COMPOSITE SPECIMEN TESTING TO EVALUATE THE EFFECTS OF PAVEMENT LAYER INTERFACE CHARACTERISTICS ON CRACKING PERFORMANCE

By

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To my parents
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By

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Open graded mixture which is widely used for Open Graded Friction Course (OGFC) has considerably lower values of fracture energy density and dissipated creep strain energy density to failure than dense-graded mixture. Since those OGFC may be ‘first front’ in resisting top-down cracking, previous research has suggest that the quality of the OGFC mixture and the bond between OGFC and the structural layer affects top-down cracking performance. The primary objective of this study is to identify a method to evaluate the effect of interface bonding condition on top-down and reflective cracking within the composite pavement system.

A composite specimen interface cracking (CSIC) test was developed to evaluate the effects of pavement layer interface characteristics on cracking performance. The following factors were considered and evaluated when developing the testing system: loading mode, specimen symmetry, stress concentration method and specimen curved end surface reinforcement. Proper data collection and interpretation methods were developed to properly account for the complex stress distribution and progressive damage during the test. Three types of interface conditions were evaluated for top-down cracking, while two types of interface conditions were evaluated for reflective cracking.
In addition, the effect of OGFC on top-down cracking was evaluated using this newly developed test method. Novabond® when used as a bonding agent between the OGFC and underlying structural layer, polymer modified asphalt emulsion (PMAE), increased the top-down cracking performance of composite pavement. More generally, it was determined that the effectiveness of bonding agent is closely related to its brittleness. Trackless tack coat, which is also polymer modified, but much more brittle than Novabond®, was determined to have a negative effect on top-down cracking performance. As compared with conventional tack coat, Novabond® was determined to improve the reflective cracking resistance of composite pavement. Novabond® application rate was determined to have a significant effect on the top-down and reflective cracking resistance. The introduction of an OGFC with conventional tack coat on dense-graded mixture was determined to reduce the cracking resistance of composite pavement as compared with pavements without OGFC. The research clearly illustrated the importance of interface bond and flexibility on top-down and reflective cracking performance.
CHAPTER 1
INTRODUCTION

1.1 Background

Since first constructed by California Department of Highways in 1944, OGFC has been widely used in the United States (NCHRP 2000). With primarily single sized and gap-graded gradation, OGFC has a much higher percentage of air voids, in the range of 15% to 25%, as compared to dense-graded mixture (Kandhal and Mallick 1998). This high air void content gives OGFC a great deal of potential to improve road safety under wet conditions by reduction in hydroplaning and tire splash and spray, especially in southern parts of the United States with frequent high intensity short-duration rainfall events. However, there are several problems associated with OGFC, including low durability and rutting resistance, and decreasing porosity through voids clogging. Most of the OGFC research work done so far has been related to function issues, such as skid resistance, permeability and noise reduction. Most existing pavement design guidelines consider the OGFC as a wearing surface layer with no structural value.

However, it is recognized that OGFC mixtures may be the 'first front' in resisting top-down cracking. Thus it is necessary to evaluate the fracture resistance of the OGFC. Open graded mixture has considerably lower values of fracture energy density and dissipated creep strain energy density to failure than dense-graded asphalt mixture based on specimens produced in the laboratory (Koh 2009). However, fracture resistance of open graded mixture from field cores has not been measured because of difficulties in recovering representative specimens from thin OGFC layers.

Based on the analysis of findings from pavement field sections in Florida (e.g. SR-16 in Bradford County, FL and US-27 in Highlands County, Florida), there is suggestive
evidence that the quality of OGFC and the effectiveness of the bond between OGFC and the structural mixture affects top-down cracking performance. A bonded OGFC is an open graded HMA mixture laid on a dense-graded mixture using a relatively thick polymer modified asphalt emulsion, such as Novabond®. Polymer modified asphalt emulsion seals existing pavement and bonds the OGFC to the underlying surface. The relatively thick nature of the polymer modified asphalt emulsion allows it to migrate upwards into the OGFC, filling voids in the aggregate and creating an interface of high cohesion. Some of the potential advantages of bonded OGFC are dissipation of stresses and increased fracture resistance of the OGFC near the interface. In addition, recent laboratory work at the University of Florida (Birgisson et al. 2006) suggests that cracks that develop either in the OGFC or the HMA structural layer can be effectively arrested and/or deterred with appropriate interface conditions and bonded interface formed at the bottom of the OGFC, which reduces the rate of creep and damage of the composite system. However, limited work has been done to develop a suitable fracture performance test (and test conditions) that can characterize the effect of bonded interface on top-down cracking.

Therefore, it is necessary to identify and develop a method to evaluate the effect of bonded interface on top-down or reflective cracking within the composite pavement system. This test may also serve as an appropriate method to evaluate the effect of OGFC or other thin layers on top-down cracking.

1.2 Hypothesis

The use of highly cohesive interface formed by introducing a relatively thick polymer modified asphalt emulsion between asphalt mixture lifts (surface to structural, structural to existing) can increase the resistance to top-down or reflective crack
propagation by dissipating stresses or by reducing stresses transmitted through the interface.

1.3 Objectives

The objectives of this research may be summarized as follows:

- Develop a composite specimen testing method for the evaluation of bonded interface on top-down and reflective cracking resistance;
- Evaluate the effect of bonded interface on top-down cracking resistance;
- Evaluate the effect of bonded interface on reflective cracking resistance;
- