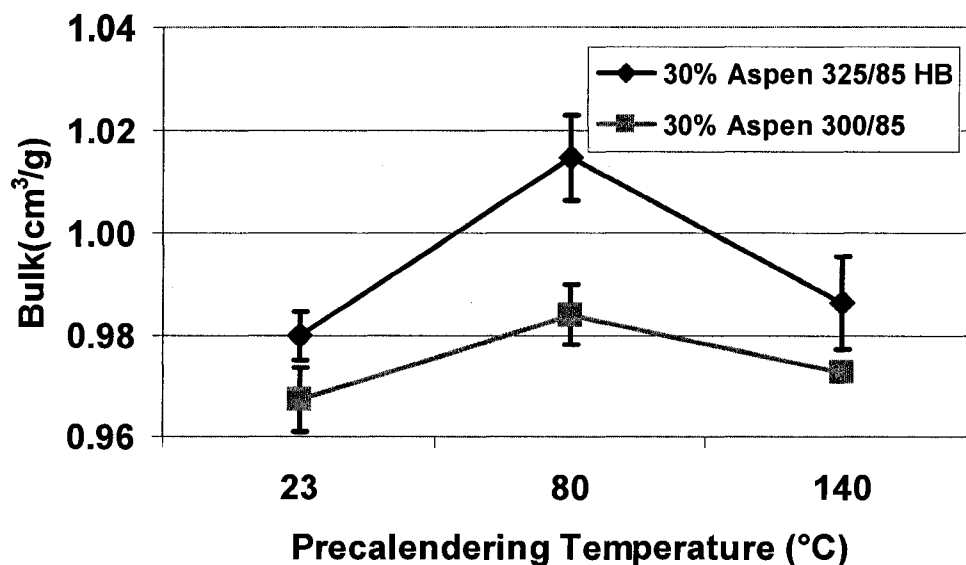
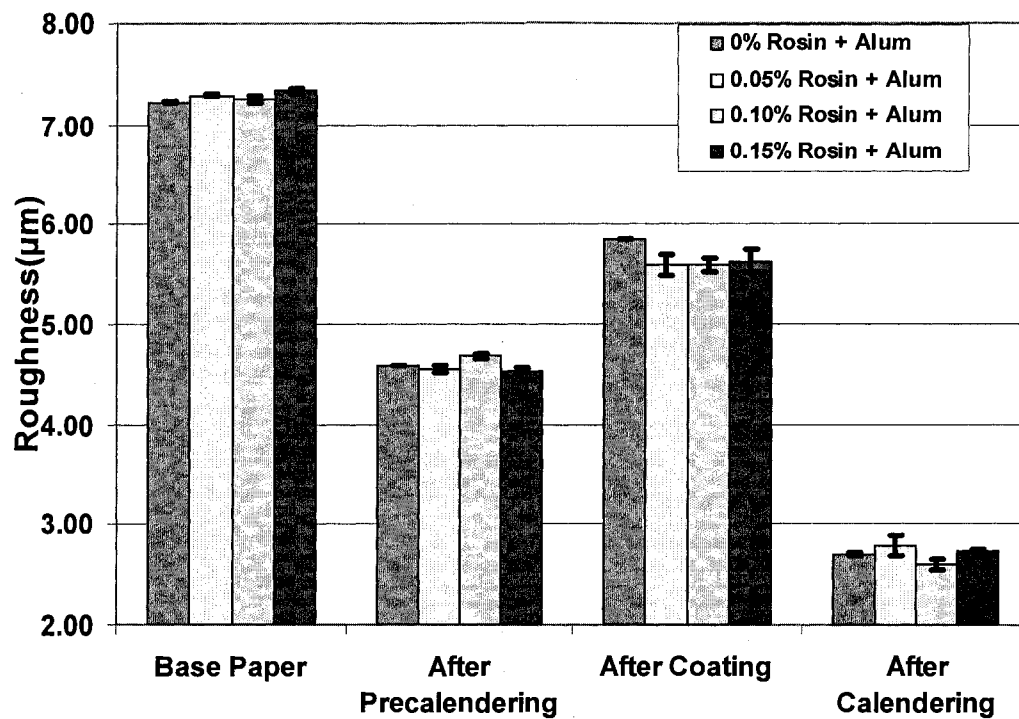


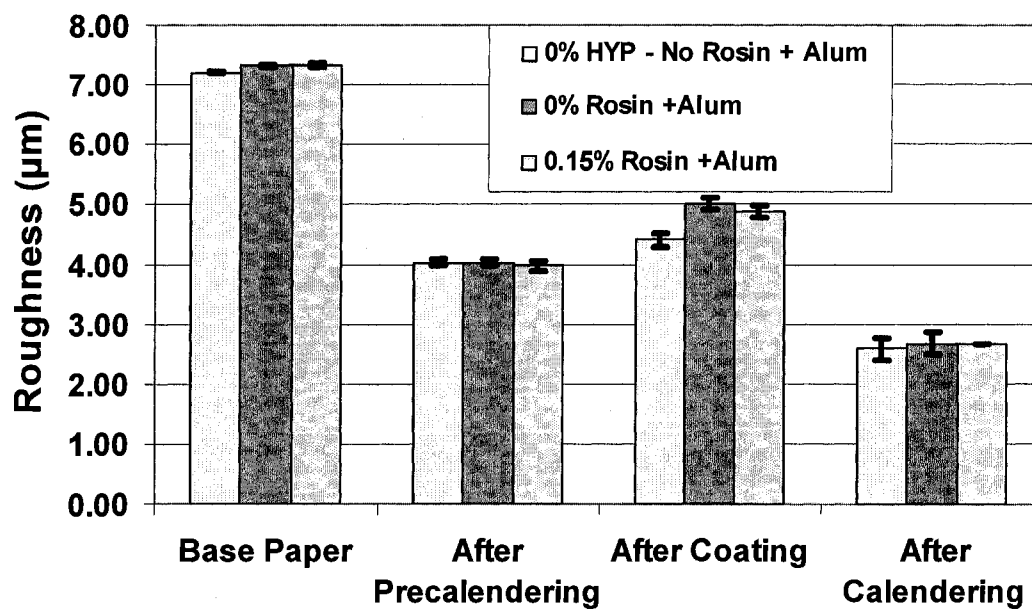
Figure 4.14: Comparison of the Coated Calendered Bulk Between the High-yield Pulps with 30% HYP Precalendered at Different Temperatures

4.3.5. Effect of Rosin + Alum Internal Size

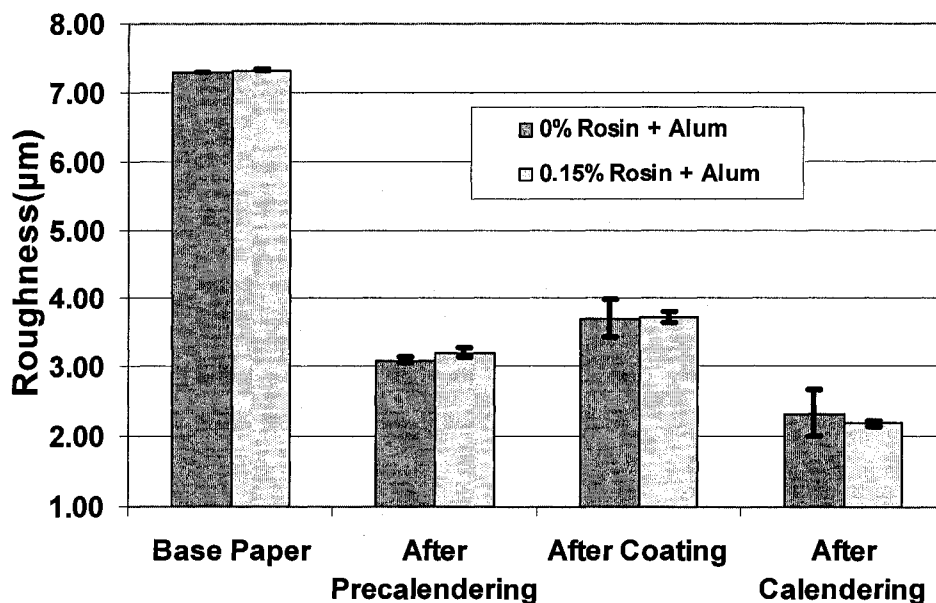
The effect of internal sizing on the roughness of paper samples precalendered at different temperatures reveals a similar trend to that of the water treated samples discussed in Chapter 3. As shown in Figure 3.15 of section 3.4.5, rosin-alum sizing and rosin-alum level had little or no impact on the roughness of the paper samples after water application (consistent with Forseth and Helle [19]). However, in the case of pigment coated handsheets, the samples precalendered at 23°C did exhibit a decrease in roughness after coating (Figure 4.15(a)) because as shown by the SEM (Figure 4.18), sizing improves coating holdout such that the surface is no longer bare of coating. This could help to improve the smoothness of these samples.



(a)



(b)



(c)

Figure 4.15: Roughness of Paper Samples with Various Levels of Internal Sizing at Different Precalendered Temperatures for 30% Aspen 325/85 HB (a) Samples Precalendered at 23°C; (b) Samples Precalendered at 80°C; (c) Samples Precalendered at 140°C

Unlike the roughness after coating, rosin-alum size had a statistically significant impact on the final bulk of the coated calendered paper samples. According to Skowronski and Lepoutre [13], thickness increase and hence the bulk increase is due to the contribution of both: the recovery of decollapse fibres due to the destructive action of water and increased sheet thickness due to the coating layer. Since internal sizing improves coating holdout, there could be more coating on the surface of the paper resulting in a bulkier sample.

The effectiveness of the alum-rosin size is dependent on the precallendering temperature: samples precallendered at 23°C had the highest difference in bulk between the 0.15 wt% rosin-alum sized samples and the unsized samples, i.e. 0.98 to 1.00 cm³/g (Figure 4.16). The SEM pictures (Figure 4.18) illustrate the effect of internal sizing on the coating holdout of paper samples

precalendered at this temperature. For the unsized samples precalendered at 23°C, the coating seems to have penetrated and filled the pores of the paper as suggested in section 4.3.4. However, for the sized samples precalendered at 23°C, sizing reduces the rate of coating penetration and improves coating holdout. However, for the 0.05wt% rosin-alum samples (Figure 4.17(a)), the level of sizing was not adequate to hold the coating on the paper surface.

For the samples precalendered at 80 and 140°C, the effect of rosin-alum size on the bulk of the coated calendered sample seems to be less pronounced. This occurs because the unsized samples could already have good coating holdout. Consequently, internal sizing only had slight improvements in bulk at these precalendering temperatures.

Table 4.9: Statistical Analysis Between Sized and Unsized Paper Samples with 30% Aspen 325/85 HB at Different Precalendering Temperatures

Comparison	Bulk After Calendering
23°C: Sized and Unsized	96
80°C: Sized and Unsized	59
140°C: Sized and Unsized	56

- Pair-wise t-test between two samples assuming equal variances
- “Unsized-Sized” indicates a comparison between unsized and sized samples (0.15wt%)
- Confidence Level > 90% shows a statistical significant difference between the pairs and <85% shows statistical insignificance difference.

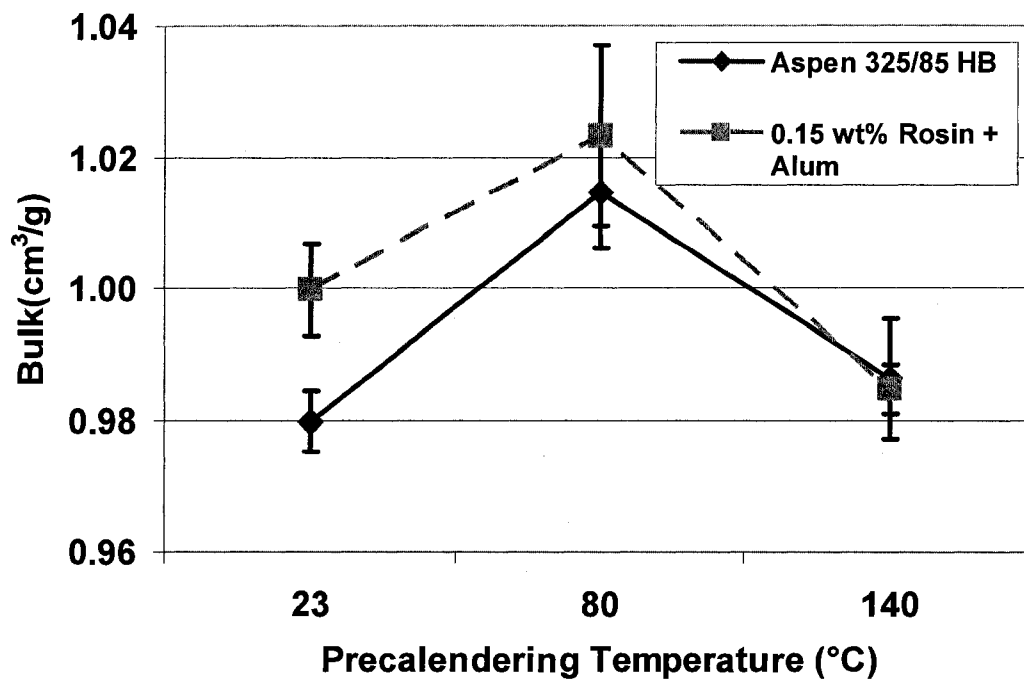
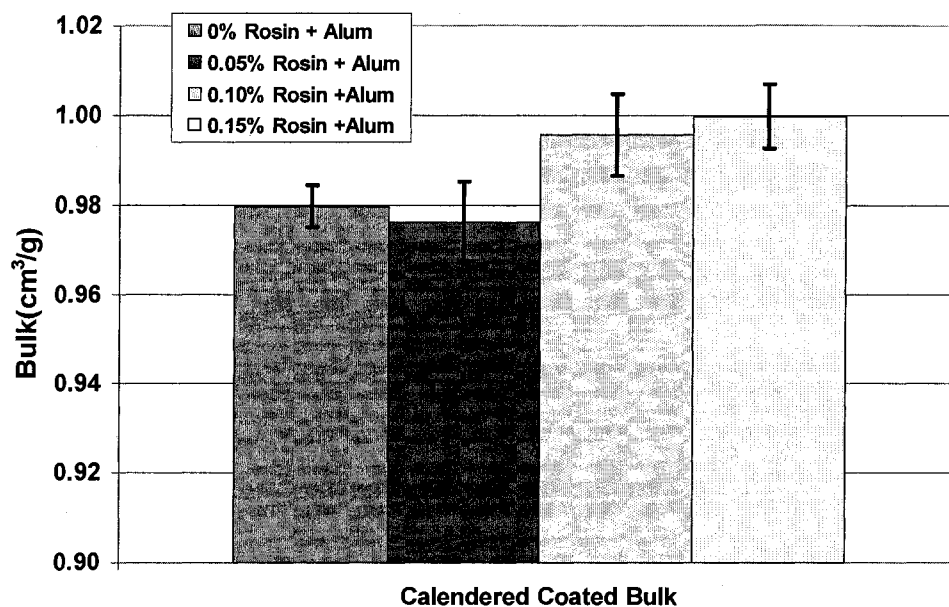
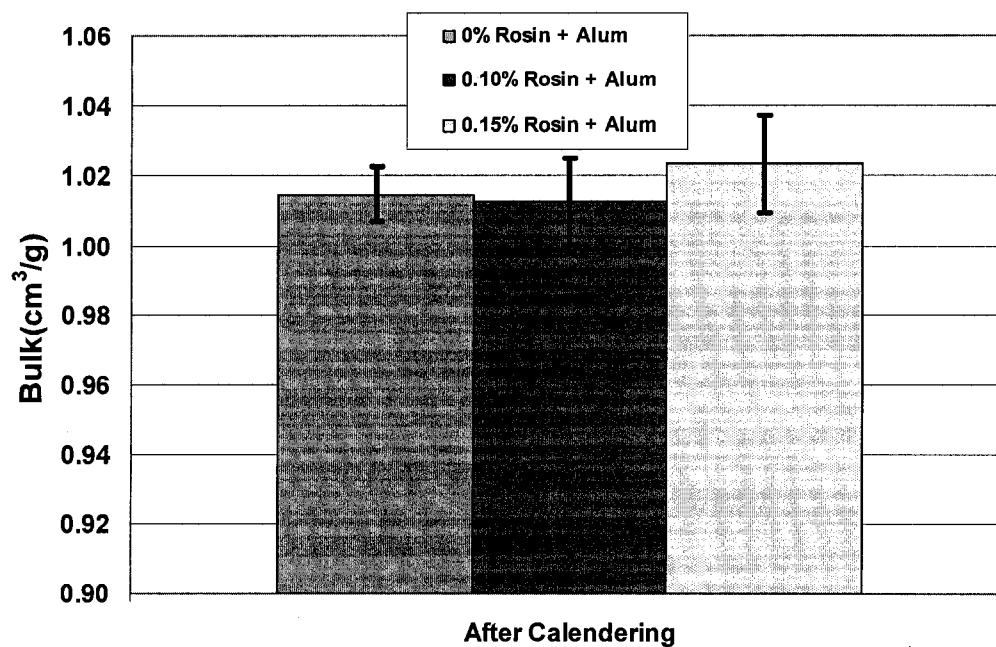


