Rheological characterization of tack and viscoelasticity of compositions of crepe coating used in the Yankee dryer

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ABSTRACT: The vast majority of tissue production uses creping to achieve the required set of properties on the base sheet. The Yankee coating helps to develop the desired crepe that in turn determines properties such as bulk and softness. The adhesion of the sheet to the Yankee surface is a very important characteristic to consider in achieving the desired crepe. The coating mix usually consists of the adhesive, modifier, and release. A good combination of these components is essential to achieving the desired properties of the tissue or towel, which often are determined by trials on the machine that can be time consuming and lead to costly rejects. In this paper, five compositions of an industrial Yankee coating adhesive, modifier, and release were examined rheologically. The weight ratio of the adhesive was kept constant at 30% in all five compositions and the modifier and release ratios were varied. The normal force and work done by the different compositions have been shown at various temperatures simulating that of the Yankee surface, and the oscillatory test was carried out to explain the linear and nonlinear viscoelastic characteristic of the optimal coating composition.

Application: Towel and tissue producing mills can predict the behavior of coating compositions before performance trials are carried out on the Yankee dryers. Combinations of coatings can be tested for their rheological properties to determine which composition will give the best creping and quality performance without the need for large-scale machine trials.

Creping is one of the key technologies used in tissue production. For creping, as in many areas in tissue technology, much of the information available on Yankee coatings is kept proprietary by tissue manufacturers [1]. In creping, the dried paper adhered to a large drying cylinder called the Yankee is peeled off the cylinder with a stationary doctor blade, resulting in folds in the final tissue paper sheet. Crepe in the tissue paper is evaluated and measured by various techniques because it is largely responsible for creating the final “feel” and sensory properties of the tissue paper. As a key technology in tissue making, the Yankee coating system used in this process is one of the factors resulting in the most patents and research.

Situated at the interface between the Yankee dryer surface and the tissue web during operation is the Yankee coating. The Yankee coating is a complex agglomerate of chemical additives that is sprayed onto the Yankee surface to help with adhesion of the tissue web and its release and also to protect the Yankee surface. Coating typically consists of adhesive, modifier, and release and sometimes a separate monoammonium phosphate part that serves as the base layer to protect the Yankee surface.

The surface of the Yankee has a highly polished or a smooth finish that promotes an efficient heat transfer from the Yankee surface to the sheet and reduces the wear on the creping blade [2]. The fiber-to-fiber bonds are broken down as the high-speed traveling web on the Yankee surface impacts onto the doctor blade and introduces a submillimeter wavelength corrugation in the tissue [3]. The creping action’s impact on the final structure in the tissue can be seen and measured by the frequency and amplitude of the corrugated folds in the tissue paper that comes out of the Yankee. These patterned folds are also present in the final tissue. For example, tissue paper crepe of high frequency is described as “finer” and is usually desirable because it produces softer tissue products. Furthermore, this creping action increases the bulk and absorbency of the tissue, improves the stretch, and enhances the softness of the tissue and hand-feel properties.

Several potential variables can affect the creping process. These variables are machine mechanical setup and spray boom mechanics (e.g., blade loading, blade geometry, and blade pocket angle), coating chemistries (e.g., number of coating components, ratio of components, and amount of coating used), and process variables (e.g., the Yankee temperature and speed, crepe ratio, fiber types, wet-end chemical additives, moisture, and pH) [4]. Several researchers have reported laboratory, pilot, and commercial machine trials that have been carried out to investigate how changes in these three variables can affect the performance of the coating mix on the Yankee surface. The scope of this paper is limited to understanding how the relative proportion of coating chemicals affects creping.

The first part of the Yankee coating, which is a complex agglomerate, is the Yankee adhesive. The most common Yankee adhesives are polyvinyl alcohol, polyacrylamide, polyamine, and those based on polyaminoamide-epichlorhydrin (PAE) chemistry such as the crosslinking and noncrosslinking PAEs [5].

The second part of the Yankee coating is the modifier. Crepe modifiers typically serve to influence the properties of the adhesive, such as lowering its hardness and increasing the water absorption capacity, and as such must possess some degree of miscibility with the adhesive polymers and have low vapor pressure at dryer temperatures. Some modifier options include ester glycols, poly glycols, and tertiary and quaternary nitrogen compounds [6].

The third part is the release agent. The release is an important factor in creating the Yankee coating because it controls the release of the tissue. Most release materials are oil based, such as emulsified oils, surfactant-type materials, or petroleum distillates. Release agents aid in the uniform release of the web at the crepe blade and lubricate and protect the blade from wear [2].

