DEPARTMENT OF TRANSPORTATION

Is Seal Coating Counterproductive or Not?

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Final Report 2020-34

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While seal coating has been widely used as a cost-effective strategy in asphalt pavement preservation by MnDOT and local agencies with great success, some cities and counties in Minnesota have reported their concerns about the premature stripping of street pavements that have been seal coated. The objective of this study was to diagnosis whether seal coating was counterproductive in asphalt pavement preservation. In this study, the research team investigated the mechanisms accountable for asphalt pavement stripping under seal coats and provided recommendations. Comprehensive field and laboratory data collection was conducted to diagnose premature stripping. Some possible causes of stripping were proposed after preliminary diagnoses. For example, one proposed cause was that due to the weak bond strength of the asphalt pavement, the underlying seal coating could be prone to premature stripping under high-moisture and multiple freeze-thaw conditions. Corresponding laboratory testing was then conducted. Based on the research conducted in this study, it cannot be simply concluded that seal coating is counterproductive.

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EXECUTIVE SUMMARY

While seal coating has been widely used as a cost-effective strategy in asphalt pavement preservation by MnDOT and local agencies with great success, some cities and counties in Minnesota have reported their concerns about the premature stripping of street pavements that have been seal coated. In this project, a Michigan Tech research team investigated the mechanisms accountable for asphalt pavement stripping under seal coats and provided recommendations. The Michigan Tech research team identified three research areas that are expected to have measurable beneficial outcomes: 1) determine whether the seal coating is useful to extend the service life of the pavement, 2) find out why stripping occurs under seal coats and provide some methods to solve it, and 3) make recommendations for the implementation of seal coating on street asphalt pavements.

A comprehensive field data collection was conducted to diagnose premature stripping. Data collection included the service condition of existing pavement, the mix design underneath, the occurrence of stripping, the material type of seal coat, etc. Some possible causes of stripping were proposed after diagnosis. For example, one proposed cause was that due to the weak bond strength of the asphalt pavement, the underlying seal coating may be prone to premature stripping under high-moisture and multiple freeze-thaw conditions. Corresponding laboratory testing was then conducted. Two newly developed laboratory tests, Michigan Tech's interface bond test (IBT) and shear bond test (SBT), were employed to evaluate the interface bond strength and shear bond strength of asphalt pavement under seal coating in different temperatures, moisture conditions, and freeze-thaw cycle conditions for various asphalt-emulsion and aggregate combinations. In addition, the proposed IBT test was used for testing the interface bond strength of pavement cores with different pavement ages, material types of seal coats, and degrees of pre-existing damage to evaluate the seal coated pavements.

The laboratory IBT and SBT test results concluded the following: 1) the interface and shear bond strength between the laboratory seal coat layer and asphalt pavement layer decreased with the increase of freeze-thaw cycles. The presence of fewer voids in the seal coat reduced the microstructural damage due to possible ice expansion of voids during freeze-thaw cycles, and thus the larger aggregates produced an increase in microstructural damage; 2) the combined performance of polymer-modified asphalt-emulsion (named AE-1 in this report) and aggregate Granite FA-2.0 was optimal for low-temperature resistance, while the optimal aggregate type for freeze-thaw cycle resistance was Trap-Rock 1/8 inch minus (with the range of aggregate types and emulsion application rate of 0.36 gal/yd2 selected in this study); 3) the weak asphalt-aggregate combination in the seal coat application and the increased freeze-thaw cycles were the main factors for premature stripping of many seal coat asphalt pavements. Due to the multiple freeze-thaws and other factors, asphalt may be stripped from the aggregates of the asphalt mixture layers and the seal coat layer; 4) based on the test results from the newly developed laboratory interface bond test on the pavement cores, it was concluded that when partial damage occurs in the seal coats, further deterioration accelerates in the pavement system.

It should be noted that the above-mentioned laboratory testing results were based on a limited number of asphalt pavement cores. The asphalt pavement structures studied in this project have different historical asphalt mixture designs. It is challenging to confirm the exact reason for premature stripping since the historical asphalt mixture design information is unavailable. Based on the research conducted in this study, it cannot be simply concluded that seal coating is counterproductive.

CHAPTER 1: INTRODUCTION AND BACKGROUND

This study aimed to address the problem of asphalt pavement stripping under seal coating in Minnesota. A comprehensive field data collection was conducted to diagnose premature stripping. Data collection included the service condition of existing pavement, the mix design underneath, the occurrence of stripping, and the material type of the seal coat. Corresponding laboratory testing was conducted to verify the hypotheses. Based on the testing results, the research team then aimed to 1) determine whether seal coating is useful to extend the service life of the pavement, 2) find out why stripping occurs under seal coats and provide some methods to solve it, and 3) make recommendations on the implementation of seal coating on street asphalt pavements.

To answer the question “Is seal coating counterproductive or not?” the research team investigated the following sources:

- The Federal Highway Administration (FHWA) website
- Minnesota Department of Transportation (MnDOT) website
- The National Academies website
- American Society of Civil Engineers (ASCE) Civil Engineering database
- Google and Google Scholar website
- Science Direct website

Table 1-1. Preservation method comparison

Method	Cost (dollar/yd^2)	Typical Treatment Life (Years) Based on Pavement Condition		
		Good	Fair	Poor
Chip Seal	0.8-1.5	6-8	4-6	3-4
Fog Seal	0.3-1.5	1-3	Limited use	Not recommended
Bio Fog Seal	1.0-1.6	3-5	Limited use	Not recommended
Slurry Seal	1.3-2.2	6-7	Limited use	Not recommended
Micro-Surfacing	2.5-3.5	12-15	7-12	5-7

1.1 INTRODUCTION

Asphalt pavement preservation treatments restore pavement surface conditions and protect the underlying pavement, which can defer the need to rehabilitate or reconstruct asphalt pavements. There are several different types of surface treatment methods, such as chip seal, fog seal, bio fog seal, slurry seal, and micro surfacing. Chatti et al. (Chatti et al. 2017) reported some examples to illustrate the application for select preservation treatments, including empirical approach-micro surfacing, mechanistic-empirical approach-thin overlay, and performance-based laboratory and field tests-chip seal. Asphalt pavement was used to show how these approaches could establish a relationship between material, pavement construction quality characteristics, and performance. The treatment performance is typically evaluated by the life cycle of the surface treatment itself and the life extension of the underlying asphalt pavement layers. Table 1-1 compares the different preservation methods researched thus far, while Table 1-2 summarizes the critical properties of the available seal coat alternatives. The two tables are from the report Alternatives to Seal Coats (Corporation 2016).

Table 1-2. Seal coat alternatives summary

Method	Key notes
Micro-surfacing	• Works well in areas with excessive turning movements • Does not require cover aggregate (no loose chips) • Resistant to scraping or abrasion from carbide snowplow blades • Can correct the surface profile to some degree (fills minor ruts and other surface irregularities)
Slurry Seal	• Works okay in areas with excessive turning movements • Does not require cover aggregate (no loose chips) • Resistant to scraping or abrasion from carbide snowplow blades
Chip Seal	• The most common approach • Can restore or improve skid resistance • Vehicle damage from flying stones (loose chips)
Fog Seal & Bio Fog Seal	• Can minimize the impact from the traveling public and adjacent homeowners in urban areas • Is spray applied • Reduces scraping or abrasion from carbide snowplow blades • Loss of skid resistance, especially during rain events

Seal coating has been in use for over 50 years in the United States (Jackson 1990). As part of their roadway maintenance program, Gransberg et al. (Gransberg 2005) surveyed United States public highways and various road agencies to determine if seal coating was used. From this survey, Gransberg et al. (Gransberg

2005) were able to identify the best practices in seal coating design and construction. It was determined that the United States public highways, along with the agencies, use seal coating on both high and low volume roads. Seal coating is an economical type of asphalt pavement treatment that was designed for single-layer aggregate-asphalt. Seal coating is applied to prime-sealed granular pavement surfaces to waterproof the surfaces of sub-layers, produce smooth and high-skid-resistant surfaces for vehicles, and protect pavement against the detrimental effects of traffic and climate. Seal coating also is used on the unbound granular base in countries such as Turkey, South Africa, New Zealand, and Australia (C Gürer 2010; Distin 2008; Holtrop 2008). Compared to hot mix asphalt pavement, the performance of seal coating on the unbound granular base can be affected by numerous factors before and after construction (Cahit Gürer et al. 2012). The surface temperature, material properties, equipment, asphalt temperature, aggregate spreading and rolling, and time between asphalt spraying and aggregate spreading should be considered during the seal coat construction, as these affect the performance of the seal coat. The time between the asphalt spraying and aggregate spreading affects the efficiency of the bond between the aggregate and asphalt, with any lack of bond causing degradation, such as stripping. Seal coating has been widely used as a cost-effective strategy in asphalt pavement preservation. MnDOT has conducted studies that identified areas with lower density, higher air voids, and stripping under seal coating (Rettner and Tompkins 2017; Wood and Cole 2013; Wood 1999; Lukanen 1997).

1.2 MECHANISM OF STRIPPING OF ASPHALT PAVEMENT UNDER SEAL COATING

Many asphalt pavements under seal coating suffer from premature stripping, and states are progressively specifying the use of antistripping agents. It has been reported by Fromm (Fromm 1974) that the stripping of aggregates from asphalt initiates at the bottom of the asphalt pavement and gradually moves up. This is most likely due to highly compacted pavement. Water may enter the asphalt pavement from the granular base, infiltrate through the seal coating surface cracks, or seep in from the sides (due to the hydraulic gradient) and deteriorate the pavement under the seal coating, which subsequently causes stripping. Figure 1-1 shows a conceptual diagram for the stripping mechanism. Normally, the moisture or water could migrate into the interface of asphalt and aggregate, and the potential osmotic difference causes diffusion across the asphalt film, wear and tear of asphalt binder film, seepage by air voids, and diffusion from the pores of the aggregate to the interface due to its partial coating (S.K. Das 2004). Some studies reported that the damage would be minimal if the stripping is restricted to coarse aggregates; however, if stripping occurs with fine aggregates, then the influence will be severe since these aggregates are major constituents in the asphalt mixtures (Kennedy, Roberts, and Lee 1982; Taylor and Khosla 1983). The relationship between stripping and how the seal coat was applied to the asphalt pavement needs to be analyzed.

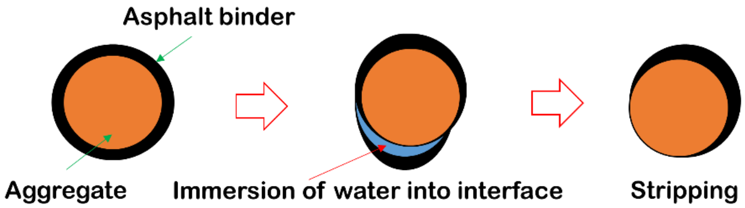


Figure 1-1. Conceptual diagram for stripping mechanism

1.3 FIELD PERFORMANCE OF SEAL COATING AT THE DIFFERENT APPLIED SITUATIONS

Kandhal (Kandhal 1994) has described factors that can induce the premature stripping of asphalt pavement under seal coatings, such as inadequate pavement drainage, inadequate compaction degree of asphalt mixture, excessive dust coating on aggregate, and inadequate drying of aggregate. Kandhal et al. (Kandhal, Lubold, and Roberts 1989; Kaukuntla 2014) reported that if excessive water (or moisture) is present in the asphalt pavement, surface, or subsurface, then the asphalt pavement can strip prematurely. Stripping is a localized phenomenon that occurs in areas of pavement and is caused by inadequate subsurface drainage. Inadequate compaction of HMA material is probably the most common construction-related factor to cause premature stripping. Terrel et al. (Terrel and Shute 1989; Kaukuntla 2014) have developed the concept of pessimum voids percentage for stripping, as shown in Figure 1-2. Figure 1-2 shows that at less than 4.0% voids (region A), the asphalt mixture is virtually impermeable to water, but most asphalt pavements are constructed in regions B and C. The asphalt mixture strength becomes less affected by water when the voids increase to region D and beyond. The pessimum voids, shown in regions B and C, are the opposite of optimum (Kandhal 1994). Parker (Parker Jr 1989; Kaukuntla 2014) studied the influence of inadequate drying of aggregate on the stripping of asphalt pavement, and the results indicated that a high residual-moisture percentage in the aggregate before mixing with asphalt binder increases the potential for stripping.

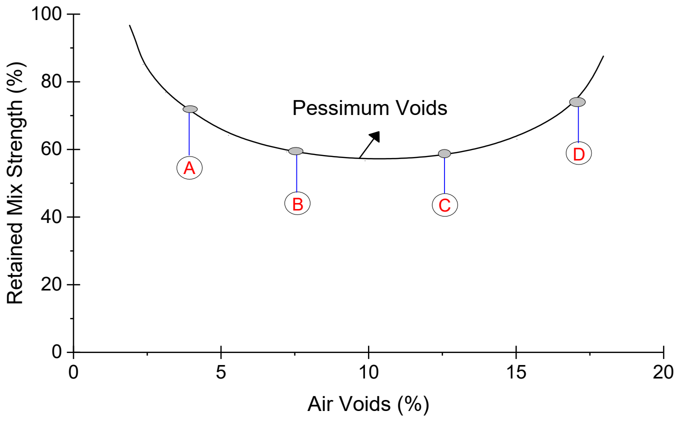


Figure 1-2. Air-void content vs. retained mix strength, the region of pessimum (Terrel and Shute 1989; Kaukuntla 2014)

In addition, the appropriate selection of an asphalt pavement preservation treatment and the corresponding design require proper characterization of the pretreatment asphalt pavement condition. Meanwhile, the pavement should be structurally sound, and the preservation treatment also should be applied at an optimum time with respect to both distress types and the rate of deterioration in the existing pavement. The location, timing, and selection of the preservation treatment also significantly affect the stripping resistance of the asphalt pavement under the seal coating (Chatti et al. 2017; Peshkin and Hoerner 2005; Anderson et al. 2014). Therefore, the relationship between the seal coating and the distresses in the asphalt pavement under the seal coating should be considered in seal coating practices.

1.4 OIL FUNCTION AND EMULSION APPLICATION IN SEAL COATING MATERIALS

The distress of bleeding also happens in some asphalt pavements under seal coating. Typically, hot asphalt binder, asphalt emulsion (with 67% asphalt binder), or cutback asphalt (with 85% asphalt binder) are used in seal coating. An asphalt emulsion consists of three components: asphalt binder, water, and an emulsifying agent (surfactant). Emulsions are usually divided into three classification grades: cationic (positive electrical charge), anionic (negative electrical charge), and non-ionic (only cationic and anionic can be used in seal coating construction and maintenance). The schematics of the catatonic and anionic emulsions are shown in Figure 1-3. CRS-2 and CRS-2P are the most commonly used types of asphalt emulsions for seal coats in Minnesota. Zhai et al. (Zhai, Salomon, and Miliron 2006; Salomon et al. 2008; Hanz, Johannes, and Bahia 2012) designed different tests to simulate the application of some asphalt emulsions, which include CRS-2 and CRS-2P, in the field. They reported that the rheological tests generated useful results to understand the emulsion breaking behavior of different asphalt emulsions.

Cutback asphalt may be used for seal coating. However, it is not generally used in Minnesota. The use of cutback asphalt has declined rapidly due to its high cost and use of harmful solvents; cutback asphalt consists of asphalt cement dissolved in a solvent, typically kerosene or gasoline. The solvent softens the asphalt binder and allows it to be pumped and sprayed at reasonably low temperatures. As the solvent evaporates into the atmosphere, only the asphalt binder remains; once the solvent has evaporated, the cutback has fully cured (Wood, Janisch, and Gaillard 2006). Ghaly et al. (Ghaly, Ibrahim, and Noamy 2014) evaluated the benefits of using cutback asphalt in seal coating in a controlled laboratory. It was determined that the low viscosity (high oil content) cutback asphalt was more effective than the seal coating with high viscosity (low oil content) asphalt. Wasiuddin et al. (N.M. Wasiuddin et al. 2013) investigated the sensitivity of the sweep test for both emulsion and hot asphalt concerning aggregate mineralogical types, aggregate pre-coating, aggregate moisture content, asphaltic material types, and application rates of asphaltic materials. The results determined that hot asphalts performed better than emulsions with limestone aggregate. With gravel aggregate, CRS-2P performed better than hot asphalt and CRS-2. The performance of the applied emulsion on the other types of aggregate and the function of oil in the seal coating materials were unable to be determined. Therefore, the oil function in the seal coating materials and the performance of the emulsions applied on different aggregate require further study.

1.5 OIL MOISTURE DAMAGE AND INTERLAYER STRENGTH QUANTITY/QUALITY CHECK

The moisture damage of asphalt pavement under seal coating is an extremely complicated mode of distress, and previous moisture damage studies have mainly focused on the performance of undamaged asphalt pavement without seal coats. For example, Cui et al. (Cui et al. 2015) studied the effect of traffic-load-induced mechanical damage and evaluated moisture damage in HMA pavement by permeability tests and the Hamburg Wheel Tracking Device (HWTD) tests. Grenfell et al. (Grenfell, Apeagyei, and Airey 2015) used surface energy measurements of the constituent asphalt binder and aggregate from the rolling bottle and the saturation aging tensile stiffness (SATS) tests to better understand the underlying processes and mechanisms of moisture damage. Seal coating, a commonly used surface treatment in Minnesota, does not significantly increase structure capacity when it is used on the surface of asphalt pavement. Moderately severe cracks and other distress like moisture damage should be repaired, and the surface should be cleaned before treatment. Tack coating could significantly increase the strength and fatigue life of the asphalt pavements at a low cost because of its ability to provide a uniformly thin, tacky, adhesive film without running off the asphalt pavement or causing slippage between the old and new pavement surface. The moisture resistance of seal coated asphalt pavement should be analyzed, and thus it can be determined how to improve the moisture resistance of asphalt pavement under seal coating. In addition, weak interlayer bonding leads to a reduction in the service life of seal coated asphalt pavement, so the identification and measurement of parameters affecting interlayer shear and tensile strength are becoming increasingly important. Graziani et al. (Graziani et al. 2017) presented the effects of test temperature and interlayer deformation rate on the interlayer shear strength of double-layered asphalt pavement, and the experimental data shows that the interlayer deformation rate and the structure temperature have a significant influence on the shear strength. Furthermore, the general practice of improving the interlayer strength is to apply a tack coat over an existing asphalt pavement surface before seal coating. Panda et al. (Panda, Prakash Giri, and Bikash Sutradhar 2015) explored the influence of setting time of tack coat material on the bond strength of the asphalt-based structure layers combination, and the test results indicated that the setting time, temperature, tack coat type, and application rate of tack coat affected the interlayer bond strength. Das et al. (R. Das et al. 2017) also evaluated the effect of pavement surface type, tack coat material, and application rate on the interface bond strength between an HMA overlay and underlying pavement layers in the field. The results show that the interface bonding strength increased with the service time in all field projects and for all surface types. Therefore, an interlayer strength quantity and quality check of asphalt pavement under seal coating is needed.