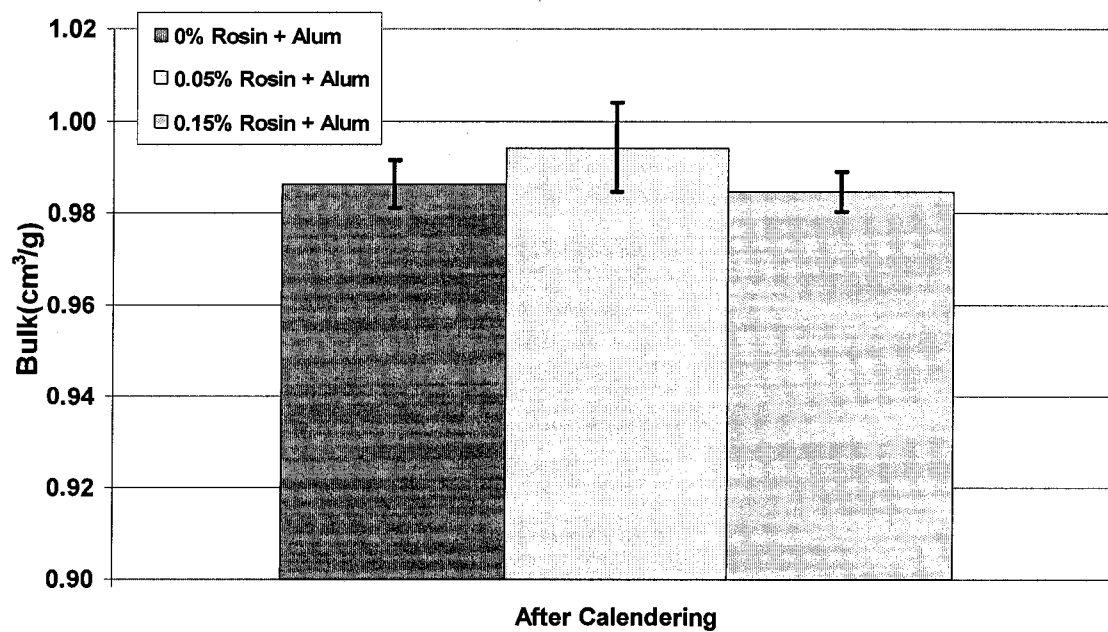
Figure 4.16: Thickness of Sized and Unsized Paper Samples with 30% Aspen 325/85 HB at Different Precalendering Temperatures. Sized Sample had 0.15wt% Rosin-alum Size



(a)

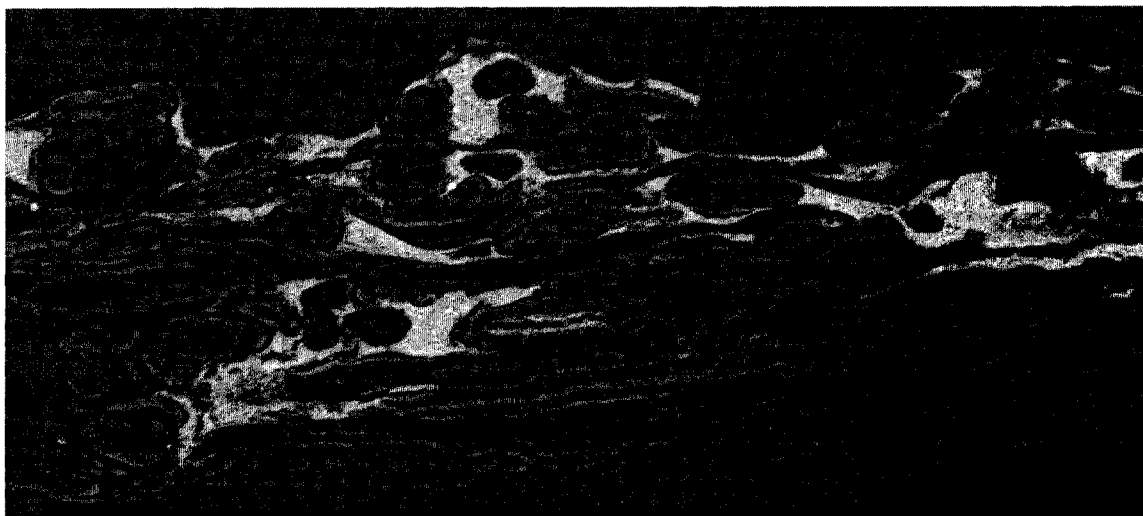


(b)

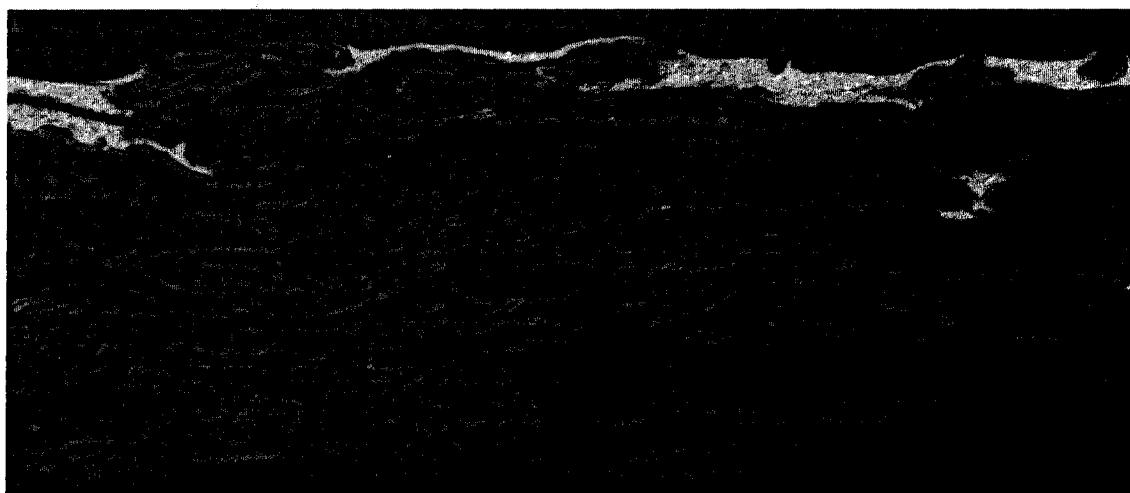


(c)

Figure 4.17: Roughness of Paper Samples with Various Levels of Internal Sizing with 30% Aspen 325/85 HB at Different Precalendered Temperatures (a) Samples Precalendered at 23°C; (b) Samples Precalendered at 80°C; (c) Samples Precalendered at 140°C



(a)



(b)

Figure 4.18: SEM Images Showing Coating Holdout of Sized and Unsized 30% Aspen 325/85 Samples Precalendered at 23°C (a) Unsized Sample; (b) Sized Sample. Images Viewed under Back Scattered Electron at 500 X, 15 kV

To determine if there is interaction between the precalendering temperature and the internal sizing level, factorial design of experiments using two factors was carried out. Three levels for precalendering temperature and sizing were examined and Table 4.10 shows the bulk of the coated calendered samples under various conditions. Using MS Excel, two factorial design with

five replicates was carried out and the results of the analysis are shown in Table 4.11. The analysis is based on three null hypotheses and the determination of acceptance or rejection of the hypothesis were based on threshold P-values of $> 90\%$ and $<85\%$, respectively. The three hypotheses are shown below:

- (1) H(1): Precalendering Temperature(PT) means are the same
- (2) H(2): Internal Sizing Level(IS) means are the same
- (3) H(3): No interaction exist between PT and IS

The hypothesis that interactions do not exist between the precalendering temperature and internal sizing level is generally tested first. Since the P-value is greater than 90%, there is strong evidence to conclude that an interaction effect exist between the two factors. The effect of internal sizing is most effective at low precalendering temperatures because the pores of the paper could be more open compared to higher temperatures. In addition, it can be concluded that the hypothesis: precalendering temperature means are the same can be strongly rejected. This implies that the precalendering temperature level has a strong independent effect of the bulk of paper samples. However, the hypothesis: internal sizing level means are the same can be accepted implying that it does not have an independent effect on the bulk. Its effect on the bulk is not large enough compared to the interaction effects.

Table 4.10: Two Factorial Design at Three Levels of Precalendering Temperature and Internal Sizing Level on the Bulk of Coated Calendered Paper Samples

Precalendering Temperature(°C)	Internal Sizing Level (%)		
	0	0.10	0.15
23	0.96	0.99	0.99
	0.97	1.01	1.02
	0.99	1.02	1.00
	0.99	0.97	0.99
	0.99	1.00	1.00
80	1.00	1.01	1.04
	1.04	1.01	1.03
	1.00	0.99	1.01
	1.01	1.01	1.02
	1.01	1.02	1.01
140	1.00	1.00	0.98
	0.99	1.01	1.00
	0.99	1.00	0.98
	0.98	1.00	0.99
	0.98	1.00	0.98

Table 4.11: Results from Anova: Two Factors with Five Replicates

Null Hypothesis	P-value (%)	Accept or Reject
H(1): Precalendering Temperature(PT) means are the same	100	x
H(2): Internal Sizing Level(IS) means are the same	83	✓
H(3): No interaction exist between PT and IS	97	x

✓ :If P-value < 85%, Accept the null hypothesis

x :If P-value > 90%, Reject the null hypothesis

4.4. Conclusions

The papermaking conditions including: HYP content, HYP type, internal sizing, and precalendered temperature affected the bulk of coated samples calendered to a target gloss.

- As the HYP content increased, the bulk of the coated calendered sample also increased. This was due to bulkier HYP fibres. Samples with 30% HYP were rougher after coating compared to 0% HYP, however, the difference in gloss was insignificant and these samples did not require additional calendering to get to the target 75° TAPPI gloss of 32.
- Handsheets made of 30% Aspen 325/85 HB had 1-3% higher coated calendered bulk compared to Aspen 300/85.
- The bulk of coated calendered samples increased as the precalendering temperature increased up to 80°C. SEM results show that at low precalendering temperatures coating sank into the basesheet leaving the surface bare of coating; as a result, decreasing the bulk. For samples precalendered above 80°C, on the other hand, permanent crushing of fibres and thermoplastic softening by the high temperature could have led to the reduced bulk seen in these samples. The optimal precalendering temperature for bulk preservation in this study was 80°C.
- The effective of internal sizing on the bulk of coated calendered samples is correlated to precalendering temperature. It is more effective at low precalendering temperature because it promotes good coating holdout.

5. CHAPTER 5 – MULTIVARIATE ANALYSIS ON THE BULK OF COATED PAPERS CONTAINING HIGH-YIELD PULP

5.1. Introduction

In chapter 4, some of the key papermaking variables that affected the bulk of coated calendered papers were investigated. However, bulk could be sensitive to small changes in coating weight and the importance of coating weight variations was not examined. Hence, in this chapter the combined effect of rosin-alum size, precalendering temperature, high-yield pulp type, and % high-yield pulp substituted on the bulk of coated calendered paper are re-evaluated to include the effect of coating weight using multivariate analysis with the aid of commercial statistical software (SIMCA-P, Umetrics Inc).

5.2. Overview of Model Parameters

A multivariate statistical analysis was done using Projection to Latent Structures by Partial Least Squares (PLS) to understand the relationship between the predictor variables (X) and the response variables (Y). The predictor variables included high-yield pulp content, high-yield pulp type, internal sizing level (HST), precalendering temperature ($^{\circ}\text{C}$), precalendering temperature squared, the product of internal sizing and precalendering temperature, coating weight (g/m^2), and $\log_e(\text{Final Gloss})$. The bulk after final calendering was selected as the response (or Y) variable. Table 5.1 summarises the experimental data used to obtain the statistical model, which includes 26 different conditions representing 122 specimens.

