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Polytetrafluoroethylene (PTFE) vs. PTFE-Free Coatings on Paper Label: Analysis of Label Mechanical and Performance Properties

Chuqi Su
cs4030@rit.edu

RIT

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By

Chuqi Su

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College of Engineering Technology

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Rochester Institute of Technology

College of Engineering Technology

Department of Packaging and Graphic Media Science

Primary Thesis Advisor: Bilge Altay, Ph.D.

Secondary Thesis Advisor: Bruce Leigh Myers, Ph.D.

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ABSTRACT

Post-printed water-based (WB) coatings, commonly known as aqueous coatings, have gained popularity for paper-based label manufacturing because of their environmentally friendly characteristics. Polytetrafluoroethylene (PTFE) is one of the common additives added to the WB coatings to achieve heat resistance and rub resistance properties for the final product. PTFE is a synthetic fluoropolymer of tetrafluoroethylene, and is a category of Polyfluorinated Substances (PFAS). As of January 2024, the sale of food packaging containing PFAS is prohibited in the state of Minnesota, with expectations that this regulation will extend to other states because of the proven harm of PFAS to both humans and animals. PTFE-free WB coatings are emerging as an alternative; thus prompting the need to assess their performance. This research investigates whether PTFE-free WB coating can match the performance of PTFE WB coating for food packaging. The discussion focuses on comparing the impact of these coatings on mechanical properties and label performance of paper labels to inform potential future adopters of PFTE-free aqueous coatings for paper-based label application of mechanical properties and label performance factors as compared to aqueous coatings containing PFTE. The result shows that PTFE-free coating could be an acceptable alternative coating. The tested PTFE-free coating equals or exceeds the PTFE coatings for rub, humidity, grease, heat, and pressure resistance abilities and present similar water resistance characteristics.

Keywords: Aqueous coating, Polytetrafluoroethylene, Water-based coating, Mechanical properties, Label performance, Paper label

CHAPTER I

INTRODUCTION

1.1. Introduction to Offset Printing

Offset is among most commonly used printing technology in the label printing industry due to its fast-printing speed and high-quality output. In an offset printing press, there are three basic cylinders: the image cylinder, the blanket cylinder, and the impression cylinder. These three cylinders work with the inking and dampening system in the press to form an image. An offset printer schematic from Nguyen's research (2021) is shown in Figure 1 as reference. Before printing, the printing image is photochemically produced on a metal plate. During the printing, the offset press operator mounts the imaged plate on the cylinder. The offset process is based on the repulsion of oil and water (Kumar & Saini, 2016). When the plate cylinder starts to rotate, the ink rollers from the inking system contact the plate that mounting on image cylinder, inking the image area on plate cylinder. The dampening system wets non-imaged area on plate cylinder with water. Water is chemically structured to reject ink, allowing for clean separations between colored and non-colored areas on the print. After than, the plate cylinder transfer image to the blanket cylinder. Once the printing substrate passes through the blanket and impression plate, the image transfers to the substrate (Romano & Riordan, 2007).

A four-color printing offset press typically has four ink units, each containing ink of one of the four colors used in printing. With a growing demand for more colors and increased printing efficiency, offset presses with additional ink units and a coating unit have become common. Figure 2 shows a cross-section of a Heidelberg XL 106 press from Heidelberg website. Heidelberg XL 106 press is among the commonly used for label printing. It includes eight ink units to accommodate various color requirements, along with a coating unit positioned after the last ink unit. This unit applies a coating to the printed labels. Once coated, the labels proceed to a drying unit adjacent to the coating unit. As a result, the labels emerge from the press imaged, coated, and dry, greatly improving printing efficiency.

Due to its fast speed, high quality, and suitability for long runs, offset printing technology is highly favored by the label printing industry. According to the Label & Narrow Web website, offset printing plays a significant role in the high-end prime label market, capturing a considerable portion. When both conventional offset and digital offset are considered, it emerges as the second most utilized technology within the label industry. There are two categories for typical offset labels: first is the non-combination label for long runs, including detergent, sink cleaning products, and high-end food products. The second category includes health and beauty items, cosmetics, and wine products (Kenny, 2010).

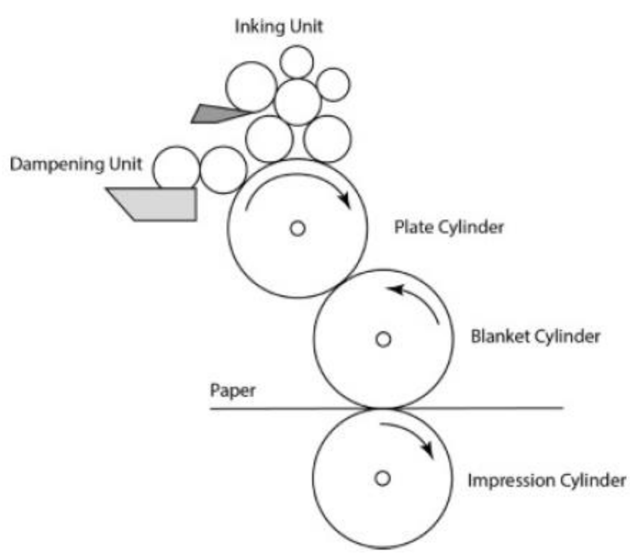

Figure 1. Schematic of Offset Printing

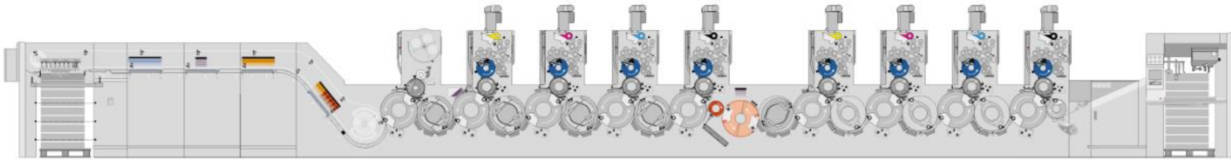

Figure 2. Cross-section of a Heidelberg XL 106 press

1.2. Water-based Coatings for Barrier Properties

Paper and paperboard offer excellent characteristics for packaging applications, including stable mechanical properties, light weight, effective light barrier properties, ease of conversion and printing, recyclability, and utilization of renewable resources (Rhim & Kim, 2009). According to the Markets and Markets forecasting, paper and paperboard materials occupy one-third of the global packaging industry share (Trent, 2019; Tyagi et al., 2021).