CHAPTER 2: FIELD DATA COLLECTION FOR STRIPPING AREAS ON PAVEMENTS

Field data collection is essential for identifying the causes of asphalt pavement stripping under seal coating for many cities in Minnesota. A survey of the variation in air voids of many streets may have been done in previous studies; this data can also be used in this project. Data collection will focus on the following aspects according to the existing field data from American Engineering Testing (AET).

2.1 FIELD SAMPLE COLLECTION LOCATIONS

In the early stages of this project, from November to December 2017 and November to December 2018, AET visited eight cities/counties in Minnesota as field sample collection sites, as shown in Figure 2-1, which provided the field data for project research. The original/initial field data collection plan is summarized in Appendix I-1. Of the locations considered for field sample collection, only eight cities/counties in Minnesota were selected for inclusion based on a combination of factors, i.e., the ability to obtain cores, the traffic and climate conditions, the possibility of stripping, and the age of pavement. The field sample collection pictures are presented in Appendix I-2 and Appendix I-3. All of the collected pavement cores are in a diameter of 200 mm (8 inches).

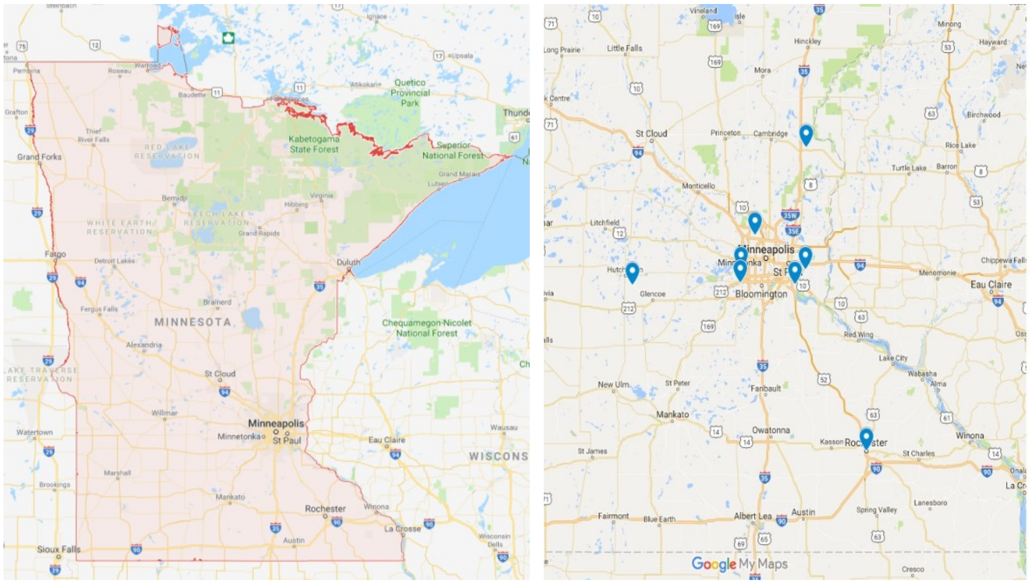


Figure 2-1. State of Minnesota view (left image) and the locations of field sample collection (right image, sources: ©2019 google maps). the selected eight cities/counties are city of Brooklyn Park, city of Eden Prairie, city of Inver Grove Heights, McLeod county, city of Minnetonka, city of Rochester, city of Woodbury, and Chisago county

2.1.1 Asphalt Pavement Samples without Seal Coating

8-inch cores of old asphalt pavement samples without seal coating were collected for comparison. Four cores each were taken from 6- to 9-year-old asphalt pavement and 10- to 20-year-old asphalt pavement in Minnetonka, Minnesota. The sample sites, latitudes, and longitudes are presented in Table 2-1.

Table 2-1. Asphalt pavement samples without seal coating

Pavement age	Sample ID	Latitude	Longitude
6-9 years	MN DH#1	44.96481736	-93.46580216
	MN DH#2	44.96483715	-93.46583463
	MN DH#3	44.96483809	-93.46732568
	MN DH#4	44.96486005	-93.46733491
10-20 years	MN DO#1	44.91562106	-93.43815971
	MN DO#2	44.91562092	-93.43818371
	MN DO#4	44.91559263	-93.43777997
	MN DO#3	44.91559956	-93.43777286

2.1.2 Seal Coated Pavement with Granite Aggregates

The selection of stone aggregate directly affects the performance of seal coated pavements. There are two types of aggregates usually used in seal coated pavement: granite aggregate and trap rock aggregate. Granite aggregate is a common type of felsic intrusive igneous rock that is granular and phaneritic in texture. In order to analyze the stripping mechanism of seal coated pavement with granite aggregate, a sample of partially damaged seal coated pavement and good performance seal coated pavement were selected for different usage times of 0-3 years, 6-9 years, and 10-20 years. The sample sites for the study are shown in Table 2-2.

2.1.3 Seal Coated Pavement with Trap-Rock Aggregates

Trap rock is any dark-colored, fine-grained, non-granitic intrusive or extrusive igneous. Trap rock is used as a standard seal coating aggregate in Minnesota. In order to analyze the stripping mechanism of seal coated pavement with trap rock aggregate, pavement cores of partially damaged seal coated pavement and good performance seal coated pavement were collected for different usage times of 0-3 years, 6-9 years, and 10-20 years. The sample sites for the study are described in Table 2-3.

In Tables 2-2 and 2-3, N/A = Not Applicable; Good Performance = There is no significant stripping that occurred on the surface of seal coating pavement; Partially Damaged = There is initial stripping or partial stripping (damage of seal coats) that occurred on the surface of the seal coating pavement.

2.2 LABORATORY MATERIALS PROVIDED BY MNDOT

The main objective of the laboratory test is to find out the compatible asphalt-emulsion and aggregate which results in minimum chip loss or maximum aggregate retention. This laboratory test evaluates the seal coated pavement of both trap rock and granite aggregates in coated and uncoated conditions. The used asphalt-emulsion includes CRS-2P and CSS-1H. Statistical analysis was done during the laboratory test to identify the parameters affecting the performance of seal coated pavement. The laboratory test measured the tensile strength between the seal coating layer and old asphalt pavement, the shear strength between the seal coating layer and old asphalt pavement, the low-temperature adhesive strength of aggregate in the emulsions, the curing performance of emulsions, and the aggregate by the brooming of surface treatment.

The selection of laboratory materials for this study depended on the commonly used materials in Minnesota. LRRB, MnDOT, and the research team prepared a list of pavement materials to be sampled, shown in Appendix I-1, which consists of aggregate with different sizes and asphalt-emulsions. In order to investigate the property, change of the aggregate used in seal coating as the stripping occurred, some loose seal coating materials pulled from seal coated pavements were also provided by LRRB.

Table 2-2. Seal coating pavement with granite aggregates

Pavement age (Year)	Partially damaged			Good performance		
	Sample ID	Latitude	Longitude	Sample ID	Latitude	Longitude
0-3	MN MC#1	44.90062127	-94.05315752	No.2	N/A	N/A
	MN MC#E	44.90062531	-94.05315259	No.3	N/A	N/A
	MN MC#2	44.90065662	-94.05316705	N/A	N/A	N/A
	No.1	N/A	N/A	N/A	N/A	N/A
6-9	EP#1	44.82085749	-93.46230201	EP#5	44.82471751	-93.47043580
	EP#2	44.82086203	-93.46235748	EP#6	44.82472222	-93.47046935
	EP#3	44.82357205	-93.46564558	EP#7	44.82717237	-93.47306520
	EP#4	44.82359668	-93.46563598	EP#8	44.82718793	-93.47306906
10-20	RCHSTR#1	44.06692606	-92.49961385	No.5	N/A	N/A
	RCHSTR#2	44.06693501	-92.49960048	No.6	N/A	N/A
	RCHSTR#3	44.07461115	-92.50466184	N/A	N/A	N/A
	RCHSTR#4	44.07460266	-92.50467042	N/A	N/A	N/A

Table 2-3. Seal coating pavement with trap-rock aggregates

Pavement age (Year)	Partially Damaged			Good Performance		
	Sample ID	Latitude	Longitude	Sample ID	Latitude	Longitude
0-3	No.7	N/A	N/A	No.9	N/A	N/A
	No.8	N/A	N/A	No.10	N/A	N/A
	N/A	N/A	N/A	N/A	N/A	N/A
	N/A	N/A	N/A	N/A	N/A	N/A
6-9	MN BP#1	45.11711623	-93.32914346	MN BP#4	45.11797043	-93.31896536
	MN BP#2	45.11711168	-93.32916623	MN BP#5	45.11797898	-93.31896155
	MN BP#3	45.11753424	-93.32852339	MN BP#6	45.11799129	-93.31890400
	No.4	N/A	N/A	MN BP#7	45.11797898	-93.31892103
10-20	WB#1	44.91319872	-92.90642584	IGH#1	44.81419018	-93.09659572
	WB#2	44.91319912	-92.90643923	IGH#2	44.81418050	-93.09660966
	WB#3	44.91211938	-92.90578848	IGH#3	44.81386032	-93.09651928
	WB#4	44.91211537	-92.90584858	IGH#4	44.81387308	-93.09652641

CHAPTER 3: EVALUATION OF INTERFACE BOND TEST FOR ASPHALT PAVEMENTS UNDER SEAL COATING

This task aimed to evaluate the effect of aggregate and asphalt-emulsion types on the durability of seal coats in Minnesota. In this study, the Michigan Tech's Interface Bond Test (IBT) was employed to assess the interface bond strength between the asphalt-emulsion based seal coat layer and the asphalt pavement under varying temperatures (25°C, 0°C, and -10°C) and multiple freeze-thaw cycle conditions (N=0, 1, 2, …, 5) for different asphalt-emulsion and aggregate types. The Vialit test was employed to evaluate the adhesion of asphalt to aggregates, utilizing temperatures of -10°C, -22°C, and -26°C for several types of asphalt-aggregate combinations. The research team analyzed the causes of premature stripping in the seal coats and evaluated the durability of the seal coats by analyzing the obtained results.

3.1 EXPERIMENTAL PROGRAM

3.1.1 Materials

Two main materials used in seal coat application are asphalt and cover aggregate. The asphalt is normally an asphalt-emulsion. The cover aggregate can be either crushed or natural. The cover aggregate used in seal coats should be dust-free, clean, hard, and uniform to provide a durable and tight seal coat surface on the asphalt pavement. Four kinds of aggregates were used in this study: Red-Rock FA-2.5, Granite FA-2.5, Granite FA-2.0, and Trap-Rock 1/8 inch minus. Samples of each aggregate type can be seen in Fig.1 (a). In the field seal coat application, the recommended asphalt-emulsion application rates for Granite FA-2.0, Granite FA-2.5, Red-Rock FA-2.5, and Trap-Rock 1/8 inch minus are 1.13 L/m^2 (0.25 gal/yd^2), 1.63 L/m^2 (0.36 gal/yd^2), 1.63 L/m^2 (0.36 gal/yd^2), and 0.99L/m^2 (0.22 gal/yd^2), respectively. The gradation and the majority chemical composition of aggregates are shown in Tables 3-1 and 3-2, respectively, based on the seal coat design method used in Minnesota (Wood, Janisch, and Gaillard 2006) and the Material Safety Data Sheet (MSDS) of the proposed aggregates.

The asphalt-emulsions under study included two asphalt emulsions, AE-1 and AE-2, which were produced by using original PG 58-28 asphalt binders. The asphalt-emulsion-1 (AE-1) is a polymer modified cationic water-based emulsified asphalt while asphalt-emulsion-2 (AE-2) is an ordinarily cationic water-based asphalt-emulsion designed for use as a binder for the seal coats. According to the MSDS of the asphalt-emulsions, the compositional difference between AE-1 and AE-2 is mainly due to the percentage by weight of the volume of binder, deionized water, and oil distillates. As expected, AE-1 includes a higher content of polymer modifier and oil distillates by weight than AE-2, with as much as three times the content of polymer modifier and oil distillates of AE-2. In contrast, AE-2 displays a higher percentage of deionized water by weight. Mostly the compounds displayed similar percentages of catatonic emulsifiers, petroleum asphalt, hydrogen sulfide, and polycyclic aromatic compounds, making them ideal archetypes to test against each other.

Table 3-1. Fine aggregate (fa) gradations used in this study (Wood, Janisch, and Gaillard 2006)

Sieve size (mm)	Percent passing the sieve (%)			
	Red-Rock FA-2.5	Granite FA-2.5	Granite FA-2.0	Trap-Rock (1/8 inch minus)
12.5	100	100	100	100
9.50	100	100	100	100
6.30	0-80	0-80	100	100
4.75	0-50	0-50	0-100	90-100
2.36	0-12	0-12	0-40	60-90
1.18	0-5	0-5	0-10	30-60
0.595	N/A	N/A	N/A	10-40
0.300	N/A	N/A	0-5	5-30
0.150	N/A	N/A	N/A	0-25
0.075	0.0-1.0	0.0-1.0	0.0-1.0	0-15

3.1.2 Michigan Tech's Interface Bond Test

The goal of Michigan Tech's Interface Bond Test (IBT, developed at Michigan Technological University) is to investigate the interface bond strength between the seal coat and asphalt pavement. As weak interface bond strength may be linked to premature stripping, the IBT can be used to determine the interface bond strength between the seal coat and asphalt pavement under possible temperature conditions. For instance, if the interface bond strength is unsatisfactory, then the seal coat may not be an ideal tool for asphalt pavement maintenance. Tests were performed with prepared laboratory samples to determine interface bond strength with a Material Testing System (MTS). Seal coat and asphalt pavement samples were used to test the interface bond strength of the seal coat (AE-1 and AE-2) with the asphalt pavement at different temperatures and multiple freeze-thaw cycles.

Here, laboratory seal coats were prepared based on the seal coat design method used in Minnesota (Wood, Janisch, and Gaillard 2006). After 15 minutes of basic curing, the laboratory seal coats sample was compressed with a rubber roller (80-B0178/A3 from Controls Group USA) to simulate the compression process in the field. In order to make sure the aggregates were well bonded with asphalt pavement (foundation), the seal coats sample was allowed to cure for 12 hours after the rubber roller compression process. Then, 50 mm diameter sample cylinders cut from the laboratory seal coat were subjected to the

IBT tests. Multiple freeze-thaw cycles were applied in this test to examine their influence on the performance of seal coated asphalt pavement, especially in cold regions. The detailed procedure of a single freeze-thaw cycle is as follows: i) seal coat samples were submerged in a room temperature water bath for 6 hours; ii) the samples were placed in a refrigerator at -18°C for 6 hours and then again submerged in a room temperature water bath for 6 hours prior to testing. If the sample needed to undergo multiple rounds of freeze-thaw cycles, then step-ii was performed until the total desired number of cycles were completed.

Table 3-2. Composition/information on ingredients of used fine aggregate

Component(s) chemical name	Percent of weight (Approximate, %)		
	Red-Rock FA-2.5	Granite FA-2.0/2.5	Trap-Rock (1/8 inch minus)
Silicon dioxide	50-65	70-72	<1
Aluminum oxide	15-20	13-15	10-20
Ferrous oxide	5-30	1-2	2-20
Ferric oxide			
Magnesium oxide	0-4	<1	1-15
Calcium oxide	1-2	1-2	5-15
Sodium oxide	7-10	3-4	0-12
Potassium oxide	1-5	4-5	0-3

In addition, the aluminum caps/molds were hot glued to both faces of the cut sample. The sample was then set to cure for 24hrs. Given that the bond strength between the aluminum mold and hot glue was estimated to be over 2.2MPa, with the bond strength between the hot glue and asphalt pavement estimated to be about 1.4-1.5MPa, the interface bond strength between asphalt-emulsions at just 0.7-1.5MPa was found to be the least strong bond. The strength of hot glue is over 13.5MPa. Thus, when performing an interface bond strength test at different temperatures, the interface bond was expected to be the first to fail when the MTS used a loading of 0.83mm/sec., with the threshold value at 19.6N. The partial view and the schematic of the IBT test by MTS are presented in Figure 3-1. Furthermore, a typical IBT test (AE-1 with Trap-Rock at 25°C) loading curve by MTS is shown in Figure 3-2. The IBT specimen performs at the linear-elastic region before structural damage occurs. As such, the maximum load just before the specimen ruptured was selected to evaluate and express the interface bond strength between the seal coat and asphalt pavement at different test temperatures.

