INFLUENCE OF MOISTURE CONTENT ON SEALABILITY AND CONVERTIBILITY OF COATED PAPERS IN VERTICAL FORM FILL SEAL (VFFS) MACHINES

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ABSTRACT

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Influence of moisture content on the sealability and convertibility of coated papers in vertical form fill seal (VFFS) machines

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The effect of moisture on the sealability and converting efficiency of fiber-based packaging materials depends largely on coating type. Dispersion-coated papers exhibited inconsistent behavior with an increase in moisture content, while polyethylene-coated papers' seal strength is relatively higher and possesses stable values. This study focused on analyzing the influence of different relative humidity levels and temperature conditions on sealability and convertibility of polyethylene and dispersion-coated papers on vertical form fill seal (VFFS) packing processes. The experiments were carried out under three climatic conditions: 50% RH at 23 °C (standard), 80% RH at 23 °C (high humidity), and 85% RH at 38 °C (tropical). To determine the performance of materials, seal strength, sealing window properties, frictional resistance, and surface roughness were measured. The dispersion-coated papers showed a slight increase in seal strength under tropical conditions. However, they possess a narrow sealing window and inconsistent behavior as humidity and temperature increased, but PE-coated papers demonstrated uniform behavior. Static and dynamic coefficients of friction and surface roughness values indicated that dispersion coatings softened with the rise in moisture, which can lead to enhanced feeding resistance and runnability. The findings demonstrate the importance of humidity and temperature control in the achievement of reliable performance of the packaging. The results are useful in terms of optimizing the process parameters and contributing to the transition over to sustainable fiber-based packaging materials.

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ABBREVATIONS

ASTM	American Society for Testing and Materials
COF	Coefficient of Friction
Disp	Dispersion coated
ISO	International Organization for Standardization
PE	Polyethylene coating
RH	Relative Humidity
R_a	Arithmetic mean roughness
SEM	Scanning Electron Microscopy
VFFS	Vertical Form Fill Seal

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DECLARATIONS

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1 Introduction

The contemporary packaging sector not only serves as a solution for protecting and delivering products, but it also reflects an increasing environmental responsibility. The trend towards sustainability around the world has put greater efforts into finding alternatives to traditional materials and led to innovations in material sciences and manufacturing technologies.

1.1 Background

The packaging industry is a major user of plastics, resulting in environmental pollution. In Europe, almost 40 % of plastic is used for packaging applications (European Commission 2025). The use of paper and cardboard for packaging purposes can significantly reduce these harmful environmental impacts by providing a higher recycling rate of 80-85 % as compared with other materials. These figures indicate that packaging is an important area for sustainability improvement by adopting fiber-based recyclable materials (Eurostat 2024).

Paper is manufactured from renewable and biodegradable resources, has a higher recycling ratio, and therefore, it is well-suited to the goals of the circular economy. The environmental and legislative concerns have resulted in a slowly flourishing industry trend of paperisation in flexible packaging (Smithers 2021). Paper behaves differently from plastic, especially in reaction to moisture content, which is a significant factor in packaging processes such as Vertical Form Fill Seal (VFFS). Therefore, understanding and managing moisture sensitivity is necessary for getting adequate sealability and convertibility performance. Although fiber-based materials are more environmentally friendly, their use in the flexible packaging process needs to be examined carefully in terms of characteristic physical and mechanical behavior.

Common plastic like polyethylene (PE) or polypropylene (PP) gives good sealability and machinability. On the other hand, paper is a hygroscopic material; its physical and mechanical properties depend on humidity conditions. An increased degree of moisture increases the flexibility of paper but decreases its tensile strength, whereas if the degree of moisture is too low, the paper tends to be brittle and easily torn (Khwaldia 2013, p. 3439).

This influence of moisture includes the alteration in seal strength and convertibility of the VFFS machines. Consequently, dimensional stability and smooth runnability of paper require proper moisture levels. As per standard industry practices, paper is usually kept in controlled climate conditions of 23°C and 50% relative humidity (RH) before and after operations (Graphic Arts Technical Foundation 2021).

A typical flexible packaging application requires coated paper that has barrier properties and, at the same time, permits heat sealing. The paper substrate gives stiffness printability, whereas the polymer coating ensures requisite sealability and barrier properties. The forming and sealing process of this composite structure, however, is different from that of homogeneous plastic film.

VFFS machines are widely used to pack products in bags and pouches. These are specially designed for plastic-based films. Hence, the introduction of paper-based materials can result in several issues, such as high friction and resistance in smooth material flow due to enhanced stiffness. In recent research, it was demonstrated that friction is a key element for paper runnability in VFFS machines. It has been concluded that the coefficient of friction is a significant factor that can influence the smoothness of a coated paper running through a VFFS system, and hence, therefore, material flow can be improved by using low-friction surfaces, such as Teflon-coated forming tubes or textured steel components (Merabetene et al. 2025, pp. 5–15). In the same way, the geometry of forming the shoulder plays an essential role: poorly conceived shoulder may induce too high stress, resulting in wrinkles or breakage of the paper web. To solve this, researchers delved into optimized forming shoulder designs to effect a newly designed shoulder that was proven to reduce wrinkles and enhance convertibility of paper-based products on VFFS machines (Merabtene et al. 2024, pp. 131–140). This points out the fact that mechanical changes or customized parts can be required to support the characteristics of paper.

Alongside convertibility, the second crucial consideration is a good heat-sealing performance. In VFFS, seals are created by heated jaws. However, paper-based fibrous structures with a coating behave differently in comparison with plastic-based films and require special heating temperatures for effective sealing. For instance, polyolefin films, in comparison to paper-based laminates, produce more air-tight seals under the same conditions (Hauptmann et al. 2020, pp. 120–123). In the same way, optimum pressure is also necessary for improving seal integrity. Such considerations give sufficient rationale to seek optimum dwell time, temperature, pressure, and seal bar design for reliable sealability of coated papers, making it an active area for research.

In case of coated packaging papers used in VFFS machines, the moisture content impacts the sealability and convertibility. Recent studies, by Hauptmann et al. (2020, pp. 118–123), have demonstrated that seal strength of paper-based laminates is largely influenced by the moisture content and climate conditions. A study conducted by Merabetene et al. (2022, p. 232) has revealed that a decrease in the moisture content of paper by 35% makes it considerably brittle and prone to tearing. It can also cause runnability issues, such as web breaks or bad folding. This shows that keeping an appropriate level of moisture is crucial not only for smooth runnability but also for strong and regular heat seals.

In a nutshell, this trend toward sustainable packaging using paper is accompanied by benefits as well as challenges. Coated papers provide biobased material that can be recycled and serve as an alternative to plastic films. However, efficient convertibility of the material and seal integrity on existing packaging lines in use (such as VFFS machines) is not that easy. Other factors like material friction, stiffness, thermal behavior, and moisture content all play a critical role. Among them, moisture content is one of the most important factors that has various implications on the behavior of paper. The previous work indicates that inappropriate moisture level could compromise seal strength (Hauptmann et al. 2020, p. 119). This introduces the theme of the present study, which will investigate the influence of moisture level on the sealability (formation of strong, leak-free seals) and convertibility (processing in packages at high speeds, without problems) of coated papers in VFFS filling.

1.2 Motivation

Considering the above scenario, there is a need to research and enhance the performance of paper-based packing materials under different moisture conditions. Government and customer sustainability pressure is pushing the packaging sector to replace plastic with recyclable fiber-based packaging materials. However, inept use of these materials on current machinery could stop their implementation. The driving force behind this work is to facilitate the transition to sustainable packaging by assuring the successful transition to the desired seal quality and runnability with coated paper materials in VFFS.

In the industrial context, the packaging manufacturers have to achieve high throughput and low downtime; it would be unacceptable to get a drop in throughput and switch to a paper-based film that constantly jams the machine or gives imperfect seals. So, it is important to determine under which conditions the coated papers can run perfectly and seal appropriately. One of such controllable factors is moisture content that can be controlled through storage climate or pre-conditioning of the reels, and it could prove the difference in successful implementation of paper in VFFS (Hauptmann et al. 2020, p. 119). By understanding moisture effects, manufacturers can determine guidelines (such as humidity control in the plant, or pre-drying/pre-humidifying the material) to optimize the performance. This is both economically significant (less wastage, rework, stoppages of machines) and environmentally significant (more extensive use of recyclable materials rather than plastics).

The present scientific literature provides evidence that moisture is critical in affecting sealability and runnability of fiber-based packaging materials but also highlights the existence of a knowledge gap. Although recent work has investigated these effects using tray sealing systems or flat-jaw lab heat sealers, which do not represent the dynamics of reel-fed vertical form fill seal (VFFS) systems. The coated paper's performance under the impact of moisture content during form-fill-seal processes is one of the topics that still demands research, as confirmed by Merabtene et al. (2022, p. 232), who identified it as an important line of future study because it directly affects the practical feasibility of switching to paper-based packaging.

This thesis is motivated by unavailability of sufficient knowledge regarding the impact of moisture content on sealability and convertibility of coated paper materials in the packaging industry. The previous studies have highlighted it as an important factor, but its effect across different moisture conditions is yet to be evaluated (Hauptmann et al. 2020, p. 119). The objective of this research is to find the influence of various moisture conditions on the sealability and convertibility of dispersion and polymer-coated papers and establish ideal moisture conditions. In short, the goal is to facilitate in practical adoption of sustainable coated papers by providing clear instructions in material handling and machine settings.

1.3 Objectives

The following research objectives have been formulated keeping in view the background and motivation. The first objective is to determine the quality of heat seals on coated papers that will be conditioned at different moisture levels, i.e., 50%, 80%, before testing in a VFFS machine. This will be done by measuring seal strength, checking seal integrity (airtightness), and noting any potential changes in sealing parameters (optimal pressure, dwell time & temperature) with a shift in moisture. Although in the initial plan 30% RH was chosen as the third climatic condition, however, it was not achievable in the available laboratory settings. Therefore, it was revised, and typical tropical conditions, i.e., 85% RH & 38 °C, were chosen as they represent actual climatic conditions in various worldwide regions and industrial-scale packaging. In this way, the effect of worst conditions on sealing and convertibility parameters can be understood.

The second objective involves analyzing the effects of moisture variations on paper runnability, frictional resistance against the machine (jams), or the formation of wrinkles or cracks in the final product due to moisture changes. The purpose is to point out issues that can evolve at different moisture levels.

The final aim is to find the best moisture range, which could lead to a good balance of sealability and convertibility. Moreover, guidelines regarding changes in material processing or changes in material will be proposed to reduce moisture-related effects.

By pursuing the objectives, the research aims to comprehensively study both aspects of sealing and converting about moisture content, which would achieve the main intent of enhancing the use of paper-based packaging in the VFFS systems.

1.4 Research Problems and Questions

Main Research Problem: How can efficient sealing and effective convertibility performance be achieved in polymer and dispersion-coated papers in VFFS machines, at different RH levels?

To address this problem, the study is divided into the following questions and sub-questions.

Main Questions

- How varied moisture content in coated papers influence the seal strength and integrity in VFFS machines?
- In which ways, different moisture proportions affect the convertibility and runnability of coated papers in VFFS?
- Using which strategies or parameters can one counteract moisture-related effects in the process of VFFS?

Sub questions

- How will moisture changes (moderate, high & tropical conditions) affect the sealability of paper?
- What is the connection between RH values and seal strength?
- How is moisture content related to convertibility (surface-roughness, wrinkling, and runnability)?
- How do the various levels of moisture impact the friction and flow of material?
- Does any pre-conditioning of coated papers (e.g., RH levels) result in the best sealability and runnability?
- Can standard guidelines be drafted to ensure stable performance in different climate conditions?

By answering the above questions, the research problem can be addressed.

1.5 Scope

The main focus of the thesis is to study the analyse the impact of moisture proportion on sealability and convertibility of coated papers in VFFS machines. The goal is to understand how varying moisture affects the performance of paper-based packaging.

Firstly, the study consists of a literature review to explain the critical factors that influence the sealability and convertibility. Secondly, the experimentation will be done on Polymer and dispersion-coated papers that will be treated under various moisture conditions to replicate real-world circumstances. The study will evaluate seal quality by measuring mean peel force through qualitative and quantitative analysis, and convertibility by noting material runnability and visually checking surface defects.

Limitations.

The results of this study will be valid for specific materials and conditions under which experimentation will be done. The thesis aims to provide useful conclusions by providing practical data and analysis based on controlled experiments. The relative humidity conditions being used during experiments are based on packaging environments. The environmental aspect is taken as the starting point, while the focus will remain on the technical and material aspects for the sustainable development of the packaging industry. Staying within these limitations, the study can present detailed and valid findings without having to delve into tangential concerns.

2 Literature Review

This chapter will discuss the vital concepts about fiber-based coated papers and their use in sustainable packaging industry. Paper coating types and their functional properties, working mechanism of Vertical Form Fill Seal (VFFS) machines, and the impact of moisture on paper behaviour have been analyzed. Moreover, the relevant research gap is identified by reviewing the previous studies on the effect of humidity on sealability and convertibility of coated papers.

2.1 Fiber-Based Coated Papers

The efforts to replace plastic-based flexible packaging with sustainable options have increased considerably due to strict legislation regarding environmental protection and increasing consumer demand. Out of available options, fiber-based coated papers have surfaced as a viable choice due to their renewability, recyclability and biodegradability without compromising on performance. However, different coatings are required for appropriate performance in moisture-sensitive and high-barrier-demanding applications due to their porosity and hygroscopic nature. These coatings are applied not only to increase the paper's resistance against air and water vapors, but also they improve its important properties like heat sealability, strength, and printing quality. These coatings are critical to match the functional characteristics of plastics and, at the same time, help in successfully shifting towards sustainable practices (Kathuria & Zhang 2022, p. 2).

