Mechanical Properties of Durable Pavement Marking Materials and Adhesion on Asphalt Surfaces

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16. Abstract <p>Mechanical properties of commercially available temporary pavement marking (TPM) tapes and thermoplastic materials used as permanent pavement markings (PPM) were investigated using the non-destructive Tape Drape Test and conventional mechanical testing. The impact of temperature and aging on the adhesion of TPM tapes and thermoplastic PPM applied to asphalt core surfaces with various surface roughness and treatments was determined using a modular peel fixture and shear adhesion tests. The adhesion of TPM tapes to model smooth surfaces decreased as surface temperature was increased from 0 to 40°C (32 to 104°F). For some tapes, reduced adhesion and brittle broken fracture were observed at the lowest investigated temperature of -20°C (-4°F). The adhesion of tapes applied to asphalt decreased significantly within 1 week of aging at -25°C (-13°F). Ghost markings were more likely at higher aging temperatures. For PPM thermoplastics, better adhesion to asphalt was observed for higher application temperatures and rougher surfaces. Asphalt emulsion treatments reduced the adhesion of thermoplastics and increased the likelihood of adhesive failure after 5 months of aging at -25°C (-13°F). More ductile PPM thermoplastic materials had better adhesion to both smooth and rough asphalt surfaces compared to thermoplastic materials with a more brittle mechanical response.</p>			
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EXECUTIVE SUMMARY

Introduction

The goal of this project was to evaluate the properties and performance of both temporary and permanent pavement marking materials that are currently used for asphalt and concrete pavements in the Midwestern United States. Research objectives were to (1) design and optimize new testing and analysis methods to characterize the mechanical and adhesive properties of pavement marking materials; and (2) evaluate the structure and properties of commercially available pavement marking materials and assess their durability on pavement surfaces maintained at different temperatures and ages. Commercially available temporary pavement marking (TPM) tapes and thermoplastic materials used as permanent pavement markings (PPM) were the pavement marking materials selected for investigation in this project.

Methods

To address the first research objective, the Tape Drape Test was first developed to measure the elasticity of TPM tapes in a non-destructive way that required minimal instrumentation. Next, a modular peel fixture was constructed to measure the force required to peel TPM tapes from immovable substrates and validated through a series of peel tests on consumer tapes and model surfaces. Finally, the peeling and tearing behavior of TPM tapes was investigated using a new metric for tape removability called the Tear Resistance Ratio.

To address the second research objective, the viscoelastic properties and critical transition temperatures of TPM tapes were measured by performing dynamic mechanical analysis of the tape's top layer and adhesive layer and by peel testing using the modular peel fixture in conjunction with smooth model pavement surfaces maintained at temperatures ranging from -20 to 40°C (-4 to 104°F). The adhesive performance of TPM tapes was then determined for tapes applied to asphalt core surfaces that were subsequently aged from 1 day to 5 months at -25, 25, and 32°C (-13, 77, and 90°F). For thermoplastic PPM, laboratory tests were first performed to measure the thermal degradation, fracture toughness, and flexural behavior of the thermoplastic materials. Then shear adhesion tests were conducted to determine how the adhesion of the different thermoplastic materials was influenced by characteristics of the asphalt surface (including surface temperature, surface roughness, sealant treatment) and aging duration and temperature.

Findings

The Tape Drape Test yielded quantitatively similar modulus values for most commercial TPM tapes in comparison to conventional testing techniques and also resulted in more realistic modulus values for tapes with raised surface patterns. For the variety of commercial tapes that were tested with the modular peel fixture, higher peel strengths were observed for tapes with reinforced backing layers and tapes adhered to smooth surfaces. For the relatively slow testing rates investigated in the project,

all commercial TPM tapes had Tear Resistance Ratios greater than 1, indicating that tapes were more likely to peel rather than tear during removal.

For TPM tapes, the critical transition temperatures were used to define an effective operational temperature range for each tape. Measurement of peel strength from model smooth surfaces maintained at temperatures within the operational temperature range revealed that less force was required for tape removal as the surface temperature was increased from 0 to 40°C (32 to 104°F). For some tapes, reduced peel forces were measured at -20°C (-4°F) and brittle broken fracture was observed when the temperature was below the tape's critical transition temperatures. When tapes were applied to asphalt core surfaces, peel forces were approximately constant for most tapes for 3 months of aging at 25 and 32°C (77 and 90°F), while the peel force significantly decreased for all tapes within 1 week of aging at -25°C (-13°F). Ghost markings were observed for some tapes and were more likely at higher aging temperatures. The inherent mechanical properties of the TPM tapes appeared to influence their adhesive performance on asphalt surfaces, with relatively more flexible, low-moduli tapes exhibiting greater adhesion than less flexible, high-moduli tapes. However, the unknown chemical contributions of the tape's pressure sensitive adhesive layer to its overall adhesion to asphalt obfuscate the structure-property-performance relationships of these materials.

For thermoplastic PPM, the shear adhesion test proved to be a practical measure of debonding (failure) energy of thermoplastics materials applied to asphalt surfaces. Better adhesion was observed for PPM applied at increased asphalt surface temperatures. Native (un-cut) asphalt surfaces also resulted in improved adhesive performance than smooth (cut) surfaces. Initially, thermoplastic PPM applied to surfaces sealed with rapid penetrating emulsions (RPE) were more likely to fail at higher energies and in a cohesive manner compared to untreated asphalt surfaces. After 5 months of aging, PPM thermoplastics exhibited decreased debonding energies at all aging temperatures. At the coldest temperature (-25°C), the RPE treatment resulted in very low debonding energies and adhesive failure whereas thermoplastics applied to untreated surfaces displayed larger debonding energies and primarily cohesive failure. The inherent mechanical properties of the PPM thermoplastics also influenced their adhesive performance on asphalt surfaces, with the more ductile thermoplastic exhibiting greater adhesion to both smooth and rough asphalt surfaces than the more brittle thermoplastic.

Implementation

While future field testing is needed, over the course of this project no single product or pavement marking type demonstrated superior performance in all situations. Therefore, INDOT should continue to consider a wide variety of pavement marking products for inclusion on the list of approved construction materials. The four testing and analysis methods demonstrated in this project—the Tape Drape Test, the peel tests utilizing the modular peel fixture, the Tear Resistance Ratio, and the shear adhesion test—could be implemented by engineers tasked with evaluating the performance of new pavement marking products for the INDOT New Product Evaluation Committee as well as by manufacturers of TPM tapes and PPM thermoplastic materials.

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1. INTRODUCTION

1.1 Motivation

Pavement markings are essential elements of roadways, including thermoplastic materials used as permanent pavement markings (PPM) and adhesive tapes used as temporary pavement markings (TPM), both of which provide drivers with clear and defined travel paths through work zones. The installation success and ultimate durability of pavement markings are strongly dependent on pavement surface properties as well as environmental conditions such as temperature and relative humidity. Indeed, many manufacturers suggest that pavement marking materials be installed on dry pavements in temperatures above 50°F (10°C). Given these constraints, it can be difficult to successfully install PPM in low temperatures, necessitating the use of TPM for late-season construction projects.

The majority of technical challenges with both PPM and TPM are caused by incompatibilities between the marking materials and the pavement materials, ultimately leading to pavement markings with decreased performance and service life. For example, TPM on asphalt pavements are typically less durable due in part to the oily surface of the asphalt and coefficient of thermal expansion mismatch between the asphalt and marking material. Alternatively, there are times when TPM are effectively too durable, requiring complex removal processes involving water blasting and surface grinding which are energy intensive and damage the surface of the pavement. Additionally, the mechanical properties of the PPM and TPM materials themselves, such as modulus and viscoelasticity, can also be influenced by environmental conditions (e.g., temperature) which could either increase or decrease marking material durability.

1.2 Approach, Objectives, and Benefits

The overall goal of this project was to evaluate the properties and performance of TPM and PPM products that are currently utilized for asphalt and concrete pavements in the Midwestern United States. To achieve this goal, this project adopted a materials-centric research approach to ultimately determine how the structures and properties of the marking materials impacted their adhesion to pavement surfaces and thus their overall performance through the development and demonstration of new testing methods and protocols.

The research objectives of this project were the following.

1. Design and optimize new testing and analysis methods to characterize the mechanical and adhesive properties of pavement marking materials.
2. Evaluate the inherent thermal and mechanical properties of commercially available TPM tapes and PPM thermoplastics and assess their durability on pavement surfaces maintained at different temperatures and ages.

Outcomes from this project are anticipated to result in a number of benefits. First, the creation of new characterization equipment and testing procedures can be used in the future by product manufacturers for the development of pavement marking materials as well as DOT engineers for the evaluation of new products. Second, the temperature and aging conditions evaluated in this project will allow for better matching of pavement marking products with specific roadway applications and environments. Third, by combining the novel characterization techniques and data from currently utilized pavement marking materials, this project establishes a protocol for evaluation of future technologies that will enable product/vendor selection decisions.

1.3 Dissemination of Research Results

During the course of this project, research results were compiled and disseminated to the construction materials community through the following publications.

- Rencheck, M. L., Gohl, J. A., Grennan, H. P., Erk, K. A., & Davis, C. S. (2021). Assessing the elastic modulus of pavement marking tapes using the tape drape test. *Transportation Research Record*, 2675(8), 570–579. <https://doi.org/10.1177/0361198121999623>
- Gohl, J. A., Thiele-Sardina, T. C., Rencheck, M. L., Erk, K. A., & Davis, C. S. (2021). A modular peel fixture for tape peel tests on immovable substrates. *Experimental Mechanics*, 61, 1209–1213. <https://doi.org/10.1007/s11340-021-00738-1>
- Son, H., Erk, K. A., & Davis, C. S. (2021). Substrate temperature effects on the peel behavior of temporary pavement marking tapes. *The Journal of Adhesion*. <https://doi.org/10.1080/00218464.2021.2008369>

Key findings from these publications are described in this report. Publication abstracts and complete citation information are included in Appendix A, B, and C.

1.4 Organization of Report

Commercial pavement marking products were obtained from different companies for investigation in this project. TPM tapes were provided by 3M (Stamark 710 series), Advanced Traffic Materials (120 series), SWARCO (Director 2 series), and Brite-Line (Delta-line TEM 100). Commercial PPM thermoplastic materials were provided by Ennis-Flint, Inc. (Thermo Drop alkyd thermoplastic and HPS®8 Integrated Multipolymer). Chapter 2 provides a review of relevant literature about the TPM tapes and PPM thermoplastics used as pavement marking materials. Chapter 3 describes a new non-destructive testing method to assess the elastic modulus of TPM tapes. Chapter 4 describes a new testing apparatus designed to measure the adhesion of TPM tapes on pavement surfaces. Chapter 5 demonstrates the use of a new metric to assess tape removability. Chapter 6 summarizes key

results on the dynamic mechanical properties of different TPM tapes and their performance on pavement surfaces exposed to different temperatures for different lengths of time. Chapter 7 summarizes key results on the thermal and mechanical properties of PPM thermoplastics and their subsequent mechanical removal from pavements with different surface roughness, sealant treatments, and aging temperatures. Chapter 8 provides some concluding remarks on pavement marking performance at low temperatures.

