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Tack Coat Installation Performance Guidelines

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16. Abstract

A tack coat is a thin application of asphalt (typically emulsified) used to bond pavement layers together so that they act monolithically. Lack of bonding can lead to fatigue cracking, delamination, slippage and other distresses. This study was undertaken to explore the impacts of various tack coat materials, application rates, and other variables on tack coat performance. The ultimate original goal was to develop a tack coat quality acceptance system. As the study progressed, some of the original objectives and tasks were modified or dropped. Laboratory testing of lab- and field-fabricated specimens using a monotonic direct shear test was used to evaluate the factors of interest. The findings showed that the most commonly used tack materials in Indiana, AE-NT and SS-1h, can perform, with the AE-NT exhibiting somewhat better performance overall. INDOT's tack specifications could be clarified. The current applications rates are reasonable but could be refined to provide more guidance for use on different types of surfaces, as widely recommended nationally. The use of spray pavers and alternate tack materials should be further explored. Planned spray paver trial projects could provide the opportunity to expand on the results of this project, to explore other test methods, gain more experience with shear testing, and assess typical tack applications on non-experimental projects to assess the state of the practice. Additional implementation studies may help to refine a performance test and criteria for use to assess tack coat quality. The importance of tack coats should be emphasized to contractors and field personnel.

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EXECUTIVE SUMMARY

TACK COAT INSTALLATION PERFORMANCE GUIDELINES

Introduction

A tack coat is a thin application of asphalt or emulsion placed between asphalt pavement layers to bond them together. Although tack coat is a relatively inexpensive item, its bond failure during or after construction has a great impact on pavement performance and can lead to distresses, including top-down fatigue cracking, delamination, potholes, slippage or shoving, and other effects.

INDOT specifies tack coat practices, including types of materials and construction, in Section 406 of the Standard Specifications. However, it is not clear if the specified range of application rates is necessary and appropriate for currently used materials and construction practices. There is a need to develop methods that assess tack coat quality, including materials, application rates, and performance testing related to long-term pavement performance.

This study investigated the performance of lab- and field-fabricated specimens when various tack types and application rates are applied to concrete and asphalt substrates using a monotonic direct shear test.

Findings

- Other states have had success with the use of conventional, non-tracking, and polymer-modified tack materials when properly applied.
- Tracking tack is a common problem, which has led to increased use of so-called non-tracking tack. Non-tracking tacks reduce, but do not necessarily completely eliminate, tracking.
- A variety of tests exists to assess tack coat quality and/or uniformity in the lab or in situ, but the most commonly used methods are variations of direct shear testing.
- AE-NT produced higher shear strengths, fracture energy and flexibility indices than SS-1h when tested in direct shear and analyzed using the basic principles of the Illinois I-FIT test. On an asphalt substrate, the AE-NT also had lower variability.
- On a concrete substrate, the higher residual application rate (0.10 gal/syd) yielded higher shear strength than the low residual rate (0.03 gal/syd). On an asphalt substrate, the medium residual rate (0.05 gal/syd) produced the highest bond strength.
- Field cores from a trial project using a spray paver exhibited shear strengths equal to or better than a well-applied conventional tack. In addition, the spray paver cores showed much lower variability, which suggests a more uniform application was achieved in the field.
- The use of spray pavers in some other states has led to significant decreases in longitudinal and transverse cracking after five to six years, presumably by making the pavement layers act monolithically. Several states now use spray pavers routinely for certain applications.
- Testing of core samples from a trial project using polymerized VRAM tack material revealed that the VRAM had lower shear strengths, fracture energies and flexibility indices than the control, but the specimen remained intact after shearing.

Implementation

- Based on the findings of this study, some changes to the INDOT Standard Specifications have already been implemented. First, the application rates have been clarified to be undiluted spray rates and dilution has been explicitly prohibited. Different application rates are now specified for different surface types to be more detailed and more in line with nationally recognized rates. The specifications continue to require that tack be placed on clean, dry surfaces. AE-NT and SS-1h have been retained in the specifications, while less commonly used materials have been deleted. The use of AE-NT could be encouraged since its overall performance was somewhat better than SS-1h.
- Additional field trials using spray pavers and alternate tack materials should be constructed and evaluated to (a) expand on the findings of this study, (b) explore other test methods, (c) gain more experience with shear testing, and (d) assess typical tack applications on non-experimental projects to assess the state of the practice. Additional implementation studies may help to refine performance tests and criteria for use when assessing tack coat quality.
- Lastly, the impacts of tack coats on pavement performance should be stressed to contractors, project engineers, and inspection staff. Simply drawing attention to the importance of proper tack coat application and uniformity may help improve performance.

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1. INTRODUCTION

A tack coat is a thin application of asphalt or emulsion between asphalt pavement layers to provide adequate bonding. Although tack coat is a relatively inexpensive item, its bond failure during or after construction has a great impact on pavement performance and can lead to distresses including top-down fatigue cracking, delamination, potholes, slippage or shoving, and others. In 2010, four miles of I-65 near Brookston exhibited high severity delamination as a result of weak interface bonding. The delaminated pavement was replaced by a mill/fill during the fall of 2010. Poor bonding is also reportedly the cause for pavement deterioration on I-65 near Lebanon.

Without a good bond between asphalt pavement layers, the layers may not act as a monolithic structure, essentially reducing the effective pavement thickness. This can reduce the load carrying capacity of the pavement and lead to top-down fatigue cracking. An inadequate bond can also result in slippage of one layer over the other, which typically produces crescent-shaped cracks, or delamination of the surface.

Tack coats are essential to ensure that asphalt pavements last the design life. INDOT is using the Mechanistic-Empirical Pavement Design Guide (MEPDG) for the structural design of pavements, which assumes a full-bonding condition at interfaces between asphalt pavement layers. However, the full-bonding condition is not clearly defined nor can it be measured, as there is no standard test method for the evaluation of in situ interface bonding conditions. In addition, MEPDG analysis, recently conducted as part of an INDOT in-house study (Lee, Ahn, Shah, & Sommer, 2013), showed that the interface bonding condition significantly affects top-down fatigue cracking and roughness (IRI). This finding is more critical for asphalt overlays since a new interface is created close to the pavement surface.

A satisfactory tack coat must be applied at the appropriate application rate; too light an application will not have adequate bond strength, and too heavy an application may cause the upper layer to slide or slip over the underlying layer during or after construction. Tack coats are often diluted with water, so it is important to clarify if the application rate is the bulk rate or residual asphalt. Different surfaces will have different tack coat demands. A milled surface may provide better mechanical interlock with the subsequent overlay but may require more tack because of the greater surface area. Similarly, an open or "dry" surface may require more tack than a smooth, dense surface. For example, a smooth concrete surface typically will not require a heavy tack coat application.

In addition to having the appropriate overall application rate, the application should be uniform over the surface. A "streaky" tack coat will not bond well and, in extreme cases, the heavier streaks may bleed through the surface layer.

There are various existing tack coat tests used in the field or in the lab. One disadvantage of many of these methods is that they require coring of the pavement immediately after construction. In addition to being destructive, this is only a spot test and does not evaluate the uniformity of the application. Another disadvantage of existing test methods is that they assess the condition at the time of construction but generally do not give any indication of the effects of time on the bonding. The effective service life of a tack coat is largely unknown.

1.1 Problem Statement

INDOT specifies tack coat practices including types of materials and construction in Section 406 of the Standard Specifications. It is not clear, however, if the specified range of application rates is necessary and appropriate for currently used materials and construction practices. In addition, INDOT does not have a tack coat quality acceptance process. There is need for developing a means to assess tack coat quality, preferably related to long-term pavement performance. Development of the system should consider lab and field (in situ) tack quality measurement methods and minimum material and construction requirements to ensure that asphalt pavements last for the design life. Ideally reliable performance tests could make it possible to have end result type tack coat specifications and do away with specified tack coat application rates and other requirements.

1.2 Objectives

The ultimate, original objective of this research was to develop a tack coat quality acceptance system that would help to ensure adequate bonding exists between asphalt pavement layers in order to improve pavement performance. Such a system would require an appropriate test method or methods to be used to assess the adequacy of the tack coat application. The tests considered included laboratory and field measurements simulating the pavement service life, not only the condition of the tack coat at the time of construction. Lastly, it was originally intended to evaluate the need to develop calibration factors for MEPDG interface bonding conditions to properly account for less than full bonding during pavement design. As the study progressed, some of these original objectives were modified or dropped, as described herein.

1.3 Work Plan

Addressing the objectives of this study was initially envisioned to require the following tasks. As the research progressed, however, the Study Advisory Committee (SAC) recommended a number of modifications, as described below. In addition, pilot field projects were constructed and were added to this study.

Task 1: Literature Review

A thorough literature review was conducted to identify potential tack coat performance tests; tack coat application best practices; and the effects of varying pavement, climatic and material conditions on tack coats.

Task 2: Review of Current Practices and Specifications

State specifications were reviewed early in this project, and a summary was reported to the SAC. Near the end of the project, a National Cooperative Highway Research Program (NCHRP) Synthesis study entitled *Tack Coat Specifications, Materials and Construction Practices* (Gierhart & Johnson, 2018) was published. This synthesis is described in Chapter 2.

Task 3: Development/Evaluation of Field and/or Lab Tack Coat Performance Test(s)

Existing and potential, innovative test methods were identified in this task. The methods included both laboratory and field (in situ) tests. This task also included developing an experimental design for the evaluation of various factors affecting tack coat performance. After much discussion, the SAC directed the efforts towards laboratory test methods to evaluate the bond between layers as opposed to field tests to evaluate either the bond strength or the application rate and uniformity. While some SAC members expressed a desire for proactive specifications regarding the application rates and surface conditions, others wanted tests that would include the effects of construction variables. Ultimately, the effects of application rates, aging, temperature and material type were explored through lab testing. Testing of cores taken after paving was preferred for performance testing as opposed to assessing application rates or bond strength and/or uniformity of application in the field. This is because field testing introduces logistical and safety issues, plus INDOT personnel are not always available to conduct field testing on a routine basis. Coring is a spot test that may not detect all issues, but it is similar in concept to spot tests of density and other factors used to assess construction quality.

Task 4: Exploration of Tack Coat Variables in APT

This task was planned to build test sections in the Accelerated Pavement Testing (APT) Facility to explore the impact of variables such as tack coat application rates, cleanliness of the surface, tack vs. no tack, and perhaps different tack coat materials, on the performance of tack coats under controlled conditions. This testing was also expected to help develop a tack coat performance model and calibration factors for MEPDG interface bonding conditions to properly account for less than full bonding to be used during pavement design. In one previous study, slippage was observed in the APT under heavy loading. There was, however, a general lack of confidence that the APT could reliably reproduce bond failure. This lack of confidence, plus the high cost of constructing APT sections, eventually led the SAC to recommend dropping this type of testing and using the resources to conduct more testing on field projects.

Task 5: Field Verification of Tack Coat Performance Tests

Limited testing was performed on various field projects to assess bond strength using the direct shear test method identified in Task 3. These results are discussed in Chapter 3.

Task 6: Development/Refinement of Tack Coat Performance Model

The original vision for the study included developing a performance model and calibration factors for layer bonding for use in the MEPDG based on APT testing. Since the APT testing was dropped, as explained in Task 4, this task was also dropped from the study.

Task 7: Development of Tack Coat Quality Acceptance System

The results of the previous tasks were to be used to develop recommendations for the means to assess and/or ensure tack coat quality. The final recommendations include clarifying the specification requirements, continuing to use current materials while exploring the use of new materials, considering refinement of the application rates, and conducting more research to further investigate construction and testing options (spray pavers and pull-off testing, in addition to continued shear testing).

Task 8: Reporting and Deliverables

This task covered the preparation of a final report documenting the entire research project as well as recommendations regarding specification changes and other courses of action for consideration by INDOT. Semi-annual progress reports were written and SAC meetings held.

2. LITERATURE AND SPECIFICATION REVIEW

A literature review and an examination of state specifications were performed early in the project to identify potentially helpful specifications, test methods and best practices from other states. Throughout the project, the research team continued to look for pertinent literature. The specifications are summarized in 2.1 and the most pertinent literature is summarized in 2.2. A more detailed literature review, prepared by a graduate student temporarily assigned to the project, is included in Appendix A for the interested reader.

2.1 State Specifications

Specifications from 48 states and two Canadian provinces were reviewed online. Not surprisingly, there were similarities and differences observed between the different agencies.

A wide range of materials are used as tack coats, but emulsions are the most common by far. Most of the emulsions are slow-setting (SS-1, SS-1h, SS-1hp) or cationic slow-setting (CSS-1, CSS-1h). Only a few states allow medium-setting (MS-2) or rapid-setting (RS-1, RS-1h, RS-2, CRS-1, CRS-2, CRS-2P) emulsions to be used. A couple of states allow use of rapid-curing cutback (RC-70), but cutbacks have largely fallen into disfavor for environmental and health reasons. Viscosity graded asphalt cements (AC-20 or AC-30) or performance graded asphalt binders (e.g., PG 64-22, PG 76-22M) are allowed by several states. Non-tracking tacks are being specified by an increasing number of states; these include AE-NT, NTSS-1hm and a number of proprietary products. Note that "h" in a tack coat designation signifies that it is made with a harder base asphalt, which may help reduce tracking. Non-tracking tacks are typically produced with an even harder base than regular emulsions; they are intended to be quite hard shortly after placement so that traffic does not disturb them, then to be "reactivated" when hot asphalt mix is placed on top. In their 2018 synthesis study, Gierhart and Johnson (2018) estimated that emulsions comprise nearly 80% of the tack materials used in the USA and non-tracking or, as they called them, "reduced tracking" materials comprise another 20%. Less than half a percent of the tack used in the USA is asphalt binder.