2.1.1 Types of Coated Papers and Materials

Fiber-based coated papers are divided into different types based on chemical nature and desired functional characteristics of the coating used. The main types include:

Polymer-based Coatings used materials such as polyethylene (PE), polypropylene (PP), and polylactic acid (PLA) that are laminated or extruded on paper substrate. These are used to increase paper’s water & grease resistance and better heat sealability performance. However, they are difficult to recycle in conventional paper recycling units (Jahangiri, Mohanty & Misra 2024, p. 4936).

Dispersion coatings are waterborne emulsions that are made from natural or synthetic latexes, acrylic polymers, and starch blends. They can be recycled in typical mechanical recycling units and provide midway barrier properties. They, however, may cause deinking and repulping problems depending on their composition (Jahangiri, Mohanty & Misra 2024, p. 4936).

Bio-based coatings are obtained from renewable biopolymers like chitosan, alginate, cellulose derivatives, and starch, and are studied further due to their sustainability (Basu, Plucinski & Catchmark 2017, p. 4080). Various studies have demonstrated that chitosan with carboxymethyl cellulose (CMC) can form bio-based coatings that have excellent barrier properties, are compostable, and recyclable (Chi et al. 2023, pp. 12250, 12259).

Nano Composite Coatings are made by adding nanofillers such as silica, clay, or cellulose nanocrystals into dispersion or biopolymer matrices in order to enhance the mechanical and barrier characteristics. Silica-based nanocomposite polymer coatings provide high water vapor barrier performance and durability than those of normal polymers while maintaining flexibility (Martins, Ribeiro & Farinha 2021, p.1).

The choice of materials often becomes a compromise between the barrier properties, sustainability, processability, and costs. The use of hybrid systems can further optimize these properties, especially in the VFFS processing.

2.1.2 Functional Properties and Packaging Relevance

The requirements of the coated paper should cover essential functional necessities of flexible packaging. It must have moisture, grease, and gas barrier, heat sealability under varying pressure and temperature conditions, good mechanical integrity, and be compatible with recycling systems (Khwaldia, Arab-Tehrany & Desobry 2010, pp. 82–83; Hauptmann et al. 2020, pp. 118–123).

PE-coated papers are commonly preferred due to their reliability and seal strength, but they have repulping problems due to delamination and poor fiber recovery (Kathuria & Zhang 2022, p. 2). On the other hand, bio-based coatings have been generally hydrophilic, and this decreases their water vapor resistance at high RH. Indicatively, Jahangiri, Mohanty & Misra (2024, p. 4936) reported that most bio-based formulations have sharply declining barrier at 60% and above RH unless chemically crosslinked or reinforced with hydrophobic fillers.

Mechanical testing has demonstrated that in high-speed production, coating layer thickness and uniformity are critical in determining the tear resistance, sealing edge strength, and wrinkle formation. In their study, Christophliemk et al. (2023, pp. 4–5, 8–9, 19) showed that using thin multilayer PVOH coating applied in passes of ~1 g/m² at speeds around 400 m/min produces surfaces with least defects and pinholes, resulting in increased barrier resistance and good formability under stress.

2.1.3 Trade-Offs and Process Integration

A critical issue in using coated papers at industrial level is to maintain the delicate balance between the sustainability and performance metrics. Using high-performance polymers creates challenges in recycling, while more sustainable options result in high production costs. Moreover, the coating formulations should be printable and machinable to allow brands to utilize the current infrastructure with little redesign (Hauptmann et al. 2020, pp. 118–122).

The sealing behavior under VFFS settings is critical. Several bio-based coatings have poor thermoplastic flow and poor barrier behavior, limiting their sealing capability in heat-based operation. Research work has found that polysaccharide-based coatings exhibit low thermoplastic flow and hydrophilicity, resulting in incomplete sealing and barrier properties. They also noted that these challenges could be addressed by material engineering and adequate coating design that enhances the flow of coating and thermal response (Basu, Plucinski & Catchmark 2017, pp. 4080–4091).

Current research is putting emphasis on improving coating flow and surface energy properties to promote good sealing performance. Studies are shifting from lab tests to simulations of VFFS systems to be more realistic and relevant to the industry (Hauptmann et al. 2020, pp. 117–121, 123–126). Table 1 below presents the main characteristics, performance attributes, and sustainability aspects of the key types of coating used in fiber-based packaging.

Table 1. Characteristics of key coating types used in fiber-based packaging (Chi et al. 2023; Kathuria & Zhang 2022; Jahangiri, Mohanty & Misra 2024; Basu, Plucinski & Catchmark 2017; Martins, Ribeiro & Farinha 2021).

Coating Type	Material Examples	Barrier Performance	Sealability	Recyclability
Polymer based	PE, PP, PLA	Excellent	High	Low
Dispersion based	Latex, acrylics, starch	Moderate	Moderate	High
Bio based	Chitosan, CMC, alginate	Improving	Moderate to high	High
Nanocomposite enhanced	Silica+ biopolymers	High	High	Moderate to high

2.2 Form Fill Seal (VFFS) Packaging Process

The working principle of VFFS machines and performance of fiber-coated papers during different packaging operations, i.e., forming, sealing, and convertibility in automated packaging, will be covered.

2.2.1 Overview of VFFS Machine Operation

Vertical Form Fill Seal (VFFS) machines are common in the packaging industry because of their speed, small size and flexibility in packaging different products. The process starts with the unwinding of flexible packaging material from the roll and giving it tubular form using a forming collar, filling it with the product, and then closing its both ends to make a pouch. The cycle entails vertical sealing of longitudinal edge and the horizontal sealing of the top and bottom of the pouches (Emblem & Emblem 2012, pp. 451-453).

In terms of smooth feeding, low friction, and fast heat sealing, this process setup is optimized for conventional plastic films. However, using fiber-based coated papers on same system brought new mechanical issues. These materials are comparatively rigid, less elastic, and likely to wrinkle or delaminate around the forming shoulder, where the paper must fold itself into position. Whereas convertibility, i.e. characteristic of material to smoothly flow through the machine, depends on paper’s bending stiffness, friction, and surface strength (Desoki, Morimura & Hagiwara 2011, pp. 32-34, 36, 38-39).

Recent research work by Merabtene et al. (2024, pp. 131-135) identified the role of forming shoulder design, web tension control, and material surface treatment in runnability and the quality of formed tube. Low-friction coatings of a smooth nature enhance feed uniformity and reduce paper damage during forming. Main components of VFFS can be seen in Figure 1.

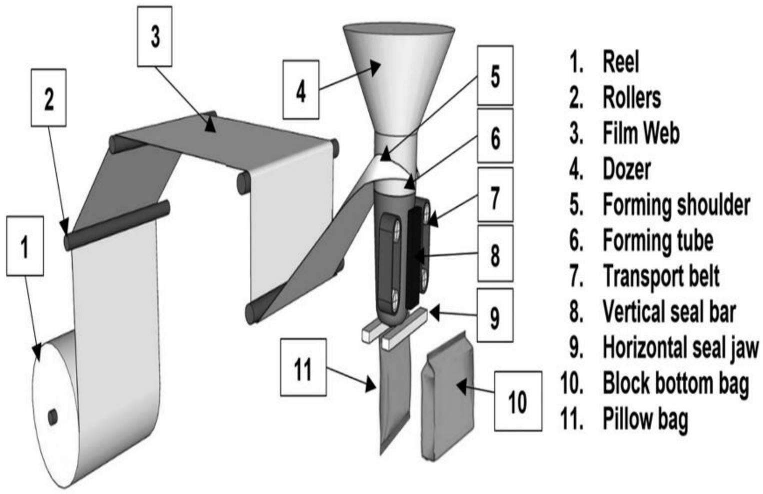

Figure 1. Schematic of a vertical form, fill, and seal (VFFS) packaging machine (Merabtene et al. 2023, p. 668).

2.2.2 Packaging Material Requirements for VFFS Systems

The packaging material must meet certain standard requirements, i.e., mechanical, thermal and surface performance for an efficient VFFS operation. Important characteristics include flexibility, tear resistance, good sealing behavior, friction resistance and compatibility with the machine.

Coefficient of friction (COF) is a significant factor that controls the movement of material through the roller and over the forming shoulder. A large COF and excessive web tension lead to a higher contact pressure along the curve of bend, which may result in difficulties in conversions and tearing of material (Merabtene et al. 2024b, p.137). Variable RH has a strong influence on COF of paper materials. According to Fellers et al. (1998, pp. 225–230), an increase in the moisture content enhances friction, mainly due to an increase in surface free energy and adhesive force. Kawashima, Sato, and Yamauchi (2008, pp. 336–339**)** reported that COF increases up to ten times under humid conditions because of the capillary adhesion and the swelling of fibers. Excessive friction during VFFS operation may disrupt web transport; in the case of CHP BAR A polymer-coated paper, the polymer attached to the forming tube experienced stick-slip, which produced heat and inhibited efficiency in transportation (Merabtene et al. 2024a, p. 661. To facilitate easier handling, there is an increasing usage of friction-modifying additives or multilayer coatings that help to reduce deformation of the material. Slip additives are added to coating formulations to reduce the coefficient of friction by migrating to the surface and creating a lubricating coating in thin layers, enabling easier web transport by forming components (Merabtene et al. 2024a, p. 656). Table 2 provides a comparison between the coefficient of friction, seal initiation temperature, and relative stiffness values for bio-based, pe-coated, and disp-coated papers. The data shows that PE-coated papers have low friction and a wider seal initiation temperature range.

Table 2. Summary of key sealing and mechanical properties for fiber-based coatings (Merabtene et al. 2023, pp. 668–677; Ying et al. 2022, pp. 618–621).

Coating Type	**Dynamic COF**	**Seal Initiation Temperature °C**	**Relative Stiffness**
PE-coating	Low friction and smooth sliding	~90–130	Moderate
Dispersion coating	More than PE coated	≥100	Higher than PE; prone to stiffness effects depending on grammage
Bio-based coating	Higher Friction	Typically, ≥120	Usually stiffer due to polysaccharide matrix

2.2.3 Sealability and Heat-Sealing Mechanisms

The final crucial step in VFFS process is heat sealing. It guarantees the integrity of the packages, provides barrier protection, as well as the safety of the products. In the case of fiber-based papers, sealing is also influenced by the type of coating, the porosity of the substrate, moisture content, and sealing bar design. Inappropriate sealing parameters may cause lack of adhesion, channel leakage, or fiber break (Merabtene et al. 2023, pp. 668-677).

Sealability is quantified by its seal strength (N/25 mm), seal appearance and fiber tear percentage for coated papers. Seal quality is greatly determined by the geometry of the seal bar. Serrated seal jaws produce localized pressure and interfacial shear stress, leading to perpendicular orientation of laminate chains and enhanced seal strength and leak resistance (Merabtene et al., 2023, pp. 675-676). They are more effective and bond the surface better than flat seal bars, especially on coarser paper surfaces. Microscopic imaging also shows that serrated jaws enhance the interlocking of the fiber and minimize the air channels in the seal area (Merabtene et al. 2023, pp. 675-677). Figure 2 shows SEM images of seal interfaces using different seal bar geometries.

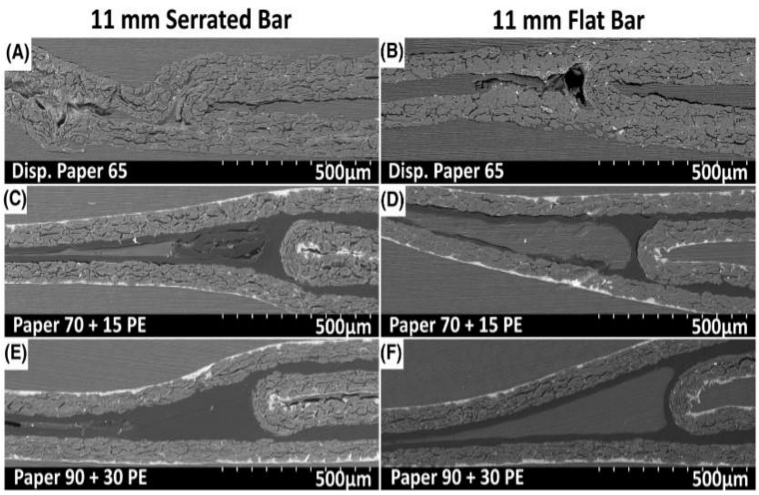

Figure 2. SEM images comparing seal quality using 11mm serrated and flat bars across coated paper substrates (adapted from Merabtene et al. 2023, p. 676).

2.3 Seal Performance and Evaluation Methods

This section will describe the criteria for evaluating coated paper materials in terms of heat seal performance in VFFS machines. It will explain the role of seal parameters, forms of seal failure, and the methods to be used in examining the quality of the seal analytically. This knowledge is essential for the optimization of sealability and package integrity of sustainable fiber-based systems.

2.3.3 Parameters Affecting Heat Seal Strength

Sealing temperature, dwell time, pressure, coating composition, and the seal bar geometry affect heat seal strength. The factors determine the strength, peelability, or leakiness of the seal. A comparative analysis of a PE-coated paper with a disp coated sample showed that the PE-based samples exhibit twice the seal strength under similar VFFS conditions. The authors explained this performance of PE-coated papers due to their ability to seal over broad temperature range and an improved thermoplastic flow behavior (Merabtene et al. 2023, pp. 668–674).

Research on performance of coated paper discovered that polyolefin-based coating performed well in terms of cooled seal strength (maximum >1.14 N/mm), whilst PVOH coating was lower, though it rose with cooling. However, by comparison, the acrylic-coated materials had excellent hot tack but low post-cooling strength (Bamps et al. 2024, pp. 885, 894, 896-97).

