The Effect of Coating Temperature on the Mechanical and Adhesive Properties of Polypropylene-Coated Kraft and Duplex Papers

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ABSTRACT

This study explores the impact of coating temperature on the mechanical and adhesive properties of Polypropylene (PP)-coated Kraft and Duplex papers, with a focus on sustainable packaging applications. PP coatings were applied at three different temperatures, 150°C, 200°C, and 230°C, using a hot press method. The mechanical properties, including tensile strength and peel strength, as well as the surface morphology of the coated papers, were evaluated. The results revealed that both the tensile and peel strength significantly improved as the coating temperature increased, with the best performance observed at 230°C. For the Kraft paper, the tensile strength increased from 2,548.1 kPa at 150°C to 2,748.8 kPa at 230°C, while the peel strength increased from 122.6 N to 151.5 N. The duplex paper showed a similar trend, with the tensile strength rising from 1,570.0 kPa at 150°C to 1,836.8 kPa at 230°C and the peel strength increasing from 107.9 N to 132.1 N. The Scanning Electron Microscopy (SEM) analysis revealed that higher temperatures resulted in more uniform PP coatings, leading to improved adhesion. These findings suggest that the reduced polymer viscosity at higher temperatures enhances the polymer penetration, improving the bonding to paper fibers. This study highlights the potential of temperature optimization to enhance the performance of PP-coated papers, contributing to the development of sustainable packaging materials.

Keywords-PP coating; coating temperature; tensile strength; adhesive strength: sustainable packaging

I. INTRODUCTION

In 2022, the Asia-Pacific region emerged as the dominant contributor to the global plastic production, accounting for over 50% of the total output [1]. China produced approximately 32% of the world's plastics, followed by Japan (3%) and other Asian countries collectively contributing around 17% [2]. Despite this high production, only about 9.5% of the global plastics were derived from recycled materials, underscoring a continued dependence on the virgin fossil-based feedstocks and highlighting the challenges of transitioning to a circular economy.

Southeast Asia, in particular, has been identified as a significant contributor to both the plastic production and waste generation [3]. Countries, such as Indonesia, Thailand, Vietnam, Philippines, and Malaysia, generate large volumes of domestic plastic waste [4]. For instance, Indonesia produces approximately 10.2 million tons of plastic waste annually, positioning it among the top contributors to regional plastic pollution. Additionally, nations like the Philippines, Vietnam, and Malaysia are sources of marine plastic debris. While efforts to promote recycling and reduce the plastic pollution have been made, structural and policy-related obstacles continue to hinder the progress in the region.

Globally, the packaging industry consumes nearly 40% of the total plastic production, with polymers, such as Polyethylene (PE), PP, Polystyrene (PS), and Polyethylene terephthalate (PET) being commonly utilized [5]. Among these, PP is particularly prominent, accounting for 16% of the global demand due to its favorable mechanical, chemical, and processing properties, making it widely adopted in packaging applications [6].

However, the extensive use of plastic packaging presents severe environmental concerns due to its non-biodegradability and persistence in ecosystems [7]. This has increased the interest in developing sustainable and biodegradable alternatives, particularly for packaging applications [8]. Packaging not only protects the products and prolongs the shelf life, but also plays a critical role in the consumer communication and branding. As such, the search for alternative materials has centered on paper due to its biodegradability, renewability, and recyclability [9].

Despite these advantages, paper suffers from inherent limitations in the mechanical performance, especially under wet conditions, and its poor resistance to water, oil, and chemicals reduces its viability in packaging requiring barrier properties [10, 11]. To address these shortcomings, various surface modification strategies have been explored. Coating paper with polymers has emerged as a promising technique to enhance its mechanical integrity and resistance to the environmental factors [12].

Among polymer coating materials, PP stands out due to its excellent strength, durability, chemical resistance, affordability, and potential for biodegradability under specific formulations [13]. Various coating techniques, such as extrusion, dip coating, and hot pressing are employed to apply PP onto paper substrates [12]. The hot press method—combining heat and pressure—enables a uniform polymer adhesion and penetration, improving both the coating homogeneity and bonding strength [14].