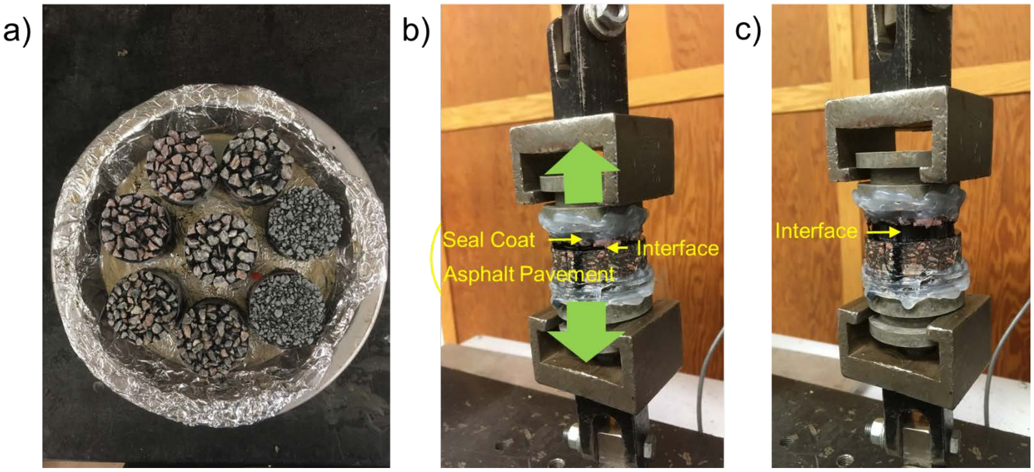


Figure 3-1. Cross-section and schematic of IBT test by material testing system (mts): a) laboratory IBT samples, b) before IBT test, and c) after IBT test

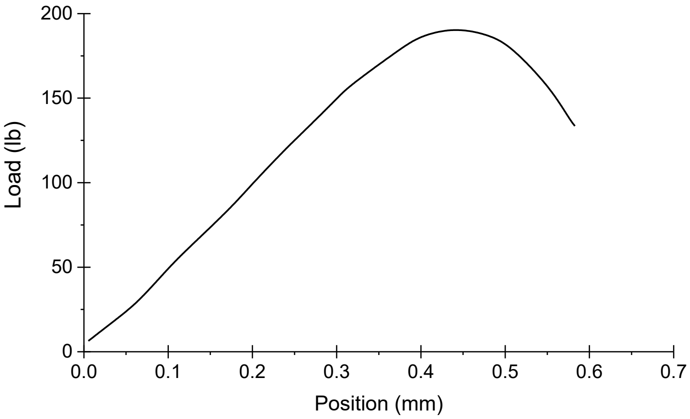


Figure 3-2. Typical IBT test results (AE-1 with Trap-Rock at 25°C)

3.1.3 Vialit Test

The Vialit test aims to evaluate the adhesive performance of asphalt-emulsions and aggregates at low temperatures. The Vialit test follows the EN12272-3 testing standard, which assesses the adhesion between asphalt-emulsions and aggregates under a series of cold conditions. Adhesion is an essential property for the integrity of the asphalt mixture and related construction materials (Song et al. 2017; Shi, Mukhopadhyay, and Zollinger 2018). This study utilizes temperatures at -10°C, -22°C, and -26°C for several types of asphalt-emulsions (AE-1 and AE-2) and aggregates (Red-Rock FA-2.5, Granite FA-2.5, Granite FA-2.0, and Trap-Rock (1/8 inch minus)). The asphalt-emulsion type and aggregate type were selected to simulate best the adhesive performance of the currently used seal coat.

Samples were prepared with 79g (1.90 L/m^2) of asphalt-emulsion on clean and dry stainless-steel plates (20cm×20cm). Exactly 100 washed and graded aggregate particles were placed in 10×10 rows onto the emulsion. After 15 minutes of curing, the sample was compressed with a rubber roller. The sample was then allowed to cure at room temperature (25°C) for a minimum of 12hrs. Once cured, the individual plates were conditioned at three different temperatures for 30 minutes. Plates were assembled in the Vialit apparatus individually and faced down. A 500g steel ball was dropped from a distance of 50cm onto each stainless-steel plate for three hits. After each drop, the plate was examined, and the remaining aggregate particles were counted (Gheni and ElGawady 2017). For example, Figure 3-3 illustrates the test sample before and after the Vialit test, where the final retained aggregate number out of 100 aggregate in the asphalt-emulsion is 56; thus, the final retention ratio of this specimen is 56%. The test apparatus used in the Vialit test can be seen in Figure 3-3(a). Figures 3-3(b) and 3-3(c) illustrate the test sample before and after the Vialit test, respectively. In addition, in order to highlight the aggregate distribution pre and posttest, Figures 3-3(b) and 3-3(c) were adjusted to Figures 3-3(d) and 3-3 (e) by ImageJ, respectively. In the manipulated image, the color red denotes the position of aggregate retained in the asphalt emulsion.

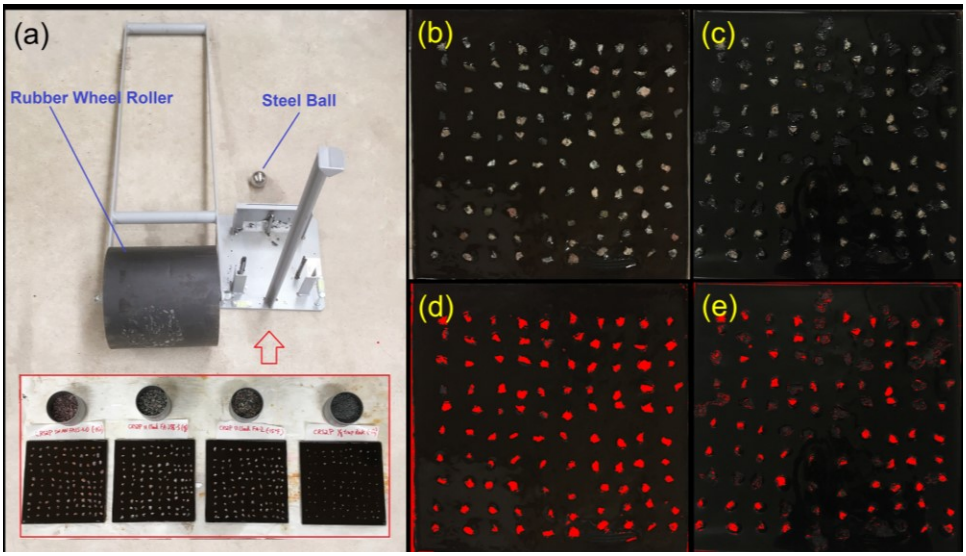
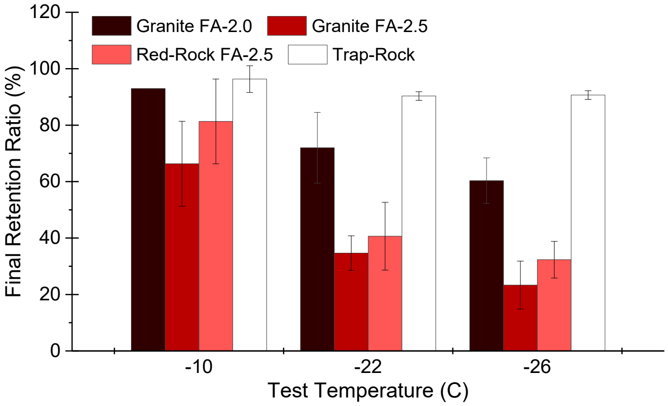


Figure 3-3. Vialit test set-up and typical Vialit test results (ae-1 with Trap-Rock): a) Vialit set-up, b) and d) samples before Vialit test, c) and e) samples after Vialit test

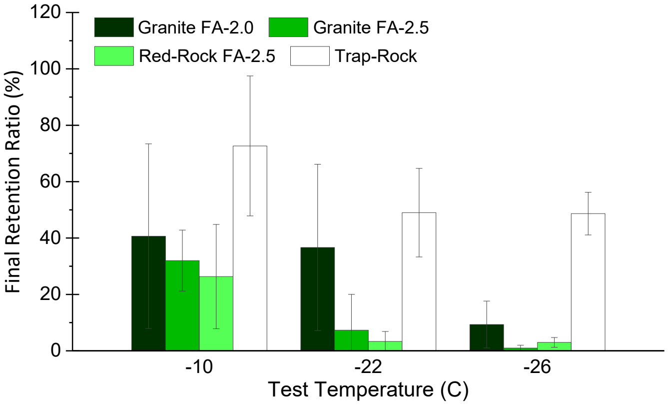
3.2 RESULTS AND DISCUSSION

3.2.1 Adhesive Performance of Asphalt-Emulsion and Aggregates

In order to evaluate the low-temperature durability of asphalt-emulsion based seal coats, the performance of the four kinds of aggregates in conjunction with the asphalt-emulsions AE-1 and AE-2 were tested using the Vialit procedure found in this section. Figures 3-4 (a) and (b) display the results for all four aggregate types and for both emulsions, where the average final retention ratio value for each aggregate type can be found at one of three temperatures. The error bars demonstrate the ±1 standard deviation from the average value. Figure 3-4 (a) presents the final retention ratio of the aggregates tested within the AE-1 emulsion at different temperatures, while Figure 3-4 (b) illustrates the final retention ratio of the aggregates embedded in AE-2 at different temperatures. It can be observed that, in general, the final retention ratio of aggregate decreased proportionally with a decrease in temperature for both emulsion types. It must be noted, however, that the AE-1 samples using trap rock slightly increased in retention ratio from -22°C to -26°C. This result indicates that lower temperatures result in weaker adhesive performance, or durability, between the aggregate and the asphalt-emulsions. Mostly this is because the asphalt-emulsion became fragile and glassy after freezing and thus subject to brittle behavior upon impact. The testing also revealed that AE-1 had a better low-temperature adhesive performance for all aggregate types than that of AE-2. The trials also revealed the performance of different combinations of asphalt-emulsion and aggregate, concluding that aggregate type and binder both had a significant impact on the final retention ratio of aggregates.



(a) Final retention ratio of ae-1 with four aggregates



(b) Final retention ratio of ae-2 with of four aggregates

Figure 3-4. Adhesive performance of AE-1 and AE-2 with four aggregates at different temperatures

In general, the aggregate type with the best performance or the highest average final retention ratio for aggregate on the AE-1 surface can be ranked as follows: Trap-Rock> Granite FA-2.0> Red-Rock FA-2.5> Granite FA-2.5. The average final retention ratio ranked from highest retention to least retention of the aggregates on the AE-2 surface was found to be ranked similarly with Trap-Rock> Granite FA-2.0> Granite FA-2.5> Red-Rock FA-2.5. From these rankings, it can be observed that aggregate size plays a large part in adhesion, as the smaller sized aggregate displayed higher retention ratios. For instance, in both the AE-1 and AE-2 seal coat, at the same asphalt-emulsion application rate, Trap-Rock displayed the best adhesive properties with asphalt-emulsion with a maximum retention average of 98% in the AE-1 and 75% in AE-2 emulsion. The reason for the superior performance of the Trap-Rock may be due to both the aggregate size and composition. Compositionally, as shown in Table 3-2, the Trap-Rock possesses a higher calcium oxide content than the Granite and Red-Rock aggregate. The higher calcium ion content on the surface of

Trap-Rock may have produced a stronger ionic bond with the carbonyl group in the asphalt-emulsion. In addition, the smaller size of the aggregate particle may form a stronger bond with the asphalt because bond strength is proportional to the interlayer area between the asphalt and aggregate particles. Therefore, smaller aggregates are better able to resist the hit impacts by the steel ball than the larger aggregates of the same material. For example, Granite FA-2.0 displayed a maximum average of 93% retention at -10°C, while Granite FA-2.5 displayed a maximum average of 66.33% retention at -10°C for AE-1. The disparity between highest retention becomes less dramatic for the AE-2 emulsion but remains significant, where FA-2.0 displays a maximum average of 40.67% at -10°C, while FA-2.5 displays a maximum average of 32% at -10°C. For both AE-1 and AE-2, the smaller grain size was found to outperform the larger grain size for all three tested temperatures.

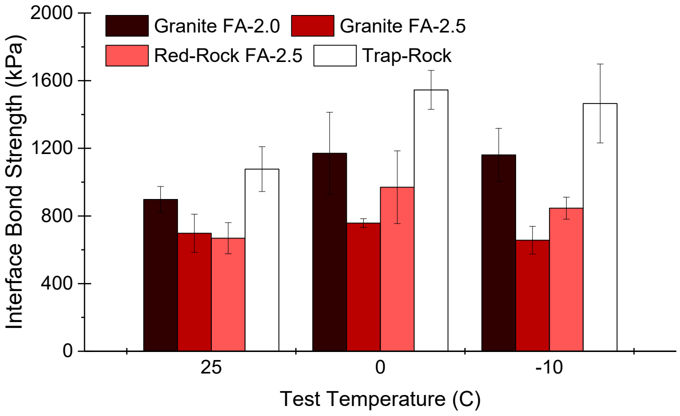
Although aggregate size played an essential role in adhesive performance, the material composition was also found to affect performance. For instance, the Red-Rock FA-2.5 aggregate performed better than Granite FA-2.5 when combined with AE-1 but displayed worse performance than the Granite FA-2.5 aggregate when combined with the AE-2 binder. From Table 3-2, it can be seen that the Granite has higher silica content in comparison to the Red-Rock aggregate. The higher silica content in Granite FA-2.5 may have produced stronger hydrogen bonds to the asphalt-emulsion AE-2 (Park, Jo, and Park 2000; Xu and Wang 2016). The propensity to form hydrogen bonds generated along the Granite-asphalt interface can explain the stronger adhesion between Granite and AE-2. In contrast to AE-2, the polymer-modified asphalt-emulsion (AE-1) contains less asphalt on the unit surface of aggregate, and therefore the chance to generate hydrogen bonding may be reduced. In addition, it has also been reported that the modifier can change the wettability of the asphalt binder (N. Wasiuddin, Zaman, and O'Rear 2008). Thus, it can be assumed that AE-1 has a lower surface free energy on the Red-Rock type aggregate, which may be the reason for the more durable performance. The combination between lower surface free energy and the likeliness of hydrogen bonding, therefore, produced different adhesive performances between the aggregate particle’s outer surface and the asphalt-emulsion. The poor adhesive performance between aggregate and asphalt in seal coat application may be one of the reasons that many asphalt pavements underneath seal coat suffers from premature stripping at low-temperature conditions.

3.2.2 Specific Statements to Vialit Test Results

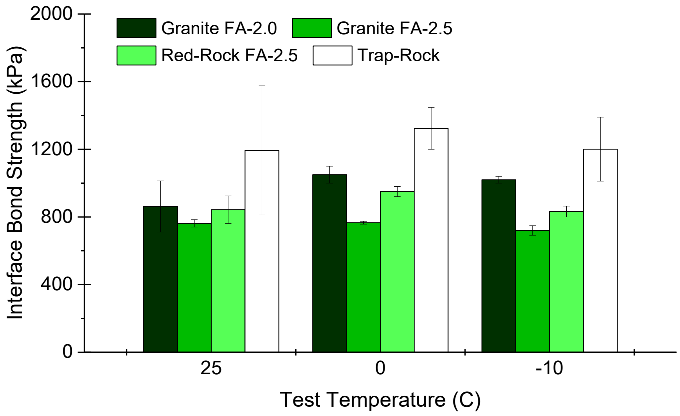
Although the Vialit test follows the EN12272-3 testing standard to assess the adhesion between asphalt-emulsions and aggregates under a series of cold conditions, the test results are insufficient to reveal the engineering performance of seal coats with various asphalt-aggregate combinations. Because the aggregate size in the seal coat is much smaller than those in regular asphalt mixtures, with the same asphalt-emulsion application rate of 0.42 gal/yd^2 (or 1.90 L/m^2) the size effect of the aggregates may be larger than the real adhesion effects between the aggregate and asphalt materials. Thus, the research team suggests that the results from the Vialit test should only be used as a reference rather than used in engineering applications directly.

3.2.3 Interface Bond Strength between Seal Coat and Pavement under Varying Temperatures

The durability of seal coats on asphalt pavement is partially determined by the interface bond strength between the seal coat layer and the asphalt pavement. Therefore, a weak interface bond strength between the seal coat layer and the asphalt pavement may contribute to the failure of asphalt pavement under seal coat with premature stripping. In consideration of the possible cold service conditions for the seal coat in the field, the interface bond strength of the seal coats at 25°C, 0°C, and -10°C was tested. Figure 3-5 illustrates the laboratory interface bond strength of AE-1 and AE-2 seal coats at different temperatures. Each bar in this figure represents the average interface bond strength value of three replicates, and the error bars demonstrate ±1 standard deviation from the average value. In this figure, the effect of the asphalt-aggregate combinations on the interface bond strength at different test temperatures is displayed. From Figure 3-5 (a) and (b), it can be seen that at 25°C, the interface bond strength was higher for AE-2 than for AE-1. For instance, for the aggregate Red-Rock FA-2.5, the average bond strength was found to be 668kPa and 842kPa. However, while AE-2 displayed a greater average strength for all of the aggregate types, both Granite FA-2.5 and 2.0 aggregates displayed very similar strengths. In particular, Granite FA-2.0 was found to have a strength of 867kPa for AE-1 and 861kPa for AE-2. Trap-Rock performed the best for the asphalt-emulsion with 1.63 L/m^2 application rate, with a bonded strength of 1077kPa for AE-1 and 1193kPa for AE-2. This could be caused by the higher percentage of fine aggregate particles in the employed Trap-Rock, as well as by the interactions between the aggregate particles and asphalt. For instance, the higher calcium ion content on the surface of Trap-Rock may have developed more ionic bonds with the carbonyl group in the asphalt-emulsion.



(a) AE-1 seal coats



(b) AE-2 seal coats

Figure 3-5. Interface bond strength for AE-1 and AE-2 seal coats at different temperatures

In both AE-1 and AE-2 based seal coats, Trap-Rock displayed the highest maximum for all three temperatures. The most considerable bond strength for both Trap-Rock emulsion combinations was recorded at 0°C, with 1545kPa recorded for AE-1 and 1324kPa recorded for AE-2. According to Reference (Wood, Janisch, and Gaillard 2006), in the field seal coat application, for aggregate particles to remain on the asphalt pavement, they need to be approximately 70% embedded into the asphalt. Thus, different types of aggregate have different requirements for asphalt-emulsion application rates. However, in this study, in order to evaluate the effect of the aggregate types on the interface bond strength between seal coat and asphalt pavement, IBT samples were prepared with the same application rate of 1.63 L/m^2 of asphalt-emulsion. The application rate for Trap-Rock and Granite FA-2.0 was higher than each individual recommended application rate. This explains the lower air voids composition in the aggregate layer of

Trap-Rock and Granite FA-2.0 in comparison to the aggregate layer of Granite FA-2.5 and Red-Rock FA-2.5. The presence of fewer air voids increases the contact interface area with asphalt for the smaller size range of aggregate, and thus, larger aggregates produce a decreased contact interface. This may be the reason why the smaller sized aggregate particles resulted in more muscular bond strength between the seal coat and the asphalt pavement when using the same asphalt-emulsion application rate.

