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Research Article

Installation and implementation of proper tack coat application

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ABSTRACT

Tack coat is a form of bituminous emulsion placed between two bituminous layers, so that the two layers can act as a single monolithic unit to sustain the traffic loads. Several studies have been conducted on evaluating the proper tack coat application to ensure superior shear strength. The objective of this paper is to synthesize existing literature, research projects and agency specifications regarding the practice of tack coat application. Proper tack coat application depends on several factors such as tack coat type, application rate and its coverage, temperature, storage condition, pavement surface texture and condition, cleanliness of the surface, asphalt distributor and its consistency, curing or setting time, quality of compaction, and so on. Overall, it contains a comprehensive review of all the known literatures and documents a synthesis study on all those factors impacting the performance of tack coat.

Keywords: Tack coat, Interlayer, Shear, Bonding, Emulsion

1. Introduction

Pavement structure comprise of multiple layers of pavement and assumes that all layers work together as one layer or single monolithic unit. It includes one or more layers of asphaltic materials and an ideal way to improve the existing pavement structure, such as vehicle roadway, parking lot or other traffic bearing structures. These layers consist of binder material, aggregate rock, shell, recycled pavement materials, various additives, fillers, and so on. The boundary between these two consecutive layers is known as layer interface and the stress distribution is highly influenced by the adhesion conditions at layer interface. If the adhesion bonding is not achieved in between existing pavement structure and new asphalt pavement layer or successive layers delamination or separation occurs into constituent layers, which may cause a number of structural distress (slippage and fatigue cracking).

In order to have strong interlayer bonding, successive layers can act as a strong monolithic unit bonding material which is known as tack coat placed between the layers. In general bituminous emulsion is normally used as tack coat prior to overlay on an existing or newly constructed pavement layer. Tack coat acts as bonding agents between each lift of pavement section, increase the adhesion bonding and fuse the layers together. According to ASTM D8 “Tack coat (bond coat) is an application of bituminous material to an existing relatively non absorptive surface to provide a through bond between old and new surfacing” (ASTM D8-02). It helps reduce slippage and sliding of the layers relative to other layers in the pavement structure during use or due to wear and weathering of the pavement structure. It is believed that the most vulnerable locations are distress where traffic is accelerating or decelerating (traffic signals or horizontal curves). As a result it is important that the bonding between interlayer should be strong to sustain such failure. The practice of proving tack coat application in order to increase the interlayer bonding is very old and its performance evaluation methods have been developed for many years. The performance of tack coat application depends on several factors such as tack coat type, tack coat application rate, temperature, pavement surface texture and condition, dry or wet condition, cleanliness of the surface, asphalt distributor and its consistency, curing or setting time, quality of compaction, and so on.

This paper presents an extensive review on construction practices and factors that influence performance properties of tack coat application. Different tack coat types and their application rates, preservation techniques, the coverage on the pavement surface, setting time, various surface condition and their texture, aggregate and mixture type, influence of moisture and test device that were used to analyze the bonding strength of tack coat have been discussed in details.

2. Materials and preservation criteria

2.1 Tack coat type

A tack coat is an application of bituminous material to a pavement surface prior to the placement of a subsequent lift of asphalt mixture for the purpose of providing a thorough bond between the two surfaces. A proper bond between pavement layers is essential in order to provide a monolithic pavement structure (Mohammad et al., 2012). In general four types of tack coat materials used for increasing the interlayer bonding strength are:

(1) Hot asphalt cement
(2) Asphalt emulsion

(3) Asphalt cutbacks
(4) Trackless tack coat

The literature review suggests that the most common applied tack coat material is emulsified asphalt.

2.1.1 Asphalt Binder or hot asphalt cement

As we know asphalt is a class of black or dark-colored (solid, semisolid, or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, pitches, and asphaltites are typical. It can be used as a tack coat material. PG 64-22, PG 76-22, PG 76-22M and PG 58-28 are the common binder type used as tack coat material (West et al., 2005). It was reported that hot asphalt cement can provide high shear strength compared to some emulsified asphalt (CRS-2, CRS-2L, CSS-1 and SS-1) (31, 32). The main advantage of using asphalt binder is that it does not require any curing time. However, the requirement of high temperature in order to make the asphalt fluid enough through distributor is a serious safety concern for the workers. Also, it is costly as it requires high energy to maintain the binder fluidity at high temperature for uniform application (HMAP Handbook − US Army Corps of Engineers, 2000). In the United States, Georgia reported to use asphalt binder as their tack coat material (Mohammad et al., 2008)

2.1.2 Asphalt Cutback

Asphalt cutback is a blending of asphalt binder and some form of petroleum distillates. The distillates evaporate or cure out when applied as a tack coat and only leave the residual asphalt as the bonding agent in the tack coat (Asphalt Institute, 2011). The speed at which the solvent evaporates is a function of solvent type and percentage of residual asphalt in the asphalt cutback. The use of asphalt cutback is decreasing because it contains volatile chemicals which is harmful to the environment (Mohammad et al., 2012; Roberts et al., 1991).

According to literature and AASHTO (Ghaly et al., 2014; Al-Qadi et al., 2008; Du, 2011) asphalt cutbacks are divided into the following three types, based on the relative speed of evaporation:

- Rapid-curing (RC): asphalt binder combined with a light diluent of high volatility, generally with a boiling point similar to gasoline or naphtha. Grades include RC-70, RC-250, RC-800, and RC-3000 (AASHTO 2012)
- Medium-curing (MC): asphalt binder combined with a medium diluent of intermediate volatility, generally with a boiling point similar to kerosene. Grades include MC-30, MC-70, MC-250, MC-800,

and MC-3000 (AASHTO 2012)

- Slow-curing (SC): asphalt binder combined with oils of low volatility. Grades include SC-70, SC-250, SC-800, and SC-3000. AASHTO no longer maintains specifications for SC cutbacks (ASTM 2015)

2.1.3 Asphalt emulsion

According to Asphalt Emulsion Manufacturers Associations 2009 "Asphalt emulsion is a combination of three basic ingredients: asphalt, water, and small amount of an emulsifying agent. In the same process, these components are introduced into a mechanism known as a colloid mill, which shears the asphalt into tiny droplets. The emulsifier, which is a surface-active agent, keeps the asphalt droplets in a stable suspension and controls the breaking time. The result is a liquid product with a consistency ranging from that of milk to heavy cream, which can be used in cold processes for road construction and maintenance". It is widely used than hot asphalt binder or cutback asphalt because of its application at lower temperatures which enables it to become more uniform, energy-saving, and safer application (Roberts et al., 1991). Also, asphalt emulsions do not contain any harmful volatile chemicals and do not pose risks to workers' health. According to FHWA, the definition of emulsified asphalt has been divided into three parts (FHWA, 2016). Undiluted emulsion refers to an emulsion which consists primarily of a paving grade asphalt binder, water, and an emulsifying agent, diluted emulsion defines as an emulsion with additional water added to it. The most common dilution rate is 1:1 (one part undiluted emulsion and one part additional water). The last one residual asphalt refers to the remaining asphalt after an emulsion has set, typically 57% to 70% of the undiluted emulsion.

In general, asphalt emulsions are classified into three categories, based on the electronic charge surrounding the asphalt binder particles which are: anionic, cationic, and nonionic. Anionic and cationic asphalt emulsions are the most commonly used emulsified tack coat materials. Emulsions are further classified on their settling time as well. For example: rapid-set (RS), medium-set (MS), slow set (SS), and quick set (QS) have been adopted to simplify and standardize this classification. Also, if it is cationic (positively charged) emulsions. The letter "C" in front of the term (CSS) indicates that the emulsion is cationic. Based on the survey the most common types of emulsions used for tack coats include slow-setting grades of emulsion (SS-1, SS-1h, CSS-1, and CSS-1h) (Paul and Scherocman, 1998; Cross and Shrestha, 2004).