The coating temperature is a critical parameter in the polymer coating process, as it significantly influences the viscosity and flow behavior of the polymer, its ability to wet and bond with the paper surface, and the overall performance of the composite material [15, 16]. As the temperature increases, the viscosity of PP decreases, allowing for a better penetration into the paper substrate and more uniform coating. This reduction in viscosity at higher temperatures promotes stronger interfacial adhesion between the polymer and paper fibers, which enhances the mechanical strength and moisture resistance. Previous studies have highlighted the critical influence of temperature on the adhesive properties of polymers. For example, authors in [17] investigated how the temperature enhances the mechanical properties of polymer-coated materials, noting the beneficial effects of viscosity reduction at elevated temperatures. Similarly, authors in [18] discussed optimizing the temperature and polymer properties to improve the adhesion strength between coatings and substrates. Other studies have also explored the molecular interactions during the hot press process, which influence the performance of the coating [19].

Based on these considerations, the current study investigates the effect of the coating temperature on the mechanical and adhesive performance of PP-coated Kraft and Duplex papers. Specifically, it evaluates the changes in the tensile strength, elongation at break, and peel strength at three coating temperatures—150°C, 200°C, and 230°C. Additionally, surface morphology analysis using SEM is conducted to assess the coating uniformity and polymer interaction with the paper fibers.

II. MATERIALS AND METHOD

A. Materials

This study utilized two types of paper substrates—Kraft paper and Duplex paper—each with a basis weight of 350 Grams per Square Meter (GSM). The Kraft paper had a thickness ranging from 0.4 mm to 0.45 mm, while the Duplex paper had a thickness ranging from 0.5 mm to 0.55 mm. The paper samples were cut into standardized dimensions of 10 cm × 10 cm to ensure uniformity across all tests. The coating material used was PP, with a nominal thickness of 100 microns. All materials, including the paper substrates and the PP sheets, were procured from local manufacturers in Indonesia to ensure availability and consistency.

The surface roughness of the Kraft and Duplex paper substrates was measured using a Mitutoyo SJ-201 Surface Roughness Tester from Japan before the hot press process to assess its impact on the PP coating adhesion. The test was performed after calibrating the instrument with a standard block, using a cut-off length of 0.8 mm and a measuring length of 5 mm. Multiple measurements were taken from different areas of each paper to ensure the accuracy, and the roughness parameter *Ra* (average roughness) was used for analysis.

B. Hot Press Process

The PP coating was applied using a hot press method under controlled thermal conditions, as shown in Figure 1. Three distinct coating temperatures—150°C, 200°C, and 230°C—were selected to evaluate their influence on the bonding performance and mechanical properties of the coated papers. For each sample, a PP sheet was placed directly over the paper substrate, and the assembly was positioned between the heated platens of a hot press machine. A uniform pressure of 1.0 MPa was applied during the process to ensure the consistent adhesion across the paper surface. The pressing duration was maintained at a fixed 5 min for all temperature conditions. Following the hot pressing, the samples were allowed to cool at ambient room temperature to facilitate the solidification of the PP layer and complete the coating process.

C. Tensile Testing

Mechanical characterization was conducted using a universal testing machine (MRC brand, China) with a maximum load capacity of 2000 kg. Tensile strength testing was performed under both dry and wet conditions to assess the influence of moisture on the mechanical properties of the coated papers.

Fig. 1. Hot press machine.

In the dry condition, the specimens were mounted directly onto the machine, and the tensile force at failure was recorded. For the wet condition, the specimens were submerged in 50 mL water for 5 min before testing, simulating the moisture exposure, and a similar testing procedure was then repeated. The tensile stress values were calculated based on the breaking force data obtained from the machine, providing insights into the tensile performance of Kraft and Duplex papers at different coating temperatures.

D. Peel Testing

The peel strength test was conducted to determine the adhesive bond strength between the PP coating and the paper substrates. A controlled peeling force was applied using a specialized apparatus, and the force required to delaminate the coating was recorded. This test provided quantitative data on the coating's adhesion quality under varying thermal treatment conditions.

E. Surface Morphology Analysis

SEM analysis was carried out to evaluate the surface morphology and coating uniformity before and after the application of PP. Small sections of both Kraft and Duplex paper samples were examined using Hitachi FlexSEM1000 at magnifications of 50× and 500×. This analysis aimed to observe the interaction between the PP coating and the paper surface, assess the polymer penetration, and detect the structural changes resulting from different coating temperatures.

