Designing paper and board barrier constructions for food contact applications

ALAN M. PIWOWAR AND GREG WELSCH

ABSTRACT: This study examines the effect of multiple factors on barrier performance for purpose-built paper and paperboard constructions produced on an industrial pilot coater machine. Impacts from precoat latex chemistry, application method (flooded nip with bevel blade, jet with bevel blade, and pre-metered film coater, laboratory rod drawdown) and precoating calendering were studied in relation to resulting porosity, roughness, and barrier (liquid water, moisture, and oil). Results reveal a complex interaction between controllable and uncontrollable factors, offering insight for designing advanced barrier coatings on cellulosic substrates.

Application: A better understanding of key attributes driving barrier performance in coated paperboard articles is needed. We utilized an industrial pilot coater to produce several purpose-built barrier constructions, with a focus on the impact of coating application method and latex chemistry on liquid water, moisture, and oil barrier.

Cellulose-based packaging offers a sustainable alternative to traditional all-plastic constructions, particularly in single-use food and beverage applications. In its natural state, cellulose provides relatively weak resistance against common food substances such as water, moisture, and oil, and therefore requires a protective layer for barrier performance.

Achieving a high-functioning, cellulose-based barrier construction is a complex process. Simply applying a barrier coating or film to cellulosic substrates is often insufficient for meeting performance requirements. Substrate characteristics (e.g., roughness, porosity), coating application methods, coating chemistry, and more can influence finished article performance. A thorough understanding of multiple aspects of finished article construction is therefore needed for ideal barrier design.

In this study, we evaluated purpose-built, pilot coater-constructed samples to understand the influence of multiple variables on barrier performance. Variables for this study included: substrate (commercially available 90 g/m² paper vs. 350 g/m² board), precoat composition (pigment-rich formulations with traditional and barrier latex binders), precoat application method (flooded nip with bevel blade metering, jet-application with bevel blade metering, grooved rod pre-metered film transfer coater, and laboratory drawdown rod coater), and precoat calendering (uncalendared vs. 2-nip calendering). Standardized tests were used to assess precoat properties as well as liquid water barrier, moisture barrier, and oil resistance for top-coated finished articles.

BACKGROUND

Motivation for this work arises from the challenge of creating a cost-effective, high-performing barrier construction. Sealing an untreated or uncoated substrate in a single pass with a barrier layer typically requires a relatively high coat weight (> 10 dry g/m²). Since most water-based barrier coating chemistries are higher cost relative to traditional coating formulations, optimizing performance with a reduced coat weight, pre-barrier layer (precoat) reduces costs and improves sustainability by using less raw material.

Many published investigations can be found illustrating the importance of a precoating structure and its impact on a subsequent second layer coating performance. Gaskin et al. [1] studied the influence of several precoat variables on print performance of topcoating surfaces. They found precoats applied at higher solids content and higher initial drying rate (faster immobilization) affected precoat porosity, resulting in better hold-out of the following topcoat. Pokharel et. al. [2] studied the influence of cellulosic nanofibrils as a precoat for water-based barrier coatings. In that work, the authors noted that the barrier properties of the overall construction could be improved via precoating methods.

Rättö [3] et al. demonstrated that pre-calendering can also be an important tool when preparing a paper substrate to accept a barrier coating. Pre-calendering reduces roughness, allowing a thinner barrier coating to be applied. Different calendering technologies can impact coating porosity and roughness in different ways.

Work by Boyle et al. [4] demonstrated that for a topcoat, coating application technique had a dramatic impact on starch migration from a precoat into the topcoat. Starch migration was significantly higher when a topcoat was applied using a jet applicator compared to flooded nip, suggesting coating pore structure is impacted by the application method. We have not uncovered any prior research where coating methods have been compared for the purpose of determining if the basecoat application technique had an impact on barrier coating holdout and the resulting performance.

EXPERIMENTAL

Coating formulations

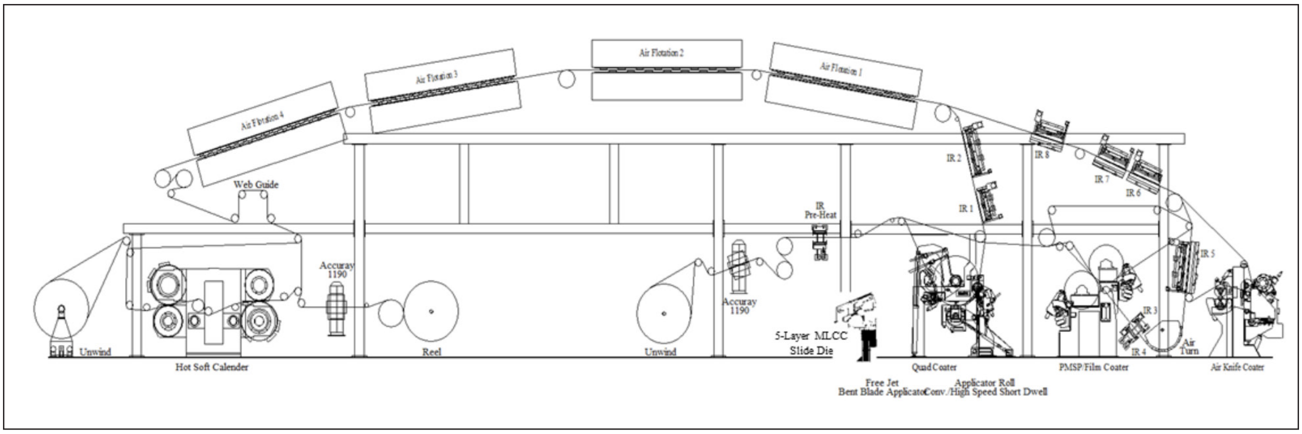
Coating formulations and properties are shown in **Table I** and **Table II**, respectively. Standard precoat (referred to as "A" in this paper) uses a typical carboxylated styrene-acrylic (SA) latex with an approximate glass transition temperature of 22°C. Modified precoat (referred to as "B") uses the same SA latex but incorporates a coating modifier designed to enhance smoothness during calendering. Barrier precoat (referred to as "C") contains an SA/styrene butadiene (SB) copolymer barrier latex (co-SA/SB). Barrier topcoat (referred to as "D") is a blocking resistant barrier product containing a hybrid starch-co-SA/SB emulsion referred to as Barrier SCE. Since D was applied using a slide die curtain coater, an extensional rheology modifier was included to aid curtain formation and stability.

	Standard Precoat	Modified Precoat	Barrier Precoat	Barrier Topcoat
Symbol	**"A"**	**"B"**	**"C"**	**"D"**
Calcium carbonate, fine	65	65	65	
Calcium carbonate, ultrafine	35	35	35	
Standard SA	14	14		
Barrier co-SA/SB			20	
Barrier SCE				100
Coating modifier		7		
Thickener				0.6
Rheology modifier A	0.1	0.1	0.1	
Rheology modifier B				6.6
SA: styrene acrylic latex; co-SA/SB: styrene acrylic/styrene butadiene copolymer; Barrier SCE: barrier topcoat "D" with hybrid starch-co-SA/SB emulsion.				

I. Coating formulations.

	Standard Precoat	Modified Precoat	Barrier Precoat	Barrier Topcoat
Symbol	**"A"**	**"B"**	**"C"**	**"D"**
Flooded nip				
Solids, wt%	66.4	60.5	66.3	41.8
pH	7.7	7.9	7.6	7.0
Brookfield viscosity (20 rpm, #4, 23°C)	1420	1430	1410	740 (100 rpm)
Jet application				
Solids, wt%	67.1	61.1	66.9	41.8
pH	8.2	7.9	7.8	7.0
Brookfield viscosity (20 rpm, #4, 23°C)	2960	3260	4280	740 (100 rpm)
Film transfer (pre-metered size press)				
Solids, wt%	66.4	61.4	66.9	41.9
pH	7.6	7.9	.6	7.0
Brookfield viscosity (20 rpm, #4, 23°C)	1540	1400	1520	744 (100 rpm)