2.3.4 Seal Integrity, Failure Modes, and Testing Standards

Seal integrity is the physical continuousness and airtightness of the sealed area. It is a very important quality attribute in foods and medical packaging, where a breach may cause contamination or spoilage of goods. The common seal failure modes include peel failure, Fiber tear, channel leaks and delamination. Peel failure occurs when the seal separates at adhesive boundary. Fiber tear is the result of strong bond between paper layers. Insufficient sealing pressure or uneven heat causes the channel leaks (Merabtene et al. 2023, pp. 675-677). Finally, higher levels of humidity and temperature variations can weaken the coating bond, resulting in delamination.

Higher temperatures greatly lower the seal strength in medical packaging, with spunbonded high-density polyethylene (HDPE, commonly marketed as Tyvek) materials decreasing nearly half of their peel resistance when warmed between room temperature and 43°C

(Dixon et al. 2007, pp. 1533, 1537). This reveals the significant role of controlling the conditions of sealing and particularly in sterilization.

Commonly used standard tests include ASTM F88/F88M. These include peeling tests on universal testing machines to measure seal strength (N/25 mm). The burst and creep tests are also used and particularly in the quality assurance arena. In addition to the standard setup, ASTM F88 provides three test methods: A, B, and C that attribute to the differences in support of the sample tails and the seal regions during the test. Configuration influences peel angles and stress distribution, thus influencing measure of seal strength. Indication of peak force versus average force or energy under the curve should also be reported because those measures capture different aspects of seal loading performance (ASTM International 2015). Inflation-based testing, such as burst testing or creep-to-failure testing (ASTM F1140, F2054), should be used in addition to peel testing to assess whole-package integrity and local isolations of seal weaknesses in non-peelable or rigid packaging (ASTM International 2015).

2.3.5 Promising Analytical Techniques for Seal Quality Evaluation

Several promising analytical methods present non-destructive and sensitive alternatives to standard seal testing. As an example, electrical capacitance tomography (ECT) with autoencoders can identify seal defects in the process of high-speed in-line packaging by analysing variation in capacitance (Pan et al. 2022, pp. 1-10). Principal Component Analysis (PCA), which is a multivariate data technique, on accelerometer signals can be used to identify inconsistencies in sealing via process control charts, allowing anomalies in the packaging to be identified before the package is damaged (Ostyn, Darius, De Baerdemaeker & De Ketelaere 2007, pp. 216-221). Moreover, machine learning and infrared thermography have been demonstrated as suitable tools in identifying thermal seal discontinuities, such as contamination or non-uniform bonding, in real time (Guillot 2023, pp. 1–15). The inventions are part of an industry trend in closing the destructive sampling practice with automated, inline assurance devices that offer enhanced quality control with reduced wastage of products and inspection time (Harper, Blakistone, Litchfield & Morris 1995, pp. 336-339).

2.4 Convertibility of Coated Papers in VFFS Machines

Convertibility is the capability by which coated paper materials can be processed in the high-speed VFFS machines without any failure or defects. Paper stiffness, surface friction, moisture content and structure of parts of a machine are some of the principal factors that affect the convertibility. This section will shortly describe mechanical, material, and environmental factors that influence the convertibility of coated papers (Merabtene et al. 2025, pp.12–14).

2.4.1 Mechanical Challenges in Paper Feeding and Folding

Coated paper webs in VFFS systems experience complicated deformations when they are folded, bent, and stretched through rollers and forming shoulders. In contrast to flexible plastic films, fiber-based material is less pliable, with lower elongation and greater stiffness, and tends to experience web breaks and wrinkling, and surface cracking during converting.

Merabtene et al. (2022, pp. 223, 232-238) found that paper-based packaging material tends to exhibit wrinkling, buckling, and localized surface damage while moving through forming shoulder and sealing zones. These mechanical problems are closely related to high frictional interaction, brittleness due to moisture, and poor control of web tension during the folding and forming stages.

2.4.2 Impact of Moisture on Runnability

The runnability is directly affected by the moisture content because properties of coated paper, such as stiffness, flexibility, and coefficient of friction (COF), are very moisture sensitive (Merabtene et al. 2024a, p. 655). These findings about COF were carried out after conditioning samples under standard testing conditions (23 °C and 50 % RH) for 48 hours for reliable results. At increased humidity, cellulose-based materials are prone to softening and stick-slip, due to the plasticization of these materials by moisture. According to Merabtene et al. (2025, pp. 12–13), plasticization of the cellulose film under tropical conditions (85 % RH, 38 °C) led to stickiness and hence an increase in friction, resulting in poor runnability. These effects of humidity show that paper-based materials are sensitive to environmental conditions, and this can affect their behavior during packaging processes.

2.4.3 Forming Shoulder Design and Friction Optimization

The forming shoulder is a vital component of VFFS on which the flat webs are converted into tubes. Improper shoulder design may exert too much pressure on a coated paper, leading to folding defects and surface damage. Merabtene et al. (2024b, pp. 133–140) designed an optimized geometry of forming shoulders with a smoother curvature and offset fillet that enhanced the runnability of coated papers. In the experimental apparatus, Teflon tape was put over the forming tube to reduce friction at the surface, due to which convertibility was principally improved by the optimized shoulder geometry. With dispersion-coated papers, the friction at the tube-web interface was reduced, and wrinkling was much reduced when the new design was used, allowing forming to be finished more smoothly. The enhanced shoulder also made the material tracking and alignment at the high forming speeds.

2.4.4 Material Conditioning and Pre-Treatment Strategies

Preconditioning of the coated paper reels before conversion is an imperative practice. Despite scanty scholarly research on the topic, the current best practices in the field of paper conservation advise storing and converting conditions be kept at 23 °C and 50-55 % RH to stabilize paper properties. This prevents curling, dimensional instability, static buildup, and uneven feeding, which can have a disastrous effect on convertibility in VFFS machines (Condair 2015).

Besides, it is recommended that coated paper rolls be left to acclimatize at least 24 hours within the production environment so that they can achieve moisture equilibrium. There are also non-contact pre-warming systems used in some facilities in proximity to forming sections to limit the risk of surface tension variation and web breaks. Although these practices are based mainly on the information contained in technical and manufacturer manuals, they are commonly employed in the industry to achieve stable and high performance in terms of converting speed (Graphic Arts Technical Foundation 2021).

2.5 Effect of Relative Humidity (RH) on Paper-Based Packaging

Relative humidity greatly influences the working behavior of the coated paper in packaging, as it changes the mechanical strength, moisture barrier, and responsiveness of the materials used in the paper packaging. Subsections below discuss literature studies on the impact of RH on mechanical and barrier attributes, seal performance, and hygroscopic nature of paper-based substrates.

2.5.1 Influence of RH on Mechanical and Barrier Properties

Due to the hygroscopic nature of cellulose fibers, paper-based packaging demonstrates RH-sensitive mechanical performance. Papers at high humidity levels (>75 % RH) take up moisture, and this phenomenon causes plasticization, an increase in elongation at break, and a decline in tensile strength. This may diminish their printing, conversion, or packaging performance (Khwaldia, Arab-Tehrany & Desobry 2010, pp. 82–83; Condair 2015).

In a study, Wang et al. (2020, pp. 1, 4–6) showed that a cellulose stearoyl ester coating on calendared paper could enhance water vapor resistance, but tensile index decreased and elongation at break increased with increase of coating layer thickness, providing flexibility. On the same note, Bedane, Xiao & Eić (2014, p. 870) observed that permeability of water vapor in PLA-coated papers rose rapidly at RH ~75 % indicating a great loss of barrier capacity. Figure 3 shows the effects of increase in coating grammage, like increase in RH levels. The graph shows that tensile strength drops slightly while the elongation at break increases with increase in coating grammage. It is evident from Figure 3 that as coating grammage increases from S_o to S_7, tensile index decreases while elongation at break increases

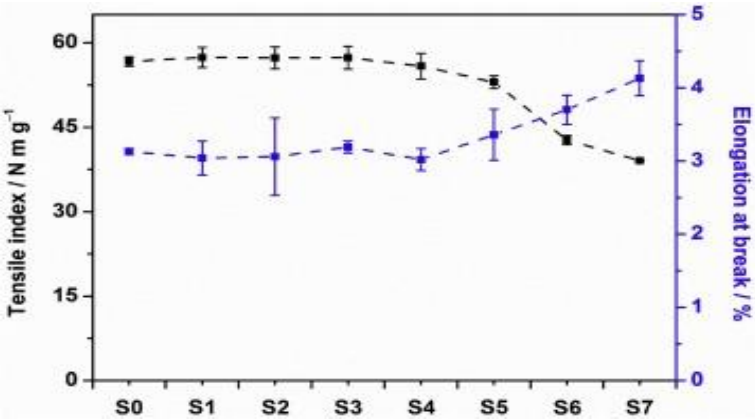

Figure 3. Tensile index and elongation at break for coated papers (Wang et al. 2020, p. 5).

2.5.2 RH Effects on Sealability and Handling

The seal strength and the quality of the formation of heat-sealable paper materials are directly affected by RH (Hauptmann et al. 2020, p. 126). Low RH levels can cause the paper to be brittle and prone to cracking (Niskanen 1993, p. 645). While higher moisture levels decrease thermal conductivity and slow the process of seal initiation, which impacts seal integrity (Hauptmann et al. 2020, p. 125).

Chalier, Peyches-Bach, Gastaldi & Gontard (2007, pp. 871–872) demonstrated that the permeability of aroma compounds in wheat gluten-coated papers was not linearly related to RH and affected seal adhesion because of the swelling caused by water. Likewise, Khwaldia, Arab-Tehrany & Desobry (2010, pp. 82–83) determined that the barrier strength of hydrophilic coatings is weakened by higher RHs because of enhanced absorption of water and weakened cohesion at seal boundaries.

2.5.3 Hygroscopic Behavior of Coated Paper Materials

Hygroscopic nature of paper influences its surface morphology and dimensional stability. It leads to absorption of moisture, fiber swelling, deformation, and loosening of coating-substrate bonding (Lindstad et al. 2025, pp. 380–387).

Lindner, Heider, Reinelt & Langowski (2019, pp. 1–2, 11–15) measured the extent to which RH-related hygroexpansion of paper substrates resulted in cracking of aluminum vapor-barrier coatings. They noticed that the RH and effective resistivity of the aluminum coatings were linearly related, which was controlled by mechanical straining due to moisture swelling, whereas at higher RH, cracks dominate the resistivity. Moreover, Bedane, Xiao & Eić (2014, pp. 867–868) used the GAB isotherm model to explain PLA and PHBV coatings that blocked or water accessible sites and led to lower equilibrium moisture content.

2.6 Research Gaps and Summary

This section highlights the important points from studied literature and points out certain knowledge gaps related to the influence of moisture content on sealability and convertibility of coated papers in VFFS machines. These gaps will form the need for experimental work presented in the thesis.

2.6.1 Gaps in Literature on Coated Paper Sealability

Past studies have revealed that variable moisture influences the thermal beaviour, adhesivity, and sealing performance of coated papers (Hauptmann et al. 2020, pp. 117–120; Khwaldia, Arab-Tehrany & Desobry 2010, pp. 82–83). Seal strength and integrity are influenced by various dynamics such as coating composition, design of seal bar and different process constraints, specifically dwell time, pressure, and temperature (Merabtene et al. 2023, pp. 668–669; Bamps et al. 2024, pp. 885–888). However, most of the previous studies appear to have been conducted using laboratory-sized equipment like tray sealers or the flat-jaw heat sealers that do not match the continuous high-speed feeding, forming, and sealing cycles of the VFFS systems. A limited study has been carried out to find the influence of different moisture contents on seal initiation temperature, sealing window, and seal integrity using VFFS apparatus. In addition, there is a lack of empirical evidence relating the moisture effects of material changes to the optimized sealing parameters in these systems.

2.6.2 Gaps in Literature on Coated Paper Convertibility

Convertibility of coated paper depends on factors such as stiffness, flexibility, paper surface friction, and dimensional stability, which are moisture sensitive (Merabtene et al. 2024a, pp.

655–662; Khwaldia 2013, pp. 3440–3448; Condair 2015). While some previous research efforts have focused on individual effects, i.e., reduction of friction, redesigning of forming shoulder, and pre-conditioning but little work has been done to understand these effects in parallel with varying moisture levels imitating VFFS systems. Little research has been conducted to analyze the effect of moisture variation on web tension stability, folding behavior and wrinkle formation, and feeding consistency in a continuous high-speed operation.

2.6.3 Combined Knowledge Gaps

The existing literature discusses sealability and convertibility as separate topics, whereas in industrial VFFS packaging, they are very closely correlated. For instance, a certain moisture value that improves its flexibility and feeding may result in decreasing seal strength. There is currently no integrated model to define the optimum RH range for these closely linked effects or defined optimal RH ranges for these two properties in polymer-coated and dispersion-coated papers. Summary of key insights:

- Moisture content affects both sealability and convertibility but understanding their combined influence in VFFS machine is still under study.
- Standard guidelines or optimal operational parameters to simultaneously achieve a balance between sealability and convertibility are missing.
- There remains lack of aspect of realism in the laboratory studies and industrial guidelines that are not experimentally validated for coated papers.

This thesis work will aim to fill these gaps by conducting a laboratory-based sealability and convertibility experiment on polymer- and dispersion-coated papers under three controlled relative humidity conditions (50 %, 80 % at 23 °C, & 85 % at 38 °C), using VFFS equipment simulating industrial forming, filling, and sealing behavior and operation.

3 Methodology

This chapter describes the experimental setups, methods, and materials used to evaluate the effect of different climatic conditions on the sealability and convertibility of disp and Pe-coated papers in the VFFS machine.