III. RESULTS AND DISCUSSION

A. Influence of Coating Temperature on Tensile Strength

The tensile strength of both paper types increased significantly with higher coating temperatures, as illustrated in Figures 2 and 3. This trend suggests that elevated temperatures enhance the penetration and adhesion of PP to paper fibers, improving the mechanical performance of the laminated paper structures.

The tensile strength of both paper types increased significantly with higher coating temperatures, indicating that the elevated temperatures enhance the penetration and adhesion of PP to paper fibers. In dry conditions, the tensile strength of Kraft paper increased from 2,548.1 kPa at 150°C to 2,748.8 kPa at 230°C, while Duplex paper exhibited similar but lower values, increasing from 1,570.0 kPa at 150°C to 1,836.8 kPa at 230°C. This improvement in tensile strength is a direct result of the better adhesion between the PP and the paper, facilitated by the higher temperature, which reduces the viscosity of the polymer, allowing it to spread more evenly and bond more effectively with the paper fibers.

Under dry conditions, Kraft paper exhibited a progressive increase in tensile strength from approximately 21.6 kPa at 150 °C to 32.1 kPa at 230 °C, as portrayed in Figure 2. Duplex paper followed a similar upward trend, increasing from 30.5 kPa to 39.2 kPa over the same temperature range. The more substantial strength values observed in Duplex paper are attributed to its smoother surface, which supports better film formation on the surface, despite the lower penetration compared to Kraft paper. The improved adhesion is facilitated by higher temperatures, which lower the viscosity of PP, enabling more uniform distribution and stronger bonding to the cellulose fibers [20].

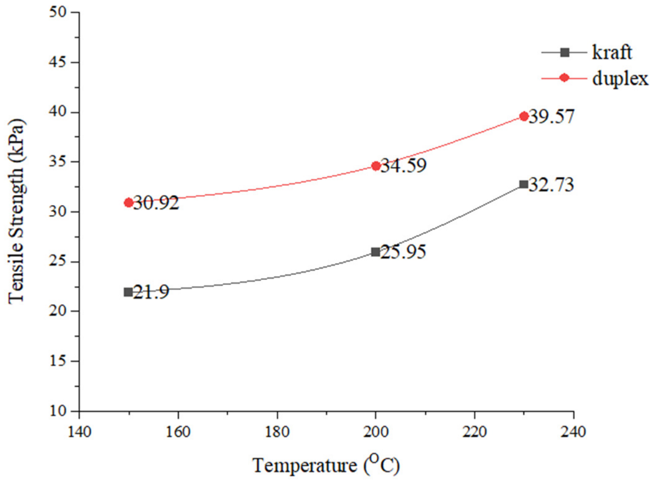

Fig. 2. Dry tensile strength of Kraft and Duplex papers at various coating temperatures.

Under wet conditions, both papers experienced reduced tensile strength due to the moisture-induced weakening of the paper fibers, as depicted in Figure 3. Nonetheless, the strength still increased with temperature. Kraft paper's wet tensile strength rose from 1,047.4 kPa at 150 °C to 1,256.2 kPa at 230 °C, while Duplex paper improved from 1,103.2 kPa to 1,402.4 kPa. These results confirm that the PP coating provides partial water resistance, particularly at higher temperatures, which helps maintain the structural integrity even in moist environments [12, 15].

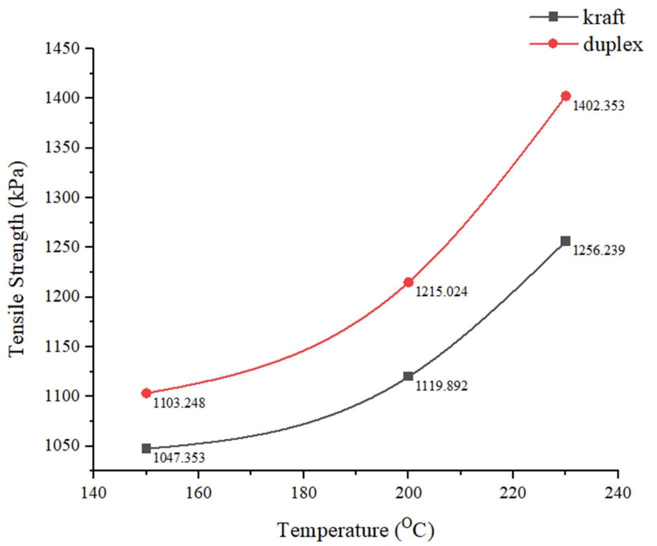

Fig. 3. Wet tensile strength of Kraft and Duplex papers at various coating temperatures.