2. LITERATURE REVIEW

2.1 Tapes Used as Temporary Pavement Markings (TPM)

According to a recent survey of all DOTs in the United States, temporary tape is the second most frequently used TPM in work zones following traffic paint. Approximately 92% of DOTs deploy temporary tape to some degree on intermediate asphalt surfaces, and 64% of DOTs deploy tape for final asphalt surfaces (Brown & Edara, 2021). The National Transportation Product Evaluation Program (NTPEP) Datamine 3.0 is a collective database used by state Departments of Transportation (DOTs) to share performance data on products used in transportation applications. This database was used to find performance data on the INDOT-approved TPM tapes. Relevant datasets were identified for the following commercial tapes that are investigated in the present project: Tape 3 (Wisconsin DOT; AASHTO, n.d.e), Tape 1 (Pennsylvania DOT; AASHTO, n.d.c and n.d.d), and Tape 4 (Minnesota DOT; AASHTO, n.d.a and n.d.b). Each study examined intrinsic tape strength, adhesive bond strength, and surface residuals both immediately after removal and 30 days after removal on asphalt and concrete over a 6-month period. Intrinsic tape strength was qualitatively evaluated by the total number of tape fractures during removal; adhesive bond strength was assessed by the relative amount of effort exerted by a person to remove the tape; and surface residuals were estimated as the percentage of noticeable “ghost markings” leftover after removal. Qualitative result tabulations are shown in Table 2.1 in which “1” denotes relatively ideal results (e.g., few tape fractures upon removal; high adhesive strength; no noticeable residuals) while “10” denotes relatively poor results (e.g., many tape fractures upon removal; low adhesive strength; obvious residuals).

From Table 2.1, Tape 1, and Tape 4 were easier to remove on asphalt than concrete, while Tape 3 displayed similar performance on asphalt and concrete. All tapes left residual ghost marks on the surfaces after removal, with Tape 4 being the most noticeable and Tape 1 being the least noticeable. Tape strength tended to decrease over the 6-month period, while the adhesion strength was consistent over the 6-month period except for Tape 4 tape on concrete which appeared to exhibit stronger adhesion over time. For all tapes, ghost markings after removal were more noticeable with tape age, but the majority of ghost markings became less

noticeable 30 days after removal. Trends in tape performance were more prevalent when observing tapes over the period of 6 months than comparing tape brands to one another. Additionally, environmental impacts were not specified throughout the course of any of the studies which could cause variations in tape performance.

In addition to the NTPEP Datamine 3.0 database, other state DOTs have conducted more in-depth studies on pavement marking performances on roadways. Michigan DOT and Michigan State University (Lee et al., 1999); Florida DOT and University of Florida (Ellis et al., 1999); Texas DOT and Texas A&M (Cho et al., 2013; Songchitruksa et al., 2011); Nebraska DOT and University of Nebraska-Lincoln (Cho et al., 2011); and Iowa DOT and Iowa State University (Hawkins et al., 2012) have conducted studies related to pavement marking—with Iowa and Texas primarily focusing on TPM tapes and Nebraska, Florida, and Michigan focusing more on PPM. The Texas and Iowa DOT studies are briefly described here as they are the most pertinent to this report.

In 2012, Iowa conducted a study to evaluate TPM tapes and paints in work zone areas with emphasis on cross-over areas of highway construction zones (Hawkins et al., 2012). TPM tapes and paints were exposed to more wear in cross-over zones with the inside pavement marking experiencing more wear than the outside pavement marking. Specimens from Tape 1, Tape 2, and Tape 3 were applied for a 56-day period, and tape performance was evaluated by considering intrinsic tape strength, adhesive strength, and extent of ghost markings after removal. All tapes performed well over the 56-day period except for tapes placed over a rough surface or tapes damaged by a vehicle. Tape 1 and Tape 2 specimens displayed the best tape strength and adhesion. After removal, only 30% of surfaces displayed ghost markings from Tape 2 and Tape 3 while 60% of surfaces in contact with Tape 1 displayed residuals.

In 2007, Texas conducted a study to determine best practices for selecting pavement marking materials to improve traffic control guidelines in work zones (Songchitruksa et al., 2011). To create a decision matrix, Monte Carlo simulations were employed considering pavement marking materials (traffic buttons, thermoplastic, tape, and paint), substrate type (asphalt or concrete), annual average daily traffic (AADT), material cost, reapplication cost, project duration, and pavement marking durability. The resulting decision matrices showed recommended pavement marking material as a function of AADT per lane and project duration. On asphalt, traffic buttons (raised pavement markers) were the most cost-effective marking material for high-AADT areas with a long project duration. For short project durations in low-AADT areas, paint was recommended. Thermoplastic was recommended for medium duration projects in moderate-AADT areas. On concrete, the paint and traffic button markings were primarily recommended for use with the thermoplastic recommended in only one scenario. Independent

TABLE 2.1
Summary of Datamine 3.0 TPM tape performance studies (adapted from NTPEP Datamine 3.0 at <https://ntpep.transportation.org>)

Asphalt Surface–Tape 1, Tape 3, Tape 4												
Month	Internal Tape Strength			Adhesive Bonding Strength			Residuals After Removal (immediate)			Residuals 30 days After Removal		
1 (June)	1	1	1	3	4	3	3	5	8	2	–	1
2	1	1	1	2	3	1	3	5	8	3	3	5
3	1	1	1	3	3	1	1	5	9	1	5	5
4	2	1	2	2	4	3	3	5	9	3	5	6
5	1	–	2	1	–	2	3	–	9	2	–	–
6	3	–	–	3	–	–	3	–	–	–	–	–

Concrete Surface–Tape 1, Tape 3, Tape 4												
Month	Internal Tape Strength			Adhesive Bonding Strength			Residuals After Removal (immediate)			Residuals 30 days After Removal		
1 (June)	1	1	1	4	4	4	4	5	10	3	–	1
2	1	1	2	4	4	2	4	4	10	3	1	4
3	1	1	2	5	5	2	3	5	9	3	3	3
4	2	2	2	6	4	3	4	5	9	3	5	5
5	2	–	1	4	–	1	3	–	9	3	–	–
6	3	–	–	6	–	–	4	–	–	–	–	–

Note: Qualitative results with 1 as best and 10 as worst performance.

The **black numbers** correspond to Tape 1, the **red numbers** correspond to Tape 3, and the **blue numbers** correspond to Tape 4.

simulations were also performed for asphalt and concrete both in ideal and non-ideal conditions. When conditions were non-ideal, traffic buttons dominated the decision-matrices. All matrices rarely recommend the use of TPM tapes for application regardless of project duration or AADT with fewer recommendations to be placed on concrete than asphalt.

2.2 Thermoplastic Materials Used as Permanent Pavement Markings (PPM)

Major external factors, including the condition of the roadway surface, traffic volume, and environmental conditions, can result in adhesive and cohesive failures of thermoplastic materials employed as permanent pavement markings. PPM performance is affected by the type of pavements (material and grade) as well as the condition of the pavements (age, cleanness, and dryness), all factors that are known to directly influence the adhesion of PPM to roadway surfaces. Deterioration of PPM due to traffic depends on AADT, type of traffic, heavy vehicle percentages, and roadway speed limit. In northern climates, PPM can also be significantly damaged through snowplowing and salt/aggregate use in winter. Additionally, internal factors will also influence the performance of PPM on different roadways, including the intrinsic material properties of the PPM (e.g., elastic modulus, tensile strength, hardness) and how these properties change in response to environmental conditions, such as variation in temperature and humidity.

In 2004, Texas DOT with the Texas Transportation Institute (TTI) created a pavement marking handbook

including information on material selection, installation, and inspection guidelines for various types of pavement markings (thermoplastic, water-based, pre-formed tapes, and epoxy) considering various external factors (TxDOT, 2004). Inspection guidelines were determined for each step: preliminary, pre-installation, during application, final acceptance, and determining when restriping. For example, during installation, thermoplastic PPM formed strong adhesive bonds to freshly paved asphalt by thermally fusing with the hot surface. Such heat-induced fusion was not possible with freshly placed concrete. Thus, some hot-applied marking materials, such as thermoplastic PPM, were not recommended for use on concrete surfaces.

The majority of other state DOT studies have mainly focused on how PPM retroreflectivity diminishes over time on real roadways. Michigan DOT evaluated marking materials at 50 different sites from 1994 to 1997 (Lee et al., 1999). Pavement markings used in the study were polyester, thermoplastics, waterborne paints, and tapes. The amount of snowfall (and thus snowplowing) was determined to be the most significant factor in retroreflectivity decay. A study supported by Idaho DOT involving laboratory-based accelerated aging using thermoplastic and waterborne paint PPM and found that their performance in retroreflectivity, color change, and durability was similar to field performance when thermoplastic markings generally last longer than waterborne markings (Mohamed et al., 2020). The waterborne markings were observed to peel while the thermoplastic material changed to a darker color due to abrasion of the marking surface texture. Additionally, the waterborne material percent loss

followed a logarithmic function while the eroded thermoplastic marking followed a linear trend under the simulated loading system. In 2009, the North Carolina DOT and the North Carolina State University established a transportation asset management system to estimate the current and future condition of PPM (Rasdorf et al., 2009). ANOVA and longitudinal data analysis methods were utilized to investigate how the regional impact (e.g., mountain, central, and coastal areas) affected the retroreflectivity of thermoplastics and paints. Based on the retroreflectivity data, various models were developed, including retroreflectivity degradation models.

As expected, pavement properties will strongly influence the performance and durability of PPM. In particular, PPM applied to sealed asphalt pavements have exhibited reduced performance and service life. Pavement sealing treatments are used to protect pavement surfaces from oxidation and mechanical damage due to traffic volumes and environmental effects including UV exposure, temperature cycling, and precipitation. Asphalt-based fog seal surface treatments have been generally used for bituminous pavements (Smith & Romine, 2001). The main ingredient of fog seal is emulsified asphalt, which is diluted with water and surfactants and then sprayed onto the pavement surface at or near ambient temperature.

While the use of sealants can enhance the durability of pavements, a current concern is that sealants reduce the performance and durability of pavement marking materials applied to the sealed areas. In 2003, Texas DOT and Texas Transportation Institute investigated PPM on new seal-coated roadways and observed that PPM paints did not last a full year (Gates et al., 2003). Also, the retroreflectivity of thermoplastic markings reduced more rapidly over time on seal-coat than hot-mix asphalt concrete surfaces. In a study by Minnesota DOT with Iowa State University, key problematic issues for pavement marking failure on chip seal and micro surfaces were addressed with potential solutions and strategies (Hawkins & Smade, 2011). Fog sealants were typically used as a primer over the old stripe to improve adhesion but sometimes caused adhesion problems resulting in pavement marking loss when applied on rumble stripes.

3. OBJECTIVE 1A: ASSESSING TPM TAPE MODULUS BY THE TAPE DRAPE TEST

3.1 Overview

This section describes the research results obtained during the investigation of the various modulus measurements of the TPM tapes. The objective of this study was to show that the most effective method for rapidly assessing the modulus of TPM tapes is the “Tape Drape Test.” This objective was accomplished by first measuring the modulus of each tape through two conventional techniques: tensile testing and bend testing. Next, the Tape Drape Test was developed and validated as an alternative modulus measurement

approach. Finally, the effectiveness of this new measurement strategy was demonstrated by direct comparison of the three modulus assessment methods. The primary finding was that the Tape Drape Test yields quantitatively similar modulus values compared to the conventional test methods and was less sensitive to the presence of raised surface patterns. A complete description of the theoretical background, experimental methods, quantitative results, and supporting discussion was published in *Transportation Research Record* (refer to Appendix A).