The relative proportion in which these components are combined depends on the needs and desired final properties of the grade of tissue being produced. The coating property can be adjusted by changing the ratio of the components. Archer and others [5,7] explained how adjusting a coating property along one axis will result in concurrent movement along one or both of the other axes using a coating space model in 3D. These axes that define the coating film properties include adhesion of the moist web to the Yankee surface at the pressure roll nip, durability of the coating package in high moisture conditions of drying and creping, and the softness (or hardness) of the coating to provide the appropriate level of blade tip penetration during creping.

Ho et al. [3] developed a pilot tissue creping test rig that measures creping effectiveness online by varying the Yankee temperature, coating add-on rate, and rewind tension. Creping effectiveness was measured online from reduction in web length and the force required to doctor the tissue off the cylinder and offline by measuring the change in thickness, strength, and stretch of the samples. The test was carried out using dried rolls of a specialty uncreped tissue grade as feed; the test rig machine does not have a forming and pressing section. By increasing the temperature on the Yankee, the thickness, stretch, and strength increased at a high constant coating add-on rate of 300 mg/m^2. The base sheet properties of thickness, stretch, and strength decreased with increased web tension at the same add-on rate.

Lu and others [8] subjected three commercial creping adhesives to peel adhesion (at 180° angles), rewettability, and insolubility tests in the laboratory. The three adhesives are conventional crosslinking PAE that crosslinks and hardens during use on the hot Yankee surface, a conventional precrosslinked PAE, and a novel proprietary adhesive. Two different profiles at 93°C and a short drying period (30 s) and 110°C and a longer drying period (5 min) were used in the test to simulate low temperature/high moisture and high temperature/low moisture conditions, respectively.

The crosslinking PAE had a high insolubility and low rewettability and was more suited for the low temperature/high moisture application. The precrosslinked PAE had low insolubility, easily washed away from the Yankee surface, and was very rewettable; therefore, it was a better option for the high temperature/low moisture application. The proprietary adhesive possessed properties that were between these conventional PAE additives and could be used in a wider range of applications.

The viscoelastic property of coating can be used to describe the adhesion performance of the coating. The storage modulus represents the elastic or solid portion of the material whereas the loss modulus represents the viscous portion. A higher loss to storage modulus ratio (tan delta) indicates a liquidlike coating with low cohesion strength and can be used to describe the precrosslinked PAE. By contrast, a higher storage to loss modulus (low tan delta) indicates that the coating hardens at the pressure roll and can describe the crosslinking PAE. The novel adhesive should have viscoelastic properties that are between the two PAEs [8]. Viscoelasticity has been used to predict tack in different bonding applications, especially in pressure sensitive adhesives (PSAs). Extensive studies have been done to establish a relationship between shearing rheology and tack or peel adhesion in PSAs. The formation of fibrils is essential for a good tack performance, and the highest tack strength occurs when the adhesive is not strongly crosslinked [9]. Little has been reported on the correlation between shearing rheology and coating adhesives.

Furman [2] did a similar peel test experiment to that of Lu at 90° angles by applying paper strips on a heated metal panel. Different types of adhesives were compared by measuring the force required to peel the paper strips off the heated metal surface coated with these adhesives. The modified polyacrylamide was found to give a significantly higher adhesion than the polyvinyl alcohol, polyamine, and PAE adhesives. This test was scaled up to the machines. The results were consistent with the laboratory results and support the use of the laboratory test as a screening tool

Limited work has been published on predicting the performance of creping coating compositions over a range of temperatures and compositions on a laboratory scale. Choi and Patterson [4] investigated 38 individual runs of samples at different adhesive, modifier, and release compositions using a crepe simulator (Yankee, crepe blade, roll, and other components in miniature). The results from the study provided the ability to predict coating package performance over various conditions. They showed that at a constant Yankee temperature and pressure roll loading, an increase in the release relative to the adhesive decreases the crepe force. Conversely, an increase in the modifier percentage augments the crepe force.

In this paper, five compositions of an industrial Yankee coating adhesive, modifier, and release were examined at dif-

Coating Additives	Density, g/cm³	Viscosity at 20°C, mPa·s	pH	Flash Point, °F
Adhesive	1.05–1.07	50–100	4.4–5.4	Does not flash
Modifier	0.96–1.04	300–700	6.2–7.2	>200.1
Release	0.91	25	5.5–6.0	351.0

I. Physical properties of coating additives.

ferent temperatures using both tack testing and viscoelastic measurements. The weight ratio of the adhesive was kept constant at 30% in all five compositions and the modifier and release ratios were varied. The maximum normal force and work done by the different compositions have been shown at various temperatures simulating that of the Yankee surface. The oscillatory test was carried out to explain the linear and nonlinear viscoelastic characteristic of the optimal coating composition.

EXPERIMENTAL

Three commercial creping coating additives (adhesive, modifier, and release) were used for the experiments. These additives are shown in **Table I**. The adhesive comprises 10% monoammonium phosphate and 20% plasticizer incorporated into it by the chemical manufacturer.