II. Coating properties.



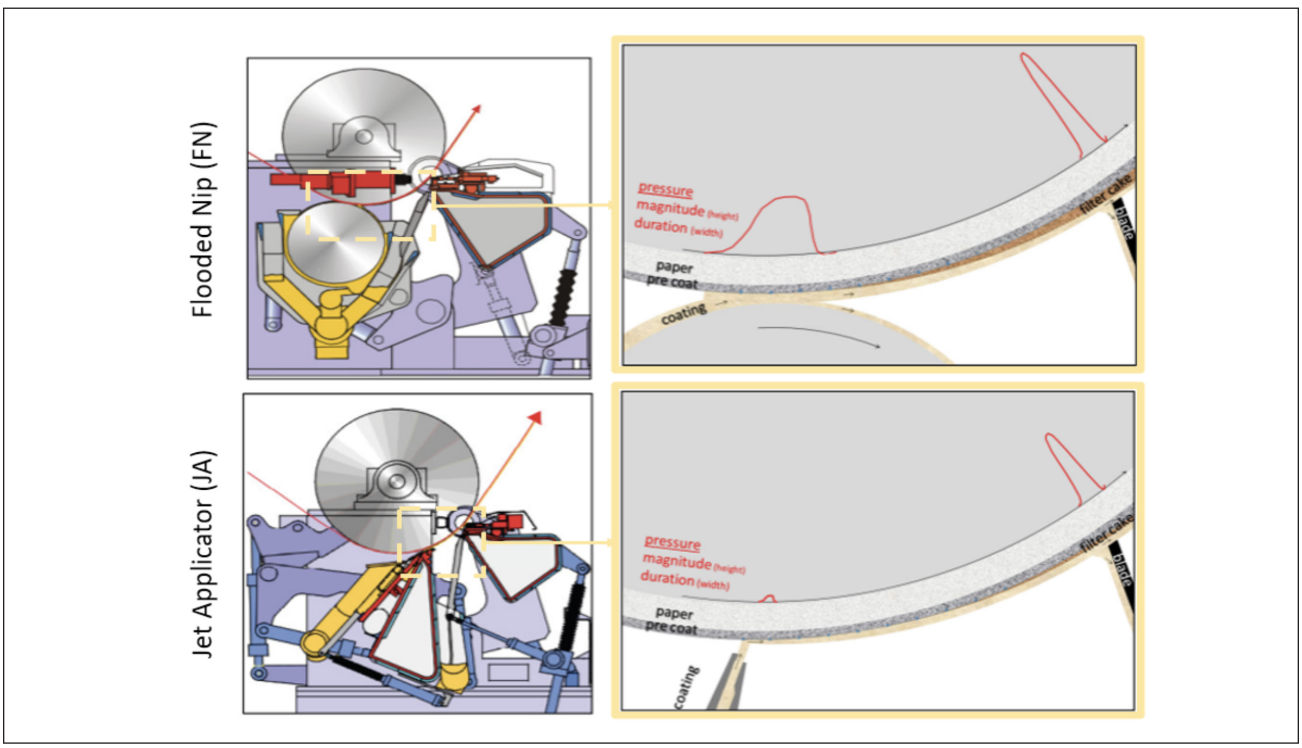
1. Schematic of Trinseo's Midland pilot coater.

All precoat formulas were pigmented using a blend of fine and coarse calcium carbonate. An effort was made to maintain latex-to-pigment ratios, but the authors highlight here that formulation C contains a higher relative amount of latex (20 parts vs. 14 parts).

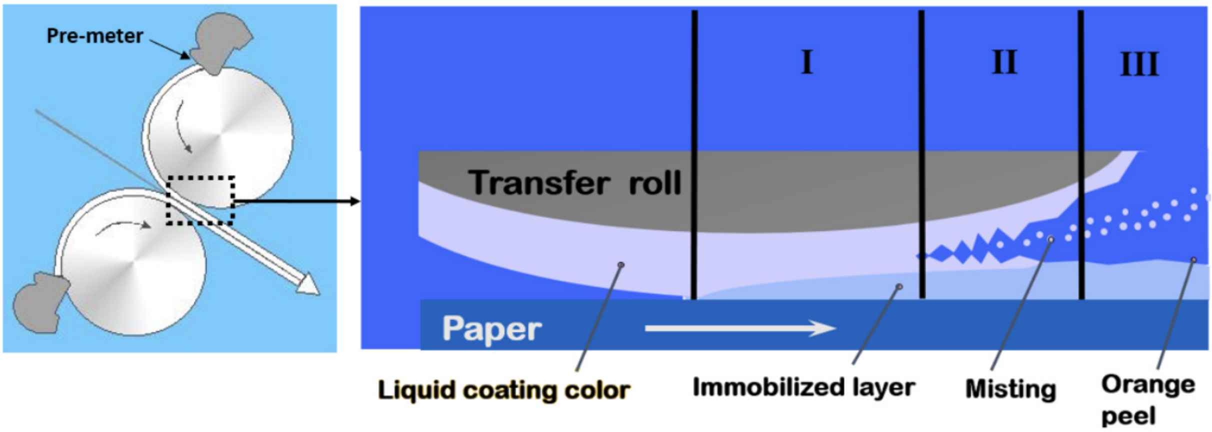
Coating applicator technologies

Precoat formulations were applied at the Trinseo pilot coater in Midland, MI, USA, a schematic of which is shown in **Fig. 1**. For the pilot coater portion of the study, three different coating applicators were used: flooded nip (FN), jet applicator (Jet), and a film coater (FT; film transfer), also known as a pre-metered size press (PMSP). Target coat weight was 10 dry g/m^2. Topcoats were applied using a slide-die multilayer curtain coater (MLCC) with one slot application at a target coat weight of 5.5 dry g/m^2. This relatively low coat weight target was selected to amplify subtle differences among study variables, including contributions from the precoat.

Jet and flooded nip are long dwell applicators (distance between application and metering is about 0.4 to 0.6 m), with details shown in **Fig. 2**. With flooded nip, coating is applied to the substrate by an applicator roll turning in a pan filled with formulation, essentially "flooding" the nip between applicator roll and the backing roll carrying the substrate. After exiting the nip, a metering element (in this study a beveled blade) smooths the coated substrate surface. Importantly, substrate passing through a flooded nip



2. Comparison of flooded nip (top) and jet applicator (bottom). Left: equipment layout. Right: highlighted region describing magnitude and duration of pressure pulse prior to metering [4].



3. Film transfer application.

experiences a pressure pulse that increases dewatering, typically resulting in higher coating penetration compared to an application with a low-pressure pulse. Pressure pulse magnitude varies based on application properties but is estimated at between 0.5 and 4 bar [5-8]. Since the coating has experienced significant dewatering, effective viscosity of the applied material increases such that during metering, high blade pressure is required (relative to coating that retains a high-water content) to achieve target coat weight, further increasing effective pressure experienced by the coated article. Formulation is estimated to reside on the surface of the article for 1.0 ms before metering occurs (dwell time) at the run speed evaluated.

Jet application uses a pressured chamber to force formulation through a narrow slit or nozzle (roughly 0.8 to 1.2 mm in gap width) onto a moving substrate, as shown in Fig. 2. In contrast to flooded nip, jet application does not produce a significant pressure pulse, and the coating essentially remains undisturbed on the substrate surface until encountering a metering element, which in the case of this study was a beveled blade. Overall, jet application produces a lower coating penetration force compared to flooded nip, and coatings applied with a jet applicator show less dewatering. Dwell-time between application and metering for a jet applicator is less than flooded nip (roughly 0.1 ms), further influencing dewatering characteristics.