Paper is comprised of a permeable cellulose framework. The hydrophilic nature of cellulose and fiber network porosity limits the water-vapor barrier properties of paper (Khwaldia et al., 2009). Paper packaging readily absorbs moisture from the surroundings or from food, causing it to lose its physical and mechanical durability. Moisture can migrate within paper through the diffusion of water vapor in the empty spaces and in condensed form through the walls of fiber cells (Khwaldia et al., 2009).

Because of papers' susceptibility to contamination and breakdown when exposed to water, oil, and heat, applying a post-printed aqueous coating is crucial to provide essential protection for paper-based labels (Tyagi et al., 2021). The label industry seeks materials that are less hazardous and more environmentally sustainable than incumbent products while maintaining important performance characteristics, including barrier properties. Stable WB coatings can meet these requirements (Bakker et al., 2022).

WB coating, also called dispersion coating, can provide high-quality barrier functions such as heat, water, and grease resistance for prints. WB coating can also offer various finishes such as gloss and matte to enhance the optical properties of prints and attract customers. Approximately 60%-70% of the composite of WB coating is water, while 25%-35% is solid material, and 5% is additives. The main ingredients of WB coating include acrylate, styrene acrylate, alkaline-neutralized resins, polyethylene waxes, silicones, and film-forming agents (Bozhkova et al., 2017). The formulation of WB coating depends on the specific properties they provide, and different coating companies may offer different formulations. The working mechanism of WB coating involves drying out water after it is applied to the prints, leaving the solid content to form a thin film on the print as a coating.

WB coating with polymer-based additives, also known as petroleum-based coating, is a traditional WB coating that has been used in food packaging for at least a decade. Polymers like Polyethylene (PE) and Polypropylene (PP), the two most widely used synthetic polymers, can be added to WB coating (Tyagi et al., 2021). Even though these polymers itself are not water-soluble, they will disperse in the WB coating as small particles. They will not clump together and sink to the bottom. Petroleum-based coatings can provide outstanding barrier properties against grease and moisture for food packaging.

Due to the climate change trend in recent years, governments and industries are becoming more focused on developing eco-friendly and sustainable products. WB coating with biodegradable additives, also called bio-based coating, have been developed. Biodegradable additives can be broken down by biological action within six months, whereas polymer-based coating additives would need hundreds of years to break down in the environment (Bozhkova et al., 2017). Starch, soy protein, pectin, and chitosan are commonly used additives for bio-based coating. Bio-based coatings have a drawback in that they are still unable to attain the equivalent level of barrier properties found in petroleum-based coatings (Tyagi et al., 2021).

1.3. Statement of Problem

The purpose of this research is to evaluate and compare the PTFE-free and PTFE WB coating performance on paper labels. A thorough examination of existing literature yielded no documented studies that compare PTFE and PTFE-free WB coating; the present research will focus on the influence of PTFE-free and PTFE coating on label mechanical properties and label performance.

1.4. Hypotheses

H_0: PTFE-free WB coating can achieve the same level of mechanical and label performance properties as the PTFE WB coating.

H_1: PTFE-free WB coating cannot achieve the same level of mechanical and label performance properties as the PTFE WB coating.

1.5. Objectives of the Research

The first objective of this research is to explore the learning from the past to find out relevant data to use as a comparison in this study. The second objective of the study is to explore unprinted papers were subject to paper characteristic tests, including thickness and basis weight measurement, to describe the basic structural properties of the paper. The third objective of the study is to investigate structural, mechanical and barrier properties of offset printed and PTFE coated papers. The fourth objective of the study to investigate structural, mechanical and barrier properties of offset printed and PTFE-free coated papers, then compare to the PTFE coated papers. Printed and coated substrates were tested for mechanical properties and label performance. The mechanical properties of the papers were analyzed using tests focused on the label-finishing process, including coefficient of friction, dry and wet rub, and wet blocking. The coefficient of friction test determines the force to separate two sheets of label samples during finishing. Dry and wet rub tests measure the abrasion resistance of label coating. The wet blocking test measures the durability of label coating under high pressure and replicates the humidity present in a typical label finishing environment. To assess label performance, the printed and coated papers were tested for water absorptiveness, heat resistance, and grease resistance. These tests gauge the performance of the label coating under conditions involving high volumes of water and oil, as well as at elevated temperatures. In conclding the study, the overall research finding will be reported and future studies will be suggested.