The five compositions of coating additives as shown in **Table II** were weighed out with a weighing balance in vials. The components of each composition were homogenized with a vortex mixer to yield a uniform sample. The experiments were conducted with an MC 302 parallel plate rheometer (Anton Paar; Styria, Austria) with a 25-mm plate.

For the tack tests, tack analysis for adhesive coatings was selected on the rheometer with a 0.3-mm spacing between both plates and a pull up speed of -5 mm/s with 50 measuring points. The instrumental procedure for the tack test is as follows. The homogenized sample is dispensed from the vial with a disposable pipette onto the stationary bottom plate and the measuring system is operated so that the upper plate is lowered and positioned in contact with the sample with the constant normal force applied. After a short wait time, the measuring system is moved upward from the sample with a constant speed of -5mm/s and the pull force is measured in negative values.

For the oscillatory tests, the 0.3-mm plate spacing was maintained and amplitude sweep performed from 0.1% to 1000% at a standard constant frequency of 10 rad/second (1 Hz). Rheoplus software (Anton Paar) installed on a remote PC recorded the experimental data. The surface temperature of the rheometer plates was selected to simulate the temperature at the Yankee surface (except for the 25°C temperature) and was regulated by a Julabo F32 water jacket (Julabo; Allentown, PA, USA).

RESULTS AND DISCUSSION

The experimental method used in this work is a simple and relatively faster way to measure tack adhesion of coating used on the Yankee dryer. This eliminates the trial and error involved with large-scale machine trials. The efficiency of creping is related to how well the paper web adheres to the dryer, which is dependent on the performance of the coating mix. Liquids will be more or less tacky within a range of viscosity. As the viscosity of the liquid increases or decreases, the tack decreases in both cases [9].

Tack characteristics of the coating compositions

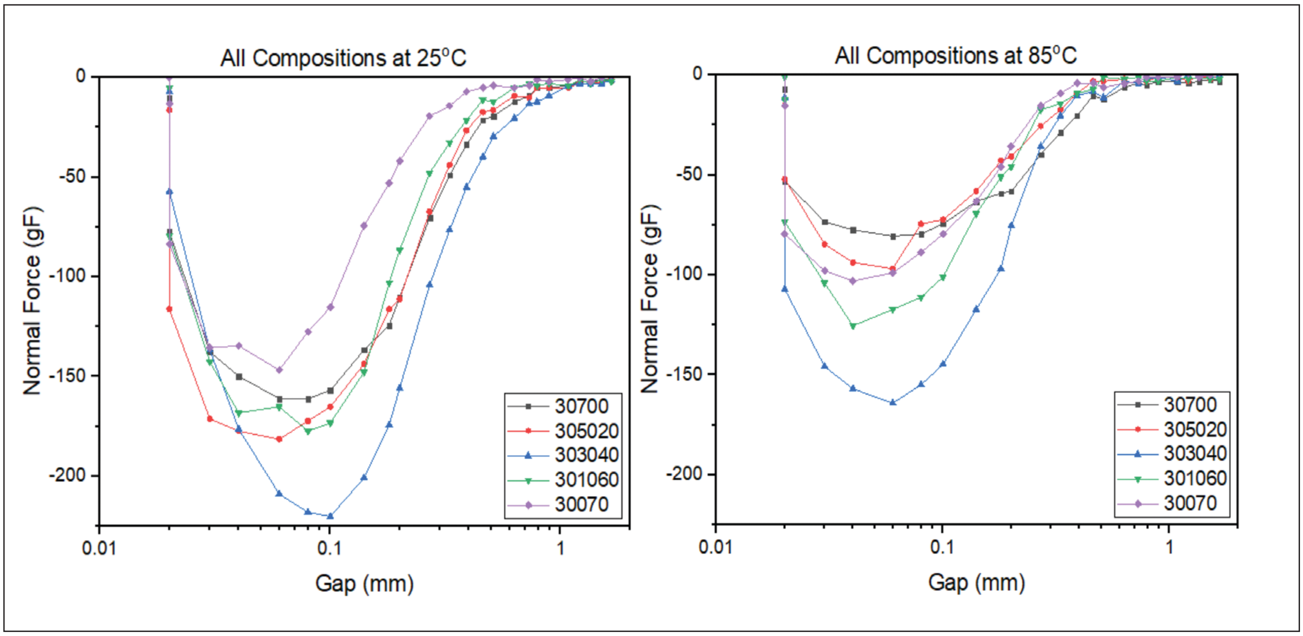
The analysis criteria in the results shown in **Figs. 1** and **2** are the maximum pull force that is represented by the peak of the curve and the energy (or work) of separation calculated by the area below the force-displacement curve [10]. Adhesive bonding failures are either cohesive or adhesive in nature. A cohesive failure occurs in the bulk layer of the adhesive and an adhesive failure occurs at the interface between the adhesive and the material being adhered [11].

