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CRITICAL EVALUATION OF THE MECHANICAL AND CHEMICAL PERFORMANCE OF THE MULTI-LAYER (BOPP+ METALLIZED CPP) FLEXIBLE PACKAGING LAMINATES

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Abstract
This study provides the mechanical and chemical performance of multi-layer flexible packaging laminates composed of Biaxially Oriented Polypropylene (BOPP) and Metallized Cast Polypropylene (Met CPP). The research focuses on how varying conditioning temperature (10°C,25°C and 45°C) impacts substrate properties, including Seal strength, Bond strength, Coefficient of friction (COF), Water Vapor Transmission Rate (WVTR) and Oxygen Transmission Rate (OTR).

Doing the experiments indicates that ambient conditioning (25° C) provides the most consistent mechanical performance, provides the highest seal and bond strength; however, in the chemical barrier, performance is highest at a lower temperature (10°C) because of the reduced molecular mobility, which minimizes gas and moisture permeation. On the other hand, at the higher temperature (45°C) it is found that it increases permeability and reduces surface resistance with an increase in slip, meaning a lower Coefficient of Friction (COF), reducing shelf-life protection of the flexible food packaging.

Keywords: Flexible Packaging, BOPP/Met CPP, WVTR, OTR, Coefficient of Friction (COF)

Introduction

In the 1980s, the use of packaging began to grow dramatically, but chemical knowledge was still low because of the lack of sources and technological progress. In the 1990s, environmental laws tightened up considerably, changing the face of the flexible packaging industry [1]. At that time, two to three laminate structures were bonded with solvent-based adhesives and barrier performance was achieved with materials such as aluminium and nylon [2]. During this time period, technological development progressed slowly and chemical safety was not given high priority. With the introduction of solventless lamination in the 1990s, rapid innovation began to influence the industry. In response to regulatory requirements, five-to seven-layer laminate structures were adopted and the use of metallised films was widely implemented [3]. In this period, strict standards were implemented for food contact safety to improve control of chemical migration and the durability of packaging materials. Meanwhile, printing technologies have made great strides, leading to greater efficiency, faster production and better print quality. As a result, the combination of these developments led to the gradual transition of flexible packaging to a safer, more advanced and high-performing system than that of the previous decade [4]. The structure of packaging materials has evolved throughout time, making the product not only protected from oxygen and water vapour but also supported by other properties like mechanical strength, tight sealing and many reopenings and closures. Although aluminium foil is known for its protective qualities [5]. The development of flexible packaging has been driven by the continuous progress in material science and barrier technologies. In this phase, the industry mainly depends on simple single layer such as paper and regenerated cellulose-based films. These transparent films gained wide acceptance during the mid-twentieth century because of their good clarity and print quality [6].

The development of flexible packaging with the adoption of cellulose film and advanced polymer materials, along with Polyamide and EVOH and metallised films, has enhanced the mechanical strength and barrier efficiency [7].

Biaxially orientated polypropylene (BOPP) films, in particular have become as one of the most popular high-growth films in the global market in recent years [8]. Controlling the atmosphere and ensuring mechanical strength are crucial in the beverage and food packaging industries and are dependent on the gas-transport properties and stiffness of polymer films [9]. Cast Polypropylene (CPP), on the other hand, is a non-oriented polypropylene film known for its superior heat sealability, flexibility and puncture resistance. As CPP is widely used as the inner sealing layer in laminate structures due to its ability to form strong hermetic seals at relatively low temperatures [10]. When metallized (Met-CPP), a thin aluminium layer is deposited onto the film surface, significantly improving its oxygen and moisture barrier properties while maintaining good sealability [11]. In the multilayer laminates combination of BOPP and metallized CPP in multilayer laminates results in a synergistic structure where BOPP provides mechanical strength and printability while Met-CPP contributes enhanced barrier performance and heat sealing functionality. Such laminates are extensively used in food packaging applications, including snacks, confectionery and ready-to-eat products where protection against moisture, oxygen and contamination is critical for extending shelf life [12].