3.1 Research Design

The study is based on a comparative experimental design that involves assessing various important functional parameters, i.e., sealability and convertibility of disp and Pe-coated papers under different moisture conditions. The relative humidity RH and temperature are independent variables, while the seal failure mechanism, seal strength, and convertibility indicators are the dependent variables in this work. To study and simulate the challenges faced in paper packaging storage and processing in various climatic conditions, samples were conditioned at humidity levels, i.e., 50% RH at 23 °C (standard), 80% RH at 23 °C (high humidity) & 85% RH at 38 °C (tropical) to sort out optimal conditioning parameters. A schematic diagram describing the methodology workflow is given below.

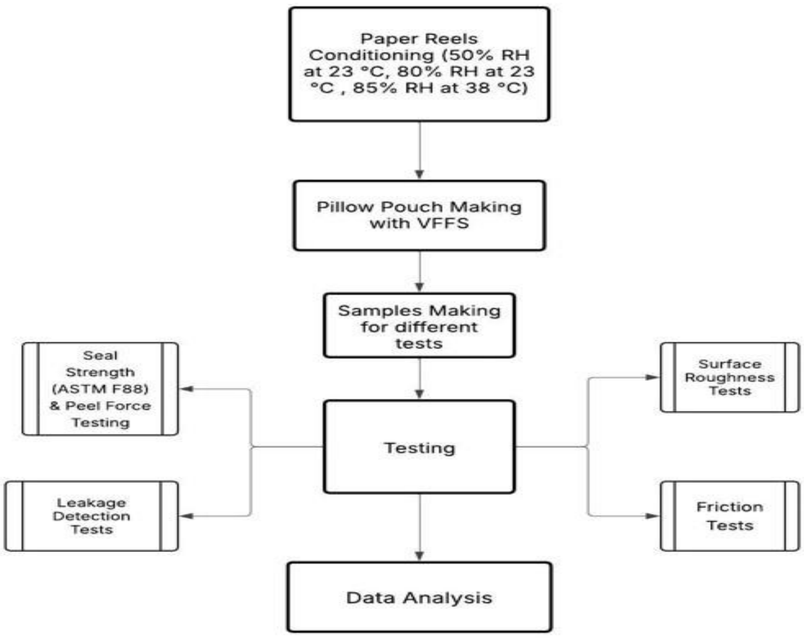

Figure 4. Workflow of Experimental Methodology.

3.2 Materials

Dispersion and PE-coated papers were used for testing. Properties of paper materials used are given below in Table 3.

Table 3. Materials and Specifications

Material Name	**Material grammage (g/m^2)**	**Material Thickness (µm)**	**Coating Type**	**Applications**
PE Coated	70	65	PE	Moisture barrier, VFFS
Disp Coated	75	76	Dispersion	Sustainable packaging, dry food packaging,

Material grammage and thickness were a little higher for disp-coated paper. The experiments were conducted using the following equipment:

- Memmert HPP750 Climate Chamber
- GKS Packaging Test VFFS Machine, Model: (GKS COMPACK CP 350).
- Shimadzu Universal Testing Machine (UTM)
- Leakage Test Setup (custom laboratory setup, Patent Blue V 0.05%)
- Friction testing with LabVIEW Data Acquisition System (custom setup, sliding block method)
- Keyence VR-3200 3D Optical Profilometer

3.3 Sample Preparation and Conditioning

Dispersion and PE-coated paper reels were first placed in Memmert HPP750 climate chambers for 24 hours to saturate them with the RH levels and Temperatures as shown in the figure mentioned in section 3.1. This 24-hour conditioning period was supposed to be enough for uniform moisture absorption; however, complete equilibrium might not have been achieved across all layers of paper reels, due to which results might not depict significant effect or difference of moisture change on sealability and convertibility. After that, pillow-type pouches were made using the VFFS machines. Table 4 describes the sample dimensions for each test and the number of repetitions. At least 20 pillow bags were made at each RH and temperature for both paper types for sample making. The chamber used for conditioning is shown in Figure 5 (a) & and paper reels inside it are shown in Figure 5 (b).

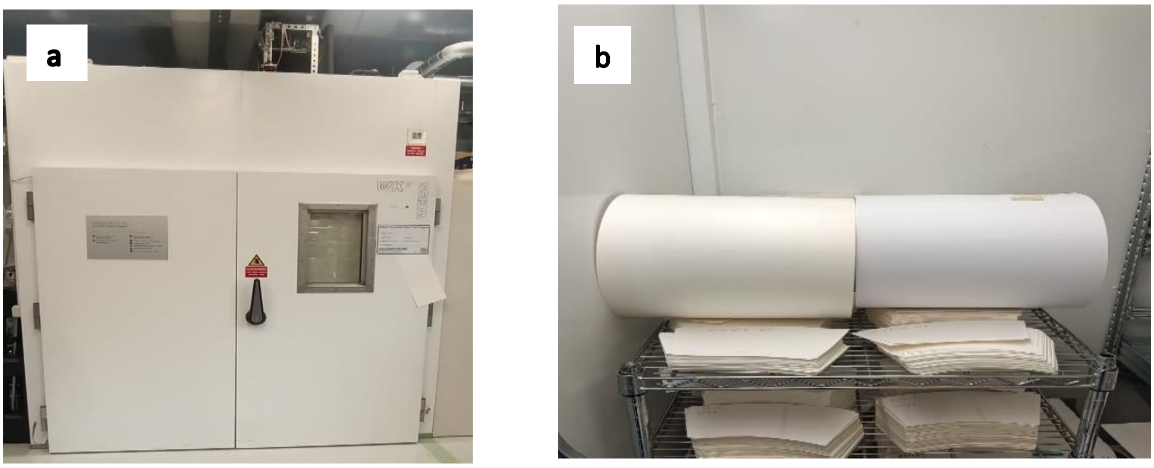

Figure 5. (a) Climate chamber.   (b) Paper reels inside the chamber.

The samples were properly conditioned, and standard practices were followed while finalizing their dimensions. An optimum quantity of samples was created for each test to get reliable results. Table 4 describes the summary of different tests, the quantity & repetition of samples, and their dimension.

Table 4. Sample dimensions and number of replicates

Test Type	Sample Dimensions	No. of Repetitions
Manual Seal Failure Mechanism Analysis (ASTM F88)	25 mm x 75mm	20 strips per temperature & RH
Seal´/Peel Strength (UTM)	25 mm x 75mm	10 strips per Temp & RH
Friction Testing in MD	63.5 x 63.5 mm	6 samples per RH, uncoated side
Surface Roughness Measurement	100 mm x 100 mm	5 samples per RH, for conditioned and converted, conditioned and unconverted, and unconditioned
Leakage Testing	110 mm x 140 mm	3 at each temperature per RH

The samples for peel test, friction, and surface roughness tests were conditioned for 24 hours before testing. Samples for manual seal failure mechanism were fabricated from pouches that were made from paper reels that were earlier conditioned before converting. Tests for checking surface roughness were done for unconditioned, conditioned, and converted and conditioned and unconverted samples. Figures 6 (a & b) & Figure 7 (a, b) show the samples made for seal strength, friction, surface roughness measurement, and Leakage testing. The arrows on the friction test samples showed the machine direction.

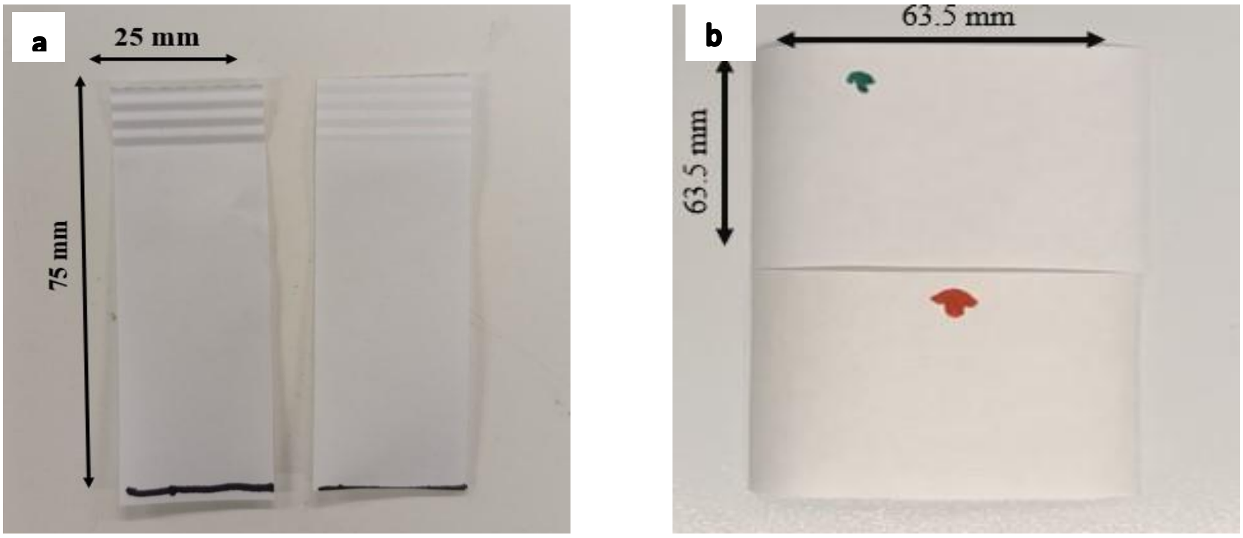

Figure 6. (a) Sample for seal strength test. (b) Friction test sample.

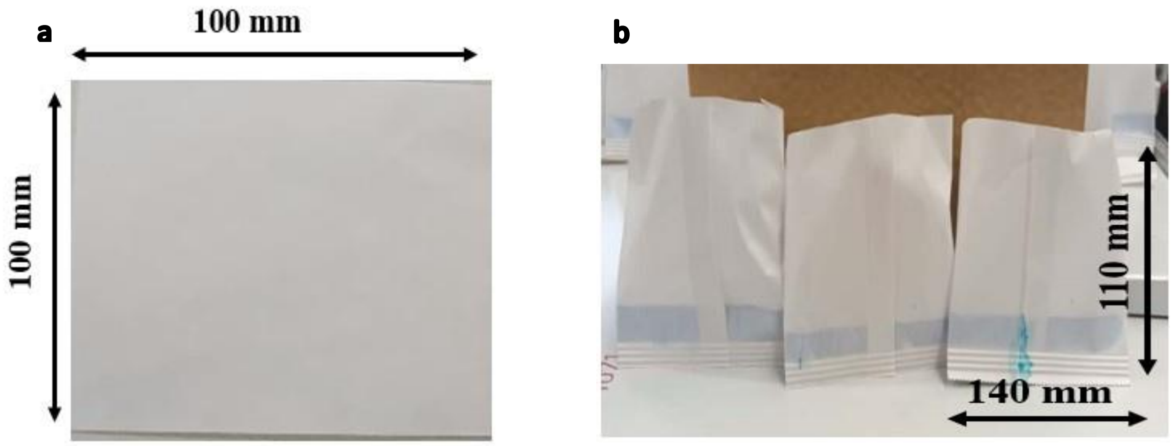

Figure 7. (a) Surface roughness test sample. (b) Leakage test samples.

3.4 Experimental Procedures

This section will elaborate on the process of conducting various tests using different equipment. A brief description of each of the tests is provided below.

3.4.1 Pillow Pouch Making Using VFFS

The conditioned reels were used to produce pillow bags using the GKS Packaging Test VFFS Machine (Model: GKS COMPACK CP 350), which were later utilized in sample preparation for various tests, as shown in Figure 8. The sealing jaw pressure was adjusted to 6 bar for all samples, with a fixed dwell time of 0.5 seconds, while the sealing temperature was varied between 100°C and 160 °C, with an increasing step of 20 °C to find the appropriate sealing window.

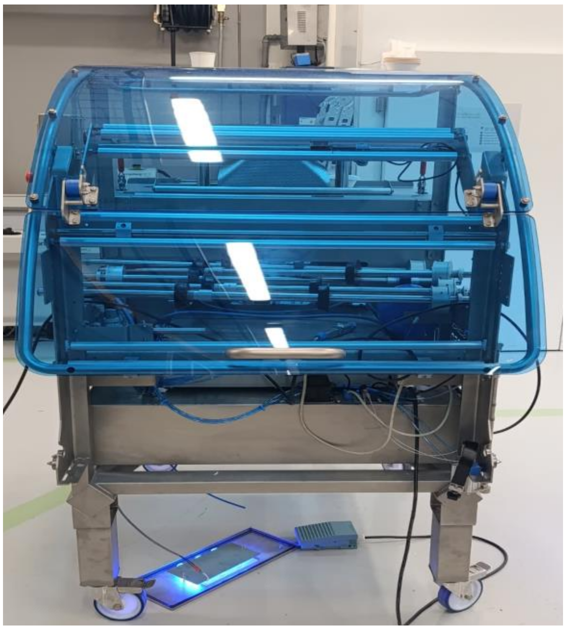

Figure 8. VFFS machine (Model GKS COMPACK CP 350).

Table V describes the main machine parameters utilized. All other parameter values (e.g., flip-over delay, vibration times, perforation delay) were kept the same during whole pouch making to reduce variability and get consistent results.

Table 5. VFFS sealing and operating parameters

Parameters	**Value Range**	**Remarks**
Sealing Jaw Pressure	6 bar	Kept constant
Sealing Temperature	100°C to 160 °C step of 20 °C	To find sealing window
Dwell time	0.5 Seconds	Fixed
Pouch length & width	230 mm & 140 mm	-

The pillow bags made were of a uniform size and sealing profile. Figure 9 shows the structure of pouches. These raw or main pouches were then utilized for making samples for seal strength testing, manual seal failure mechanism analysis, surface roughness, and leakage testing.