CHAPTER II

LITERATURE REVIEW

Paper and paperboard possess porous structures due to the fiber network containing numerous hydroxyl groups; they inherently have low resistance to water and oil. WB coating for paper packaging will be a significant strategy to achieve higher barrier function for food packaging (Bozhkova et al., 2017). The barrier function includes water resistance, grease resistance, and resistance against moisture. According to Tyagi's review (2021), there are different types of WB coatings for paper-based packaging. Most of the WB coatings for paper-based packaging fall into two categories: conventional petroleum-based coatings and bio-based coatings. Petroleum-based coatings, include high density polyethylene, low density polyethylene, polyethylene terephthalate, metalized Polyethylene terephthalate, ethylene vinyl alcohol, polyvinyl chloride, and PTFE, among others. Bio-based coatings include cellulose acetate, starches, pectin, chitosan, alginate, polylactic acid, polyvinyl alcohol, among others.

Conventional petroleum-based coatings could provide exceptional hydrophobicity barriers for paper surfaces. However, the downside of petroleum-based coatings is also distinct. They are limited by fossil oil resources and are not easy to recycle. They requires hundreds of years to biodegrade them. Compared to petroleum-based coatings, bio-based coatings have the potential to pave the way for creating innovative methods of producing fully biodegradable and functional paper coatings for food packaging. Nevertheless, challenges stemming from the processing of many biopolymers in their pristine state, such as hydrophilicity, crystallization tendencies, brittleness, melt instabilities, and seal ability issues, may impede their widespread industrial utilization. The following section reviews previous research on bio-based coatings and petroleum-based coatings.

2.1. Bio-Based Additives Coating

Starch, among the array of biodegradable polymers, emerges as a notable contender due to its widespread availability, cost-effectiveness, and thermoplastic characteristics. Nevertheless, its utility is significantly hampered by inherent traits such as high hydrophilicity and susceptibility to microbial degradation (Wu et al., 2009; Gontard et al., 1994). According to Ni's study (2018), increasing the dosage of ZnO NPs (zinc oxide nanoparticles) in the starch-based coating could enhance the overall coating film roughness and achieve higher water resistance properties and antimicrobial effects for food packaging. ZnO NPs are widely regarded as non-toxic, safe for biological systems, and are compatible with living organisms. They find extensive application in various everyday uses, including as carriers for drugs, ingredients in cosmetics, and components in medical fillings. Additionally, they have obtained a "GRAS" (Generally Recognized as Safe) designation from the FDA (Hong et al., 2013). Drawing from this understanding, Ni's study has devised a method to enhance the hydrophobic properties of starch films and papers. This method involves utilizing a dispersion system comprising starch/ZnO/chitosan and subjecting it to basic mechanical treatment. In Ni's study, the method to increase the dosage of ZnO NPs in starch-based coating used carboxymethyl cellulose (CMC) as the capping agent for ZnO NPs, aiming to enhance the compatibility between starch and ZnO NPs while augmenting the flexibility of the starch coating layer. The results of Ni's study show that increasing the dosage of ZnO NPs in starch-based coating greatly improves hydrophobic characteristics, heat resistance, and antimicrobial activity, while also significantly decreasing the water vapor transmission rate (Ni et al., 2018).

Alginate and chitosan are water-soluble biopolymers that are renewable resources from the environment and become environmentally friendly additives for bio-based coatings. In Kopacic's research (2018), alginate and chitosan were used as additives in the WB coating for food packaging to prevent the migration of grease, water vapor, water, and volatile organic compounds into packed food. Alginate, a polysaccharide found naturally in brown algae, is commonly found in sodium and calcium salt forms. Widely utilized in the food industry as additives, alginates and their derivatives are deemed safe for use as functional barriers in food-contact materials. The market includes various water-soluble alginate formulations applicable with standard coating equipment utilized in the paper and packaging industries (Nesic et al., 2016; Wong et al., 1995; Da Silva et al., 2012). Chitosan is a plentiful natural polysaccharide sourced from chitin, which is found in the exoskeletons of crustaceans and insects. Significantly, economically viable quantities are already derived from waste generated by the fishing industry, primarily during the processing of shellfish (Fernandes et al., 2010; Nordqvist et al., 2007; Reis et al., 2011; Thakhiew et al., 2010; Vrabic et al., 2018). In Kopacic's research, chitosan and alginate were added into two bio-based coatings, respectively. Two bio-based coatings were applied under the same conditions on two different paper grades using a laboratory draw-down coater from RK Printcoat Instruments Ltd. (Litlington, UK). The results showed that grease resistance improved while it was possible to reduce water vapor transmission and migration of volatile organic compounds compared to uncoated paper. The wettability and water absorption characteristics of papers coated with chitosan and alginate were discovered to depend on the substrate, and these properties could be notably influenced by bio-based coatings (Kopacic et al., 2018).

Butylene succinate is a human-safe and environmental-friendly additives of bio-based coating for the paper-based packaging. Some companies have been transitioning to bio-polymers coating to achieve the water/oil resistance of paper substrates. In previous literature, WB coatings based on chitosan, starch, polyvinyl alcohol has been studied as first layer, which was covered by a zein protein top layer (e.g. Hamdani et al., 2022; Hamdani et al., 2020; Kansal et al., 2020).

Polybutylene succinate has been recently studied as alternative sustainable material and found to have water resistance of 15.5 ±0.1 g/m^2 based on COBB 1800 test based on TAPPI T441 at 1800 seconds and oil resistance of Kit #12. In a different study, zein and polyvinyl alcohol-based coating was analyzed to replace PFAS and found water resistance of 3 g/m^2 based on COBB 60 test based on TAPPI T441 at 60 seconds and the oil resistance of Kit #12 (Hamdani et al., 2020). Although the TAPPI 441 standard is utilized for water resistance testing in multiple studies, it has been observed that the timeframes used in these studies differ.