2. Research Methodology

2.1 Materials

BOPP and Metallised CPP are manufactured and brought to the company by Polyplex Corporation Limited. It is widely used in flexible packaging, food packaging and the medical industry. The sealing of BOPP and metallised CPP laminates was carried out a constant temperature of 140 degree Celsius with a dwell time of 1 second and a sealing pressure of 2.5 bar. The sample was conditioned at 10 degree Celsius for 24 hours before testing and seal strength was measured according to the ASTM F88. Typical sealing range of CPP is between 130-150 degrees Celsius and 140 degrees is used because of its higher efficiency with the consistency of sealing. The thickness of the Multilayer film (BOPP + Mett CPP) is 40microns.

2.2 Methods

2.2.1 Seal Strength

Seal strength test was performed by using a seal strength tester (Labthink C630H Heat Seal Tester), Medford, USA we taken rectangular samples (250mm x 15mm) for seal strength testing at a temperature of 140 degree Celsius and the sealing area is 40mm x 10mm. We applied a sealing pressure of 2.5 bar and a dwell time of 1 second. Now the sealing strength is measured in N/15mm by using the standard ASTM F88.

2.2.2 Bond Strength

A bond strength test was conducted by using a universal testing machine (UTM)(Instron 68TM-10, Boston, MA, USA) by taking a rectangular sample size (250mm x 15mm) with a crosshead speed of 300mm/min. By using the standard ASTM D1876 bond strength test, is used to check the interlayer adhesion, support seal integrity, barrier performance and resistance to mechanical stresses and is measured in N/15mm.

Bond Strength=Force (N)/Sample Width (mm)

2.2.3 Coefficient of Friction (COF)

Coefficient of friction (COF) testing was performed by using a COF tester (**RDM Test Equipment CF-800XS**) according to ASTM D1894 standard. By using rectangular film samples of size 150mm x 63.5mm with the sled area of 63.5mm x 63.5 mm. The test was performed at 24 degree Celsius and 54 % relative humidity. A standard sled of 200 g mass was placed on the laminate surface and pulled at a speed of 150mm/min. The COF test is carried out to check the critical evaluating machinability, handling characteristics and performance of flexible packaging laminates and the COF test has no unit.

2.2.4 Water Vapour Transmission Rate(WVTR)

water vapour transmission rate (WVTR) was determined using a water permeability tester (Mocon Aqatran 3/34 series) under controlled temperature and relative humidity by mounting a sample with a size of 50cm2 by using the ASTM F1249.WVTR test is carried out to check the moisture barrier properties, shelf life performance and water vapour transmission resistance of multi- layer flexible packaging laminates and expressed in g/m2/day for 24 hours.

2.2.5 Oxygen Transmission Rate (OTR)

Oxygen transmission rate (OTR) was measured using an oxygen permeability tester (Mocon OX-TRAN 2/22H) under controlled environment and relative humidity by using a sample size of 50cm2. By using the ASTM D3985, the test is carried out for 24 hours to check the product protection ability, oxygen barrier properties and shelf-life performance of multi-layer laminates and the test is measured in cc/m2/day.

3. Results and Discussions

3.1 Seal Strength

In the fig.1. the sealing strength was determined by sealing the BOPP/Met CPP laminate for 24 hours at 10°C, 25°C and 45°C and then sealing it at 140°C. Average seal strength values at 10°C were found in the range of 19.58 to 21.34 N/15 mm, which shows a little bit poorer bonding due to the lower mobility of polymer chains. Moreover, better intermolecular diffusion and bonding are indicated by higher values of seal strength in the range of about 25.4 to 27.8 N/15 mm at 25 °C (ambient condition). The seal strength was also reduced to some extent (~22.6 to 24.8 N/15 mm) at 45°C as compared to ambient conditions. This may be due to the polymer softening to some extent or structural relaxation prior to sealing. Overall, the results suggest that ambient conditioning (25°C) gives the best seal strength, but that lower and higher conditioning temperatures.