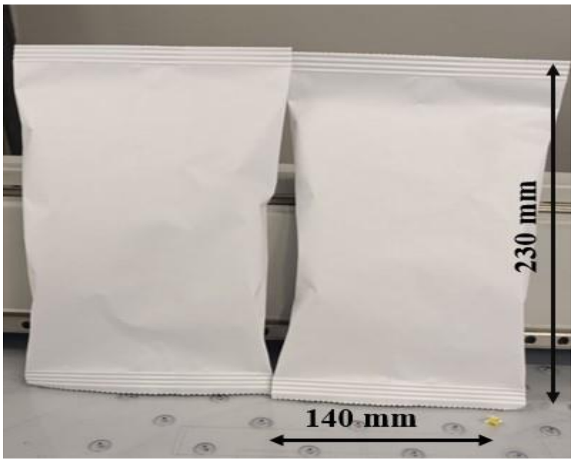

Figure 9. Pillow-type pouches.

3.4.2 Seal Failure Mechanism Analysis and Seal Strength Testing

The seal strength was measured using the Shimadzu Universal Testing Machine (UTM). The failure modes were identified in accordance with ASTM F88/F88M, which is a standard Test Method for Seal Strength of Flexible Barrier Materials. Test specimens of rectangular shape and size of 25 mm × 75 mm were cut from the sealed regions of pillow bags. The cut strips were then clamped in the UTM Griper and peeled at a constant crosshead speed of 300 mm/min. The seal strength was then recorded in terms of maximum peel force per unit width. The Shimadzu Universal Testing Machine (UTM) used for seal strength measurement is shown in Figure 10.

Figure 10. Shimadzu Universal testing machine.

The Trapezium X software was used for measuring peel force. The first step was selecting the peel test type and method. Next, the number of batches and quantity per batch were set. Afterward, the sample was represented with relative humidity level, temperature, and paper type. In the next step, force calibration was done by software by performing E-CAL, and finally, the stroke was set to zero before starting testing. The distance between the two grippers of UTM was kept up to 25 mm. After the test is finished, the software provides force displacement curve, maximum, and mean peel force. In this way, seal strength was measured at 120, 140 & 160 °C for all RH levels. The illustrative examples of the output of UTM in terms of software and closer view of the test setup are shown in Figure 11 below.

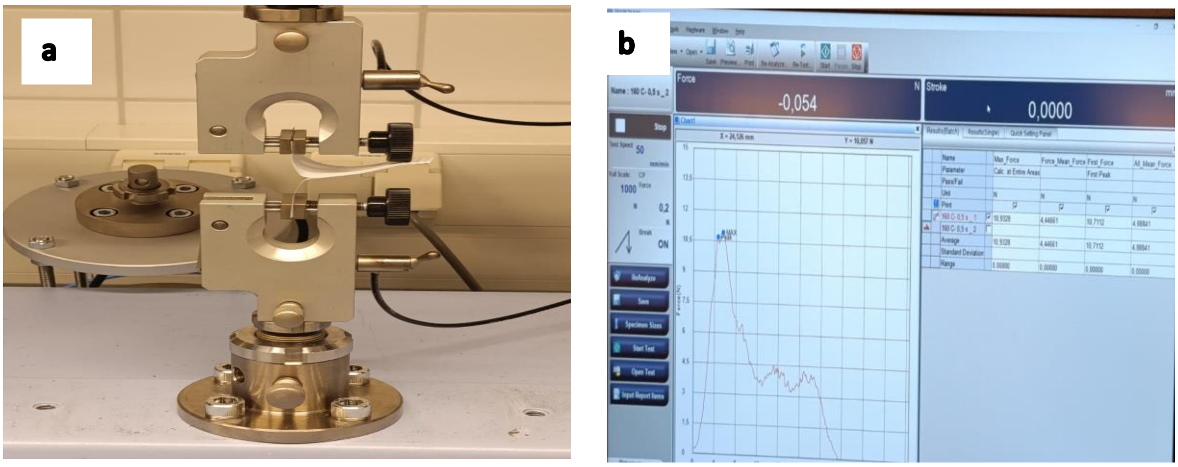

Figure 11. (a) Close view of peel test setup. (b) Force–displacement curve.

Qualitative and quantitative analyses were carried out to evaluate the seal strength and make a comparison between them. The seal failure mechanism was classified into adhesive, cohesive, or mixed modes as per ASTM F88 definitions. In quantitative analysis, the values of peel force and force vs. displacement curves were observed to understand the influence of different climatic conditions on seal strength. Figure 12 shows the seal strength test strips after manual and machine peel for PE-coated paper conditioned at tropical conditions and converted at 140 °C. The figure shows that there is considerable paper pick-up and fiber tear in PE samples, indicating strong seal formation.

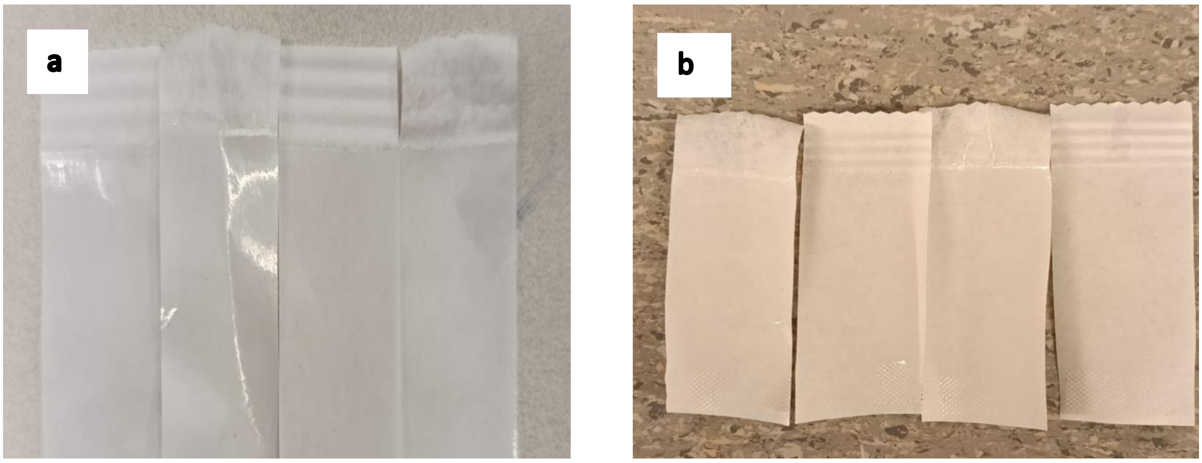

Figure 12. (a) Manual peeling. (b) Machine peeling of PE-coated paper strips at 140 °C.

3.5 Surface Roughness and Friction Testing

Keyence VR-3200 3D Optical Profilometer was used to measure the surface roughness of conditioned and converted samples, conditioned and unconverted samples, and unconditioned samples to get deep understanding of moisture and machine converting effects on surface roughness for both types of papers. The measurements were taken on the uncoated side, as it mainly accounts for convertibility and friction during pouch making. VR-3000 G2 software was employed for in-depth analysis and to measure Ra and Rz values. The software consists of two sections: the first one views, and the other provides the result by analyzing the sample. Before scanning, the XYZ origin was set to zero, and the manual camera brightness of 4.5 ms was used. The magnification value of 12x was selected. After that the sample was placed on profilometer stage. Next, the auto-stitching and auto focus were activated. A step value of 40 mm was used for the XY stage. Afterward, the measurement was started. When the inspection was completed by the viewer, the measurement results were opened in the analyzer. After that, the measurement reference plan was fixed, and the surface shape correction function was utilized to avoid distortions. Finally, surface roughness was measured using the Line R function. Figure 13 shows Keyence VR-3200 3D Optical Profilometer used for surface roughness measurement and its output.

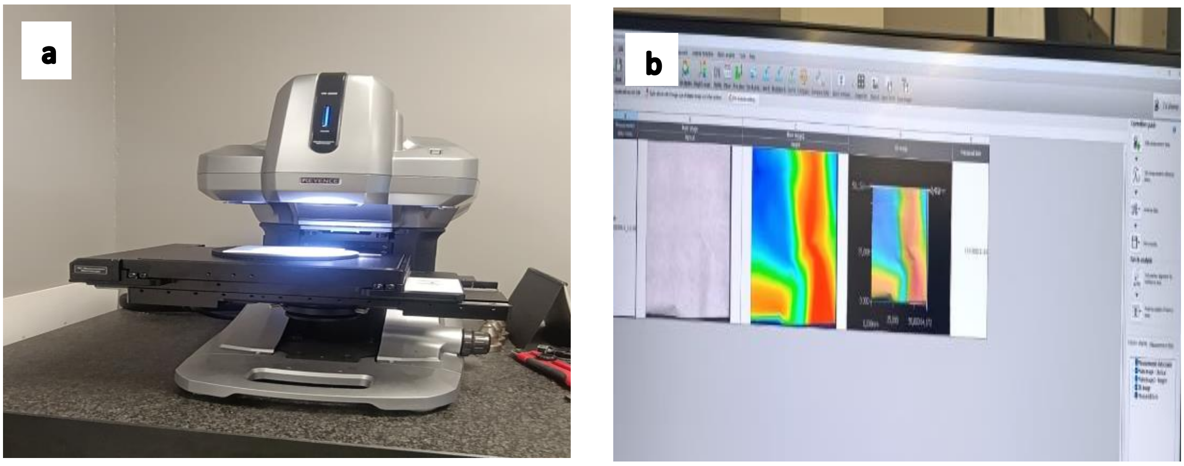

Figure 13. (a) VR-3200 3D Optical Profilometer. (b) Surface roughness Output

Using the above methodology, values of R_a and R_z were calculated. R_a stands for average arithmetical mean roughness, and it defines the average deviation in surface smoothness from the mean line. Rz describes the average distance between the highest points and lowest depressions in a surface. All the results were noted and saved in Excel.

3.5.1 Friction Testing

A custom friction testing setup was utilized along with LabVIEW 2020 data acquisition system. The conditioned sample was attached to the base of the slider, and coefficients of friction were noted for uncoated sides for both papers. The friction testing was done on paper side of samples, as it comes in contact with the machine components, and to replicate the actual conditions of converting and packaging. This setup helps to analyze effect of variable moisture on the runnability of paper. A constant support of 1.962N was applied, and each sample was slid for 14 cm before stopping it. The sample time was fixed at 100 ms, and the averaging factor of 50 was adjusted. A scaled speed of 2.40 was used for the slider. The LABVIEW interface provided real-time frictional force, graphical output, and force displacement curves from which coefficients of static and dynamic friction were calculated. After performing all tests, the results were exported to Excel. Figure 14 shows the typical friction test setup. Figure 14 shows the sample attached to the slider and the whole friction testing setup.

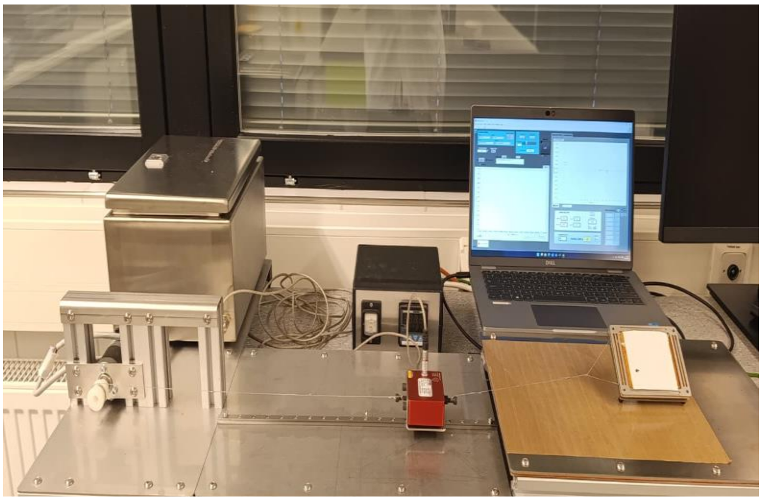

Figure 14. Custom tribometer with LabVIEW system used for friction testing.

3.6 Leakage Testing

The seal integrity and airtightness were checked using a custom-made setup, consisting of 0.05% Patent Blue V dye solution and a syringe for injecting the same into the samples. The sample was made by cutting the full pouch into two halves. The leakage and air tightness of both upper, lower, and vertical seals were tested. Using a syringe, 5ml of the solution as mentioned above was injected into each pouch. After that, the solution was allowed to remain in sample pouches so that it could penetrate through weaker seals, and seal integrity could be verified. Figure 15 shows the setup for testing the seal integrity of disp-coated papers converted at 120 °C. The leakage test adds reliability to seal integrity under functional stress situations

Figure 15. Example of pouch leakage test performed in the immersion setup.

3.7 Data Collection & Analysis

Data from all tests was collected from the equipment-related software and manually. The Shimadzu Universal Testing Machine (UTM), along with Trapezium X software, provided seal strength values and created force–displacement graphs. The data through the methods and results option was exported to Excel. The Keyence VR-3200 3D Optical Profilometer provided roughness parameters (Ra, Rz) through its analysis software. The results of surface roughness tests were saved in PDF format. The friction testing equipment, in conjunction with LabVIEW software, provided static and dynamic friction coefficients along with force-distance graphs, and the data was exported to Excel. Moreover, the seal failure mechanism was analysed manually, and the strength pattern of seals at different RH levels and temperatures was noted. Finally, seal integrity was also observed manually by putting the dye solution in the samples for 2 hours. Moreover, enough trials as mentioned in Table 4 were carried out to ensure reliable results. Seal strength, surface roughness, and friction test results were exported to Excel and then expressed or compared by making graphs, figures, or tables as shown in Chapter 3. Before finalizing the data, it was sorted, and irregular values were filtered out that probably emerged due to a personal error in the experimental procedure. Leakage results were expressed as a percentage failure based on visual observations. Qualitative observations, such as seal failure modes, were combined with quantitative outcomes to provide a comprehensive analysis of the data.