The advantage of the slow-setting grades over the rapid-setting grades is that they can be diluted and diluted emulsions provide the additional volume needed for the distributor to function at normal speed when lower application rates are used and diluted emulsion flows easily from the distributor at ambient temperatures allowing for a more uniform application (Asphalt Institute, 1992). However, the disadvantage of diluted slow-setting emulsions is that it may take several hours to break or even several days to completely set. Also, caution must be taken on an overlay tacked with slow settings because it may cause slippage failure to the pavement at its early life (Mohammad et al., 2012).

2.1.4 Trackless tack coat

Trackless tack coat is composed of polymer modifier and hard base asphalt and designed to reduce the tracking problems associated with traditional tacks. The material is activated by the heat from hot lift of asphalt when the new layer put on it and it bonds with new overlay (Seo et al., 2016). It was reported that trackless tack coat has higher shear strength compared with conventional tack coat CRS-1 and SS-1. (Clark et al., 2012; Mohammad et al., 2011; Raposeiras et al., 2013; Hakimzadeh et al., 2012). Bae et al. (2010) found that the bonding performance of trackless tack coat increased with the decrease of temperature and it has superior performance compared to CRS-1 at 40°C. The high temperature grade for CRS-1 was PG 58 whereas for trackless tack coat it was PG 82. Although it has high brittleness which resembles its high interface shear strength, it may be vulnerable in cold region due to its low top-down cracking resistance (Chen, 2009; Ziari and Khabiri, 2007; Leng et al., 2008; Chen et al., 2012).

2.2 Materials storage/preservation

NCHRP Report 516 documented the proper storage, handling, sampling and testing of asphalt emulsion. It mentioned that tack coat materials must be stored and handled properly to optimize their effectiveness. Manufacturer's guide and instruction should be followed and most manufacturers have technical support on hand to provide guidance, and many provide written guidance. The material storage should have best tank types, maximum storage times, agitation, storage temperature, compatibility with other liquids, contamination, freezing, and boiling. For general emulsion storage, handling, and sampling guidelines, the Asphalt Institute's MS-19 Basic Emulsion Manual provides thorough information that has been established through a long history of successful use.

Storage tanks need to be insulated for protection from freezing and for efficient use of heat. Propellers should be turned slowly (approximately 60 RPM) to gently circulate the material. Agitating the emulsion should be done carefully because higher rates will typically increase the chances that the emulsion will lose its homogenous consistency and separate in the tank. Forced air should always be prohibited to agitate the emulsion, because it may also cause the emulsion to break in the tank, separating the asphalt from the water. Different types of emulsions require different set up for pumps, valves, lines and the proper storage temperature, which will be critical to the preservation of the material. Table 1 presents the recommended storage temperatures for standard emulsion grades. In general, emulsions should be stored between 10°C (50°F) and 85°C (185°F). Water evaporates more quickly at elevated temperatures and triggered the change of characteristics of asphalt emulsion. The emulsion should never be allowed to freeze, which will break the emulsion in the tank. Also, heating the emulsion to above the boiling point of water should be done carefully because premature breakdown of the emulsion occurs on the heating surface.

Table 1. Recommended storage temperatures for standard emulsion grades (Gierhart and Johnson, 2018; Asphalt Institute, 2008)

Grades	Temperature	
	Minimum	Maximum
QS-1h, CQS-1h	10°C (50°F)	50°C (125°F)
RS-2, CRS-1, CRS-2, HFRS-2, CMS-2, CMS-2h, MS-2, MS-2h, HFMS-2, HFMS-2h	50°C (125°F)	85°C (185°F)
RS-1, SS-1, SS-1h, CSS-1, CSS-1h, MS-1	10°C (50°F)	60°C (140°F)

3. Construction and proper implementation of tack coat

3.1 Surface condition

3.1.1 Surface type/texture

Surface type plays an important role in increasing the interlayer shear strength. The upper layer mixture properties and texture of the existing layer have great influence on the tack coat properties. It was reported that milled surface of both asphalt and PCC pavement has superior shear strength compared to non-milled pavement surface (Sholar et al., 2004; Tashman et al., 2006; Al-Qadi et al., 2008). It is due to the rough surface of the pavement which occurs due to the milling machine resulting good interlayer bonding and high shear strength. Curtis et al. (1993) suggested that if tack coat is applied on an existing milled surface the bonding between tack coat and aggregate is crucial whereas if tack coat is placed on the top of a newly paved layer the bonding with the asphalt binder is more important. Song et al. (2015) reported that surface texture depth also plays a vital role where the higher shear strength was observed by providing higher surface depth between OGFC and underlying layer.

Mixture type and aggregate gradation significantly affect the shear strength of tack coat (Kruntcheva et al., 2006; Collop et al., 2009). Chen et al. (2010) compares the shear strength among three mixture types which are: dense graded asphalt concrete (DGAC), stone matrix asphalt (SMA) and porous asphalt concrete (PAC). The results showed that DGAC-DGAC system has higher shear strength, followed by PAC-DGAC and PAC-SMA. Another study by Song et al. (2017) found that OGFC-BM has higher adhesive bonding compared to OGFC-TLD at same application rate. This is due to BM’s coarser aggregate gradation which produce high interlayer roughness. It is worth to note that chemistry between emulsion type and aggregate has significant effect on tack coat properties. Cationic emulsions has better adhesive and coating when mixed with negatively charged aggregates such as gravel and siliceous whereas anionic emulsions has better bonding with positively charged aggregates such as limestone (NAPA, 2013).

3.1.2 Surface preparation

Most of the literature suggest that tack coat should be applied on clean surface. The dust surface can create de-bonding by delamination or sliding the pavement surface. There are several ways to clean the pavement surface which are: mechanical brooming, flushing the surface with water, or blowing off debris using high-pressure air (FDOT, 2016; Gierhart and Johnson, 2018). According to Florida DOT "Before applying any bituminous material, remove all loose material, dust, sand, dirt, caked clay, and other foreign material which might prevent proper bond with the existing surface for the full width of the application. Take particular care in cleaning the outer edges of the strip to be treated, to ensure the prime or tack coat will adhere. When applying prime or tack coat adjacent to curb and gutter, valley gutter, or any other concrete surfaces, cover such concrete surfaces, except where they are to be covered with a bituminous wearing course, with heavy paper or otherwise protect them as approved by the Engineer, while applying prime or tack coat. Remove any bituminous material deposited on such concrete surfaces". However, NCHRP 712 reports that dusty conditions exhibited greater interlayer shear strength than clean conditions when tested with a confining pressure.

3.1.3 Moisture content

Moisture content also plays an important role for getting a proper tack coat application. NCHRP Report 712 determined that, for the effect of water on tacked surfaces in the majority of cases, there was no statistically significant difference between wet and dry conditions. Data indicate that a small amount of water can be flashed away by the hot HMA mat and thus have less effects on the quality of tack coat. However, the authors suggested that the surface be clean and dry to avoid the negative effects of water on the bonding at the interface. Sholar et al. (2004) reported that large amount of water can reduce the shear strength of tack coat, especially during construction as rainwater can significantly reduce the inter layer shear strength of tack coat material. There is no specified limit of moisture content that may present during tack coat application but dry and clean surface is recommended by all studies.

3.2 Material distributor and tack coat coverage

The application of track coat begins after finishing the surface preparation. The good tack coat application should be uniform and have a "double lap" or triple lap" coverage. In this process the vehicle related adjustments and coverage of tack coat play a vital role for the proper tack coat application. Extensive search on literature from agency, DOT and NCHRP indicates the following important parameters regarding material distributor and tack coat coverage.