There was also a substantial amount of variability in the application rates specified by different agencies according to the review of online specifications and confirmed by the 2018 synthesis study. One notable difference is how the application rates are specified. Some states specify residual rates that are the amount of asphalt residue remaining after the emulsion breaks and sets. (Breaking of an emulsion is when the water in the emulsion starts to separate from the asphalt residue and is typically signaled by a change of color from brown to black. An emulsion is set when all of the water has evaporated.) Other states quantify the tack in terms of the amount applied in either diluted or undiluted form. Tack emulsions are sometimes diluted, typically at a 1:1 ratio, with water so that greater amounts can be pumped through the distributor to increase the spray pressure. In addition, some specifications, including Indiana's, are somewhat vague about how the application rate is specified. Section 406.05 of Indiana's 2018 Standard Specifications says merely "The asphalt material shall be uniformly applied at the rate of from 0.05 to 0.10 gal/syd, or as otherwise specified or directed." The intent is reportedly for this to specify the undiluted spray rate, but that is not explicitly stated; dilution is not mentioned in either 406 or the material specifications (902.01(b)). Gierhart and Johnson (2018) reported that 21% of agencies specify residual rates, 52% use undiluted application rates, 27% use diluted rates and 17% are unclear. Workshops supported by FHWA and conducted by the Asphalt Institute recommended specifying the residual amount of tack since the amount of asphalt in an emulsion can vary, especially if dilution is allowed in the field where the dilution rate cannot be well-controlled. Diluted or straight emulsions should have their percent residue calculated and reported. Misinterpretation of the application rate can result in much less asphalt being available to bond the layers together, so specifications should be very clear on this point.

Residual application rates found in the literature ranged from 0.01 to 0.27 gal/syd (0.003–0.9L/m^2). The most common residual application rates found by Gierhart and Johnson (2018) were around 0.025–0.045 gal/syd on new asphalt lifts, 0.035–0.05 gal/syd for existing asphalt, 0.040–0.050 for milled asphalt and new or existing Portland cement concrete (PCC), and 0.045–0.060 for milled PCC. These values tend to be somewhat lower than those recommended in recent research (Mohammad, Elseifi, Bae, Patel, Button, & Scherocman, 2012), by FHWA (2016) and by NAPA (2013). See 2.2 for more details on the recommended rates.

Specifications do typically call for greater amounts of tack on oxidized surfaces than newly placed lifts since the asphalt film has not been worn off a new lift by traffic. Specifications also typically call for more tack on milled surfaces because of the greater surface texture of the milled surface. Some specifications and research recommendations call for heavier tack coats on PCC to improve the bond, but others recommend lighter applications to avoid introducing a slip plane at the often smooth interface of the PCC and overlay. Heavier tack coats on PCC might be acceptable if the tack is polymer-modified (and therefore very "sticky").

Most of the tack coat tests identified by the specification review dealt with the physical properties of the emulsions and residues. These tests included penetration, storage stability, solubility, sieve test, residue by evaporation, and others. While specifying the properties of the tack materials is probably necessary, they do not guarantee satisfactory performance of the material in the field. Many states have implemented or are considering bond strength tests; these are described in the literature review.

The specification review did reveal additional similarities among agencies. For example, 31 of the 50 agencies require that the surface tack is applied to be clean and dry; one of those states also permits application when the surface is "slightly damp." At least 18 agencies require that the tack break before paving commences. Only six agencies were identified that explicitly disallow dilution of the tack. Gierhart and Johnson (2018) state that modern distributor trucks are capable of maintaining adequate pressure at lower application rates and therefore dilution should not be necessary.

2.2 Literature Review

This section summarizes the pertinent findings from a detailed review of the literature relating to tack coats. A longer, more comprehensive review is included in

Appendix A for the interested reader. Literature was identified by searching the Transport Research International Documentation (TRID) database and Google.

2.2.1 Importance of Tack Coats

It is well-established that the layers in an asphalt pavement or asphalt overlay need to be bonded together to act monolithically. If the layers are not well-bonded, strains will not be transferred effectively from one layer to the next, so the pavement will act as if it is a thinner cross section. This can result in fatigue cracking. Also, surface courses can separate from the underlying layer and delaminate, producing a shallow, flat-bottomed pothole and resulting in poor ride quality. Surface courses can also slip over the underlying layer, either because of a lack of tack or an excess that produces a slip-plane at the interface. All of these distresses can shorten the life of the pavement or require more maintenance than a well-bonded pavement.

Various studies dating back decades have estimated the impacts of a tack coat on pavement life. Estimates of the reduction of service life from a poor tack coat range from 50% to 75% (Gierhart & Johnson, 2018). In Minnesota, it has been estimated that the service lives of one-third to one-half of pavements in the state may be reduced by 25% due to poor bonding (Johnson, Cole, & Pantelis, 2015). As Gierhart and Johnson (2018) point out, the cost of tack is insignificant (0.1%–0.2% of total project cost) compared to the high cost to rehabilitate a failed pavement.

2.2.2 Tack Coat Construction Practices

Tack coat application rates vary widely across the country, as noted in the specification review. Gierhart and Johnson (2018) compared three national sources of recommended application rates; these are presumably some of the best, most recognized recommendations. Table 2.1 compares the national guidelines from FHWA, NAPA and NCHRP 712.

Almost all state specifications call for tack coats to be applied to clean, dry pavements. Dirt on the surface to be paved could interfere with the bond and the tack could, in fact, bond to the dirt and not the pavement. Construction traffic could then lift the tack off the surface. Minnesota did field experiments to evaluate the effects of a dirty surface on the MnROAD low volume loop. Sections were tacked, deliberately contaminated, and paved; other sections were tacked and paved without contamination; one section was contaminated and paved without tack; and a final section was paved with no tack and no contaminant. The surface was not milled. The contaminant consisted of material passing the No. 8 (2.36-mm) sieve and fine sand. Two different residual tack rates were used (0.10 and 0.03 gal/ syd). Paving occurred before the tack had broken. None of the cores taken days after paving were bonded. A second set of cores was pulled about six months after construction; of 33 cores attempted, 11 separated during coring or core removal. There was a much higher success rate from the clean, tacked sections (90% intact cores) than from the contaminated sections (40% intact cores). The sections that were not tacked yielded somewhat fewer intact cores than the tacked sections. (Johnson et al., 2015)

McGhee and Clark (2009) observed that dirty or unsound pavements in Virginia contributed to poor bonding. They especially noted that "scabbing," when thin, loosely bound fragments of milled surfaces remain, led to bond failures. On the other hand, Mohammad and Elseifi (2014) found that surfaces dusted with silty-clay (AASHTO A4) at a rate of 0.07 lb/ft^2 actually had higher bond strength than a clean surface. Although Mohammad and Elseifi found higher bond strengths, the overwhelming consensus is that a clean surface is preferred by far; however, their results do suggest, perhaps, that a small amount of fine dust may not cause excessive failures. Surface cleaning is most typically performed by power brooms, sometimes supplemented with air blowing. Flushing the surface with water can also be done (Gierhart & Johnson, 2018), but is not common. If, indeed, a small amount of dust does not interfere with the bond, these cleaning methods may be adequate.

The verdict on the need for the surface to be dry is also somewhat mixed, though again there is general consensus that dry is better. FHWA (2016) recommends a dry surface, as do most state specifications. Mohammad et al. (2012) compared the bond strength of wet and dry surfaces and found no statistically significant differences in a limited study. To be conservative, they recommended the surface be dry. Sholar, Page, Musselman, Upshaw, and Moseley (2004) found that tacked specimens that were wetted before the overlying layer was applied were weaker in shear than dry specimens. So, although emulsified tack coats are often further diluted and the presence of a small amount of water, say from a very light rain, *might* not be a cause for concern, it is safer to avoid water on the surface either before or after application of the tack.

TABLE 2.1
Residual tack rates (gal/syd) recommended by national research.

Surface Type	FHWA (2016)	NAPA (2013)	NCHRP (Mohammad et al., 2012)
New Asphalt	0.02–0.05	0.03–0.04	0.035
Existing Asphalt	0.04–0.07	0.04–0.06	0.055
Milled Surface	0.04–0.08	0.03–0.05	0.055
PCC	0.03–0.05	0.04–0.06	0.045

Tracking of tack by traffic picking the tack up and carrying it down the road is a commonly reported problem. Tracking removes the tack from the wheelpaths where it is most needed, can lead to "globs" of tack and dirt being dropped in front of the paver, and is unattractive when tracked onto nearby pavements, where excessive amounts could create a friction problem. Non-tracking tacks were developed to combat this problem. Another possible solution is the use of a spray paver. A spray paver shoots the tack immediately in front of the screed, so the asphalt mix is placed before the emulsion has a chance to break and the tack is not disturbed by traffic. Spray pavers allow the application of heavy tack coats, if desired. Spray pavers reportedly produce a better bond, reduce cracking by making the layers act monolithically, and prevent vehicles from getting tack on them (Johnson & Barezinsky, 2016).

The Kansas Department of Transportation had seen an increase in fatigue cracking beginning in the early 2000s. After five or six years, on projects where they used a spray paver, they observed a reduction in transverse cracking of 88%–90% and of longitudinal cracking of 67%–99% compared to control sections tacked and paved conventionally. As of 2016, KDOT has been using spray pavers routinely for asphalt overlays over concrete and using for overlays over asphalt on a project by project basis (with control sections for comparison). Missouri also reported a decrease of longitudinal cracking at six years of over 89% and of transverse cracking of over 31%. (Johnson & Barezinsky, 2016)

2.2.3 Tack Coat Test Methods

Tack coat test methods can be categorized as field or laboratory methods. There are various field tests to assess the uniformity of tack coat applications or the in situ bond strength. Since the SAC directed that the focus of this study be on lab testing, the field methods will not be detailed here; there is some information on field tests in Appendix A.

Among the laboratory test methods, there are various ways to measure the bond strength. The term "bond strength" is used in this report as a generic term for the strength at the interface between two pavement layers. This strength can be measured in one of three testing configurations; tension, direct shear and torsional shear. Of 12 states that currently perform bond strength testing, eight use direct shear, four use field tension and two use lab tension (Gierhart & Johnson, 2018). Torsional shear is rarely used, so the term "shear strength" used in this report refers to the interface bond strength measured in direct shear. It is interesting to note that Texas used to use a tension test in the field; they have eliminated this test in favor of a lab shear test (Gierhart & Johnson, 2018).

Shear tests seem to be the preferred method because they are relatively easy to perform and to analyze. The most extensive recent tack coat research, reported in NCHRP Report 712 used a shear test developed in Louisiana (Mohammad et al., 2012). This device has an optional normal load. The test procedure developed by Florida DOT (Sholar et al., 2004) does not require a normal load, further simplifying the test device. Mohammad does not always use confining pressure, even though he developed a device to apply it; not using a normal load makes the test more practical for DOTs (Das et al., 2019). West, Zhang, and Moore (2005) found the use of confining pressure to have a statistically significant effect when testing at high temperature. Many researchers have found the shear test capable of differentiating between different materials, application rates and conditions (Salinas et al., 2013; Sholar et al., 2004; Willis & Taylor, 2015; Zaniewski, Knihtila, Rashidi, 2015).

The type of test to use in this study was the subject of several discussions at SAC meetings. Since slippage failures are rarely observed in Indiana, there was some feeling that a pull-off (tension) test might be a better option. The principal investigator spoke in favor of using a shear test for practicality and in light of its successful use in Florida, Michigan and elsewhere. Besides, she maintained that if there is a lack of bond between layers, there will be shear at the interface when the pavement deflects under load; this is illustrated in Figure 2.1 (Kim, Arraigada, Raab, & Partl, 2011).

One of the most commonly used shear tests is that developed by the Florida DOT or slight variations of that. This procedure uses monotonic direct shear with no normal load, a strain-controlled displacement rate of 2 in./min., and 6 in. gyratory or core specimens (Sholar et al., 2004). A testing jig holds the two sides of the test specimen with the tacked interface in a small gap between the shear plates. The jig is placed in a Material Testing System (MTS) machine, which applies the shear loading. The test is typically performed at 25°C but can be performed at other temperatures. The device used in this study is shown in Figure 2.2.

2.2.4 Tack Coat Materials and Performance

Many studies have compared the behavior of different types of tack coat materials applied to different substrates at different rates. For brevity, they will not be summarized in detail here; the interested reader is referred to Appendix A and the recent NCHRP Synthesis for more detail. Only a few references of particular interest will be summarized here.

There is a substantial amount of interest in Indiana in the use of non-tracking tack and its performance compared to conventional tack. Hall and Ramakrishnareddy (2012) found no significant differences in the lab shear strength of SS-1 compared to NTSS-1. Zaniewski et al. (2015) used lab shear testing to compare SS-1h and NTSS-1hm. They found that the NTSS-1hm produced the higher shear strengths. Lab simulated milling did not result in higher shear strengths.