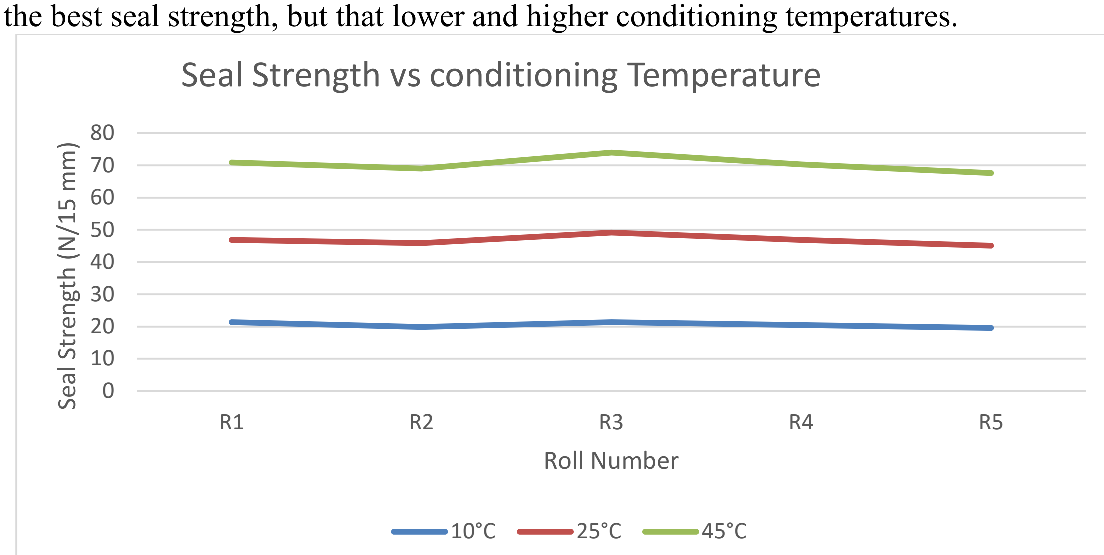

Fig.1. Seal Strength vs Conditioning Temperature

3.2 Bond strength

The bond strength of BOPP/Met CPP laminate was studied after conditioning for 24 hours at 10°C, 25°C and 45°C.

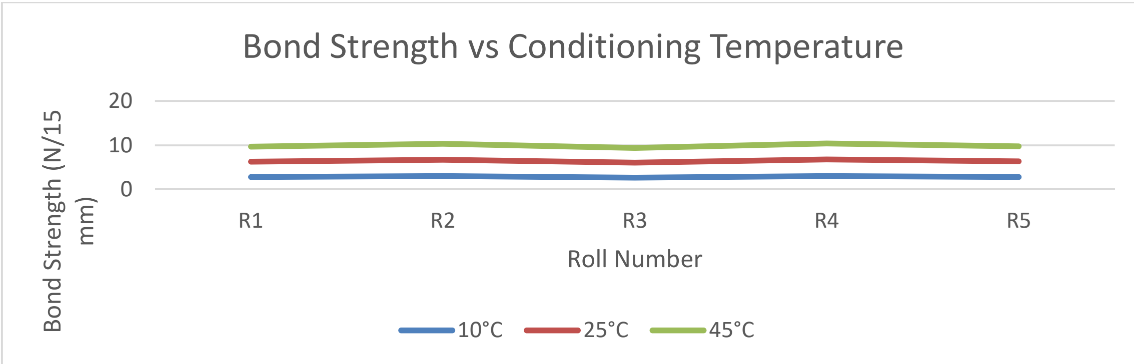

Fig.2. Bond Strength vs Conditioning Temperature

The finding shows that in fig.2. the bond strength values were relatively lower at 10°C (~2.64 to 3.18 N/15 mm) due to the insufficient intermolecular contact and the decreased mobility of the polymer chains. At 25°C (ambient condition) higher binding strength values (~3.29 to 3.74 N/15 mm) were observed, implying better adhesion owing to better interfacial bonding and higher molecular diffusion. Bond strength values were similar at 45°C, but varied slightly (~3.18 to 3.85 N/15 mm), which may be attributed to structural relaxation or thermal softening effects on the adhesive performance. The results generally indicate that ambient conditioning gives the best bonding performance with slight variations toward lower or higher temperatures slightly effect intermolecular bonding efficiency.

3.3 Coefficient of Friction (COF)

The surface behaviour of BOPP+Metallised CPP laminate was studied at different temperature of 10°C, 25°C and 45°C using coefficient of friction (COF). To ensure reliability and reproducibility, static and kinetic COF measurements were performed on five individual rolls.