4 Results and Discussion

This section explains the output obtained from the experimental phase mentioned in Table 4. The section comprises four major parts: seal strength analysis, expressed as the mean peel force (N/25 mm); qualitative seal failure assessment; surface roughness evaluation; leakage testing; and frictional behavior. It will primarily demonstrate the effect of variable moisture levels, i.e., 50% RH (standard), 80% RH (intermediate), and 85% RH at 38°C (tropical), on the sealability and convertibility of disp and pe-coated papers.

4.1 Seal Strength Results Analysis

Seal strength was measured under the experimental procedures and circumstances mentioned in Chapter 3. Both quantitative and qualitative analyses were performed. Samples made at three sealing temperatures: 120 °C, 140 °C, and 160 °C were used for testing. Seal strength is defined in terms of mean peel force (N/25 mm), i.e., the average force required to separate the sealed layers along a 25 mm width. These values directly measure the seal's strength and provide an estimation of bonding strength.

4.1.1 Effect of Temperature and Humidity on Sealability- Dispersion Coated Paper

The effect on seal strength of disp-coated papers with changes in temperature at three humidity conditions is shown using a line graph. On the x-axis, sealing temperatures are mentioned while on Y-axis mean peel force at three different humidity levels is depicted.

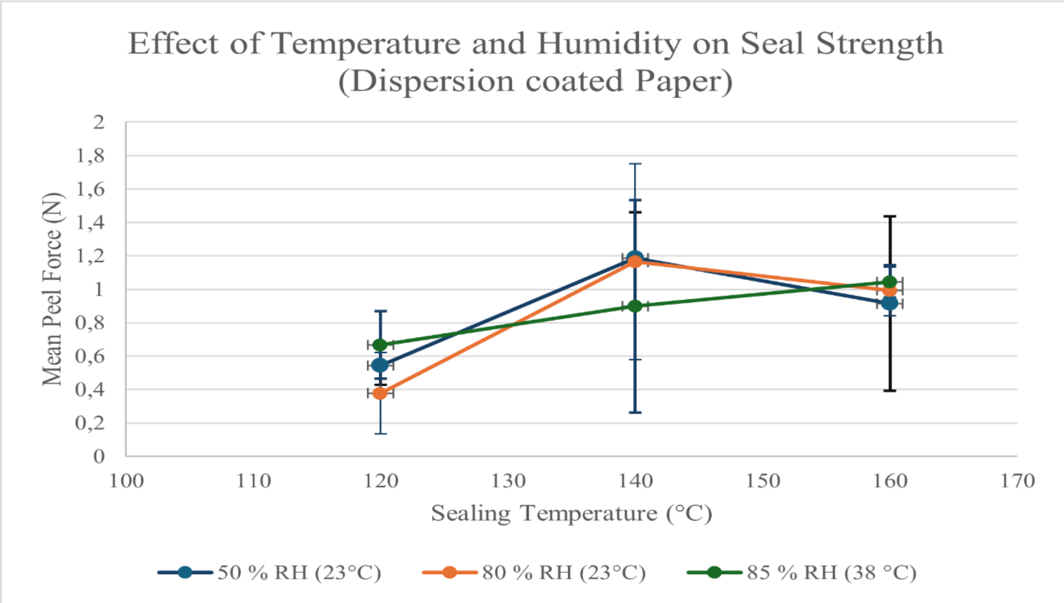

Figure 16. Effect of Temperature and Humidity on Seal Strength of Dispersion Coated Paper.

From Figure 16, it is evident that dispersion-coated paper has shown a nearly nonlinear relationship between the sealing temperature and mean peel force. It is sensitive to humidity and possesses a narrow sealing window. It can be clearly seen that with an increase in sealing temperature, seal strength increased from 120 °C to 140 °C and decreased thereafter for humidity levels of 50% & 80 % RH at 23°C. Contrastingly, at tropical conditions, 85 % RH at 38°C, the seal strength is increased slightly at 160 °C, but it is still lower than the maximum seal strength at 140 °C for the other two humidity conditions. At 120 °C, the mean peel force was low (≈ 0.54 N at 50 % RH) because the dispersion coating did not melt or fuse completely. At 140 °C, polymer coalescence was optimal and therefore resulted in a maximum peel force of 1.18 N at 50% RH. However, as stated earlier at 160 °C, seal strength decreased (≈ 0.91 N) due to localized overheating and partial thermal degradation of the coating. If we study the effect of a change in humidity conditions, it can be noted that with an increase in RH levels from 50 % RH to 80 % RH, the seal strength values show an inconsistent change. At 120 °C, the peel force decreases slightly from 0.54 N to 0.38 N at 140 °C, the values are almost the same (1.18 N and 1.16 N), whereas at 160 °C, the seal strength increases slightly to 0.99 N at 80% RH compared with 0.91 N at 50% RH. This indicates that humidity has a low and nonlinear effect. But again, in tropical conditions, humidity and temperature increase have given higher values of mean peel force because the elevated temperature has increased moisture evaporation despite a higher humidity level, except at 140°C, where it is lower, possibly due to high moisture. The small differences in seal strength values despite changes in humidity levels & temperature may be because paper reels were stored for only 24 hours, which may be an insufficient period and may have resulted in limited moisture diffusion across all layers in paper reels. The standard deviation bars show variation across the peel force values, indicating that disp-coated papers are sensitive to high humidity levels, resulting in inconsistent seal formations. Based on the mean peel force data, the sealing performance was found to be stable for disp-coated papers around 135–145 °C at 50% RH, where the seals are strong without any over-fusion or degradation. Therefore, this range represents as an indicative stable range, instead of an optimum sealing window.

4.1.2 Effect of Temperature and Humidity on Sealability – PE Coated Paper

The sealing behavior of PE-coated paper towards varying temperatures and humidity levels is illustrated in Figure 17.

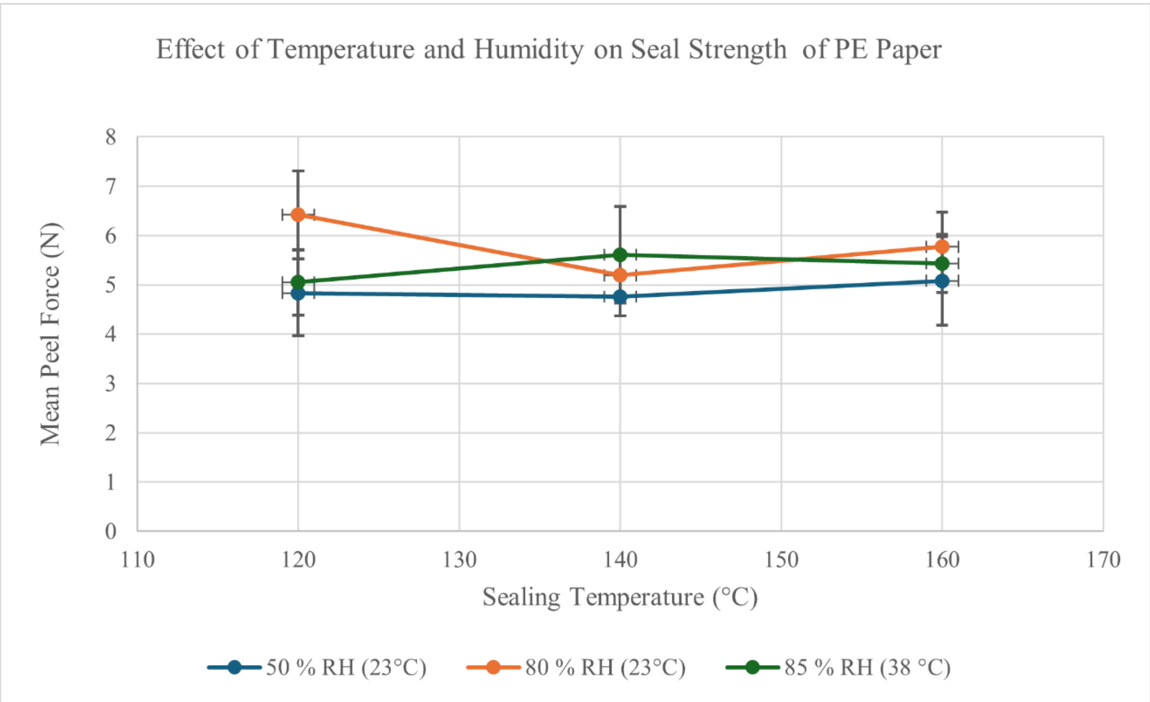

Figure 17. Effect of temperature and humidity on seal strength of PE-coated paper.

Figure 17 depicts that PE-coated paper has shown a stable and constant horizontal trend at all sealing temperatures. It means that PE-coated papers possess a wider sealing window. Compared to DC-coated paper, at 120 °C, its seal strength is already high (≈ 4.8 N), demonstrating good melting and polymer flow at lower temperatures. Minor irregularities are seen with an increase in temperature; the mean peel force decreased slightly at 140°C, however, it again increased at 160 °C and remained between the mean values of 4.7 N & 5.6 N. Looking at humidity effects, at 80 % RH, the higher humidity has led to surface softening and better polymer interdiffusion, resulting in the highest peel force of ≈ 6.4 N as compared to other RH levels. The general trend is that with an increase in humidity levels, its peel force values have remained high and constant. The overall variation in values is small, less than (±15 %). The Standard deviation values were also smaller and more consistent than those for dispersion-coated paper. The optimum sealing window for PE-coated papers is comparatively wider, ranging from 120–160 °C under 50–80 % RH, within which seal strength was optimal and cohesive failure dominates. This also indicates that PE-coated papers have excellent environmental stability and reliable sealability under varying conditions. There is comparatively less probability of experimental uncertainty as the conditioning period was 24 hours, and this effect seems to have a negligible impact on PE-coated papers due to their hydrophobic property and resistance to moisture.

4.1.3 Comparison Between Dispersion and PE Papers

For comparing the seal strength of disp and pe-coated papers across three humidity levels, an optimal temperature of 140°C has been chosen because both papers showed good sealability at this temperature, and it is included in their optimum sealing window. Figure 18 shows the effect of different humidity levels on seal strength for both types of paper. The comparison clearly shows that PE-coated paper has 4-5 times higher seal strength at all humidity levels. With an increase in humidity, dispersion-coated paper's mean peel force is slightly reduced, while PE-coated samples show constant and stable behavior. It means dispersion-coated paper is more sensitive to increasing humidity as compared to PE, which forms uniform chain entanglement.

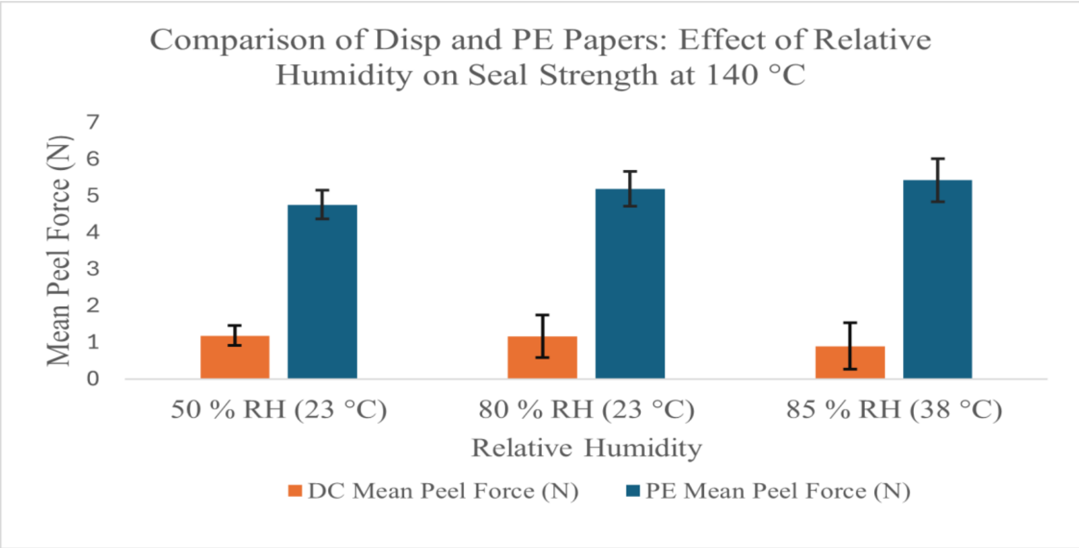

Figure 18. Seal strength of Dispersion and PE papers at different RH levels (140 °C).

Table 5 shows the maximum seal strength of PE and Disp-coated papers at different Rh levels and corresponding temperatures.

Table 5. Maximum seal strength of Dispersion and PE-coated papers at different RH levels

Relative Humidity / Temperature °C	Disp coated max mean Peel Force (N)	Temperature (°C)	PE-coated max mean Peel Force (N)	Temperature (°C)
50 % RH (23 °C)	1.185	140	4.76	140
80 % RH (23 °C)	1.164	140	6.42	120
85 % RH (38 °C)	1.043	160	5.43	140

It is obvious from the table that dispersion-coated paper has the highest seal strength value at 140°C/ 50 %RH, and it is decreased with an increase of temperature and RH value due to increased moisture and polymer degradation. On the other hand, PE-coated paper showed consistently higher seal strength values at all conditions and a peak at 140°C/ 50 %RH. In conclusion, PE showed consistent behavior for all temperatures and humidity levels as compared to dispersion-coated paper.