3.2 Methods

To remove tape from a surface, a critical force for debonding must be achieved, and this “peel force” is inversely related to a tape’s elastic modulus. Thus, tapes with lower moduli are more likely to display greater adhesion to surfaces, e.g., pavements. For each brand of TPM tape, the modulus was determined using three distinct approaches. All tests were performed on Tape 1, Tape 2, and Tape 3. First, tensile testing was performed on several samples of the various brands of TPM tape using a commercial load frame. Next, three-point bend testing was performed on each tape. Finally, Tape Drape Tests were performed to compare results to the two more conventional modulus assessment methods. Each test setup is shown in Figure 3.1. All tests were performed in a 25°C laboratory environment.

Each tensile testing trial determined the stress (σ) and strain (ϵ) applied to the tape from the measured force (F) and displacement (Δl). A typical experimental setup for tensile testing is shown in Figure 3.1a. The σ can be calculated from F/A where A is the cross-sectional area ($A = wt$) and ϵ can be calculated from $\Delta l/l_o$ where l_o is the initial length of the specimen. The tensile modulus (E_{Tens}) was then determined from Hooke’s Law as $E_{Tens} = \sigma/\epsilon$.

Three-point bend testing was employed to determine the flexural modulus (E_{Flex}) of the TPM tapes. When the strain to failure is low, typically, the E_{Flex} is similar to the E_{Tens} . Therefore, by determining the E_{Flex} via three-point bend testing, the tape modulus is also able to be determined. A typical three-point bend testing set-up is shown in Figure 3.1b. During each trial, the crosshead moved down in the y-direction causing a deflection (v) in the tape. Similar to tensile testing, F and v values were used to determine E_{Flex} . A similar analysis technique for determining E_{Tens} was used to determine E_{Flex} , by taking the ratio of the bending stress (σ_{bend}) and bending strain (ϵ_{bend}). The ratio of the bending stress (σ_{bend}) can be calculated through Equation 3.1, and ϵ_{bend} can be calculated through Equation 3.2.

$$\sigma_{bend} = \frac{3Fd}{2bt^2} \quad (\text{Eq. 3.1})$$

$$\epsilon_{bend} = \frac{6vt}{d^2} \quad (\text{Eq. 3.2})$$

Figure 3.1 Photos of various modulus measurement experiments performed on TPM tapes annotated with relevant geometric and experimental parameters. (a) Tensile testing, (b) three-point bend testing, and (c) Tape Drape Testing (used with permission from Rencheck et al., 2021).

Adapted from the textile industry, the Tape Drape Test was used to determine the stiffness of fabrics by measuring the angle of drape due to gravity as a function of the overhang length (l_h) needed to reach a measured angle (θ). The experimental set-up of the Tape Drape Test is shown in Figure 3.1c. Each tape was measured with the PSA side down (representative of how the tapes are applied to road surfaces). θ is measured from horizontal to the line formed between the end of the tape draping off the table (Point O in Figure 3.1c) and the edge of the stage (Point S in Figure 3.1c). The horizontal line going through point S sets the reference for $\theta = 0^\circ$. The change in length due to gravity (bending length (c)) is related to l_h and θ (Equation 3.3) which is then used to determine the flexural rigidity (G) (Equation 3.4):

$$c = (l_h) \left(\frac{\cos \frac{\theta}{2}}{8 \tan \theta} \right)^{1/3} \quad (\text{Eq. 3.3})$$

$$G = (9.81 \times 10^{-12}) \omega c^3 \quad (\text{Eq. 3.4})$$

where ω is the areal density ($\omega = ab$) given in g/mm^2 . G is the resistance to bending of a structure when one end is fixed. G can be related to E through t and the Poisson's ratio (ν) as thicker structures will have a greater G . The relationship between E and G is shown in Equation 3.5.

$$E_{\text{Drape}} = (G) \left(\frac{12(1-\nu^2)}{t^3} \right) \quad (\text{Eq. 3.5})$$

3.3 Results

The E values from all the characterization techniques for all the tape brands were compared and listed in Table 3.1. E_{Tens} and E_{Flex} were in good agreement for all tape brands, while E_{Drape} was only in agreement with E_{Tens} and E_{Flex} for Tape 2.

The differences in the modulus values determined from the Tape Drape Test were found to result from morphological differences in the tapes themselves. While the tapes are all comprised of similar materials,

TABLE 3.1
Comparison of elastic modulus results

	Tape 1	Tape 2	Tape 3
E_{Tens} (MPa)	8.6	44.2	119.0
E_{Flex} (MPa)	6.7	43.4	89.9
E_{Drape} (MPa)	14.8	46.9	15.9

the structure and topographies were different. Micrographs of each tape brand are shown in Figure 3.2. The most noticeable difference between the tape structures were the ridges on the surface of Tape 3. Upon further observation, the ridges on Tape 3 were thicker and had a greater stiffness than the flat portions between ridges. Depending on how the tensile and flexural test specimens were cut from the tape, these ridges influenced the measured modulus. This led to a modulus value not representative of the full width of tape, which was apparent in the anomalously high E_{Tens} and E_{Flex} results for Tape 3. The dramatic increase in E was not measured by the Tape Drape Test because the testing specimen was topographically and structurally representative of the bulk. Thus, the drape modulus is more appropriate to use in subsequent predictions of the peel behavior of the tapes as it replicates how the tape will be used in the real world.

3.4 Conclusions and Implications

The following conclusions resulted from this study.

- The modulus of TPM tapes can be accurately and efficiently measured with the Tape Drape Test. This method yielded results comparable to those obtained with conventional tensile and flexural testing and was less sensitive to the presence of raised surface patterns that resulted in overestimated moduli in the conventional tests. The modulus is inversely related to adhesion so easy assessment of this parameter is critical.
- Tape 1 had the lowest modulus. Tape 2 exhibited a higher modulus ($3\times$ greater than Tape 1). Tape 3 had a high modulus when measured by conventional means but a modulus comparable to Tape 1 via the Tape Drape Test.

Figure 3.2 Structure of TPM tapes: (a) Tape 1, (b) Tape 2, and (c) Tape 3 (adapted with permission from Rencheck et al., 2021).

A number of implications resulted from this study. First, the Tape Drape Test is an effective modulus measurement approach that requires very little instrumentation/equipment and can be performed anywhere that a flat surface is available. In the future, the Tape Drape Test can be used to correlate tape elastic modulus with important environmental conditions (e.g., temperatures) and tape performance (e.g., adhesive strength, durability, ease of removal, presence of surface residuals). Second, care must be taken in measuring the modulus of patterned tapes to ensure that the observed modulus is representative of the bulk tape. Finally, the discrepancy in the Tape 3 modulus measurements was directly related to the patterned structure of the polymer top layer. Periodic ridges gave rise to misleading high modulus results as a result of geometric stiffening in the smaller samples of tape utilized for traditional testing. Since the shape of a TPM tape during removal is most closely resembled by the Tape Drape Test, this method is a superior way of quantifying the modulus to predict peel adhesion behavior for patterned tapes.

4. OBJECTIVE 1B: DESIGN AND TESTING OF A MODULAR PEEL FIXTURE

4.1 Overview

This section describes the research results obtained during the development of a portable peel fixture that enables 90° peel adhesion tests to be performed on

immovable substrates such as installed concrete and asphalt roadways. The objective of this study was to demonstrate the usefulness of the fixture. This objective was accomplished by measuring the peel force as a function of distance for several commercially available consumer tapes and substrates. Several widths of tapes and peel rates were tested to demonstrate that the expected peel behavior was measurable and reproducible via the new modular fixture. The primary finding was that the Modular Peel Fixture (MPF) yields reasonable, reproducible peel strength values and is sensitive to changes in the tape sample width and rate of peel. A complete description of the theoretical background, experimental methods, quantitative results, and supporting discussion was published in *Experimental Mechanics* (refer to Appendix B).

A peel test uses an energy balance approach to relate the peel force (P) to the effective work of adhesion (W),

$$W = \frac{P}{b} (1 - \cos\theta) \quad (\text{Eq. 4.1})$$

where b is the width of the tape and θ is the peel angle (Anderson et al., 1976; Gent & Kaang, 1987; Kendall, 1971, 1973) W is comprised of the thermodynamic work of adhesion and energetic losses within the tape due to bending. While W is not a true measurement of the work of adhesion, it has been referred to as the “effective work of adhesion” or “work of detachment” (Rivlin, 1997). Using W values, adhesive performance of different tapes can be compared. For a

90° peel angle, this equation simplifies further so that $W = P/b$.

4.2 Methods

A modular peel fixture (MPF) was designed, constructed, and implemented to enable 90° peel tests of TPM tapes to be performed on immovable substrates such as roadways. Existing tape peel fixtures rely on either (1) moving the substrate laterally through a system of pulleys or motors or (2) mounting expensive and sensitive instrumentation on a frame that is then placed on the roadway. In the first case, only small, lightweight substrates can be tested. This precludes large and dense surfaces like asphalt or concrete from being used. In the second case, a translating stage and costly load cell are mounted on a triangular frame and physically moved above the surface as the tape is peeled away. In this case, the risk of damage to the instrument is very high and the maximum peel force is limited to the capacity of the installed transducer and pulling force of the motor.

To overcome the limitations of the existing 90° tape peel adhesion test methods, the MPF was invented. It is comprised of a large aluminum frame in the outline of a triangular prism (see Figure 4.1). A carriage is pulled along a rail on the 45° angled portion of the frame by a cable attached to a tensile load frame through a system

of pulleys. By attaching one end of the tape to be tested to the vertical face of the carriage and the other end to the immovable surface of interest, the 90° peel adhesion strength of the tape (P) is measured by recording the force to pull on the cable (P_m) with the tensile tester. The mass of the carriage ($\sim F_N$) and friction (F_F) of the carriage wheels on the rail are accounted for through a straightforward mass balance shown schematically in the inset in Figure 4.1b. A few initial calibration tests were performed to determine the coefficient of friction and carriage mass prior to peel adhesion testing.

Peel tests were performed by carefully applying commercial tapes to clean substrates, affixing the substrates to the horizontal flat portion of the MPF, attaching an unadhered portion of the tape to the vertical face of the carriage, and then pulling on the cable to cause the carriage to translate at 45° relative to the substrate along the upper track of the MPF. Force and displacement of the pulley were recorded over each test as the adhered portion of the tape was pulled away from the substrate at a constant 90° angle.

Three sets of experiments were performed. First, the peel strength of invisible office tape on a clean glass substrate was determined while varying the width of the tape and the peel rate. Second, the peel force of various commercial tapes (invisible office tape, duct tape, masking tape, transparent tape, and electrical tape) was measured from a clean glass substrate. Third, the

Note: The colored points on the graph correspond to the time lapse frame above and indicate forces measured at each instant during the test.

Figure 4.1 Modular peel fixture (MPF) design. (a) Schematic of key parts of MPF. (b) Photo of final MPF design. Inset shows forces accounted for in final tape peel adhesion strength measurements. (c) Photographs of a typical tape peel test showing that the 90° peel angle is perfectly maintained and accompanied with a representative peel force as a function of distance plot (used with permission from Gohl et al., 2021).

peel force of invisible office tape was measured from various substrates (polymethyl methacrylate, Bakelite, glass, steel, plywood, asphalt, and cement). By calculating the effective work of adhesion for all tapes and substrates, a comprehensive overview of the MPF performance as an adhesion characterization tool was presented. All tests were performed in a 25°C laboratory environment.