The high-yield pulp type was characterised based on the corresponding bulk value provided by the supplier (TEMBEC Enterprises Inc.) as shown in Table 3.3. The relationship between HST

and Bulk was characterised using the sigmoid function (see Equation 5.1). The $\log_e(\text{Final Gloss})$ was used to symbolize the relationship between final gloss and the bulk of coated calendered samples. It is known that the bulk has a logarithmic relationship with gloss [60]. As a result, modeling the logarithmic interaction between bulk and final gloss would be more representative of the true relationship. For precalendering temperature, a quadratic term is added to better understand the relationship between bulk and precalendering temperature. As shown in Figure 4.12, the relationship between precalendering temperature and the bulk is non-linear. In fact, it is closer to a quadratic relationship. The level of sizing was measured using a Hercules Sizing Tester according to the TAPPI T530 standard method [33]. Finally, to account for the possible interaction effect between precalendering temperature and internal sizing mentioned in section 4.3.5, a lumped term of the product of precalendering temperature and internal sizing is used.

$$Bulk = K \times \frac{1}{1 + e^{-HST}} \dots\dots\dots \text{Equation 5.1}$$

$K = \text{constant}$

Table 5.1: Model Parameters

Cond #	BW(g/m ²)	HYP(%)	Pulp Type(cm ³ /g)	HST(s)	PT(°C)	CW(g/m ²)	Ln(Gloss)	Bulk
1	60.6	30	2.3	1.7	80	6.6	3.5	1.01
2	61.4	30	2.3	1.7	23	7.4	3.5	0.98
3	62.4	30	2.3	1.7	50	8.2	3.5	0.99
4	60.4	30	2.3	1.7	110	7.2	3.5	0.99
5	60.0	30	2.3	1.7	140	5.5	3.5	0.99
6	61.3	0	-	1.7	80	6.7	3.5	0.96
7	59.5	10	2.3	1.7	80	7.9	3.4	0.96
8	59.0	20	2.3	1.7	80	6.7	3.4	0.98
9	59.6	30	2.3	1.7	80	5.5	3.5	1.00
10	61.4	30	2.3	1.7	80	7.2	3.5	1.01
11	59.7	30	2.3	4.4	80	7.0	3.4	1.02
12	58.0	30	2.3	4.4	140	6.5	3.4	0.98
13	60.4	30	2.3	4.4	23	7.5	3.4	1.00
14	63.3	30	2.3	2.2	140	5.9	3.4	0.99
15	59.9	30	2.3	2.2	23	10.2	3.5	0.97
16	60.1	30	2.3	2.6	23	9.1	3.5	1.00
17	57.5	30	2.3	2.6	140	5.1	3.5	1.00
18	60.7	30	1.72	1.7	80	7.4	3.4	0.98
19	61.5	30	1.72	1.7	23	10.1	3.4	0.97
20	61.5	30	1.72	1.7	140	6.0	3.5	0.97
21	61.1	30	1.72	2.2	80	8.1	3.5	0.97
22	60.4	30	1.72	2.6	80	7.3	3.5	1.00
23	60.6	30	1.72	4.4	80	7.8	3.4	1.00
24	58.6	30	1.72	4.4	23	7.7	3.5	1.01
25	61.3	30	1.72	2.2	23	9.4	3.5	0.97
26	58.9	30	1.72	2.6	23	9.4	3.5	0.97

BW – Basis Weight, Pulp Type – High-yield Pulp Type, PT – Precalendering Temperature, and CW- Coating Weight

5.3. Introduction to PLS Regression Modeling

PLS modeling is used to determine the correlation and importance of wood species, furnish type, papermaking conditions, and calendering on the final bulk of coated papers. PLS modeling can handle data that is noisy, dependent and have a large number of predictor variables [62]. The graphical representations of the results are easily interpreted and can be used to deduce the correlation between the predictor and response variables, and to predict their impact on the coated calendered bulk of the paper samples.

In PLS modeling the data is pre-processed by mean-centering and scaling to a unit variance. This is advantageous since some predictor variables; such as precalendering temperature, have a large range and variance; while others such as HST, have a small variance. To ensure that each variable made an equal contribution to the model, they were scaled to a unit variance. Furthermore, mean-centering was used to improve the interpretability of the model [63].

5.4. Results and Discussion

5.4.1. Model Performance

Figure 5.1 shows the Principal Component Analysis (PCA) obtained from the regression model. A principal component is linear combination of predictor variables (or input parameters) that explains most of the variance in these variables and optimises the correlation between the predictor and response variables. In PCA analysis, the goodness of fit and predictive ability are quantified by the corresponding R^2 and Q^2 values, respectively.

Higher R^2 and Q^2 values indicate that the model fits the data better. From Figure 5.1, the first, second, and third components explained 50.8, 11.4 and 1.0% of the variance in the bulk of the paper samples, respectively. Although the R^2 value approaches 1 as the model complexity (i.e. the number of principal components) increases, the prediction ability (Q^2) may exhibit a decreasing trend with the number of principal components. The $Q^2 = 0.474, 0.551$, and 0.513 for one, two, and three principal components, respectively. As a result, the predictive ability of the model decreased and a trade-off between R^2 and Q^2 is required to obtain the optimal number of principal components. In general, a good model is obtained when the number of component is chosen to have $0.5 < R^2 < 1$ and $0.5 < Q^2 < 1$ and the difference between R^2 and Q^2 is less than 0.2-0.3 [63]. In this work, two principal components were used to explain the variability of the predictor (input) variables on the final bulk of coated samples and to predict the variability in the input parameters.

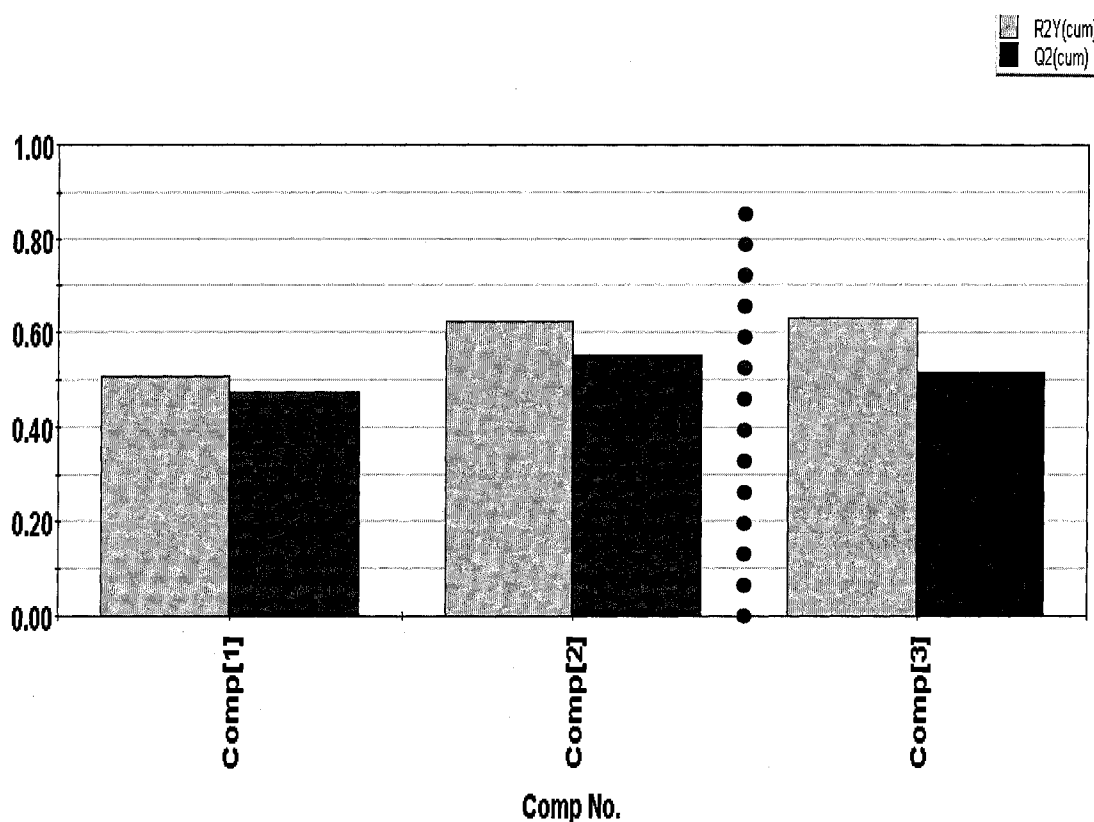


Figure 5.1: Principal Component Analysis of Data. Two Principal Components were Used in this Work

5.4.2. Identification of Outliers - Score Plots

The score plot could be used to identify possible outliers in the sample. This is done to refine the model in an attempt to increase the model fit and its predictability. Figure 5.2 shows the score plot in this study. In this plot, each sample (or observation) is given a pair of scores, $t[1]$ and $t[2]$, that corresponds to the value of the principal component for that observation. Regions of clusters (i.e. observations with similar scores, $t[1]$ and $t[2]$) occur with the paper samples treated under similar conditions. Figure 5.2 shows that only six samples fall just outside the Hotelling's T^2 95%, which represents a good data set.

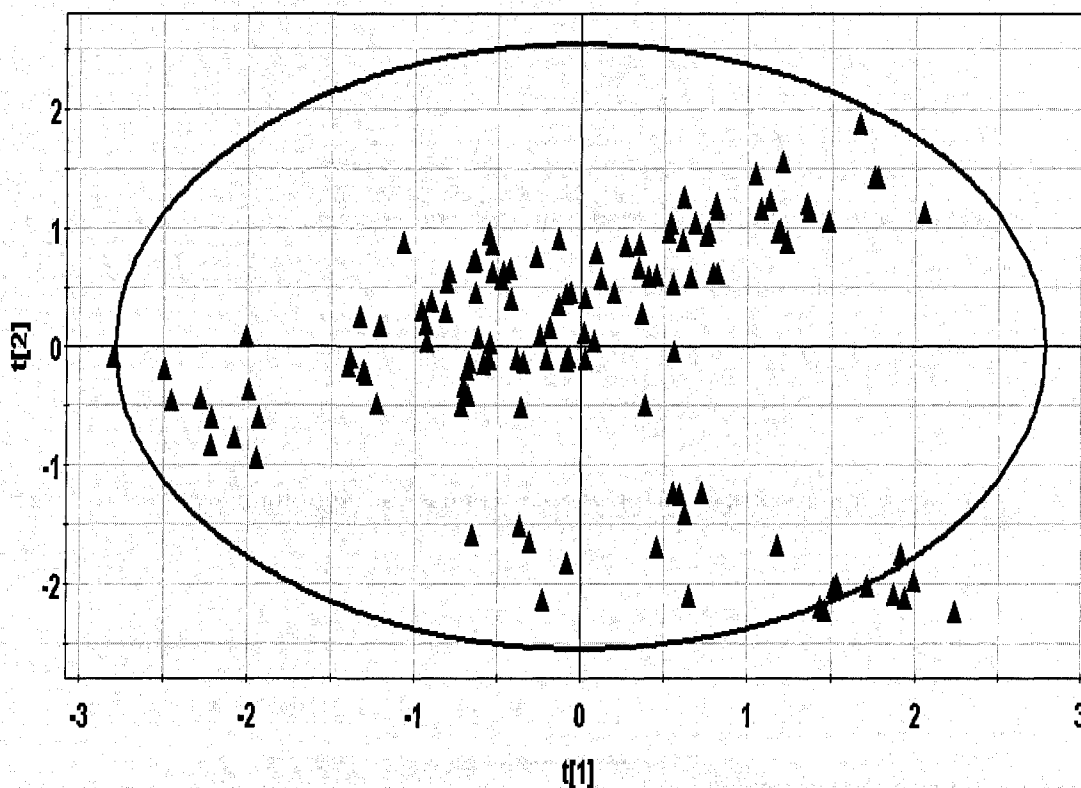


Figure 5.2: Score Plot

5.4.3. Loading, VIP, and Coefficient Plots

A loading plot is a graphical representation of the effect of each predictor variable on the principal component. In PLS, each variable is assigned weights ($w^*c [1]$, $w^*c [2]$) corresponding to each principal component. Figure 5.3 shows the plot of the $w^*c [2]$ against $w^*c [1]$. Highly correlated X-variables are represented by clusters; however, no region of cluster is seen implying that the X-variables may not be strongly correlated. X-variables that are close to the axes have little or no impact on the respective principal component. For example, $\ln(\text{Gloss})$ is close to the y-axis; therefore, it has little influence on the first component. On the contrary, HST is furthest from the y-axis and has the strongest influence on the first component. To deduce the importance of each variable on the model, an imaginary line connecting the origin to the 'Bulk' can be drawn. A perpendicular line from the X-variable of interest can be projected to this imaginary line. The importance of each variable is determined by the distance from this origin where the projected and imaginary lines meet. The further away from the origin, the more important the variable is to the overall model. X-variables, whose projection and imaginary lines meet on the opposite side of the y-axis (using the side with 'Bulk' as the reference) are negatively correlated to the 'Bulk'. And the X-variables that are on the same side of the y-axis as the 'Bulk' is positively correlated. For example, as the coating weight increased the final bulk of the sample decreases. Further information of the importance and correlation of the X-variables to the final bulk is given in subsequent paragraphs.

The variable influence on projection (VIP) plot is an alternative graphical representation of the importance of the papermaking and process properties on the final bulk of coated papers. The VIP score is the weighted sum of squares of the PLS weights, $w^*c [1]$ or $w^*c [2]$, taking into account the amount of explained Y-variance in each dimension [63]. The VIP plot gives the

relative importance of each predictor variable on the final bulk. However, it does not provide information about the correlation of these variables to the bulk. The coefficient plot shown in Figure 5.5 provides this information. It shows the regression model consisting of the PLS regression coefficients mean centered and scaled to a unit variance. In general, variables with VIP scores less than 0.5 are considered to have no significance on the response variables (Y) and greater than 1.0 have strong influence on the final bulk. Explanations of the importance and correlation of each X-variable is given below:

- HST(s) – Internal sizing level had the most influence on and is positively correlated to the final bulk of coated calendered paper samples. As mentioned before, internal sizing level promotes good coating holdout and increases the amount of coating on the surface of paper. As a result, as the internal sizing level increases, the bulk of the coated calendered sample also increases. However, as the HST increases, the bulk does not increase linearly. After a certain maximum HST level, the bulk of the paper samples will be unaffected. Hence, a sigmoid function was used to capture this unique relationship.
- HYP (%) - High-yield pulp content is the second most influential parameter on the coated calendered bulk. It is positively correlated to the final bulk, i.e. as the HYP content increases, the final bulk of the coated calendered samples increases. This is due to the presence of bulkier HYP fibres. There is more volume expansion for these samples during the coating process, resulting in a bulkier coated calendered sample.
- Coating Weight (g/m^2) – in this study, coating weight varied from 5.1 to 10.2 g/m^2 . It was found that coating weight was an important factor in determining the bulk of coated calender samples. Although, a higher coating weight implies a thicker coating layer and

potentially more water transferred to the base paper and more fibre swelling, it is negatively correlated to the final bulk. One explanation for this is that the coating layer is twice as dense compared to paper fibre (1.8 g/cm^3 [21] to 0.9 g/cm^3) and bulk is the inverse of density. Hence, a denser coating layer reduces the overall bulk of the coated paper sample. Also, paper samples precalendered at low temperatures could have poor coating holdout and excessive coating penetration into the base paper. This serves to further reduce the bulk of the coated calendered paper samples.