Furthermore, in general, the interface bond strength weakened with lower temperatures. For instance, at 0°C, the interface bond strength of the AE-1 and AE-2 seal coats experienced a decrease in strength for Granite FA-2.0. For example, AE-1 was measured to have an average bond strength of 1170kPa at 0°C and 1161kPa at -10°C. Similarly, AE-2 was measured to have a strength of 1050kPa at 0°C and 1020kPa at -10°C. The interface bond strength of the seal coats at 0°C and -10°C was found to be significantly higher than at 25°C. This may be caused by the asphalt's tendency to become more brittle and harder at low temperatures. It is evident that the interface bond strength of the seal coats slightly decreased from 0°C to -10°C, and the percentage decrease in strength reveals the significance of the aggregate/emulsion combination in terms of performance. For example, from 0°C to -10°C, the decrease rate in the strength of AE-1 and Granite FA-2.0 was 0.81%, which was the smallest decrease in the performance of all the combinations. In contrast to AE-2, with Granite FA-2.0, the decrease in strength was 2.86%. The Red-Rock FA2.5 aggregate/emulsion combination produced the most significant strength and performance decrease, falling 12.79% from 0°C to -10°C for AE-1 and 12.42% for AE-2. More interestingly, despite the high performance of the Trap Rock, strength fell significantly from 0°C to -10°C, with AE-1 experiencing a decrease in strength of 5.32% and AE-2 a decrease of 9.29%. It can be seen that in all cases from 0°C to -10°C, AE-1 aggregate combinations produced smaller reductions in strength. This implies that the AE-1 seal coat is more stable than the AE-2 seal coat at low temperatures. These results also illustrate that the low-temperature stability of the asphalts with Granite performed better than with Red-Rock and Trap-Rock. Therefore, the combined performance of AE-1 and Granite FA-2.0 is optimal from the viewpoint of low-temperature stability.

3.2.4 Interface Bond Strength between Seal Coat and Pavement after Multiple Freeze-Thaw Cycles

In order to investigate the effect of multiple freeze-thaw cycles on the seal coat application, AE-1 seal coat samples were run through five separate freeze-thaw cycles. The interface bond strength of different asphalt-aggregate combinations was compared. To more clearly and correctly demonstrate the effects of multiple freeze-thaw cycles on the interface bond strength, the average interface bond strength value was calculated from several replicated samples. Figure 3-6 illustrates the results of the freeze-thaw cycles using a ±1 standard deviation to display error bounds. As illustrated, when the freeze-thaw cycle number increases, the interface bond strength between the seal coat layer and the asphalt pavement layer decreases. For example, after the first freeze-thaw cycle, the interface bond strength decreasing rate of AE-1 with Granite FA-2.0, Granite FA-2.5, Red-Rock FA-2.5, and Trap-Rock was 14.36%, 43.19%, 13.77%, and 12.35%, respectively. Regarding performance under freeze-thaw conditions, the seal coat combination with AE-1 and Granite FA-2.5 had the highest rate of interface bond strength loss for the first freeze-thaw cycle. However, after the second freeze-thaw cycle, the interface bond strength loss for all the samples exceeded 30%, excluding the interface bond strength loss of the seal coat with Trap-Rock, which was just 16.15%. In the next repetitive freeze-thaw cycles, the interface bond strength of the seal coat with Trap-Rock continued to decrease (or the interface bond strength loss-rate continued to increase), while the interface bond strength loss rate of the other samples approached equilibrium.

Furthermore, after the fifth freeze-thaw cycle, the interface bond strength decreased to a total of 58.13%, 51.22%, 45.36%, and 65.69% for Granite FA-2.0, Granite FA-2.5, Red-Rock FA-2.5, and Trap-Rock, respectively. It can be seen that after the fifth freeze-thaw cycle, the Trap Rock seal coat displayed the most considerable total loss in interface bond strength at 65.69%. Since the loss of interface bond strength was greater than 40% for all aggregate emulsion combinations, the effect of the freeze-thaw cycle can be considered significant. Moreover, the freeze-thaw cycle may be seen as a critical external factor in the premature stripping of pavement under the seal coat.

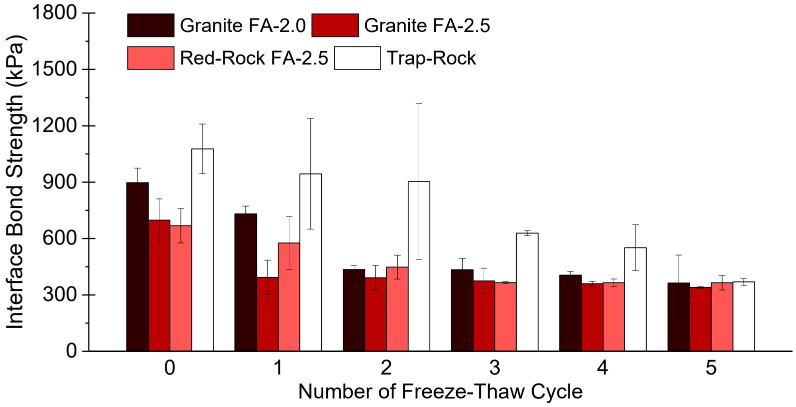


Figure 3-6. Interface bond strength for AE-1 seal coat with multiple freeze-thaw cycles

The seal coat tested with Trap-Rock displayed the best resistance to the freeze-thaw cycles despite displaying the most significant percentage decrease in strength. The surface properties and the smaller aggregate size range of the Trap-Rock may be concluded to have had a positive impact on the resistance to the freeze-thaw cycle of seal coat. As mentioned in the Reference (Wood, Janisch, and Gaillard 2006), the asphalt-emulsion application rate used in this study (0.36 gal/yd2) for the Trap-Rock and Granite FA-2.0 was higher than the recommended application rate. Therefore, a lower air void composition was present in the seal coat layer with the Granite FA-2.0 and Trap-Rock when compared with the seal coat layers of Granite FA-2.5 and Red-Rock FA-2.5. The presence of fewer voids reduced the microstructural damage due to ice expansion of voids during the freeze-thaw cycles, and thus the larger aggregates produced an increase in microstructural damage. This may be the reason that the smaller aggregate particles resulted in higher resistance to the freeze-thaw cycles. For example, after the first freeze-thaw cycle, the interface bond strength loss rate of the seal coat with Granite FA-2.0 and FA-2.5 was 14.36% and 43.19%, respectively.

3.3 SUMMARY AND CONCLUSIONS

This study focused on the characteristics of the durability of asphalt-emulsion based seal coat, and the effect of the asphalt-aggregate combination at cold temperatures and with multiple freeze-thaw cycles. Michigan Tech's Interface Bond Test (IBT) was also applied to assess the interface bond strength between the seal coat layer and asphalt pavement layer under varying temperatures and several freeze-thaw cycles for different asphalt-aggregate combinations.

Four main conclusions can be derived from the study results:

(1) Polymer-modified asphalt-emulsion (AE-1) based seal coat has a better adhesive performance than the seal coat with the ordinary asphalt-emulsion (AE-2); the material mineral composition of aggregates played a significant role in influencing the durability of the seal coat application.

(2) The interface bond strength between the laboratory seal coat layer and asphalt pavement layer decreased with the increase of freeze-thaw cycles. The presence of fewer voids in seal coat reduced the microstructural damage due to ice expansion of voids during the freeze-thaw cycles, and thus the larger aggregates produced an increase in microstructural damage.

(3) The combined performance of AE-1 and Granite FA-2.0 is optimal from the viewpoint of low-temperature stability, while the optimal aggregate type is Trap-Rock 1/8 inch minus (within the range of aggregate types selected in this study) for freeze-thaw cycle resistance;

(4) Weak asphalt-aggregate combination in seal coat application and increased freeze-thaw cycles are the main factors for premature stripping of many seal coat asphalt pavements.

In this chapter, the interface bond strength results focused solely on seal coats with a 0.36 gal/yd^2 (1.63L/m^2) asphalt-emulsion application rate. In reality, in the field, the seal coat application would occur with different application rates as each aggregate/asphalt emulsion combination has an optimal application ratio. For example, the currently used asphalt-emulsion application rates for Granite FA-2.5 and FA-2.0 are about 0.36 gal/yd^2 (1.63L/m^2) and 0.25 gal/yd^2 (1.13L/m^2), respectively. These application rates may also have a significant impact on the durability of pavement under seal coat application. Thus, if possible, including other application rates of asphalt in durability performance analysis of seal coats is recommended in future work.

CHAPTER 4: EVALUATION OF SHEAR BOND TEST FOR ASPHALT PAVEMENTS UNDER SEAL COATING

Shear bond strength is a crucial indicator for revealing the bond qualities of seal coat with asphalt pavement. The objective of this task is to develop a laboratory approach of the shear bond test (SBT) to characterize the shear bond strength of a seal coat with asphalt pavement. This task investigated the shear bond strength between the seal coat and asphalt pavement of several asphalt-aggregate combinations and different asphalt-emulsion application rates. Moreover, in order to characterize the influence of temperatures and freeze-thaw cycles on the durability of the seal coat, several test temperatures and multiple freeze-thaw cycles were applied in the proposed SBT. The laboratory test outcomes suggested that weak shear bonding of the seal coat with asphalt pavement is in part because of the multiple freeze-thaw cycles suffered and the raw materials used. Along these lines, it is necessary to choose the proper combination of asphalt-emulsion and aggregate in the application of the seal coat, particularly in colder climate regions.

4.1 EXPERIMENTAL PROGRAM

Table 4-1. Gradation of aggregate used in sample foundation (asphalt mixture)

Sieve size	Control points (%)		Restricted zone (%)		Passing (%)
	lower	upper	lower	upper	
19.00mm	100	N/A	N/A	N/A	100
12.50mm	90	100	N/A	N/A	100
9.500mm	N/A	90	N/A	N/A	95.2
4.750mm	N/A	N/A	N/A	N/A	73.7
2.360mm	28	58	39.1	39.1	54.7
1.180mm	N/A	N/A	25.6	31.6	43.7
0.600mm	N/A	N/A	19.1	23.1	32.4
0.300mm	N/A	N/A	15.5	15.5	18.1
0.150mm	N/A	N/A	N/A	N/A	8.1
0.075mm	2	10	N/A	N/A	5.2

< 0.075mm	N/A	N/A	N/A	N/A	N/A

The gradation and mineral composition of the cover aggregate and the asphalt-emulsions used in seal coats were reported in Chapter 3. The asphalt mixtures used in the foundation of the test samples are similar to SPWEA440E. The virgin PG 58-28 asphalt was used for the preparations of sample foundations (asphalt mixture). The nominal maximum aggregate size was 9.5mm. The details of the gradation are shown in Table 4-1. The average bulk specific gravity (dry) of aggregate is 2.60, and the asphalt content was 5.75%. The mixing temperature of the asphalt mixture was 150±2°C. 75 gyrations (600kPa) were applied under 135°C to each prepared asphalt mixture, and the average percent air voids was 4.0%.

The objective of Michigan Tech's shear bond test (SBT), which was developed at Michigan Technological University, is to determine the shear bond strength between the seal coat and asphalt pavement. As weak shear bond strength between the seal coat and asphalt pavement may be connected to untimely stripping, the proposed SBT was implemented to determine the shear bond strength under certain possible materials and environmental conditions. Materials and environmental conditions were obtained by applying varying asphalt-aggregate combinations, asphalt application rates, temperatures, and various freeze-thaw cycles. The SBT illustrates execution where, for instance, if the shear bond strength is weak, the seal coat may not be a suitable material for asphalt pavement maintenance.

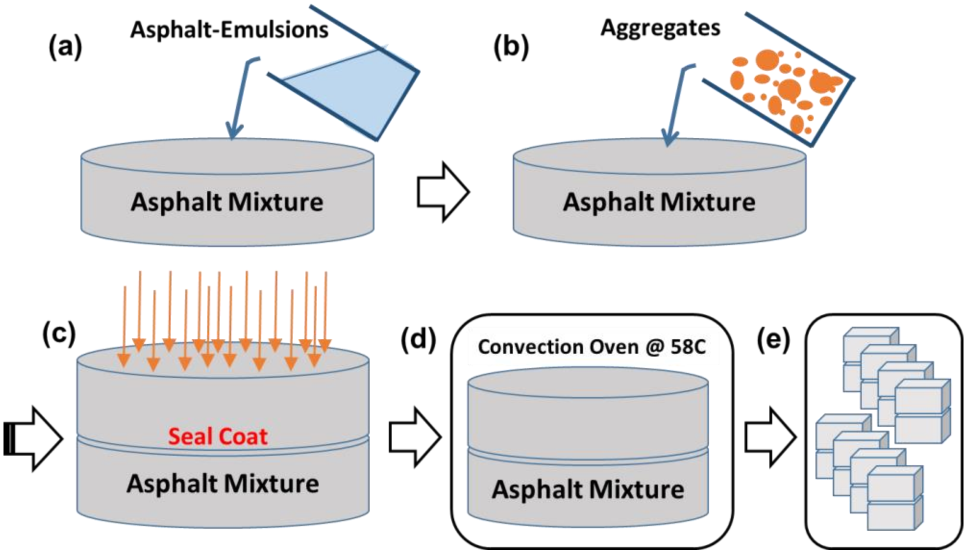


Figure 4-1. Laboratory sample preparation steps: a) spraying asphalt-emulsions, b) spraying aggregates, c) compressing sample by using rubber wheel roller, d) oven curing, and e) cutting sample to square shape (2×2 inches)

In order to investigate the shear bond strength of the laboratory seal coats, the laboratory SBT samples were prepared according to the preparation steps in Figure 4-1. Here, laboratory seal coat samples for the SBT were prepared based on the seal coat design method used in Minnesota (Wood, Janisch, and Gaillard 2006). First, the large core samples (150mm diameter) were cut and allowed to dry. Samples were then wiped with a cloth or paper towel to remove dust and to maintain a clean surface. Asphalt-emulsion was then applied to the clean surface according to the asphalt-emulsion application rates used in this study. Considering the core samples were limited in size by a radius of 150mm, asphalt-emulsion was applied using a weight conversion into grams. Aggregate was then applied according to type specifications. An equivalent core sample was then prepared with emulsion and placed down upon the aggregate emulsion core. This extra step was performed in order to prevent stress concentration from an excessively small shear contact surface, which could impact the experimental results. The rubber wheel roller was then used to compact the sample for twenty passes. The samples were then transferred to an oven and left to cure for one hour at 58°C. After the sample had cured for 24 hours at room temperature, smaller samples in the shape of 2×2-inches cubes were cut.

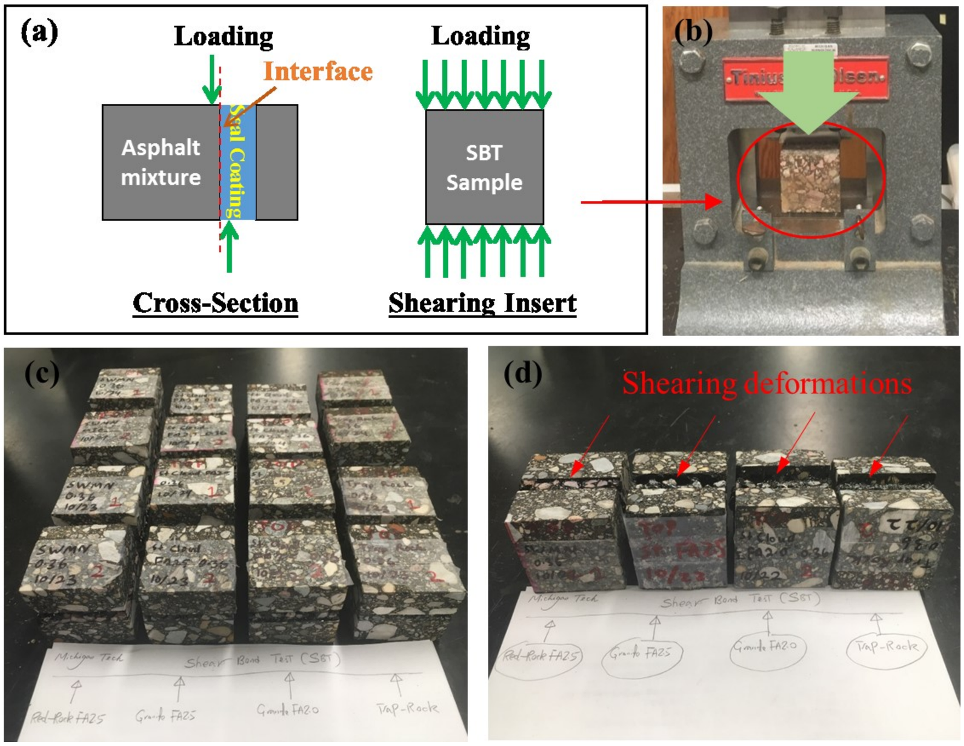


Figure 4-2. Cross-section and schematic of SBT by material testing system (MTS): a) schematic of SBT, b) laboratory SBT, c) sample before SBT, and d) sample after SBT

After the SBT samples were prepared, the laboratory SBT was applied. Figure 4-2 (a) illustrates the cross-section and schematic of SBT by the Material Testing System (MTS). The shear bond strength of the seal coats was expected to fail with a loading rate of 50mm/min, as shown in Figure 4-2 (b). The shear bond strength of the SBT samples was calculated by dividing the peak load by the cross-sectional area of the sample. Although the shear bond strength of the seal coats is also affected by the loading rate, in order to emphasize the research focus on the materials and environmental conditions, the influence of the loading rate was not considered in this study. Figure 4-2 (c) and (d) presents the samples before SBT and after SBT. It can be seen that different shearing deformations were also displayed in different samples.

The following procedure was used to simulate the influence of a single freeze-thaw cycle on the shear bond strength of seal coat with asphalt pavement. First, SBT samples were placed in a room temperature water bath. The samples were left submerged for six hours to ensure that moisture penetrated the bulk of the chip seal pore space. Next, SBT samples were transferred to a freezer to simulate the freezing event within the freeze-thaw cycle. In order to maintain consistency, samples were conditioned at -18°C for six hours for each freeze event. After freeze conditioning, the samples were returned to the room temperature water and allowed to thaw for six hours. The second thawing (submergence) represents the end of one freeze-thaw cycle. Once the total desired number of freeze-thaw cycles was achieved, the process was completed. Several freeze-thaw cycles were conducted, with a maximum of five cycles used. Cycles greater than five were investigated in preliminary runs but were found to produce statistically equivalent results to that of five freeze-thaw cycles.