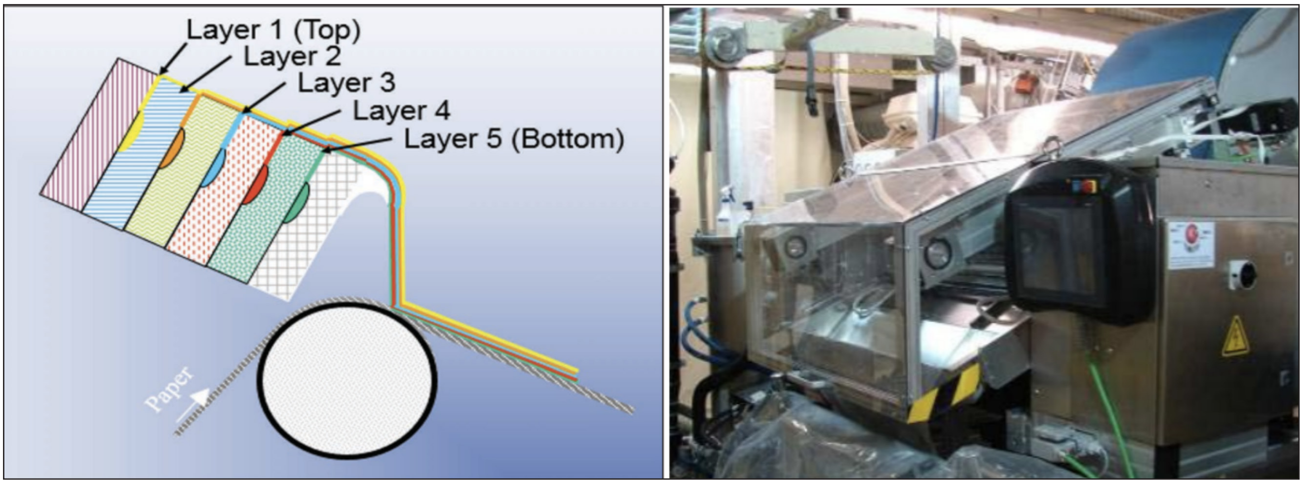
Film transfer applies a coating onto an applicator roll prior to substrate interaction and is a considered a "short-dwell" application, as shown in **Fig. 3**. Shortly after formulation is applied to a substrate, the coated article passes through a nip formed between two applicator rolls, experiencing a short duration, low pressure pulse. As coating exits the nip, a film split occurs and no further smoothing takes place, resulting in an "orange-peel" type pattern, distinctly different to smooth blade metered coatings. A comparison of application properties is shown in **Table III**.

In addition to pilot coated samples, laboratory samples produced using a drawdown coater (RK Model K303, RK PrintCoat Instruments; Royston, UK) are included for comparison. This device mechanically pulls a wire-wound grooved rod evenly across the base sheet at a fixed coating speed (5 m/min). Commonly, this method is used to estimate barrier performance in the laboratory prior to evaluation at pilot scale production. For laboratory samples, the drawdown coater was used to apply both precoats and topcoats.

A slide die curtain coater was used to apply a topcoat of water-based barrier formulation D. Curtain coating is a low-impact application method providing contoured coating with-

	Flooded Nip – Blade	Jet – Blade	Film Coater
Coating application (relative)			
Dwell time	10x	1x	2x
Pressure pulse	10x	1x	2x
Coating metering			
Surface type	Smoothened	Smoothened	Rough
Coating thickness	Varies	Varies	Semi-contour

III. Application comparison.



4. Multilayer curtain coating [9].

out a secondary metering element (**Fig. 4**). Formulation is pumped through a narrow opening in the die, producing a falling liquid film. Due to gravity, the liquid film flows over the edge or lip of the coater assembly, forming a continuous thin curtain onto the moving substrate below. Curtain coated film adjusts to variations on a substrate surface, contouring to high and low points, theoretically forming a uniform thickness layer. With no secondary metering element, there is reduced risk of scratches or breaks in the coating, as long as the formulation forms a consistent, cohesive curtain and is properly deaerated prior to application.

Calendering

For this study, offline calendering was carried out on some precoated paper samples (jet applicator) to understand impact of smoothness and densification on applied topcoat barrier performance. Prior to topcoating, jet-applied precoated paper substrates were 1-pass, 2-nip supercalendered using soft rolls at 330 m/min with the precoated side of the sheet in contact with a steel roll surface held at 95°C. Stack pressure was set to 210 kN/m. After calendering, exiting sheets had a surface temperature of around 47°C.

Test methods

Roughness (Parker Print-Surf)

Roughness was measured using a TMI Print-Surf Roughness tester (Model 58-06-00, TMI Group; New Castle, DE, USA) as described in TAPPI Standard Test Method T 555 “Roughness of paper and paperboard (Print-surf method).” The Parker Print-Surf (PPS) method measures air leakage between a substrate and a clamped measuring head. Rate of air leakage and pressure differential is used to calculate the surface roughness and is expressed in microns (µm). Higher values indicate rougher surfaces.

Porosity (Gurley densometer)

Sample porosity was assessed using a Gurley 4340 Automatic Densometer and Smoothness tester (Gurley Precision Instruments; Troy, NY, USA) following TAPPI T 460 “Air resistance of paper (Gurley method).” The densometer measures the amount of time for a volume of air to pass through a sheet under a given pressure (referred to as Gurley seconds). For this study, values represent the time (in seconds) to displace 10 cc of air through a 1-in.^2 section of the substrate (standard measurement uses 100 cc).

Liquid water absorption (Cobb test)

Liquid water absorption was determined following TAPPI T 441 “Water absorptiveness of sized (non-bibulous) paper, paperboard, and corrugated fiberboard (Cobb test).” Commonly referred to as the Cobb method, this test’s results are reported in grams per meter squared (g/m^2), with higher values indicating higher water absorption.

Moisture barrier (permeability cups)

Moisture barrier was measured using the Dessicant Method of ASTM E96 “Standard test methods for water vapor transmission of materials.” A wax blend was used to seal substrates to in-house permeability cups containing desiccant. Weight of the test apparatus was measured before and after exposure to 23°C and 50% relative humidity (RH) at atmospheric pressure for 24 h. Results are reported as grams per meter squared per day (g/m^2/day), with higher values indicating increased moisture transmission.

Oil barrier (in-house “oil drop” method)

Oil barrier was assessed visually using an in-house oil drop method. Briefly, a drop of over-the-counter Canola vegetable oil is placed onto the coated substrate and visually assessed initially, after 1 h, and after 24 h. Ratings are based on oil permeation into the coated article: 0 = no oil migration; 1 = pinhole formation; 2 = saturation but not breakthrough; and 3 = total breakthrough.

Experimental design

Barrier construction variables employed in this study are

Variable	Levels	Notes
Substrate	2	90 g/m^2 (paper); 350 g/m^2 (board)
Precoat: Formulation	4	None, standard, standard w/additive, barrier
Precoat: Application	4	Flooded nip, jet, film transfer, rod (lab)
Precoat: Weight	1	10 dry g/m^2
Precoat: Calendering	2	Yes, no
Topcoat: Composition	2	None, SCE barrier coating
Topcoat: Application	2	MLCC, rod (lab)
Topcoat: Weight	1	10 dry g/m^2
SCE: barrier topcoat "D" with hybrid starch-co-SA/SB emulsion; MLCC: multilayer curtain coater.		

IV. Variables examined in purpose-built barrier constructions.

shown in **Table IV**. A total of 256 constructions were possible based on parameters, with about 120 sample constructions produced and evaluated in this study. Please note that film transfer was used as an application method on paperboard only (not paper), and calendering was only applied to jet-coated precoated paper articles.

RESULTS

Data in the following sections are plotted by substrate (paper or paperboard).

For paperboard samples, the performance of Formulation D (applied using slide die curtain coater) is included to demonstrate the effectiveness of a barrier layer (applied at 6 dry g/m^2) without precoat. Performance of precoat and the total article (precoat/topcoat) is organized by precoat application method: FN (flooded nip), Jet (jet applicator), and FT (film transfer). To facilitate visual interpretation:

- Formulation A sample data are colored red.
- Formulation B sample data are colored yellow.
- Formulation C sample data are colored blue.
- Uncoated substrate is colored gray.

Additionally, formulation letters are inserted in each column for clarity. Error based on typical measurement variability (not included in figures for clarity) is approximately 5% relative standard deviation (RSD), except for MVTR, which was 10%. Average values for each measurement are reported above each column.

Presentation of paper data follow a similar pattern to board, with two exceptions. First, no data were collected for Formulation D applied directly to paper. Second, film transfer data were not collected, and therefore not included. Instead, data from calendered, jet-applied formulations are included. Please note that only the precoated article was calendered prior to the application of Formulation D (i.e., total finished article was not calendered).