Salinas et al. (2013) did field testing to compare conventionally applied SS-1h and SS-1hp to non-tracking SS-1vh applied with a spray paver. The SS-1vh performed better than the SS-1h at all application rates; life cycle cost analysis indicated it was also more cost effective.

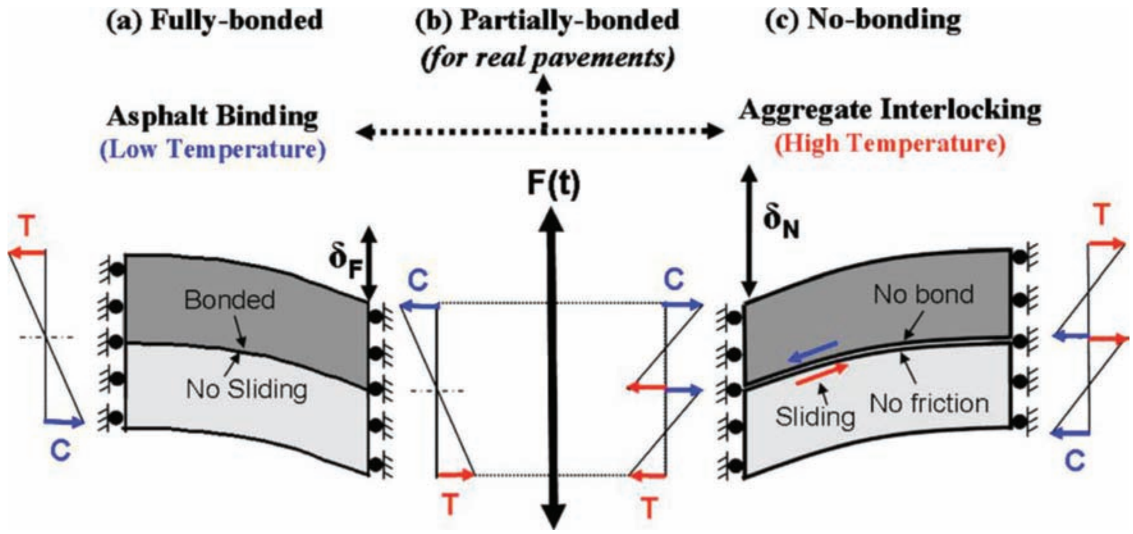

Figure 2.1 Pavement bonding stress distribution (Kim et al., 2011).

Figure 2.2 Shear apparatus in MTS machine.

They also looked at the effects of cleaning method and surface type using field cores tested in shear. They found milled HMA to yield higher shear strengths than milled PCC. A comparison of brooming vs air blasting showed mixed results. Air blasting produced slightly higher shear strengths on HMA with SS-1h than brooming; the opposite was observed on PCC pavements with SS-1vh. While air blasting may produce a cleaner surface, the authors note its use can be problematic, especially in urban areas. Their results also confirmed what many others have noted regarding the optimum application rates for milled surfaces compared to new lifts; that is, milled surfaces require higher application rates.

The Missouri DOT recently increased their tack application rates after seeing examples of delaminated layers in field cores and national recommendations calling for heavier tack coats. Following this specification change, they did lab and field research to ascertain if the changes were appropriate or if additional changes should be made. They used a direct pull-off (tension) test in the lab to evaluate eight tack products at up to four actual application rates (0.03–0.10 gal/syd; estimated residual rates of 0.018 to 0.06 gal/syd) applied to concrete and asphalt substrates. They reported that the pull-off testing was highly variable. They did find that the tensile strength increased as application rate increased up to about 0.1 gal/syd, however rates this high could be problematic to apply in the field. In lab testing, freezing the specimens before testing resulted in about a 30% loss of strength; the polymer-modified tacks showed somewhat less loss than non-modified tacks. There is some concern that the harder asphalts used in non-tracking tacks might be more brittle after freezing; in this lab experiment the non-tracking tacks did not exhibit higher losses than conventional tacks. A field trial allowed coring after construction and after one winter; both the conventional tack and a non-tracking tack showed a decrease in tensile strength after one winter but the strengths were similar. Undiluted polymerized tack had the lowest loss of strength but was very difficult to use in the field and experienced severe pick up on tires. Based on this research, it was recommended that MoDOT use Trackless Tack or allow contractors to use rapid setting emulsions in a spray paver instead. (Blomberg & Denkler, 2018).

3. RESEARCH APPROACH AND FINDINGS

This chapter describes the research approach, including the experimental design, factors studied, materials and test methods. Then the test results and data analysis are presented for the laboratory-prepared specimens and specimens collected from two field experiments; one

TABLE 3.1
Preliminary test matrix.

		AC											
		Unaged					Aged						
			Milled					Milled					
			Before Break		After Break			Before Break		After Break		PCC	
Tack	**Rate (residual)**	**Smooth**	**Clean**	**Dirty**	**Clean**	**Dirty**	**Smooth**	**Clean**	**Dirty**	**Clean**	**Dirty**	**Unaged**	**Aged**
None	None	×	×				×	×					
SS-1H	Low (0.03 gal/yd^2)	×	×	×	×	×	×	×	×	×	×	×	×
	High (0.10 gal/yd^2)	×	×	×	×	×	×	×	×	×	×	×	×
AE-NT	Low (0.03 gal/yd^2)	×		×	×	×	×		×	×		×	×
	High (0.10 gal/yd^2)	×		×	×	×	×		×	×		×	×
Polymer Modified	0.10 gal/yd^2			×	×	×			×	×			

looking at the use of a spray paver and the other exploring the use of Void Reducing Asphalt Membrane (VRAM) as a tack material.

3.1 Experimental Design

Different variables were discussed with members of the Study Advisory Committee (SAC) and a preliminary test matrix was developed as seen in Table 3.1. Each "x" in the test matrix represents one replicate of the given variables. Key variables of interests were: tack rate, surface cleanliness, surface texture, change of bond strength over time, and difference in bond strength when paving on broken or unbroken tack coat.

The test matrix was modified over the course of the project in consultation with the SAC. For example, after discussions about how best to simulate a dirty surface, it was decided to drop that part of the study. A medium application rate was added to part of the experimental design, as outlined later. Obtaining cores of milled pavement to test was surprisingly difficult. Eventually a project with a willing contractor was found and cores taken, but they were too large to fit in the testing jig and no reliable way to shave them down could be identified. Rather than try to simulate in the lab paving before the emulsion broke, samples were collected from a field project utilizing a spray paver and were compared to samples from a conventionally tacked pavement section. Samples from the spray paver project and a VRAM project were also added to the project. A sample of a polymer-modified tack was procured but because of logistics its shelf life had elapsed before it could be used to fabricate lab-produced specimens; the VRAM field trial used a polymer-modified tack that was tested in this project.

3.2 Materials

Two different asphalt mixtures were obtained to produce the laboratory samples for the study—an intermediate mix with a nominal maximum aggregate size (NMAS) of 19.0 mm and a surface mix with a NMAS of 9.5 mm. The job mix formulae are shown in Appendix B.

TABLE 3.2
Average G_{mm} and G_{mb} of asphalt mixtures.

Mix Type	Avg. G_{mm}	Avg. G_{mb}
Surface (9.5 mm)	2.551	2.352
Intermediate (19 mm mix)	2.572	2.440
Spray Paver Mix	2.646	2.563

Mixture properties were verified and gyration levels to use to produce the test specimens were determined as follows. To soften the asphalt mixtures, the five-gallon buckets were placed in an oven at 260°F for about six hours. Sample sizes in accordance with AASHTO T 209-12 were separated out for each mixture to obtain the theoretical maximum specific gravity (G_{mm}). The mixes were separated into samples of approximately 5.0 kg and were placed into individual pans to be used for compaction of samples.

Two samples for each mix type were tested using AASHTO T 209-12 to find the G_{mm}. Initially two specimens were compacted for each mix type to determine the bulk specific gravity. The average bulk specific gravity (G_{mb}) of the two initial specimens for each mix was determined using AASHTO T 166-13. Table 3.2 shows the averages of G_{mm} and G_{mb} for each mix. (This table also includes the mix used in a later study of tack applied with a spray paver.)

Samples were compacted using the Superpave Gyratory Compactor (SGC) with a target air void percentage of 7.0 $\pm$ 0.5%. To soften samples in preparation for compaction, the surface and intermediate mixes were heated at 285°F for two hours. Various numbers of gyrations were tested until the target air void percentage was achieved. Table 3.3 lists the ideal number of gyrations for each mix type to achieve the target air

TABLE 3.3
Design number of gyrations to achieve target air void percentage.

Mix Type	Avg. No. of Gyrations
Surface Mix (9.5 Mm)	64
Intermediate Mix (19 Mm)	54
Spray Paver Mix	38

void percentage; these gyration levels were used later to compact the shear test specimens as described in Section 3.4. (This table also includes the mix used in a later study of tack applied with a spray paver.) AASHTO T 166-13 was used to determine the percent air voids. Samples rested overnight before testing to allow sufficient time to fully cool to room temperature.

3.3 Test Method

The Florida DOT has been using a shear test to evaluate tack coat quality since about 2004. The test is conducted on 6 in. diameter field cores for forensics and as a performance test. The method, standardized as FM 5-599, Florida Method of Test for Determining the Interlayer Bond Strength Between Asphalt Pavement Layers, is conducted at a temperature of 77.0 $\pm$ 1.8°F and a loading rate of 2.0 in./min. The core is held in a jig which grips the core on opposite sides of the tack coat interface. Shear is applied across the interface, and a load vs. deformation curve is plotted. The maximum load is determined and the interlayer bond strength (in shear) is calculated as follows:

$$IBS = \frac{Pult}{\pi D^2/_4}$$

Where IBS = Interlayer bond strength, psi; P_{ult} = ultimate load applies, lb; D = specimen diameter, in. FDOT uses an IBS of 50 psi as the remove and replace level but typically sees values in excess of 100 psi and sometimes 200 psi. This is the test method used in this research, though in some cases laboratory-fabricated specimens and different test temperatures were used, as detailed in 3.4 and 3.5.

A pull-off (tension) test using an available testing device (Proceq DY-2) used for pull-off testing on concrete was attempted during the initial shake-down testing. While this might work for testing in situ pavements, it did not work well for testing 6 in. core specimens in the lab as it would not seat well on the small diameter specimen. Future work could possibly explore other pull-off testing options.

3.4 Shear Test Specimen Preparation—Initial Shake-Down Testing

At the beginning of the laboratory phase of the project, it was first necessary to establish the testing procedures to be used. This section describes the efforts undertaken to determine how best to approach the sample preparation.

TABLE 3.4
Amount of tack needed in beaker to achieve correct residual application rates.

Tack Type	App. Rate	Mass of Tack, g
SS-1H	Low	8
	Medium	12–12.5
	High	16–17
AE-NT	Low	8.5–9
	Medium	13–13.3
	High	17.4–17.5

Samples of the intermediate mixture were compacted in the gyratory to a height of about 3 in., and the air void percentage was determined. (Initially taller specimens were compacted and sawn, but this proved to be inefficient from a time standpoint.) AASHTO T 166-13 was used again to determine the air void percentage of each test specimen. Specimens with air voids of 7.0% $\pm$ 0.5% were used for tack application.

Two types of tack (SS-1h and AE-NT) were used for this study and were applied at two or three different residual application rates in different parts of the research (as detailed in 3.5). The rates were categorized as low, medium and high and the target values were 0.03, 0.05 and 0.10 gal/syd, respectively. The values were chosen to represent the midpoint and extremes in INDOT's specification for tack application. To achieve the correct application rates the target values were converted from gal/syd to ml/in^2. Using the cross sectional area, an amount of tack needed, in milliliters, was determined. For the actual application of the tack, it was measured in a glass beaker and then poured in a circular motion onto the sample. A 3 in. foam brush was used to evenly distribute the tack on the whole surface. After two practice samples, it was determined that measuring the tack needed in milliliters was not accurate enough. Using the data collected from the first two samples, it was possible to back calculate the amount of tack needed in grams. That mass of material was poured onto a tared specimen sitting on a balance, then the tack was distributed with a foam brush. The mass applied was adjusted to account for tack adhering to the brush. While this method also had some variability, it proved to be more accurate than the previous method. This technique was used in the rest of the project.

Originally the specimens were cured at room temperature, but to expedite the curing process and to simulate field curing temperatures more closely, specimens were cured in an oven at 40°C (104°F). Table 3.4 shows the final estimates of tack needed in the beaker to achieve the correct tack rate for each tack type and rate.

The SAC wanted to verify that the tack was cured before the surface mix was placed to help ensure consistency from specimen to specimen. Therefore, the changes in mass of six replicate samples each at the low and the high application rates were monitored to ascertain when the mass leveled off, which would occur when essentially all of the water had evaporated. The mass

TABLE 3.5
Mass change recordings.

t (min)	t (h)	Sample Mass (g)	Tack Mass (g)	% Tack Mass Change	Change in %
0	0.00	2685.30	11.70		
20	0.33	2683.80	10.20	12.82	
40	0.67	2683.23	9.63	17.69	4.9
60	1.00	2682.80	9.20	21.37	3.7
80	1.33	2682.35	8.75	25.21	3.8
100	1.37	2682.15	8.55	26.92	1.7
120	2.00	2382.05	8.45	27.78	0.9

TABLE 3.6
Residual application rate calculation.