4.2 RESULTS AND DISCUSSION

4.2.1 Impact of Asphalt-Aggregate Combination on Shear Bond Strength

In order to determine the performance of seal coat at different asphalt-aggregate combinations, the shear bond strength of the seal coat of the four kinds of aggregates in conjunction with AE-1 and AE-2 was evaluated by using SBT at 25°C. All of the SBT samples were prepared at an identical asphalt-emulsion application rate of 1.63 L/m^2 (0.36 gal/yd^2). Figure 4-3 illustrates the outcomes for every one of the four total aggregate types and for both asphalt-emulsions, where each bar displays the average shear bond strength value of three replicates, with the error bars demonstrating ±1 standard deviation from the average value. According to Figure 4-3, the results show that the aggregate-asphalt combinations significantly influenced the shear bond strength of the seal coat. The shear bond strength of AE-1 seal coats was found to be higher than those of AE-2 seal coats. This result indicates that the polymer-modified asphalt-emulsion (AE-1) performs better in terms of interface bonding with aggregates in the seal coats. The AE-1 seal coat with Trap-Rock 1/8-inch minus, Granite FA-2.0, Granite FA-2.5, and Red-Rock FA-2.5 was found to have a shear bond strength of 412kPa, 276kPa, 236kPa, and 257kPa, respectively, while the AE-2 seal coat with these kinds of aggregates was found to have a strength of 270kPa, 243kPa, 214kPa, and 206kPa, respectively. Trap-Rock 1/8-inch minus is referred to as Trap-Rock in the following discussions. The Trap-Rock seal coat displayed the highest shear bond strength with asphalt pavement. This could be due to the higher percentage of fine aggregate particles in the Trap-Rock as well as the cooperation between the aggregate particles and asphalt; for example, the higher calcium ion content on the surface of Trap-Rock may have grown progressively ionic bonds with the carbonyl group in the asphalt.

The larger aggregate sizes generally resulted in a weaker shear bond strength with the seal coat under the same asphalt-emulsion application rate. Figure 4-3 depicts that for the AE-1 seal coats, the shear bond strength of the Granite FA-2.5 seal coat was 17% higher than those of the seal coat on Granite FA-2.0. According to Handbook 2006 (Wood, Janisch, and Gaillard 2006), the asphalt-emulsion application rate in this section for the Trap-Rock and Granite FA-2.0 was higher than the advised application rate. Therefore, a lower void composition was present in the smaller aggregate seal coat. The expanded void space increased the contact interface area with asphalt for a similar size range of aggregate, and thus larger aggregates produced a diminished contact interface (Leng et al. 2008; Reitzel et al. 2000). This might explain why the smaller sized aggregates resulted in a more muscular shear bond strength between the seal coat and asphalt pavement when the same asphalt-emulsion application rate was administered.

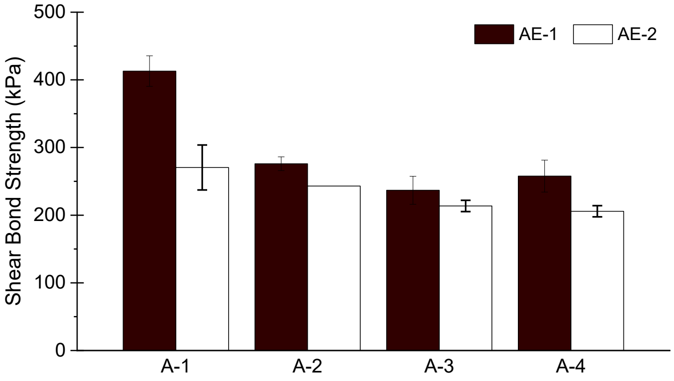


Figure 4-3. Shear bond strength for AE-1 and AE-2 seal coat with the aggregate of (a-1) Trap-Rock, (a-2) Granite FA-2.0, (a-3) Granite FA-2.5, and (a-4) Red-Rock FA-2.5

In addition, in spite of aggregate size playing an essential role in the shear bond strength of the seal coat, the mineral composition of aggregate was also found to affect the strength. Figure 4-3 illustrates that the Red-Rock FA-2.5 aggregate presented a higher performance than Granite FA-2.5 when combined with AE-1. However, Granite FA-2.5 presented a worse performance than the Granite FA-2.5 aggregate when combined with the AE-2. Table 4-1 displays a higher Silica content found in Granite than in Red-Rock. The higher silica content in Granite FA-2.5 may have contributed stronger hydrogen bonds to AE-2 (Park, Jo, and Park 2000; Xu and Wang 2016; You et al. 2019). The tendency to form hydrogen bonds produced along the Granite-asphalt interface can clarify the reason for the more durable bonding between Granite and AE-2. As opposed to AE-2, the polymer-modified asphalt-emulsion, AE-1, contains less asphalt on the unit surface of aggregate, and therefore the opportunity to create hydrogen bonding may be reduced. In addition, it has also been discovered that the modifier can change the wettability of the asphalt (N. Wasiuddin, Zaman, and O'Rear 2008; You et al. 2019). Hence, it can be concluded that AE-1 has a lower surface free energy on the Red-Rock type aggregate, which results in more durable performance. The combination of lower surface free energy and the likeliness of hydrogen bonding along these lines created a diverse bonding between the aggregate particles' outer surface and the asphalt.

4.2.2 Impact of Asphalt Application Rate on Shear Bond Strength

According to Reference (Wood, Janisch, and Gaillard 2006), for field seal coat application, approximately 70% of an aggregate's height must be embedded into the asphalt in order for aggregate particles to remain on the asphalt pavement. Thus, different types of aggregate must have different requirements for the asphalt-emulsion application rate. The SBT samples used in this section were applied using the optimum asphalt-emulsion application rate for each aggregate type, and then the test results were compared with the results from the samples with the same asphalt-emulsion application of 1.63 L/m^2 (0.36 gal/yd^2).

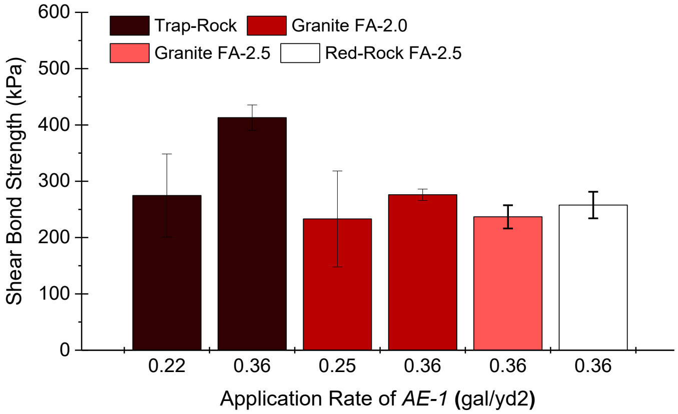


Figure 4-4. Shear bond strength for AE-1 seal coat at different asphalt application rates

Figure 4-4 displays the shear bond strength of the AE-1 seal coats at different asphalt-emulsion application rates and a test temperature of 25°C. At the recommended asphalt-emulsion application rate, the shear bond strength of seal coat with asphalt pavement is 274kPa, 233kPa, 236kPa, and 257kPa for the Trap-Rock, Granite FA-2.0, Granite FA-2.5, and Red-Rock FA-2.5 seal coats, respectively. From these results, it can be seen that the Trap-Rock seal coat obtained the highest shear bond strength with asphalt pavement. This is due to the size of aggregates and the unique mineral compositions of Trap-Rock, which is explained in detail in Section 3.1. Aggregate size also played a significant role in the magnitude of shear bond strength. For instance, at the optimum asphalt-emulsion application rate, the Granite FA-2.5 seal coat performed better under shear than compared with Granite FA-2.0 seal coat. The results concluded that at the same height embedment percentage of aggregate in a seal coat, larger sized aggregate provided better durability of seal coat for shear loading from vehicles. In addition, under the same aggregate type conditions, the shear bond strength of seal coat with asphalt pavement increased with the increase of the asphalt-emulsion application rate. A possible reason for the better performance of the higher asphalt-emulsion application rate seal coat is the higher percent embedment of aggregate in the seal coat.

4.2.3 Impact of Environmental Temperature on Shear Bond Strength

Considering the conceivable cold service conditions for the seal coat in the field, the shear bond strength of seal coat with asphalt pavement at 25°C, 0°C, and -10°C was examined in this section by using SBT. All of the SBT samples were set up at the equivalent asphalt-emulsion application rate of 1.63 L/m^2 (0.36 gal/yd^2). Fig.5 illustrates the results for all four aggregate-based AE-1 seal coat, where each bar represents the average shear bond strength value of three replicates, and the error bars demonstrate ±1 standard deviation from the average value. In general, the shear bond strength of seal coat with asphalt pavement was higher with lower test temperatures, which may be caused by the asphalt's tendency to become more brittle and harder at low temperatures. The test data shown in Figure 4-5 confirms this assumption. For instance, from 25°C to 0°C, the increased rate in shear bond strength of the Trap-Rock seal coat with asphalt pavement was 258%, which is the smallest increase in all the combinations.

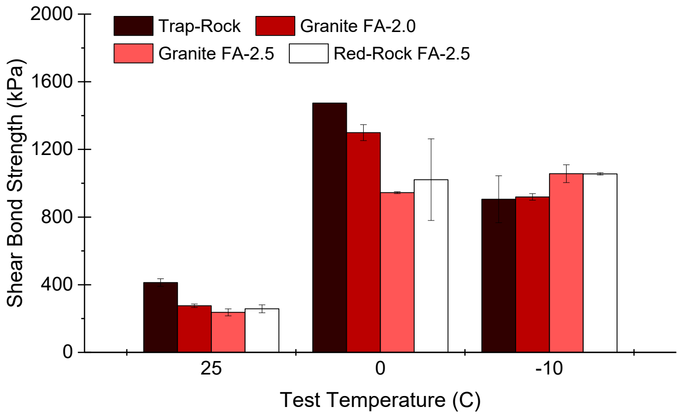


Figure 4-5. Shear bond strength for AE-1 seal coat at different SBT temperatures

In addition, as expected, shear bond strength was weakened with low temperatures. Decreasing temperatures produced a proportional decrease in shear bond strength with asphalt pavement, falling 38% from 0°C to -10°C for Trap-Rock and falling 29% for Granite FA-2.0. However, from 0°C to -10°C, the shear bond strength of Granite FA-2.5 and Red-Rock FA-2.5 seal coats with asphalt pavement slightly increased with the test (or environmental) temperatures. Early environmental temperature decreases from 0°C to -10°C produced an increase in the strength with asphalt pavement of 12% and 3% for Granite FA-2.5 and Red-Rock FA-2.5 seal coat, respectively. This implies that the seal coat with larger sized aggregate is more stable with asphalt pavement than the seal coat with smaller sized aggregate at low temperatures. It should be noted that the above-mentioned phenomenon does not mean that the seal coat performs better at low temperatures. These comparisons can only be applied to predict the low-temperature durability of seal coat at different asphalt-aggregate combinations. For example, for the Trap-Rock seal coat, the shear bond strength with asphalt pavement was 1476kPa, which was the highest shear bond strength with asphalt pavement at 0°C, while Granite FA-2.5 and Red-Rock seal coats showed the best performance at -10°C.

4.2.4 Impact of Multiple Freeze-Thaw Cycles on Shear Bond Strength

In order to investigate the effect of multiple freeze-thaw cycles on the shear bond strength of the AE-1 seal coat with asphalt pavement, SBT sample tests were performed through five separate freeze-thaw cycles. The shear bond strength of the laboratory seal coats with various asphalt-aggregate combinations was compared. In order to accurately and thoroughly demonstrate the effects of various freeze-thaw cycles on the shear bond strength, the average shear bond strength value was computed from multiple replicated samples, as shown in Figure 4-6. All of the SBT samples were arranged at the same asphalt-emulsion application rate of 1.63 L/m^2 (0.36 gal/yd^2).

Figure 4-6 demonstrates that the shear bond strength of seal coat with asphalt pavement decreased with the increase of freeze-thaw cycles. After the first freeze-thaw cycle, the decrease rate for the shear bond strength of Trap-Rock, Granite FA-2.0, Granite FA-2.5, and Red-Rock FA-2.5 seal coats were 12%, 2%, 0.8%, and 2%, respectively. Under freeze-thaw cycle conditions, the Trap-Rock seal coat had the highest rate of shear bond strength loss for the first freeze-thaw cycle. Therefore, it can be concluded that although the performance of Trap-Rock is the best overall, its ability to resist the freeze-thaw cycle is arguably the worst (most temperature-sensitive). This trend was also reflected in the performance of the next repetitive freeze-thaw cycles. After the fifth freeze-thaw cycle, the shear bond strength of the Trap-Rock seal coat with asphalt pavement was reduced by 58%, which is the greatest reduction of all the combinations. In addition, it was found that the larger sized aggregate provided better durability of seal coat for multiple freeze-thaw cycles. For instance, the Granite FA-2.5 seal coat had better resistance to multiple freeze-thaw cycles compared with Granite FA-2.0; the shear bond strength loss ratios were 46% and 48%, respectively, after five freeze-thaw cycles. Nevertheless, after five freeze-thaw cycles, the shear bond strength loss of the Red-Rock FA-2.5 seal coat was higher than that of the Granite FA-2.5 seal coat, falling 52% and 46% for Red-Rock FA-2.5 and Granite FA-2.5 seal coats, respectively. According to the information from section 2.1, it can be seen that both Granite FA-2.5 and Red-Rock FA-2.5 have mostly the same aggregate gradation/aggregate size assignment. The difference between the resistances of multiple freeze-thaw cycles of seal coats also may be the micro-interactions due to mineral composition. Therefore, the aggregate size range and mineral compositions can be said to have a significant effect on the resistance of the seal coat to the multiple freeze-thaw cycles.

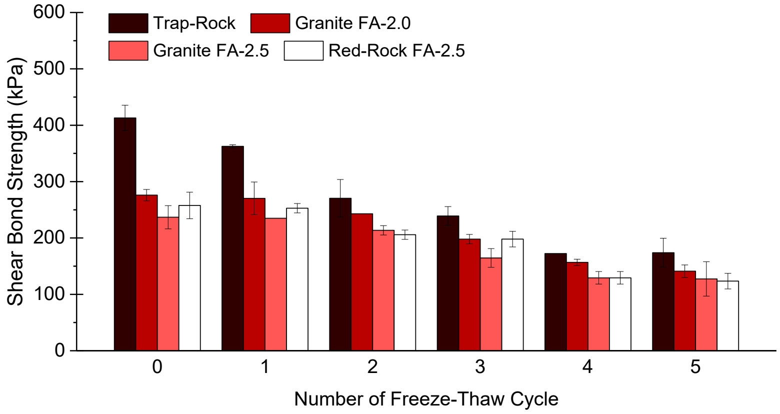


Figure 4-6. Shear bond strength for ae-1 seal coat with multiple freeze-thaw cycles

4.3 SUMMARY AND CONCLUSIONS

This task investigated the shear bond strength between the seal coat and asphalt pavement of several asphalt-aggregate combinations and asphalt-emulsion application rates. To test shear bond strength between chip seals and asphalt pavement, a new laboratory approach, Michigan Tech's shear bond test (SBT), was developed. In order to characterize the influence of environmental temperatures and freeze-thaw cycles on the durability of the seal coat, distinct test temperatures and various freeze-thaw cycles were also applied in the proposed SBT.

There are seven main conclusions which can be derived from SBT results under environmental conditions:

(1) The shear bond strength of AE-1 seal coats was higher than that of AE-2 seal coats. This result indicates that the polymer-modified asphalt-emulsion (AE-1) performs better in terms of interface bonding with aggregates in the seal coats.

(2) Trap-Rock seal coat obtained the highest shear bond strength with asphalt pavement. This could be encouraged by the higher percentage of fine aggregate particles found in the Trap-Rock as well as the chemical interactions present between the aggregate particles and asphalt.

(3) Generally, larger aggregate size resulted in weaker shear bond strength of seal coat under the same asphalt-emulsion application rate. Although aggregate size is a critical factor in determining the shear bond strength of the seal coat, the mineral composition of aggregate was also found to affect the strength.

(4) At the same embedment percentage of aggregate in a seal coat, larger sized aggregate provided better durability of seal coat for shear loading from vehicles. In addition, under the same aggregate type conditions, the shear bond strength of seal coat with asphalt pavement increased with the increase of the asphalt-emulsion application rate.

(5) In general, the shear bond strength weakened with low temperatures. However, the seal coat with larger sized aggregate was more stable with asphalt pavement than the seal coat with smaller sized aggregate at low temperatures.

(6) The shear bond strength of seal coat with asphalt pavement decreased with the increase of freeze-thaw cycles. Although the Trap-Rock produced the highest shear bonding performance, its ability to resist the freeze-thaw cycle is the worst of all four aggregate types. The larger sized aggregate in the seal coat could improve the resistance for the multiple freeze-thaw cycles.

(7) Materials and environmental combinations have a significant impact on the shear bond strength of seal coat with asphalt pavement. The material and structural design of the seal coat should consider these factors to improve the durability of the seal coat for the preventive maintenance treatment of asphalt pavements.

CHAPTER 5: PRELIMINARY DIAGNOSIS OF THE STRIPPING OF ASPHALT PAVEMENTS UNDER SEAL COATING

Seal coating is used as a cost-effective strategy in asphalt pavement preservation, yet many cities in Minnesota have reported their concerns about the stripping of pavements under seal coating. As a result, a growing number of agencies are choosing not to use seal coating. A goal of this task is to evaluate whether stripping is caused by seal coating. If so, then what is the mechanism for this? Is seal coating counterproductive on pavements in Minnesota? This task will directly investigate this problem through laboratory testing on asphalt pavement cores and laboratory samples.

5.1 DIAGNOSIS OF THE STRIPPING: LABORATORY EVALUATIONS

According to the literature and previous laboratory testing results, the stripping of pavement under seal coating is due to at least the following: 1) multiple freeze-thaw cycles, 2) moisture damage, and 3) asphalt loss from the surface of aggregates (as depicted in Figure 5-1). Therefore, in this task, the research team evaluated the impact of multiple freeze-thaw cycles, moisture damage, and asphalt loss on the interface bond strength of seal coats with asphalt pavement. The newly developed Michigan Tech Interface Bond Test (IBT) was used in this task for the interface bond strength evaluations. The details of the IBT and the respective seal coat preparations and curing time are the same as those in Chapter 3.

Figure 5-1. Comparison between asphalt mixtures before and after stripping: initial asphalt mixtures (left image) and partial asphalt loss from aggregate surface (right image). Both images are from Michigan Tech Asphalt Lab

5.1.1 Multiple Freeze-Thaw Cycles

This section is the same as the *3.2.3 Interface Bond Strength between Seal Coat and Pavement after Multiple Freeze-Thaw Cycles*.