- Pulp Type – Pulp type is an important factor that affects the bulk of coated calendered samples. Two types of Aspen HYP were used in this study: Aspen 325/85 HB and Aspen 300/85. Aspen 325/85 HB fibres were bulkier than the Aspen 300/85 fibres (see Table 3.3). As the bulkiness of the Aspen fibres increases the final bulk of the coated calendered paper samples increases.
- PT- Precalendering temperature affects coating holdout and volume expansion of paper fibres. The relationship between precalendering and bulk is non-linear (Figure 4.12). In fact, this relationship is closer to a quadratic relationship. By adding a quadratic term to the model, the R^2 and Q^2 values improved by 10.3 and 11.1%, respectively. This proves that a quadratic term was needed to explain the relationship between precalendering temperature and the final bulk. For principal component (PC) 1 and 2 (Figure 5.5), the 'x²' term was negatively correlated to the bulk; whereas, the 'x' term was positively correlated to the bulk. Since bulk is mostly influenced by PC 1, this implies there is an optimum precalendering temperature that promotes maximum bulk. Above and below this temperature, the bulk decreases. In this study, this temperature was 80°C (Figure 4.12).

- PT and HST - The R^2 and Q^2 improved by 2.0 and 0.5%, respectively when the combined PT and HST term was added to the PLS regression model. As mentioned earlier, the effectiveness of internal sizing is dependent on the precalendering temperature: internal sizing is more effective at low precalendering temperature because these samples have poor coating holdout and coverage compared to higher precalendering temperatures.
- Baseweight- Basis weight is negatively correlated to the final bulk. Bulk is inversely related to basis weight.
- Ln Gloss – the $\log_e$ of the final gloss had the least influence on the final bulk and has a slight negative correlation to the final bulk. All the paper samples were calendered to a similar gloss and the low VIP score of the Ln Gloss values suggests that the paper samples were calendered to same 75° TAPPI gloss level. In addition, a higher Ln Gloss values resulted in a lower bulk because these samples were subjected to more calendering.

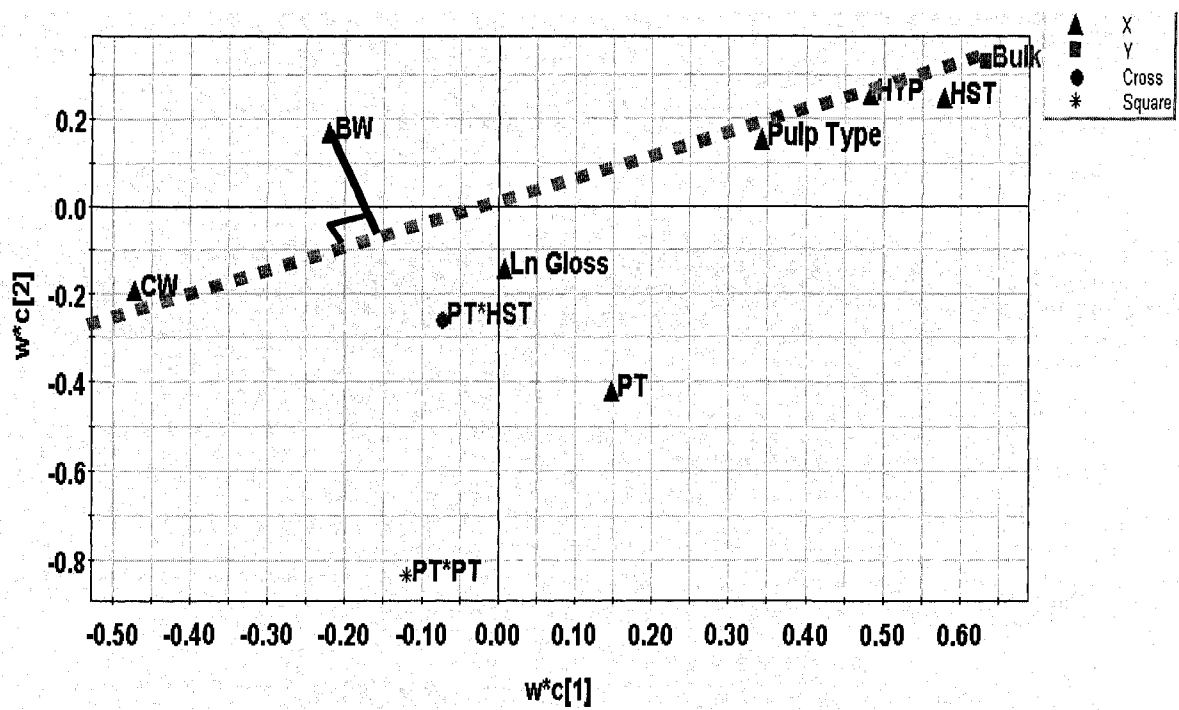
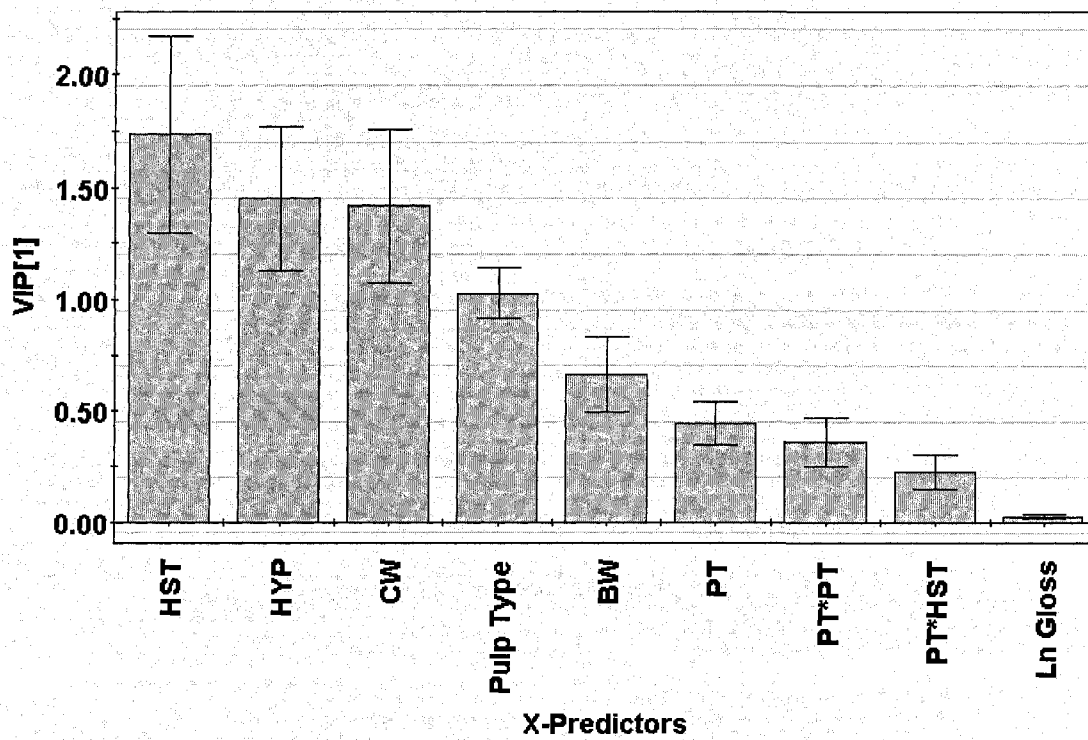
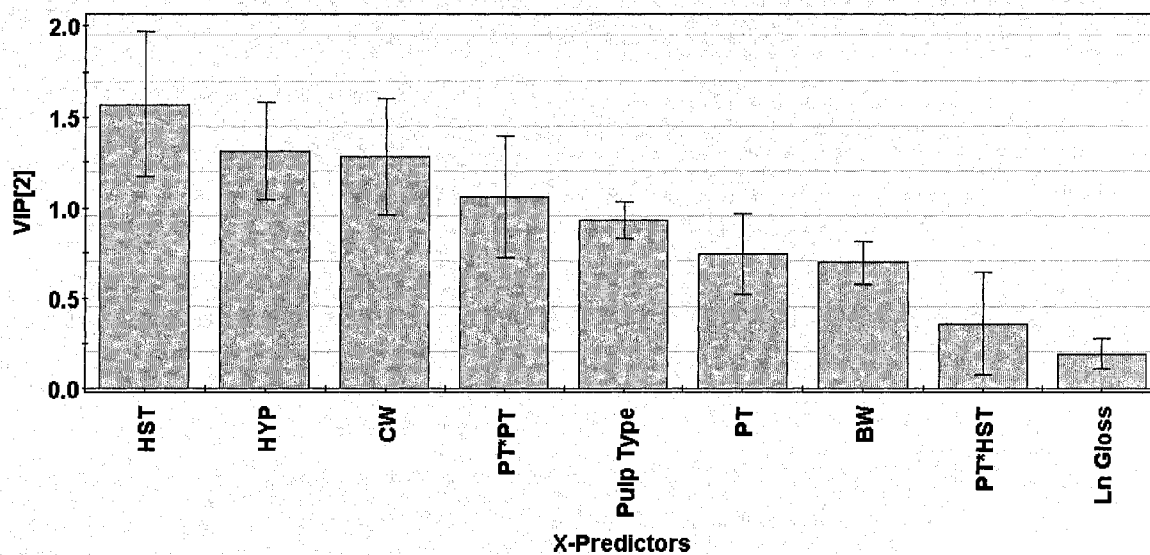


Figure 5.3: Loading Plot

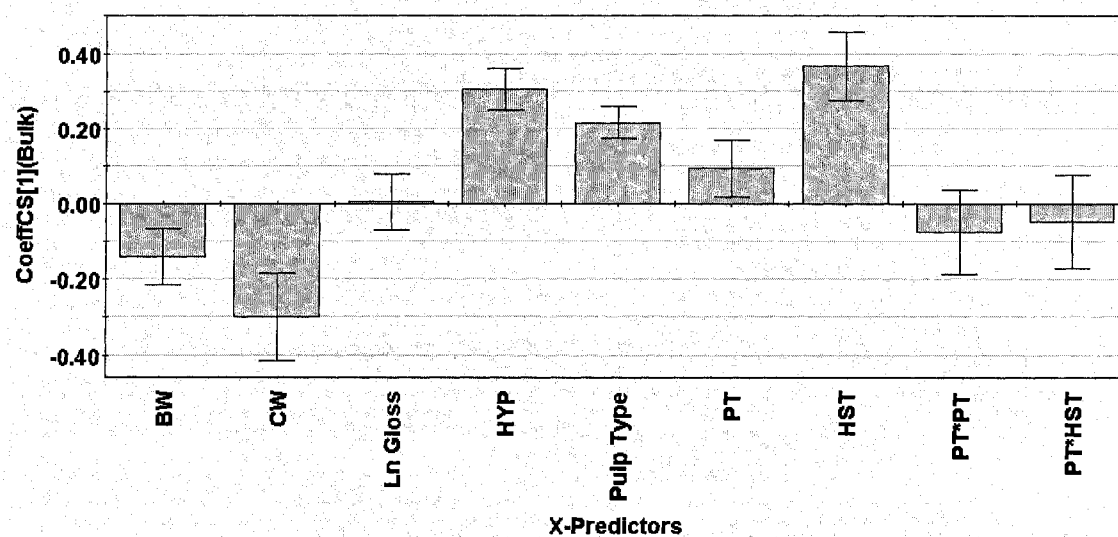


(a)

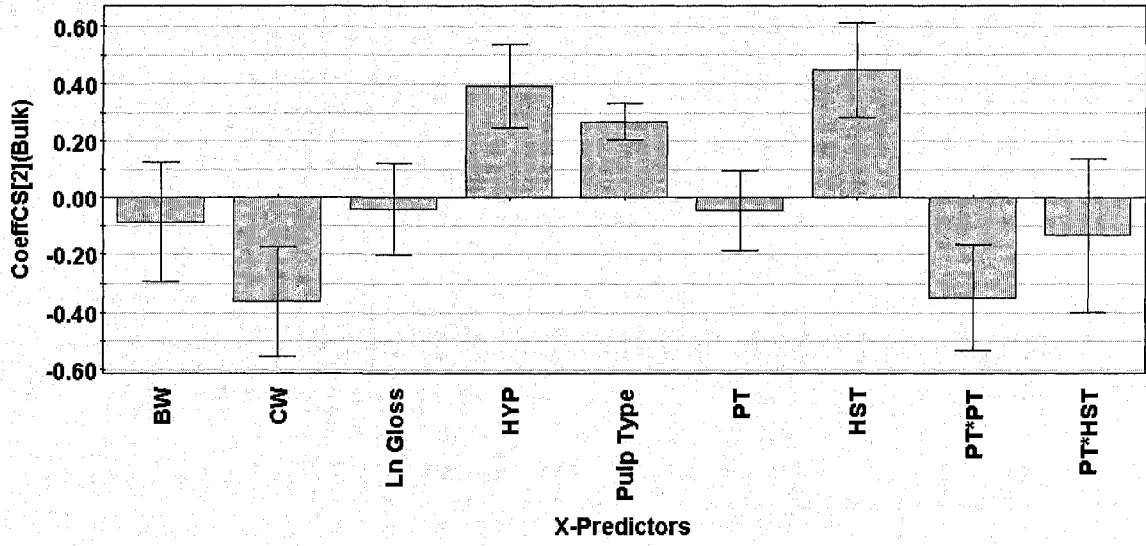


(b)

Figure 5.4: Variable Influence on Projection Plot. Shows the Relative Importance of Each Variable to the Bulk (a) First Principal Component; (b) Second Principal Component



(a)



(b)

Figure 5.5: Coefficient Plot. Shows the Correlation Between the Predictors Variables and the Bulk (a) First Principal Component; (b) Second Principal Component

5.4.4. Observed vs. Predicted Plot

The regression model shown in Figure 5.6 evaluates the predictive ability of the model by comparing the actual bulk to the predicted bulk. There is a cluster of points around the 45° line that passes through the origin. This represents a model with good predictive power with $R^2 = 0.62$. The final PLS regression model is:

$$y_{BULK} = 0.818 - 0.00467x_{CW} - 0.000729x_{BW} + 0.238\left(\frac{1}{1 + e^{-x_{HST}}}\right) + 0.00105x_{HYP} + 0.0182x_{PULP} \\ + 0.00157x_{PT} - 4.00 \times 10^{-6}x_{PT}^2 - 0.00112x_{PT}\left(\frac{1}{1 + e^{-x_{HST}}}\right) - 0.0134x_{\ln(Gloss)}$$

where y_{BULK} = bulk after calendering (cm^3/g); x_{CW} = Coating Weight(g/m^2); x_{BW} = Basis Weight(g/m^2); x_{HYP} = High-yield Pulp(%); x_{PULP} = High-yield Pulp Type; x_{PT} = Precalendering

Temperature(°C). The equation represents the unscaled x and y variables. The predictive ability of the model is illustrated in Appendix C. It should be noted that this model was not validated.