Item	Quantity
Density of Tack	0.99 g/ml
Mass of Sample	2673.60 g
T_0 Mass	2685.30 g
T_{2h} Mass	2682.05 g
Beaker	68.98 g
Beaker + Tack	86.36 g
Beaker – Tack	69.35 g
Brush	14.51 g
Brush + Tack	19.64 g
Tack (T_0)	11.88 g
Tack (T_{2h})	8.45 g
Vol. Wet Tack	12.00 ml
Vol. Dry Tack	8.54 ml
Residual Application Rate	0.30 ml/in^2 (0.10 gal/syd)

change was recorded every 20 minutes for each sample throughout the curing process. An example of the mass change recording is illustrated in Table 3.5. For this study, when the values in the "Change in %" column were less than 1.0%, a tack coat was considered cured or set. It was determined that a curing time of about two hours was sufficient for both tack coat materials when applied at both the high and the low rates.

The data collected during the mass change was also used to calculate the residual rate of the tack coat emulsion. The target residual application rate needed to be met with an error of $\pm$0.01 gal/syd to be considered acceptable for further use. Table 3.6 is an example of the calculations performed to determine the residual application rate.

Compaction of the upper (surface) lift was performed in the Superpave gyratory compactor after the tack coat was cured. Originally the specimens were compacted 24 hours after tack application to ensure that the emulsion was fully cured. However, this was not indicative of normal field conditions so the procedure was changed and compaction was completed immediately after the tack was cured for two hours in the oven. The tacked intermediate mix specimen was placed in the bottom of the gyratory compactor mold and about 2.6 kg of a surface mix was placed on top. To achieve the target air void percentage on the surface mix, the number of gyrations needed for a full size sample (5.0 kg) was reduced by 10 gyrations.

After tack application and compaction of the top lift, unaged specimens were tested in shear about four days after compaction. Aged specimens were conditioned for five days at 85$\pm$3°C, in accordance with AASHTO R 30, prior to shear testing. To shear the specimens, each specimen was placed into the shear attachment for the Materials Testing System (MTS) machine with the interface centered between the gaps of the shear plates. The specimen was then subjected to a loading rate of 2 in./min. Figure 2.2 shows the shear apparatus used for this experiment. The axial load and axial displacement were recorded during the loading and data points were collected every 0.1 second. Bulk specific gravity testing, following AASHTO T 166-13, was performed to verify the air void percentage after shear testing was completed. A majority of the specimens were not able to be tested for air void percentage after shear testing due to not fully shearing.

During shear testing of the first 30 specimens, slippage was observed. Due to the slippage, similar strength values, and a majority of the specimens not completely shearing and separating, the shear apparatus was sent to Purdue's mechanical shop to be modified to add stirrups to prevent the two halves from arching outward. With the equipment back, six specimens (three high-rate AE-NT and three no tack) were constructed and tested again. A significant increase in strength was obtained with no visual indication of slipping occurring during testing. The modified testing jig was then used in the actual data collection effort.

3.5 Data and Analysis—Laboratory-Prepared Specimens

This section describes the testing used in the actual testing phase (following shake-down) of the project. Results of testing HMA over concrete and HMA over HMA, to simulate overlays over concrete and asphalt respectively, are presented.

Two residual levels, low and high, of two commonly used tacks (SS-1h and AE-NT) were tested in this study. A medium level (0.05 gal/syd) was added for testing the HMA over HMA specimens. The tack samples were supplied by Seneca Petroleum. The amount of liquid required for the low residual (0.03 gal/syd) and high residual (0.10 gal/syd) rates were determined based on residual tack at the end of two hours of curing in an oven set to 104°F (40°C).

3.5.1 HMA on Concrete Base

To simulate and evaluate the bond strength of an asphalt overlay over concrete, the shear strengths of tack coat applied to concrete specimens were tested. Six-inch concrete cylinders, measuring about 4 in. high, were cast and moist-cured for a period of 45 days. Since the typical plastic molds used in concrete are 6 in. in diameter (= 152.4 mm) whereas the typical Superpave gyratory molds are 150 mm, the plastic molds were lined with flexible plastic sheeting to account for the difference in diameter of the two molds, prior to casting the concrete specimens.

At the end of the concrete curing period, the specimens were removed from the humidity chamber and allowed to air dry for a period of 24 hours before tack application. Tack (SS-1h and AE-NT at low and high rates) was applied to the surface and cured at 104°F for two hours, in the same manner discussed earlier (section 3.4).

Surface course HMA (PG 64-22) was preheated to 285°F for two hours in preparation for compaction using a Pine Superpave Gyratory Compactor. A concrete specimen with the cured tack was first placed in the heated SGC mold. Then the preheated surface mix (about 3 kg) was loaded on top of the tack coat and the whole mold assembly was placed in the SGC and compacted. Shear tests was conducted on these specimens (three replicates per treatment combination); the results are shown in Table 3.7.

Shear strength values from the SS-1h specimens were lower than those observed in AE-NT specimens, with the lowest strength observed in the case of low rate of SS-1h. Two-factor ANOVA (α = 0.05) was conducted on the strength test data to assess the significance of residual and tack type. Both residual and tack type were found to be significant, with p-values of 1.12 e^{-5} and 0.0170, respectively. (If the p-value is less than the α level, that factor is considered statistically significant; the p-value is the probability of observing a more extreme value, so a low value means it is unlikely.) Interaction between the two factors was not statistically significant (p-value = 0.0819). Further analyses, based on single factors alone, indicated that in the case of AE-NT, the residual rate did not affect the shear strength of the bond. All other combinations were found to be statistically significant, as shown in Table 3.8. I.e., residual rate is significant for SS-1h, and tack type is significant at both low and high residual rates.

At the suggestion of the SAC, a type of fracture analysis was explored to see if it could help differentiate between the factors. Following the procedure laid out in Illinois Test Procedure 405, the Illinois Flexibility Index Test (I-FIT), the area under the curve (work of fracture, W_f) was calculated and used to determine the fracture energy (G_f) and Flexibility Index (FI). It should be noted that in departure from the I-FIT test, these test specimens were neither semi-circular nor notched. The ligament area ($Area_{lig}$) adopted for calculations was the surface contact area between the two layers. Additionally, these specimens with HMA over a concrete base, did not exhibit a typical post peak curve but instead showed a sharp fracture point (Figure 3.1). Due to the absence of an inflection point, the slope of the post peak curve (|m|) was calculated using the last few points after the peak.

From the load vs. displacement curves, the fracture energy (G_f) and Flexibility Index (FI) can be calculated using the following expressions. The value of A was taken as 0.01, although this is truly applicable only to the semi-circular notched specimen configuration as described in Illinois Test Procedure 405. Specimens that have lower %AV, field cores, aged and brittle specimens tend to have lower FI compared with specimens with higher %AV, lab-compacted pills, and unaged specimens.

$$G_f = \frac{W_f}{Area_{lig}} \text{ in Joules/m}^2$$

$$FI = \frac{G_f}{|m|} \times A$$

Table 3.9 shows the average parameters (three replicates) used in the calculation of the FI. Due to the assumption of the same sample geometry factor (A = 0.01) meant for semi-circular notched specimens and other deviations from the test protocol, the values of FI shown in Table 3.9 cannot be used for direct comparison with specimens tested according to the protocol. However, relative comparisons within the dataset can be made. Regardless of residual rate, specimens with AE-NT tack had a higher fracture energy and flexibility index compared with SS-1h.

3.5.2 HMA on HMA Base

A similar set of testing was conducted on specimens with HMA as the base on which the tack was applied and cured. The base specimens, measuring about 3 in. high, were compacted to 7% air voids using the intermediate (19-mm) mix. Tack was applied on three

TABLE 3.7
Shear strength of HMA over tacked concrete base (unaged).

Tack	App. Rate	Avg. τ_f, psi	Std. Dev., psi
AE-NT	Low	340	22
	High	358	36
SS-1h	Low	137	41
	High	224	21

TABLE 3.8
ANOVA results of HMA over tacked concrete base.

Factors	Hypothesis	p-value	Conclusion
AENT	$\mu_{low} = \mu_{high}$	0.4772	Not Stat. Sig.
SS-1h	$\mu_{low} = \mu_{high}$	0.0306	Stat. Sig.
Low	$\mu_{AENT} = \mu_{SS\text{-}1h}$	0.0040	Stat. Sig.
High	$\mu_{AENT} = \mu_{SS\text{-}1h}$	0.0016	Stat. Sig.

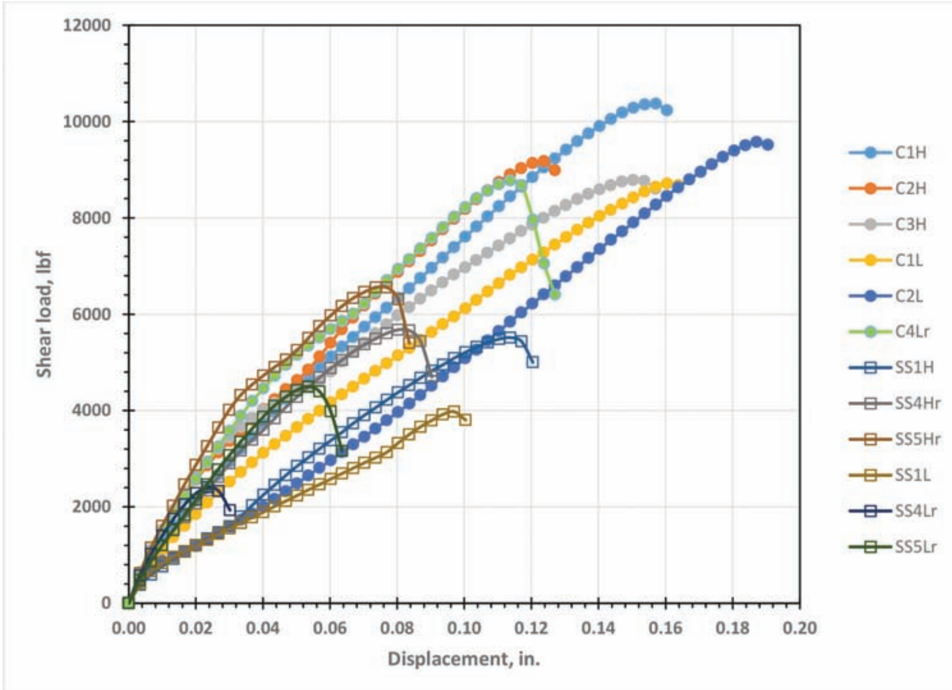

Figure 3.1 Load vs. displacement curves for the HMA over concrete specimens.

TABLE 3.9
Flexibility index parameters (unaged).

Tack	App. Rate	W_f (J)	$Area_{lig}$	|m|(kN/m)	G_f (J/m^2)	FI
AE-NT	Low	93.2	0.017	15183	5438	0.00358
	High	96.8	0.017	8664	5681	0.00656
SS-1h	Low	17.2	0.017	28636	1012	0.00035
	High	40.7	0.017	36369	2390	0.00066

replicate base specimens for each test combination; i.e., three residual rates (low, medium and high) and two aging conditions. Following the two-hour curing procedure, the lower base specimen with the cured tack was placed in the preheated gyratory mold, followed by the known mass of preheated surface mix (at 275°F) and then compacted to yield approximately 7% air voids. Unaged shear testing was performed two to three days after compaction of the surface layer.

To investigate the effect of long-term aging on the tack strength, a subset of these compacted specimens was subjected to conditioning at 185°F (85°C) for five days according to AASHTO R 30. Shear testing of these specimens was conducted two to three days after long-term conditioning.

Table 3.10 shows the average shear strength and standard deviation of the aged and unaged HMA shear specimens. In general, the AE-NT specimens show lower variability (lower standard deviation) and slightly higher strength compared with the SS-1h specimens. In addition, the shear strength of PG 64-22 alone as a tack, at the low rate, was also tested based on interest by the SAC. (Field trials using asphalt binder as tack were planned but eventually dropped because suitable distributors capable of pumping it were not readily available in the state.) The variability of these specimens was significantly higher than other two tacks tested (AE-NT and SS-1h), possibly because of the binder's thickness and difficulty in spreading it uniformly. The average shear strength of the PG 64-22 tack was similar to the high application rate of emulsion tacks. Figures 3.2 and 3.3 show the data presented in graphical format.

It can be seen that specimens with AE-NT tack had slightly higher shear strength compared with the SS-1h tacked specimens. Similarly, unaged specimens were generally stronger than the aged specimens. Of the three residual rates tested, specimens with medium residual rate performed better than low and high rates, indicating that there may be an optimal application rate. Three-factor ANOVA conducted using the entire dataset indicates that all the factors and their interactions were statistically significant. The p-values obtained from ANOVA are shown in Table 3.11.

For comparison purposes, the Flexibility Index parameters were also calculated for these specimens (making the same assumptions stated earlier in Section 3.5.1)

TABLE 3.10
Flexibility index parameters (unaged and aged).