5.1.2 Moisture Damage and Asphalt Loss

Aside from the lack of freeze-thaw resistance, one of the issues of concern is the moisture resistance of the proposed seal coat samples. In order to evaluate the influence of moisture damage and asphalt loss on the interface bond strength of seal coat with asphalt pavements, the laboratory characterization steps shown in Figure 5-2 were developed in this study. In the designed testing procedures, both the asphalt loss and the interface bond strength loss of seal coat samples were evaluated. The initial status of the seal coat sample is shown in Figure 5-2(a). Before applying a laboratory moisture test, the samples were vacuum saturated with room temperature water under a pressure of 254-660.5 mmHg for 10-15 minutes and then checked to see whether the saturation degree was almost 100%, as illustrated in Figure 5-2(b).

Depicted in Figure 5-2(c), the Moisture-Induced Stress Tester (MIST) is a cyclic conditioning system that is designed to simulate the stripping mechanisms that occur in pavement structures. The MIST is a stand-alone unit that consists of a pressurized chamber that pushes and pulls water through a compacted asphalt sample, simulating the action of an automobile tire on the road. The tests can be performed at different pressures and temperatures to replicate different traffic and environmental conditions (D7870/D7870M-13 2013). Here, the MIST employed hydrostatic pore pressure supplied through a regulator to force free-water into and out of the seal coat samples with a diameter of 50 mm (2-inch). The samples were kept in water maintained at a constant temperature of 55°C (131°F), and the peak air pressure was 296 kPa (40 psi). The MIST system was capable of applying a cyclic pressure peak of approximately Lorentzian function in shape. Note that the MIST moisture conditioning was run for 500, 1000, and 1500 cycles for the seal coat samples (D7870/D7870M-13 2013; Shu et al. 2012). The asphalt loss of the seal coat sample was calculated via Eq. (5-1).

After the MIST moisture conditioning for 500, 1000, and 1500 cycles, the surface dry seal coat samples were employed in IBT with the loading rate of 50 mm/min at room temperature, as shown in Figure 5-2(d). The interface bond strength loss can be calculated via Eq. (5-2).

$$Asphalt\ Loss\ \% = \frac{M2-M3}{M1} \times 100\% \tag{5-1}$$

$$Interface\ Bond\ Strength\ Loss\ \% = \frac{Original\ Strength - Strength\ after\ MIST}{Original\ Strength} \times 100\% \tag{5-2}$$

where M1, M2, and M3 are the dry mass of the sample, the full saturated surface dry mass of the sample, and the full saturated surface dry mass of the sample after MIST cycles, respectively.

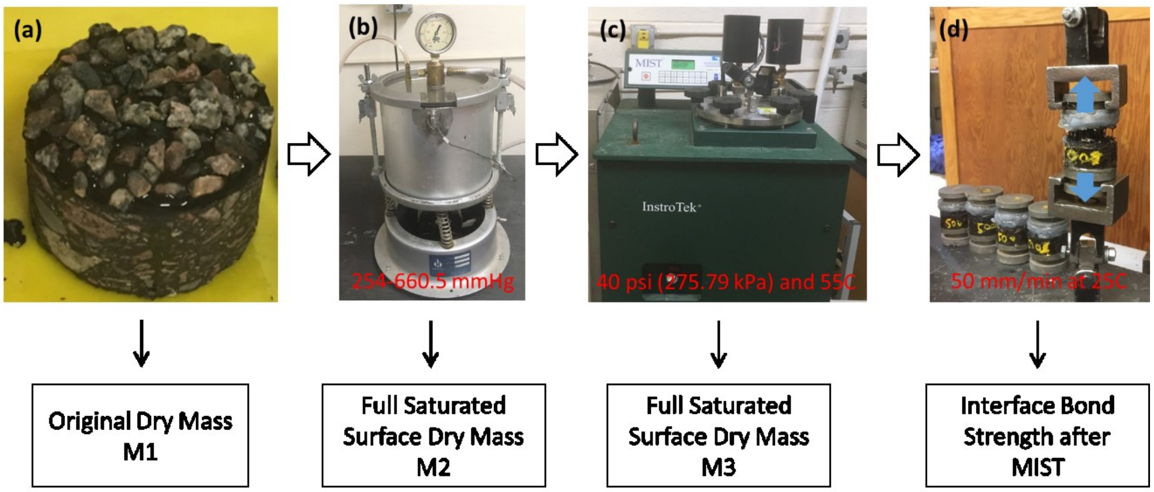


Figure 5-2. Evaluation steps of moisture damage and asphalt loss in asphalt pavement underlying seal coating

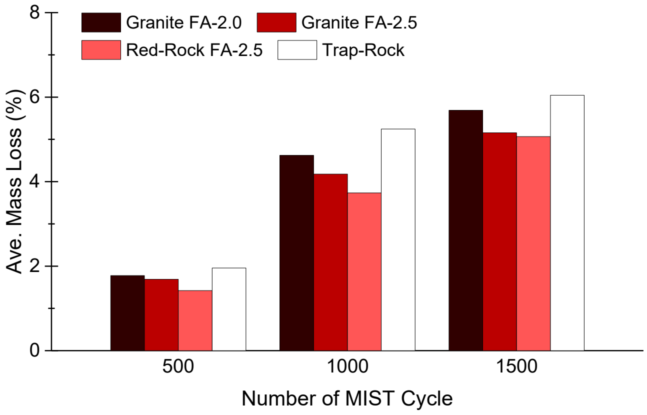


Figure 5-3. Average mass loss of asphalt from seal coat samples after mist tests

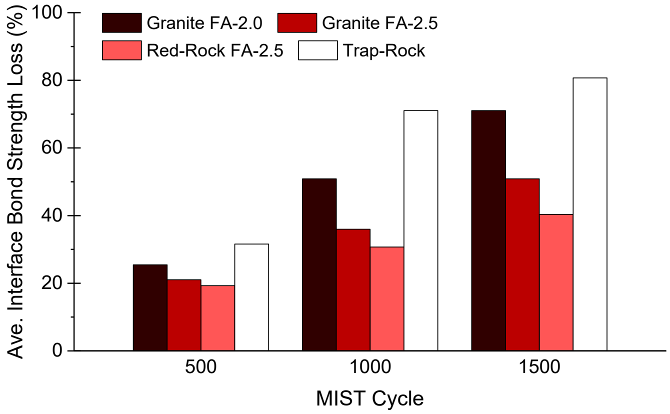


Figure 5-4. Average interface bond strength loss of seal coat samples after mist tests

Figure 5-4 depicts the mass loss of asphalt from seal coat samples after the MIST tests, and Figure 5-4 shows the interface bond strength loss of seal coat samples after the MIST tests. The presented results of the MIST cycles use a ±1 standard deviation to display error bounds. It can be observed that with the increase of the MIST cycle, there are increasing asphalt loss and interface bond strength loss. Different types of seal coat samples performed differently under the same MIST cycle. From Figure 5-4, it can be seen that after 500 MIST cycles, the interface bond strength loss rate of Granite FA-2.0, Granite FA-2.5, Red-Rock FA-2.5, and Trap-Rock were 25.1%, 19.8%, 18.2%, and 31.1%, respectively. With increasing MIST cycles, the interface bond strength of seal coat samples continued to reduce, and interface bond strength loss increased to 69.8%, 50.6%, 39.8%, and 79.9% for Granite FA-2.0, Granite FA-2.5, Red-Rock FA-2.5, and Trap-Rock, respectively. Thus, the effect of moisture damage and asphalt loss can be considered significant. Also, the surface properties and the size of aggregate in the seal coat influenced the moisture resistance of seal coat samples.

5.2 LABORATORY TESTING ON PAVEMENT CORES

5.2.1 Pavement Core Collection Locations

This section is the same as *2.1 Field Sample Collection Locations*.

5.2.2 Michigan Tech's Interface Bond Test (IBT) of Pavement Cores

The research team employed Michigan Tech's Interface Bond Test (IBT) on the collected pavement cores for the performance evaluations of asphalt pavement underlying various seal coats. Three age categories of pavement cores were used in this study: 0-3, 6-9, and 10-20 years. IBT was employed with a loading rate of 50 mm/min at room temperature. The laboratory testing results are displayed in Figures 5-7 and 5-8. The results use a ±1 standard deviation to display error bounds. Also, some of the laboratory testing examples are presented in Appendix V-2, which includes the IBT testing on the Granite seal coating pavement cores, the Trap-Rock seal coating pavement cores, and the non-seal coating pavement cores.

Tables 5-1 and 5-2 show the sampling locations of pavement cores. All of the testing cores (2-inch) were cut from the 8-inch pavement cores in order to apply the IBT.

In Tables 5-1 and 5-2, N/A=Not Applicable; Good =There is no significant stripping that occurred on the surface of seal coating pavement; Partially Damaged = There is initial stripping or partial stripping (damage of seal coats) that occurred on the surface of the seal coating pavement; however, the pavement cores were cut from the completed parts of the pavement, as shown in Figure 5-5.

Table 5-1. Sampling information for interface bond strength of seal coat

Types	Pavement age (Year)	Location	Seal coat performance
Trap-Rock Seal Coat	0-3	CSAH19 at Chisago	Good
	6-9	Windsor Ter South of Edinbrook Pkwy at Brooklyn Park	Good
	10-20	Aladin Trail at Inver Grove Heights	Good
Granite Seal Coat	0-3	CSAH9/26 at McLeod	Good
	6-9	Charlson Rd. at Eden Prairie	Good
	10-20	Modern Rd. at Brooklyn Park	Good

Table 5-2. Sampling information for direct tensile strength of asphalt pavement

Types	Pavement age (Year)	Location	Seal coat performance
Trap-Rock Seal Coat	0-3	CSAH19 at Chisago	Partially damaged
	6-9	8918 Dunbar Knoll at Brooklyn Park	Partially damaged
	10-20	Hidden Lake Dr. at Woodbury	Partially damaged
Granite Seal Coat	0-3	CSAH1 at MacLeod	Partially damaged
	6-9	Charlson Rd. at Eden Prairie	Partially damaged
	10-20	Hwy 52NE Frontage Rd. at Rochester	Partially damaged
No Seal Coat	6-9	Deer Hill at Minnetonka	N/A
	10-20	Deer Hill at Minnetonka	N/A

(a) Initial Stripping **(b) Partial Stripping** **(c) Pavement Core**

Figure 5-5. Partially damaged pavement cores' collection examples. The images are from CSAH1 at MacLeod county

Figure 5-6 depicts the IBT testing results of the good performance seal coating pavement cores; the fracture occurs between the seal coat and the asphalt pavement, which indicates that the direct tensile strength of asphalt pavement is higher than the interface bond strength of seal coat. Also, it can be observed that the interface bond strength between the seal coat and asphalt pavement increased with the pavement age increase. This may be caused by the tendency of asphalt in seal coats to become more brittle and harder after long-term aging. Meanwhile, it can be observed that the Granite seal coats performed better in bonding with the asphalt pavement compared with the Trap-Rock seal coats.

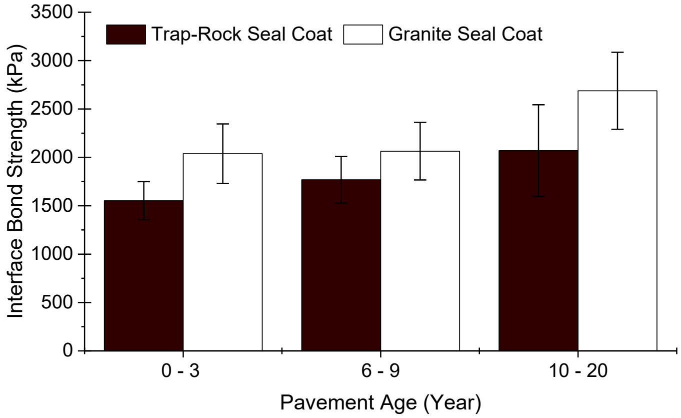


Figure 5-6. IBT testing results of good performance seal coating pavement cores: interface bond strength of seal coat with asphalt pavement. Note that the fracture occurs between asphalt pavement and seal coats during IBT testing, which indicates that the direct tensile strength of asphalt pavement is higher than the interface bond strength of seal coat

Figure 5-7 shows the IBT testing results of the partially damaged seal coating pavement cores, revealing the direct tensile strength of asphalt pavement underlying different types of seal coats. It should be noted that the direct tensile strength of the asphalt pavement was evaluated via the testing set-up of IBT, while the fractures occurred in the asphalt pavement. The results indicate that for the partially damaged seal coating asphalt pavement, the interface bond strength of seal coat is higher than the direct tensile strength of asphalt pavement because fractures occur in the asphalt pavement in IBT. In addition, the non-seal coating asphalt pavement (from Deer Hill in Minnetonka) has the highest direct tensile strength, followed by the Granite seal coating pavement and the Trap-Rock seal coating pavement. Also, except for the pavement cores with the Trap-Rock seal coat, the direct tensile strength of asphalt pavement increased with the increase of pavement age. Similarly, this may be caused by the tendency of asphalt in the pavement to become more brittle and harder after long-term aging. From 6-9 to 10-20 years, the slight decrease of the direct tensile strength of the pavement with the Trap-Rock seal coat may be due to the strength loss caused by moisture damage being more massive than the strength improvement caused by the asphalt aging in pavements.

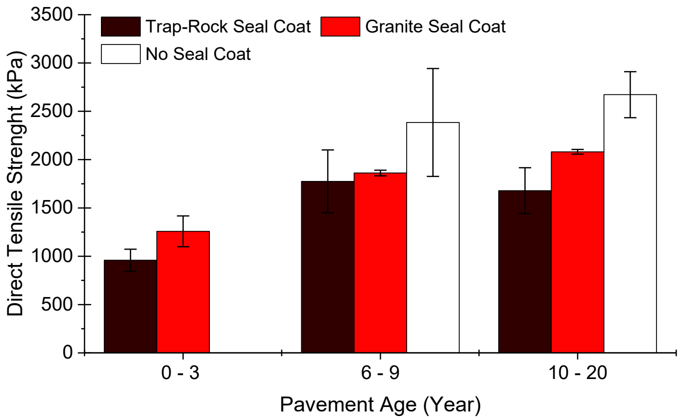


Figure 5-7. IBT testing on partially damaged seal coating pavement cores: direct tensile strength of asphalt pavement under seal coating. note that fractures occur in asphalt pavement during IBT testing, which indicates that the interface bond strength of the seal coat is higher than the direct tensile strength of asphalt pavement in the partially damaged pavements

By comparing the results in Figure 5-8, it is suggested that if partial damage occurs in the seal coat, this will accelerate the moisture damage in the pavement because environmental moisture (such as rainfall and humidity) seeps into the pavement via the damaged part of the seal coat of the pavement.

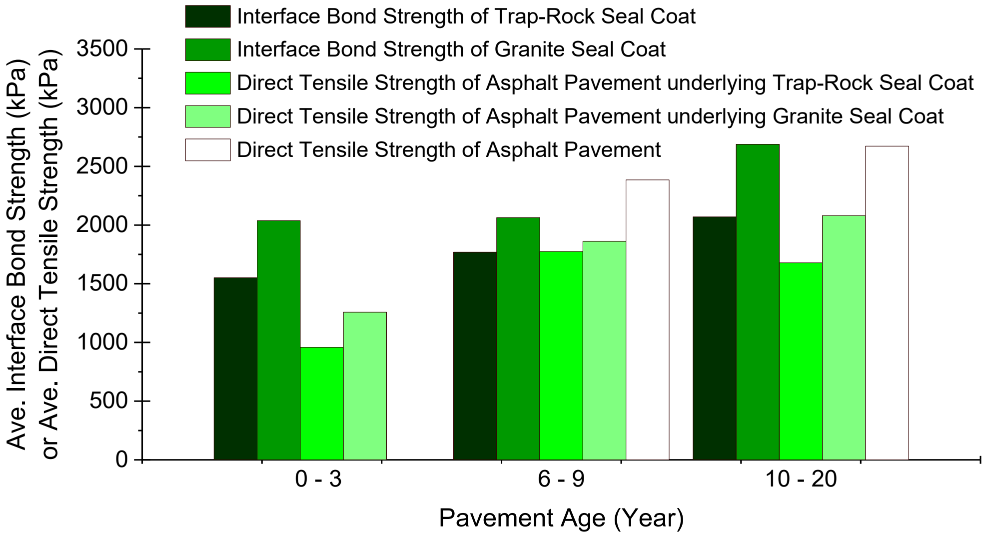


Figure 5-8. Comparisons of the interface bond strength of seal coats and the direct tensile strength of asphalt pavements in good performance and partially damaged pavement underlying various seal coats. Note that for the IBT testing on good performance pavement cores, fractures occur between the asphalt pavement and seal coats, while for the IBT testing on partially damaged pavement cores, fractures occur in the asphalt pavement

5.3 SUMMARY AND CONCLUSIONS

This task determined that the possible reasons for stripping are multiple freeze-thaw cycles, moisture damage, and asphalt loss. The newly developed laboratory IBT was used to confirm the hypothesis under certain conditions. In addition, the laboratory testing on the selected asphalt pavement cores was used to prove whether stripping is caused by seal coating and to evaluate the function of seal coating in the preservation of asphalt pavements.

The main conclusions that can be derived from the study results are as follows:

(1) For the premature stripping of asphalt pavement underlying seal coating, the effect of freeze-thaw cycles, moisture damage, and asphalt loss can be considered significant.

(2) If partial damage occurs in seal coats, further deterioration accelerates in the pavement system.

(3) The direct tensile strength of non-seal coating pavement is higher than that of partially damaged seal coating pavement based upon the limited results from the field cores. For future study, a comparison of the direct tensile strength of the non-seal coating pavement and the pavement with good performance seal coats is recommended.

CHAPTER 6: SUMMARY AND CONCLUSIONS

This project aimed to address the problem of asphalt pavement stripping under seal coating in Minnesota. A preliminary comprehensive field data collection was conducted to diagnose premature stripping of asphalt pavement underlying seal coating. The field data collection included the service condition of existing pavement, the mixture design underneath, the occurrence of stripping, and the materials of the seal coats. Some possible reasons for stripping were to be determined after diagnosis. In addition, Michigan Tech's interface bond test and shear bond test were proposed to characterize the bonding performance of seal coats with asphalt pavement. The samples were prepared with different emulsions and aggregates for seal coat with an existing HMA pavement. The test was also performed under various environmental conditions. Furthermore, the developed laboratory testing was used to verify the hypotheses of the reasons for asphalt pavement stripping under seal coating in Minnesota.