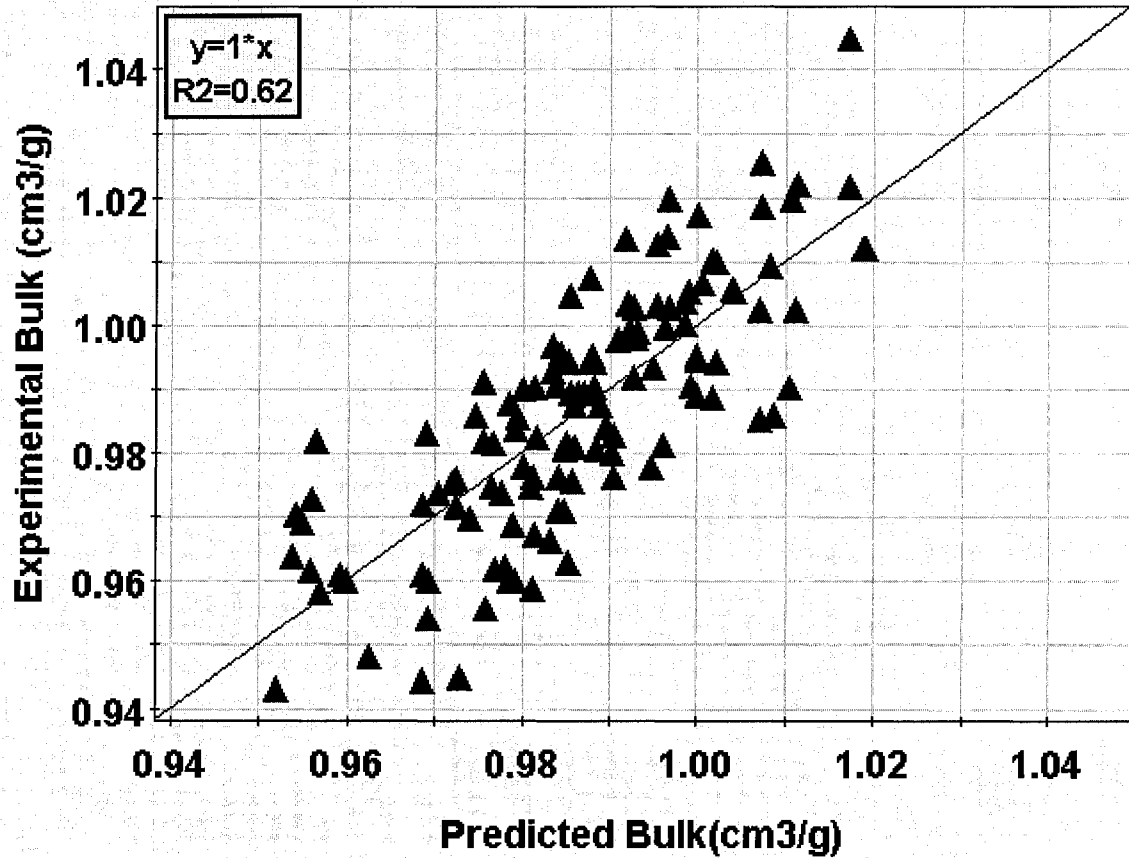


Figure 5.6: Correlation Between Actual (Observed) Bulk and Predicted Bulk

5.5. Conclusions

The effect of coating weight, high-yield pulp content, degree of internal sizing, pulp type and precalendering temperature on the bulk of paper samples after calendering was analysed using PLS regression modeling. The following were observed:

- The importance of papermaking variables on the bulk of samples decreased in the following order: internal sizing level > high-yield pulp content > coating weight > pulp type > precalendering temperature > basis weight > ln (Gloss).
- High-yield pulp content, Hercules sizing, pulp type is positively correlated to the final bulk while basis weight and coating weight is negatively correlated to the final bulk.
- Quadratic term was needed to explain the relationship between precalendering temperature and the final bulk.

6. CHAPTER 6 – CONCLUDING REMARKS

6.1. Conclusions

The effect of HYP content, HYP type, internal sizing, and precalendering temperature on bulk of coated samples calendered to a target gloss was investigated. The optimal precalendering temperature that maximises the bulk advantage of coated calendered samples containing 30% HYP was 80°C. In addition, for samples with 30% Aspen 325/85 HB there was an interaction effect between precalendering temperature and internal sizing: internal sizing was most effective at low precalendering temperatures. At various precalendering temperatures, the bulkier Aspen 325/85 HB fibres produced a 1-3% bulk advantage compared to Aspen 300/85 fibres.

Both BCTMP, Aspen 300/85 and Aspen 325/85HB, roughen more than samples with no BCTMP during water application. However, for the coating application, the roughness increase was only significant at 30% Aspen 325/85 HB substituted for HBKP. For the same amount of water applied, the change in roughness is greater for samples precalendered at 80°C compared to those precalendered at 23 and 140°C. Internal sizing has little or no effect on the roughness of coated paper samples after water and coating application.

This work makes an important contribution to papermakers because the roughening for BCTMP during coating has not been studied extensively in the past. Since this pulp has been extensively used and marketed in coated grades in recent years, it is important to understand the extent of roughening during coating. In addition, it is important to investigate the effect of different papermaking variables on the roughening of BCTMP papers. It is known that mechanical pulp roughens more than chemical pulp when wet. This increase in roughness is a concern for papermakers because it could require more calendering to achieve a targeted gloss, and hence

minimizes the bulk advantage. In this work, no additional calendering was required to acquire the targeted final gloss and the maximum bulk advantage was 6% for 30% Aspen 325/85 HB, precalendered at 80°C with internal sizing. In addition, the relative importance of each papermaking variable on the bulk of coated calendered samples had not been investigated. It is shown that all the variables studied have an effect on the bulk of coated paper samples.

6.2. Limitations and Recommendations for Future Work

The paper surface prior to coating was significantly different due to precalendering temperature and internal sizing. This meant that the coating pickup varied at the same application roll speed. Since the coating weight should be constant, minimising coating weight variations is important. Although, the coating weight variations in the experiments were small ($7.5 \pm 1.5 \text{ g/m}^2$), the PLS model illustrated that it was important. A better coating machine with a wide range of speeds could have facilitated more even coating coverage.

The factors controlling the increase in bulk during coating are volume expansion and coating layer. The relative importance of both factors on the final bulk of the coated calendered samples could be an interesting topic for future studies. This highlights the importance of applying a constant coating weight on the paper surface for accurate quantification of coating coverage and holdout to be made.

What is the effect of filler content, surface sizing, and double coating on the bulk of coated calendered samples? The effect of double coating would be difficult to study without good coating weight control. In addition, rolls of commercial papers at different IS, % HYP, and constant filler content could eliminate some experimental errors.

What is the effect of calendering speed on the bulk of coated calendered samples? Could it eliminate possible fibre crushing that occurs at high temperatures?

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Appendix A – Wetting Experiments

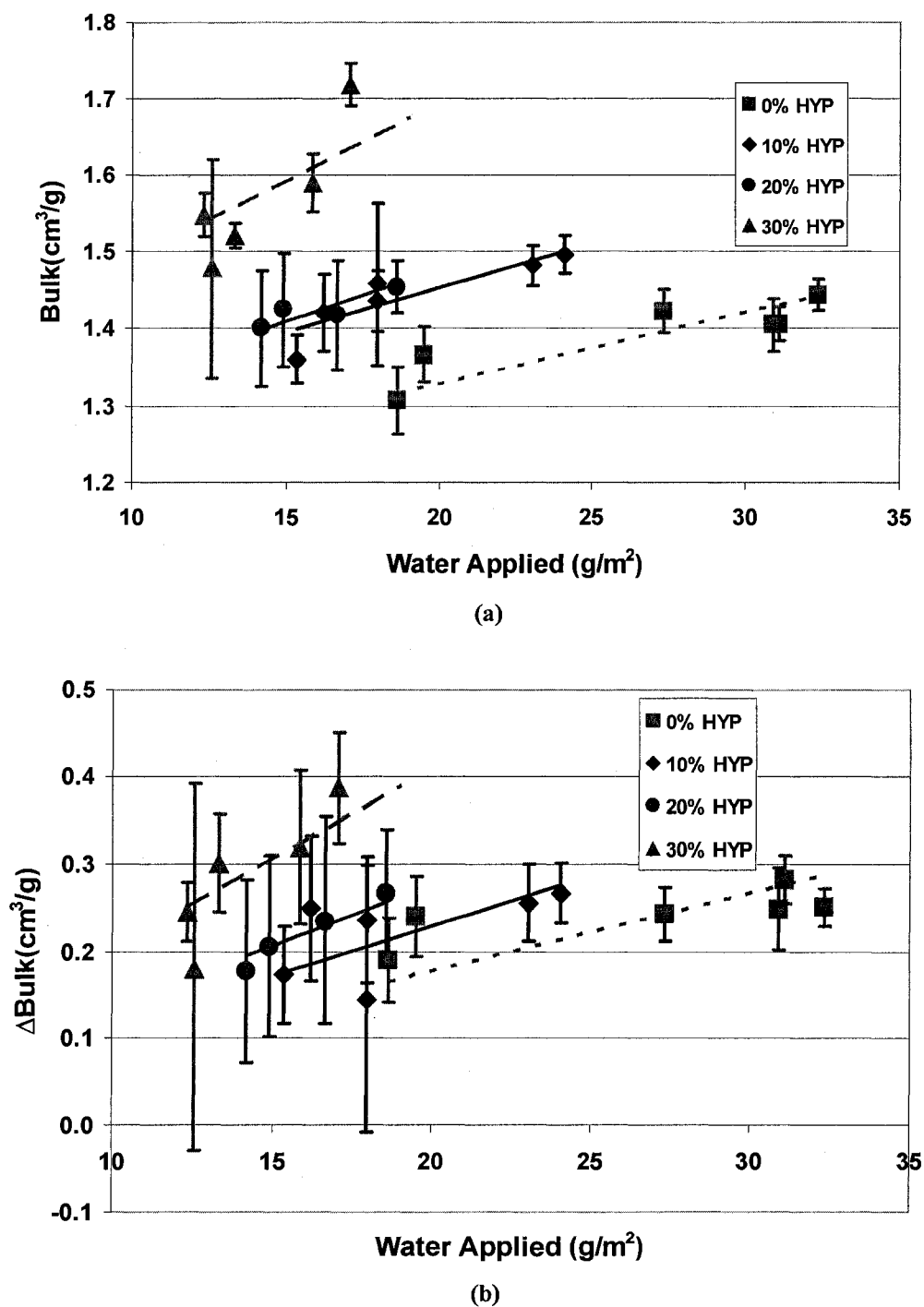


Figure A1.1: The Effect of Water Application at Different HYP Content for Samples Precalendered at 80°C and 62 kN/m (a) Bulk of Paper Samples; (b) Change in Bulk of the Paper Samples

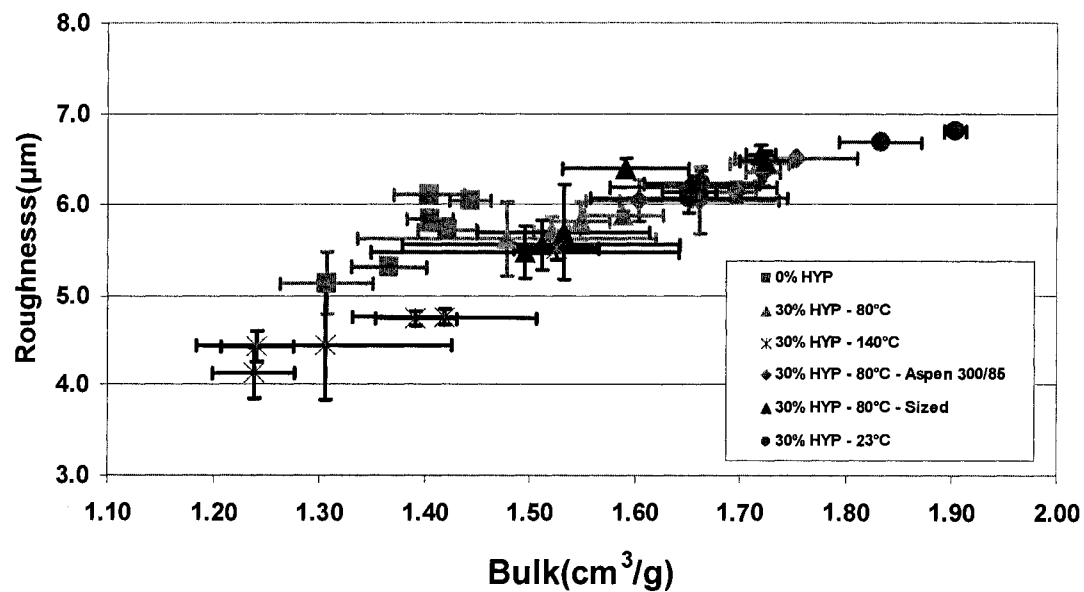


Figure A1.2: Relationship Between Bulk and Roughness After Coating

Table A.1: Full Experimental Results for Wetted Paper Samples

Condition	Water(g/m ²)	R-I(μm)	R-B(μm)	R-A(μm)	R-D(μm)	Pr-Spd	BW(g/m ²)	% HYP	IS(wt %)	T (°C)
Aspen 325/85 HB (1)	16	7.3	3.9	5.4	1.5	200	58	10	0	80
	18	7.3	4.1	5.6	1.5	150	58	10	0	80
	18	7.3	4.0	5.5	1.5	100	61	10	0	80
	15	7.3	3.8	5.1	1.3	100	61	10	0	80
	23	7.3	3.9	5.9	1.9	50	58	10	0	80
Aspen 325/85 HB (2)	24	7.3	4.2	6.0	1.8	50	58	10	0	80
	31	7.2	4.3	6.1	1.8	50	61	0	0	80
	27	7.2	4.1	5.7	1.6	100	61	0	0	80
	19	7.2	3.7	5.1	1.4	150	61	0	0	80
	20	7.2	4.0	5.3	1.3	200	61	0	0	80
Aspen 300 (3)	32	7.2	4.4	6.0	1.7	50	60	0	0	80
	31	7.2	4.0	5.8	1.8	50	60	0	0	80
	26	7.3	4.2	6.5	2.3	50	63	30	0	80
	24	7.3	4.2	6.4	2.2	50	63	30	0	80
	14	7.3	4.2	6.0	1.9	200	62	30	0	80
Aspen 325/85 HB (4)	16	7.3	3.7	4.7	1.1	150	62	30	0	80
	18	7.3	4.0	6.0	2.0	100	63	30	0	80
	18	7.3	4.3	6.1	1.8	100	63	30	0	80
	31	7.3	3.8	6.3	2.4	50	59	30	0.1	140
	28	7.3	3.2	6.0	2.8	50	59	30	0.1	140
Aspen 325/85 HB (4)	11	7.3	3.8	5.0	1.2	100	63	30	0.1	140
	16	7.3	3.5	5.2	1.7	100	63	30	0.1	140
	8	7.3	3.3	4.3	0.9	150	62	30	0.1	140
	9	7.3	3.8	4.7	0.9	200	62	30	0.1	140