Figure 1 (left) shows the behavior of the compositions at ambient temperature (25°C) and 85°C. The test was carried out at the ambient temperature as a control for the other tests that were done at temperatures typically observed during creping on the Yankee. The shape of the curve gives relevant information about the cohesive and adhesive natures of the compositions and is affected by the temperature, the pressing force, and removal speed [9].

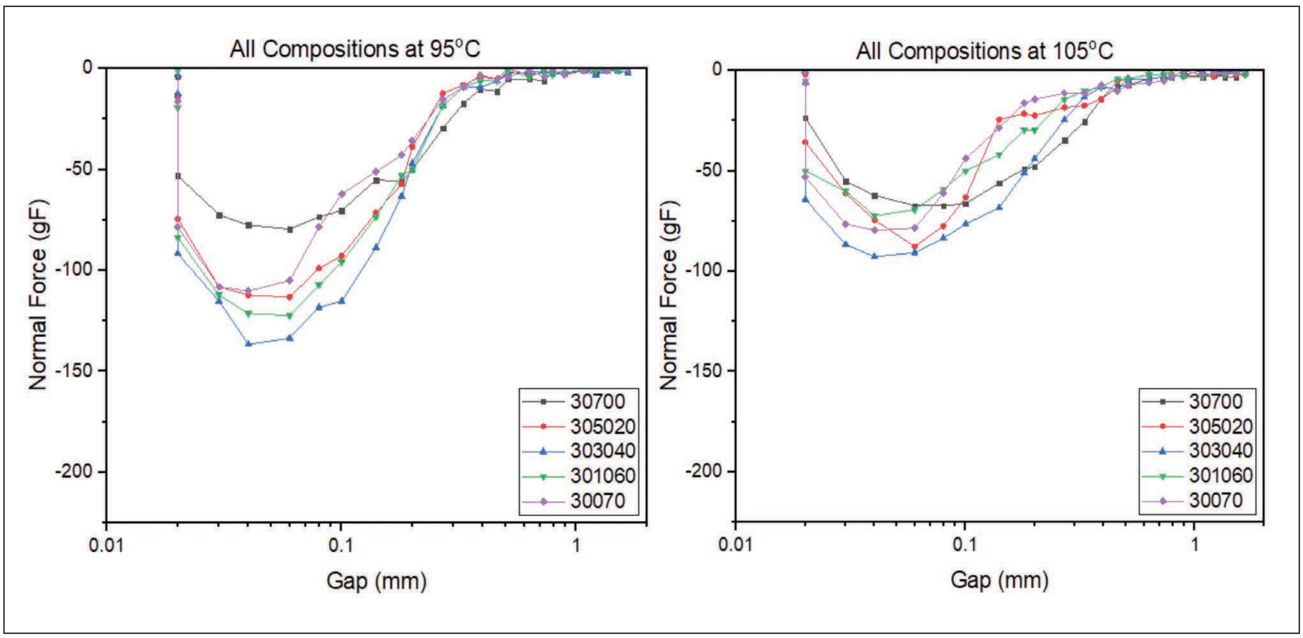
The shape of the curve gives relevant information about

Coating	25°C					85°C					95°C					105°C				
Adhesive	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Modifier	70	50	30	10	0	70	50	30	10	0	70	50	30	10	0	70	50	30	10	0
Release	0	20	40	60	70	0	20	40	60	70	0	20	40	60	70	0	20	40	60	70