Based on the laboratory testing results, the research team arrived at the following general conclusions:

(1) The interface and shear bond strength between the laboratory seal coat layer and asphalt pavement layer decreased with the increase of freeze-thaw cycles. The polymer-modified asphalt-emulsion (AE-1) performed better in terms of bonding with aggregates in the seal coats.

(2) Based on the laboratory interface and shear bond test, it was concluded that weak asphalt-aggregate combination in seal coat application and increased freeze-thaw cycles are the main factors for premature stripping of many seal coat asphalt pavements. Due to multiple freeze-thaws and other factors, asphalt may be stripped from the aggregates of the asphalt mixture layers and the seal coat layer.

(3) From the laboratory interface bond test on the pavement cores, further deterioration accelerates in the pavement system when partial damage occurs in the seal coats. Based on the research conducted in this study, it cannot be simply concluded that seal coating is counterproductive.

CHAPTER 7: RECOMMENDATIONS

Past research and this study suggest that seal coats installed in the last three decades often lead to premature asphalt surface pavement deterioration. These seal coats create a membrane that is initially impermeable to moisture, but freeze-thaw action and other environmental and operational conditions can weaken the bond and allow water to migrate and saturate the underlying surface pavement. Moisture and additional freeze-thaw cycles may then weaken the pavement surface and strip the asphalt components from the upper surface, leading to the destruction of the upper layer of bituminous.

It should be noted that the above-mentioned laboratory testing results were based on a limited number of asphalt pavement cores; in future studies, further analysis is needed, including well-controlled test sections. The current study only concluded that if partial damage occurs in the seal coats, further deterioration accelerates in the pavement system. A question that was not answered is that when there is no seal coat failure, does the seal coat provide protection for the asphalt pavement or extend the service life of the asphalt pavement?

The currently collected pavement cores have different materials conditions and service environments; although the research team has tried to evaluate the direct tensile strength of the non-seal-coated pavement and the pavement with good performance seal coats, due to the high variation of testing data, it is difficult to make a conclusion. Due to the selected asphalt pavement structures having different asphalt mixture designs (the research team cannot access the asphalt mixture design information of the non-seal-coated pavement; however, it was observed that the asphalt mixture design is different), the research team suggests that a future study should be employed in the experimental road sections with the same materials and environmental conditions to compare the direct tensile strength of the non-seal-coated pavement and the pavement with good performance seal coats for further diagnosis.

In addition, one of the benefits of this project is the ability it provided to make recommendations on the implementation of seal coating on street asphalt pavements. The freeze-thaw resistance in the seal coat depends on moisture infiltration, temperature, mechanical properties of the seal coat, and the interface between asphalt and aggregates of the seal coat. There are at least two methods to improve freeze-thaw resistance:

(1) The pre-coated aggregate method may have a positive effect on the resistance to multiple freeze-thaws of the seal coat. Typically, pre-coated aggregates are used to assist in achieving the initial bond between aggregate particles and asphalt in hot sprayed sealing work. It is particularly used to overcome potentially adverse effects arising from dust or moisture on aggregates. There are two pre-coated aggregate methods: plant pre-coated aggregates that are stockpiled for later use and field pre-coating immediately before use. To better control the pre-coating quality and promote the full bonding of aggregate and asphalt prior to use, the plant pre-coated aggregate method is recommended in the implementation of seal coating on asphalt pavements.

On one hand, the pre-coated aggregate method is expected to work such that due to the action of asphalt on the surface of aggregate, the aggregate becomes obstructed, preventing the entry of water and therefore improving the moisture resistance of seal coats. On the other hand, a better chemical affinity between the pre-coated aggregate with asphalt and asphalt emulsion in the seal coat is expected, thus preventing the seal coat failure. The better the moisture resistance is, the better the freeze-thaw resistance will be.

(2) Improved seal coating design to resist multiple freeze-thaw cycles is a critical approach in seal coating design and construction. One element of seal coating design could be to control technical parameters according to the combination of aggregate and asphalt (such as aggregate size and shape, functional groups, and pH of both the asphalt and aggregate), to improve freeze-thaw resistance. For example, a smaller-sized aggregate in a heavier rate of asphalt emulsion has a deeper embedment depth, and higher silica content in granite may produce stronger hydrogen bonds to the asphalt. Both the higher asphalt film thickness and stronger hydrogen bonds result in stronger adhesion between the aggregate and asphalt in the seal coats, thus preventing seal coat failure. A suitable material combination in the seal coating design is critical to improving freeze-thaw resistance.

REFERENCES

Anderson, R. M., P. B. Blankenship, A. Zeinali, G. N. King, & D. I. Hanson. (2014). *Optimal timing of preventive maintenance for addressing environmental aging in hot-mix asphalt pavements* (Final Rep. No. MN/RC 2014 15).

ASTM. (2013). *Standard Practice for moisture conditioning compacted Asphalt mixture specimens by using Hydrostatic Pore pressure* (D7870/D7870M-13). West Conshohocken, PA: ASTM International.

Braun Intertec. (2016). *Alternatives to Seal Coats.* St. Paul, MN: Local Road Research Board, Minnesota Department of Transportation.

Chatti, K. S. W. Haider, R. J. Eisma, G.Musunuru, Y. R. Kim, C. Castorena, & J. Adams. (2017). *Performance-Related Specifications for Pavement Preservation Treatments.*

Cui, X., J. Zhang, N. Zhang, Y. Zhou, Z. Gao, & W. Sui. (2015). "Laboratory simulation tests of effect of mechanical damage on moisture damage evolution in hot-mix asphalt pavement." *International Journal of Pavement Engineering, 16*(8), 699-709.

Das, R., L. N. Mohammad, M. Elseifi, W. Cao, & S. B. Cooper Jr. (2017). "Effects of Tack Coat Application on Interface Bond Strength and Short-Term Pavement Performance." *Transportation Research Record: Journal of the Transportation Research Board, 2633,* 1-8.

Das, S. K. (2004). *Evaluation of asphalt--aggregate bond and stripping potential.* Lubbock, TX: Texas Tech University.

Distin, T. (2008). "Spray sealing practice in South Africa." International Sprayed Sealing Conference, 1st, 2008, Adelaide, South Australia, Australia.

Fromm, H. J. (1974). "The mechanisms of asphalt stripping from aggregate surfaces."

Ghaly, N. F., I. M. Ibrahim, & E. M. Noamy. (2014). "Tack coats for asphalt paving." *Egyptian Journal of Petroleum, 23*(1), 61-65.

Gheni, A. A., & M. A. ElGawady. (2017). "Crumb Rubber as a Sustainable Aggregate in Chip Seal Pavement." Congrès International de Géotechnique–Ouvrages–Structures.

Gransberg, D. (2005). "Chip seal program excellence in the United States." *Transportation Research Record: Journal of the Transportation Research Board, 1933,* 72-82.

Graziani, A., F. Canestrari, F. Cardone, & G. Ferrotti. (2017). "Time–temperature superposition principle for interlayer shear strength of bituminous pavements." *Road Materials and Pavement Design*, vol 18, 1-14.

Grenfell, J., A. Apeagyei, & G. Airey. (2015). "Moisture damage assessment using surface energy, bitumen stripping and the SATS moisture conditioning procedure." *International Journal of Pavement Engineering, 16*(5), 411-431.

Gürer, C. (2010). "Determination of parameters affecting seal coat performance and development a performance model." PhD thesis.

Gürer, C., M, Karaşahin, S. Çetin, & B. Aktaş. (2012). "Effects of construction-related factors on chip seal performance." *Construction and Building Materials, 35,* 605-613.

Hanz, A., P. Johannes, & H. Bahia. (2012). "Development of emulsion residue testing framework for improved chip seal performance." *Transportation Research Record: Journal of the Transportation Research Board*, *2293*, 106-113.

Holtrop, W. (2008). "Sprayed sealing practice in Australia." *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice, 17*(4): 41.

Jackson, D. C. (1990). "Washington state chip seal study." *Transportation Research Record*, *1259.*

Kandhal, P. S. (1994). "Field and laboratory investigation of stripping in asphalt pavements: State of the art report." *Transportation Research Record*, *1454.*

Kandhal, P. S., C. W. Lubold, & F. L. Roberts. (1989). *Water damage to asphalt overlays: Case histories.* Nashville, TN: National Center for Asphalt Technology.

Kaukuntla, P. R. (2014). *Standard ruggedness study on moisture induced sensitivity tester (MIST)*. Stillwater, OK: Oklahoma State University.

Kennedy, T. W., F. L. Roberts, & K. W. Lee. (1982). "Evaluation of moisture susceptibility of asphalt mixtures using the Texas freeze-thaw pedestal test." Association of Asphalt Paving Technologists Proceedings.

Leng, Z., H. Ozer, I. L. Al-Qadi, & S. H. Carpenter. (2008). "Interface bonding between hot-mix asphalt and various Portland cement concrete surfaces: laboratory assessment." *Transportation Research Record, 2057*(1), 46-53.

Lukanen, E. O. (1997). *An Evaluation of Aggregate and Chip Seal Surfaced Roads at Mn/Road.*

Panda, M., J. P. Giri, & B. B. Sutradhar. (2015). "Influence of Setting Time of Tack Coat on Bond Strength of Bituminous Paving Layers." *International Journal of Transportation Engineering, 2*(4), 297-306.

Park, S., M.-C. Jo, & J.-B. Park. (2000). "Adsorption and thermal desorption behaviour of asphalt-like functionalities on silica." *Adsorption Science & Technology, 18*(8), 675-684.

Parker Jr, F. (1989). "A field study of stripping potential of asphalt concrete mixtures."

Peshkin, D. G., & T. E. Hoerner. (2005). *Pavement preservation: Practices, research plans, and initiatives*. Washington, DC: American Association of State Highway and Transportation Officials.

Reitzel, N., D. R. Greve, K. Kjaer, P. B. Howes, M. Jayaraman, S. Savoy, R. D. McCullough, J. T. McDevitt, & T. Bjørnholm. (2000). "Self-assembly of conjugated polymers at the air/water interface. Structure and properties of Langmuir and Langmuir−Blodgett films of amphiphilic regioregular polythiophenes." *Journal of the American Chemical Society, 122*(24), 5788-5800.

Rettner, D. L., & D. Tompkins. (2017). *Prevention of Stripping Under Chip Seals.*

Salomon, D., M. Thompson, G. Dur, C. Gueit, C. Deneuvillers, M. Robert, A. Lebon, & C. Sa. (2008). "Comparison of Rheological Properties for Recovered Residue from Emulsified Asphalt obtained by Three Recovery Procedures."

Shi, X., A. Mukhopadhyay, & D. Zollinger. (2018). "Sustainability assessment for portland cement concrete pavement containing reclaimed asphalt pavement aggregates." *Journal of Cleaner Production.*

Shu, X., B. Huang, E. D. Shrum, & X. Jia. (2012). "Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP." *Construction and Building Materials, 35,* 125-130.

Song, W., X. Shu, B. Huang, & M. Woods. (2017). "Influence of interface characteristics on the shear performance between open-graded friction course and underlying layer." *Journal of Materials in Civil Engineering, 29*(8), 04017077.

Taylor, M. A, & N. P. Khosla. (1983). *Stripping of asphalt pavements: State of the art (discussion, closure)*. Vol. 911.

Terrel, R. L., & J. W. Shute. (1989). *Summary report on water sensitivity.*

Wasiuddin, N. M., A. Marshall, N. E. Saltibus, A. Saber, C. Abadie, & L. N. Mohammad. (2013). "Use of sweep test for emulsion and hot asphalt chip seals: Laboratory and field evaluation." *Journal of Testing and Evaluation, 41*(2), 289-298.

Wasiuddin, N., M. Zaman, & E. O'Rear. (2008). "Effect of sasobit and aspha-min on wettability and adhesion between asphalt binders and aggregates." *Transportation Research Record: Journal of the Transportation Research Board*, *2051*, 80-89.

Wood, T. J. (1999). *Seal Coat Research Project.*

Wood, T. J., & M. K. Cole. (2013). *Stripping of Hot-Mix Asphalt Pavements under Chip Seals.* St. Paul, MN: Minnesota Department of Transportation, Research Services.

Wood, T. J., D. W. Janisch, & F. S. Gaillard. (2006). *Minnesota seal coat handbook 2006.*

Xu, G., & H. Wang. (2016). "Study of cohesion and adhesion properties of asphalt concrete with molecular dynamics simulation." *Computational Materials Science, 112,* 161-169.

You, L., Z. You, Q. Dai, X. Xie, S. Washko, & J. Gao. (2019). "Investigation of adhesion and interface bond strength for pavements underlying chip-seal: Effect of asphalt-aggregate combinations and freeze-thaw cycles on chip-seal." *Construction and Building Materials, 203,* 322-330.

Zhai, H., D. Salomon, & E. Miliron. (2006). "Using Rheological properties to evaluate storage stability and setting behavior of emulsified asphalts (white paper)." East Idaho Falls, ID: Idaho Asphalt Supply, Inc,

APPENDIX A: MATERIAL REQUIREMENTS AND SAMPLING LOCATIONS IN MINNESOTA

Material Requirements and sampleing locations

Materials types			Volume/ Weight/ Number	Locations	Contact person	Note	
CSS-1H, CRS-2P (polymer-modified)			8 gal. each	MnDOT	Paul Nolan		
Aggregate for seal coating layer		FA-1	200 lbs.	MnDOT	Paul Nolan		
		FA-2	200 lbs.	MnDOT	Paul Nolan		
		FA-3	200 lbs.	MnDOT	Paul Nolan		
Aggregate for HMA pavements			2000 lbs.	MnDOT	Paul Nolan		
Asphalt binder in asphalt pavement- PG 52-28			12 gal.	MnDOT	Paul Nolan		
Sample cores	Old asphalt pavement samples, without sealcoat, as comparision	6-8 years old	4	**Minnetonka**-Deer Hill	Darin Ellingson	YES	
		12-16 years old	4	**Minnetonka**-Deer Hill	Darin Ellingson	YES	
	Partially damaged seal coated pavement with granite aggregates	0-3 years old	4	**Mcleod**-CSAH 1	John Brunkhorst	YES (Missing one sample)	1 ✓
		6-8 years old	4	**Eden Prairie**-Charlson Rd (s-p)	Mary Krause	YES	
		12-16 years old	4	**Rochester**-Hwy 52NE Frontage Rd	Dean Koutsoukos	YES	
	Good performance seal coated pavement with granite aggregates	0-3 years old	4	**McLeod**-CSAH 9/CSAH 26	John Brunkhorst	2 NO	2 - Driving Path 3 - Non wheel Path
		6-8 years old	4	**Eden Prairie**-Charlson Rd (s-p)	Mary Krause	YES	
		12-16 years old	4	**Brooklyn Park-Modern Rd**	Jesse Struve	2 NO	5 - wheel Path 6 - Non wheel Path
	Partially damaged seal coated pavement with trap rock aggregates	0-3 years old	4	**Chisago** Country-CASH 19 (Rd14-fb)	Paul Nolan	2 NO	7 - wheel Path 8 - Non wheel Path
		6-8 years old	4	**Brooklyn Park**-8918 Dunbar Knoll	Jesse Struve	YES (Missing one sample)	4 ✓
		12-16 years old	4	**Woodbury**-Hidden Lake Dr	Klayton Eckles	YES	
	Good performance seal coated pavement with trap rock aggregates	0-3 years old	4	**Chisago** Country-CASH 19 (Rd14-fb)	Paul Nolan	2 NO	9 - Wheel Path 10 - Non Wheel Path
		6-8 years old	4	**Brooklyn Park**-Windsor Ter South of Edinbrook Pkwy	Jesse Struve	YES	
		12-16 years old	4	**Inver Grove Heights**-Aladin Trail	Steve Dodge	YES	
Loose seal coating materials pelled from	Granite as aggregates	//	200 lbs.	MnDOT	Paul Nolan		
	Trap rock	//	200 lbs.	MnDOT	Paul Nolan		
Notice: Each group of core samples are selected as much as possible on the same road, although some options are provided for some							

YES- The required field samples have been provided by AET;
NO- The required field samples have not been provided by AET.