The consistent enhancement in tensile strength under both dry and wet conditions underscores the critical role of coating temperature in the hot press lamination process. At elevated temperatures, the PP infiltrates the fibrous structure more effectively and bonds more robustly with the cellulose fibers [21]. Moreover, the uniformity of the coating layer is enhanced, resulting in better mechanical performance.

Although Kraft paper demonstrated a greater relative improvement, Duplex paper exhibited higher absolute tensile strength in both conditions. This distinction can be attributed to the different fiber structures; Kraft paper has longer fibers with a surface roughness of 9 µm, which facilitates a deeper polymer penetration [22]. This roughness allows for better mechanical interlocking between the polymer and the paper fibers. On the other hand, Duplex paper, with its denser and smoother surface roughness of 7 µm, restricts the polymer penetration but favors the surface film integrity [12].

B. Peel Test

Figures 4 and 5 present the peel test results used to quantitatively assess the adhesive strength of the PP coatings applied on the Kraft and Duplex paper substrates at three distinct coatings. The peel strength, defined as the force required to remove the coating from the paper surface, reflects the efficacy of the bonding interaction between the PP polymer and the fibrous paper matrix. The data clearly demonstrate that increasing the coating temperature significantly enhances the adhesive performance of the PP layer, resulting in stronger bonding at higher processing temperatures.

For Kraft paper, a notable increase in peel strength was observed as the coating temperature rose. At the lowest temperature of 150°C, the peel strength measured 122.625 N. Upon increasing the temperature to 200°C, the peel strength improved to 135.7 N, and further increased to 151.5 N at 230°C. This progressive enhancement in adhesive strength can be attributed to several factors. Higher coating temperatures likely increase the mobility and flowability of the molten PP, allowing it to better infiltrate the porous microstructure of the Kraft paper. This deeper penetration facilitates greater mechanical interlocking between the polymer and the paper fibers. Additionally, elevated temperatures may promote enhanced molecular-level interactions, such as van der Waals forces or potential chemical bonding, between the PP chains and the cellulose fibers. The combination of improved physical interlocking and molecular adhesion at higher temperatures results in a more robust adhesive interface. These results underscore the effectiveness of the hot press method in strengthening the adhesion of PP coatings on Kraft paper when applied at elevated temperatures.

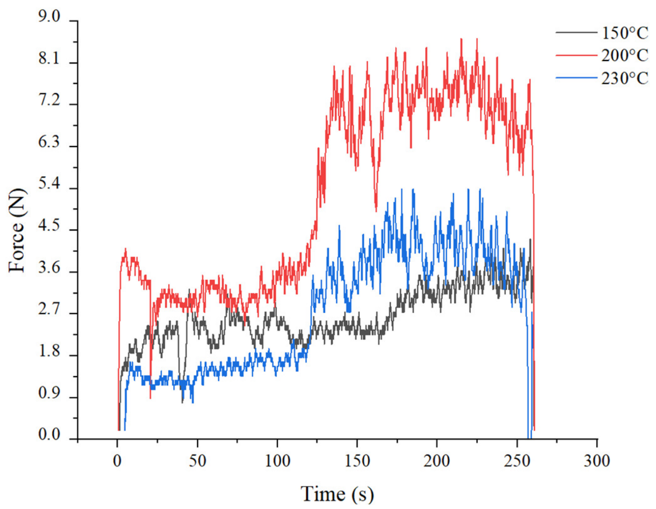

Fig. 4. Peel strength of Kraft paper at various coating temperatures.

Similarly, for Duplex paper, the peel strength also exhibited an increasing trend with temperature, although the absolute values were consistently lower than those observed for Kraft paper. At 150°C, the peel strength of the PP coating on Duplex paper was 107.91 N, rising to 122.44 N at 200°C, and reaching 132.14 N at 230°C. The observed increase suggests that higher temperatures similarly enhance the adhesive bonding on Duplex paper; however, the relatively lower peel strength compared to Kraft paper can be explained by the distinct surface characteristics of Duplex paper. Unlike Kraft paper, Duplex paper has a denser and smoother surface with fewer pores and less fibrous roughness, which limits the extent to which the molten PP can mechanically interlock with the paper fibers. This surface reduces the polymer penetration depth, thereby restricting the mechanical adhesion. Furthermore, the reduced surface roughness likely diminishes the available surface area for molecular interactions. Consequently, while higher temperatures still improve the adhesion by increasing the polymer mobility and surface contact, the overall bonding strength is inherently limited by the substrate's physical properties.