3.2.1 Asphalt distributor

Fig. 1 shows the asphalt distributor. According to Etnyre & Co (2017) the asphalt distributor should have eight major components which are:

(1) Asphalt distributor should have proper storage in order to store the liquid and liquid will be sprayed on the roadway.
(2) The heating system should be capable of maintaining the liquid at its proper spraying temperature.
(3) The asphalt pump and circulating system should be capable of maintaining homogeneity and prevent clogging of the liquid asphalt.
(4) The flushing and cleanout system should be maintained properly in order to keep the distributor unclogged and functional.
(5) The spray bar should have even distribution.
(6) The power system should be capable of operating all pumps, drives and controls.
(7) The metering and control system should be capable of allowing the operator to spray at different application rates.
(8) The chassis should provide the gross vehicle weight rating adequate to support the loaded distributor.

Fig. 1. Asphalt distributor (NCHRP 516)

Apart from that several other categories need to be evaluated before applying tack coat on the surface which are:

- Clogged nozzles
- Nozzle size

- Nozzle orientation
- Distribution bar pressure and speed
- Spray bar height
- Calibration of distributor
- Maintaining consistent temperature
- Tracking due to haul trucks

These categories are described with more details in following paragraphs.

1) Clogged nozzles

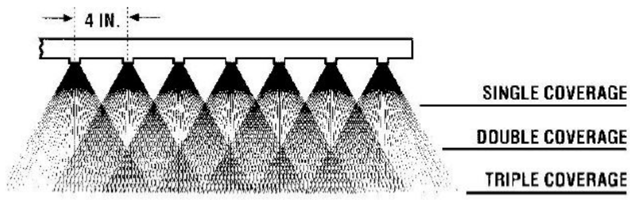
If the nozzles are not properly cleaned and flushed, it can create streaks on the pavement surface without tack. It should be noted that when emulsions are sprayed at high temperature compared to the ambient temperature, the asphalt binder residue often clogs the asphalt distributor nozzle when it cools after the distribution work is done.

2) Nozzle size

In general the size of the nozzle depends on the surface treatment. Chip seal treatment requires to have larger openings of nozzle because of its thicker liquid application whereas tack coat application requires nozzle with small openings due to thinner liquid. As a result a distributor with incorrect nozzle size for tack coat application can cause non-uniform appearance. Also, using too small size nozzle can create too much pressure resulting surface with spider web coating of tack coat material. It is better to follow the recommendation of the manufacturer in term of nozzle size and configuration that best fit the type of liquid to be sprayed. Fig. 2 shows the nozzle size and their coverage.

(a)

Fig. 2. (a) Examples of different nozzle sizes for application; (b) Display of single, double and triple overlay coverage (FHWA 2016)



(b)

Fig. 2. (a) Examples of different nozzle sizes for application; (b) Display of single, double and triple overlay coverage (FHWA 2016) (Continue)

3) Nozzle orientation

It is recommended to set all nozzle at the same angle (15° to 30°) to the axis of the spray bar in order to prevent the spray of liquid asphalt from interfering with adjacent spray nozzles. The emulsion from the nozzle spray will intersect if the nozzles are oriented parallel with the spray bar resulting a non-uniform surface. Also, if nozzles are angled closer to perpendicular with the spray bar it will create uncoated streaks because fans will not overlap. The lack of uniform angle will cause thicker or thinner coverage on the pavement and different coverage will create streaks and gaps in the tack coat. The recommended orientation can prevent steaking by providing overlap by keeping the spray fans of emulsion from interfering with each other.

4) Distribution bar pressure and speed

It is required that pressure within the distributor must be capable of forcing the tack coat material out of the spray nozzles at constant rate along with constant speed. If the pressure is not consistent the emulsion will simply dribble out of nozzles resulting non-uniform application rates or zebra stripe pattern.

5) Spray bar height

Spray bar height should remain constant during the application of tack coat. The too much low bar height can cause streaks whereas too much high bar height result non-uniform transverse coverage. It should be noted that sometimes there are areas which can be inaccessible for the distributor spray bar. In such case, use of spray wand can be helpful. With careful applications of spray wand proper coverage might be achieved.

6) Calibration of distributor

According to ASTM D 2995 there are two methods to calibrate asphalt distributor. At first the asphalt distributor sprays the tack coat over the pad which are weighted before and after in order to determine the application rate in $1/m^2$ (gsy). The first method determines the transverse and longitudinal application rate along with variability in the application rate of the emulsion applied to the pavement surface. The second method determines the transverse and longitudinal application rate along with variability in the application rate of the residual applied from emulsified asphalt applications to the pavement surface from asphalt distributor. It is recommended by the FHWA that asphalt distributor should be calibrated annually as a minimum and at the site a trail tack coat application should be done in order to check the nozzle operation.

7) Maintaining consistent temperature

The asphalt distributor should be capable of maintaining consistent temperature of the tack coat material so that the material can have adequate flow. It is worth to note that excessive heating can cause the emulsion to break before spraying to the pavement surface. Table 2 presents the guideline temperature for asphalt emulsion in terms of spraying and storage temperature.

Table 2. Recommended temperature of asphalt spray and storage for asphalt emulsion

Type and Grade	Spraying Temperature, °F	Storage Temperature, °F
RS-1, SS-1, SS-1h, CRS-1, CSS-1, CSS-1h	70 - 160	70 - 140
RS-2, CRS-2	140 - 185	125 - 185
Non-Tracking Tack	160 - 180	120 - 130
Polymer-Modified Emulsion	140 - 180	120 - 130

8) Tracking due to haul trucks

The most common problem regarding constructing tack coat is that haul trucks normally drive on the applied tack coat resulting the removal of tack coat material from the surface leading to slippage and delamination. There are three methods to overcome this challenge which are:

- Apply the tack coat to the pavement surface underneath the paver just ahead of the screed. It can be done with a special paver consists of a tack coat spray bar. A spray paver has dual functions: a) act as an asphalt distributor and b) act as an asphalt paver. The tack coat sprayed beneath the paver, behind the paver tracks and in front of the screeds which eliminates the possibility of any vehicle driving over the tack, having it stick to the tires and tracking it. The advantage is that the tack application settles on the pavement surface without any exposure to the dust or debris. However, potential concern may be the lack of given time for emulsion to break properly and having not any visual sight to see whether or not the tack coat is being sprayed uniformly.
- Using the material transfer vehicle (MTV)
- Using of modified tack coat materials without the stickiness or pick up problems.

3.2.2 Tack coat coverage

In order to have a uniform tack coat coverage parameters such as nozzle patterns, spray bar height, pressure, vehicle related adjustment, tack coat type, its application rate and settings are pivotal (Hachiya et al., 1997; ASTM D 2995-99). Also, it is always recommended to have double lap or triple lap coverage because single coverage can create streak even if one individual nozzle get wrong. It was reported that 90-95% tack coat coverage with uniform tack coat application can ensure maximum strength between layers (West et al., 2005; Al-Qadi et al., 2008). It was estimated that a loss of 10% in bond strength can decrease the life of pavement by 50% (Mohammad et al., 2012). Other research study concluded that 30% bond loss can trigger from having no bond to a decrease of 70% to 75% of pavement life (Brown and Brunton, 1984; Roffe and Chaignon, 2002). Fig. 3 shows the example of proper tack coated surface.

Fig. 3. Properly tacked surface (NCHRP 516)

3.3 Tack coat application rate

Selection of an optimum tack coat material and its application rate significantly contribute to the interlayer shear strength of upper and lower layer. The optimum tack coat application is required because too much application of tack coat can introduce slip plane which can decrease the bonding between layers. However, there is no consensus on what amount of tack coat application rate can be the optimum where shear strength will be maximum. The optimum word resembles the rate where the tack coat application should not become excessive so that slip plane can be avoided. Other than that some researchers mentioned that optimum tack coat application can ensure maximum interlayer shear strength (Raposeiras et al., 2013; Al-Qadi et al., 2008) whereas others found that this factor does not have significant effect on the interlayer shear strength (Mohammad et al., 2002; Canestrari and Santagata, 2005; Wheat, 2007; Mrawira and Yin, 2006). Pavement surfaces with different condition have such as old, milled and new pavement requires different rate of tack coat application.