2.2. Petroleum-based Addtivies Coating

Petroleum-based polymers for petroleum-based coatings possess distinct characteristics, notably their malleability, making them more resilient to physical impacts than materials like metal, glass, and ceramics. In the food and beverage industry, petroleum-based coated paper containers are prevalent. Polyolefins such as polypropylene and polyethylene are extensively produced for coating due to their affordability, flexibility, chemical inertness, recyclability, ease of processing, non-toxicity, and biocompatibility (Chaudhry et al., 2012; Guillard et al., 2018). Besides polyolefins, materials like, polymethylpentene, polyethylene, and polystyrene are favored for use in petroleum-based coatings for paper-based food packaging.

Polypropylene is commonly used as a material for petroleum-based coatings. It stands as one of the most extensively utilized thermoplastics globally, owing to its ease of processing, favorable mechanical properties, and economical pricing (Karian, 2003). Nonetheless, polypropylene does have some drawbacks that restrict its application in certain contexts. Among these limitations is its inadequate oxygen barrier, which hinders its widespread adoption within the packaging industry (Ray & Okamoto, 2003). Previous research by Khalaj (2016) showed that nanocomposites of polypropylene, OMMT (montmorillonite), and iron could be a solution to improve the oxygen barrier for polypropylene food packaging. In this research, the nanocomposites were prepared by combining polypropylene and MMT with or without nano-iron particles in a twin-screw extruder. The results showed that OMMT enhances the oxygen and water vapor barrier properties and rigidity of the composites (Khalaj et al., 2016).

PTFE is one kind of the petroleum-based additives for WB coating enhance the packaging heat and rub resistance (Dhanumalayan & Joshi, 2018). PTFE is a synthetic fluoropolymer derived from tetrafluoroethylene and falls under the fluoropolymer category of PFAS (Lohmann et al., 2020). PFAS have been widely applied as coatings on packaging substrates to prevent the penetration of water and oil (Hamdani et al., 2023). PFASs coated paper finds widespread use in items such as sandwich wrappers, french-fry boxes, and bakery bags. However, the migration of PFASs into food and their subsequent presence in landfills and compost post-disposal pose risks of prolonged exposure to harmful chemicals, underscoring concerns regarding the use of PFAS in food packaging. According to epidemiological studies, exposure to long-chain PFAS-contained products also can contribute to kidney and testicular cancer, low birth weight, thyroid disease, decreased sperm quality, pregnancy-induced hypertension, and immunotoxicity in children. Furthermore, toxicological investigations in animals have established connections between exposure to PFAS and changes in mammary gland development, reproductive and developmental toxicity, testicular cancer, obesity, and immune suppression (Schaider et al., 2017). To address this issue, in 2006, the Environmental Protection Agency (EPA) initiated a program aimed at gradually phasing out emissions and products containing long-chain PFASs by 2015. In the same year, the FDA began regulating the use of long-chain (>C-8) PFASs in direct food contact. The SF 20 regulation, signed into law in June 2021 and active in January 2024 in Minnesota, prohibits the utilization of PFAS on food packaging labels (Tsang, 2021). Eleven states have implemented measures to gradually eliminate the use of PFAS in food packaging (Safer States, 2024). Because of the concern about the adverse health effects of PFAS, prominent coating manufacturers have developed PTFE-free WB coating as an alternative to reduce PFAS residue on the labels. The alternative PFAS coating include shorter-chain PFASs and polyfluorinated polyether-baes polymer. The shorter-chain PFASs has less bio-accumulative. Modified starches, polyvinyl alcohol, polylactic acid composites, carboxymethyl cellulose (CMC), sodium alginate are good for long-chain PFASs replacement (Tyagi et al., 2021).

In conclusion, this literature review section reviews the research on bio-based additives coating and petroleum-based additives coating application. Even though the bio-based additives coating could not achieve the same level of barrier properties as petroleum-based additives coating, adding other materials such as chitosan, alginate, and ZnO NPs to the bio-based coating could greatly increase its barrier properties. Also, polyvinyl alcohol-based coating was discovered to be a more environmentally friendly replacement for petroleum-based coating. For petroleum-based additives coating, OMMT and iron have been found to be perfect additives for enhancing the oxygen barrier for polypropylene food packaging.

CHAPTER III

MATERIALS AND METHODS

The chapter presents the methods, followed by material usage and characterization. The pre and post-print testing procedure is discussed at the end.

3.1. Methods

Based on the previous research, this research selects critical label barrier properties including water, grease, heat resistance and hydrophobicity properties as coating evaluation. In addition to label barrier properties, this research also choose coating mechanical properties included coefficient of friction (kinetic), dry rub and wet rub resistance and wet blocking according industry guideline. Two paper stocks, denoted Paper A (60#) and Paper B (47#) were used as testing substrates. Papers A and B were printed and coated using a Heidelberg XL 106 Sheetfed Offset Press. Testing included analyzing unprinted Papers A and B, and then again after the papers were printed and coated.

3.2. Materials Utilized

Table 1 summarizes the materials utilized. As indicated in Table 1, two paper stocks, referred to as Paper A (60#) and B (47#), were printed and coated in the Heidelberg press. The viscosity of PTFE-free and PTFE coating was recorded at 15-20 seconds. The coatings were applied via an anilox roll on the press on the coating unit; the parameters of the anilox roll were 60° angle, 6.5 BCM cell volume, and a 280 LPI line screen, with a hexagonal cell shape.

Table 1. Summary of materials utilized

Paper		
Paper A: 60# coated one side	Paper B: 47# coated one side	
Water-based Coating		
PTFE Coating	PTFE-free Coating	
Printing Press		
Heidelberg XL 106 Sheetfed Offset Press including a sheeting unit (roll to sheet converter at the paper feed), multiple ink units, a coating unit, and a drying unit		
Coating Anilox Roll		
60° angle	6.5 BCM cell volume, hexagonal	280 LPI line screen

3.3. Materials Characterization

The primary materials used in the study were paper and WB coatings. As the properties of these are germane to describing them as materials, the characterization testing is presented, together with a discussion of methods.