Condition	Water(g/m ³)	R-I(μm)	R-B(μm)	R-A(μm)	R-D(μm)	Pr-Spd	BW(g/m ²)	% HYP	IS(wt %)	T (°C)
Aspen 300 (5)	9	7.3	4.3	5.3	0.9	200	58	30	0.15	80
	12	7.3	4.4	5.5	1.1	150	58	30	0.15	80
	15	7.3	4.2	5.6	1.4	100	59	30	0.15	80
	18	7.3	4.2	5.6	1.4	100	59	30	0.15	80
	24	7.3	4.3	6.2	1.9	50	51	30	0.15	80
Aspen 325/85 HB (6)	24	7.3	4.3	6.2	1.9	50	51	30	0.15	80
	25	7.3	4.1	6.2	2.1	50	58	30	0.1	80
	26	7.3	4.4	6.5	2.1	50	58	30	0.1	80
	17	7.3	4.1	5.8	1.7	100	55	30	0.1	80
	14	7.3	4.3	5.8	1.5	100	55	30	0.1	80
Aspen 325/85 HB (7)	12	7.3	4.3	5.5	1.2	150	62	30	0.1	80
	12	7.3	4.2	5.5	1.3	200	62	30	0.1	80
	26	7.3	3.8	5.9	2.1	50	60	30	0.15	140
	24	7.3	4.1	6.3	2.2	50	60	30	0.15	140
	16	7.3	3.7	5.2	1.5	100	59	30	0.15	140
Aspen 325/85 HB (8)	15	7.3	3.6	5.3	1.7	100	59	30	0.15	140
	12	7.3	3.8	4.7	0.9	150	61	30	0.15	140
	12	7.3	3.2	4.8	1.6	200	61	30	0.15	140
	21	7.3	4.1	5.9	1.8	50	59	30	0.15	80
	17	7.3	4.5	6.5	1.9	50	59	30	0.15	80
Aspen 325/85 HB (8)	16	7.3	4.1	5.9	1.7	100	58	30	0.15	80
	13	7.3	4.0	5.7	1.7	100	58	30	0.15	80
	13	7.3	4.3	5.6	1.4	150	58	30	0.15	80
	12	7.3	4.5	5.8	1.3	200	58	30	0.15	80

Condition	Water(g/m ³)	R-I(μm)	R-B(μm)	R-A(μm)	R-D(μm)	Pr-Spd	BW(g/m ²)	% HYP	IS(wt %)	T (°C)
Aspen 300 (9)	20	7.3	4.4	6.0	1.6	50	64	30	0.1	80
	19	7.3	4.1	5.8	1.7	50	64	30	0.1	80
	18	7.3	4.2	5.8	1.6	50	62	30	0.1	80
	16	7.3	4.2	5.9	1.7	100	62	30	0.1	80
	10	7.3	4.1	5.3	1.1	150	64	30	0.1	80
	10	7.3	4.2	5.3	1.0	200	64	30	0.1	80
Aspen 325/85 HB (10)	27	7.3	4.3	6.5	2.2	50	62	30	0.15	80
	25	7.3	4.3	6.5	2.2	50	62	30	0.15	80
	22	7.3	4.4	6.4	2.0	50	58	30	0.15	80
	11	7.3	4.2	5.5	1.3	100	58	30	0.15	80
	14	7.3	4.2	5.7	1.5	150	64	30	0.15	80
	14	7.3	4.3	5.6	1.3	200	64	30	0.15	80
Aspen 325/85 HB (11)	25	7.3	4.0	5.9	2.0	50	63	20	0	80
	26	7.3	3.9	5.9	2.0	50	63	20	0	80
	19	7.3	4.2	6.0	1.8	100	63	20	0	80
	17	7.3	4.0	5.7	1.7	100	63	20	0	80
	14	7.3	4.1	5.7	1.5	150	58	20	0	80
	15	7.3	4.0	5.5	1.6	200	58	20	0	80
Aspen 300 (12)	27	7.3	5.4	6.5	1.2	50	61	30	0	23
	25	7.3	5.2	6.5	1.3	50	61	30	0	23
	16	7.3	4.9	5.9	1.0	100	58	30	0	23
	18	7.3	5.0	6.0	1.0	100	58	30	0	23
	14	7.3	5.0	5.8	0.7	150	62	30	0	23
	13	7.3	5.1	5.8	0.7	200	62	30	0	23

Condition	Water(g/m ²)	R-I(μm)	R-B(μm)	R-A(μm)	R-D(μm)	Pr-Spd	BW(g/m ²)	% HYP	IS(wt %)	T (°C)
Aspen 325/85 HB (13)	32	7.3	5.5	6.8	1.3	50	59	30	0	23
	31	7.3	5.0	6.7	1.7	50	59	30	0	23
	17	7.3	5.1	6.2	1.1	100	57	30	0	23
	16	7.3	5.0	6.1	1.1	100	57	30	0	23
	16	7.3	5.3	6.2	1.0	150	56	30	0	23
	16	7.3	5.1	6.1	1.0	200	56	30	0	23
Aspen 325/85 HB (14)	17	7.3	3.9	5.5	1.6	50	59	30	0	140
	13	7.3	3.6	4.7	1.2	50	59	30	0	140
	8	7.3	3.8	4.4	0.7	100	59	30	0	140
	11	7.3	3.8	4.8	0.9	100	59	30	0	140
	11	7.3	3.7	4.4	0.8	150	60	30	0	140
	8	7.3	3.6	4.1	0.5	200	60	30	0	140
Aspen 300 (15)	14	7.3	4.1	5.2	1.1	50	58	30	0	140
	16	7.3	3.7	4.9	1.2	50	58	30	0	140
	18	7.3	4.3	5.4	1.1	100	62	30	0	140
	17	7.3	4.2	5.2	1.0	100	62	30	0	140
	11	7.3	3.8	4.4	0.5	150	58	30	0	140
	12	7.3	3.9	4.4	0.5	200	58	30	0	140
Aspen 300 (16)	20	7.3	5.2	6.2	1.0	50	57	30	0.1	23
	24	7.3	5.4	6.5	1.1	50	57	30	0.1	23
	23	7.3	5.6	6.5	0.9	100	61	30	0.1	23
	18	7.3	5.2	6.1	1.0	100	61	30	0.1	23
	14	7.3	5.1	5.8	0.7	150	60	30	0.1	23
	14	7.3	4.9	5.8	1.0	200	60	30	0.1	23

Condition	Water(g/m ²)	R-I(μm)	R-B(μm)	R-A(μm)	R-D(μm)	Pr-Spd	BW(g/m ²)	% HYP	IS(wt %)	T (°C)
Aspen 300 (17)	21	7.3	5.0	6.2	1.2	50	58	30	0.15	23
	23	7.3	5.3	6.3	1.0	50	58	30	0.15	23
	18	7.3	5.1	6.1	1.0	100	62	30	0.15	23
	17	7.3	5.4	6.3	0.9	100	61	30	0.15	23
	15	7.3	5.1	5.9	0.8	150	62	30	0.15	23
Aspen 300 (18)	10	7.3	5.5	5.8	0.3	200	62	30	0.15	23
	31	7.3	5.3	6.6	1.3	50	62	30	0.1	23
	33	7.3	5.4	6.7	1.4	50	62	30	0.1	23
	20	7.3	5.2	6.3	1.1	100	57	30	0.1	23
	21	7.3	5.4	6.5	1.1	100	57	30	0.1	23
Aspen 300 (19)	14	7.3	5.4	6.2	0.8	150	64	30	0.1	23
	12	7.3	5.0	5.6	0.7	200	64	30	0.1	23
	32	7.3	5.5	6.8	1.3	50	61	30	0.15	23
	35	7.3	5.7	6.9	1.2	50	61	30	0.15	23
	19	7.3	5.5	6.4	0.9	100	61	30	0.15	23
	26	7.3	5.4	6.6	1.2	100	61	30	0.15	23
	17	7.3	5.5	6.3	0.8	150	60	30	0.15	23
	13	7.3	5.2	6.1	0.9	200	60	30	0.15	23

- R-I = Roughness of Handsheets
- R-B = Roughness Before Precalendering
- R-A = Roughness After Precalendering
- R-D = Roughness Change During Wetting
- Pr-Spd = Print Speed
- IS = Internal Sizing Level
- BW = Basis Weight

Appendix B – Coating Experiments

Table B. 1: Full Experimental Results for Coated Paper Samples

Cond # - Nips	BW (g/m ²)	B ₀ (cm ³ /g)	B _p (cm ³ /g)	B _c (cm ³ /g)	B _f (cm ³ /g)	R _o (μm)	R _p (μm)	R _c (μm)	R _f (μm)	CW (g/m ²)	HST (s)	R-A (%)	Gf (G.U)	HYP (%)	Pulp Type	PT (°C)
1 (2.2)	61	1.83	1.22	1.24	1.00	7.32	4.09	5.07	2.64	7.6	1.7	0	30	30	325/85 HB	80
	64	1.84	1.16	1.21	1.04	7.32	4.00	4.86	2.73	6.2	1.7	0	28	30	325/85 HB	80
	58	1.82	1.19	1.21	1.00	7.38	4.08	5.26	2.60	6.1	1.7	0	34	30	325/85 HB	80
	59	1.82	1.20	1.23	1.01	7.33	4.10	4.97	2.72	6.7	1.7	0	31	30	325/85 HB	80
	60	1.77	1.20	1.17	1.01	7.27	3.87	4.89	2.53	6.5	1.7	0	35	30	325/85 HB	80
2 (2)	64	1.77	1.25	1.23	0.96	7.30	4.56	5.95	2.55	7.2	1.7	0	35	30	325/85 HB	23
	62	1.79	1.24	1.23	0.97	7.22	4.60	5.82	2.72	7.6	1.7	0	32	30	325/85 HB	23
	61	1.72	1.23	1.22	0.99	7.24	4.79	6.02	2.91	7.7	1.7	0	31	30	325/85 HB	23
	60	1.81	1.29	1.31	0.99	7.23	4.46	5.74	2.63	6.1	1.7	0	32	30	325/85 HB	23
	61	1.73	1.26	1.24	0.99	7.15	4.54	5.67	2.67	8.3	1.7	0	34	30	325/85 HB	23
3 (2)	62	1.80	1.28	1.20	0.99	7.26	4.46	5.65	2.83	9.1	1.7	0	32	30	325/85 HB	50
	64	1.75	1.22	1.20	0.99	7.24	4.43	5.42	2.59	7.9	1.7	0	33	30	325/85 HB	50
	64	1.80	1.25	1.23	0.98	7.30	4.60	5.78	2.56	7.6	1.7	0	36	30	325/85 HB	50
	60	1.75	1.32	1.20	1.00	7.24	4.61	5.69	2.78	8.6	1.7	0	30	30	325/85 HB	50
	63	1.75	1.28	1.22	0.99	7.24	4.64	5.75	3.00	7.9	1.7	0	30	30	325/85 HB	50
4 (2)	60	1.84	1.22	1.23	1.00	7.38	3.95	5.18	2.54	6.1	1.7	0	34	30	325/85 HB	110
	57	1.86	1.20	1.24	0.99	7.37	3.64	5.20	2.71	7.7	1.7	0	34	30	325/85 HB	110
	63	1.76	1.14	1.15	0.99	7.32	3.74	4.84	2.69	7.0	1.7	0	33	30	325/85 HB	110
	61	1.80	1.22	1.25	0.98	7.37	3.96	5.13	2.64	7.7	1.7	0	33	30	325/85 HB	110
	62	1.83	1.18	1.24	0.98	7.29	3.91	5.25	2.67	7.7	1.7	0	33	30	325/85 HB	110
5 (2)	57	1.89	1.20	1.13	0.98	7.32	3.01	3.72	2.34	4.8	1.7	0	33	30	325/85 HB	140
	56	1.97	1.16	1.18	0.96	7.30	3.47	3.69	2.35	6.9	1.7	0	34	30	325/85 HB	140
	60	1.95	1.12	1.12	0.99	7.33	2.97	3.59	2.37	6.2	1.7	0	34	30	325/85 HB	140
	63	1.80	1.13	1.10	1.00	7.29	3.04	3.72	2.30	5.1	1.7	0	32	30	325/85 HB	140
	64	1.72	1.11	1.13	0.99	7.19	2.99	3.78	2.30	4.5	1.7	0	37	30	325/85 HB	140