II. Coating compositions by weight tested at different temperatures.

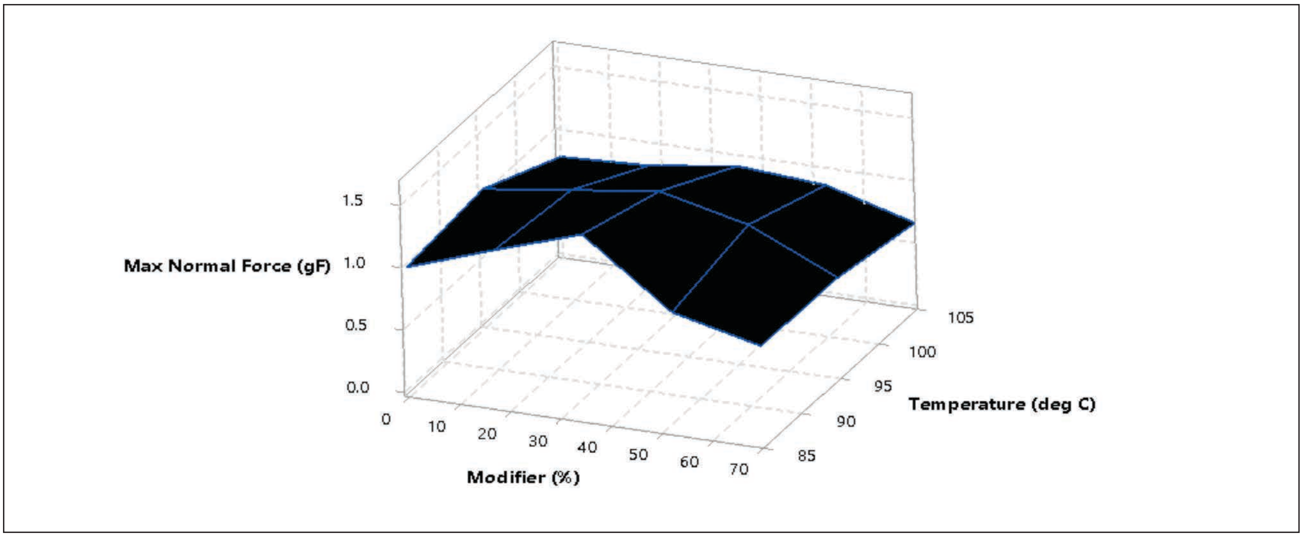


1. Force-displacement curve of all five compositions at 25°C (left), and force-displacement curve of all five compositions at 85°C (right).

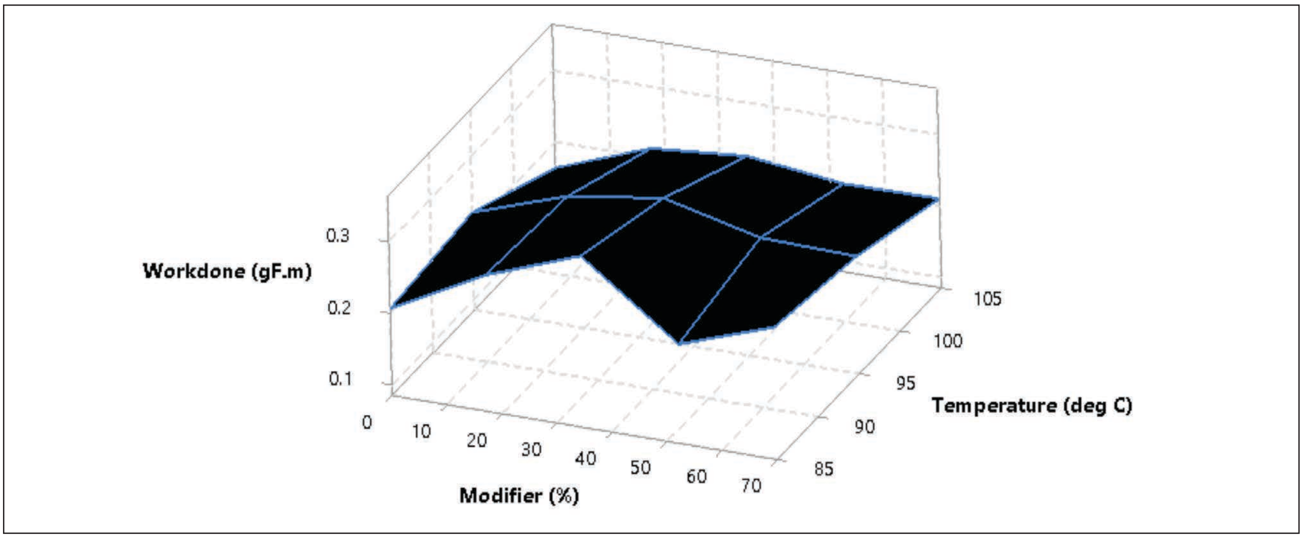


2. Force-displacement curve of all five compositions at 95°C (left), and force-displacement curve of all five compositions at 105°C (right).

the cohesive and adhesive natures of the coating composition. The minimum force and the surface area above the normal force curve are used as analysis criteria. The maximum force is a measure of the cohesive behavior and the surface area is a measure of the energy required for separation or of the adhesive behavior [10]. If there is a steep fall in the curve and a deep spiked negative minimum force (maximum pull force) followed by a steep rise in the curve, the sample is low-deformable, stiff, and tends to form cracks [9,10]. If there is a shallow fall in the curve, then the sample normally shows more pronounced stringing (smooth rise in curve and stretching along the horizontal axis). The 303040 composition appears to have the highest cohesion shown by the highest pull force (-220.25 gF) and more adhesion from the large area under the graph because it stretches along the horizontal axis more than the other compositions. The 303040 was easily identified as having the most tack, even by feeling between the fingers. The 30070 composition with no modifier has the smallest pull force and the least area under the curve. The 30070 curve also appears to be the steepest. The other three