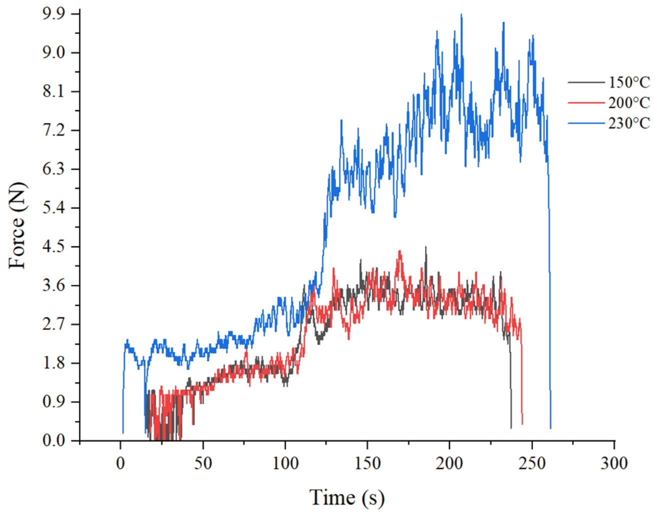

Fig. 5. Peel strength of Duplex paper at various coating temperatures.

C. *Surface Morphology*

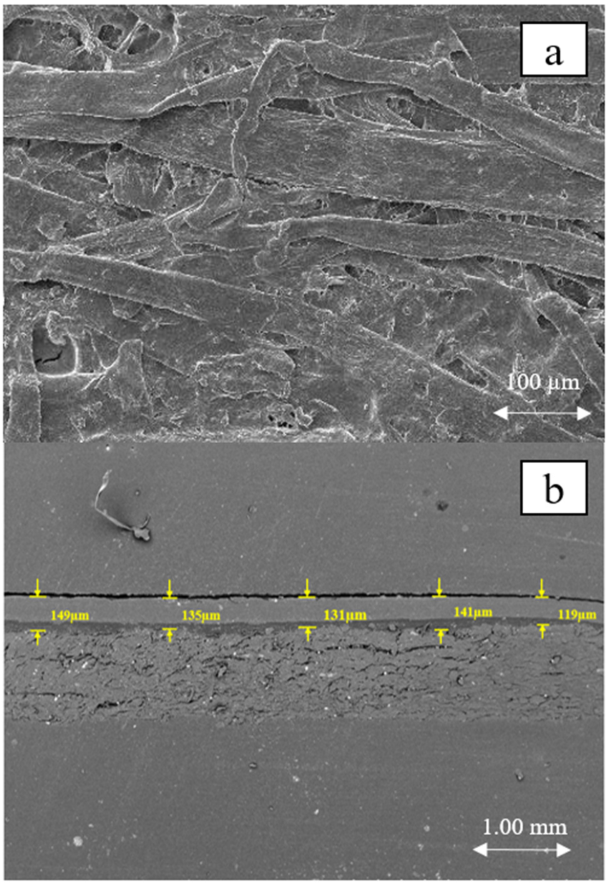

Fig. 6. SEM of Kraft paper: (a) surface at 500× magnification, (b) cross section at 50× magnification.

The SEM analysis provided critical insights into the surface morphology of the coated papers and the influence of the coating process on the uniformity and effectiveness of the PP layer. The SEM images evidenced in Figure 6 for Kraft paper and Figure 7 for Duplex paper illustrate the results after coating.

Prior to coating, Kraft paper exhibited a rough and porous surface with visible gaps between the fibers, a characteristic that facilitates the penetration and bonding of PP, as seen in Figure 6(a). After coating, the PP layer appeared uneven, with areas of greater thickness alongside spots with insufficient coverage. However, the coating resulted in a more uniform layer. The PP adhered more effectively to the paper, filling the inter-fiber gaps and producing a smoother, more consistent surface, as presented in Figure 6(b). These observations suggest that surface characteristics, such as porosity and roughness, enhance the permeability of PP into the paper substrate, yielding a more homogeneous coating that improves both the mechanical strength and adhesive properties of Kraft paper [23].