Roughness

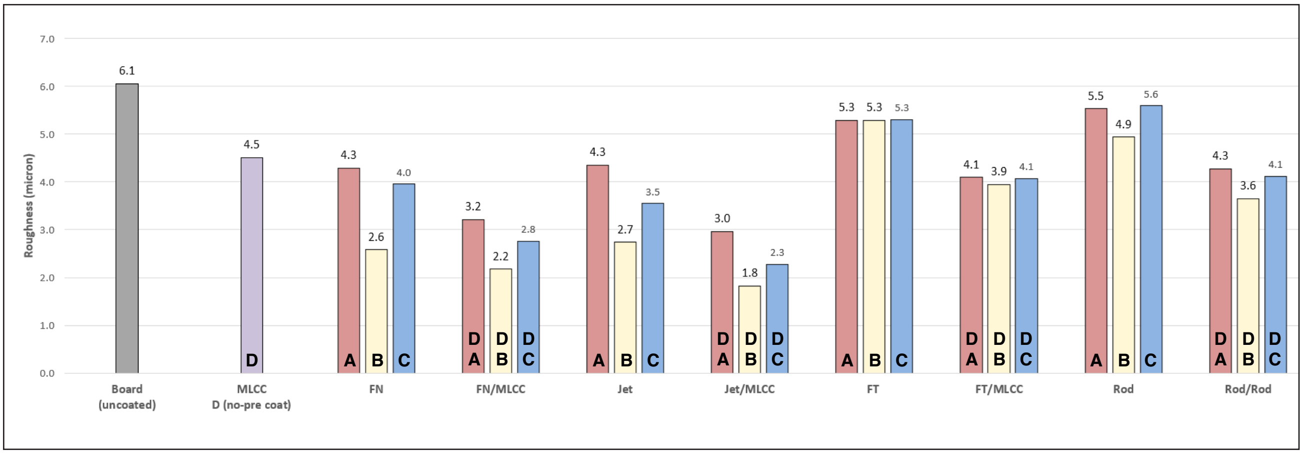
Roughness refers to the unevenness or irregularity of the substrate surface, measured as deviation from the mean average plane. In barrier applications, high surface roughness can affect liquid and gas permeation by causing inconsistent coating thickness and defects like fiber protrusion. Board and paper examined in this study had uncoated surface roughness of 6.1 ± 0.2 µm and 5.3 ± 0.4 µm, respectively.

Paperboard surface roughness is reduced after pilot coater application of precoat and further reduced with topcoat application, as shown in **Fig. 5**. Absolute and relative changes are not equal, indicating an influence from both precoat formulation and application type.

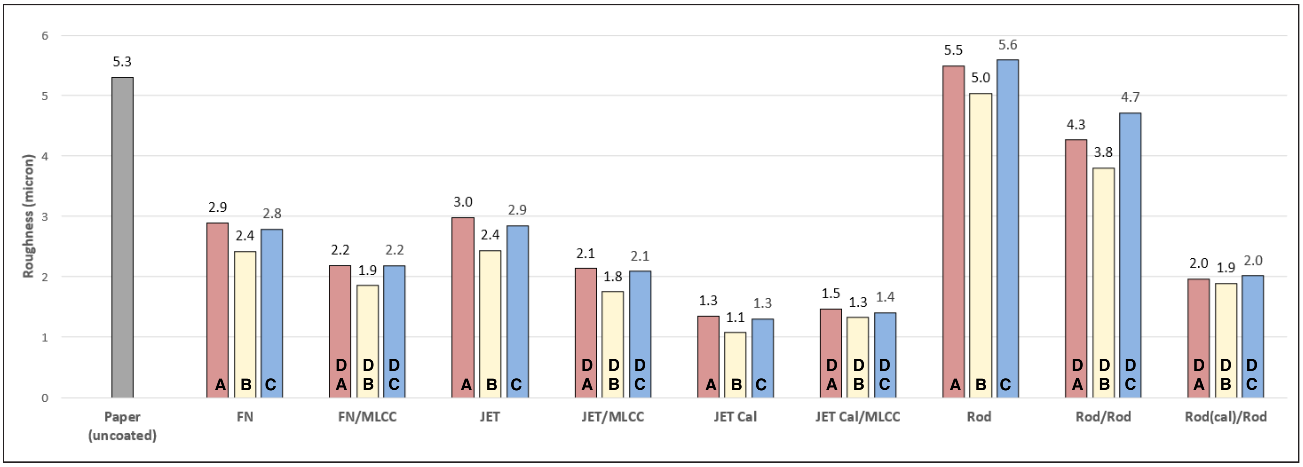
Interestingly, all precoat formulations perform similarly when applied by film transfer on paperboard, with roughness reduced by only 15%, indicating film transfer is inefficient at surface smoothing. This aligns with application technique expectations, as film split at the outgoing transfer nip creates an uneven "orange-peel" surface. Applying Formulation D as a topcoat on film transfer precoated board using curtain coating improves roughness by about 25%, but total double-coated (precoat and topcoat) articles remain relatively rough (4 µm).

Flooded nip and jet applied precoats produce similar reductions in roughness for individual precoat formulations (e.g., Formulation A applied with FN performs the same as Formulation A applied using Jet). For these application methods, precoat formulation appears to have an impact on roughness. Formulation B reduces roughness the most and Formulation A the least. Applying Formulation D as a topcoat further reduces roughness of precoated board by 15% to 35%, suggesting some leveling occurs, even with curtain application and subsequent processing.

In addition to pilot coater samples, similar samples produced at laboratory scale were also examined. For roughness on paperboard, laboratory coated samples (precoat and topcoat applied using rod drawdown coater) are about



5. Parker Print-Surf roughness (microns) for paperboard. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater.)



6. Parker Print-Surf roughness (microns) of paper. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Jet: jet applicator; Cal: calendered; MLCC: multilayer curtain coater; Rod: lab drawdown coater; Rod(cal): calendered lab drawdown coater.)

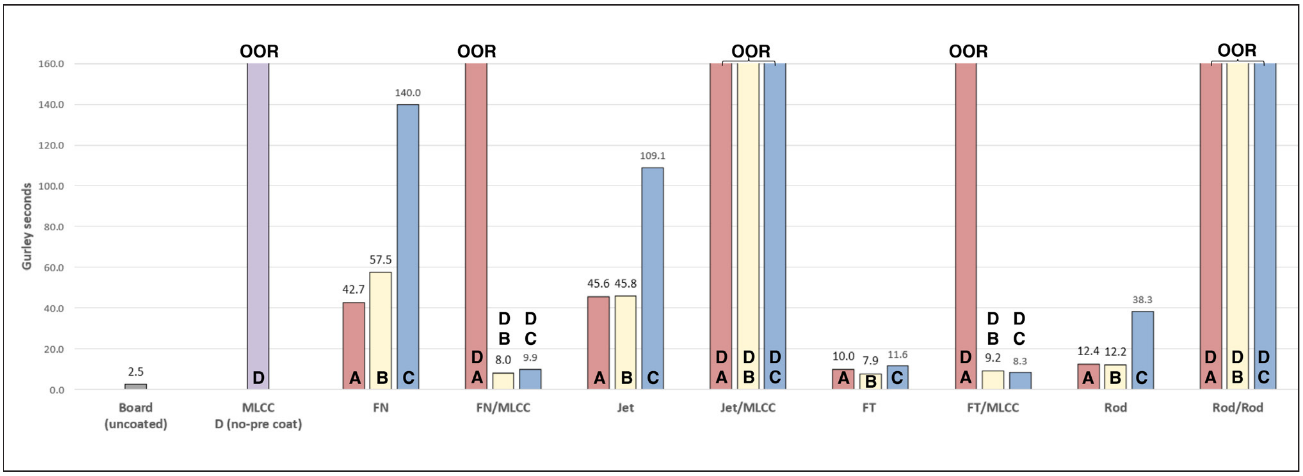
as efficient at reducing roughness as film transfer samples.

Overall differences in precoated board roughness may be explained by composition. Formulation B contains a coating modifier designed to promote low film density (a thicker coating at equal coat weight). After blade metering, surface smoothing may be improved as the board moves through the paper machine (burnishing) or during windup (compression). Formulation C presumably outperforms Formulation A due to its higher latex loading (20 pts vs. 14 pts). High latex loading may impact coating density, packing efficiency, and overall coating plasticity. Film transfer samples have the highest roughness and show no differentiation by formulation. As previously discussed, high roughness and lack of differentiation for film transfer is likely due to film split, as seen in Fig. 3.