4.3 Results

4.3.1 Peel Force Dependence on Tape Width and Peel Rate

To demonstrate the accuracy and precision of the MPF to the effective work of adhesion, invisible office tape on a clean glass substrate was utilized for this set of experiments. As expected, the peel force increased linearly with tape width (Figure 4.2a). When these peel force values were normalized by the respective tape widths, a consistent value of $W \approx 100 \text{ N/m}$ was obtained. At low peel rates ($< 1 \text{ mm/s}$), the effective work of adhesion or “work of detachment” was independent of peel rate. However, once a critical threshold peel rate is reached, the effective work of adhesion increases significantly with peel rate (Figure 4.2b).

4.3.2 Peel Strength of Various Tapes

The adhesive strengths of various consumer tapes were measured utilizing the MPF on a clean glass substrate. The peel force was normalized by dividing by tape width at each point and then this effective work of adhesion was plotted as a function of distance (Figure 4.3).

Several of the pressure sensitive adhesive (PSA) tapes (invisible office, transparent, and masking tape) had a consistent, relatively low value of $W \approx 150 \text{ N/m}$. However, electrical tape exhibited a higher value of $W \approx 200 \text{ N/m}$. Upon further inspection of the data and

tensile testing of each tape, it was determined that this higher effective adhesion value of the electrical tape was caused by the extensibility of the backing layer, not the strength of the adhesive layer itself.

More interestingly, the adhesive strength of duct tape was not only much higher than all other PSA tape products measured but the W values fluctuated significantly in a periodic manner as a function of distance. By observing the debonding behavior of each duct tape peel test while performing a peel experiment, it became clear that the high peel forces and sudden dips were directly related to the spacing of the weft yarns in the reinforcing fabric layer incorporated in the design of the duct tape. This result is an important insight that can be related directly to TPM tapes that also have a plain-woven fabric reinforcement that likely increases overall peel forces and could potentially cause a similar periodically varying peel behavior.

4.3.3 Peel Strength of Tapes Removed from Various Substrates

To further demonstrate the utility of the MPF, the effective work of adhesion of invisible office tape on several surfaces was measured (Figure 4.4). The adhesion values fell into one of three categories. For smooth surfaces (excluding poly (methyl methacrylate), PMMA), W values were relatively high and all fell between 100 and 150 N/m. For very rough surfaces like plywood, asphalt or cement, W was much lower. The anomalous result of the extremely high peel strength of the invisible office tape measured against PMMA is likely due to a chemical effect. The acrylate functional groups on the PMMA surface are very chemically similar to the n-butyl acrylate that comprises the PSA layer of invisible office tape.

4.4 Conclusions and Implications

The following conclusions resulted from this study.

Note: For the log-log axes in (b), 5 mm/s is approximately equal to 12 in/min.

Figure 4.2 Average MPF adhesion measurements of invisible office tape on glass. (a) Peel force and (b) effective work of adhesion (“work of detachment”) as a function of tape width and peel rate (used with permission from Gohl et al., 2021).

Figure 4.3 Adhesive peel strength of various consumer tapes from a smooth glass substrate. Effective work of adhesion as a function of peel distance. The first portion of the data (prior to 8 mm) is omitted due to start up effects and experimental artifacts (used with permission from Gohl et al., 2021).

Figure 4.4 Adhesive peel strength of invisible office tape on several surfaces with varying roughness values and surface chemistry (used with permission from Gohl et al., 2021).

- The MPF enables reproducible, quantitative peel adhesion tests to be performed on immovable substrates.
- The peel strength of most consumer tapes from smooth glass is similar. Duct tape has a periodic variation in peel strength along its length due to the reinforcing fabric layer between the PSA and backing layer, leading to a much higher average peel strength. Electrical tape had a slightly higher effective work of adhesion due to its high extensibility.
- Excluding chemical effects, PSA tapes have a consistent, moderate adhesion to smooth surfaces and have a much lower adhesion on rough substrates.

A number of implications resulted from this study. First, the MPF is a reliable measurement system that can be utilized to perform tape peel experiments on immovable surfaces such as roadways. Second, peel strength of tapes is strongly dependent on the structure of the backing layer. Reinforcing fabric leads to much higher peel strengths while highly extensible backing layers lead to just slightly elevated peel forces. Further, the periodic structure of the fabric can lead to a non-uniform peel force similar to the stick-slip phenomenon in friction studies. Finally, the surface roughness of the substrate has an overwhelming effect on the adhesion of PSA tapes. The smoother the finish, the stronger the adhesion.

5. OBJECTIVE 1C: DETERMINING THE TEAR RESISTANCE RATIO OF TPM TAPES

5.1 Overview

This section describes the research results obtained during the investigation of the tendency of a TPM tape to tear versus peel during removal from an asphalt surface. The relationship between the tearing and peeling forces has been named the Tear Resistance Ratio (TRR). The objective of this study was to evaluate the tear resistance of TPM tapes during removal from the roadway. This objective was accomplished by measuring the tear force of four types of TPM tape utilizing the trouser tear method and the force required to peel each TPM tape from an asphalt surface using the MPF described in Chapter 4. TRR was then calculated as the ratio of tear force to peel force. The primary finding was that all TPM tapes displayed relatively high TRR and were more likely to peel from the asphalt surfaces rather than tear at the relatively slow removal rates investigated in the laboratory. Through this test method, the removability of TPM tapes could be evaluated and peeling versus tearing behavior could be predicted.

Note: All tests were performed in a 25°C laboratory environment.

Figure 5.1 (a) Trouser tear testing configuration. The right schematic image shows the front view of tear testing, and the inserted image shows the sample geometry with TPM tapes (sample width is 20 mm for scale). (b) Modular peel fixture setup and schematic side view image of tape peel test to measure peel force on the asphalt surface.

5.2 Methods

The tear force was measured for TPM tapes based on the ASTM D1938-19. Figure 5.1 shows the trouser (Mode III) tear test configuration. The trouser tear samples were prepared by cutting the tapes into 80 mm by 20 mm specimens with a 20 mm pre-tear, as shown in the inserted image in Figure 5.1a. These specimens were oriented parallel and perpendicular to the length direction of the tape to observe any anisotropic effects associated with tearing the tape across its width or along its length. The precut “legs” of each specimen were clamped to a tensile tester as shown, and a uniaxial separation displacement was applied to the TPM tapes with a 4 mm/s displacement rate.

The 90° peel tests were performed with a custom-built 90° peel tester to measure peel force for TPM tapes on 6-inch diameter native (un-cut) asphalt core surfaces, as shown in Figure 5.1b (Gohl et al., 2021). TPM tapes were cut to 40 mm by 270 mm and adhered to the asphalt core surface with a pressure of 103 kPa (15 psi) for 10 seconds. Peel force was measured at a 5 mm/s peel rate (11.8 in/min) at a peel length of 180 mm (7 in). Note that the peel rate utilized here was similar to the rate of 5.08 mm/s (12 in/min) specified in peel force testing guidance provided by one tape manufacturer (3M, 2011).

5.3 Results

5.3.1 Tear and Peel Test Results

Figure 5.2a shows the measured tear force profiles for each tape with the tear propagating along either the tape length or width directions. All TPM tapes cut along the width direction tore perpendicular to the precut direction, while the tapes cut along the length direction tore parallel to the precut direction as shown in the inserted pictures in Figure 5.2a(ii). As a result, the tear distance for length direction tests was longer than width

direction experiments. Nevertheless, the tear forces for all TPM tapes were similar regardless of the pre-tear direction. Figure 5.2b shows the measured peel force profiles for each tape as it was removed from the asphalt surface. Since some TPM tapes have ridges on the top layer, and the designs of the ridges varied between tape brands, the presence of periodic peaks in the peel force data and the spacings of these peaks varied for the different brands of TPM tapes.

5.3.2 Tear Resistance Ratio (TRR)

Figure 5.3a reports the average tear forces for TPM tapes. These force values were averaged over the distance of the propagating crack or tear until the TPM tape was torn through or the load frame reached a grip separation distance of 120 mm. Tear propagation was observed to occur from the pre-tear tip either straight along the length of the sample (120 mm grip displacement) or horizontally across the specimen, ending the tearing test prematurely. Tape 4 had the greatest average tear force while Tape 3 had the lowest tear force. The thickness of the TPM tapes was relatively constant with respect to the large tearing lengths tested here; so, for the purposes of this study, tape thickness was taken as a constant value. Figure 5.3b reports the average peel force of TPM tapes from asphalt surface. Tape 1 had the greatest average peel force while Tape 4 had the lowest peel force. Based on the average tear and peel force values, the Tear Resistance Ratio (TRR) was calculated using Equation 5.1, also shown in Figure 5.3c.

$$TRR = \frac{\text{Tear Force (N)}}{\text{Peel Force (N)}} \quad (\text{Eq. 5.1})$$

When the $TRR > 1$, the tearing force is higher than the peel force, indicating that the tape has a relatively high tear resistance and will peel rather than tear when removed from the surface, which may allow for efficient

Figure 5.2 (a) Measured tear force profiles for (i) Tape 1, (ii) Tape 2, (iii) Tape 3, and (iv) Tape 4. Inserted schematic image in (i) and the pictures in (ii) represent the sample cutting direction and tear test results along the length and width direction, respectively. (b) Peel force profiles on asphalt surface for (i) Tape 1, (ii) Tape 2, (iii) Tape 3, and (iv) Tape 4.

Figure 5.3 (a) Average tear force for TPM tapes. Error bars represent one standard deviation over 5 tests. (b) Average peel force for TPM tapes. Error bars represent one standard deviation over 2 tests. (c) Tear resistance ratio (TRR) for each of the four brands of TPM tapes tested. The yellow line represents the threshold criterion distinguishing an expected tendency for peeling ($TRR > 1$) or tearing ($TRR < 1$).

pavement marking removal. On the other hand, when the $TRR < 1$, the tape has a relatively low tear resistance and is thus expected to tear rather than peel since the force required to tear the tape is lower than the force required for peeling. $TRR < 1$ is considered to be an unfavorable result as it indicates that the tape could be more difficult to remove and may come off of the asphalt surface in small pieces. As shown in Figure 5.3c, the TRR of all TPM tape brands tested was greater than 1, indicating that all TPM tapes displayed high tear resistance and are thus more likely to peel off without tearing when removed from the road surface.

5.4 Conclusions and Implications

The following conclusions resulted from this study.

- The peeling and tearing behavior of TPM tapes was investigated using a new metric—the Tear Resistance Ratio (TRR)—for tape removability.
- Based on the calculated TRR values, commercial TPM tapes were more likely to peel rather than tear during removal for relatively slow testing rates (~ 12 in/min).

It is important to note that both peel and tear tests are expected to be rate dependent. Peel forces increase dramatically as peel rate increases (refer back to

Figure 4.2b) while tear force increase slightly with rate. Therefore, the findings of this initial set of experiments, where both peel and tear tests were performed at relatively low rates of 12 in/min (0.01 mph) are only representative or predictive for carefully removed tapes. If the tapes are removed at much higher rates (e.g., slow vehicle speeds like 5–10 mph), the TRR will almost certainly decrease and tearing would be more likely, particularly for the tapes with TRR values just over 1, such as Tape 1 in Figure 5.3c.