3.4. Paper Characterization

A small number of unprinted sheets for each paper were reserved for paper characterization testing. The unprinted paper samples were stored in a measurement lab for 48 hours before testing. The relative humidity of the testing lab is maintained at 40%-50%, and the room temperature is maintained at 73 °F.

Paper characterization of the unprinted sheets was measured for thickness using a process described in the TAPPI (Technical Association for Pulp and Paper Industry) / American National Standards Institute (ANSI) standard T411 om-21 (2021), and for basis weight in GSM (grams per square metre) using the process described in TAPPI / ANSI T410 om-19 (2019). The paper characterization results are shown in Table 2.

Table 2. Unprinted paper characterization

	Thickness (mils)	
	Paper A (60#)	Paper B (47#)
Mean	3.0	2.5
Standard Deviation	0.1	0.1
	Basis Weight (g/m^2)	
Mean	89	70
Standard Deviation	0.20	0.25

Note. Results based on five number of individual readings

3.4. Water-based Coating Characterization

The WB coatings were tested for viscosity. The viscosity was measured using a #3 Zahn cup at 77 °F. The results and coating ingredients are presented in Table 3.

Table 3. WB coating characterization

	PTFE	PTFE-free
Viscosity (Seconds)	15 - 20	15 - 20
	Ingredients	
Water %	60 - 70	60 - 70
Solids %	30 - 40	30 - 40
Sodium Dioctyl Sulfosuccinate %	< 4.0	< 4.0
Ammonium Hydroxide %	< 2.0	< 2.0

As indicated in Table 3, water is the major composition of both the PTFE and PTFE-free coatings tested: water comprises 60% -70% of the coating material, with solid materials comprising 30-40% of the coating composition. Sodium dioctyl sulfosuccinate and ammonium hydroxide are the basic components of the solid materials in the coatings. The remaining ingredients are withheld by the coatings manufacturers.

3.5. Printing and Coating Process

The samples were printed and coated at Multi-Color Corporation, a label manufacturing company in Rochester, New York. The respective papers were fed into the press as a paper roll and then cut into sheets in the sheeting unit. Label images were printed on the sheets using oil-based offset lithographic printing inks by the inking units. Following the image printing, the respective coatings were applied on papers via an anilox roller in the coating unit. Finally, the samples were dried in the drying unit of the press. Since 60-70 % of WB coatings are water; the remainder is comprised of solid materials. When the WB coating is applied to the substrate, the water component evaporates, and the solid particles form a water-insoluble film on the substrate. The heat capacity of the drying unit was set at 60%, and the end temperature of the paper was recorded at 95-100° F. Printed and coated samples of each paper were retained for subsequent testing.

Both the unprinted paper samples and printed and coated paper samples were stored in a measurement lab for 48 hours before testing (relative humidity 40-50% / 73°F).

3.6. Post-print and Coating Testing

The post-print testing is divided into two categories: label mechanical properties tests for the printed and coated paper, and label performance tests for the printed and coated paper. The label mechanical properties tests for printed and coated papers included the coefficient of friction, dry rub resistance, wet rub resistance, and wet blocking. The label performance tests included water resistance, grease resistance, heat resistance and contact angle. According to TAPPI T491 om-08, the water resistance of paper was measured by water absorptiveness test descript in TAPPI

T441om-20 for 120 seconds. The wet blocking test was conducted with methods consistent with the ASTM D918-99, as follows:

- Two printed and coated samples were cut to 1.25 x 1.25 inches
- A pipette was used to place a single drop of water on one of the cut samples
- The two samples were placed face to face under 50 psi pressure for 48 hours
- The samples were separated, and visually analyzed

The heat resistance test followed an internal procedure used by the printing facility, as follows:

- Two printed and coated samples were cut to 2 x 5 inches
- Two printed and coated samples were placed under two clamping jaws for ten seconds
- The samples was heated up until 250 °F during these ten seconds
- The samples were separated, and visually analyzed

The contact angle will be measured ten times after the water droplet drops on PTFE and PTFE-free coating. The interval time of each measurement is one second. The corresponding standards for the respective tests are shown in Table 4

Table 4. Post-print and coating tests and standards

Label Mechanical Properties	
Test	Standard
Coefficient of friction (kinetic)	TAPPI / ANSI T549 om-20
Dry rub resistance	TAPPI / ANSI T830 om-18
Wet rub resistance	TAPPI / ANSI T830 om-18
Wet blocking	ASTM D918-99
Label Performance Tests	
Water Absorptiveness	TAPPI / ANSI T441 om-20
Grease Resistance	TAPPI / ANSI T559 cm-12
Heat resistance	Internal Printing Facility Guideline
Contact Angle	TAPPI/ANSI T458 cm-14

The majority of the testing was conducted using the Tappi/ANSI procedure. The only exception was the wet blocking test, which followed the ASTM procedure. The heat resistance test was carried out following the internal printing facility guideline of the Multi-Color Corporation. The test results for the mechanical and performance properties of the label were discussed in the following chapter.

CHAPTER VI

RESULTS AND DISCUSSION

Results of the post-printed and coated labels begin with a presentation of the mechanical properties, followed by those tests that describe label performance factors.