Tack	App. Rate	Unaged		Aged	
		Avg. τ_f, psi	Std. Dev., psi	Avg. τ_f, psi	Std. Dev., psi
AE-NT	Low	462	9	400	9
	Medium	568	6	547	5
	High	442	6	441	9
SS-1h	Low	435	3	475	7
	Medium	544	17	500	18
	High	404	10	392	8
PG 64-22	Low	444	30	428	31

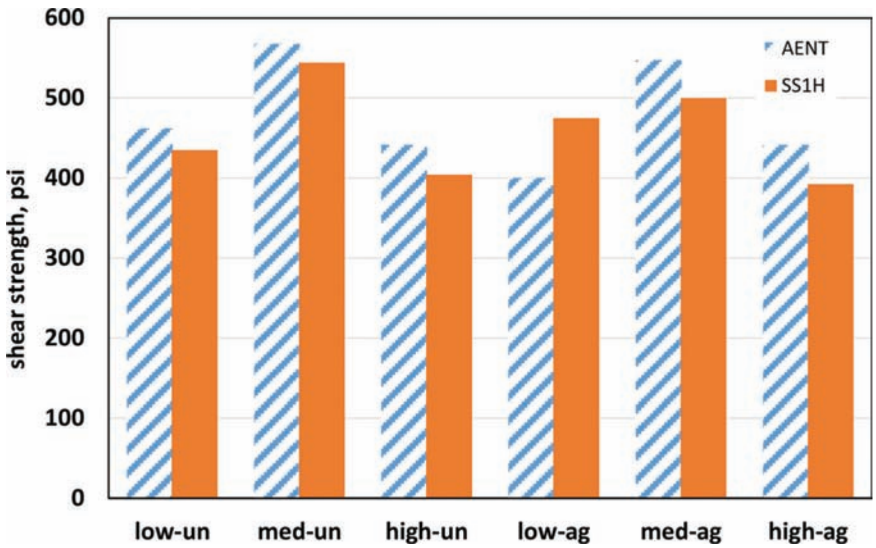

Figure 3.2 AE-NT vs. SS-1h shear strength of low, medium and high rates specimens (unaged and aged conditions).

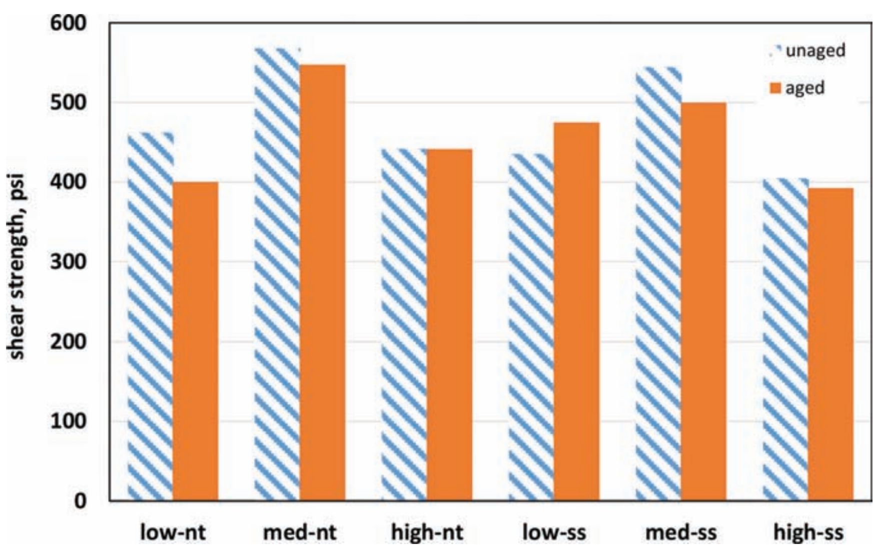

Figure 3.3 Unaged vs. aged shear strength of low, medium and high rate specimens (AE-NT and SS-1h tack).

and presented in Table 3.12. Like the previous specimens with a concrete base, HMA specimens too did not show a well-defined post-peak behavior with a clear inflection point. Therefore, the slope calculations were done by manually selecting points in the tail region based on visual observation. The FI values of the

TABLE 3.11
ANOVA results of tack on HMA base.

Factors	Hypothesis	p-value	Conclusion
Tack	$\mu_{AENT} = \mu_{SS\text{-}1h}$	<0.0001	Stat. Sig.
Rate	$\mu_{low} = \mu_{med} = \mu_{high}$	<0.0001	Stat. Sig.
Age	$\mu_{unaged} = \mu_{aged}$	2.5e-05	Stat. Sig.
Tack × Rate		<0.0001	Stat. Sig.
Tack × Age		0.0016	Stat. Sig.
Rate × Age		0.0122	Stat. Sig.
Tack v Rate × Age		<0.00001	Stat. Sig.

TABLE 3.12
Flexibility index parameters.

Tack	Rate-Condition	W_f (J)	$Area_{lig}$ (m^2)	|m| (kN/m)	G_f (J/m^2)	FI
AE-NT	Low-Unaged	334	0.018	26455	18853	0.0071
	Med-Unaged	434	0.018	45567	24579	0.0054
	High-Unaged	333	0.018	21818	18853	0.0086
SS-1h	Low-Unaged	268	0.018	24530	15149	0.0062
	Med-Unaged	373	0.018	24480	21122	0.0086
	High-Unaged	252	0.018	33399	14256	0.0043
AE-NT	Low-Aged	240	0.018	30510	13572	0.0044
	Med-Aged	436	0.018	41965	24654	0.0059
	High-Aged	298	0.018	36065	16857	0.0047
SS-1h	Low-Aged	297	0.018	29942	16796	0.0056
	Med-Aged	315	0.018	33925	17799	0.0052
	High-Aged	226	0.018	30895	12764	0.0041
PG 64-22	Low-Unaged	277	0.018	30189	15813	0.0052
	Low-Aged	237	0.018	42446	13524	0.0032

unaged specimens appear to be slightly higher than those of the aged specimens. This is to be expected as aging makes the mix relatively brittle.

3.6 Data and Analysis—Field Specimens

During the course of this research, INDOT allowed the construction of two field trial projects relevant to this study. One was a comparison of a spray paver to conventional tack application and paving (i.e., a distributor truck and paver). The other was a project comparing polymerized VRAM (Void Reducing Asphalt Membrane) used as tack compared to SS-1h. Cores were obtained from the test and control sections on each project and tested in the lab, as described before. The results of that testing are presented here.

3.6.1 Spray Paver Samples

During the fall of 2017, field cores were obtained from two sections of SR135 near Greenwood, IN. One section of the pavement contained the traditional SS-1h tack application (control) between the surface and intermediate layers, whereas spray paver tack application was used in other section. The research team was not present during construction, but believes the overlay was placed on a milled surface, based on the appearance of the sheared cores. A modified asphalt emulsion was used in the spray paver. As interest in the usage of spray pavers is increasing in the state, field cores were obtained from these sections of the pavement and sent to the North Central Superpave Center (NCSC) for lab testing for comparison with the control section.

In addition to shear testing of unaged and aged specimens, and the calculation of Flexibility Indices as discussed in 3.5.1, the effect of test temperature was also investigated in this portion of the project. One subset of the specimens was cooled overnight to 4°C prior to testing. Average shear strength and standard deviations are presented in Table 3.13 and Figure 3.4.

Higher variability in shear strength was observed in the control specimens (SS-1h) as opposed to the spray paver specimens. Test data indicate that long-term aging and lower test temperatures increase the strength of the spray paver specimens. For the control specimens, however, aging appeared to be beneficial only at 4°C. Statistical analysis to examine the effect of the three factors and their interactions (temperature, age and application type) indicated that only test temperature was significant (Table 3.14).

TABLE 3.13
Average shear strengths of tack of field cores.

Applic.	Test Temp.	Condition	Avg. τ_f, psi	Std. Dev., psi
Spray Paver	@room temp.	Unaged	247	48
		Aged	304	87
	@4°C	Unaged	315	57
		Aged	498	81
SS-1h	@room temp.	Unaged	310	133
		Aged	282	54
	@4°C	Unaged	362	140
		Aged	449	108

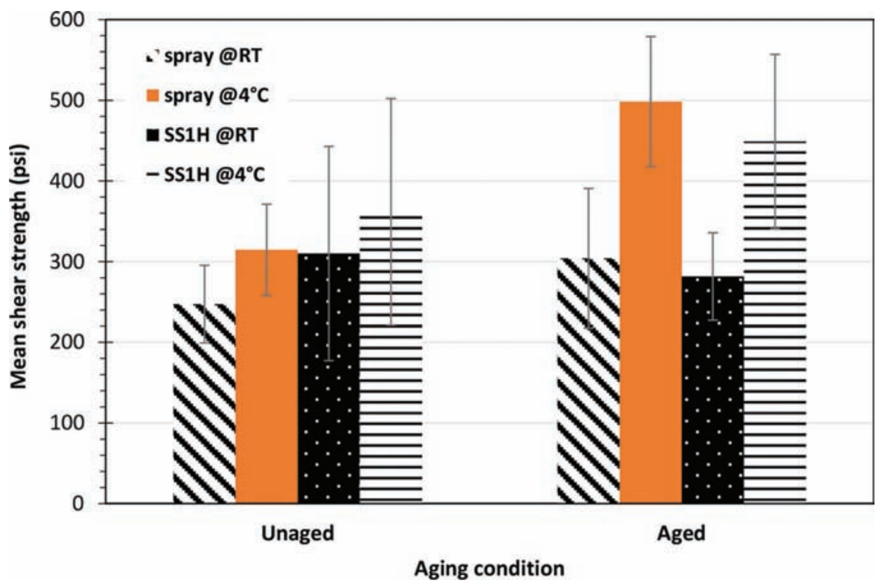

Figure 3.4 Spray paver vs. control specimens.

TABLE 3.14
Three-factor ANOVA results.

Factors	p-value	Conclusion
Tack App. Method	0.8104	Tack app. not stat. sig.
Temperature	0.0067	Test temp. stat. sig.
Age	0.0705	Ageing cond. not stat. sig.
Tack × Temp.	0.7856	Interaction b/w tack app. and test temp. not stat. sig.
Tack × Age	0.2566	Interaction b/w tack app. and age not stat. sig.
Temp. × Age	0.1357	Interaction b/w tack app. and test temp. not stat. sig.
Tack × Temp. × Age	0.9413	Three-way interaction not stat. sig.

The average Flexibility Index parameters shown in Table 3.15 indicate that aging did not decrease the FI of specimens tested at room temperature. Specimens tested at 4°C (Table 3.16) gave mixed results. These contradictory results could be explained by the high variability in the calculated slope and G_f values. For example, the slope of the spray paver specimens ranged from 7931 to 25081 kN/m for the unaged condition and 5130 to 38928 kN/m for the aged condition tested at room temperature. At 4°C, the slope of the unaged and aged specimens varied from 2926 to 11514 kN/m and 14662 and 61590 kN/m, respectively.

3.6.2 VRAM Samples

Field core samples (five replicates each) were also obtained from test sections on SR26 near Richmond, IN, during November 2016. In addition to the control samples with SS-1h as tack, a second set of samples with VRAM (Void Reducing Asphalt Membrane) was also obtained for comparison. VRAM is a polymer-modified asphalt material. Table 3.17 shows average shear strength and standard deviation of these specimens along with the FI parameters.

The shear strength of SS-1h was higher than the VRAM specimens in both the unaged and aged conditions. However, upon shear failure the two layers of the SS-1h specimens completely separated, while in the case of VRAM specimens the two layers stayed stuck together and needed to be pried apart to separate the two layers (as seen in Figure 3.5).

Since aging tends to make the specimens brittle, a lower FI would be expected for aged specimens compared with unaged specimens, though VRAM samples would be expected to age harden less than conventional materials because of the high polymer content. This trend was not observed in the VRAM nor with the control specimens. In the Spray Paver study (3.6.1), the

TABLE 3.15
Flexibility index parameters (@room temperature).

Tack	Age	W_f (J)	$Area_{lig}$ (m^2)	G_f (J/m^2)	|m| (kN/m)	FI
Spray Paver	Unaged	89	0.017	13862	5346	0.0049
	Aged	120	0.017	25880	7221	0.0045
Control (SS-1h)	Unaged	141	0.017	23344	8460	0.0036
	Aged	116	0.017	19790	6955	0.0043

TABLE 3.16
Flexibility index parameters (@4°C).

Tack	Age	W_f (J)	$Area_{lig}$ (m^2)	|m| (kN/m)	G_f (J/m^2)	FI
Spray Paver	Unaged	99	0.017	7318	5903	0.0111
	Aged	219	0.017	32444	13048	0.0051
Control (SS-1h)	Unaged	134	0.017	27469	8074	0.0036
	Aged	169	0.017	16681	10065	0.0085

TABLE 3.17
Strength and flexibility index parameters (VRAM trial).

Tack	Age	τ_f (std.dev.) (psi)	W_f (J)	|m| (kN/m)	G_f (J/m^2)	FI
VRAM	Unaged	209 (34)	119	7732	7113	0.0092
	Aged	176 (22)	87	6962	5215	0.0075
Control (SS-1h)	Unaged	291 (43)	134	14235	8056	0.0057
	Aged	340 (16)	173	22723	10388	0.0046

Figure 3.5 VRAM specimen (left) and SS-1h (right) after failure.

high variability in m-value and hence, G_f and FI, might account for this contradictory behavior, but in this study the range of slope values did not show such high variability. No explanation for this observed inconsistency in field specimens (as opposed to the lab prepared specimens) could be found at this point. However, there were suggestions that the construction of the test section did not proceed as planned and the mix placed on top of the VRAM may not have been hot enough to fully mobilize the VRAM. This could have affected the strength, wicking and fracture of these specimens.