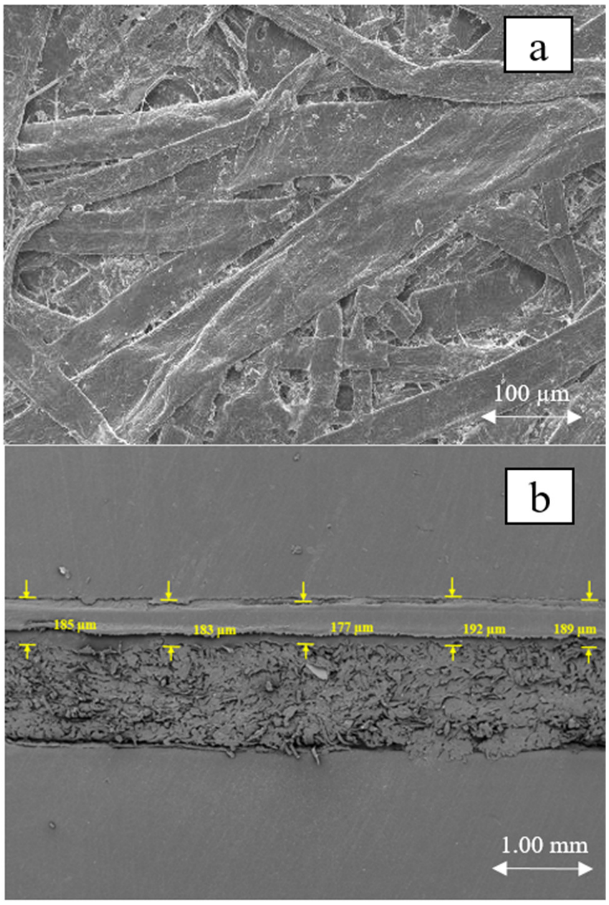

Fig. 7. SEM of Duplex paper: (a) surface at 500× magnification, (b) cross section at 50× magnification.

In contrast, the surface of Duplex paper prior to coating was smoother and less porous, featuring a more compact fiber arrangement. This compactness initially rendered Duplex paper less conducive to the coating adhesion compared to Kraft paper. After coating at 230°C, the PP layer was visible but uneven, resembling the pattern seen on Kraft paper at the same temperature. However, the coating became increasingly consistent, with reduced variation in thickness. The higher temperatures enabled better adhesion of PP to the smoother, denser surface of Duplex paper, facilitating the formation of a stronger bond and resulting in a more uniform and effective coating layer, as depicted in Figures 7(a) and 7(b) [24].

The SEM findings for both Kraft and Duplex papers align with the mechanical testing results, particularly the observed improvements in the peel strength and tensile strength at elevated temperatures. These results highlight the significant role of the temperature in optimizing the PP distribution and adhesion. Increasing the temperature reduces the flow resistance of the PP melt, allowing it to spread more evenly across the paper surface and penetrate deeper into the fiber matrix. This enhanced penetration and uniform coating establish a stronger interface between the paper and the coating, which is essential for improving the overall mechanical performance of the coated paper.

D. Discussion

The results of this study indicate that increasing the coating temperature significantly enhances both the tensile strength and peel strength of PP-coated Kraft and Duplex papers. Specifically, the data show that the mechanical properties improve with higher coating temperatures, with the most substantial improvements observed at 230°C. These findings are consistent with previous studies that have reported similar trends in polymer-coated materials [17]. This enhancement can be primarily attributed to the reduction in polymer viscosity at elevated temperatures, which allows for better penetration into the paper fibers, thereby improving the overall bonding between the polymer and the substrate.

In particular, the reduction in PP viscosity at higher temperatures enables a more uniform flow and improved penetration into the paper fibers. As the temperature increases, PP's viscosity decreases, allowing the molten polymer to flow more easily and fill the gaps between the paper fibers more effectively. This uniform distribution enhances the adhesion between the polymer and the cellulose fibers, leading to improved mechanical properties, such as tensile strength and peel strength. The SEM analysis further supports these findings, showing that higher temperatures result in more uniform PP coatings, with better adhesion to both Kraft and Duplex papers. The uniformity in coating observed in the SEM images at 230°C suggests that the higher temperature allows for a better coverage of the paper surface, improving both the interfacial bonding and the overall mechanical strength of the coated paper.