The lower application rates are recommended for new or subsequent layers whereas intermediate range is for normal surface conditions on an existing relatively smooth surface. Old, oxidized, cracked, pocked or milled asphalt, and PCC pavements require higher application rate. Application of tack coat should be more on open-textured surface compared to tight and dense surface (HMAP Handbook – US Army Corps of Engineers, 2000). Also, it is worth to note that dry surface is required more tack coat material compared to flushed surface. Milled surface is required higher residual asphalt because of its increased surface area whereas new HMA layer is required only half as much residual asphalt (Cross and Shrestha, 2004). NCHRP 712, FHWA Tech Brief on Tack Coats, NAPA's QIP 128, WVDOT, and OHIO published typical tack coat application rate based on the surface condition. Table 3 presents these tack coat application rates according to the surface type.

Table 3. Recommended tack coat application based on the surface type

NCHRP Report 712			
Surface type	Residual application rate (gsy)	Approximate bar rate undiluted (gsy)	Approximate bar rate diluted 1:1 (gsy)
New asphalt mixture	0.035	0.058	0.12
Old asphalt mixture	0.055	0.09	0.18
Milled asphalt mixture	0.055	0.09	0.18
PCC	0.045	0.08	0.15

FHWA Tech Brief on Tack Coats			
Surface type	Residual rate (gsy)	Approximate bar rate undiluted (gsy)	Approximate bar rate diluted 1:1 (gsy)
New asphalt	0.02-0.05	0.03-0.07	0.06-0.14
Existing asphalt	0.04-0.07	0.06-0.11	0.12-0.22
Milled surface	0.04-0.08	0.06-0.12	0.12-0.24
PCC	0.03-0.05	0.05-0.08	0.10-0.16

NAPA QIP 128 Best Practices for Emulsion Tack Coats			
Existing condition	Residual asphalt binder (gsy)	Applied undiluted emulsion (gsy)	Applied diluted emulsion (gsy)
New asphalt	0.03-0.04	0.04-0.06	0.09-0.12
Old, aged asphalt	0.04-0.06	0.06-0.09	0.12-0.18
Milled asphalt	0.03-0.05	0.04-0.07	0.09-0.15
PCC	0.04-0.06	0.06-0.09	0.12-0.18

Table 3. Recommended tack coat application based on the surface type (Continue)

OHIO Proper Tack Coat Application			
Pavement condition	Residual (gsy)	Undiluted (gsy)	Diluted (1:1)
New HMA	0.03-0.04	0.05-0.07	0.10-0.13
Oxidized HMA	0.04-0.06	0.07-0.10	0.13-0.20
Milled surface (HMA)	0.06-0.08	0.10-0.13	0.20-0.27
Milled surface (PCC)	0.06-0.08	0.10-0.13	0.20-0.27
PCC	0.04-0.06	0.07-0.10	0.13-0.20

WVDOT		
Existing pavement	Undiluted (gsy)	Diluted (gsy)
New HMA	0.04-0.05	0.08-0.10
Oxidized HMA	0.07-0.10	0.13-0.20
Milled surface	0.10-0.13	0.20-0.27
PCC	0.07-0.10	0.13-0.20

3.4 Curing time and quality of compaction

Curing time indicates the tack coat break and set time. As tack coat break is the moment when water separates enough from the asphalt to show a color change from brown to black and tack coat set when all the water has evaporated, leaving only the residual asphalt. Some refer to this as completely broken. It is well recognized practice that an emulsion is given time to completely set before new mix is placed on top of the tack coat material (Hachiya et al., 1997; Sholar et al., 2004). Laboratory and field data indicate that interface shear strength increases with curing time (Tashman et al., 2006; Sholar et al., 2004; Chen and Huang, 2010; Tran et al., 2012). There is no agreement among literatures about how much curing time should be given to have proper curing. Hasiba et al. (2012) reported that with conventional paver 2 h curing time is required whereas Hachiya et al. (1997) suggested curing time with 24 hours. In the United States, many State DOT's have their specified curing time for emulsion break and set. For example: Alaska DOT specifies maximum of 3 hours curing time for CSS-1, Arkansas DOT has maximum 72 hours of curing time for SS-1 and Texas DOT has maximum setting period of 45 minutes for SS-1 and MS-2 (West et al., 2005; Roberts et al., 1991). However, study also showed that new layer was placed on top of unset and unbroken tack coat and no detrimental effect was observed (HMAP Handbook − US Army Corps of Engineers, 2000). In Europe tack coat is often applied to the pavement surface underneath the paver without giving time for break and set. The reason is that the emulsion will break immediately upon contact with the loose hot mix and it ensure the bond between interlayer surface (Chen and Huang, 2010; Zhang, 2017). In the United States, Novachip™ construction process used the emulsion spray method (Estakhri and Button, 1994, 1995).

Interlayer bonding strength also depends on the compaction technique, effort and quality. The compaction can be done by ramming, vibration or static rollers and so on. It was reported that bonding strength is increased when upper layer was compacted right on tack coat (Chen and Huang, 2010; Vaitkus et al., 2012).

4. Test devices for tack coat application

Dr. Jacob Uzan developed the first direct shear test device to identify the interlayer bond strength and used this to test a single paving grade binder 60-70 pen which was used as a tack coat in between a dual-layer system of dense-graded asphalt mixtures (Uzan et al., 1978). Anocona Shear Testing Research and Analysis (ASTRA) Interface Shear test was a modification to the direct shear test where horizontal load is applied along the interface of dual-layered sample at constant rate and a constant normal load is also applied on top of the specimen until failure (Santagata et al., 1993; Santagata and Canestrari, 1994). Based on the same principle (horizontal shear load to test specimen) LTRC Direct Shear Test was developed by Louisiana Transportation Research Center (LTRC) where horizontal load was applied to the specimen of asphalt concrete with a constant load of 50 lbs/min at a given temperature until the sample fail. Test devices such as Leutner Shear Test, Florida Direct Shear Test, Louisiana Interlayer Shear Strength Tester (LISST), Layer-Parallel Direct Shear (LPDS) Test, NCAT Shear Test applies shear load in vertical direction.

Leutner Shear Test was developed in Germany where a vertical load was applied to a double-layer sample specimen with a strain controlled mode at a constant rate of 2 in/min at 21.1°C until failure (Leutner, 1979). The equipment was capable of finding the maximum shear load and corresponding maximum displacement. LISST consists of a shearing and reaction frame with a gap of 0.5 in. (12.7 mm) between them where shearing frame is allowed to move and reaction frame remain fixed. It is capable of testing two different sizes sample (4 in or 100 mm and 6 in or 150 mm diameter). A constant displacement of 0.1 in/min (2.54 mm/min) and minimum value of 40 psi was categorized as a bond strength criteria (Mohammad et al., 2009, 2010). Florida Direct Shear Test is developed by Florida DOT where samples can be roadway cores or laboratory fabricated and do not require to be trimmed in order to place in the device. The gap width between shear plates is 0.19 in. Inside environmental chamber allows it to test sample at different temperatures and vertical load is applied with a strain control mode at a constant rate of 2 in/min until failure (Sholar et al., 2004). LPDS is used to measure the normal average shear stress and maximum shear stiffness in order to determine the quality of the mixture and the interlayer shear properties of the tack coat material. Both lab and pavement cores can be tested with a cylindrical composite specimen of 3.94 in diameter. It is modified by Swiss Federal Laboratory for Materials Testing and Research and a gap of 0.079 in (2 mm) is given between shearing rings (Raab and Partl, 2004, 2008). NCAT was developed by Alabama DOT-National Center for Asphalt Technology where specimen size of 5.9 in can be tested with a height of each layer greater than 1.97 in but less than 5.9 in. (West et al., 2005). Laboratorio de Caminos de Barcelona Shear Test (LCB) was developed by DOT, Technical University of Catalonia, Spain in order to measure the shear strength, shear modulus and specific cracking energy. The device is placed the dual-layer sample as a beam is located over two supports and vertical load is applied to the sample at a constant speed of 0.05 in/min in the middle of the two supports until failure occurs. The ATacker^{TM} is a lab or in situ test device invented by Introlek, Inc. and can provide both shear and tensile strength. The procedure is to detach the tack coat plates or contact plate and tack coat pavement using a pull or torque force. Virginia Shear Fatigue Test calculates the number of shear loading cycles at failure in order to determine the optimum application rate of asphalt binder tack at interface between two layers. It can measure the maximum shear stress of each cycle, shear stress against the number of cycles of failure and optimum tack coat application rate. A 0.10-s half sine wave is used as cyclic shear load followed by a relaxation period of 0.9 s until failure occurs (Donovan et al., 2000).