Two-factor ANOVA of the two factors (tack type and age) and their interaction indicated that age was not a significant factor but tack type and the interaction between age and tack was significant at the α level of 0.05.

4. CONCLUSIONS AND RECOMMENDATIONS

The findings of this research are presented here. First, the findings from the literature are reviewed. Next the findings from the lab testing are summarized, followed by the findings from the field trials. Based on the results of the review of the agency specifications and literature, the following conclusions can be reached.

- The importance of tack coats to pavement performance is indisputable.
- There is widespread concurrence that tack should be applied to clean, dry surfaces.
- Brooming is the most commonly used cleaning method. Air blasting may yield a cleaner surface and improve the bond somewhat but its use is problematic, especially in urban areas.
- The literature and specification reviews showed that SS-1h and AE-NT (or other non-tracking tacks) are used by many states. Use of non-tracking tacks represents a substantial share of the tack materials used in the USA.
- Tracking is a serious concern leading to increasing popularity of non-tracking tacks.
- Non-tracking tacks yield similar or higher bond strengths than conventional emulsions.
- Though there are concerns that non-tracking tacks may exhibit brittleness at low temperatures because of their harder base asphalt, there are reports showing non-tracking and conventional tacks exhibit similar losses in strength. There are suggestions that polymerized tacks may perform better after experiencing low temperatures.
- Spray pavers are effective at eliminating tracking and allow for heavier tack rates.
- Experience in Kansas and Missouri shows significantly reduced cracking in pavements constructed with spray pavers after five or six years, presumably because better bonding makes the layers act monolithically.
- Shear testing in the lab is the most commonly used performance test. Direct shear without a normal force is preferred for simplicity and has been used successfully in some states for many years.
- Many specified application rates are lower than recommended. There is general consensus that the application rates should be higher for aged and milled surfaces than for newly placed lifts.

The testing of lab-fabricated specimens in this research led to the following conclusions.

- When testing asphalt placed over a concrete substrate, the high residual application rate (0.1 gal/syd) led to higher shear strength.
- Both the application rate and tack type were statistically significant in two-factor ANOVA. When comparing tack type at the low vs. high rates, the rate was not a significant factor for the AE-NT, but it was significant for SS-1h, perhaps suggesting the AE-NT is less sensitive to changes in the application rate.
- Using fracture analysis similar to the I-FIT analysis technique (with several assumptions and deviations), AE-NT on PCC yielded higher fracture energy and Flexibility Index compared to SS-1h.
- On HMA, AE-NT showed slightly higher shear strength and lower variability than SS-1h. The residue from AE-NT is considerably stiffer and more viscous at room temperature than that of SS-1h.
- PG 64-22 as tack was difficult to use in the lab, leading to high variability. The average shear strength was similar to the SS-1h at the high application rate, which was not the optimum. Since distributors capable of handling asphalt binder tacks are not readily available in the state, use of this type of tack is probably not feasible. Asphalt binder is very rarely used as a tack material in the USA.
- Tack type, rate and age were all statistically significant factors.
- Fracture-type analysis indicates unaged tacks have higher (better) flexibility indices than aged tacks, as expected since aging generally increases brittleness.
- The medium residual application rate produced higher fracture energy and flexibility index than the low or high rates for both the AE-NT and SS-1h.

The testing of field samples from trial projects using a spray paver and VRAM as a tack material led to the conclusions below.

- The use of the spray paver produced average shear strengths equal to or better than the conventional distributor and paver combination in the aged condition at both room temperature and at 4°C. In the unaged condition, the average strength of the specimens from the spray paver section at room temperature was slightly lower than the other conditions.
- The spray paver specimens exhibited much lower variability overall, suggesting better uniformity of application in the field.
- Aging and lower temperature increased the strength of the spray paver specimens.
- VRAM specimens had lower shear strengths, fracture energies and flexibility index than SS-1h specimens, which was not expected.
- The post-peak behavior of the VRAM specimens was very different from that of the SS-1h specimens. The VRAM still held the specimens together whereas the SS-1h specimens separated cleanly at the interface.

4.1 Recommendations

In consideration of the conclusions from all parts of this research, the following recommendations are offered for INDOT's consideration.

- To help ensure adequate performance of asphalt pavements and overlays, some changes to the specifications and practices may be advisable.

- The specifications should clearly state in section 406 that the basis for the application rate (undiluted spray rate) and dilution should be explicitly banned. If INDOT does want to allow dilution, the specifications should require this to be performed by the supplier and field dilution should be banned. The percent residue should be reported if dilution is allowed.
- The INDOT Specifications in regards to applying tack to clean and dry surfaces seem to be as thorough and detailed as those in other states, but should be emphasized and enforced.
- While the most commonly used tack coat materials used in the state (AE-NT and SS-1h) generally performed well in these tests and are reportedly widely used in other states, the AE-NT performed somewhat better than the SS-1h so perhaps its use should be encouraged.
- INDOT should consider exploring more use of polymer-modified tacks for high volume applications and overlays on concrete.
- Reportedly AE-T and AE-PMT are no longer being produced, so they could be dropped from the specifications (902.01(b)).
- INDOT may consider requiring different application rates on different types of surfaces. The currently specified rate appears to be within the ranges specified by various national sources, but may be on the low side for existing and milled surfaces and on the high side for PCC surfaces.
- There is some conjecture that the SS-1h field sections evaluated here may have performed better than routine tack coats because of the increased scrutiny on tack coats on those experimental sections. Attention to detail can lead to better performance. Future research efforts (such as the proposed spray paver study discussed below) should include testing cores from random, non-experimental projects to assess the current state of the practice.
- The importance of the tack coat should be reinforced and more attention focused on it. Eventually use of a performance test may serve to focus contractors' attention on this vital factor.
- A study of five field trial paving installations using a spray paver has been proposed (but not yet funded). As proposed, this study would expand on the limited testing done in the current study, explore the use of a pull-off test in addition to the shear test used here, and include testing cores from non-experimental projects to assess the state of the practice. Additional cores can be taken from the spray paver and VRAM trials studied here and can be tested to further explore the effects of aging.
- Shear testing appears to be appropriate for testing tack coat materials because of its simplicity and successful use in other states. More testing should be done to explore whether it can clearly differentiate poor and well performing tack applications. In addition, other testing methods, such as a tension test, could be investigated.
- This research did not yield an absolutely definitive test method to use to assess tack quality but is a first step in that direction. The research did confirm that INDOT's current application rates are reasonable, though they could be refined and the specifications could be clearer. The materials commonly used in the state could be expected to perform well if properly applied, but there are other materials and application methods that should be considered and researched.

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APPENDIX A: LITERATURE REVIEW 8/31/2016

By Kelsey Keller, Graduate Student

Types of Tack Coats

There are many type of tack coat that can be categorized as cationic or anionic; rapid, medium, or slow setting; and tracking or non-tracking. Research performed by Mohammad, Wu, and Raqib (2005) compared eight different tack coat materials. Of the six emulsions (CRS-2P, CRS-2L, SS-1, CSS-1, SS-1h and SS-1L) and two asphalt binders (PG 64-22 and PG 76-22M), the two materials that produced the greatest bond were CRS-2L and CRS-2P.

According to responses from a survey conducted by Paul and Scherocman (1998) about the current practices pertaining to tack coat use in various states, most states use slow-setting emulsions. The most common emulsions used were SS-1, SS-1h, CSS-1, and CSS-1h.

Hall and Ramakrishnareddy (2012) used two asphalt emulsions for their experiment, SS-1 and NTSS-1. Overall, the results showed that SS-1 and NTSS-1 were not significantly different in their performance. SS-1 produced higher shear strength with a 25 mm by 25 mm mix type combination, while NTSS-1 produced high shear strength with a 12.5 mm by 25 mm mix type combination.

Zaniewski et al. (2015) concluded from their experiment that SS-1h and NTSS-1hM performed the best out of all the tack coat materials used and that the highest bond strengths were achieved with a milled surface.

Salinas et al. (2013) conducted field tests with conventional pavers that applied SS-1h and SS-1hp and spray pavers that applied a non-tracking tack coat (SS-1vh). SS-1vh had the best overall performance, but since it is applied with a spray paver, SS-1hp is recommended as the best tack coat to use. SS-1hp, while more difficult to work with in the field, produced greater shear strength than SS-1h that will help increase the service life of the pavement.

Surface Type

Whether a pavement is milled or unmilled contributes to the overall bond strength that is obtained with the application of a tack coat. According various research experiments, a better bond is achieved at the interface when the underlying layer is milled (Tashman et al., 2006; Tran et al., 2012; West, Zhang, & Moore, 2005). When the Florida Department of Transportation Shear Tester was used, Tashman, Nam, and Papagiannakis (2006) found that the presence of tack coat did not significantly affect the shear strength for milled surfaces.

Zaniewski et al. (2015) simulated milling for the specimens in the laboratory portion of the experiment. Despite the milled specimens having higher bond strength, statistical analysis did not find any statistically significant difference between the milled surface bonds and the cut surface bonds.

Johnson et al. (2015) studied the effect of a contaminated surface on bond strength. To contaminate the surface, 6200 g of minus #8 material and 4250 g of fine sand were used. When cores were taken two days after paving the new HMA layer, no cores survived coring. Cores were taken again five months after paving and 33 cores were obtained. Based off the 33 cores it was determined that clean interfaces were bonded 90% of the time while contaminated surfaces only had a successful bond 40% of the time.

Mohammad and Elseifi (2014) also examined the effects of a clean or dusty surface. The dusty surfaces produced greater bond shear strength than clean conditions, especially when a confining pressure of 20 psi was applied during testing. The dusty condition was defined as applying an AASHTO A4 (silty-clay) soil on the existing condition at a rate of 0.07 lb/ft^2. In the same report, the effects of a wet or dry surface were studied. The wet condition was achieved by spraying water at a rate of 0.06 gal/syd on top of a tacked surface, which the authors believe simulate a light rainfall. With and without confining pressure, there was no significant difference between the wet and dry conditions. The researchers suggest that the temperature of the new HMA layer would evaporate the residual water on the surface and that it there does not affect the overall bond strength.

Leng, Ozer, Al-Qadi, and Carpenter (2008) studied bonding on specimens with PCC bases that were smooth, transversely tined, and longitudinally tined. At lower application rates (around 0.02 gal/syd), the interface shear strength was statistically higher for both tined surfaces compared to the smooth surface. However, as application rate increased, the effects of surface texture became less pronounced as the effects of tack coat became more notable. At a testing temperature of 20°C, smooth surfaces were more sensitive to tack coat than the tined surfaces. It was also noted that testing was performed without normal pressure and that the interface shear strength would most likely increase for the tined specimens if normal pressure was introduced. The direction of tining did not affect the interface shear strength, but overall provided a better bond than a smooth surface.

Salinas et al. (2013) evaluated milled HMA and milled PCC surfaces in the laboratory and field. The main conclusion from testing was that milled HMA created a bond with greater interface shear strength than milled PCC. SS-1h and SS-1vh were the two types of tack coat used when evaluating the effect of surface type on the bond strength.

Temperature

Tack coat is sensitive to temperature in the field and in the laboratory. When conducting laboratory tests, temperature usually has the greatest impact on bond strength (Hall & Ramakrishnareddy, 2012; West et al., 2005). West et al. (2005) performed tests at three temperatures. The results made it evident that the bond strength significantly decreases as the temperature increases. West suggests conducting bond strength tests at intermediate temperatures (77°F). At this temperature, normal pressure did not have an impact on bond strength which allows for a simpler test procedure sans a normal confining pressure.

Bae, Mohammad, Elseifi, Button, & Patel (2010); Choi, Crisp, Airey, Collop, and Elliott, (2006); Leng et al. (2008); and Mohammad, Bae, Elseifi, Button, and Scherocman (2009) concluded that as the testing temperature increases the shear strength decreases, similar to the conclusions made byWest et al. (2005).

Application Rate

Two different kinds of application rates are measured often in the application of tack coat—residual application rate and actual application rate. Once a tack coat is applied, it needs time to break, or set. In this time evaporation occurs which leaves less material on the existing surface than when it was applied. Residual application rate measures the amount of tack on the surface after it breaks. More often, it is the residual application rate that provides the most information for analyzing the bond strength. Application rates are generally specified with a range of target values.

Paul and Scherocman (1998) conducted a survey that was distributed to state Department of Transportation engineers. The survey consisted of questions about current practices with tack coat and fog seal. According to the responses from the survey, most states used slow-setting emulsions for tack coats and the residual application rates ranged from 0.06 to 0.26 L/m^2 (0.01 to 0.06 gal/syd).

Mohammad, Raqib, and Huang (2002) performed a study with four emulsions (CRS-2P, SS-1, CSS-1, SS-1h) and two asphalt binders (PG 64-22 and PG 76-22M). Residual application rates of 0.00, 0.02, 0.05, 0.1, and 0.2 gal/syd were used. Shear testing was performed to evaluate the performance of each and the optimum application rate was found to be 0.02 gal/syd (specifically with the CRS-2P emulsion).