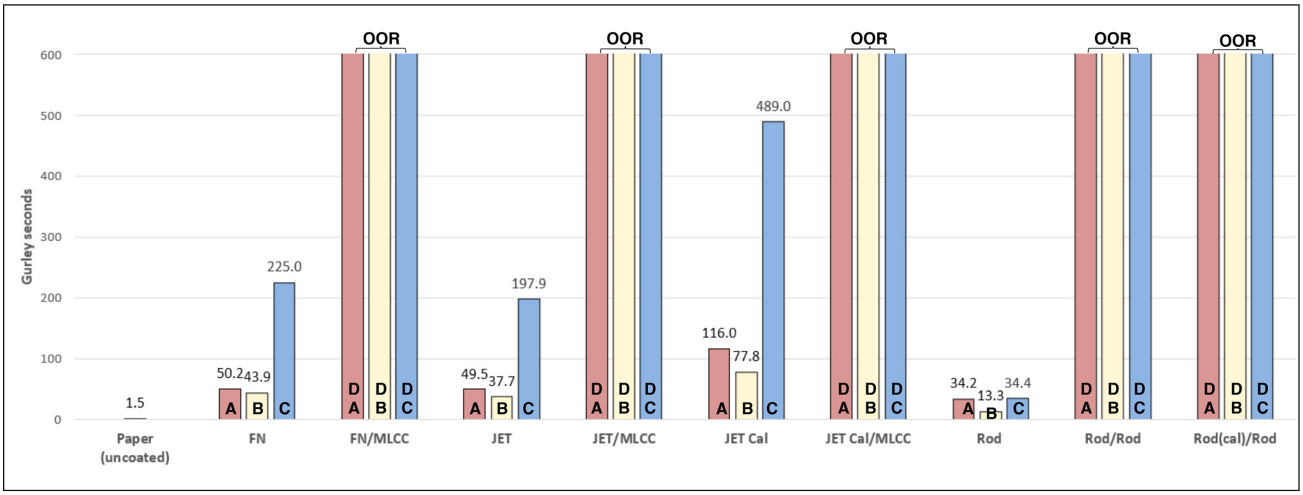
Roughness values for paper substrates are shown in **Fig. 6**. As with paperboard, all pilot coater-applied precoats reduce roughness. Flooded nip and jet applications have essentially the same impact on roughness. Calendered samples (Jet only) show a significant reduction in roughness relative to uncalendared, but topcoating with Formulation D does not improve values further. Precoat chemistry also influences the final article roughness, with Formulation B providing the greatest reduction. However, on paper, Formulation C and Formulation A equally impact roughness, rather than Formulation C outperforming Formulation A, as seen in the paperboard evaluation.

Uncalendered laboratory rod coated samples produce significantly different values when compared to pilot coater samples. Precoat only samples do not show a roughness reduction relative to uncoated paper, and precoat/topcoat samples reduce roughness by about half of pilot coater samples. However, precoat calendered laboratory samples with topcoat are similar to pilot coater finished articles.

Overall, paper and board precoated samples exhibit a range in roughness values, which provides an opportunity for differentiation when evaluating barrier performance of total article constructions.



7. Porosity (measured as Gurley seconds) for paperboard samples. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater; OOR: out of range.)



8. Porosity (measured as Gurley seconds) for paper samples. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Cal: calendered; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater; Rod(cal): calendered lab drawdown coater; OOR: out of range.)

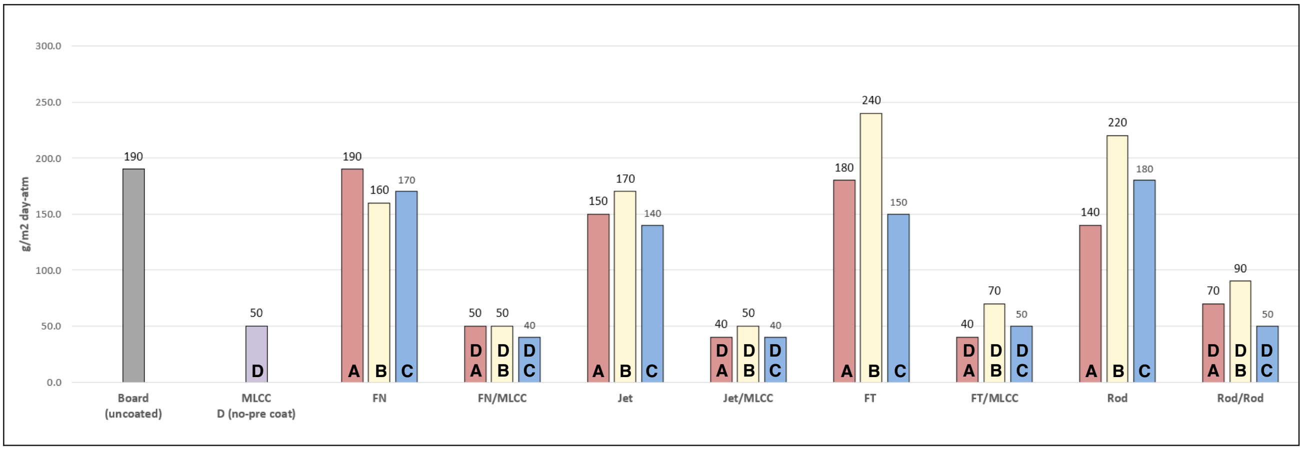
Porosity

Paper and paperboard are porous materials, often containing a significant volume fraction of air that influences compressibility and ability to absorb fluids (e.g., oil, water). Paper selected for this study (90 g/m²) has a porosity of 1.5 ± 0.1 Gurley seconds, and the paperboard (350 g/m²) has a porosity of 2.5 ± 0.2 Gurley seconds, indicating both are relatively open or porous sheets.

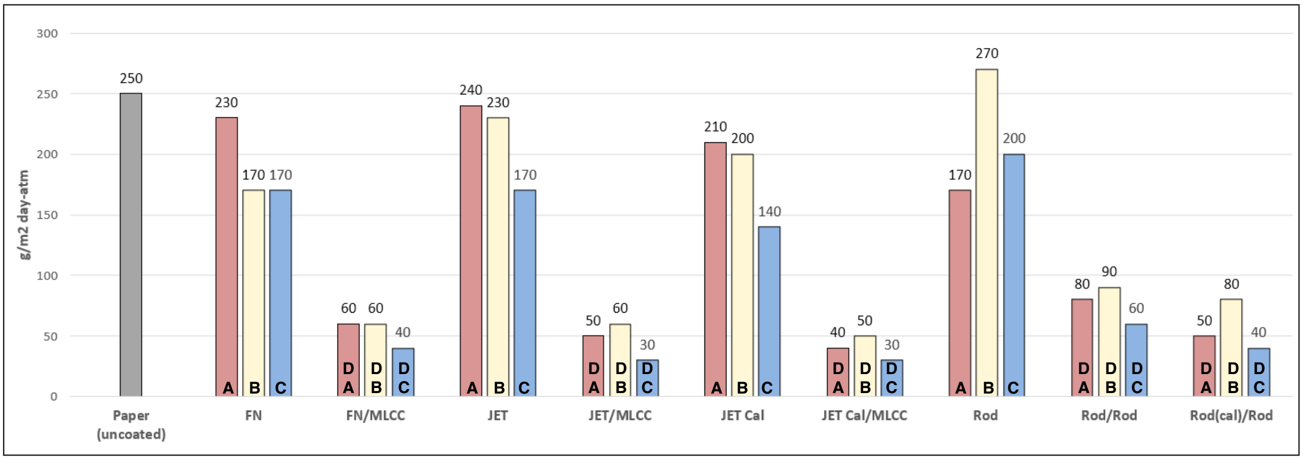
Porosity measurements were collected using a Gurley densometer, with results shown in **Fig. 7** and **Fig. 8**. Higher values indicate longer time for air to pass through a sample, signifying sheet "closedness." Several coated samples restricted movement of air through the substrate effectively enough to "seal" the sheet. In those situations, Gurley seconds are listed as out of range (OOR).

When considering porosity, FT is least effective at sealing the board, while Jet and FN applications are more effective and provide similar levels of coated article porosity reduction. Formulation C is most effective at reducing porosity, while Formulations A and B have lower effectiveness and produce similar results. On paperboard, Formulation D applied with MLCC produces an OOR value, indicating it effectively seals the substrate.

Since Formulation D seals the paperboard surface as a single layer, it is surprising that not all total article samples (precoat + topcoat) are OOR. When considering FN and FT, application of Formulation D on precoated paperboard produces an OOR over Formulation A, but not Formulations B or C. For FN, applying Formulation D worsens sheet porosity of board precoated with B and C. This unexpected result may indicate an unmeasured issue, such as coating disruption during sample preparation, possibly due to intersheet adhesion (localized or microscopic blocking). Further complicating this interpretation is that porosity is reduced as



9. Moisture vapor transmission rate for paperboard samples. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Cal: calendered; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater.)