Cond # - Nips	BW (g/m ²)	Bo (cm ³ /g)	Bp (cm ³ /g)	Bc (cm ³ /g)	Bf (cm ³ /g)	Ro (μm)	Rp (μm)	Rc (μm)	Rf (μm)	CW (g/m ²)	HST (s)	R-A (%)	Gf (G.U)	HVP (%)	Pulp Type	PT (°C)
6 (3.2)	61	1.66	1.66	1.13	0.96	7.29	4.03	4.73	2.74	7.0	1.7	0	31	0	N/A	80
	57	1.68	1.68	1.12	0.97	7.31	4.11	4.80	2.76	7.6	1.7	0	32	0	N/A	80
	64	1.60	1.60	1.08	0.97	7.15	3.96	4.30	2.39	6.2	1.7	0	32	0	N/A	80
	60	1.64	1.64	1.07	0.96	7.08	3.82	3.95	2.44	5.9	1.7	0	32	0	N/A	80
	64	1.60	1.60	1.08	0.94	7.25	4.24	4.26	2.54	6.8	1.7	0	30	0	N/A	80
7 (2)	58	1.68	1.68	1.12	0.98	7.48	3.82	4.58	2.77	6.8	1.7	0	31	10	325/85 HB	80
	59	1.72	1.72	1.11	0.95	7.46	4.02	4.70	2.59	7.8	1.7	0	33	10	325/85 HB	80
	63	1.78	1.78	1.07	0.95	7.41	4.49	4.88	2.65	9.0	1.7	0	31	10	325/85 HB	80
	58	1.72	1.72	1.09	0.98	7.24	4.20	4.41	2.67	8.3	1.7	0	30	10	325/85 HB	80
	59	1.65	1.65	1.05	0.95	7.25	3.94	3.89	2.36	7.4	1.7	0	29	10	325/85 HB	80
8 (2)	61	1.74	1.74	1.12	0.99	7.31	3.77	4.27	2.42	6.1	1.7	0	30	20	325/85 HB	80
	58	1.81	1.81	1.15	0.98	7.24	4.10	4.40	2.50	6.2	1.7	0	31	20	325/85 HB	80
	61	1.79	1.79	1.11	0.96	7.30	3.97	4.28	2.33	8.1	1.7	0	31	20	325/85 HB	80
	58	1.68	1.68	1.08	0.98	7.38	4.08	4.31	2.72	6.5	1.7	0	30	20	325/85 HB	80
	58	1.75	1.75	1.14	0.99	7.26	4.05	4.47	2.58	6.4	1.7	0	30	20	325/85 HB	80
9 (2)	59	1.78	1.19	1.16	1.02	7.27	3.60	4.36	2.74	5.2	2.2	0.05	32	30	325/85 HB	80
	61	1.87	1.16	1.12	0.99	7.25	3.24	3.85	2.49	5.8	2.2	0.05	32	30	325/85 HB	80
	61	1.85	1.17	1.20	1.01	7.26	3.84	4.51	2.47	7.9	2.6	0.1	32	30	325/85 HB	80
	62	1.82	1.18	1.22	1.01	7.26	3.81	4.56	2.47	7.3	2.6	0.1	32	30	325/85 HB	80
	64	1.84	1.18	1.21	0.99	7.31	3.75	4.64	2.46	7.3	2.6	0.1	33	30	325/85 HB	80
10 (2)	61	1.87	1.16	1.11	1.01	7.23	3.46	4.02	2.57	6.6	2.6	0.1	31	30	325/85 HB	80
	59	1.83	1.19	1.09	1.02	7.30	3.41	4.13	2.63	6.9	2.6	0.1	33	30	325/85 HB	80
	61	1.92	1.08	1.24	1.04	7.35	4.04	4.73	2.68	6.5	4.4	0.15	32	30	325/85 HB	80
	58	1.95	1.10	1.21	1.03	7.32	4.01	5.03	2.64	9.0	4.4	0.15	32	30	325/85 HB	80
	58	1.83	1.09	1.24	1.01	7.38	3.99	4.92	2.58	6.4	4.4	0.15	33	30	325/85 HB	80
11 (2)	60	1.82	1.09	1.22	1.02	7.30	4.00	4.89	2.80	6.7	4.4	0.15	30	30	325/85 HB	80
	62	1.86	1.08	1.27	1.01	7.34	3.82	4.81	2.58	6.4	4.4	0.15	27	30	325/85 HB	80

Cond # - Nips	BW (g/m ²)	Bo (cm ³ /g)	Bp (cm ³ /g)	Bc (cm ³ /g)	Bf (cm ³ /g)	Ro (μm)	Rp (μm)	Rc (μm)	Rf (μm)	CW (g/m ²)	HST (s)	R-A (%)	Gf (G.U)	HYP (%)	Pulp Type	PT (°C)
12 (2.4)	58	1.90	1.04	1.11	0.98	7.29	2.93	3.49	2.19	6.4	4.4	0.15	30	30	325/85 HB	140
	57	1.88	1.05	1.11	1.00	7.28	3.16	3.45	2.27	6.3	4.4	0.15	29	30	325/85 HB	140
	58	1.88	1.03	1.14	0.98	7.32	3.22	3.59	2.23	7.4	4.4	0.15	30	30	325/85 HB	140
	56	1.91	1.00	1.26	0.99	7.35	3.14	3.81	2.08	5.5	4.4	0.15	32	30	325/85 HB	140
	60	2.03	1.08	1.21	0.98	7.28	3.22	3.74	2.12	6.8	4.4	0.15	33	30	325/85 HB	140
13 (2.3)	59	1.93	1.13	1.17	0.99	7.33	4.48	5.53	2.72	7.6	4.4	0.15	31	30	325/85 HB	23
	59	1.96	1.12	1.19	1.02	7.38	4.53	5.43	2.74	7.6	4.4	0.15	31	30	325/85 HB	23
	61	1.97	1.12	1.23	1.00	7.29	4.56	5.78	2.69	7.4	4.4	0.15	29	30	325/85 HB	23
	62	1.85	1.22	1.16	0.99	7.33	4.56	5.79	2.77	7.6	4.4	0.15	31	30	325/85 HB	23
	63	1.81	1.10	1.06	1.01	7.26	2.76	3.84	2.24	5.7	2.2	0.05	32	30	325/85 HB	140
15 (2)	63	1.82	1.16	1.14	0.98	7.26	3.27	3.74	2.23	6.2	2.2	0.05	32	30	325/85 HB	140
	58	1.85	1.25	1.21	0.96	7.30	4.65	5.71	2.75	11.2	2.2	0.05	32	30	325/85 HB	23
	63	1.79	1.23	1.21	0.97	7.33	4.60	5.54	2.86	10.3	2.2	0.05	32	30	325/85 HB	23
	61	1.85	1.26	1.21	0.96	7.28	4.52	5.30	2.54	9.8	2.2	0.05	34	30	325/85 HB	23
	59	1.80	1.25	1.21	1.00	7.26	4.52	5.75	2.71	9.4	2.2	0.05	33	30	325/85 HB	23
16 (2.4)	59	1.82	1.24	1.20	0.98	7.31	4.49	5.64	3.04	10.2	2.2	0.05	30	30	325/85 HB	23
	62	1.72	1.27	1.21	0.99	7.32	4.66	5.72	2.62	10.8	2.6	0.1	36	30	325/85 HB	23
	60	1.74	1.27	1.27	1.01	7.24	4.72	5.51	2.42	6.7	2.6	0.1	34	30	325/85 HB	23
	61	1.62	1.23	1.24	1.02	7.19	4.66	5.67	2.66	7.4	2.6	0.1	34	30	325/85 HB	23
	59	1.85	1.30	1.24	0.97	7.24	4.64	5.48	2.54	10.4	2.6	0.1	33	30	325/85 HB	23
17 (2.6)	57	1.90	1.28	1.33	1.00	7.23	4.65	5.74	2.66	10.1	2.6	0.1	32	30	325/85 HB	23
	58	1.96	1.12	1.15	1.00	7.26	2.63	3.35	1.94	5.6	2.6	0.1	34	30	325/85 HB	140
	58	1.87	1.09	1.14	1.01	7.24	2.67	3.50	2.00	4.6	2.6	0.1	31	30	325/85 HB	140
	57	1.94	1.17	1.27	1.00	7.28	3.24	3.94	1.98	4.7	2.6	0.1	35	30	325/85 HB	140
	57	1.87	1.11	1.16	1.00	7.32	2.80	3.53	1.96	4.5	2.6	0.1	33	30	325/85 HB	140
	57	1.87	1.17	1.07	1.00	7.31	3.05	3.73	2.46	6.0	2.6	0.1	31	30	325/85 HB	140

Cond # - Nips	BW (g/m ²)	Bo (cm ³ /g)	Bp (cm ³ /g)	Bc (cm ³ /g)	Bf (cm ³ /g)	Ro (μm)	Rp (μm)	Rc (μm)	Rf (μm)	CW (g/m ²)	HST (s)	R-A (%)	Gf (G.U)	HYP (%)	Pulp Type	PT (°C)
18 (2.4)	59	1.69	1.13	1.13	0.99	7.33	3.70	4.53	2.68	7.1	1.7	0	31	30	300/85	80
	59	1.65	1.19	1.15	0.98	7.35	3.78	4.70	2.90	7.9	1.7	0	29	30	300/85	80
	61	1.70	1.17	1.14	0.99	7.36	3.91	4.62	2.69	6.9	1.7	0	27	30	300/85	80
	63	1.73	1.15	1.13	0.98	7.32	3.75	4.41	2.68	7.8	1.7	0	28	30	300/85	80
	63	1.73	1.13	1.13	0.97	7.33	3.63	4.41	2.76	7.1	1.7	0	32	30	300/85	80
19 (2.2)	58	1.72	1.13	1.24	0.96	7.32	5.01	5.49	2.47	10.6	1.7	0	30	30	300/85	23
	64	1.71	1.19	1.21	0.97	7.33	4.80	5.64	2.85	9.9	1.7	0	30	30	300/85	23
	60	1.71	1.17	1.22	0.98	7.33	4.78	5.79	2.81	10.4	1.7	0	30	30	300/85	23
	63	1.73	1.15	1.23	0.96	7.34	4.84	5.61	2.74	10.0	1.7	0	31	30	300/85	23
	62	1.75	1.13	1.24	0.96	7.34	4.72	5.48	2.83	9.4	1.7	0	31	30	300/85	23
20 (2.6)	61	1.65	1.06	1.08	0.97	7.30	2.79	3.41	2.16	5.3	1.7	0	34	30	300/85	140
	63	1.62	1.05	1.06	0.98	7.32	2.87	3.53	2.49	5.6	1.7	0	32	30	300/85	140
	64	1.69	1.04	1.08	0.97	7.34	2.95	3.68	2.39	6.3	1.7	0	31	30	300/85	140
	63	1.68	1.09	1.13	0.97	7.32	3.05	3.82	2.38	5.6	1.7	0	31	30	300/85	140
	57	1.78	1.11	1.14	0.97	7.34	3.25	4.11	2.45	7.2	1.7	0	30	30	300/85	140
21 (2)	63	1.63	1.18	1.15	0.98	7.29	3.89	4.54	2.57	7.6	2.2	0.05	34	30	300/85	80
	61	1.66	1.17	1.13	0.97	7.25	3.84	4.70	2.78	8.4	2.2	0.05	31	30	300/85	80
	64	1.66	1.16	1.12	0.97	7.27	3.96	4.46	2.60	8.1	2.2	0.05	33	30	300/85	80
	59	1.65	1.19	1.14	0.99	7.29	3.82	4.45	2.61	7.9	2.2	0.05	34	30	300/85	80
	58	1.66	1.19	1.12	0.96	7.30	3.79	4.35	2.60	8.4	2.2	0.05	34	30	300/85	80
22 (2)	62	1.71	1.17	1.14	0.99	7.29	3.78	4.41	2.72	7.3	2.6	0.1	33	30	300/85	80
	62	1.67	1.17	1.16	1.00	7.26	3.80	4.48	2.54	6.9	2.6	0.1	33	30	300/85	80
	59	1.77	1.19	1.18	0.99	7.29	3.87	4.77	2.78	7.3	2.6	0.1	32	30	300/85	80
	60	1.68	1.19	1.12	1.01	7.29	3.84	4.57	2.80	7.9	2.6	0.1	33	30	300/85	80
	59	1.71	1.17	1.15	0.98	7.32	3.86	4.82	2.90	7.0	2.6	0.1	33	30	300/85	80

Cond # - Nips	BW (g/m ²)	Bo (cm ³ /g)	Bp (cm ³ /g)	Bc (cm ³ /g)	Bf (cm ³ /g)	Ro (μm)	Rp (μm)	Rc (μm)	Rf (μm)	CW (g/m ²)	HST (s)	R-A (%)	Gf (G.U)	HYP (%)	Pulp Type	PT (°C)
23 (3)	61	1.71	1.20	1.16	0.99	7.24	3.69	4.60	2.86	7.5	4.4	0.15	32	30	300/85	80
	62	1.73	1.18	1.16	0.99	7.32	3.78	4.68	3.03	7.9	4.4	0.15	32	30	300/85	80
	59	1.78	1.19	1.14	1.00	7.27	3.85	4.79	2.88	8.3	4.4	0.15	30	30	300/85	80
	59	1.76	1.20	1.15	1.01	7.25	3.83	4.69	2.83	7.8	4.4	0.15	30	30	300/85	80
	62	1.69	1.16	1.16	0.99	7.31	3.74	4.74	2.81	7.7	4.4	0.15	32	30	300/85	80
24 (3)	59	1.69	1.22	1.15	1.02	7.24	4.63	5.36	2.55	7.1	4.4	0.15	36	30	300/85	23
	62	1.70	1.19	1.16	1.01	7.28	4.47	4.91	2.68	6.1	4.4	0.15	33	30	300/85	23
	59	1.71	1.19	1.11	1.00	7.26	4.38	5.01	2.83	9.2	4.4	0.15	33	30	300/85	23
	56	1.71	1.19	1.16	1.00	7.22	4.65	5.27	2.80	9.4	4.4	0.15	33	30	300/85	23
	56	1.64	1.19	1.17	1.00	7.25	4.65	5.11	2.79	6.7	4.4	0.15	29	30	300/85	23
25 (2.2)	59	1.58	1.17	1.09	0.94	7.28	4.56	5.30	2.65	10.1	2.2	0.05	33	30	300/85	23
	63	1.64	1.16	1.11	0.98	7.27	4.44	5.28	2.84	9.2	2.2	0.05	29	30	300/85	23
	63	1.62	1.18	1.13	0.96	7.29	4.57	5.26	2.64	9.2	2.2	0.05	35	30	300/85	23
	63	1.63	1.16	1.11	0.96	7.32	4.50	5.17	2.72	9.5	2.2	0.05	33	30	300/85	23
	58	1.69	1.18	1.13	0.99	7.27	4.48	5.29	2.71	9.0	2.2	0.05	32	30	300/85	23
26 (2)	56	1.63	1.21	1.16	0.97	7.23	4.63	5.25	2.80	9.6	2.6	0.1	35	30	300/85	23
	57	1.73	1.20	1.16	0.97	7.29	4.49	4.97	2.68	9.3	2.6	0.1	31	30	300/85	23
	61	1.68	1.18	1.17	0.98	7.31	4.53	5.30	2.74	9.8	2.6	0.1	29	30	300/85	23
	58	1.73	1.19	1.16	0.98	7.29	4.55	5.14	2.73	9.2	2.6	0.1	32	30	300/85	23
	63	1.69	1.16	1.17	0.96	7.33	4.44	5.03	2.51	9.0	2.6	0.1	32	30	300/85	23