6. OBJECTIVE 2A: IMPACT OF TEMPERATURE AND AGE ON ADHESION OF TPM TAPES

6.1 Overview

This section describes the research results obtained during the investigation of adhesion of TPM tapes at different ages and environmental conditions. The objective of this study was to evaluate the adhesion of TPM tapes based on the intrinsic viscoelastic properties of the tape as well as the aging time of the tape-surface interface at various temperatures. This objective was accomplished by directly measuring the dynamic mechanical properties of PSA and the top layer of TPM tapes as well as using the modular peel fixture (Chapter 4) to measure the peel force of TPM tapes on a model stainless steel surface maintained at temperatures from -20 to 40°C (-4 to 104°F). The influence of aging on the adhesion of TPM tape to asphalt surfaces was also investigated by using the modular peel fixture to measure the peel force of TPM tapes from tape-asphalt samples stored and aged for various times and temperatures. The primary findings were that the peel force decreased with increasing temperature for all tapes on the model surface and some tapes failed in a brittle manner when the temperature was below the glass transition temperature (T_g) of the top layer and below the transition temperature (T_R) from glassy-to-rubbery behaviour of the PSA. When tapes were applied to asphalt core surfaces, peel forces were approximately constant for most tapes over 3 months of aging at 25 and 32°C (77 and 90°F) while the peel force significantly decreased for all tapes within 1 month of

aging at -25°C (-13°F). A detailed description of the experimental methods, quantitative results, and supporting discussion was published in *The Journal of Adhesion* (refer to Appendix C).

6.2 Methods

For each TPM tape specimen, the dynamic mechanical properties of the PSA and top layer were measured with a double-lap shear and tensile geometry, respectively. Figure 6.1a shows the custom built, double-lap shear fixture used to measure the dynamic mechanical properties of the PSA. Properties, including the elastic storage modulus (G'), the viscous loss modulus (G''), and the loss tangent ($\tan \delta$), were measured using an oscillatory strain with a linear temperature sweep function through dynamic mechanical analysis (DMA). A 0.5% and 0.2% oscillatory strain were applied through the thickness of PSA and the length of top layer at a frequency of 1 Hz, respectively. The temperature was increased from -20 to 40°C (-4 to 104°F) in 5° increments, and the dwell time was 2 minutes at each temperature.

To quantify the adhesive properties of all tapes, 90° peel tests were performed with the modular peel fixture described in Chapter 4 (Gohl et al., 2021) at -20 , 0 , 25 , and 40°C , as shown in Figure 6.1b. A model stainless steel substrate was used and placed on a stainless steel box. A thermocouple was used to monitor the substrate temperature during each peel test. To achieve the desired temperatures, the box was filled with dry ice and ice with table salt to attain temperatures of -20 and 0°C , respectively. For measurements at 25°C and 40°C , the stainless-steel substrate was placed on the lab bench and a hot plate, respectively. After 10 minutes dwell time at each temperature, the peel test was performed with 1 mm/s (2.4 in/min) peel rate at a peel length of 160 mm (6.3 in). The average peel force was determined for the region from 40 to 120 mm (1.6 to 4.7 in).

To evaluate the influence of age on adhesive properties of TPM tapes on real pavement surfaces, tapes were aged at -25 , 25 , and 32°C (-13 , 77 , and 90°F) for 1 day, 1 week, 1 month, 3 months, and 5 months after adhering tapes on the surface of a 6-inch diameter

Figure 6.1 (a) Double-lap shear fixture. The left image shows the double-lap shear fixture clamped on the DMA instrument. The right schematic shows the side view of the double-lap shear fixture with TPM tape. Inset images are the top and side view of the fixture. (b) and (c) 90° peel test fixture and schematics of peel test configuration with TPM tapes for (b) temperature experiments and (c) aging experiments with model and asphalt surfaces (used with permission from Son et al., 2021).

asphalt core. A 90° peel test was performed with 1 mm/s peel speed when the temperature of aged asphalt surface equilibrated to 25°C. Figure 6.1c shows 90° peel configuration for an aging test, including an inset image that shows the sample preparation in which 4 specimens of tape were applied to a single asphalt core. Images of the asphalt cores were taken prior to tape application and after peel testing to determine the presence of surface residuals following tape removal (i.e., “ghost markings”).

6.3 Results

6.3.1 Viscoelastic Properties of the PSA and Top Layer

The performance of a PSA is highly dependent on its bulk viscoelastic properties, as they generally control the conformability and adhesive strength. To increase contact area on a rough surface and form a strong bond, a PSA must remain in the rubbery plateau zone over the range of operating temperatures (Lim et al., 2006). Thus, it is important that the typical operating temperature window is selected over which the PSA exhibits rubbery plateau behavior.

The blue dotted line in Figure 6.2 indicates the transition temperature (T_R) from the transition zone (shaded) to the rubbery plateau zone (unshaded), which is defined as the temperature at which $\tan \delta = G'' / G' = 1$ (Benedek & Feldstein, 2008). All the tapes tested here have a T_R in the temperature range of interest as shown in Figure 6.2. Above T_R , all tapes exhibited greater elastic behavior than viscous behavior (i.e., $G' > G''$).

Below T_R , Tape 1, Tape 2, and Tape 4 showed fluctuated results since storage and loss moduli of PSAs exceeded the capacity of the DMA load cell. Based on the results, optimal operating temperatures of all TPM tapes were defined. In the temperature range studied here, Tape 3 displayed the largest operating temperature range, from -15 to 40°C and Tape 1 had the smallest operating temperature range, from 5 to 40°C.

The dynamic mechanical properties of the top layer were measured over the same temperature range used for the PSAs and are shown in Figure 6.3. For all tapes and temperatures, G' of the top layer exceeded G'' and thus $\tan \delta$ values were less than 1, clearly illustrating the elastic character of the tape top layers.

The red dashed line in Figure 6.3 indicates the glass transition temperature (T_g) of the top layer, defined here as the peak of $\tan \delta$ (Michels et al., 2015). Tape 2 and Tape 4 had T_g of approximately 5°C, and T_g of Tape 3 tapes was approximately 0° as shown in Figure 6.3. The glass transition temperature of Tape 1 was not in the investigated temperature range, but we expect it would be below -20°C. Below T_g , G' dramatically increased.

6.3.2 Peel Strength at the Potential Operating Temperature

The average peel force was calculated over distances of 40 mm to 120 mm at the tested temperatures. In Figure 6.4, the dashed and dotted lines indicate the T_g of the top layer and T_R of the PSAs, respectively. The peel force of Tape 4 increased as the temperature

Figure 6.2 The dynamic mechanical behavior of PSAs for (a) Tape 1, (b) Tape 2, (c) Tape 3, and (d) Tape 4. The vertical dotted line indicates the transition temperature (T_R) from transition zone (shaded region) to rubbery plateau zone. Inserted schematic image in (c) shows double lap shear configuration for PSA. A 0.5% oscillatory shear strain was applied to the PSAs at a frequency of 1 Hz (used with permission from Son et al., 2021).

Figure 6.3 The dynamic mechanical behavior of top layers for (a) Tape 1, (b) Tape 2, (c) Tape 3, and (d) Tape 4. The vertical dashed line indicates the glass transition temperature (T_g) of the top layer. Inserted schematic image in (d) shows the tensile configuration for top layer. A 0.2% oscillatory tensile strain was applied to the top layer at a frequency of 1 Hz (used with permission from Son et al., 2021).

decreased to 0°C and decreased at -20°C. Tape 2 exhibited a similar trend to Tape 4 and displayed similar peel forces between 25 and 40°C. The peel forces of Tape 1 and Tape 3 decreased inversely with temperature as shown in Figure 6.4a.

The influence of temperature on peel force magnitude can be explained through viscoelastic relationships. Jensen et al. (2009) defined an empirical relationship between viscoelastic parameters such as plateau modulus (G_0), loss tangent ($\tan\delta$), and PSA peel force (P_{peel}), as in Equation 6.1,

$$\frac{P_{peel}}{tWG_0} \propto f(\tan\delta_{\omega_{peel}}) \quad (\text{Eq. 6.1})$$

where t is the thickness, w is the width, and ω_{peel} is the peel frequency defined as 1 over peel velocity. It is important to note that the loss tangent was written as a function ($f(\tan\delta_{\omega_{peel}})$) since peel force is not directly proportional to but dependent on the loss tangent. Equation 6.1 explains the observation that the peel force for each TPM tape decreased as temperature increased since the plateau modulus and loss tangent were proportional to temperature as shown in Figure 6.2. Energy dissipation increased as loss tangent increased at lower temperatures, so the peel force was greater.

The brittle broken fracture mode was observed below both T_g of the top layer and T_R of the PSA. As a result, the average peel force decreased at -20°C for Tape 2 and Tape 4. Below T_g , the bending stiffness of the top layer increases. Below T_R , the PSA loses conformability

and becomes harder to deform, which affects adhesive strength to the surface. As a result, it is expected that bending strength of the top layer and the adhesive strength of PSAs compete during the peel test. Since the bending stiffness of the top layer was greater than the interface strength between PSAs and the surface, the tape peeled before the local angle between tape and surface reached 90°. Figure 6.4b explains this brittle broken fracture behavior in the context of TPM tapes. Although both T_g and T_R for Tape 3 tape were higher than -20°C, the brittle broken fracture mode was not observed. This was likely because of the structure of the top layer with stiff ridges distributed on the flat region. The ridge region was thicker and stiffer than the flat region. Therefore, the bending stiffness of the ridge region was greater than the flat region (Rencheck et al., 2021). Brittle broken fracture occurred in the ridge region but only over a short distance due to the length of the ridge as shown in Figure 6.4a (iii, inset graph).

6.3.3 Controlled Aging of TPM Tapes

To evaluate the effect of aging time on adhesion of TPM tapes, the 90° peel test was performed with TPM tapes on asphalt cores, which aged for 1 day, 1 week, 1 month, 3 months, and 5 months at 3 different temperature (-25, 25, and 32°C). As shown in Figure 6.5, the peel force of all tapes did not have significant changes by 1 day, but it decreased when the aging time increased by 1 week at -25°C. All tapes then slightly increased peel force over 3 months. For the aged TPM tapes at 25°C and 32°C, the peel force was

Note: The dotted and dashed lines show transition temperature (T_R) from glass transition zone to rubbery plateau zone of PSAs and glass transition temperature (T_g) of the top layers, respectively. The error bars represent a standard deviation of 3 tests. Inserted graphs represent the peel profile for each tape at the tested temperature.

Figure 6.4 (a) The average peel force with respect to the surface temperature for (i) Tape 1, (ii) Tape 2, (iii) Tape 3, and (iv) Tape 4 removed from a model stainless steel surface. (b) Schematic and image explaining the observed brittle broken fracture phenomenon, shown here for Tape 2 (used with permission from Son et al., 2021).

approximately constant over 3 months, with a slight increase observed after 5 months. Tape 1 samples aged at 25°C displayed large deviations, so the 1 month aged result was not affected by aged time.

Images of asphalt core surfaces before and after aging and peel testing were analyzed to evaluate the presence of ghost markings after a given aging period. Figure 6.6 shows representative ghost marks on an asphalt core surface. As shown in Table 6.1, ghost marks were observed for Tape 1 and Tape 3 aged at higher temperatures and longer durations. Tape 2 and Tape 4 did not result in any visible ghost markings, perhaps indicating the existence of a threshold peel force value for the formation of ghost markings as these tapes both displayed relatively low peel force values in Figure 6.5.