4.1. Label Mechanical Property: Paper Coefficient of Friction Test

The coefficient of friction test results of Paper A and B printed and coated samples are shown in Table 5. The coefficient of friction as defined by TAPPI / ANSI T549 om-20 (2020) includes both static and kinetic friction testing. The kinetic friction value is of particular importance for label finishing; it refers to the ratio of the force needed to maintain consistent relative motion between surfaces to the normal force (TAPPI / American National Standards Institute, 2009) Label manufacturing companies typically focus on kinetic friction rather than static friction. Therefore, only the kinetic values are discussed in the results.

Table 5. Coefficient of Friction (kinetic) for post-printed and coated labels

	Paper A		**Paper B**	
	PTFE	PTFE-free	PTFE	PTFE-free
Mean	0.2	0.2	0.2	0.2
Standard Deviation	0.0	0.0	0.0	0.0

Note. Results based on 5 number of individual readings

As illustrated in Table 5, both papers A and B coated with PTFE-free and PTFE coating show the same value of kinetic friction. This result indicates that PTFE-free coating will not change the intrinsic coefficient of friction value.

4.2. Label Mechanical Property: Dry and Wet Rub Resistance

Rub resistance is assessed by both a dry rub test and a wet rub test. The dry and wet rub test as defined by TAPPI / ANSI T830 om-18. Both tests conducted 1,600 rubs on the samples.

For wet rub resistance test, a pipette was used to place two drops of water on the base sample before rubbing. As this test requires a visual analysis, the post-testing results are illustrated in Figures 3 and 4.

Paper A with PTFE Coating

Paper A with PTFE-Free Coating

Paper B with PTFE Coating

Paper B with PTFE-Free Coating

Figure 3. Dry rub resistance test

As shown in the dry rub test result in Figure 3, no noticeable ink was picked up, and no marks were visible on either Paper A or Paper B after dry rub testing. The results suggest that PTFE-free and PTFE coating provide satisfactory levels of dry rub resistance for the papers tested.

Turning to wet rub resistance is shown in Figure 4, a noticeable amount of ink was picked up in Papers A and B with both the PTFE-free and PTFE coating, although it is observed that Paper B exhibited better wet rub resistance than Paper A.

Paper A with PTFE Coating

Paper A with PTFE-Free Coating

Paper B with PTFE Coating

Paper B with PTFE-Free Coating

Figure 4. Wet rub resistance test

4.3. Label Mechanical Property: Wet Blocking Test

Blocking refers to the undesirable adhesion between two surfaces under pressure and temperature constraints. According to Skillington (2010), "The occurrence of blocking between two coated paper surfaces in contact with each other can be influenced by factors such as temperature, pressure, surface roughness, and surface energy" (p. 29). Block testing assesses the coating's ability to protect substrate and ink under the application of pressure and in elevated humidity conditions. Figure 5 illustrates the results.

Paper A with PTFE Coating

Paper A with PTFE-Free Coating

Paper B with PTFE Coating

Paper B with PTFE-Free Coating

Figure 5. Wet blocking test

A visual analysis of the wet blocking test indicates no noticeable ink pickup with Paper A for either the PTFE-free or PTFE coated papers. For Paper B, there is a discernable ink pick-up area in both the PTFE-free and PTFE-coating samples. The ink pick-up area of the PTFE-free coating appears to be less than the PTFE coating.

4.4. Test for Label Performance Properties: Water Resistance

The water absorptiveness test, conducted in accordance with the TAPPI/ANSI T441 om-20 instructions, provides data used for analyzing the water resistance of the printed and coated samples. The results of the water absorptiveness test of printed and unprinted Paper A and B samples are shown in Table 6.

Table 6. Water absorptiveness test: weight of water grams per square meter

	Paper A		**Paper B**	
	PTFE	PTFE-free	PTFE	PTFE-free
Mean (g/m^2)	31	35	6	6
Standard Deviation	3.1	1.5	0.6	2.1

Note. Results based on 5 number of individual readings

According to the water absorptiveness test definition, the test result indicates the amount of water absorbed in a limited time frame by one square meter of a testing substrate (TAPPI / American National Standards Institute, 2020).

A lower value of the water absorption suggests that the coating could better prevent water penetration. For Paper A, the water absorption value of PTFE coating is lower than that of PTFE-free coating. For Paper B, PTFE-free coating has the same test value as PTFE coating. There is more variance in water absorption values with the PTFE coating than the PTFE-free coating for Paper A; the opposite was observed with Paper B.

4.5. Test for Label Performance Properties: Grease Resistance

Like the rub resistance and wet blocking tests, the grease resistance test relies on a visual analysis. The grease resistance test follows the TAPPI /ANSI T559 cm-12 standard instructions. Visual results of the grease resistance test for of printed and coated paper A and B samples are shown in Figure 6.

Paper A with PTFE Coating

Paper A with PTFE-Free Coating

Paper B with PTFE Coating

Paper B with PTFE-Free Coating

Figure 6. Grease resistance test

In the case of Paper A, neither PTFE nor PTFE-free coatings exhibited noticeable ink pickup after the test solution was wiped off within fifteen seconds. This contrasts with the results for Paper B, where most of the ink was picked up by the testing solution.

4.6. Test for Label Performance Properties: Heat Resistance

The heat resistance test follows the internal printing facility guideline instructions. Visual results of the heat resistance test for of printed and coated paper A and B samples are shown in Figure 7.