4.1.4 Qualitative Seal Failure Analysis (ASTM F88 Visual Classification)

The seal samples made at the temperature and humidity conditions mentioned in Chapter 3 were visually analyzed in accordance with ASTM F88 standard to determine the seal failure mechanism. The purpose was to understand how seal failure behavior changes with an increase in temperature and variable humidity conditions. The manual analysis also gives an idea about seal strength. The seal failure mechanism was classified into adhesive, cohesive, or fiber-tear as per ASTM F88 standard. Table 6 shows the summary of manual analysis of the seal at all temperatures & RH conditions.

Table 6. Summary of manual analysis of failure modes of

Dispersion and PE-coated papers.

Temperature (°C)	**RH condition**	**Disp Coated Failure Mechanism**	**PE Coated Failure Mechanism**	**Specific Observation**
100	50 % RH (23 °C)	Adhesive	Adhesive	Few Disp coated seals opened before peeling, while there was slight coating transfer in PE coated samples.
100	80 % RH (23 °C)	Adhesive	Mixed Adhesive & Cohesive	Some Disp coated seals opened themselves- Weaker seals, while little coating transfer in PE samples.
100	85 % RH (38°C)	Adhesive	Adhesive	Clean seal opening with no fiber tear in |Disp strips. There was a minor fiber tear in PE samples.
120	50 % RH (23 °C)	Adhesive	Mixed Adhesive & Cohesive	Occasional fiber tear in Disp coated papers, while thinning of one half of the sample due to coating and paper transfer in PE samples.
120	80 % RH (23 °C)	Adhesive	Cohesive & Fiber tear	Bonding improved in Disp Coated, but no fiber tear. While in PE, considerable paper pickup and transfer were seen, showing strong seal formation.

Temperature (°C)	RH condition	Disp Coated Failure Mechanism	PE Coated Failure Mechanism	Specific Observation
120	85 % RH (38°C)	Adhesive	Cohesive with fiber tear.	Ribs and depressions were visible on both halves in Disp-coated samples. But there was a significant paper tear in PE samples.
140	50 % RH (23 °C)	Adhesive with partial fiber tear	Cohesive with 60-70% fiber tear	Disp seals opened smoothly with little fiber tear. In PE PE-coated sample, one-half of the sealed area peeled off due to extensive bonding.
140	80 % RH (23 °C)	Mixed Adhesive -Cohesive mode	Cohesive & Fiber tear	Increased peel resistance and stick-slip behavior are seen in Disp-coated. Strong seals are formed in PE samples.
140	85 % RH (38°C)	Adhesive with traces of cohesive mode	Cohesive & Fiber tear	Slight coating transfer and ribs visible in Disp paper samples. There was significant fiber tear, and the ribs became obscured due to paper deposition in PE strips.
160	50 % RH (23 °C)	Adhesive	Cohesive	Slight coating transfer and about 40% fiber tear in Disp Coated samples. While a significant paper transfer occurs in PE-coated paper.
160	80 % RH (23 °C)	Adhesive	Fiber Tear	Clean peeling, visible ribs and valleys in Disp. While a significant paper deposit from one half to the other, stronger seals.
160	85 % RH (38°C)	Adhesive	Fiber Tear	Weak seals that opened occasionally were observed in disp-coated strips. Whereas there was almost 80-90% fiber tear and coating transfer in PE strips.

The observations from manual seal failure analysis show that seal strength depends only on both temperature and humidity. At 100 °C, both papers have weak seals and exhibit adhesive failure due to weak bonding and incomplete bonding. As the temperature increases from

120 °C to 140°C, both papers' seal strength increases. The dispersion-coated paper shows transition from adhesive failure to mixed adhesive cohesive failure with occasional fiber pick and seal area whitening, while the PE-coated samples showed cohesive or fiber tear failure, indicating strong seal formation. At 160°C., disp-coated samples showed irregular fiber tear and brittle failure, probably due to increased temperature. However, PE-coated samples respond to an increase in temperature with an increase in fiber tear and cohesive failure. Higher humidity levels resulted in weakening the seals in disp coated strips. However, PE-coated papers showed greater resistance to humidity and have a broader sealing window. Overall, PE-coated papers produced better & stronger seals at all RH levels and temperatures, while Disp-coated papers required strict control of conditions to get reasonable & reliable results. Figure 18 (a & b) shows the manually stretched strips of PE-coated paper at 160°Cat 50% & 80% RH levels. From the figure, it can be clearly seen that due to strong seal formation and bonding, there is noticeable fiber tear and paper pickup.

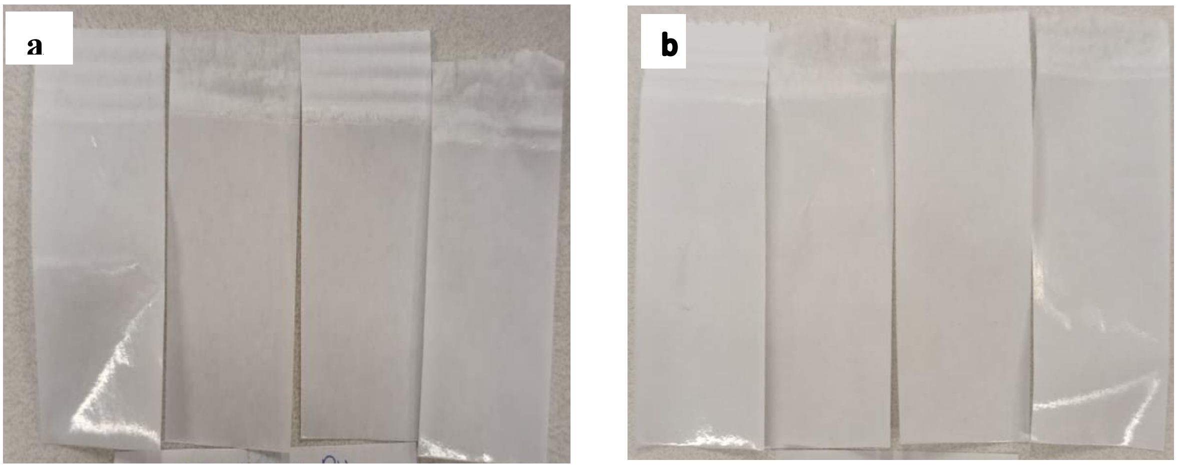

Figure 19. Manually stretched PE-coated paper strips at 160 °C: (a) 50 % RH; (b) 80 % RH.

4.2 Leakage Test Results and Seal Integrity Analysis

This section presents the findings from leakage tests in order to check seal integrity at different humidity levels. A summary of key findings is presented in Table 7. Criteria for assessing seal integrity were as Partial seal failure ≈, 30–40 % of samples, whereas Major seal failure,> 80 % of samples.

Table 7. Leakage observations for Dispersion and PE seals

RH & Temp	Disp 120 °C	Disp 140 °C	Disp 160 °C	PE 120 °C	PE 140 °C	PE 160 °C
50 % RH / 23 °C	Partial seal failure	Partial seal failure	Intact seal	Intact seal	Intact seal	Intact seal
80 % RH / 23 °C	Major Seal Failure	Intact seal	Intact seal	Intact seal	Intact seal	Intact seal
85 % RH / 38 °C	Partial seal failure	Intact seal	Intact seal	Intact seal	Intact seal	Intact seal

Table 7 shows that the disp-coated samples seal integrity was highly dependent on sealing temperatures. Partial to major seal failure was observed at all humidity levels, with the highest failure rate occurring at 80% RH & 120 °C, where most samples leaked. The seal failure in the dispersion-coated paper was due to weak adhesion and incomplete polymer fusion along the edges. From 140 °C to 160 °C, seal integrity was appropriate due to enhanced polymer fusion and cohesive strength at higher temperatures. These findings also certified the earlier results of reduced peel force under low temperature and high humidity conditions. Unlike disp-coated papers, PE-coated samples showed no leakage, resistance to all RH levels, and better heat sealing under all conditions.

4.3 Influence of Varying Relative Humidity on Runnability

Varying humidity levels can impact the performance of dispersion and PE-coated papers. Therefore, friction tests were conducted on uncoated sides to evaluate the impact of varying climatic conditions on the runnability of paper in VFFS machines. This section will explain the influences of varying climatic conditions, using mean friction coefficients, time–friction curves, and humidity-dependent trends. Static (μ_s) and dynamic (μ_k) coefficients of friction were analyzed to identify the changes in evolution from stick-slip motion to uniform sliding of the sled with RH levels.

4.3.1 Effect of Different Humidity Levels on Mean Friction Coefficients

Table 8 shows the mean static (μ_s) and dynamic (μ_k) coefficients of friction for DC and PE papers at 50 %, 80 % (23 °C), and 85 (38 °C) % RH, alongside standard deviation from mean values. It shows the change in the frictional behavior of uncoated sides with varying climatic conditions.

Table 8. Mean static (μ_s) and dynamic (μ_k) coefficients of friction for Dispersion and PE papers (uncoated sides).

RH% / °C	**Disp μ_s**	**SD (μ_s)**	**Disp μ_k**	**SD (μ_k)**	**PE μ_s**	**SD (μ_s)**	**PE μ_k**	**SD μ_k**
50/ 23°C	0.402	0.015	0.220	0.023	0.332	0.012	0.216	0,00256
80 / 23 °C	0.315	0.018	0.270	0.042	0.306	0.010	0.230	0,01537
85 / 38 °C	0.491	0.020	0.300	0.020	0.322	0.015	0.238	0,00904

From Table 8, it is evident that Disp-coated papers are sensitive to humidity changes, with μ_s rising from 0.402 at 50% RH to 0.491 at 85% RH, and μ_k increasing from 0.220 to 0.300 during the same conditions. This rise in friction coefficients for disp-coated papers is probably due to moisture absorption by the cellulose fiber alongside temperature rise that increased surface adhesion and contact area. Interestingly, μ_s decreased slightly at 80 % RH, possibly due to incomplete fiber softening despite an increase in Rh but same temperature. Higher SD is also noted at this humidity level, which shows non-uniform moisture distribution in paper. While for PE-coated papers, the rise in friction values is small and stable across all Rh levels. Although the tests were performed on uncoated side, the hydrophobic nature of the polyethylene coating has overall reduced the moisture absorption and provides smooth and uniform sliding surface. There is slight increase in μ_k from 0.216 at 50 % RH to 0.238 at 85 % RH mainly due to polymer softening at high temperatures which led to increase in surface area contact. There was a noticeable jerking motion of the slider just at the beginning of movement during testing disp coated paper. Disp coated paper is more sensitive to humid conditions, while PE coated papers exhibit stable behavior and low frictional effect even with increase in humidity levels.

4.3.2 Friction Curves

This section will focus on the stick–slip peak mechanism at the start of sliding (μ_s) and the shift to the steady μ_k plateau for dispersion and PE-coated papers at different humidity levels. The shape of COF-T curves in Figure 20 illustrates change in surface properties and humidity effects.

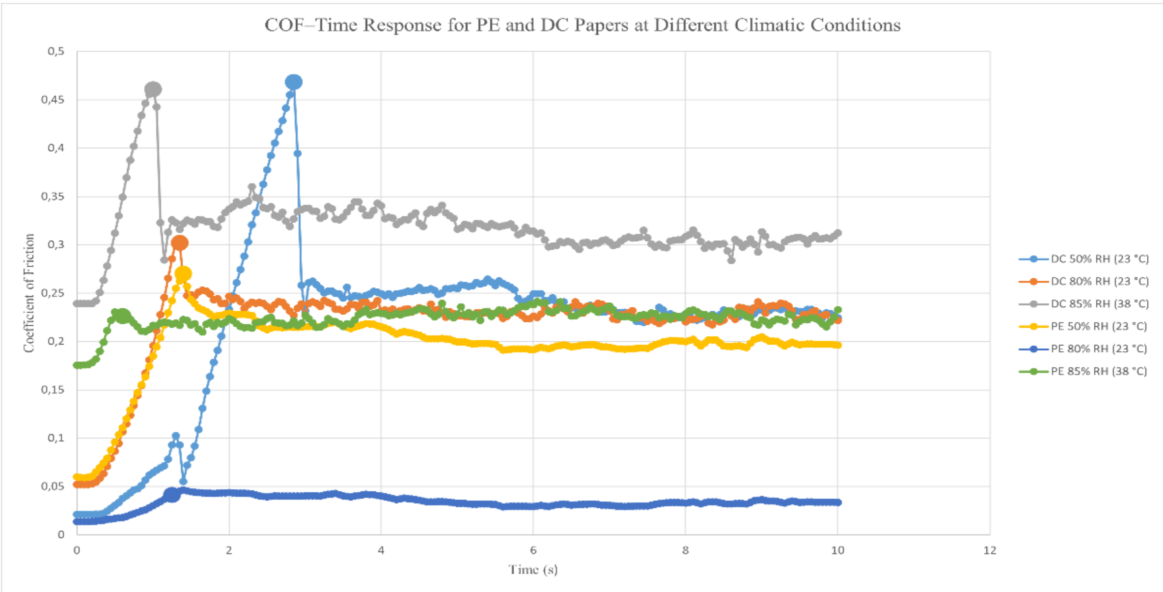

Figure 20. Friction curves for PE and Dispersion papers at different RH levels.

From the figure, it is quite clear that each RH level, μ_s, μ_k values for disp coated papers are significantly higher as compared to PE coated papers. The curve height increases constantly for Disp coated papers with increase in humidity at levels indicating enhanced motion resistance and surface adhesion. Contrarily, uncoated side of PE samples has shown lower values, reflecting PE stability and resistance to increased humidity levels. In all cases, $\mu_s > \mu_k$, confirming shift from static to dynamic state for sliding. The peak of static coefficient value for PE-coated paper comes in less time as compared with dispersion-coated paper, offering less initial resistance.

4.3.3 Effect of Humidity on Mean Friction Values

The bar graph shown below a clear comparison between mean μ_s and μ_k values for Disp and PE-coated papers at all humidity levels. The graph depicts higher sensitivity of dispersion-coated papers with an increase in moisture.