Moreover, the surface roughness of the paper substrates plays an important role in determining the coating's adhesive performance. The SEM analysis revealed that Kraft paper, with its rougher surface, allowed for better polymer penetration, leading to stronger interfacial bonding and superior mechanical properties. In contrast, Duplex paper, with a smoother surface, exhibited less penetration, resulting in weaker adhesion. However, even on Duplex paper, higher temperatures still resulted in more uniform coatings, which improved its peel strength and overall coating performance. This observation highlights the importance of surface texture in influencing the polymer's ability to bond with the paper fibers. The rougher the surface is, the deeper the polymer can penetrate, forming a stronger bond [18].

The inclusion of surface roughness measurements significantly strengthens the understanding of how the temperature influences the coating performance. Kraft paper, having a higher surface roughness compared to Duplex paper, exhibited better adhesion and mechanical properties, which can be attributed to the increased polymer penetration. For future studies, it would be beneficial to quantify the exact surface roughness values of both substrates to provide a more detailed correlation between the surface texture and adhesion. The surface roughness of paper substrates plays a crucial role in how well a polymer can adhere, as it directly impacts the mechanical interlocking between the paper fibers and the coating material.

While the temperature clearly plays a significant role in improving the mechanical properties, it is essential to consider other factors, such as the optimal hot press pressure, that could further enhance the adhesion and uniformity of the PP coatings. Future research should also focus on the biodegradability of PP-coated papers, as well as the exploration of alternative biodegradable polymers that could provide similar mechanical properties but with a reduced environmental impact [19]. The environmental sustainability of PP-coated papers could be further evaluated by investigating the long-term durability, biodegradability, and energy consumption associated with their production [25].

Additionally, future studies should consider the effects of different polymer types and coating methods on the mechanical and adhesive properties of paper-based coatings. This would contribute to the development of more sustainable and eco-friendly packaging solutions. For example, biodegradable polymers could be investigated as potential alternatives to PP, offering the same mechanical properties with a lesser environmental impact. The potential for using such coatings in the packaging industry would significantly benefit from further research into both the biodegradability of the materials and the energy efficiency of their production processes [26, 27].

The observed improvements in both the tensile strength and peel strength at higher coating temperatures corroborate with previous literature, where it was shown that the elevated temperatures enhance the polymer's ability to penetrate and adhere to paper substrates. Studies have similarly reported that an increase in temperature results in improved mechanical performance, primarily due to the enhanced flow and lower viscosity of the polymer at higher temperatures [17]. These observations underscore the importance of optimizing the coating temperature as a means of improving the overall performance of PP-coated papers in various packaging applications.

Finally, the environmental implications of these findings are significant. Given the growing concerns over plastic waste and the search for sustainable packaging materials, this research offers valuable insights into how PP-coated papers could be optimized for packaging applications, particularly in terms of the mechanical performance and adhesive strength. As the demand for eco-friendly packaging materials continues to rise, further exploration of biodegradable coatings and energy-efficient production methods will be critical in advancing the sustainability of paper-based packaging solutions [28].

IV. CONCLUSIONS

Based on the experimental results, it can be concluded that the coating temperature significantly influences the mechanical and adhesive properties of Polypropylene (PP)-coated Kraft and Duplex papers. Higher temperatures, particularly 230°C, enhance the tensile strength and peel strength in both dry and wet conditions, improving the polymer penetration and interfacial bonding between the PP and paper fibers. This improvement emerges from the reduced viscosity of PP at elevated temperatures, which enables a better adhesion and more cohesive paper structure. The Scanning Electron Microscopy (SEM) analysis further supported these findings, revealing a more uniform and smoother coating at higher temperatures, with deeper polymer penetration into the paper fibers.

While this study focused on the optimization of the coating temperature, future research should explore other factors, such as the optimization of hot press pressure and the use of alternative biodegradable polymers. Additionally, evaluating the long-term durability, biodegradability, and energy consumption of PP-coated papers will be crucial for assessing their sustainability and real-world applicability. Further studies on the thermal stability of PP using techniques, like Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) may also help to better understand the stability of the material under high-temperature conditions. Finally, these investigations will improve both the mechanical performance and environmental sustainability of PP-coated papers, advancing their potential applications in eco-friendly packaging solutions.

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