6.3.4 Structure-Property-Performance Relationships of TPM Tapes

As described in Chapter 3, the peel force required to remove tape from a surface is inversely proportional to the elastic modulus of the tape. Thus, tapes with lower moduli are more likely to display greater adhesion to surfaces, e.g., pavements. From the results in Table 3.1 for non-patterned tapes investigated at 25°C and considering that E_{Drape} was believed to be the most realistic measure of tape modulus, Tape 1 ($E_{Drape} = 14.8$ MPa) was predicted to display greater adhesion with pavement surfaces while reduced adhesion was predicted for Tape 2 ($E_{Drape} = 46.9$ MPa).

From the results described in Chapters 5 and 6, Tape 1 displayed the highest peel forces at 25°C compared with all

other tapes, including Tape 2, when removed from native asphalt core surfaces (see Figure 5.3b and Figure 6.4a). Tape 1 was also more likely to display ghost markings compared to Tape 2 (Table 6.1). These observations support the idea that the inherent mechanical properties of TPM tapes influenced their adhesive performance on asphalt surfaces, with relatively more flexible, low-moduli tapes exhibiting greater adhesion than less flexible, high-moduli tapes.

However, the ability to predict adhesive performance from elastic modulus alone is limited to first order approximations as the chemical interactions of the tape's PSA layer with asphalt surfaces are not considered in the above analysis but are expected to play an important role in tape-pavement adhesion. The PSA compositions of Tape 1 and Tape 2 were unknown and likely different, illustrated by the shear moduli differences in Figure 6.2a and b. So, while Tape 1 displayed strong adhesive performance with asphalt surfaces compared with Tape 2, the unknown chemical contributions of the PSA layer to the overall adhesive performance obfuscate the structure-property-performance relationships of these materials.

6.4 Conclusions and Implications

The following conclusions resulted from this study.

- A double-lap shear fixture was created to measure the dynamic mechanical properties for the PSA layer of TPM tapes. Knowledge of T_R allowed for an operating temperature window to be identified for each tape. Tape

Figure 6.5 The average peel force to remove TPM tape from asphalt core surfaces that were aged from 1 day to 5 months at (a) -25°C, (b) 25°C, and (c) 32°C. Error bars represent a standard deviation of 3 tests. The 1-hour points in each plot represent the control results obtained from peel testing conducted at 25°C of unaged tape specimens.

Figure 6.6 Ghost markings resulting from (a) Tape 1 after 1 day of aging at 32°C and (b) Tape 3 aged for 1 day at -25°C. The marking outlined in (b) on the asphalt core surface corresponds to the asphalt residuals on the Tape 3 specimen in the inset image.

TABLE 6.1
Observation of surface residuals (“ghost markings”) after removing TPM tapes following storage for specific temperatures and durations

Tape	Tape 1			Tape 2			Tape 3			Tape 4		
	-25°C	25°C	32°C	-25°C	25°C	32°C	-25°C	25°C	32°C	-25°C	25°C	32°C
1 Day	NG	G	G	NG	NG	NG	G	NG	G	NG	NG	NG
1 Week	NG	G	G	NG	NG	NG	NG	G	G	NG	NG	NG
1 Month	G	G	G	NG	NG	NG	NG	G	G	NG	NG	NG
3 Month	NG	G	G	NG	NG	NG	NG	G	G	NG	NG	NG
5 Month	NG	G	G	NG	NG	NG	G	G	G	NG	NG	NG

Note: Black “NG” represents no ghost marking and red “G” indicates ghost markings were observed.

3 had the largest operating temperature range from -15 to 40°C, and Tape 1 displayed the smallest operating temperature range from 5 to 40°C. The operating temperature ranges of Tape 2 and Tape 4 were from 0 to 40°C and -7 to 40°C, respectively.

- The modular peel fixture described in Chapter 4 was used successfully to determine the peel force for TPM tapes in contact with model stainless steel surfaces as well as the surfaces of asphalt pavement cores.
- The peel force for all TPM tapes removed from model smooth surfaces decreased as surface temperature increased within the operating temperature range. However, when the temperature was below T_g of the

top layer and T_R of PSA, the peel force decreased due to the brittle broken fracture mode for Tape 2 and Tape 4.

- The peel force for all aged TPM tapes at -25°C decreased within 1 week of aging, and the peel force was maintained by 3 months. For all of the aged TPM tapes at 25°C and 32°C, the peel force did not change significantly over a period of 3 months. Ghost marks were observed for Tape 1 and Tape 3 aged at higher temperatures and longer durations.

A number of implications resulted from this study. First, the inherent viscoelastic properties of the adhesive layers should remain pliable over a relatively wide

range of ambient temperature values (5 to 40°C). However, the top layer of the tapes became less flexible and even brittle when the substrate temperature was below freezing. Thus, while a TPM tape might feel “sticky” to the touch at low temperatures, the performance will be reduced than if installed and maintained at more moderate temperatures (typically > 10°C is recommended by tape manufacturers). Second, at very low temperatures, the adhesive strength of the tapes decreased rapidly (over a few days). This study reinforces the recommendations of all TPM manufacturers and contractor guidelines prohibiting the installation and continued use of TPM tapes in cold weather.

7. OBJECTIVE 2B: THERMAL AND MECHANICAL PROPERTIES OF THERMOPLASTIC MATERIALS USED AS PPM

7.1 Overview

This section describes the research results obtained during the investigation of the mechanical properties of PPM thermoplastic materials. The objective of this study was to determine an accurate and robust methodology to assess the bonding performance of PPM thermoplastics. This objective was accomplished by developing a shear adhesion test to evaluate the adhesion of PPM thermoplastics on asphalt surfaces and by performing a single edge notch bend test (SENB) to measure the thermoplastic’s fracture toughness. Thermal stability of the PPM thermoplastic was also investigated using thermogravimetric analysis (TGA). The primary finding was that the shear adhesion test proved to be a practical measure of debonding (fracture) energy of thermoplastics materials applied to asphalt core surfaces. This test was sensitive enough to differentiate the adhesive performance of thermoplastic PPM applied at different asphalt surface temperatures as well as on asphalt surfaces with different roughness values and surface treatments. Initially, thermoplastic PPM applied to surfaces sealed with rapid penetrating emulsions (RPE) were more likely to fail at higher energies and in a cohesive manner compared to untreated asphalt surfaces. After 5 months of aging, PPM thermoplastics exhibited decreased debonding energies at all aging temperatures. At the coldest temperature (-25°C), the RPE treatment appeared to deteriorate the adhesion between the thermoplastic and asphalt surface, resulting in very low debonding energies and adhesive failure whereas thermoplastics applied to unsealed surfaces displayed larger debonding energies and primarily cohesive failure. The inherent mechanical properties of the PPM thermoplastics also influenced their adhesive performance on asphalt surfaces, with the more ductile thermoplastic exhibiting greater adhesion to both smooth and rough asphalt surfaces than the more brittle thermoplastic.

7.2 Observational Study of PPM Paints on Sealed Asphalt Surfaces

As discussed in Section 2.2, the use of sealants can enhance the durability of pavements while reducing the performance and durability of pavement marking materials applied to the sealed areas. In summer 2018, INDOT engineers observed that centerline PPM (paint) applied to sealed asphalt surfaces showed significant deterioration compared with PPM applied to unsealed asphalt (see Figure 7.1). Resurfacing of both SR 104 and SR 4 occurred in June 2016 followed by re-painting in summer 2017. The roads experienced similar traffic and snow-plow conditions yet the markings on the sealed centerline of SR 4 are barely visible in Figure 7.1b. Another instance of reduced PPM performance was observed for centerline markings on SR 39 (segment north of US 20; see Figure 7.2). The pavement was resurfaced, corrugated, sealed, and painted in August 2017. By June 2018, the markings had deteriorated. As the centerline of SR 39 was grooved (sinusoidal corrugations), marking deterioration was likely not caused by snow plow activity but instead was believed to have resulted from poor adhesion of the PPM to the sealed asphalt surface.

In many instances, such as the examples highlighted in Figure 7.1 and Figure 7.2, PPM deterioration may result from a loss of adhesion driven by the ultimate reduction in contact area that occurs when liquid asphalt sealant is applied to pavement surfaces. Instead, use of rapid penetrating emulsions (RPE) has been suggested to avoid sealing the asphalt surface in such a way that marking material adhesion is compromised (Eicher & Higginbotham, 2019). Since RPE are designed to penetrate the asphalt and fill voids and

Figure 7.1 Images taken in the summer of 2018 of yellow centerlines on two Indiana state routes that were installed in summer 2016 (hot mix asphalt overlays) and re-painted in summer 2017. Both roads experienced similar traffic and snowplow conditions but no sealant was used on (a) SR 104, while asphalt fog sealant was applied to (b) SR 4 (photos taken by Tim Marker, source: T. Nantung, personal communication, May 1, 2019).

Figure 7.2 Image taken in the summer of 2018 of yellow centerline (paint) that was applied to the corrugated and sealed asphalt surface of Indiana SR 39 (photos taken by Tim Marker, source: T. Nantung, personal communication, May 1, 2019).

cracks, the natural texture of the surface is maintained. It is thus expected that PPM can form a relatively strong adhesive bond with the treated asphalt compared to other preservation and preventative surface treatments (e.g., fog seal, crack and joint sealants). It should be noted, however, that adhesion tests in this project found that thermoplastic PPM applied to RPE-treated asphalt were able to be removed at much lower forces than those applied to unsealed, untreated asphalt (described in Section 7.4.3).

7.3 Methods

Two commercial thermoplastic PPM were utilized as received, referred to herein as PPM-1 and PPM-2. PPM-1 was used for the development of various mechanical testing methods as well as an aging study to investigate how the mechanical properties of PPM-1 influenced its adhesive performance on asphalt at different aging conditions. The developed testing methods were then used to compare the material properties of PPM-1 and PPM-2 and their adhesion to asphalt surfaces with different roughness values maintained at different application temperatures.

TGA was conducted to assess the thermal stability of PPM-1 over the manufacturer suggested application temperature range of 400 to 425°F. Isothermal tests were performed at 100°C (212°F), 150°C (302°F), and 200°C (392°F) for 1 hour, in nitrogen and compressed air.

The 3-point bending test was performed to measure the flexural modulus and the bending (flexural) strength

of PPM-1 and PPM-2 using a universal testing machine (refer back to Equation 3.1 and Equation 3.2).

Fracture toughness indicates a materials' resistance to crack propagation. The single edge notch bend (SENB) test was conducted to determine the fracture toughness, K_{IC} (Adachi et al., 2008). The load, P , was applied to a notched specimen, having a half crack length of the total thickness, in the 3-point bending fixture.

$$K_{IC} = \frac{SP_c}{tw^{3/2}}f(\lambda) \quad (\text{Eq. 7.1})$$

The K_{IC} was calculated by Equation 7.1 when the specimen fractured, where

$$f(\lambda) = \frac{3\lambda^{1/2}\{1.99 - \lambda(1 - \lambda)(2.15 - 3.93\lambda + 2.7\lambda^2)\}}{2(1 + 2\lambda)(1 - \lambda)^{3/2}},$$

$\lambda = \frac{a}{w} \sim 0.5$, and P_c is the maximum load. S , t , w , and a were the span length, the specimen thickness and width, and the pre-crack length, respectively.