3. Work done versus modifier % and temperature.



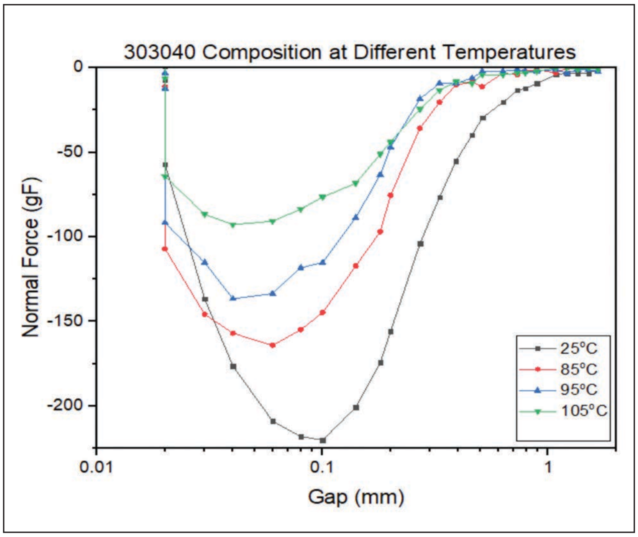
4. Maximum normal force versus modifier % and temperature.

compositions fall between these two in performance at ambient temperature.

With the continued trend toward creping at increasing temperatures and low moistures, not many dry crepe operations occur at 85°C Yankee surface temperature. The 303040 composition clearly has the highest pull force and area under the graph. Therefore, it exhibited better cohesive and adhesive characteristics relative to other compositions. The 30070 with no modifier had a higher pull force than 30700 and 305020 but falls least in terms of energy of separation or adhesion. The 30700 composition has a longer shoulder along the displacement axis and therefore shows more pronounced stringing and adhesion than the 30070 composition. The 301060 composition came in next to the 303040 composition.

Figure 2 shows the curves at 95°C and 105°C typical of the temperatures obtained during dry crepe. There is a downward trend in the pull force and work of separation from the test at 25°C as the curves appear to shrink. This is expected because as the adhesive mix becomes hardened at elevated temperatures, the modulus increases and flow resistance increases, thereby reducing the cohesive bond-to-bond interaction within the coating mix and the interfacial adhesion. The 303040 composition remains the best at these two temperatures in terms of cohesion and adhesion. The 30070 composition with no modifier maintained the same trend from the 85°C test with a higher pull force than 30700 but weaker adhesion. The stringing from the 30700 composition without release is still evident in the two graphs. The intermediate compositions of 305020 and 301060 appear to have similar characteristics at the 95°C test.

The 105°C test had the smallest pull forces and area under the curve in all compositions for the reasons already discussed. Machine trials that compared the 30700 and 305020 compositions at 96°C surface temperature showed that the 305020 base sheet had a slightly better hand feel and lower



5. Force-displacement curves of 303040 compositions at different temperatures.

moisture than the 30700 base sheet. This agrees with the laboratory data for work done, as shown in **Fig. 3**.

Maximum normal force and work of separation

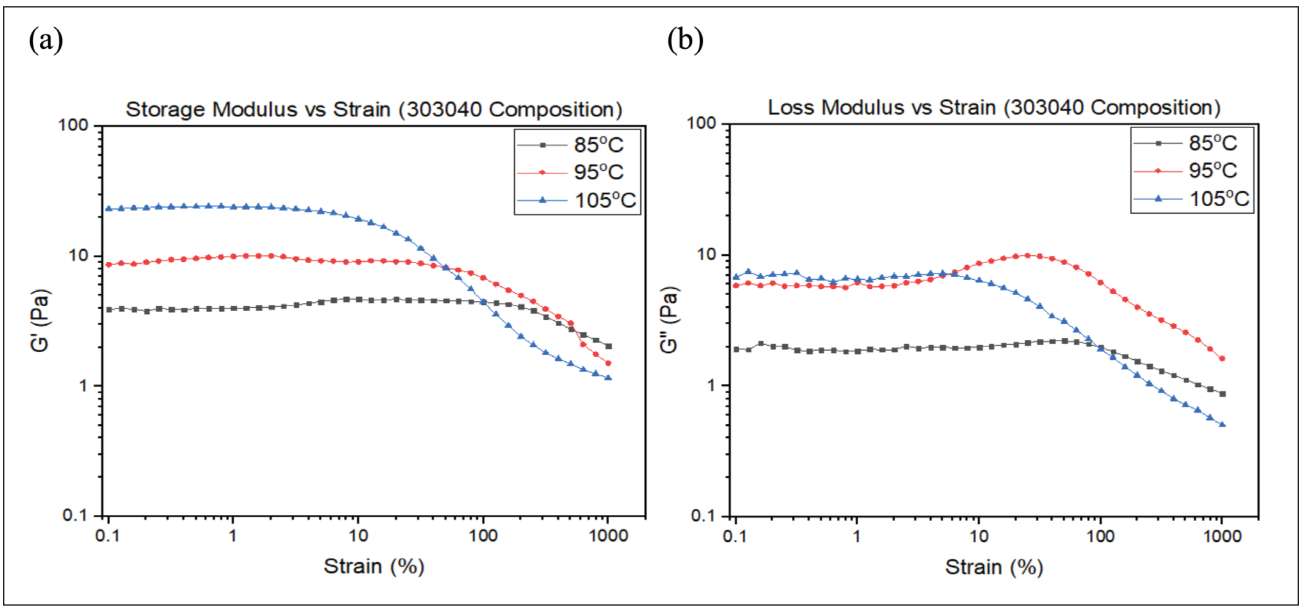
Figure 4 shows a 3D graphing of the maximum pull forces of the tack test of the compositions. The rheometer data were recorded in newtons and converted to gram force values. The adhesive ratio was held at 30% through all five compositions, and the modifier and release amounts were varied from no modifier to maximum amount of modifier. The maximum normal force can be thought of as the force required to break the cohesive bonds. As shown in the figure, there tends to be an optimal composition of the modifier for maximizing the normal force. Modifier percentages below and above this concentration show a decline in the normal force. This finding is similar to the work by Rose [6]; that is, the optimal percentage of water-based modifier (as a percentage of total adhesive) that gave the base sheet with the best hand feel is at 10% and 20%. Below and above these percentages, the hand feel quality drops.