10. Moisture vapor transmission rate for paper samples. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Cal: calendered; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater; Rod(cal): calendered lab drawdown coater.)

expected for jet-applied precoat samples (all OOR), providing no clear formulation trend for all three application methods. One possibility is that precoats applied using flooded nip dive deeper into the substrate, potentially making topcoat holdout less effective than samples that experienced lower pressure associated with jet application, although this would need to be confirmed with additional study.

Laboratory precoated samples do not reduce porosity significantly and most closely align with values observed from pilot coater applied FT. Rod top-coated laboratory samples are OOR, which is more consistent with jet applied precoats than FT or FN.

Paper shows more consistent performance than paperboard. Similar to paperboard results, flooded nip and jet applied precoats on paper perform similarly and show better sealing characteristics with Formulation C (higher latex loading). Calendering jet applied precoated samples more than doubles the time for air to pass through samples, more effectively sealing the sheet. In contrast to board samples, all topcoated paper samples produce an OOR value. As with board samples, laboratory rod-applied precoats are less effective at sealing the sheet than FN or Jet.

Barrier – moisture vapor transmission rate

Moisture vapor transmission rate (MVTR) measures the amount of water that passes through an article over time, and it is influenced by temperature, humidity, and pressure. In this study, we examined samples by mounting to a sealed vessel containing desiccant and exposing the coated side to 23°C at 50% RH at 1 standard atmosphere (atm) of pressure. Moisture passing through the coated articles adsorbs onto the desiccant surface, affecting its mass and providing the basis for the measurement. Low MVTR values indicate a better moisture barrier. The MVTR is sensitive to defects and coating variations, often leading to high measurement variability.

The MVTR for paperboard and paper is shown in **Fig. 9** and **Fig. 10**, respectively. Despite relatively high surface roughness and porosity, uncoated paperboard used in this study has a modest average MVTR at 190 grams per meters squared per day per atmosphere (g/m²/day-atm). When board is coated with Formulations A, B, or C, average MVTR decreases only slightly or not at all, with no clear trend from application type or coating composition. Precoat formulations used in this study have a relatively high pigment-to-binder level (100 pts pigments to 14 or 20 pts latex), leading to gaps or pores between pigments, which is not ideal for a gas barrier. This is supported by porosity measurements mentioned earlier (no sheets were "closed" after precoat application).

Formulation D significantly improves MVTR when applied directly to paperboard or precoated paperboard. As noted earlier, Formulation D does an efficient job of sealing the board surface, which may influence performance here.

Similar MVTR values are observed for pilot coater-finished materials, suggesting precoat porosity, roughness, and chemistry have minimal impact on performance. Laboratory rod applied-finished materials have higher moisture transmission for Formulations A and B compared with pilot coater-applied materials, but similar performance for Formulation C.

Slightly different performance is observed for paper samples, as shown in Fig. 10. Uncoated paper used in this study has an MVTR of around 250 g/m²/day-atm, which is roughly 30% higher than that of the board used. Average MVTR values for samples applied using FN are similar for both paper and paperboard, while jet-applied samples appear to have slightly worse values on paper. Calendered jet-coated materials may slightly improve performance, most notably for Formulation C at 140 g/m²/day-atm. Lab rod applied Formulation A has lower MVTR compared with pilot coater applied samples, while Formulations B and C are higher.

When coated with Formulation D, MVTR improves for all paper coated articles. Formulation C shows the best performance (30 to 40 g/m²/day-atm), while Formulation A and B are slightly higher. As a barrier precoat, Formulation C was expected to provide some boost in performance. Here, the topcoated article containing Formulation C as a precoat has a 30% lower MVTR, better than a comparable article using precoat Formulation A. Rod coated-finished articles have equal or higher MVTR than pilot coater samples. Again, Formulation C appears to provide some improved performance.

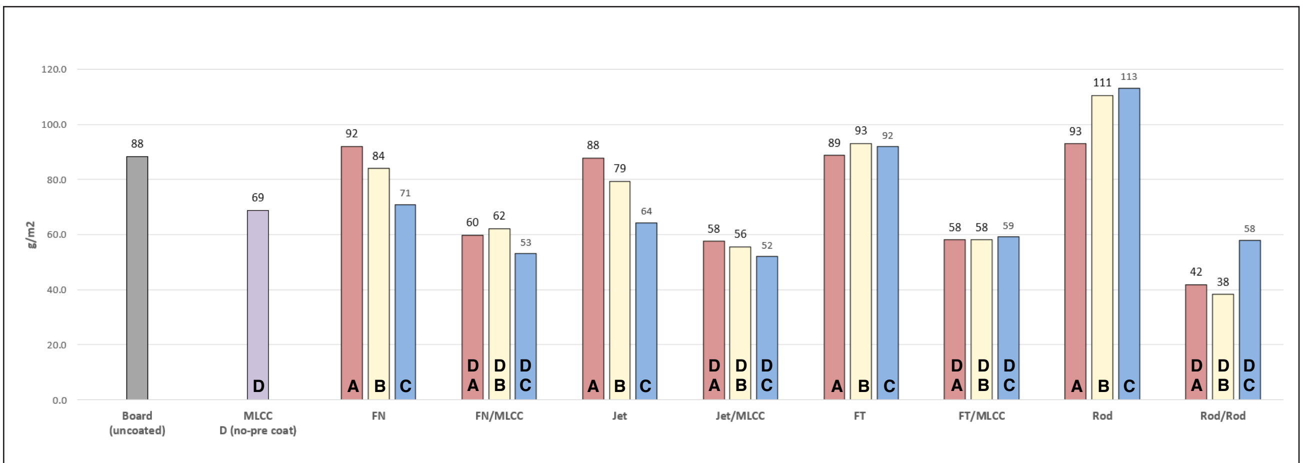
Overall, the barrier topcoat used in this study is effective at reducing moisture barrier. For paperboard, there may be only a slight impact of precoat on performance, which is notable considering the variability in precoat roughness, porosity, and chemistry. On paper, precoat composition appears more impactful, with Formulation C showing consistently improved performance, which is likely due to the chemistry used or perhaps a higher latex-to-pigment level.

Barrier – liquid water permeation

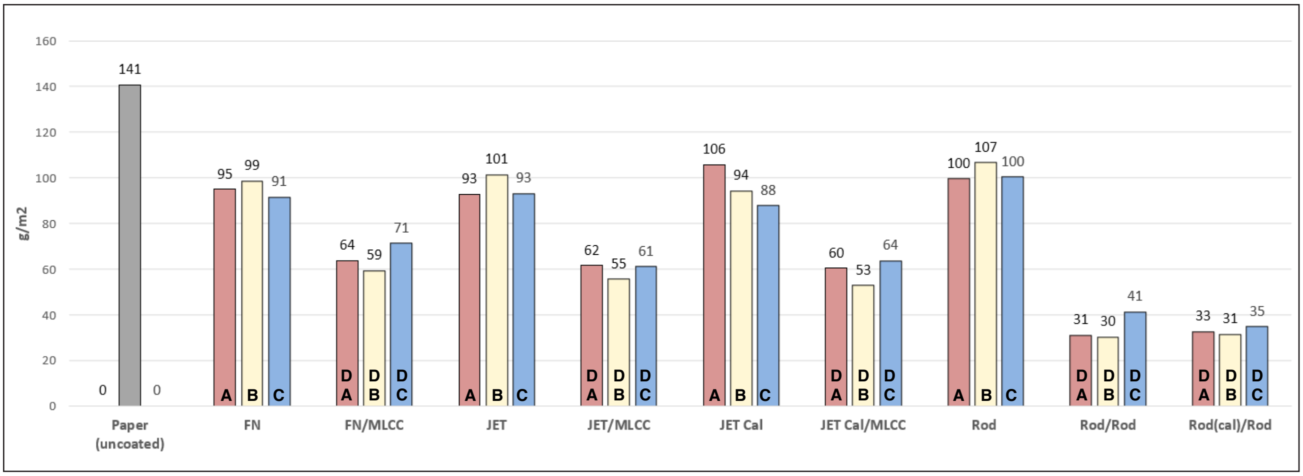
Liquid water permeation was assessed using a 2-min Cobb test. Formulation D was specifically chosen for this study, because it typically does not provide a high liquid water barrier, making it ideal for investigating the impact of precoat chemistry.