Bond strength can also be evaluated by applying tensile load and such devices are Switzerland Pull-Off Test, Traction Test, Wedge-Splitting Test, and UTEP Simple Pull-Off Test. Switzerland Pull-Off Test is used the tensile load at constant rate on a cylinder specimen of 3.94 in diameter where the sample needs to be glued and tensile strength value indicates the interlayer performance of the tack coat. Wedge-Splitting Test is developed by Technical University in Austria which used the maximum horizontal force and specific fracture energy to determine the fracture-mechanical behavior of layer bonding. Fracture energy is determined by applying a vertical load through a wedge to a dual-layered sample with a groove and starter notch along the interface at a constant rate until failure (Tschegg, 1997). UTEP Simple Pull-Off test was developed by University of Texas at El Paso where a tensile force is applied to pull off the contact plate from the tack coated surface in order to find out the tensile stress at failure (Deysarkar and Tandon, 2004). Traction Test device is invented by Ministere des Transports du Quebec, Canada where tensile force is applied at constant rate of 54 lb/s on a 4 in diameter sample size to determine the bond tensile strength.

The principle of twisting moment or torque was also used to determine the bonding strength of tack coat materials. Torque Bond Test (TBT) is considered as one of the most common torque test which was invented in Sweden and adopted in Great Britain to evaluate the thin bonded overlays (Tashman et al., 2006). The specimen bonded with the metal plate and torque is applied until the specimen fail or the maximum test value of 221 ftlb (300 Nm). TTI torsional Shear Test was developed by Texas Transportation Institute where a twisting moment with a constant rate of 2.9 E-04 radian/sec and a normal load is applied on the sample at a constant rate until failure. The evaluation of tack coat strength determined by the measurement of plastic shear strength. UTEP Pull-Off Test is used the torque force to identify the interlayer shear strength of tack coat by detaching contact plate and tack-coated pavement. The tensile stress at the point of failure is measured to identify the bond shear strength (Eedula and Tandon, 2006). Oregon Field Torque Tester (OFTT) was developed to evaluate the long-term post construction performance of tack coat materials. The developed OFTT can carry out multiple experiments in less than two hours in both field and laboratory settings and also a small platen of 2.5 in (63.5 mm) was included to reduce the cost, time and energy. A high correlation was observed between laboratory and field test results (Mahmoud et al., 2017). Woods developed two devices to measure the strength of tack coat material. Tack Coat Evaluation Device (TCED) measures the tensile and torque shear strength of tack coat material by compressing an aluminum plate to a surface with tack coat. Laboratory Bond Interface Strength Device (LBISD) is for the laboratory specimen which uses the Marshall device with a constant displacement rate 2 in/min (50.8 mm/min) (Woods, 2000).

Impulsive Hammer Test was developed at Nottingham University which is capable of measuring bonding strength of tack coat in field. It is applied with a hammer to the pavement surface at particular locations and measured the vertical dynamic response and fractal dimension number to evaluate the bond condition between layers in the field (Halim, 2004). In situ Shear Stiffness Test was developed to determine the shear strength and shear modulus of tack coat materials in the field. The strength is determined by applying a rotating force to the pavement through a test plate along with a normal weight by the test device (Sangiorgi et al., 2003).

5. Literature on tack coat bonding strength

There are several studies that have been performed on the bonding strength of tack coat application. The most referred work and probably the earliest one is conducted by Uzan et al. (1978). They studied the interface adhesion properties of asphalt layers and a 60-70 penetration binder was used for both mixed design and tack coat application. They used five application rates (0.0-0.4 lb/yd^2 or 0.0-2.0 kg/m^2), two test temperatures (77°F (25°C) and 131°F (55°C)) and five vertical pressure (0-71 psi (0-490 kPa) with a constant horizontal displacement of 0.1 in/min (2.5 mm/min). They concluded that shear resistance of the interlayer is significantly increased by the increasing vertical pressure and optimum tack application rate is observed to be double at high temperature compared to the optimum rate at low temperature.

Sangiorgi et al. (2002) used two surfacing materials [0.4 in stone mastic asphalt (SMA)] and 1.2 in hot rolled asphalt (HRA)], one binder (0.8-in dense bitumen macadams), one asphalt-stabilized base material (0.8-in dense bitumen macadams) and conducted laboratory assessment of bonding strength using Leutner shear test. Three different treatment types (tack coat emulsion, contaminated by dirt and without tack coat emulsion, and with tack coat emulsion and a thin film of dirt) were considered. The results showed that emulsion tack coat interface has higher bonding strength compared to the other binder course based on HMA and SMA surfacing condition.

Mohammad et al. (2002) used Superpave Shear Tester (SST) to evaluate the bonding strength of with a combination of four emulsions (CRS-2P, SS-1, CSS-1 and SS-1h), two asphalt binders (PG 64-22 and PG 76-22M), five residual application rate (0.00, 0.02, 0.05, 0.10 and 0.20 gal/yd^2), two test temperatures (25°C and 54°C) and constant loading of 50 lb/min (222.5 N/min). They found that CRS-2P exhibited the highest interface shear strength among all the tack coat application with an optimum application rate of 0.02 gal/yd^2.

West et al. (2005) conducted laboratory experiment in order to evaluate the best tack coat type and optimum application rate. The Albama DOT Test Method ALDOT-430 “Standard Test method for determining the Bond Strength between Layers of an Asphalt Pavement” or National Center for Asphalt Technology (NCAT) bond strength test was a product of this research. They evaluated a combination of two types of emulsions (CRS-2 and CSS-1) and one paving grade (PG 64-22), three residual application rates (0.02, 0.05 and 0.08 gal/yd^2), two mix types [0.75 in nominal minimal aggregate size (NMAS) coarse-graded and 0.19 in NMAS fine-graded], three test temperatures (10, 25 and 60°C), and three nominal pressure (0, 10 and 20 psi). They found that there is an inverse relationship between temperature and bonding strength regardless of tack coat type, application rates, mixture types and pressure levels. Paving binder exhibited the higher bond strength compared to the other emulsions. They also found that higher shear strength is observed at lower tack coat applications and confining pressure is considered as an important factor at high temperature.

Tran et al. (2012) extended this study from laboratory phase to both lab and field with computer simulation. In lab portion they studied four emulsions including one trackless tack coat, one paving grade binder, three different residual application rates, three surface conditions (milled, micro-milled and new HMA). In field portion, the study evaluated ten test sites (seven highways and three NCAT test track) with three emulsions and one paving binder, three applications. Hand wand sprayer, distributor truck and Novachip™ are used as distribution methods. Computer simulations were conducted using Bituminous Structure Analysis in Roads (BISAR). The results showed that milled HMA surface yielded high shear strength and Novachip™ spreader was good for distribution of tack coat application. Also, shear strength has significant effect due to surface thickness and stiffness and pavement temperature rather than subgrade or total pavement thickness.