- Nips – average numbers of nips needed to achieve targeted final Tappi gloss
- Bo – bulk of the handsheet, Bp – bulk after precalendering, Bc – bulk after coating, Bf – bulk after coating and calendering
- Ro – roughness of the handsheet, Rp – Roughness after precalendering, Rc – Roughness after coating, Rf – Roughness after coating and calendering
- BW – basis weight, CW – coating weight
- R-A- rosin-alum sizing level
- Gf – final gloss
- PT – precalendering temperature

Appendix C – PLS Modeling

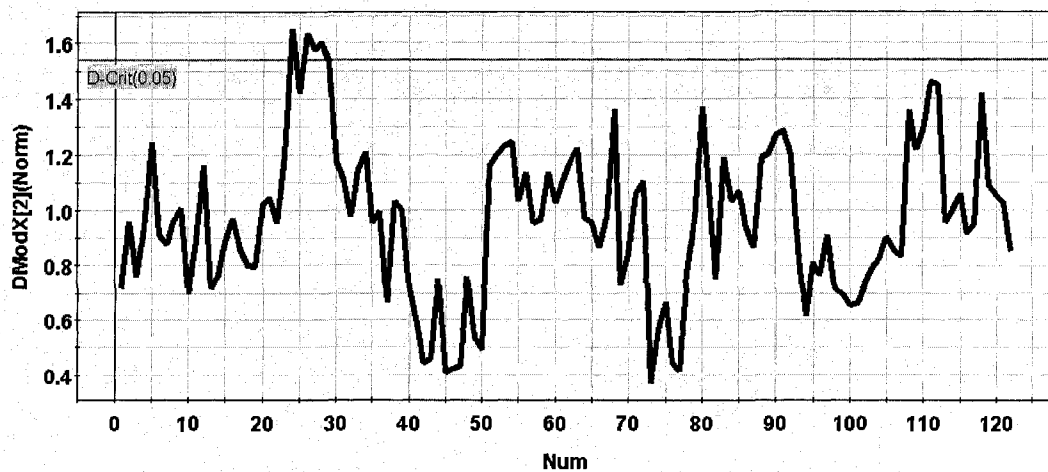


Figure C.1: DModX Plot

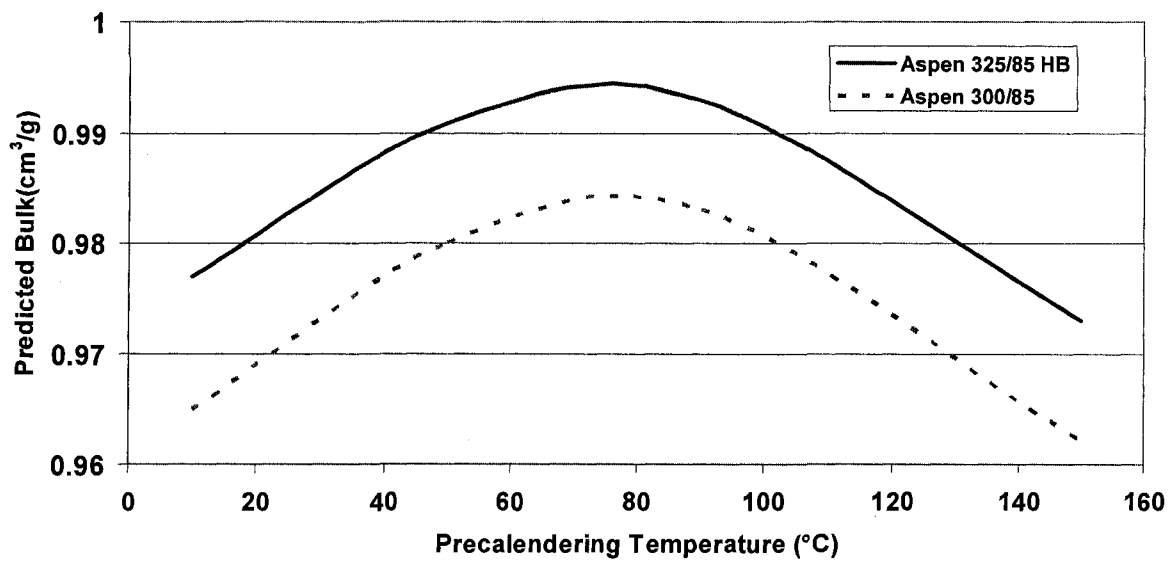


Figure C.2: Effect of Prelendering Temperature and Pulp Type on Final Bulk of Samples Containing 30% HYP and No Sizing. BW-60 g/m², Coating Weight – 7 g/m², Final Gloss – 32 G.U, HST = 1.7 s, Prelendering Temperature - 80°C

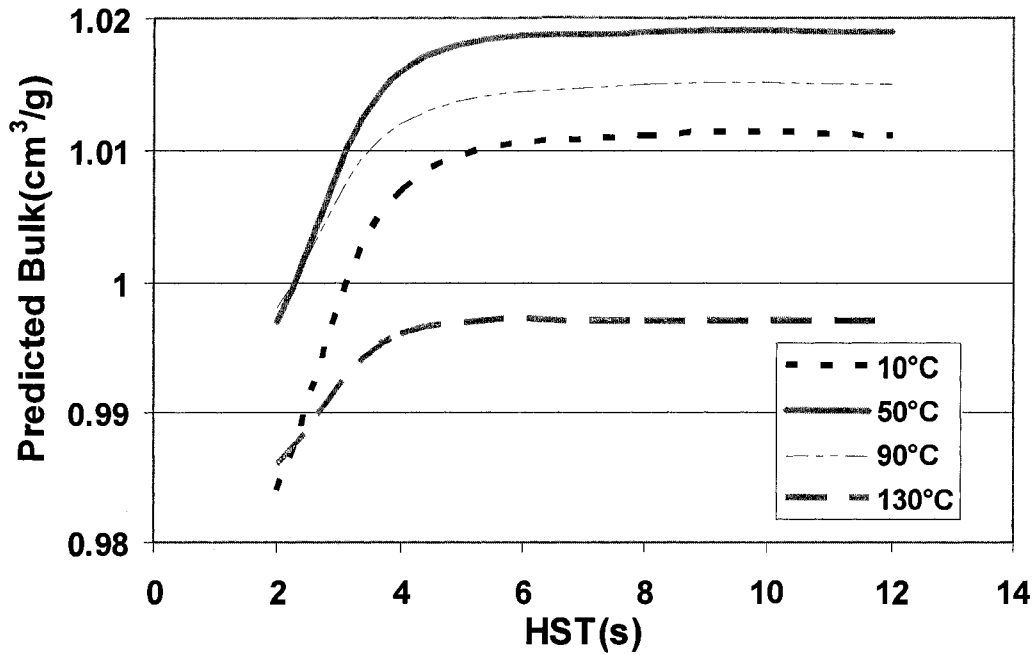


Figure C.3: Effect of Precalendering Temperature and HST on Final Bulk of Samples Containing 30% HYP. BW-60 g/m², Coating Weight – 7 g/m², Final Gloss – 32 G.U, 30% Aspen 325/85 HB

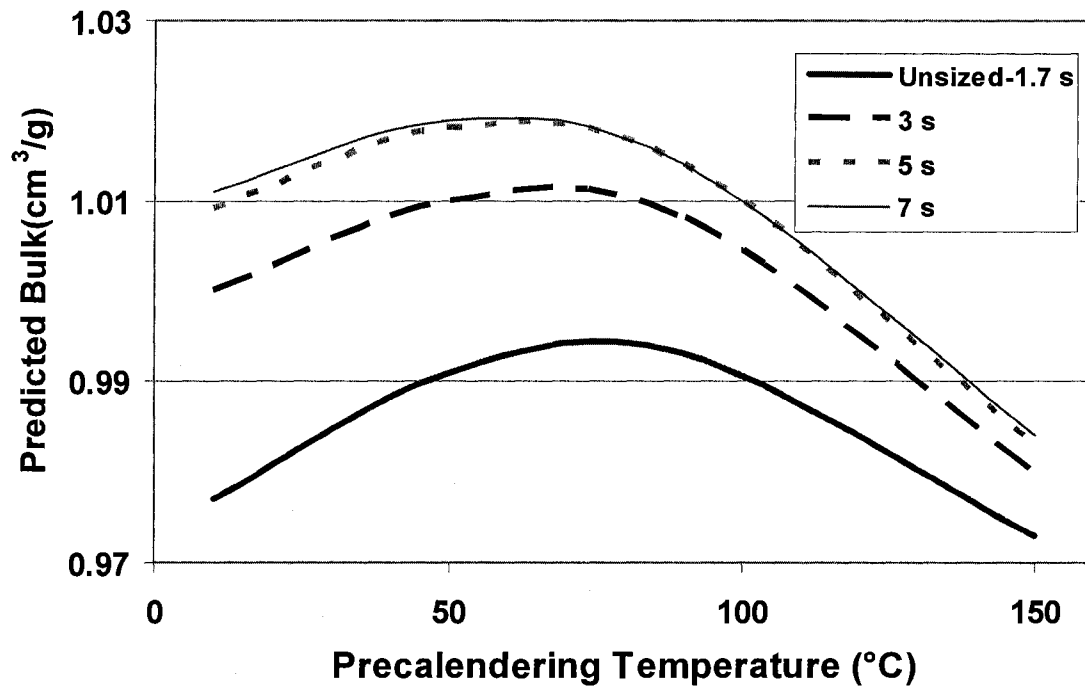


Figure C.4: Effect of Rosin-Alum Size on Final Bulk of Samples Containing 30% Aspen 325/85 HYP. BW-60 g/m², Coating Weight – 7 g/m², Final Gloss – 32 G.U, 30% Aspen 325/85 HB

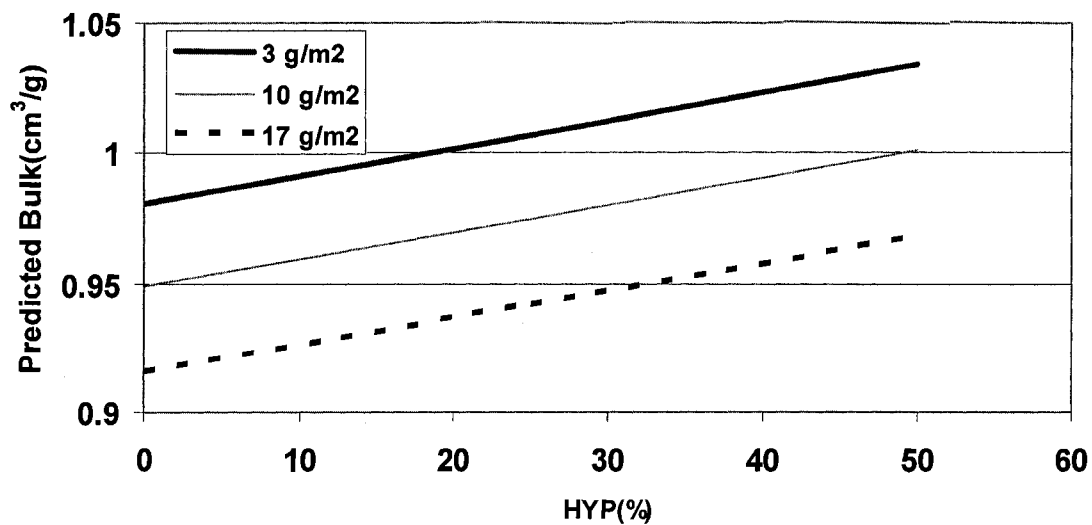


Figure C.5: Effect of Coating Weight on Final Bulk of Samples Containing Various Amounts of Aspen 325/85 HYP Contents. BW-60 g/m², Final Gloss – 32 G.U, Precalendering Temperature - 80°C, Unsized – HST -1.7s

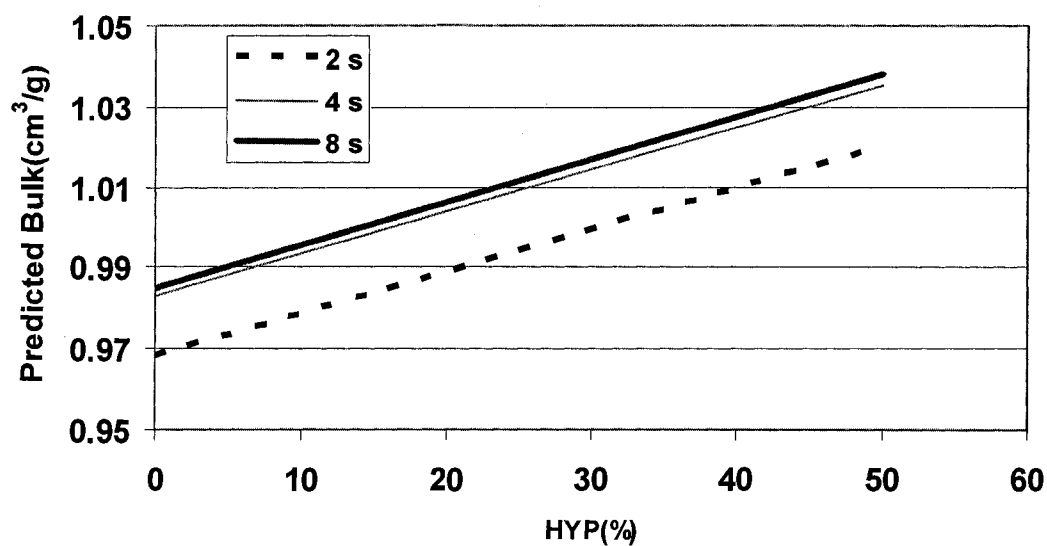


Figure C.6: Effect of Hercules Sizing on Final Bulk of Samples Containing Various Amounts of Aspen 325/85 HYP Contents. BW-60 g/m², Final Gloss – 32 G.U, Coating Weight – 7 g/m², Precalendering Temperature - 80°C