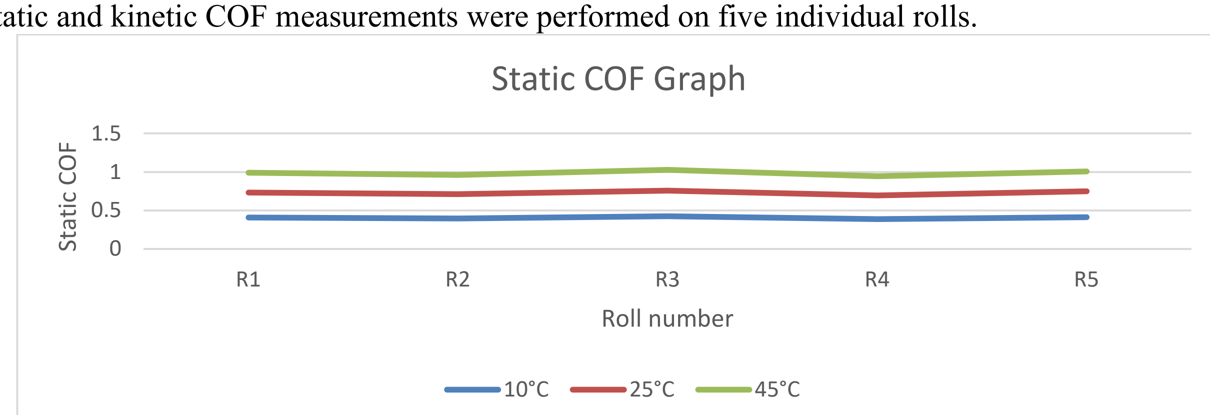

Fig.3. Static COF

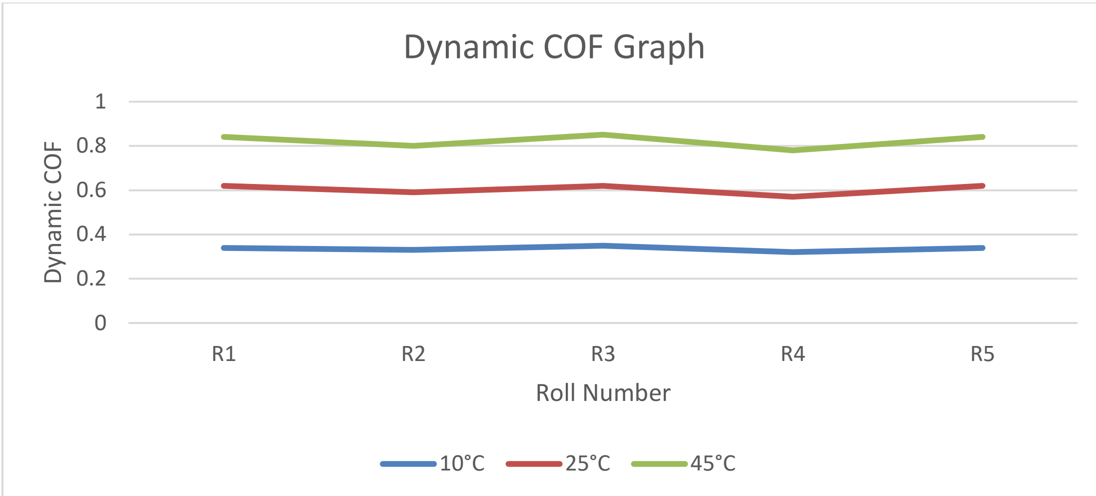

Fig.4. Dynamic COF

In fig.3. and fig.4. highest frictional values were exhibited by the laminate at 10°C with kinetic COF between 0.32 and 0.36 and static COF between approximately 0.38 and 0.43. The high values represent poor slip performance, likely due to higher surface resistance at low temperatures. A clear decrease in COF was observed with increasing temperature up to 25°C, with kinetic COF in the range of 0.25 to 0.30. This reduction indicates an increased surface mobility and improved slip properties at modest temperatures however the static COF was between 0.30 and 0.35. This reduction indicates improved surface mobility and smoother interaction between film layers under mild thermal conditions. Further reduction in COF was observed at 45°C, where static COF decreased to the range of 0.24 to 0.28 and kinetic COF ranged between 0.20 and 0.24. The decrease values at high temperature indicate enhanced slip properties, likely due to increased molecular mobility and softening of the polymer surface. Across all temperatures and rolls, it was consistently observed that static COF values were higher than kinetic COF values, which is a typical behaviour of polymeric films. Moreover, the variation among different rolls was small, indicating good process uniformity and consistency in laminate production. Overall the results demonstrate that COF decreases with increasing temperature. It may have a major impact on the machinability and handling performance of flexible packaging substances during processing and end-use applications.