Sholar et al. (2004) studied the effect on interlayer bonding strength due to moisture, application rate and aggregate interaction. They developed procedure for their new laboratory shearing device and performed in the state of Florida. They installed three field projects with four diluted emulsion application rates (no tack coat, 0.02 gal/yd^2, 0.06 gal/yd^2, and 0.08 gal/yd^2) and two diluted applications (0.02 gal/yd^2 and 0.06 gal/yd^2) combined with water to simulate rain condition. The results showed that existence of water can significantly reduce the shear strength, coarse-graded mixtures has high shear strength compared to fine-graded mixtures and milled surface exhibited superior shear strength compared to the other surface type.

Tayebali et al. (2004) conducted laboratory experiment to evaluate the bonding strength of tack coat and prime coat in asphalt concrete pavement. They studied one emulsified asphalt (CMS-2) and one hot asphalt cement (PG 64-22) as tack coat materials, three prime coats (EPR-1, CSS-1h and EA-P), three composite pavements (AC-AC, AC-PCC, and AC-CTB), 0.06 gal/yd^2 of tack coat application, 0.24 gal/yd^2 of prime coat application, and different test temperatures (AC-AC and AC-PCC testing temperatures were 70, 104 and 140°C and for AC-CTB testing temperatures were 40 and 60°C. The results showed that tack or prime coat significantly increases the shear strength of interlayer and the bond between similar surface condition (AC-AC) exhibited higher shear strength than the bind between two different surface state (AC-PCC).

Hachiya et al. (1997) conducted laboratory experiment on three cationic asphalt emulsions and three rubber-modified asphalt emulsions. They found that rubber modified emulsions exhibited higher shear strength at low temperature and PK-HR2 rubber emulsion has high shear strength among all emulsified asphalt. The optimum application rate was reported 0.04 gal/yd^2.

Buchanan and Woods (2004) investigated the effect of tack coat type, application rate, application temperatures, dilutions and emulsion setting time on tensile and torsional strength of tack coat material using Laboratory Bond Interface Strength Device (LBISD) and ATackerTM. Three emulsions (SS-1, CSS-1 and CRS-2) and one asphalt binder (PG 67-22). SS-1 and CSS-1 were evaluate at 24, 43, and 65°C temperatures whereas CRS-1 emulsions were evaluated at 49, 63 and 77°C. On the other hand, PG 67-22 was evaluated at 149°C with three application rate (0.04, 0.07 and 0.10 gal/yd^2. The results showed that PG 67-22 yielded higher bonding strength compared to other tack coat type and among emulsified tack coat types CRS-2 exhibited highest bonding strength.

Raab and Partl (2004) evaluated the interlayer adhesion strength of many tack coat types. They investigated twenty different tack coat types with two surface conditions (smooth and rough) and two compaction levels (240 and 50 gyrations) using Layer-Parallel Direct Shear (LPDS) test. The results showed that smooth surface exhibited high strength compared to specimens with rough surface because of their large contact area. Also, it was reported that addition of tack coat materials can significantly increase the adhesion properties of a wet surface. Hakim et al. (2012) reported that interface bond condition can significantly influence the stress and strain profile of a pavement. They use falling weight deflectometer (FWD) to determine the bond strength between layers.

Canestrari et al. (2005) investigated the effect of different variables on shear strength of tack coat using ASTRA shear device. Increasing shear strength was observed with decreasing temperature and emulsified tack coat ensure high peak shear stress at failure than without tack cot application.

NCHRP Report 712 or NCHRP Project 9-40 conducted by Mohammad et al. (2012) considered as one of the largest effort on evaluating tack coat properties and its effect on interlayer shear strength. Parameters which were used to evaluate the tack properties: four surface condition (Old HMA, New HMA, PCC, and milled HMA), five tack coat materials (SS-1h, SS-1, CRS-1, Trackless tack coat, and PG 64-22), four residual application rate (0, 0.031, 0.062, and 0.155 gsy), moisture condition (dry and wet), dust and clean condition, one test temperature (25°C), two confinement pressure (0 and 20), and two types of tack coat coverage (50% and 100%). The results showed that a) trackless tack coat exhibited the highest shear strength compared to the other tack coat, b) the optimum application was documented as 0.155 gsy, c) milled HMA surface provided the highest shear strength among all the surface type, d) tack coat coverage of 50% significantly reduced the interlayer shear strength because of their inconsistent and non-uniform interface bonding behavior with tacked surface, e) interlayer shear strength is observed to be increased with decrease in temperature. They recommended the existing surface to be cleaned and suggested optimum residual application rate of tack coat. LISST and LTCQT shear testing device was developed as a part of this project. Recently a synthesis report NCHRP 516 (2018) published a synthesis report from mainly four sources which are: NCHRP report 712, FHWA Tech Brief Tack Coat Best Practices, NAPA's QIP 128 (Best practices for emulsion tack coat) and FHWA/Asphalt Institute 4-hour workshop. They also conducted a survey in US and Canadian province. The survey questions covered the tack coat materials, application rate, their construction practices and current tack coat projects. Three states (Kansas, Texas and West Virginia) are used as case example of tack coat practices because of their long history with tack coat practices. The synthesis suggested several recommendations related to proper tack coat application that was discussed earlier in the paper. It was reported that fifteen states and four provinces their current tack coat project focusing on bond strength testing, performance of reduced tracking materials, reducing the amount of tracking in the field and producing general guidance of tack coat application for contractor and agency personnel.

6. Conclusions

This paper has reviewed the state of the art practices of tack coat application. Several studies were conducted on different influencing factors behind proper tack coat application. Different types of tack coat and their application rate based on the surface texture, details evaluation of different parts of asphalt distributor, test devices used for characterizing tack coat properties were discussed based on the published literature, research and agency specification. Based on the analysis of this paper, the following conclusion can be drawn:

1) Trackless tack coat showed superior performance compared to the other tack coat types. However, due to its low top down cracking resistance it may be vulnerable in cold region. Selection of tack coat material and its application rate is found to have effect on the interlayer shear strength of pavement.
2) It is important to have and follow manufacture guidelines on best tank types, maximum storage times,

agitation, storage temperature, compatibility with other liquids, contamination, freezing, and boiling. Also, instructions should be stored in terms of emulsion storage, handling, and sampling guidelines.

3) Surface type, condition and texture play an important role for proper tack coat application. Milled surface exhibited superior shear strength compared to the other surface type. It is recommended to have clean and dry surface before applying tack coat. Aggregate gradation, mixture type, and bonding between similar surface conditions have significant effect on the bonding strength.
4) The asphalt distributor with proper nozzle size, nozzle orientation, bar pressure and speed, spray bar height, temperature should be used in the field. The calibration of the distributor and field supervision during tack coat application is recommended. The uniform tack coat application with 90-95% coverage is recommended.
5) Based on the literature there is no consensus on curing time of tack coat application. In practice some agency specify curing time and on the other hand some agency apply upper layer without giving time. Future study on this particular topic is recommended.
6) In laboratory shear test is most commonly used to determine the interlayer shear strength of pavement. A suitable non-destructive test device would be more useful for field application. Further research and field study focusing on developing superior trackless tack coat and suitable non-destructive test device is recommended.

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References

A Basic Asphalt Emulsion Manual. Manual Series No. 19 (MS-19) Third edition, The Asphalt Institute, Lexington, KY.

Abd El Halim, A. O. (2004) An in-situ Shear Stiffness Test Facility for Asphalt Concrete Pavement (No. NCHRP-IDEA Project 87).

Al Hakim, B., Cheung, L. W. and Armitage, R. J. (1999) Use of FWD Data for Prediction of Bonding Between Pavement Layers. International Journal of Pavement Engineering, Vol. 1, No. 1, pp. 49-59.