The 303040 mix is the optimal composition through all the temperatures that were tested. Except for the 303040 composition at 85°C, which created the peak on the front line (85°C line) of the graph, the optimal temperature for maximizing the normal force appears to be at 95°C for all other compositions. The 70% modifier (30700) has the lowest pull force across all temperatures shown and as a result has the most cohesive failure. This has been shown with the tack curves in Figs. 1 and 2 and is closely followed by the 0% modifier composition (30070).

The work done is the energy of separation of the coating mix that indicates how much adhesion is obtained from the coating. Again, the optimal temperature for maximizing the energy of separation is at 95°C, except for the 303040 composition. The 303040 is the optimal composition at all temperatures, as shown in the 3D graph of Fig. 3. From the front view of the Fig. 3 plot, as the modifier increases, there is a downward slope and then it rises at the 70% modifier concentration for 85°C and 105°C. This is explained by the stringing of the 30700-composition shown in the tack curves. The work done for the 305020 (25.8 gF·m) composition is slightly higher than that for the 30700 (25.4 gF·m) at 95°C.

Effect of temperature

The effect of temperature is shown using the optimal composition in **Fig. 5**. The maximum normal force and area under



6. Strain amplitude sweep of the 303040 composition at constant frequency of 10 rad/sec (1 Hz): (a) storage modulus and (b) loss modulus.

the graph decreases as the temperature rises. The modulus of the polymer mix increases as a result of crosslinking and causes the coating to become stiff and brittle, thereby reducing its adhesiveness. The graph shows the test at 25°C to have an extended shoulder and therefore more stringing.

Viscoelasticity

Viscoelastic measurements give insight into the underlying microstructure of the coating mix. The rheometer oscillatory tests were used to investigate linear viscoelastic (LVE) characteristics of the coating. The primary interest in viscoelastic tests would be the storage (elastic) and loss (viscous) modulus, which describes the stiffness of the material [12]. In this case, an increasing strain amplitude was applied, and the response was given as the storage and loss modulus at the temperatures shown. **Figure 6** shows the storage and loss modulus at 85°C is the lowest and the modulus increased as the temperature increased. It has been established that the highest tack takes place when the adhesive is not strongly crosslinked [9]. The loss modulus for the 105°C test is slightly higher than that of 95°C from the starting strain (0.1%) until between 3% and 100% strain when there appears to be a weak strain overshoot that is characterized by an increase and decrease of the loss modulus.