3.4 water vapor transmission rate (WVTR)

Water Vapor Transmission Rate (WVTR) of BOPP + Metallized CPP laminates was evaluated at three different temperatures, namely 10°C, 25°C and 45°C, in accordance with ASTM F1249.

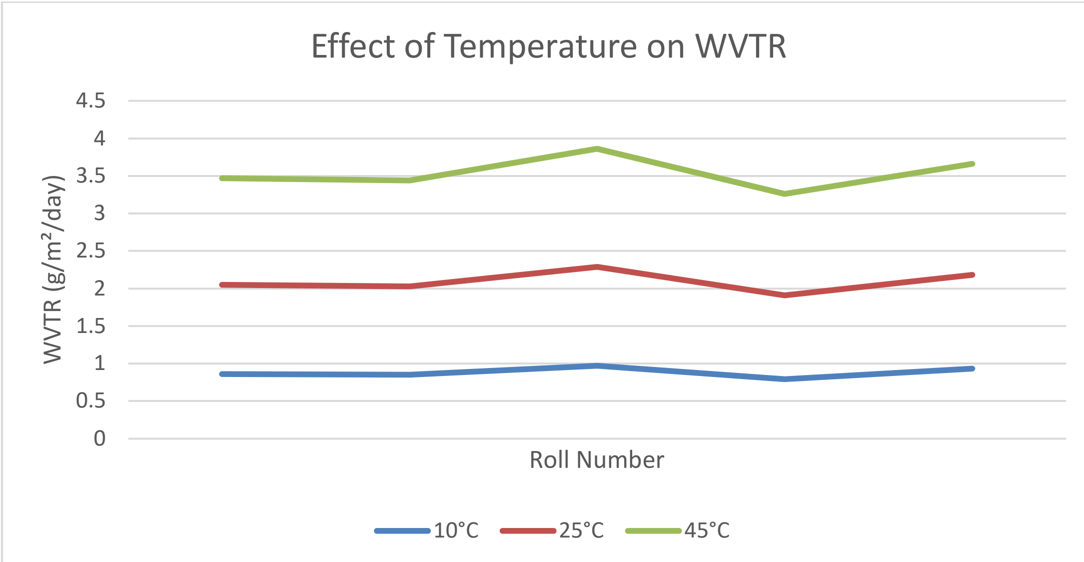

Fig.5. Effect of Temperature on WVTR

In fig.5. at 10°C, the WVTR values were observed to be relatively low, ranging approximately from 0.74 to 1.04 g/m²/day across different rolls. This shows strong resistance to moisture permeation at cooler temperatures. Among all of the samples examined, Roll 3 had shown slightly higher WVTR values, whereas Roll 4 showed the lowest values, indicating better barrier performance. At 25°C, a noticeable increase in WVTR was observed. The values ranged between 1.08 to 1.38 g/m²/day, reflecting increased moisture transmission under moderate temperature conditions. This behaviour can be attributed to enhanced molecular mobility within the polymer matrix, allowing easier diffusion of water vapour. At 45°C, the WVTR values increased further, ranging from approximately 1.30 to 1.63 g/m²/day. This significant rise confirms that higher temperatures adversely affect the barrier properties of the laminate. The increased permeability is primarily attributes to the softening of the polymer structure and increased free volume, facilitating the diffusion of water molecules. Across all temperature conditions, Roll 3 consistently showed higher WVTR values, while Roll 4 maintained comparatively lower values, indicating slight variations in material uniformity or metallization quality.