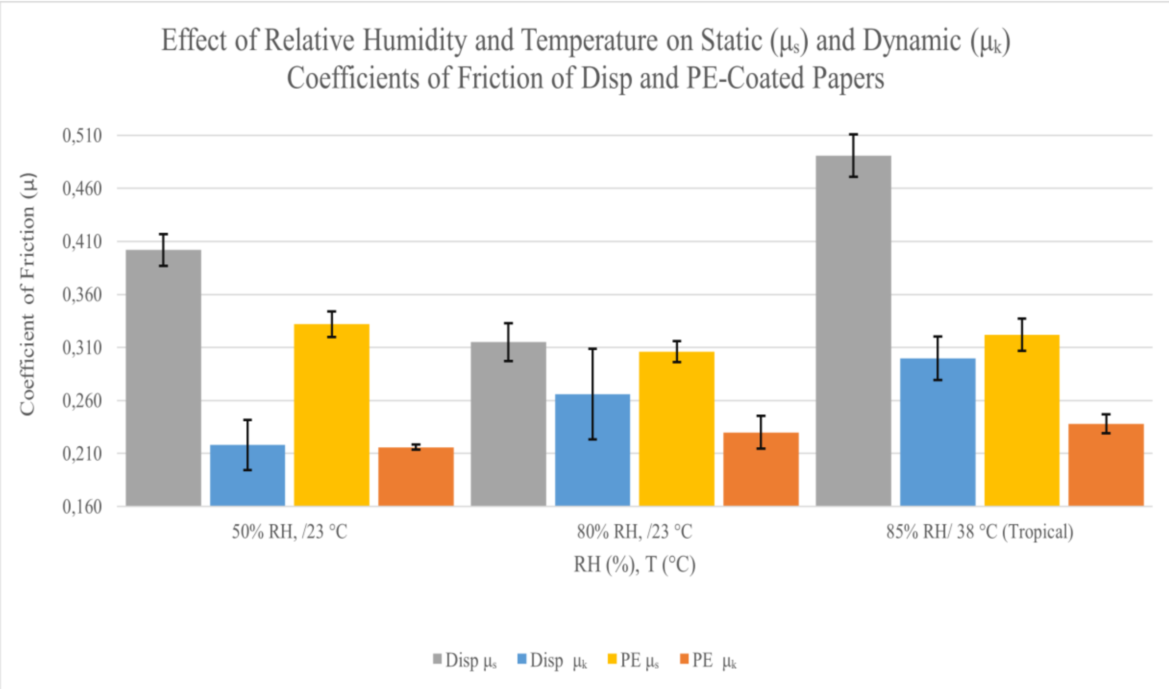

Figure 21. Effect of RH on static (μ_s) and dynamic (μ_k) friction

of Dispersion and PE papers.

From Figure 21, it can be seen that dispersion-coated paper showed an upward trend, both μ_s and μ_k rise with humidity, with μ_s peaking at 0.491 under tropical conditions (85% RH / 38 °C). On the other hand, PE showed stability across all RH levels and had lower values. The large error bars for Disp coated paper, particularly at 80 % RH, indicate a variable response to higher humidity. The trend depicts that static coefficient of Disp coated paper decreases slightly at 80% RH due to paper softening by an increase in moisture, but again surges at tropical conditions and enhances the surface adhesion. The kinetic coefficient of friction μ_k of dispersion-coated paper increases with humidity increase; however, PE-coated paper showed better resistance towards moisture and marginal changes. In conclusion, the disp coated paper showed sensitivity towards moisture changes, while the PE coated paper showed stable behaviour.

4.4 Influence of Humidity on Convertibility through Surface Roughness

Surface Roughness tests were performed to analyze the impact of varying humidity levels on the seal performance, runnability, and convertibility of coated papers (Uncoated side) for three different processing conditions mentioned in Chapter 3. This section describes the outcome of humidity using surface roughness parameters Ra (average roughness) and Rz (peak-to-valley height) for dispersion and PE-coated papers.

4.4.1 R_a Analysis

This section will outline the changes in the average roughness of disp and PE-coated papers in relation to changes in RH levels and processing conditions. The aim is to demonstrate how varying humidity levels and conversion processes impact the convertibility of materials. The line graph shown in Figure 22 illustrates the consequences of variation in humidity levels, i.e., (50 % RH / 23 °C, 80 % RH / 23 °C, and 85 % RH / 38 °C) for both converted and unconverted samples on average, roughness Ra.

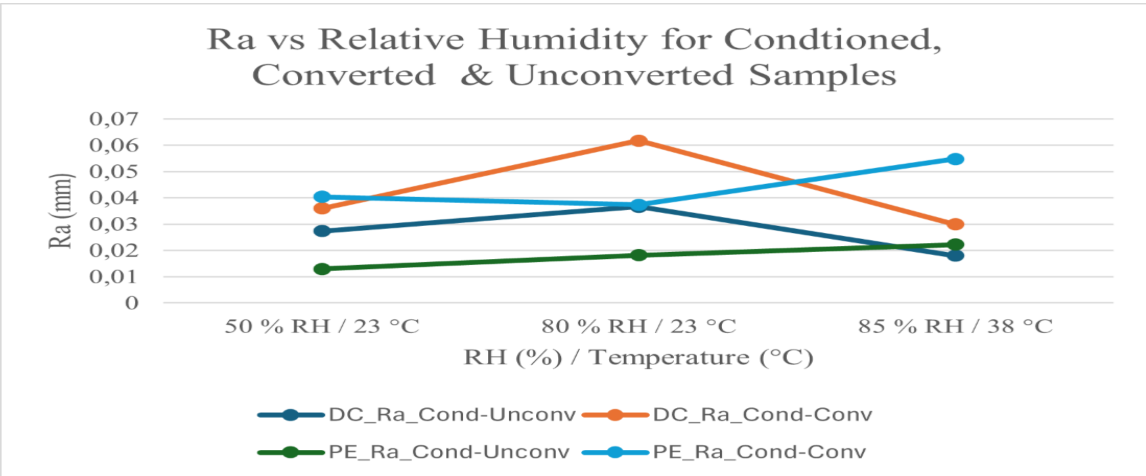

Figure 222. R_a vs RH for conditioned, converted, and unconverted Disp and PE samples.

The graph shows that a rapid rise in surface roughness of disp-coated papers at 80 % RH, as higher humidity resulted in surface swelling that ultimately led to an increase in surface roughness. This means that at higher humidity conditions, disp-coated papers can create convertibility issues like wrinkles. However, at tropical conditions, Ra value decreases marginally due to surface softening and smoothing. Comparatively, PE-coated paper is less influenced by humidity changes and exhibits a stable behavior. Another important trend is that converted samples of both types of papers have shown higher values of surface roughness due to mechanical roughening during the processing. The effect of processing conditions on the surface roughness is described in more detail in the bar graph shown in Figure 23.

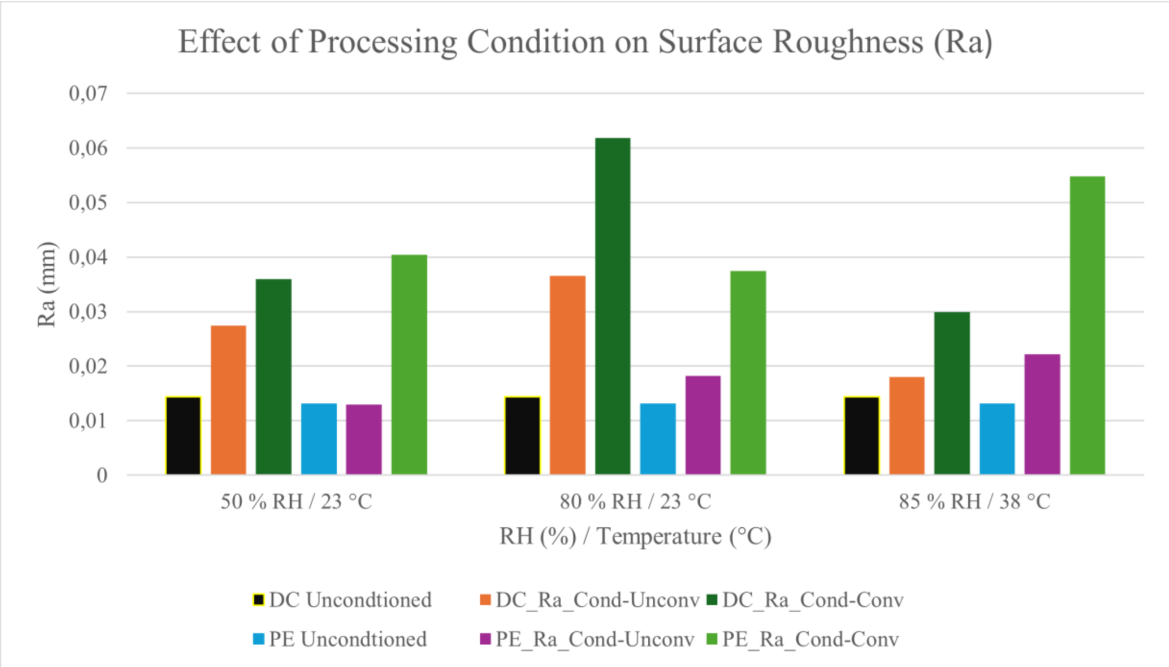

Figure 23. Effect of processing condition on surface roughness (Ra)

of Dispersion and PE-coated papers.

The conversion process has significantly increased the surface roughness values for both Disp and PE coated papers, but the effect is more prominent in Disp coated papers. From this, it can be inferred that Disp-coated papers' surface roughness increases markedly not only with an increase in humidity levels but also due to processing. Lower values of Ra for

PE-coated papers are possibly due to their hydrophobic surface. Thus, it highlights that inappropriate processing conditions can contribute to increasing the convertibility issues.

4.4.2 R_z Analysis

The influence of variable moisture and various processing conditions on Rz values, i.e., which measures the height value between the peak to valley, and provides detailed information about surface abnormalities, is presented in Table 9.

Table 9 . Mean Rz values (mm) for Dispersion and PE coated papers under different RH levels and processing conditions

Paper Type	**Condition**	**50 %RH / 23 °C**	**80 % / 23 °C**	**85 %RH / 38 °C**
Disp Coated	Unconditioned	0.072		
	Conditioned – Unconverted	0.116	0.134	0.0922
	Conditioned – Converted	0.161	0.257	0.236
PE Coated	Unconditioned	0.063		
	Conditioned – Unconverted	0.077	0.087	0.0872
	Conditioned – Converted	0.169	0.188	0.229

It is crystal clear that even before converting, the surface roughness values in terms of R_z increased consistently at each RH level for dispersion-coated papers. The highest value is recorded at 80 % RH at 23°C. After that, it decreases minutely, due to coating softening under tropical conditions. On the other side, the values of R_z for PE-coated papers remained stable under all conditions. Although PE-coated papers' value also increases marginally due to the conversion process but overall, it is more resistant to changing climatic conditions.

4.5 Relation to Convertibility and Sealing Performance

Surface roughness is a key factor in achieving efficient convertibility and seal performance as it directly impacts the friction behavior, jaw contact, and heat transfer during sealing. All these parameters are crucial for consistent and reliable packaging performance. For instance, higher values of R_a and R_z for dispersion-coated papers at 80% RH led to greater surface unevenness and friction during the converting process, and therefore less reliability. Whereas the lower and stable value of PE-coated papers increases their consistency due to better runnability and sealing behavior. A smooth surface reduces and supports high-speed speed efficient packaging.

5 Conclusions

The thesis studied the influence of moisture content on the sealability and convertibility of dispersion & PE coated papers in VFFS machines. The study was conducted at three different climatic conditions: - 50 % RH at 23 °C (standard), 80 % RH at 23 °C (high humidity), and 85 % RH at 38 °C (tropical). The goal was to detect changes in material functional response and define optimal settings for getting dependable sealing and efficient converting performance in sustainable packaging industry.

The experimentation revealed that dispersion-coated papers possess a smaller sealing window, with highest seal strength at 140 °C under 50% RH. With an increase in humidity levels, their seal strength increased with temperature up to 140 °C across all humidity levels, and then slightly reduced or became stable, depicting irregular or inconsistent behavior towards moisture. On the other hand, PE-coated papers demonstrated stable and high values of seal strength across all humidity levels, signifying a wider sealing window and significant resistance to changing humidity levels.

In respect of convertibility, static & dynamic coefficients of friction of dispersion-coated papers showed inconsistent behavior with a rise in humidity levels, while they remained nearly stable for PE-coated papers. Surface roughness results have disclosed that Disp-coated paper holds high values of R_a and R_z at elevated humidity levels due to surface softening. These results indicate that dispersion-coated papers can possibly pose runnability and convertibility defects at higher humidity levels as compared with PE papers.

These outcomes help packaging manufacturers to enhance line efficiency and reduce the production losses caused by weak seals or poor web handling. The results indicate that dispersion-coated papers give smooth feeding and good sealability around 50% RH and sealing temperatures of 135–145 °C. On the contrary, PE-coated papers are suitable for variable humidity levels.

The study supports sustainability and helps in shift towards fiber-based packaging solutions, as these materials are renewable, environmentally friendly, and can be recycled several times. Despite its useful findings, the study has some limitations, as it includes only two types of coating material and possibly somehow conditioning time role. Future work can focus on bio-based or hybrid coatings and can emphasize using inline humidity control options and testing materials at full-scale packaging lines.

In conclusion, the study has clearly demonstrated that humidity variation can impact sealability and convertibility of dispersion-coated papers, while PE-coated papers were stable at various humidity conditions. Dispersion-coated papers require relatively strict control of climatic conditions for achieving efficient performance, while PE-coated papers are stable across wide humidity levels.

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