Uncoated paperboard has an average water permeation of 88 g/m², as shown in **Fig. 11**. Formulation A does not reduce water permeation with any application method (including laboratory rod coating), while Formulation C improves liquid water resistance when applied using FN or Jet, but not FT or rod. Formulation D applied directly to board (no precoat) is about as effective as Formulation C precoat.

For all application methods, water permeation is reduced when topcoating precoated board. For FN and Jet, Formulation C is most effective, while for FT, all three precoated board samples produce similar results. This suggests



11. Paperboard water permeation (Cobb test) for paperboard samples. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater.)



12. Paper water permeation (Cobb test) for paper samples. (A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Cal: calendered; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater; Rod(cal): calendered lab drawdown coater.)

that chemistry may be less important for water barrier than other precoated surface properties, such as porosity and roughness. Formulation C provides the largest reduction in water permeation and is most effective at sheet porosity reduction, highlighting a potential relationship worth further exploration.

Rod applied precoats generate higher water permeation compared to pilot coater samples, particularly for Formulations B and C. However, when topcoated with Formulation D, water permeation values are significantly lower than pilot coater-applied samples with precoat Formulations A and B, while Formulation C performs similar to FT.

As shown in **Fig. 12**, paper has an uncoated average water permeation value of 141 g/m², which is 60% higher than paperboard despite their basis weight difference (90 g/m² for paper vs. 350 g/m² for board). This implies the paperboard used in this study is more liquid water resistant, possibly due to the presence of hydrophobic additives, such as a sizing agent.

Both FN and Jet produce similar responses on paper, with Formulation C and A showing a slight performance advantage over Formulation B. When topcoated with Formulation D, values improve to the range observed for board substrates, but with Formulation B now showing the best average performance. Formulation B's improvement in liquid water barrier may imply that the thinner, more hygroscopic paper substrate benefits from reduced surface roughness, for which Formulation B is most effective.

Laboratory rod-coated substrates again show different performance than pilot-coated samples. Precoat only results are generally similar to pilot coater samples, but when topcoated with Formulation D, laboratory produced samples are measured to have 50% lower water permeation. Calendering the precoat prior to topcoating has no impact.

Overall, water barrier results indicate the potential role of precoat influence on total article performance. Based on formulation specific performance, paperboard data may indicate that surface porosity is important for liquid water barrier, while for paper surface, roughness may be more impactful. Of course, these observations would not be exclusive to paper or paperboard, but are more representative of their base qualities, including attributes like initial liquid water barrier, presence of sizing agents, fiber source, etc. More study is required, as these results are specific to the substrates available for this work.

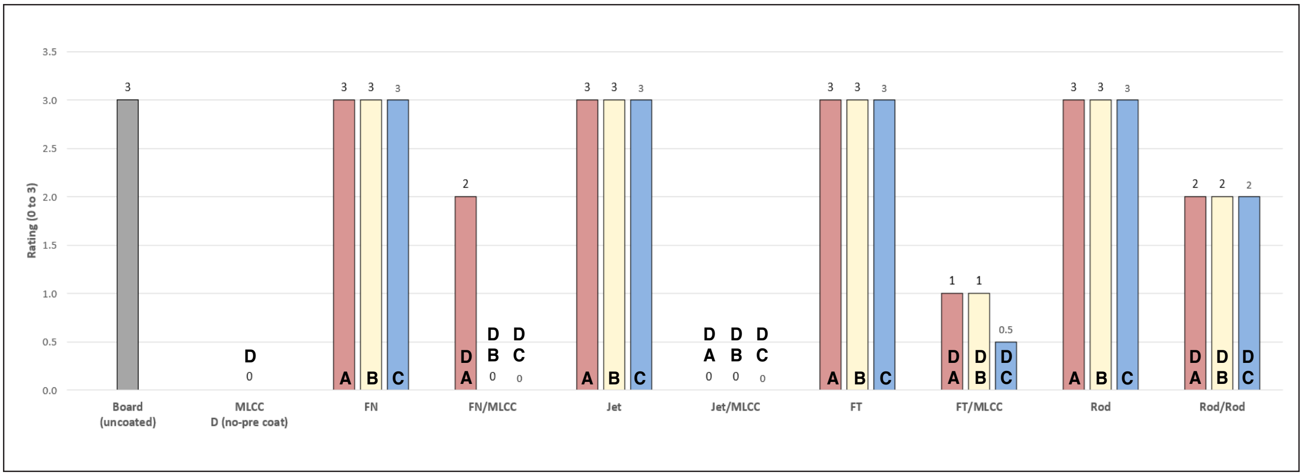
Barrier – oil resistance

Oil resistance was assessed using a simple, in-house visual method. A measured amount of canola oil (few drops) was placed onto the article surface. After 24 h, the oil was removed, and the surface was assessed as follows:

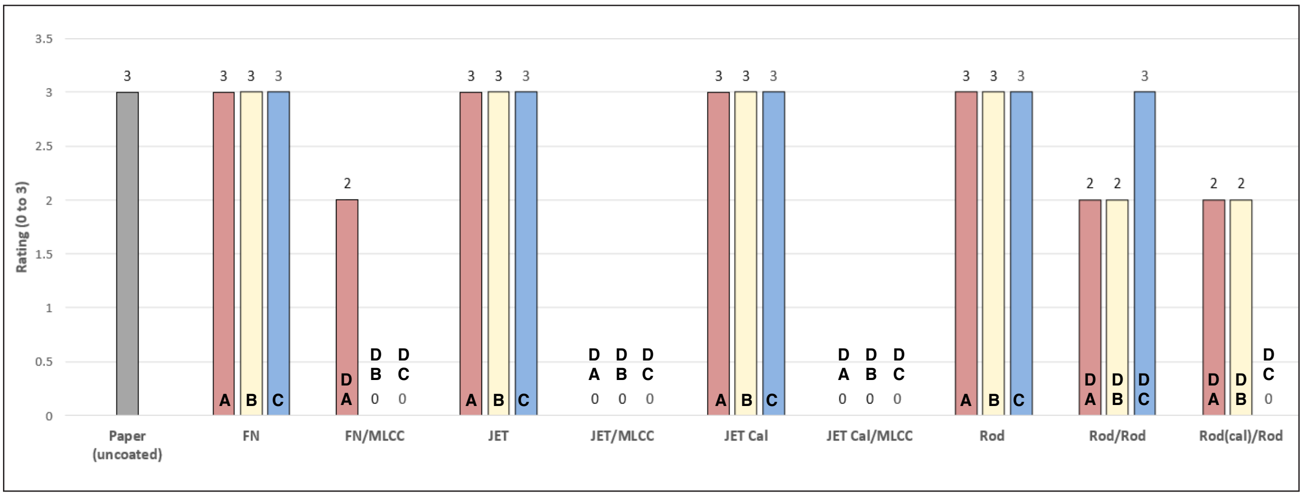
- 0: no pinholes or oil breakthrough
- 1: pinhole defects; no significant oil breakthrough
- 2: region saturation; no oil breakthrough
- 3: region saturation and oil breakthrough (oil migrates through the sheet)

Oil barrier for paperboard coated articles is shown in **Fig. 13**. The uncoated sheet has no meaningful oil barrier, with oil essentially permeating through. No precoat formulations improved oil barrier on their own. As mentioned earlier, precoats are above critical pigment volume concentration, which allows liquids (including oil and water) to move rapidly through the substrate.

Formulation D, which is effective at reducing porosity on paperboard, achieves the highest oil barrier ranking (rating 0). All board precoated samples without topcoat provide no oil barrier (rating 3). When Formulation D is applied as a topcoat on precoated substrates, varying performance is observed. For jet precoated samples, total oil hold-out is observed with a Formulation D topcoat. However, for film transfer coated precoats. lesser performance



13. Oil barrier for coated paperboard. (0: no oil migration; 1: pinholes; 2: saturation; 3 breakthrough; A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater.)



14. Oil barrier for coated paper. (0: no oil migration; 1: pinholes; 2: saturation; 3 breakthrough; A: standard precoat formulation; B: modified precoat formulation; C: barrier precoat formulation; D: barrier topcoat; FN: flooded nip; FT: film transfer; Cal: calendered; Jet: jet applicator; MLCC: multilayer curtain coater; Rod: lab drawdown coater; Rod(cal): calendered lab drawdown coater.)

is observed with a Formulation D topcoat. Flooded nip applied precoats show differing performance based on precoat chemistry, with precoat A performing worse than precoats B or C.