Al-Qadi, I. L., Carpenter, S. H., Leng, Z., Ozer, H. and Trepanier, J. (2008) Tack Coat Optimization for HMA Overlays: Laboratory Testing. Illinois Center for Transportation.

AASHTO. (2017) Standard Specification for Cutback Asphalt (Rapid-Curing Type), AASHTO Designation M 81-92 (2012) Washington, D.C.

AASHTO. (2017) Standard Specification for Cutback Asphalt (Medium-Curing Type), AASHTO Designation M 82-75 (2012) Washington, D.C.

ASTM. (2003) ASTM D 2995-99: Standard Practice for Estimating Application Rate of Bituminous Distributors. Annual Book of ASTM Standards 2003, Section 4: Construction, Volume 04.03, ASTM, West Conshohocken, PA.

ASTM. (2004) ASTM D8-02. Standard Terminology Relating to Materials for Roads and Pavements, Annual Book of ASTM Standards, Vol. 04.03.

ASTM. (2015) ASTM D2026/D2026M-15, Standard Specification for Cutback Asphalt (Slow-Curing Type). ASTM International, West Conshohocken, PA. www.astm.org.

Asphalt Emulsion Manufacturers Association. (2009) Basics of Asphalt Emulsions, FAQs, Oct. 2009, [Online]. Available: http://www.aema.org/resources/faqs/basics-of-asphalt-emulsions/.

Asphalt Institute. (2011) The Asphalt Binder Handbook. Manual Series 26 (MS-26), 1st ed. Asphalt Institute, Lexington, KY.

Asphalt Institute and Asphalt Emulsion Manufacturers Association. (2008) Basic Asphalt Emulsion Manual, Manual Series 19 (MS-19), 4th ed. Asphalt Institute, Lexington, KY.

Bae, A., Mohammad, L., Elseifi, M., Button, J. and Patel, N. (2010) Effects of temperature on interface shear strength of emulsified tack coats and its relationship to rheological properties. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2180, pp. 102-109.

Brown, S. F. and Brunton, J. M. (1984) The influence of bonding between bituminous layers. The Journal of the Institution of Highways and Transportation, Vol. 31, No. 5, 16-17.

Buchanan, M. S. and Woods, M. E. (2004) Field tack coat evaluator (ATACKer) (No. FHWA/MS-DOT-RD-04-168). Mississippi State University. Dept. of Civil Engineering.

Canestrari, F., Ferrotti, G., Partl, M. and Santagata, E. (2005) Advanced testing and characterization of interlayer shear resistance. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1929, pp. 69-78.

Canestrari, F. and Santagata, E. (2005) Temperature effects on the shear behaviour of tack coat emulsions used in flexible pavements. International Journal of Pavement Engineering, Vol. 6, No. 1, pp. 39-46.

Chen, D. H. (2009) Slippage failure of a new hot-mix asphalt overlay. Journal of Performance of Constructed Facilities, Vol. 24, No. 3, pp. 258-264.

Chen, J. S. and Huang, C. C. (2010) Effect of surface characteristics on bonding properties of bituminous tack coat. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2180, pp. 142-149.

Chen, Y., Tebaldi, G., Roque, R., Lopp, G. and Su, Y. (2012) Effects of interface condition characteristics on open-graded friction course top-down cracking performance. Road Materials and Pavement Design, Vol. 13(sup1), pp. 56-75.

Clark, T. M., Rorrer, T. M. and McGhee, K. K. (2012) Trackless tack coat materials: a laboratory evaluation for performance acceptance (No. VCTIR 12-R14).

Collop, A. C., Sutanto, M. H., Airey, G. D. and Elliott, R. C. (2009) Shear bond strength between asphalt layers for laboratory prepared samples and field cores. Construction and Building Materials, Vol. 23, No. 6, pp. 2251-2258.

Construction of Hot Mix Asphalt Pavements. Manual Series No. 22 (MS-22), Second edition, The Asphalt Institute, Lexington, KY.

Cross, S. A. and Shrestha, P. P. (2004). Guidelines for Using Prime and Tack Coats (No. FHWA-CFL-04-001).

Curtis, C. W., Ensley, K. and Epps, J. (1993) Fundamental properties of asphalt-aggregate interactions including adhesion and absorption (No. SHRP-A-341). Washington, DC: National Research Council.

Deysarkar, I. and Tandon, V. (2004) Development of an objective field test to determine tack coat adequacy. University of Texas at El Paso, Center for Transportation Infrastructure Systems.

Donovan, E., Al-Qadi, I. and Loulizi, A. (2000) Optimization of tack coat application rate for geocomposite membrane on bridge decks. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1740, pp. 143-150.

Du, J. C. (2011) Evaluation of shear strength on pavement layers by use tack materials. In Advanced Materials Research. Trans Tech Publications. Vol. 255, pp. 3176-3179.

Etnyre, E. D. and Co. Centennial Series Booklet. Asphalt Distributors, 2017.

Eedula, S. R. and Tandon, V. (2006) Tack coat field acceptance criterion (No. FHWA/TX-06/0-5216-1).

Estakhri, C. K. and Button, J. W. (1994) “Evaluation of Novachip™—Construction Report,” Research Report 553-1, Texas Transportation Institute for Texas DOT, July.

Estakhri, C. K. and Button, J. W. (1995) “Performance Evaluation of Novachip™—Ultrathin Friction Course,” Report 553-2F, TexasTransportation Institute for Texas DOT, November.

FHWA (2016) Technical Brief: Tack Coat Best Practices. FHWA-HIF-16-017. Washington, D.C.

Florida Department of Transportation. Construction Training Qualification Program, Module 4, “Surface Preparation.” Gainesville, 2016, [Online]. Available: http://www.ctqpflorida.com/books/pdf/Asphalt%20Paving%202/04%20Mod_4_Surface_Prep.pdf.

Ghaly, N. F., Ibrahim, I. M. and Noamy, E. M. (2014) Tack coats for asphalt paving. Egyptian Journal of Petroleum, Vol. 23, No. 1, pp. 61-65.

Gierhart, D. and Johnson, D. R. (2018) Tack Coat Specifications, Materials, and Construction Practices. NCHRP Synthesis of Highway Practice, 516.

Gregory, A. S., Galr, C. P., James, A. M., Patrik, B. U. and Howard, L. M. (2002) Preliminary Investigation of a Test Method to Evaluate Bond Strength of Bituminous Tack Coats. Research Report, Florida DOT, FL/DOT/SMO/02-459.

Handbook, H. M. A. P. (2000) AC 150/5370-14A. US Army Corps of Engineers, Washington, DC.

Hachiya, Y., Umeno, S. and Sato, K. (1997) Effect of tack coat on bonding characteristics at interface between asphalt concrete layers. Doboku Gakkai Ronbunshu, Vol. 1997, No. 571, pp. 199-209.

Hakimzadeh, S., Buttlar, W. G. and Santarromana, R. (2012) Shear-and tension-type tests to evaluate bonding of hot-mix asphalt layers with different tack coat application rates. Transportation Research Record, Vol. 2295, No. 1, pp. 54-62.

Hasiba, K. (2012) Development of a testing approach for tack coat application rate at pavement layer interfaces.

King, G. and May, R. (2003) New Approaches to Tack Application. Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.

Kruntcheva, M. R., Collop, A. C. and Thom, N. H. (2006) Properties of asphalt concrete layer interfaces. Journal of Materials in Civil Engineering, Vol. 18, No. 3, pp. 467-471.

Leng, Z., Ozer, H., Al-Qadi, I. and Carpenter, S. (2008) Interface bonding between hot-mix asphalt and various Portland cement concrete surfaces: laboratory assessment. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2057, pp. 46-53.

Leutner, R. (1979) Untersuchung des Schichtenverbundes beim bituminösen Oberbau. Bitumen, Vol. 41, No. 3.