Temperature, °C	γ_c, %
85	125.0
95	25.1
105	5.0

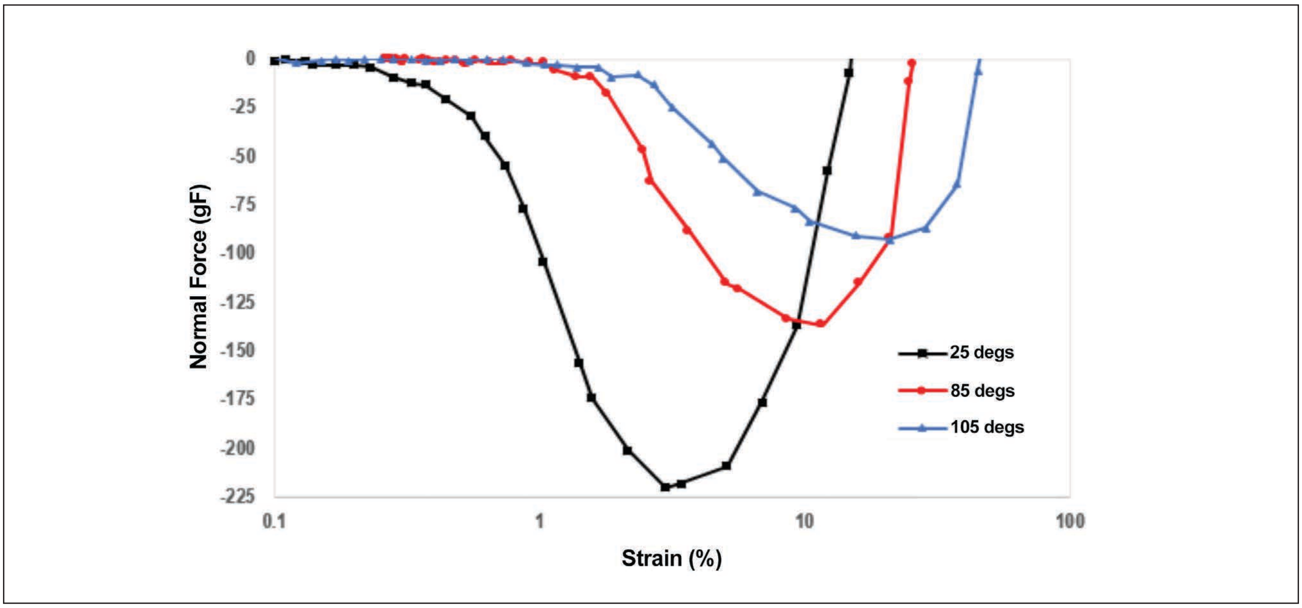
III. Critical strain at different temperatures.

The onset of the yield in the microstructure of the coating mix happens at the critical strain (γ_c), below which it exhibits linear rheological properties and above which it shows a drop in the storage modulus and is marked by nonlinear behavior [13]. **Table III** shows the critical strain as the limiting value of the LVE region for the three temperatures. The well dispersed or less brittle sample has the larger LVE region and the poorly dispersed sample or more brittle sample has the smaller LVE region. The 85°C test showed a higher cohesive and adhesive strength, while 105°C gave the least adhesive and cohesive strength.

Figure 7 shows the normal force plotted against the strain from the tack tests. This strain is different from the strain in the strain amplitude sweep shown in Fig. 6. It shows that the strain at the maximum normal force increases with increasing temperature. The 25°C test has the highest tack and maximum normal force at 2.99% strain followed by the 85°C test with maximum normal force at 11.6% and then 105°C at 20.85% strain. Generally, this test shows a trend that less tacky conditions start with a higher strain in the tack test.

CONCLUSION

This study used two methods of testing the Yankee coating system (tack testing and oscillatory rheological measurements) to screen for both optimum temperature and composition of a complex mixture critical for tissue technology. The experimental method used in this work is a simple and relatively faster way to measure tack adhesion of coating used on the Yankee dryer without going through the hassle involved with trial and error on large-scale machine trials. First, this methodology can be adopted to discover optimum conditions for Yankee coatings. Second, this study shows how the important knowledge gained in these bench studies of the combination of the coating chemicals can avoid erratic dosing/applica-



7. Normal force versus strain of the 303040 composition.

tion and reduce the total amount in mg/m² of sprayboom chemicals applied on the Yankee dryer surface for creping, thereby decreasing variable costs of chemicals.

Tack has been used to characterize five coating compositions used in creping on the Yankee dryer. It has been demonstrated in this work by holding the adhesive ratio constant at 30% and varying the modifier and release. The 303040 composition proved to be the best composition for the temperatures investigated, whereas the 30070 composition with no modifier is the least performing composition. The increasing trend of creping at low sheet moisture and making softer base sheets requires a series of trials to get the best combination of coating chemicals that will be suitable for tissue and towel grades. These trials can be done on a laboratory scale using tack and viscoelastic measurements, thereby saving time, improving productivity, and minimizing planning and costly rejects that will accrue as a result of running trials on the machine. **TJ**

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ABOUT THE AUTHORS

We chose this topic to research because we wanted to investigate the relationship between the rheological properties of coatings and their performance on the Yankee dryer. This research complements previous work that we have embarked upon in the area of rheology and fluid properties, but differs because it investigates properties of coatings used in the paper industry. The most difficult aspect of this research was correlating the viscoelastic properties to the actual performance of the coatings. We applied our experience with previous experiments to meet this challenge.

We discovered that tack characteristics of coating combinations are dependent on the temperature and rheology of the individual components of the coatings. Interestingly, the tack characteristics were optimal with almost equal weight amounts of the adhesive, modifier, and release (i.e., the 303040 composition).

This information will help predict the behavior of coating compositions before the actual performance trials are carried out on the Yankee dryers in towel and tissue producing mills. The next step is to put the findings to use. Combinations of coatings can be tested for their rheological properties to determine which composition will give the best performance in creping and quality, without having to do large-scale trials on machines.

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