3.5 Oxygen Transmission Rate (OTR)

The samples were conditioned for 24hour at 10°C, 25°C and 45°C and the oxygen transmission rate (OTR) of the BOPP/Met CPP laminate was determined.

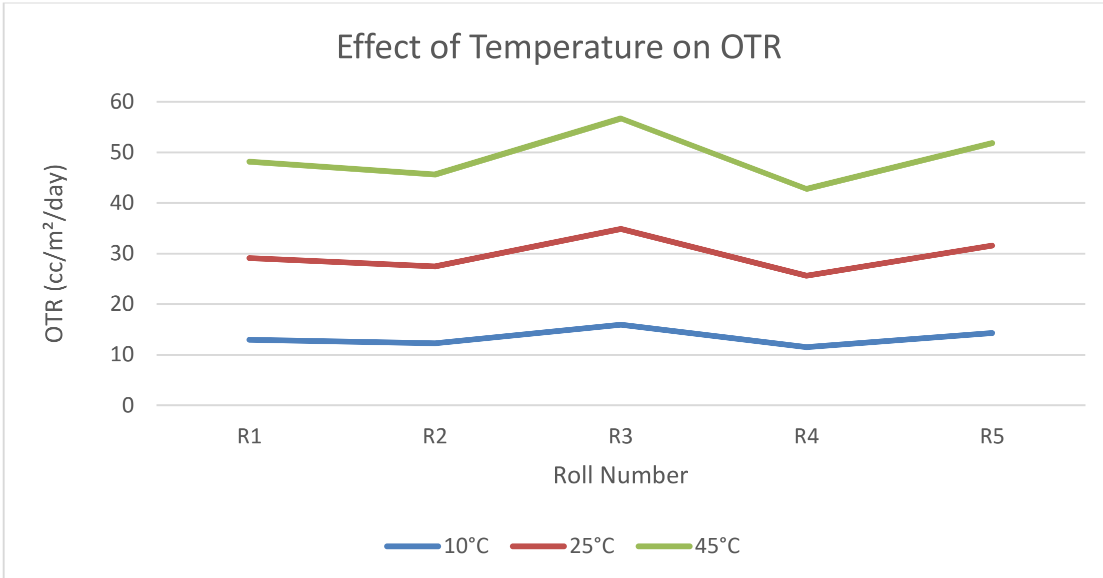

Fig.6. Effect of Temperature on OTR

In this fig.6. the average OTR values at 10°C were in the range of 11.5 to 16.0 cc/m²/day, indicating that the barrier performance of the oxygen barrier is enhanced at lower temperatures due to the reduced mobility of the polymer chains and the limited free volume. The OTR values were increased to the range of 14.1–18.9 cc/m²/day at room temperature (25°C), showing an rise in oxygen permeability. This result from the increased segmental mobility of polymer chains, which enhances gas diffusion through the film structure. At 45°C, the measured OTR values rose further, lying roughly between **17.1 and 21.8 cc/m²/day,** which points to a clear decline in barrier efficiency at higher temperature. This can be explained by the increase in molecular mobility within the polymer structure; as the material warms, the internal free volume expands slightly, making it easier for oxygen molecules to pass through. In short, the data show a consistent increase in OTR with temperature. Consequently, storing the laminate at lower temperatures helps in preserving its oxygen barrier performance more effectively.

4. Conclusion

The evaluation of the BOPP + Met CPP multi-layer laminates demonstrates that temperature is a key factor influencing both the mechanical and chemical barrier performance of flexible packaging. It was identified that at the ambient temperature (25°C) provides the highest mechanical properties, yielding 25.4 and 27.8 N/15 mm and superior bond strength ranging from 3.29 to 3.74 N/15 mm. While mechanical bonding is strongest at room temperature, barrier efficiency is enhanced at a lower temperature (10°C). This is because the reduced molecular mobility and limited free volume minimize the transmission of oxygen and water vapor. At the higher temperature, such as (45°C), adversely affects these barrier properties by increasing permeability and reducing the coefficient of friction, which enhances slip characteristics but may impact processing and shelf-life protection.

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