The cohesive fracture energy was determined by Equation 7.2 based on the load-deflection graph, where U_0 is area underneath the load-displacement curve, mg is the weight of the specimen, d_0 is displacement at fracture, and A is the fracture surface area. The mgd_0 term is assumed to be 0 since the weight of the specimen is small.

$$G_f = (U_0 + mgd_0)/A \quad (\text{Eq. 7.2})$$

For the shear adhesion test, illustrated in Figure 7.3c, asphalt cores were vertically fixed on the universal testing machine, then a shear force was applied by a flat indenter to the thermoplastic specimens until fracture was observed.

For the aging study of PPM-1, RPE was used as a sealant to evaluate the adhesion of PPM-1 on the sealed surface. RPE was applied to asphalt cores using a brush and dried at ambient temperature for at least 3 days before PPM-1 was applied. The sample preparation procedure that was used for the aging study utilized a hot-press to bond the PPM-1 specimen to the surface of a 6-inch diameter asphalt core (illustrated in Figure 7.3a). A silicone mold with square features 2 cm wide by 2 cm long and a depth of 5 mm was placed on the asphalt core and filled the thermoplastic. The top plate of the hot-press was heated to 205°C and the filled mold was then covered in aluminum foil. The hot-press applied 0.2 psi for 2 minutes. The sample was removed to add more thermoplastic to fill in any visible gaps. A pressure of 0.2 psi was again applied for 2 more minutes until the sample was removed and allowed to cool. When applying the thermoplastic on asphalt with a pressure on the mold for 4 minutes, the asphalt surface temperature reached to 55°C, close to the onset of the asphalt melting temperature. The applied thermoplastic specimens on asphalt cores were aged at -25°C, 25°C, and 32°C for 1 day, 1 month, and 5 months.

Figure 7.3 Schematic of thermoplastic sample preparation procedure using (a) a hot-press, (b) an oven, and (c) the shear adhesion test developed herein.

To evaluate the effect of surface roughness, thermoplastic PPM specimens were applied to both smooth (cut) asphalt surfaces and rough (native) asphalt surfaces maintained at different temperatures of 15°C (59°F), 25°C (77°F), 35°C (95°F), and 40°C (104°F) using a hot-plate and a freezer. Approximately 2.5 g of PPM-1 was melted in the mold in a 205°C (401°F) oven for 10 minutes. PPM-2, which has unmixed glass beads in a polymer binder, was heated and agitated using a spatula on a hot plate at 220°C (428°F) prior to heating in the oven. Then, when removing the molded thermoplastic from the oven, the surface temperature-controlled asphalt core was placed on the melted thermoplastic and inverted, as shown in Figure 7.3b. A soldering iron was additionally used at 160°C to fill any visible pores in the thermoplastic specimens with 0.5–1 g of thermoplastic.

7.4 Results

7.4.1 Thermal Stability of PPM-1

The technical data sheet states that PPM-1 is designed to be stable for 4 hours at material application temperatures of 400–425°F. However, preliminary experiments determined that the thermoplastic produced visible smoke when heated in a 400°F oven. TGA results displayed significant weight loss at 200°C (392°F) in air (Figure 7.4). The color of the thermoplastic samples darkened, as shown in the inset of Figure 7.4. Both the

weight loss and color change most likely indicated that PPM-1 thermally degraded at the manufacturer recommended application temperature.

7.4.2 Aging Study: 3-Point Bend Test of PPM-1

The flexural modulus and flexural strength of aged PPM-1 specimens are shown in Figure 7.5. The flexural modulus was determined from the linear slope of the 3-point bend test graph in the strain range 0 to 0.0005. The flexural strength was defined as the yield stress or maximum stress value. The flexural modulus of PPM-1 significantly decreased with 1 week of aging at all temperature ranges. While the flexural modulus increased after 3 months of aging at -25°C and 32°C, the flexural modulus was still lower than that of the unaged (control) PPM-1 specimen. This likely indicates that there was no significant aging time or aging temperature effects on the flexural modulus of PPM-1.

Since PPM-1 was comprised of a high loading of glass beads in a polymer binder, it exhibited brittle fracture behavior having large deviations in the mechanical test. This was likely dependent on the specimen preparation procedure, causing differences in the distribution of glass beads in each specimen and the amount of voids. Interestingly, the flexural strength of PPM-1 aged at -25°C and 32°C significantly decreased after 1 year aging, indicating that PPM-1 after 1 year of installation on pavement could become susceptible to the external stresses (e.g., traffic).

7.4.3 Aging Study: Shear Adhesion of PPM-1 on Asphalt Surfaces

Figure 7.6a displays an example of the shear adhesion raw data for PPM-1, and inset images represent three different failure modes (adhesive, cohesive, and mix-mode failure) that resulted from the shear adhesion test. The fracture energy shown in Figure 7.6b,c, and d represents the total energy required to fracture the thermoplastic specimen cohesively or adhesively from the asphalt core surface with respect to the aging time at different aging temperatures (the unaged data are

Figure 7.4 TGA isothermal test results conducted at 100, 150, and 200°C for an hour in air. The inset picture shows color changes of thermoplastic samples taken after the isothermal test at each temperature.

controls provided for comparison). The fracture energy was calculated by integrating the area under the load-displacement graph, e.g., shown in Figure 7.6a.

Before aging, PPM-1 specimens applied on RPE-treated asphalt surfaces were more likely to fail cohesively and display relatively higher fracture energies compared to the values of specimens applied on the untreated asphalt. After aging, PPM-1 specimens exhibited decreased fracture energies at all aging temperatures. Notably, PPM-1 specimens aged at -25°C for 5 months all adhesively failed on RPE-treated surfaces, and 2 out of 5 specimens displayed spontaneous adhesive failure on untreated asphalt surfaces before testing. The fracture surfaces displayed in the inset image of Figure 7.6b shows that portions of the RPE-treated surface come off from the asphalt core, likely indicating that the RPE sealant deteriorated the adhesion between PPM-1 and the asphalt surface after 5 months of aging at -25°C.

7.4.4 Effect of Mechanical Properties on Adhesive Performance of Thermoplastic PPM on Asphalt

Flexural moduli were determined from linear slopes of 3-point bend test graphs in the strain range from 0 to 0.0005 for PPM-1, and from 0 to 0.001 for PPM-2, due to their different elastic regions. Flexural modulus and flexural strength values were reported in Table 7.1. Notably, the flexural modulus of PPM-1 was approximately 24 times larger than that of PPM-2 while their flexural strength values were similar in magnitude. As shown in Figure 7.7a, PPM-1 exhibited brittle behavior with a high resistance to bending. The PPM-1 specimen fractured at the maximum stress and displaying slight plastic deformation as shown in the inset graph in

Figure 7.5 The changes in (a) flexural modulus and (b) flexural strength of PPM-1 aged at -25, 25, and 32°C, for 1 week, 1 month, 3 months, 6 months, and 1 year.

Figure 7.6 (a) An example of the load-displacement raw data from the shear adhesion test. Fracture energy results at different aging temperatures (b) -25°C, (c) 25°C, and (d) 32°C, before (“no age” control data) and after aging for 1 month and 5 months.

TABLE 7.1
Flexural modulus and flexural strength of PPM thermoplastics from a 3-point bend test

	Flexural Modulus (GPa)	Flexural Strength (MPa)
PPM-1	5.67 ± 0.69	6.66 ± 0.84
PPM-2	0.24 ± 0.05	4.00 ± 0.82

Figure 7.7b. In comparison, as shown in the main graph of Figure 7.7b, PPM-2 displayed a yield point followed by a decrease in strength and failed at a lower stress value but much higher strain. Thus, the two PPM thermoplastics displayed very different mechanical responses when loaded: PPM-1 was brittle whereas PPM-2 was compliant, the latter displaying a high capacity of stress absorption and energy dissipation before the fracture.

The load-displacement graph obtained from the SENB test is shown in Figure 7.8. The fracture toughness and the cohesive fracture energy values were indicated in Table 7.2. The fracture toughness value is a function of the maximum load and the geometry of the specimen. K_{IC} values of PPM-1 and PPM-2 were within experimental error since there was no significant difference between their maximum load values as shown in Figure 7.8. The cohesive fracture energy (G_f) was calculated by dividing the integrated area under the

load-displacement graph by the fracture area of the specimen, assuming that there was no plastic deformation. The G_f value of PPM-1 was measured to be 0.03 ± 0.01 kN/m. However, since there was significant plastic deformation observed in PPM-2 specimens, G_f could not be calculated. Comparing SENB data in Figure 7.8, PPM-1 exhibited brittle fracture behavior as crack propagation occurred immediately as the crack opening initiated. In contrast, PPM-2 exhibited stable crack propagation until fracture since significant plastic deformation occurred at the crack tip. This indicates that PPM-2 which exhibited the resistance to crack propagation required more energy than PPM-1 to be fractured under the bending stress.

The shear adhesion test developed in this project was used to determine the apparent work of debonding as the total energy required to fracture PPM specimens from the asphalt core surface. Figure 7.9 shows the shear adhesion testing raw data for PPM-1 and PPM-2 which were applied to rough (native) asphalt surfaces, as an example. In Figure 7.9a PPM-1 specimens applied at 15 and 35°C adhesively failed while PPM-1 specimens applied at 25 and 40°C cohesively failed. The slopes of graphs for PPM-1 specimens applied at 15 and 35°C increased until failure, indicating that PPM-1 exhibited dynamic adhesive fracture behavior on asphalt. On the other hand, all PPM-2 specimens displayed in Figure 7.9b adhesively failed. The slopes of PPM-2

Figure 7.7 (a) Schematic and photographic images illustrate the 3-point bend test with testing parameters. (b) Flexural stress–flexural strain curves show the comparison of 3-point bend test results for PPM-1 and PPM-2. Inset graph in (b) shows the results for PPM-1.

Figure 7.8 (a) Schematic and photographic images of the SENB test with parameters. (b) Displacement–load graph comparison for PPM from the SENB test. Inset graph shows the results for PPM-1.

TABLE 7.2
Fracture toughness and cohesive fracture energy of PPM from SENB test

	Fracture Toughness ($\text{MPa}\sqrt{\text{m}}$)	Cohesive Fracture Energy (kN/m) (kJ/m^2)
PPM-1	0.23 ± 0.04	0.03 ± 0.01
PPM-2	0.21 ± 0.03	–

graphs significantly increased beyond displacement of 2 mm as the deformation of PPM-2 specimens initiated and then decreased until failure. This indicates that PPM-2 specimens were plastically deformed when the fracture energy became equal to the adhesive energy.

As shown in Figure 7.10a, while most PPM-1 specimens applied to smooth (cut) asphalt core surfaces at 15 and 25°C failed adhesively, various failure modes including cohesive and mix-mode failure were observed for specimens applied at 35 and 40°C. PPM-1 specimens applied to the rough (un-cut) asphalt surface (Figure 7.10b) also showed various failure modes and

higher fracture energy values than results from the smooth surface. For PPM-2, adhesive failure and relatively large fracture energies were observed for all specimens on the smooth asphalt surface and most specimens applied on the rough asphalt surface.