Laboratory rod-coated precoats on paperboard perform the same as pilot coater samples (no oil barrier) but significantly worse (rating 2) for finished articles (precoat and topcoat) and show no performance differentiation based on composition (A, B, and C are equal). As with liquid water measurements, laboratory coated samples appear to poorly track performance for pilot coated substrates.

Similar oil barrier performance is observed for paper, specifically in that precoated paper provides no oil barrier and that total constructions using jet applied precoats provide excellent oil barrier performance (**Fig. 14**). However, for FN, Formulation A fails to achieve a high oil barrier. As with paperboard, laboratory coated finished articles show poor oil barrier, mostly inconsistent with pilot coated samples. Calendering of laboratory applied precoated samples does not improve performance for Formulation A or B, but interestingly does so for Formulation C.

Oil barrier performance is difficult to understand based on controlled parameters. Taken as-is, results imply that oil barrier can be influenced by precoat application method and that applying a high oil barrier topcoat is not always sufficient for achieving complete oil barrier. With flooded nip, Formulation A underperforms on both paper and paperboard. As mentioned early, Formulation A applied by flooded nip tends to be least effective at roughness reduction but is only moderately different to other precoat formulations.

There may be unmeasured factors influencing results, such as incomplete film formation (perhaps due to precoat surface energy) or coating damage while preparing sheets for analysis (e.g., coating fusing to the uncoated sheet during wind up and partial removal during sample preparation) that explain these observations. However, these scenarios fail to explain why other samples, including Formulation B, Formulation C, or jet-applied Formulation A, do not show similar performance.

CONCLUSIONS

In this study, we examined the impact of precoat composition and application methods on roughness, porosity, and barrier performance for purpose-built paper and paperboard constructions produced using pilot coater and laboratory application.

Application method clearly has an impact on roughness. Flooded nip and jet applied precoats reduced roughness more than film transfer, consistent with the known impact of metering. A smoothening additive was demonstrated to reduce roughness significantly more (30% to 40%) compared to a similar precoat formulation without an additive. Calendering precoated paper also helped reduce surface roughness (by up to 60%) compared to uncalendered samples. Surprisingly, the wide range in roughness of precoated substrates (5.3 to 1.8 µm) did not appear to directly correlate with finished article (topcoated) barrier performance.

Similarly, porosity differences were observed between samples based on application method and precoat, but those differences are challenging to explain. Topcoat barrier (Formulation D) applied directly to paperboard effectively seals the substrate (porosity value out-of-range), implying all topcoated articles should be similarly sealed. While there may be unique interactions with the precoat that prevent the barrier topcoat (Formulation D) effectiveness, other phenomena, such as unexpected sheet damage from sample preparation (localized blocking) could also drive this curious observation. As with roughness, no direct correlation between measured porosity and oil, water, or moisture barrier was identified.

Moisture barrier of finished paperboard articles was not significantly impacted by the presence of precoats used in this study or application methods. Barrier topcoat applied directly to paperboard (no precoat) produces an MVTR of 50 g/m^2/day (23°C/50% RH). With precoat, values range from 40 to 70 g/m^2 day, providing little improvement, if any. Variations in roughness and porosity (detailed previously) appear to be inconsequential (at least within the ranges shown in this study). For paper coated articles, precoat composition may impact performance with Formulation C (barrier precoat), which modestly outperforms the standard precoat formulation (Formulation A).

Liquid water barrier may be improved when using a precoat, with liquid permeation values (Cobb) decreasing by up to 25% compared to topcoat alone. Based on absolute averages, barrier precoat (Formulation C) may offer a slight advantage over other precoats when using our paperboard substrate, while on paper, Formulation B offers slightly better performance. Interestingly, calendering (laboratory or pilot coater) did not seem to impact liquid water barrier.

Formulation D provides an effective oil barrier (rating of 0) directly to paperboard, meaning improvement would not seem possible based on precoat adjustments. Despite this situation, not all finished articles provide the same level of barrier, suggesting that poor choice of precoat chemistry or application method could disrupt oil barrier performance of a topcoat.

Laboratory produced samples failed to consistently simulate output from pilot coater runs. For roughness, laboratory drawdowns most closely resemble film transfer, failing to approximate reductions in blade metered precoats, suggesting laboratory rod drawdowns are a poor approximation to industrial scale application methods that utilize post-application metering. Calendering laboratory precoated articles prior to topcoat application more closely resembles pilot coated samples, at least on paper, suggesting one approach to equalizing the coating methods.

Barrier measurements from laboratory coated samples failed to consistently match values from pilot coated samples. For moisture barrier, laboratory coated article's MVTR could be 1.8x higher than pilot coated articles. With liquid water barrier, laboratory coating overestimates performance compared to pilot coated samples, at least for substrates examined here. For both paper and paperboard, laboratory applied finished articles show significant oil penetration, meaning the laboratory technique underestimates oil barrier compared to some pilot coater applied samples.

Overall, when designing a barrier coated article, it appears that precoat selection and application method may moderately influence barrier properties or have no impact. Laboratory applied rod coated samples often differed from pilot coated systems in terms of barrier performance, suggesting their use as a guide in simulation experiments may be misleading. **TJ**

ACKNOWLEDGEMENTS

The authors would like to acknowledge the significant contributions made in support of this paper provided by the technician staff at Trinseo's application laboratory and pilot facilities in Midland, MI, USA, and its Rheinmünster, Germany, application laboratory and pilot curtain coater.

LITERATURE CITED

1. Gaskin, E., Preston, J., Findlay, A., et al., *O Papel* 81(1): 66(2020).
2. Pokharel, K., Bousfield, D.W., and Wang, J., *TAPPI J.* 24(1): 36(2025). https://doi.org/10.32964/TJ24.1.36.
3. Rättö, P., Junel, K., and Valtakari, D., *TAPPI J.* 22(11): 665(2023). https://doi.org/10.32964/TJ22.11.665.

4. Boyle, T. and Welsch, G., "Influence of applicator technology on starch migration," *TAPPICon*, TAPPI Press, Peachtree Corners, GA, USA, 2014.

5. Kuni, S. and Lares, M., "Jet coating technology for high quality board," *TAPPI Coat. Conf.*, TAPPI Press, Atlanta, 2002.

6. Ek, M., Gellerstedt, G., and Henriksson, G., *Paper Chemistry and Technology,* Vol. 3, De Gruyter, Berlin/New York, 2009, p. 356. https://doi.org/10.1515/9783110213447.

7. Renvall, S. and Antilla, T., "High speed coating development," *TAPPI Coat. Conf.*, TAPPI Press, Atlanta, 1996.

8. Stranger, K., "Vector-linear web run in the Combi-Blade," *Paper Industry Technical Association*, Bury, UK, 1999, Session 1, Paper 5, p. 37.

9. Urscheler, R., Roper, J., and Dobler, F., et al., "Multilayer curtain coating – an enabling technology for increased efficiency and new paper grades," *PTS Symp.*, Papiertechnische Stiftung, Heidenau, Germany, 2006.

ABOUT THIS PAPER

Cite this article as:
Piwowar, A. and Welsch, G., *TAPPI J.* 24(11): 549(2025). https://doi.org/10.32964/TJ24.11.549

DOI: https://doi.org/10.32964/TJ24.11.549

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

ABOUT THE AUTHORS

We studied this topic to better understand underlying paper construction attributes contributing to barrier performance to enable cost-effective, optimized product design in food contact applications. We did not uncover any prior research where coating methods were compared for the purpose of determining if the basecoat application technique had an impact on barrier coating holdout and the resulting performance.

One particularly difficult aspect of this study was the large number of samples produced on a pilot coater that required over three weeks of run time. We also found it challenging to generate broad conclusions despite such a large sample set. We were most surprised that there was a relatively minor contribution from standard precoat formulations towards total barrier performance.

Mills might consider the information presented here as they look to optimize topcoat barrier formulation and thickness. Our next step in this research is precoat modifications for improving barrier (pigment, latex loading, additives).

Piwowar is Technical Service and Development specialist at Trinseo LLC, Midland, MI, USA. Welsch is global director, Technical Service and Development, at Trinseo LLC, Midland, MI, USA. Email Piwowar at apiwowar@trinseo.com.

Piwowar

Welsch