West et al. (2005) experimented with application rate in respect to mixture type. A general trend in the experiment results was that the bond strengths decreased as the application rate increased. This trend was not observed with the coarse-graded mixture, but only in the fine-graded mixture at all tack type and normal pressure pairings. These results suggest that lower applications rates may be more effective at forming better bonds with fine-graded mixtures than higher application rates. Overall, the coarse-graded mixtures were not significantly affected by varying application rates.

Leng, Al-Qadi, Carpenter, and Ozer (2009) used SS-1hP, RC-70, and PG 64-22 as tack coats in a study using accelerated pavement testing. SS-1hP and RC-70 were applied at 0.02, 0.04, and 0.09 gal/syd, while PG 64-22 was applied at 0.04 gal/syd. Results indicated that 0.04 gal/syd was the optimum application rate, which supported results from laboratory testing (2008) conducted prior to the APT experiment.

Contrary to the results that West et al. (2005) experienced with bond strengths decreasing as application rate increased, Sholar et al. (2004) experienced higher bond strengths as the application rate increased, using a range from 0.091 to 0.362 L/m^2 (0.02 to 0.08 gal/syd).

The amount of tack coat applied is crucial to achieving a good bond. If there is too little or too much tack, a bond will fail to form (Hall & Ramakrishnareddy, 2012; Ozer, Al-Qadi, Wang, & Leng, 2012). Tran et al. (2011) suggest from the results of their experiment that milled surfaces require medium to high application rates to form proper bonds, whereas new HMA surfaces yielded higher bond strengths when the application rate was medium and low.

Field Tests

Louisiana Tack Coat Quality Tester (LTCQT)

The LTCQT is a modification of a previous device known as the ATacker by InstroTek. The LTCQT measures the ultimate load and the tensile strength. To use the device, a compressive load is applied for three minutes to adhere the test plate to the tacked surface. A tensile force is then applied until failure. The LTCQT can be used in the field or the laboratory. When used in the laboratory, it is recommended that an infrared reflective heating (IRH) lamp be used to help evaporate the tack coat. The biggest change from the ATacker to the LTCQT is the switch from manual to computerized application of the loading. (Mohammad et al., 2009)

Most commonly, cores are taken from field test sections to be tested in a laboratory. A field study performed in Minnesota by Johnson et al. (2015) took core samples two days after paving and again at five months after paving. It should be noted that none of the cores taken two days after paving were intact.

Tack Lifter

The Tack Lifter is an in situ device to measure effective emulsion application rates. The device is weighted with an absorbent foam sheet, beneath the weights, that is applied to the paving surface. The Tack Lifter is used after the tack coat is applied to the paving surface. The weighted device is placed on top of the foam sheet for 30 seconds. The mass of the emulsion absorbed by the sheet is determined and converted to emulsion application rate (EAR) using the emulsion density and area of the sheet (Rawls, Im, & Castorena, 2016). The Tack Lifter could be used as a quality control test prior to paving in the field to determine if the target application rate was achieved. The components of the Tack Lifter are illustrated in Figure A.1.

Pull-Off Test Devices

There are various pull-test devices that all perform the same basic functions. A pull-off test measures tensile force or torque-shear strength by applying either tension

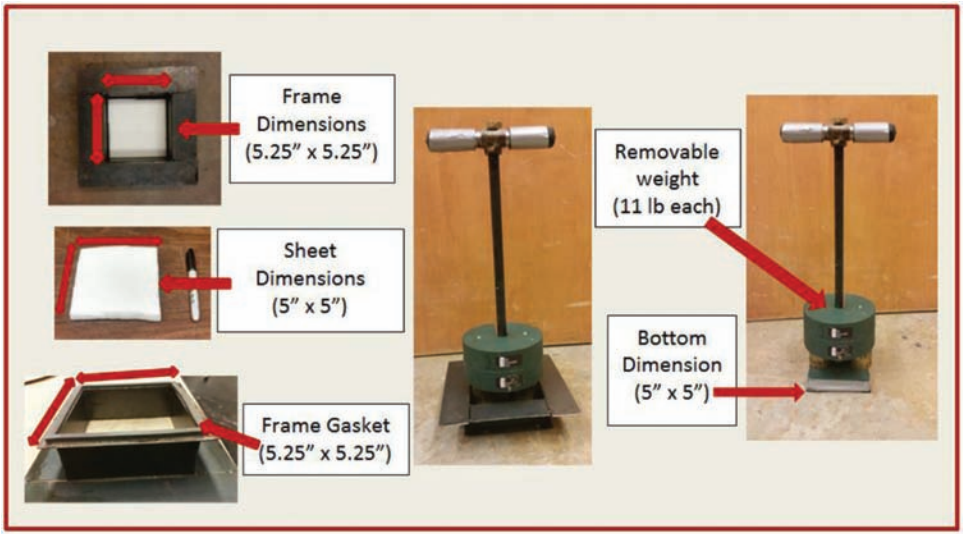

Figure A.1 Tack Lifter components.

or torque-shear via a torque wrench or some other apparatus. Two commonly used pull-off test devices are the University of Texas- El Paso (UTEP) Pull-Off Device (UPOD) and the ATacker device developed by InstroTek, Inc. The ATacker can be used in the laboratory as well (Buchanan & Woods, 2004). To use the ATacker, tack coat material is applied between two contact plates and allowed to cure. It is then subjected to compression for 60 seconds prior to the tensile or torque-shear being applied. The forces are applied manually with a drive lever or torque wrench, and a force gauge is observed to record the maximum force applied. (Buchanan & Woods, 2004)

Laboratory Tests

Apparatuses that have been designed to operate within a Marshall device or a Materials Testing System are common to test shear strength. One apparatus that the Virginia Department of Transportation (VDOT) uses consists of situating the test cylinder horizontally in an apparatus fixed to a Marshall device. The layer interface of the specimen is orientated directly between two vertical plates, one that is stationary and one that the load is applied to. The cylinder is held in place by a cylindrical plate on either end and compressed against a spring (McGhee and Clark, 2009).

The Florida DOT developed a shear device that could test both laboratory fabricated and field specimens since many devices cannot accommodate field specimens without trimming. The shear device was designed to work in the Materials Testing System (MTS). The parameters of the test are: 152.4 mm (6 in.) specimens, strain controlled, loading rate of 50.8 mm/min (2 in/min), testing temperature of 25.0°C (77.0°F), and a shear plate gap width of 4.8 mm (3/16 in.). (Sholar et al., 2004)

Donova, Al-Qadi, and Loulizi (2000) designed and constructed a fixture to be used in the MTS like the device developed by Florida DOT. This device has the capability to perform tests with either stress or deflection control. The device was designed with the purpose of testing a concrete specimen with an HMA overlay, with the load being applied to the HMA during testing. Leng et al. (2008) used the device, seen in Figure A.2, which was designed by Donovan et al. to test PCC/HMA specimens. In the testing, Leng et al. selected a monotonic testing mode, using a constant shear rate of 0.2 mm/s and no normal force.

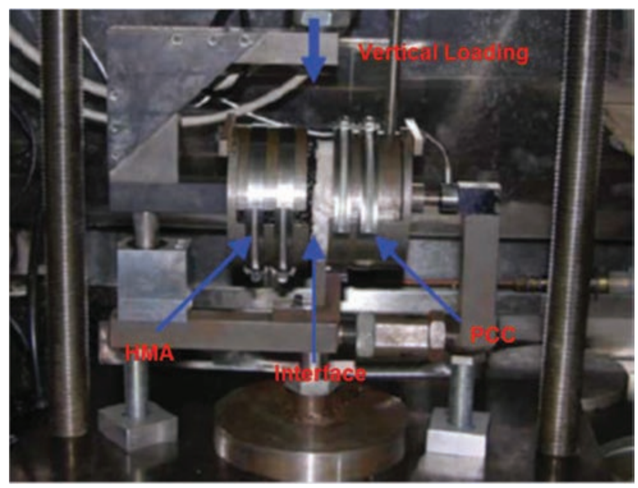

Figure A.2 Testing device developed by Donovan et al. (2000) and used by Leng et al. (2008).

Buchanan and Woods (2004) developed a shear device for laboratory testing of cylindrical specimens to obtain the interface shear strength. The device is used in a Marshall loading device similar to the one used by VDOT. A displacement rate of 2 in/min was used to apply the loading and data were recorded every 0.1 seconds until failure.

The Ancona shear testing research and analysis (ASTRA) device (Figure A.3) is a direct shear device similar to ones used in soil mechanics. It is capable of

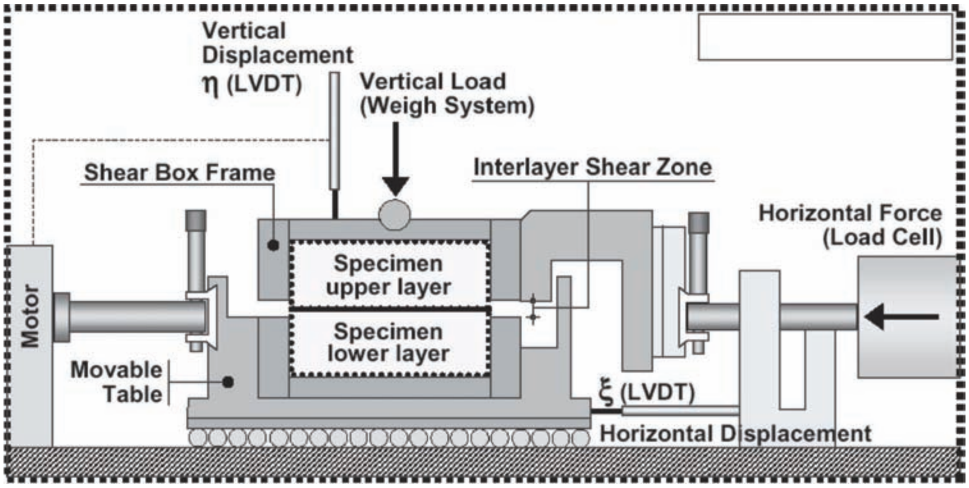

Figure A.3 ASTRA device schematic (Canestrari et al., 2005).

testing cylindrical and square specimens. The ASTRA device records shear force and horizontal and vertical displacements with respect to time into a data file. (Canestrari et al., 2005)

Accelerated Pavement Testing (APT)

Leng et al. (2009) performed full-scale APT at the Advanced Transportation and Engineering Lab (ATREL) of the University of Illinois at Urbana-Champaign. The APT plan consisted of 25 pavement sections measuring 12.5 ft. long and 12 ft. wide. The APT loading tire configuration used a 425 SWB tire, with a pressure of 120 psi, and a loading amplitude of 12–16 kip depending on the test section. T-type thermocouples and H-type strain gauges were installed in various test sections to obtain a temperature profile of the HMA overlay and to quantify strains at the interface of the PCC and HMA.

The results from the APT validated results from previous laboratory testing such as, strain responses were smallest in test sections with the optimum tack coat application rate (0.04 gal/syd) when compared with high and low rates. Between the two tack coat types used (SS-1hP and RC-70), SS-1hP generally displayed better rutting resistance than RC-70, and when applied at the optimum rate, SS-1hp displayed the lowest primary rutting. (Leng et al., 2009)

Mealiff, Hossain, and Schieber (2016) used APT to evaluate the bond strength of two tack coat types allowed by the Kansas Department of Transportation (KDOT), SS-1hP and Emulsion Bonding Liquid (EBL). Loading was achieved with a single-axle load of 18 kip. The load was applied until failure, which was defined as visible cracking. Cores were tested with pull-off tests, both in situ and in the laboratory. Results indicated that EBL performed better overall with lower rutting and higher bond strengths. SS-1hP, when applied at the recommended rate of 0.05 gal/syd, did not achieve a high enough bond strength as required by KDOT. Since EBL was applied at high rates (0.08–0.16 gal/syd), it is unclear if SS-1hP could achieve similar bond strengths if the application rate was increased.

Finite Element Analysis

Ozer et al. (2012) conducted numerical analysis using a finite element model to examine the results from the laboratory and accelerated pavement testing performed by Leng et al. (2008, 2009). One of the major conclusions drawn from the finite element analysis is that proper application rate is crucial to the service life of a pavement. Lack of tack coat application is not the only way to negatively impact the service life of the pavement. Excessive tack coat application rates drastically increased the tensile strains at the bottom of the HMA during construction. Substantial differences in longitudinal and transverse tensile in the HMA were noticed when the application rates varied.

Liu and Hao (2012) built a model in a finite element program to compare the effects of a fully-bonded interface and an interface with no bonding. The main results indicated that tack coat application can adequately decrease the tensile stress at the bottom of the HMA layer and that discontinuities between the lower asphalt layer and the base are the primary contributors to pavement rutting suggesting that discontinuities between asphalt layers do not contribute to rutting.

Dynamic Shear Rheometer (DSR)

Seo, Sakhaeifar, and Wilson (2015) used the dynamic shear rheometer (DSR) frequency sweep test to measure the rheological properties of three different non-tracking tack coat materials. The frequency sweep test was conducted using a wide range of loading frequencies (0.1 to 100 rad/sec) and test temperatures (6, 10, 22, 34, 46, 58, and 70°C). All three non-tracking tack coat materials were stiffer than the control tack coat material. This suggests that non-tracking tack coat material could help reduce rutting, but could lead to higher susceptibility to cracking.