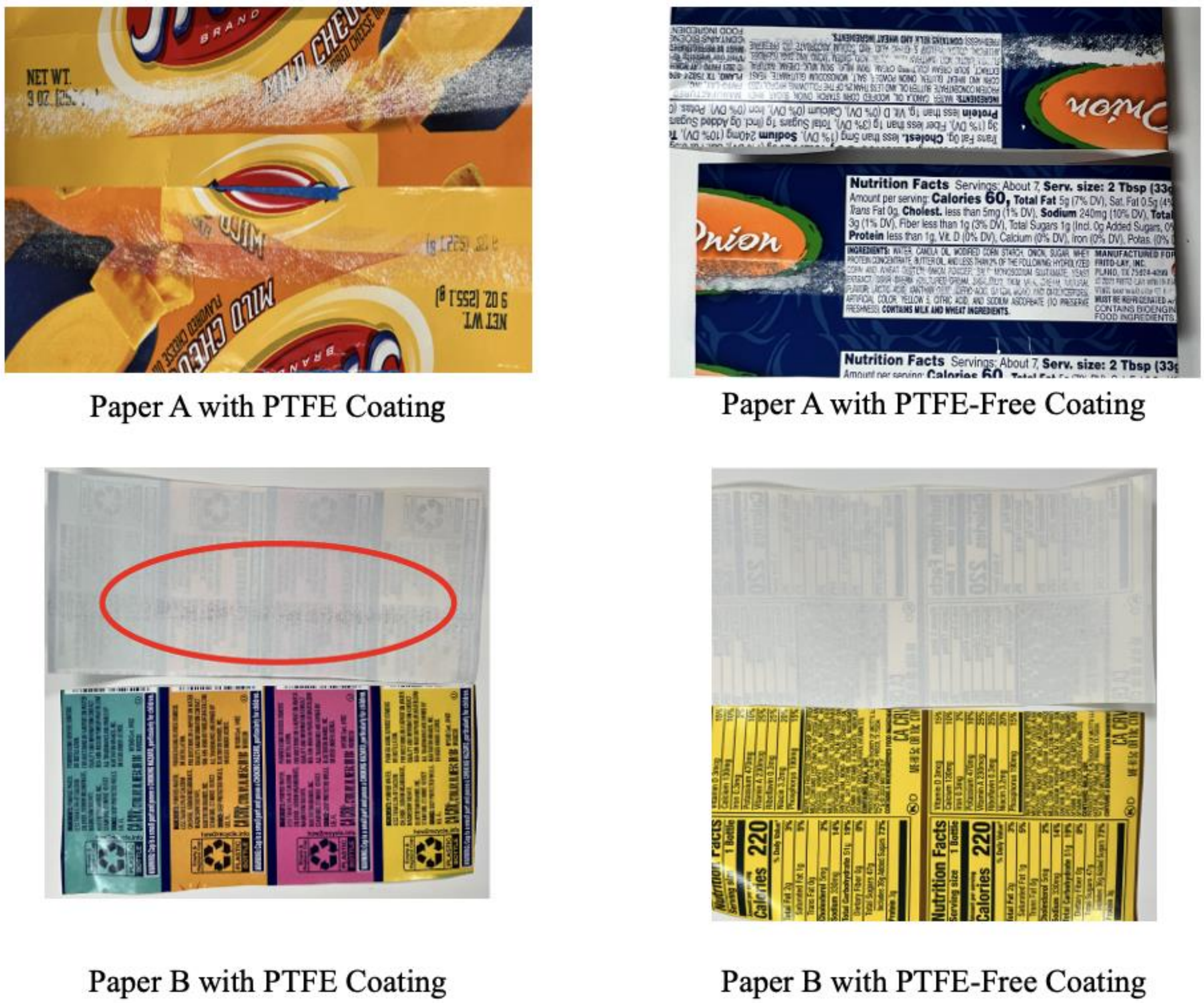

Figure 7. Heat resistance test

As shown in Figure 5, there are marks due to ink pick on both the PTFE-free and PTFE coatings on Paper A. That demonstrates that PTFE-free and PTFE coating was melting during the heating therefore the ink has been picked up to the top sample. For Paper B, the observed ink pickup on PTFE coated sample after heating was more subtle. Yet, the PTFE-free coated samples demonstrated no observable ink pick up after heating.

4.7. Label Performance Properties: Contact Angle Test

The wetting properties of the coating are important in many aspects of the end-use application of printed products (Özsoy et al., 2023). The result of the water contact angle or wettability describes whether the surface is hydrophilic or hydrophobic. When the water contact angle is greater than 90°, the surface is defined as hydrophobic. When the water contact angle is less than 90°, the surface is defined as hydrophilic (Law, 2014). The contact angle test results are shown in Figure 8 and 9, all the samples show a hydrophobic properties. The results of the contact angle are based on three measurements for each testing group. The measurement time is ten seconds. The contact angle instrument is from Rame-hart instrument (New Jersy, USA). Since the instrument requires water to be dropped manually, the volume of each droplet is not identical in each measurement, and the contact angle of each experiment will also have slight deviations affected by the droplet's volume. The difference in the volume of each droplet is ± 2 microliters. When comparing the ink and non-ink areas of paper A and paper B, the non-ink area has a higher contact angle, which means the non-ink area has better water resistance than the ink area. PTFE-free coating also showed a higher contact angle on both paper A and paper B, regardless of whether it was applied to the ink or non-ink area.