Mahmoud, A., Coleri, E., Batti, J. and Covey, D. (2017) Development of a field torque test to evaluate in-situ tack coat performance. Construction and Building Materials, Vol. 135, pp. 377-385.

Mohammad, L. N., Bae, A., Elseifi, M. A., Button, J. W. and Scherocman, J. A. (2009). Interface shear strength characteristics of emulsified tack coats. Journal of the Association of Asphalt Paving Technologists, Vol. 78, pp. 249-278.

Mohammad, L. N., Bae, A., Elseifi, M. A., Button, J. and Patel, N. (2010) Effects of pavement surface type and sample preparation method on tack coat interface shear strength. Transportation Research Record, Vol. 2180, No. 1, pp. 93-101.

Mohammad, L., Raqib, M. and Huang, B. (2002) Influence of asphalt tack coat materials on interface shear strength. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1789, pp. 56-65.

Mohammad, L. N., Hassan, M. and Patel, N. (2011) Effects of shear bond characteristics of tack coats on pavement performance at the interface. Transportation Research Record, Vol. 2209, No. 1, pp. 1-8.

Mohammad, L., Saadeh, S., Qi, Y., Button, J. W. and Scherocman, J. (2008) Worldwide state of practice on the use of tack coats: a survey. Journal of the Association of Asphalt Paving Technologists, Vol. 77, pp. 1-34.

Mohammad, L., Elseifi, M., Bae, A., Patel, N., Button, J. and Scherocman, J. (2012) NCHRP Report 712: Optimization of Tack Coat for HMA Placement, Transportation Research Board of the National Academies, Washington, D.C.

Mrawira, D. and Damude, D. J. (1999) Revisiting the effectiveness of tack coats in HMA overlays: the shear strength of tack coats in young overlays. In Proceedings of The Annual Conference-Canadian Technical Asphalt Association (pp. 115-130). Polyscience Publications; 1998.

Mrawira, D. and Yin, D. Y. (2006) Field Evaluation of the Effectiveness of Tack Coats in Hot-Mix Asphalt Paving (No. 06-1248).

National Asphalt Pavement Association. Best Practices for Emulsion Tack Coats. Quality Improvement Publication 128, Lanham, MD, Oct. 2013.

Paul, H. and Scherocman, J. (1998) Friction testing of tack coat surfaces. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1616, pp. 6-12.

Proper Tack Coat Application. Technical Bulletin, Flexible Pavement of Ohio, Columbus, OH, 2001.

Raab, C. and Partl, M. N. (2004) Effect of tack coats on interlayer shear bond of pavements. In Proceedings of the 8th conference on Asphalt Pavements for Southern Africa (CAPSA'04), Vol. 12, p. 16, September.

Raab, C. and Partl, M. N. (2008) Investigation Into a Long-Term Interlayer Bonding of Asphalt Pavements. Baltic Journal of Road & Bridge Engineering, Vol. 3, No. 2.

Raab, C. and Partl, M. N. (2004) Interlayer shear performance: experience with different pavement structures. In Proceedings of the 3rd Eurasphalt and Eurobitume Congress Held Vienna, May 2004, Vol. 1.

Raposeiras, A. C., Castro-Fresno, D., Vega-Zamanillo, A. and Rodriguez-Hernandez, J. (2013) Test methods and influential factors for analysis of bonding between bituminous pavement layers. Construction and Building Materials, Vol. 43, pp. 372-381.

Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y. and Kennedy, T. W. (1991) Hot mix asphalt materials, mixture design and construction.

Roffe, J. C. and Chaignon, F. (2002) Characterization Tests on Bond Coats: Worldwide Study, Impact, Tests, Recommendations. Presented at the 3rd International Conference on Bituminous Mixtures and Pavements, Thessaloniki, Greece.

Sangiorgi, C., Collop, A. C. and Thom, N. H. (2002) Laboratory assessment of bond condition using the Leutner shear test. In 3rd International Conference on Bituminous Mixtures and Pavements, Thessalonkiki, Greece, November, pp. 315-324.

Sangiorgi, C., Collop, A. and Thom, N. H. (2003) A non-destructive impulse hammer for evaluating the bond between asphalt layers in a road pavement.

Santagata, E., Canestrari, F. and Santagata, F. A. (1993) Laboratory shear testing of tack coat emulsion. In Proceedings of 1st world congress on emulsion, Paris.

Santagata, E. and Canestrari, F. (1994) Tensile and shear tests of interfaces in asphalt mixes: a new prospective on their failure criteria. In 2nd International Symposium Highway Surfacing.

Seo, A. Y., Sakhaeifar, M. S., Wilson, B. T. and Chowdhury, A. (2016) Bonding Strength of Non-Tracking Tack Coat (No. 16-3519).

Sholar, G. A., Page, G. C., Musselman, J. A., Upshaw, P. B. and Moseley, H. L. (2004) Preliminary investigation of a test method to evaluate bond strength of bituminous tack coats (with discussion). Journal of the Association of Asphalt Paving Technologists, Vol. 73, pp. 771-806

Song, W., Shu, X., Huang, B. and Woods, M. (2017) Influence of interface characteristics on the shear performance between open-graded friction course and underlying layer. Journal of Materials in Civil Engineering, Vol. 29, No. 8, 04017077.

Song, W., Shu, X., Huang, B. and Woods, M. (2015) Factors affecting shear strength between open-graded friction course and underlying layer. Construction and Building Materials, Vol. 101, pp. 527-535.

Tashman, L., Nam, K. and Papagiannakis, A. T. (2006) Evaluation of the influence of tack coat construction factors on the bond strength between pavement layers (No. WA-RD 645.1). Washington State Department of Transportation.

Tayebali, A. A., Rahman, M. S., Kulkarni, M. B. and Xu, Q. (2004) A mechanistic approach to evaluate contribution of prime and tack coat in composite asphalt pavements (No. FHWA/NC/2004-05).

Techbrief: Tack Coat Best Practices (2016) Asphalt Institute. Retrieved from http://www.asphaltinstitute.org/wp-content/uploads/Tack-Coat-Tech-Brief.pdf

Tran, N., Willis, R. and Julian, G. (2012) Refinement of the bond strength procedure and investigation of a specification. National Center for Asphalt Technology, Auburn, AL.

Tschegg, E. K. (1997) An efficient fracture test method for bituminous materials and layer bonds. In Proc. of the Fifth Intern. RILEM Symposium on Mechanical Tests for Bituminous Materials, Lyon, pp. 405-411.

Uzan, J., Livneh, M. and Eshed, Y. (1978) Investigation of adhesion properties between asphaltic-concrete layers. In Association of Asphalt Paving Technologists Proc, Vol. 47.

Vaitkus, A., Cygas, D., Laurinavicius, A., Vorobjovas, V. and Kleiziene, R. (2012) Research of asphalt layer bonding in Lithuanian pavement structures. Gradevinar, Vol. 64, No. 11, pp. 915-921.

West, R. C., Zhang, J. and Moore, J. (2005) Evaluation of bond strength between pavement layers. NCAT report, 05-08.

West Virginia Department of Transportation. Certified Bituminous Materials. Charleston, 2017, [Online].

West, R. C., Zhang, J. and Moore, J. (2005) Evaluation of bond strength between pavement layers. NCAT report, 05-08.

Wheat, M. (2007) Evalu [t] ation of bond strength at asphalt interfaces.

Woods, M. E. (2000) Laboratory evaluation of tensile and shear strengths of asphalt tack coats. Master's Thesis, Mississippi State University.

Zhang, W. (2017) Effect of tack coat application on interlayer shear strength of asphalt pavement: A state-of-the-art review based on application in the United States. International Journal of Pavement Research and Technology, Vol. 10, No. 5, pp. 434-445.

Ziari, H. and Khabiri, M. M. (2007) Interface condition influence on prediction of flexible pavement life. Journal of Civil Engineering and Management, Vol. 13, No. 1, pp. 71-76.