Recommended Laboratory Shear Strength

After testing cores from various projects, West et al. (2005) suggests that a bond strength of 100 psi or greater will be sufficient for proper bonding in resisting shear forces. Johnson et al. (2015) recommend average peak shear strength be 100 psi or greater with a standard deviation of 25 psi or less.

APPENDIX A REFERENCES

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APPENDIX B: JOB MIX FORMULAE

Parking Lot Mix (Surface)

INDIANA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS DIVISION
2015 HMA DMF/JMF per 401/402

HMA PRODUCER :	Rieth Riley Construction
PLANT LOCATION :	Lafayette, IN
CERTIFIED PLANT NUMBER:	3386
APPROVED DESIGN LAB :	1319

Aggregate Size	Source	Source #	Q-Number	Ledges	Gsb	DMF %	JMF %	Dolo. Test (YES/NO)?	Sample Per ___ Tons of HMA
#11 Stone	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.715	26.0%		NO	
#12 Stone	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.715	20.0%		NO	
Stone Sand	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.775	10.0%		NO	
Natural Sand	Rieth Riley - Composite	3386			2.592	17.2%		NO	
BHF	Plantsite	3386			2.800	1.8%		NO	
RAP	Plantsite	3386			2.640	25.0%		NO	

PG BINDER	Source	Source #		Binder % RAS	Binder Replacement %	Virgin Binder %
64-22	Interstate	7216	DMF	0.0%	20.0%	4.8%
70-22	Interstate	7216	JMF			
Additives/ Fibers/ Etc.	Source	Source #				

			Fine	Coarse	RAS
Design Number	**151608 D**	DMF - Fine RAP/ Coarse RAP/ RAS in mixture, %	25.0%		
		DMF - Fine RAP/ Coarse RAP/ RAS binder, extracted, %	4.8%		
Comments:		JMF - Fine RAP/ Coarse RAP/ RAS in mixture, %			
		JMF - Fine RAP/ Coarse RAP/ RAS binder, extracted, %			

	Spec	DMF Mass	JMF Mass	Volume
Base PG-Design Grade	64-22			
Mixture course	Inter/Surf			
Mixture designation	9.5 mm			
Maximum particle size	12.5 mm			
%Pass 37.5 mm	100	100.0		
%Pass 25.0 mm	100	100.0		
%Pass 19.0 mm	100	100.0		
%Pass 12.5 mm	100	100.0		
%Pass 9.5 mm	90.0-100.0	95.3		
%Pass 4.75 mm	<90.0	66.9		
%Pass 2.36 mm	32.0-67.0	43.4		
%Pass 1.18 mm		29.4		
% Pass 600 µm		20.6		
% Pass 300 µm		11.2		
% Pass 150 µm		6.2		
% Pass 75 µm	2.0-10.0	4.7		
Aggregate blend Gsb		2.681	#DIV/0!	
		HMA	WMA	
Base PG-Plant Min Temp (°F)		275	250	
Base PG-Plant Max Temp (°F)		315		
Mix compaction Temp (±9°F)		300		

	DMF	JMF
Ignition Oven Test Temperature (°F)/ (°C)	800 F/ 427 C	
Binder, ignition (actual), %	6.0%	
Binder, extracted, %	5.8%	
Extraction required? Yes* or No	NO	
Binder, calculated effective, %	4.9%	
Gyrations Nini / Ndes / Nmax	6/50/75	
Mass gyratory pill @ Ndes, g	4850	
Gmm	2.511	
Gmm w/ dry back? Yes or No	NO	
Gmm % @ Nini / Nmax	88.3/97.2	
Gmb @ Ndes	2.411	
Air Voids @ Ndes, %	4.0%	
VMA @ Ndes, %	15.5%	
VFA @ Ndes, %	74.2%	#VALUE!
Coarse agg. ang. 1 / 2 face, %	100.0/100.0	
Fine aggregate angularity	42.2	
Sand equivalency	76.6	
Dust/calculated effective binder	1.0	
Tensile strength ratio, %	83.5%	
Draindown, % (SMA or OG only)		
Pba	1.16%	#DIV/0!
VCA_{DRC}/VCA_{MIX} (SMA only >1)		
MAF by DTE for PE/PS	**1.000**	

* Extraction Note - Written request required, submit w / DMF

PRODUCER: Jason P Walters — DMF DATE: 04-06-15 — JMF DATE:

DTE SIGNATURE: — DMF DATE: 04-10-15 — JMF DATE:

DTE Notes: Uses 2015 INDOT Agg Gsbs
DMF reference history: 141608; 131616; 121607; 111608
Ignition Oven Samples Submitted:
Producer Notes: 340-035

Intermediate Mix

INDIANA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS DIVISION
2015 HMA DMF/JMF per 401/402

HMA PRODUCER :	Rieth Riley Construction
PLANT LOCATION :	Lafayette, IN
CERTIFIED PLANT NUMBER:	3386
APPROVED DESIGN LAB :	1319

Aggregate Size	Source	Source #	Q-Number	Ledges	Gsb	DMF %	JMF %	Dolo. Test (YES/NO)?	Sample Per ___ Tons of HMA
#8 Stone	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.737	21.0%		NO	
#9 Stone	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.737	17.0%		NO	
#11 Stone	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.715	14.8%		NO	
#12 Stone	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.715	13.0%		NO	
Stone Sand	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.775	5.0%		NO	
QA Fines	US Agg - Delphi	2421	Q972034	H2: L1-L3	2.775	2.0%		NO	
RAP	plant site	3386			2.640	25.4%		NO	
BHF	plant site	3386			2.800	1.8%		NO	

PG BINDER	Source	Source #		Binder % RAS	Binder Replacement %	Virgin Binder %
64-22	Interstate	7216	DMF	0.0%	24.9%	3.7%
70-22	Interstate	7216	JMF			
Additives/ Fibers/ Etc.	Source	Source #				

Design Number	**151604 D**
Comments:	

	Fine	Coarse	RAS
DMF - Fine RAP/ Coarse RAP/ RAS in mixture, %	25.4%		
DMF - Fine RAP/ Coarse RAP/ RAS binder, extracted, %	4.8%		
JMF - Fine RAP/ Coarse RAP/ RAS in mixture, %			
JMF - Fine RAP/ Coarse RAP/ RAS binder, extracted, %			

Base PG-Design Grade	64-22
Mixture course	Base/Inter
Mixture designation	19.0 mm
Maximum particle size	25.0 mm

	Spec	DMF Mass	JMF Mass	Volume
%Pass 37.5 mm	100	100.0		
%Pass 25.0 mm	100	100.0		
%Pass 19.0 mm	90.0-100.0	98.6		
%Pass 12.5 mm	<90.0	83.5		
%Pass 9.5 mm		69.4		
%Pass 4.75 mm		42.5		
%Pass 2.36 mm	23.0-49.0	25.6		
%Pass 1.18 mm		17.4		
% Pass 600 µm		12.8		
% Pass 300 µm		8.6		
% Pass 150 µm		6.4		
% Pass 75 µm	2.0-8.0	5.1		
Aggregate blend Gsb		2.709	#DIV/0!	

	HMA	WMA
Base PG-Plant Min Temp (°F)	275	250
Base PG-Plant Max Temp (°F)	315	
Mix compaction Temp (±9°F)	300	

* Extraction Note - Written request required, submit w / DMF

	DMF	JMF
Ignition Oven Test Temperature (°F)/ (°C)	800 F/ 427 C	
Binder, ignition (actual), %	4.9%	
Binder, extracted, %	4.7%	
Extraction required? Yes* or No	NO	
Binder, calculated effective, %	4.0%	
Gyrations Nini / Ndes / Nmax	8/100/160	
Mass gyratory pill @ Ndes, g	4850	
Gmm	2.566	
Gmm w/ dry back? Yes or No	NO	
Gmm % @ Nini / Nmax	84.82/97.41	
Gmb @ Ndes	2.463	
Air Voids @ Ndes, %	4.0%	
VMA @ Ndes, %	13.5%	
VFA @ Ndes, %	70.4%	#VALUE!
Coarse agg. ang. 1 / 2 face, %	100/100	
Fine aggregate angularity	45.6	
Sand equivalency	80.9	
Dust/calculated effective binder	1.3	
Tensile strength ratio, %	91.6%	
Draindown, % (SMA or OG only)		
Pba	0.97%	#DIV/0!
VCA_{DRC}/VCA_{MIX} (SMA only >1)		
MAF by DTE for PE/PS	**1.006**	

PRODUCER: Jason P Walters

DMF DATE: 03-09-15

JMF DATE:

DTE SIGNATURE: [signature]

DMF DATE: 03-13-15

JMF DATE:

DTE Notes: Uses 2015 INDOT Agg Gsbs
DMF reference history: 141613 (full design)
Ignition Oven Samples Submitted:
Producer Notes: 340-047

Spray Paver Surface Mix

INDIANA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS DIVISION
2017 HMA DMF per 401/402. DMF/JMF per 410

v17.3 3-1-17

HMA PRODUCER :	E & B PAVING, INC.
PLANT LOCATION :	INDIANAPOLIS, SOUTH HARDING STREET
CERTIFIED PLANT NUMBER:	3340
APPROVED DESIGN LAB :	987

Aggregate Size	Source	Source #	Q-Number	Ledges	Gsb	Abs %	DMF %	JMF %	Dolo. Test (YES/NO)?	Tons of HMA
#11 Steel Slag	Butler Mill Service	2772	Q992158	NA	3.650	1.30%	23.0%			
#12 Dolomite	U.S. Aggregates	2421	Q972034	Hanna 2, Ldg 1,2,3,4	2.714	1.12%	39.0%		YES	2,722
#24 Stone Sand	Hanson, Harding St.	2312	Q962011	1804-27	2.616	2.20%	18.0%			
Recycle 4.75mm	2017 Sand Rap (US 40)				2.640	1.00%	18.0%			
Fine Return					2.800	1.00%	2.0%			

PG BINDER	Source	Source #		Binder % RAS	Binder Replacement %	Virgin Binder %
70-22	Marathon, Indpls	7171	DMF	0.0%	19.2%	4.7%
76-22	Marathon, Indpls	7171	JMF			
Additives/ Fibers/ Etc.	Source	Source #				

Aggregate Design No. **173661 D**

	Fine	Coarse	RAS
DMF - Fine RAP/ Coarse RAP/ RAS in mixture, %	18.0%		
DMF - Fine RAP/ Coarse RAP/ RAS binder, extracted, %	6.2%		
JMF - Fine RAP/ Coarse RAP/ RAS in mixture, %			
JMF - Fine RAP/ Coarse RAP/ RAS binder, extracted, %			

Comments:

PG Grade, Design TSR	64-22
Mixture course	Surface
Mixture designation	9.5 mm
Maximum particle size	12.5 mm

	Spec	DMF Mass	JMF Mass
%Pass 37.5 mm	100	100.0	
%Pass 25.0 mm	100	100.0	
%Pass 19.0 mm	100	100.0	
%Pass 12.5 mm	100	100.0	
%Pass 9.5 mm	90.0-100	94.2	
%Pass 4.75 mm	<90.0	67.8	
%Pass 2.36 mm	32.0-67.0	38.7	
%Pass 1.18 mm		25.1	
% Pass 600 µm		16.4	
% Pass 300 µm		10.0	
% Pass 150 µm		6.6	
% Pass 75 µm	2.0-10.0	5.3	
Aggregate blend Gsb		2.850	
Aggregate blend Abs, %		1.33%	
Base PG-Plant Max Temp (°F)		315	
Lab compaction Temp (±9°F)		300	

	DMF	JMF
Ignition Oven Test Temperature (oF)/ (oC)	900 F/ 482 C	
Binder, ignition (actual), %	5.8%	
Binder, extracted, %	5.6%	
Extraction required? Yes* or No	NO	
Binder, calculated effective, %	4.7%	
Gyrations Nini / Ndes / Nmax	8/100/160	
Mass gyratory pill @ Ndes, g	5140	
Gmm	2.656	
Gmm w/ dry back? Yes or No	NO	
Gmm % @ Nini / Nmax	84.2 / 97.5	
Gmb @ Ndes	2.549	
Air Voids @ Ndes, %	4.0%	
Calculated Air Voids, %	4.03%	
VMA @ Ndes, %	15.7%	
VFA @ Ndes, %	74.5%	#VALUE!
Coarse agg. ang. 1 / 2 face, %	100 / 100	
Fine aggregate angularity	46.2	
Dust/calculated effective binder	1.1	
Tensile strength ratio, %	83.6%	
Draindown, % (SMA or OG only)		
ΔPb, %	-0.55%	
VCA_{DRC}/VCA_{MIX} (SMA only >1)		
MAF by DTE for PE/PS	1.057	

* Extraction Note - Written request required, submit w / DMF

DMF DATE: 12-06-17

PRODUCER: *Cindy Tucker*

JMF DATE:

DATE DMF ASSIGNED: 19-06-17

DATE JMF ASSIGNED:

DTE Notes:

DMF reference history: new 2017
Ignition Oven Samples Submitted:
Producer Notes:

About the Joint Transportation Research Program (JTRP)

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

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

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

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

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