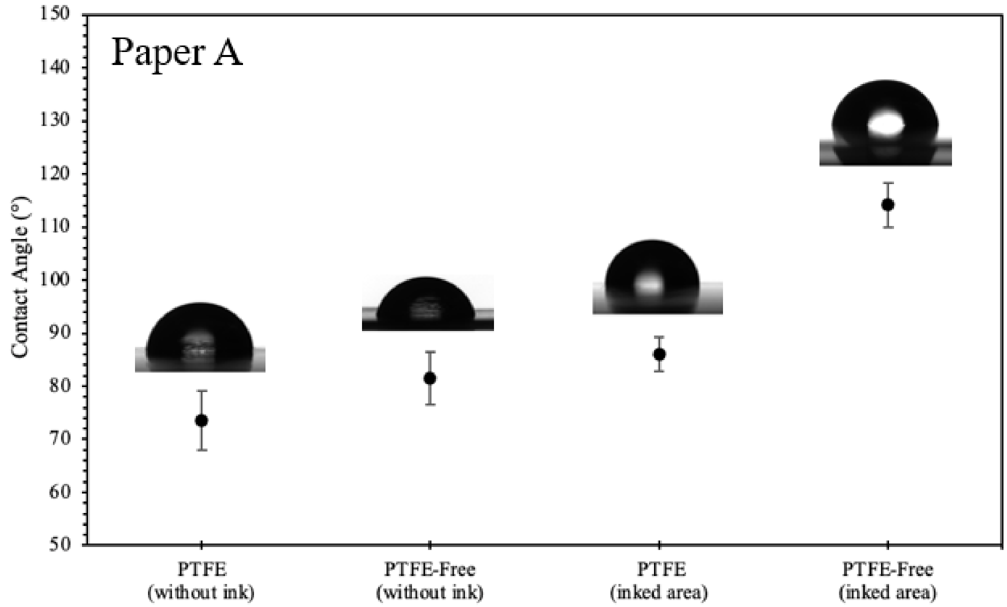

Figure 8. Contact angle result of Paper A.

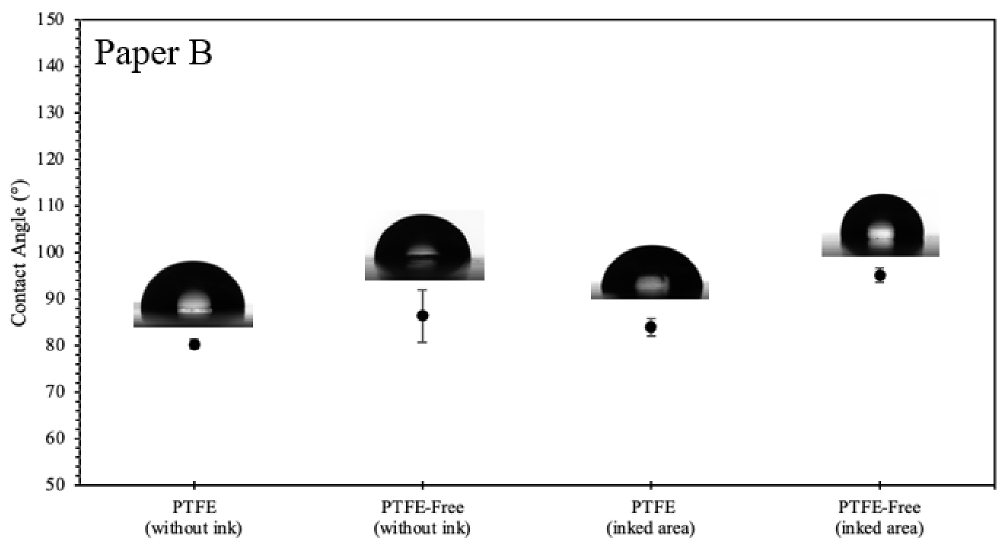

Figure 9. Contact angle result of Paper B

This section encompasses all the mechanical and performance tests of the labels, conducted in accordance with industry standards and guidelines. The subsequent section will delve into the conclusions drawn from the results and outline avenues for future research.

CHAPTER V

CONCLUSION

5.1. Conclusion of Test Results

The test results for label mechanical properties and label performance tests were utilized to analyze the performance of PTFE and PTFE-free coatings on paper labels. In the mechanical properties test, the Coefficient of Friction (kinetic) value was found to be identical for both PTFE and PTFE-free coatings. For the dry and wet resistance tests, as well as the wet blocking test, the PTFE-free coating exhibited equivalent performance to the PTFE coating. Notably, the PTFE-free coating demonstrated superior protection for Paper B in the wet blocking test. In the label performance test, the PTFE-free coating displayed comparable performance to the PTFE coating in grease resistance and heat resistance tests, with even better heat-resistant protection observed for Paper B. In the water absorptiveness test, the PTFE-free coating demonstrated equivalent performance to the PTFE coating for Paper B, while Paper A with the PTFE coating exhibited a slightly better water-resistant ability than paper with PTFE-free coating. The variance between the coatings exhibited by the water absorptiveness test results for Paper A and Paper B was especially curious: the variance was greater with Paper A water absorptivity with the PTFE coating, and with Paper B the variance was greater with the PTFE-free coating. In the contact angle test, PTFE-free coating shows a higher result than PTFE coating. Therefore, PTFE-free coating has a higher hydrophobic property than PTFE coating. This suggests that there are properties in the papers themselves that may influence the results, underscoring the need for future researchers to examine a wider array of papers in similar test procedures. Practitioners should also examine the results to the practical requirements to ascertain the potential practical implications of these findings.

5.2. Future Study

In summary, the test results suggest that for label mechanical properties and performance tests, the PTFE-free coating serves as an acceptable alternative to PTFE coating, as evidenced by similar rub, humidity, grease, heat, and pressure-resistant abilities. In some instances, notably the heat resistance and wet blocking performance, the PTFE-free coating outperformed the PTFE coating on Paper B. Despite consistent testing protocols for Paper A and Paper B, discrepancies in results were observed. These can be likely attributed to inherent differences in the paper properties of the two substrates. To obtain a comprehensive understanding of PTFE-free coating properties, it is suggested that future research expands on the testing here to include various paper stocks to better inform the discussion. Further, future researchers could examine different formulations of PTFE and PTFE-free coatings.

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