On both smooth and rough surfaces, the fracture energies of PPM-1 and PPM-2 mainly increased as the application temperature was increased (Figure 7.10a and b). Fracture energy results from the smooth surfaces were considered to primarily reflect chemical interactions on the adhesion between asphalt and the thermoplastic. Thus, the results indicated that as the

Figure 7.9 Shear adhesion test raw data of (a) PPM-1 and (b) PPM-2 performed on rough (native) asphalt surface at PPM application temperatures of 15, 25, 35, and 40°C.

Figure 7.10 Comparison of shear adhesion test on (a) smooth (cut) asphalt surfaces and (b) rough (native, un-cut) asphalt surfaces.

PPM application temperature increased, a thermal bond between asphalt and the thermoplastics via heat fusion was more likely occur, facilitating an increase in adhesion (TxDOT, 2004). In contrast, thermoplastic specimens could mechanically interlock with the rough surfaces compared to the smooth surfaces, resulting in overall fracture energies on the rough surfaces were approximately 1.5 times larger than that on the smooth surfaces. Additionally, results in Figure 7.10b reflect the different mechanical interactions that occurred between PPM-1 and PPM-2 with the rough asphalt. Referring back to the bend test results in Figure 7.7, PPM-2 was compliant enough to plastically deform resulting in higher fracture energies compared to PPM-1 (Wang & Vu-Khanh, 1996).

7.5 Conclusions and Implications

The following conclusions resulted from this study.

- PPM-1 exhibited thermal degradation during isothermal heating experiments within the application temperature range specified by the manufacturer.
- The shear adhesion test proved to be a practical measure of debonding (fracture) energy of thermoplastics materials applied to asphalt core surfaces. This test was sensitive enough to differentiate the adhesive performance of thermoplastic PPM applied at different asphalt surface temperatures as well as on asphalt surfaces with different roughness values and surface treatments.
- Greater debonding energies were observed for PPM applied at increased asphalt surface temperatures. Rough (native) asphalt surfaces also resulted in greater debonding energies compared to smooth (cut) surfaces due to the ability of the thermoplastic material to mechanically interlock with the rough surface.
- Initially, thermoplastic PPM applied to surfaces sealed with rapid penetrating emulsions (RPE) were more likely to fail at higher energies and in a cohesive manner compared to untreated asphalt surfaces.
- After 5 months of aging, PPM thermoplastics exhibited decreased debonding energies at all aging temperatures.

At the coldest temperature (-25°C), the RPE treatment appeared to deteriorate the adhesion between the thermoplastic and asphalt surface, resulting in very low debonding energies and adhesive failure whereas thermoplastics applied to unsealed surfaces displayed larger debonding energies and primarily cohesive failure.

- PPM thermoplastics with inherently greater ductility exhibited better adhesion to both smooth and rough asphalt surfaces compared to thermoplastics with a more brittle mechanical response.

A number of implications resulted from this study. First, the kettle temperature recommended by the manufacturer during the application of the thermoplastic PPM were greater than the degradation temperature measured in this study. By maintaining this product at elevated temperatures, it is possible that the thermoplastic material will be damaged before application. Future studies into reducing the kettle/application temperature so that the thermoplastic is molten but not burned could yield interesting changes to the current installation protocols. Second, installation of thermoplastic PPM on asphalt roadways at or above 35°C of pavement temperatures promote mechanical interlocking at the interface, leading to a more robust installation. Applying these thermoplastic PPM soon after the asphalt has been placed, prior to complete cooling would be beneficial to promote strong adhesion. Third, considering the shear adhesion and bending test results described here, it is likely that brittle thermoplastic PPM will be cracked and mainly cohesively fractured in the field whereas the relatively ductile thermoplastic PPM would be plastically deformed and adhesively failed on asphalt roadways due to external stress from vehicles.

8. CONCLUDING REMARKS

The results reported in the previous chapters clearly demonstrate that the adhesive performance of durable pavement marking materials in contact with asphalt surfaces was strongly dependent on a number of factors, including the physical structure and mechanical properties of the marking material, the application and environmental temperatures, the age of the applied marking material, and the nature of the asphalt surface (rough/smooth, sealed/unsealed).

While future field testing is needed, over the course of this project no single product or pavement marking type demonstrated superior performance in all situations. Therefore, INDOT should continue to consider a wide variety of pavement marking products for inclusion on the list of approved construction materials. The four testing and analysis methods demonstrated in this project—the Tape Drape Test, the peel tests utilizing the modular peel fixture, the Tear Resistance Ratio, and the shear adhesion test—could be implemented by engineers tasked with evaluating the performance of new pavement marking products for the INDOT New Product Evaluation Committee as well as by manufacturers of TPM tapes and PPM thermoplastic materials. In particular, the Tape Drape Test is

expected to be straight-forward to implement by tape product manufacturers given the minimal equipment requirements, and the modular peel fixture has the practical capability of directly testing immovable surfaces, like roadways.

Of particular interest to transportation engineers is how pavement markings perform when installed, used, and removed in the low temperatures typically experienced during early- and late-season construction projects. In particular, low temperatures could both hinder or help with the removal of marking materials from asphalt surfaces. Marking materials that require less force to remove at low temperatures could also experience greater damage due to traffic and thus decreased performance over the duration of the construction project. Marking materials that require more force to remove may exhibit better performance and service life but might result in additional complications during removal, such as the formation of ghost markings or other damage to the asphalt surface or increased tearing during removal. Though field testing is needed, this project provides some insights on the low-temperature durability of TPM tapes and PPM thermoplastics.

In this study, two of the TPM tape brands required relatively large forces to remove the tape from a smooth model surface maintained at -20°C (-4°F) (Figure 6.4). However, under the same testing conditions, the other two tape brands displayed brittle broken fracture behavior that facilitated tape removal by reducing the force required to peel the tape from the model surface. Tape age can also play an important role as the adhesive strength of all tape brands that were applied to asphalt surfaces decreased significantly after only 1 week of storage at -25°C (-13°F) (Figure 6.5), and ghost markings were less commonly observed at low temperatures (Table 6.1). In the experiments involving PPM, one thermoplastic brand stored at -25°C (-13°F) displayed exceptionally poor adhesion on RPE-treated asphalt compared with an unsealed asphalt surface after only 1 month of aging (Figure 7.4b). Both PPM thermoplastic brands investigated in this study displayed reduced adhesive performance on smooth and rough asphalt surfaces as the application temperature was reduced from 40 to 15°C (104 to 59°F) (Figure 7.8).

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APPENDICES

Appendix A. Assessing the Elastic Modulus of Pavement Marking Tapes Using the Tape Drape Test

Appendix B. A Modular Peel Fixture for Tape Peel Tests on Immovable Substrates

Appendix C. Substrate Temperature Effects on the Peel Behavior of Temporary Pavement Marking Tapes

APPENDIX A. ASSESSING THE ELASTIC MODULUS OF PAVEMENT MARKING TAPES USING THE TAPE DRAPE TEST

Rencheck, M. L., Gohl, J. A., Grennan, H. P., Erk, K. A., & Davis, C. S. (2021). Assessing the elastic modulus of pavement marking tapes using the tape drape test. *Transportation Research Record*, 2675(8), 570–579. <https://doi.org/10.1177/0361198121999623>

Publication Abstract

Temporary pavement marking (TPM) tape adhesion with roadway surfaces is critical for tape performance. The two main TPM performance issues stem from the adhesive strength. Weak adhesion results in premature detachment and excessive adhesion requires extensive removal processes that often leave ghost markings, both of which can cause dangerous confusion in road construction zones. Tape adhesion is directly related to the elastic modulus (E) of TPM tapes. Thus, accurate characterization of E before tape installation is essential to fully understand and predict the adhesion performance and ultimately the durability of TPM. To determine the most appropriate E characterization technique for three different commercial TPM tape brands, two commonly used techniques—tensile and three-point bend testing—were compared with a less common technique, the Peirce cantilever testing or “Tape Drape Test” (ASTM D1388-18). The Tape Drape Test was the only method that accurately characterized E of tapes with raised surface features. Measured E values from tensile and three-point bend testing showed significant variation caused by the structural features of the tapes. The Tape Drape Test, which can be implemented quickly in the field before tape installation with little equipment, effectively characterized E for all the tapes to inform tape adhesion performances and installation procedures.

APPENDIX B. A MODULAR PEEL FIXTURE FOR TAPE PEEL TESTS ON IMMOVABLE SUBSTRATES

Gohl, J. A., Thiele-Sardina, T. C., Rencheck, M. L., Erk, K. A., & Davis, C. S. (2021). A modular peel fixture for tape peel tests on immovable substrates. *Experimental Mechanics*, 61, 1209–1213. <https://doi.org/10.1007/s11340-021-00738-1>

Publication Abstract

Background: Peel tests are frequently used to perform measurements of adhesive strength for pressure sensitive adhesive (PSA) tapes. Current lab methodologies for 90° peel tests translate the model substrate orthogonally to the peel direction in order to maintain the peel angle, precluding testing from immovable substrates.

Objective: It was our objective to develop a peel fixture capable of testing temporary pavement marking (TPM) tapes and other PSA tapes from immovable substrates such as roadways surfaces.

Methods: We present a modular peel fixture for conducting peel experiments directly on immovable substrates. The fixture was validated through a series of peel tests on consumer tapes to reproduce the linear width dependence and viscoelastic rate dependence found in traditional peeling setups. To test the capabilities of the fixture, a series of peel tests were conducted with various tapes on controlled surfaces, and a commercial tape on various immovable substrates.

Results: We demonstrate the ability of our fixture to reproduce results reported for traditional peel tests from literature. In addition, we were able to conduct peel tests directly on immovable substrates such as the benchtop.

Conclusions: This fixture shows potential for both traditional peeling tests, and for use in in-situ peel experiments from substrates relevant to the end application of the PSA tape.

APPENDIX C. SUBSTRATE TEMPERATURE EFFECTS ON THE PEEL BEHAVIOR OF TEMPORARY PAVEMENT MARKING TAPES

Son, H. Erk, K. A., & Davis, C. S. (2021). Substrate temperature effects on the peel behavior of temporary pavement marking tapes. *The Journal of Adhesion*.
<https://doi.org/10.1080/00218464.2021.2008369>

Publication Abstract

Temporary pavement marking (TPM) tapes are utilized in road construction to delineate temporary traffic lanes and work zones. Adhesive failure of TPM tapes can therefore remove lane and work zone designations, confusing drivers and causing serious accidents, especially in high speed zones. Thus, the adhesion of TPM tapes to pavement surface plays an important role in road construction traffic safety. Pressure sensitive adhesives (PSAs) comprise the adhesive layer of TPM tapes. The adhesion of PSAs depends on their temperature-dependent viscoelastic properties. Since environmental conditions vary during construction, the adhesion of TPM tapes will change over a range of operating temperatures. The viscoelastic properties and peel force of four brands of commercial TPM tapes were characterized via double lap shear dynamic mechanical analysis and 90° angle peel adhesion testing over a range of temperatures (-20°C to 40°C). The interfacial fracture behavior and peel forces were analyzed with respect to the measured viscoelastic properties of TPM tapes. For temperatures below the glass transition temperature of the top layer and the transition temperature into the rubbery plateau of the PSA, the peel force decreased. Through this simple technique, an effective operating temperature range for each TPM tape was determined.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1 — evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at <http://docs.lib.purdue.edu/jtrp>.

Further information about JTRP and its current research program is available at <http://www.purdue.edu/jtrp>.

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