APPENDIX B: PICTURES OF FIELD SAMPLE COLLECTION (UPDATED ON 02/11/2018)

BROOKLYN PARK

Appendix Figure 1. BP#1, partially damaged, 6-9 years

Appendix Figure 2. BP#2, partially damaged, 6-9 years

Appendix Figure 3. BP#3, partially damaged, 6-9 years

Appendix Figure 4. BP#4, good performance, 6-9 years

Appendix Figure 5. BP#5, good performance, 6-9 years

Appendix Figure 6. BP#6, good performance, 6-9 years

Appendix Figure 7. BP#7, good performance, 6-9 years

EDEN PRAIRIE

Appendix Figure 8. EP#1, partially damaged, 6-9 years

Appendix Figure 9. EP#2, partially damaged, 6-9 years

Appendix Figure 10. EP#3, partially damaged, 6-9 years

Appendix Figure 11. EP#4, partially damaged, 6-9 years

Appendix Figure 12. EP#5, good performance, 6-9 years

Appendix Figure 13. EP#6, good performance, 6-9 years

Appendix Figure 14. EP#7, good performance, 6-9 years

Appendix Figure 15. EP#8, good performance, 6-9 years

INVER GROVE HEIGHTS

Appendix Figure 16. IGH#1, good performance, 10-20 years

Appendix Figure 17. IGH#2, good performance, 10-20 years

Appendix Figure 18. IGH#3, good performance, 10-20 years

Appendix Figure 19. IGH#4, good performance, 10-20 years

MCLEOD

Appendix Figure 20. MN MC#1, partially damaged, 0-3 years

Appendix Figure 21. MN MC#2, partially damaged, 0-3 years

MINNETONKA

Appendix Figure 22. MN DH#1, 6-9 years

Appendix Figure 23. MN DH#2, 6-9 years

Appendix Figure 24. MN DH#3, 6-9 years

Appendix Figure 25. MN DH#4, 6-9 years

Appendix Figure 26. MN DO#1, 10-20 years

Appendix Figure 27. MN DO#2, 10-20 years

Appendix Figure 28. MN DO#3, 10-20 years

Appendix Figure 29. MN DO#4, 10-20 years

ROCHESTER

Appendix Figure 30. RCHSTR#1, partially damaged, 10-20 years

Appendix Figure 31. RCHSTR#2, partially damaged, 10-20 years

Appendix Figure 32. RCHSTR#3, partially damaged, 10-20 years

Appendix Figure 33. RCHSTR#4, partially damaged, 10-20 years

WOODBURY

Appendix Figure 34. W#1, partially damaged, 10-20 years

Appendix Figure 35. W#2A, partially damaged, 10-20 years

Appendix Figure 36. W#2B, partially damaged, 10-20 years

Appendix Figure 37. W#3, partially damaged, 10-20 years

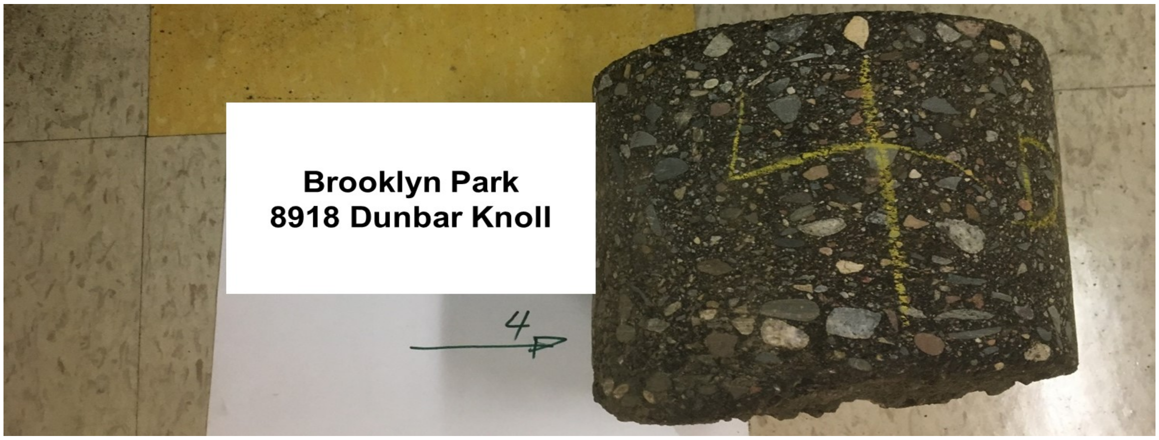
Appendix Figure 38. W#4, partially damaged, 10-20 years

APPENDIX C: PICTURES OF FIELD SAMPLE COLLECTION (UPDATED ON 11/30/2018)

MCLEOD

Appendix Figure 39. Nos. 2 and 3, good performance, 0-3 years

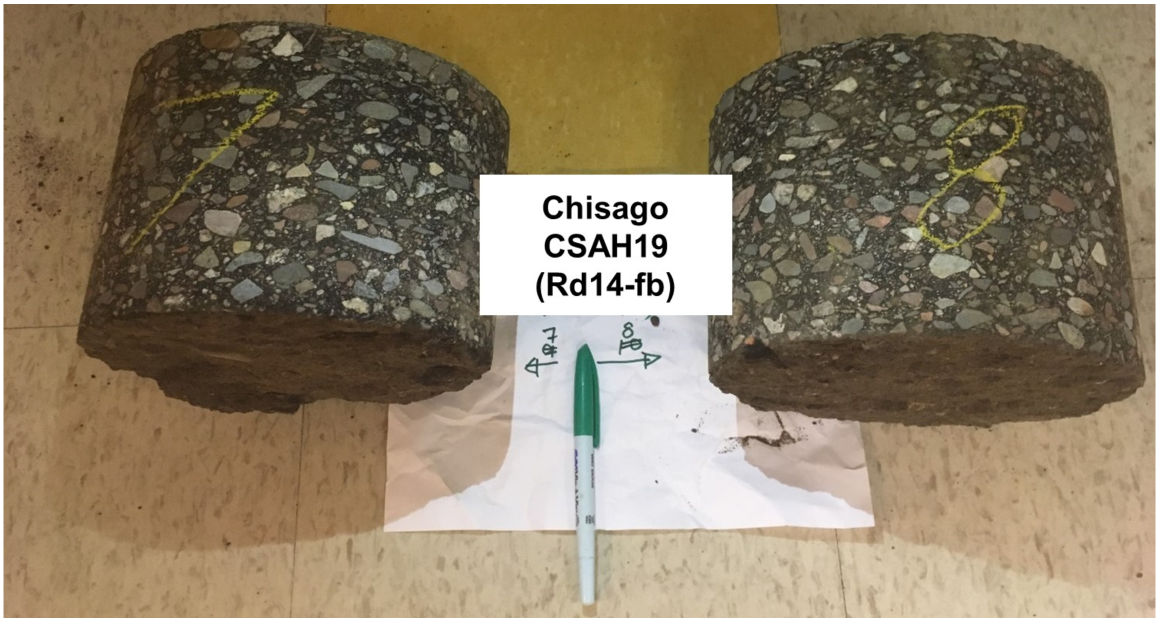
BROOKLYN PARK



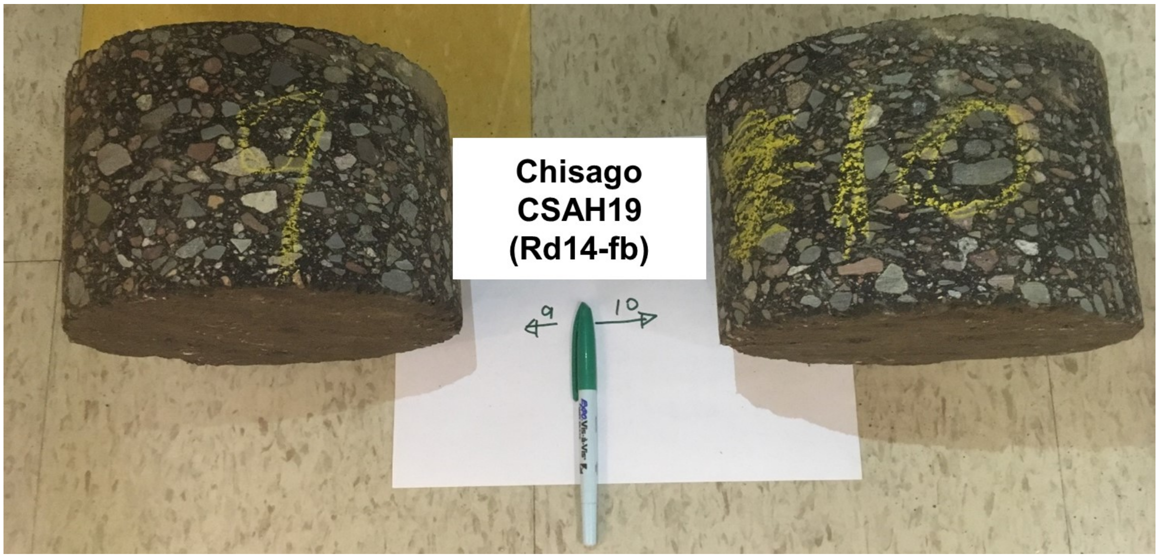
Appendix Figure 40. No. 4, partially damage, 6-8 years

Appendix Figure 41. Nos. 5 and 6, good performance, 12-16 years

CHISAGO



Appendix Figure 42. Nos. 7 and 8, partially damage, 0-3 years



Appendix Figure 43. Nos. 9 and 10, good performance, 0-3 years

APPENDIX D: STATISTICS OF THE AMOUNT OF MICHIGAN TECH'S INTERFACE BOND TEST ON LAB SEAL COATS

Combinations		Test Temperatures (25, 0, and -10°C)	Freeze-Thaw Cycles (1, 2, 3, 4, and 5)	MIST Cycles (500, 1000, and 1500)	Successful IBT Testing Sample Amount
AE-1	Red-Rock FA-2.5	3×3	3×5	3×3	33
	Granite FA-2.5	3×3	3×5	3×3	33
	Granite FA-2.0	3×3	3×5	3×3	33
	Trap-Rock	3×3	3×5	3×3	33
AE-2	Red-Rock FA-2.5	3×3	0	0	9
	Granite FA-2.5	3×3	0	0	9
	Granite FA-2.0	3×3	0	0	9
	Trap-Rock	3×3	0	0	9

It shall be noted that the average interface bond strength between the seal coat and asphalt pavement was from at least three replicates for various material and environmental conditions. And all of the asphalt emulsion application rate is 0.36 gal/yd^2. Thus, the total IBT testing lab sample amount is about 168.

APPENDIX E: STATISTICS OF THE AMOUNT OF MICHIGAN TECH'S SHEAR BOND TEST ON LAB SEAL COATS

Combinations		Test Temperatures (25, 0, and -10°C)	Freeze-Thaw Cycles (1, 2, 3, 4, and 5)	AE Application Rate (0.22, 0.25, and 0.36 gal/yd^2)	Successful SBT Testing Sample Amount
AE-1	Red-Rock FA-2.5	3×3	3×5	3×1 (0.36 gal/yd^2)	27
	Granite FA-2.5	3×3	3×5	3×1 (0.36 gal/yd^2)	27
	Granite FA-2.0	3×3	3×5	3×2 (0.25 and 0.36 gal/yd^2)	30
	Trap-Rock	3×3	3×5	3×2 (0.22 and 0.36 gal/yd^2)	30
AE-2	Red-Rock FA-2.5	3×1 (at 25°C)	0	0	3
	Granite FA-2.5	3×1 (at 25°C)	0	0	3
	Granite FA-2.0	3×1 (at 25°C)	0	0	3
	Trap-Rock	3×1 (at 25°C)	0	0	3

Note that the average shear bond strength between the seal coat and asphalt pavement was from at least three replicates for various material and environmental conditions. Thus, the total IBT testing lab sample amount is about 126.

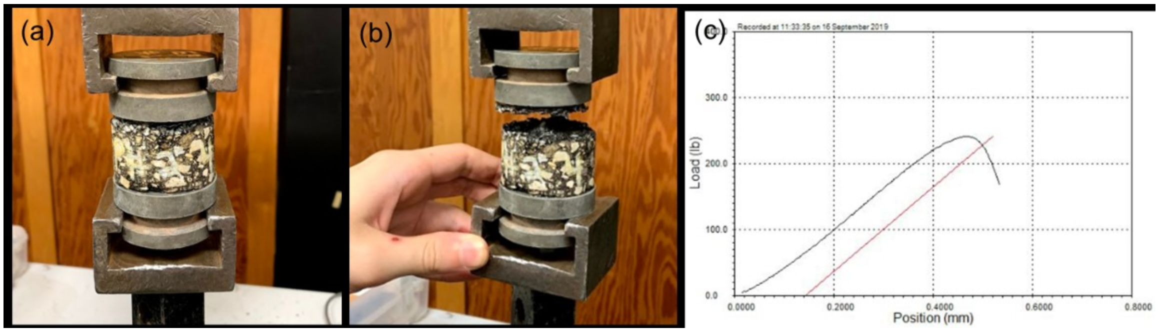
APPENDIX F: PAVEMENT CORES, EXAMPLES IN MICHIGAN TECH ASPHALT LAB

Appendix Figure 44. Height-treated pavement cores

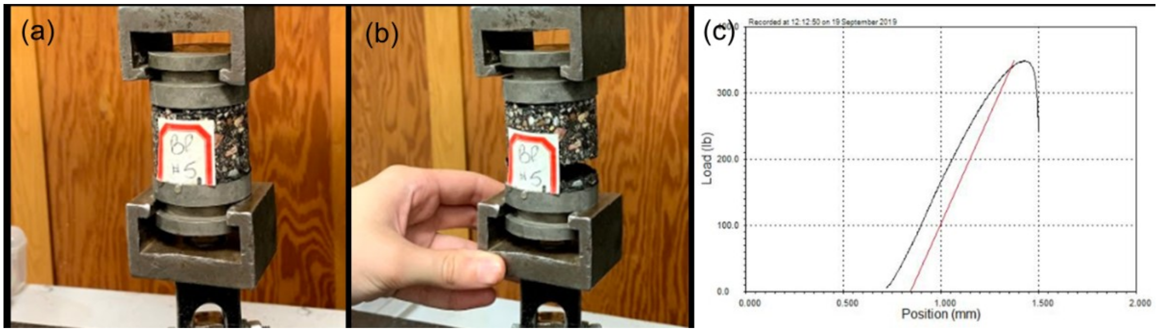
Appendix Figure 45. Partial view of 2-inch-treated pavement cores

APPENDIX G: MICHIGAN TECH’S INTERFACE BOND TEST ON PAVEMENT CORES

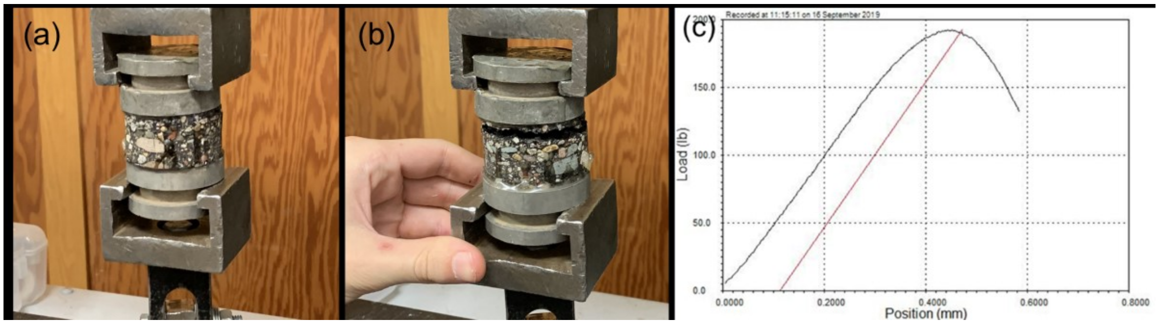
Appendix Figure 46. Overview of Michigan Tech’s interface bond test on pavement cores



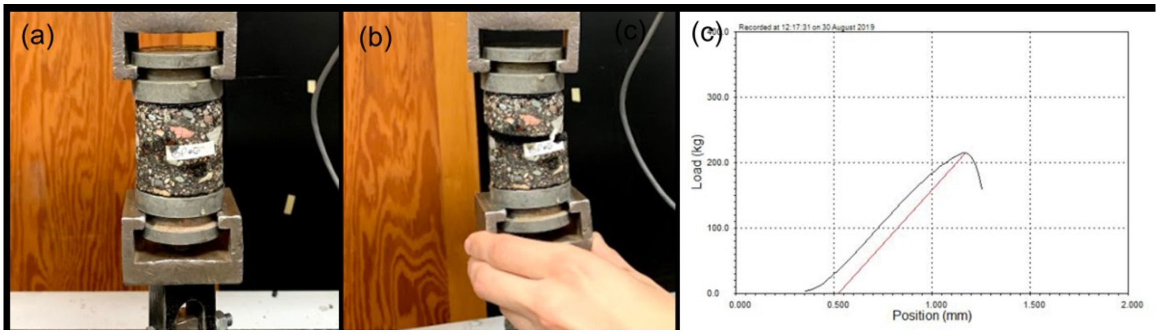
Appendix Figure 47. IBT testing on good performance pavement core with granite seal coat: (a) Before IBT, (b) After IBT, and (c) Loading Curve (Load-Position). Note that the average interface bond strength between the Granite seal coat and asphalt pavement was from at least three replicates for various pavement age conditions, i.e. 0-3, 6-9, and 10-20 years. Thus, the successful IBT testing sample amount about 3×3=9



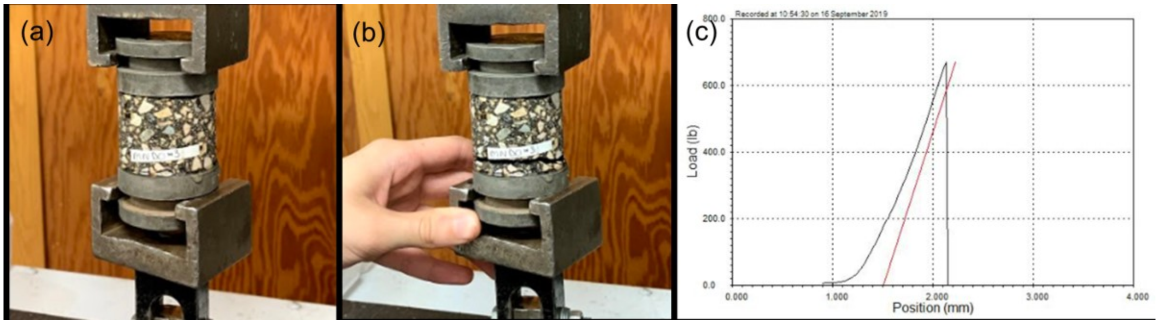
Appendix Figure 48. IBT testing on partially damaged pavement core with granite seal coat: (a) Before IBT, (b) After IBT, and (c) Loading Curve (Load-Position). Note that the average direct tensile strength of partially damaged pavement with Granite seal coat was from at least three replicates for various pavement age conditions, i.e. 0-3, 6-9, and 10-20 years. Thus, the successful IBT testing sample amount about 3×3=9



Appendix Figure 49. IBT testing on good performance pavement core with trap-rock seal coat: (a) Before IBT, (b) After IBT, and (c) Loading Curve (Load-Position). Note that the average interface bond strength between the Trap-Rock seal coat and asphalt pavement was from at least three replicates for various pavement age conditions, i.e. 0-3, 6-9, and 10-20 years. Thus, the successful IBT testing sample amount about 3×3=9



Appendix Figure 50. IBT testing on partially damaged pavement core with trap-rock seal coat: (a) Before IBT, (b) After IBT, and (c) Loading Curve (Load-Position). Note that the average direct tensile strength of partially damaged pavement with Trap-Rock seal coat was from at least three replicates for various pavement age conditions, i.e. 0-3, 6-9, and 10-20 years. Thus, the successful IBT testing sample amount about 3×3=9



Appendix Figure 51. IBT testing on pavement core with non-seal coat: (a) Before IBT, (b) After IBT, and (c) Loading Curve (Load-Position). Note that the average direct tensile strength of non-seal coating pavement cores was from at least three replicates for various pavement age conditions, i.e. 6-9 and 10-20 years. Thus, the successful IBT testing sample amount about 2×3=6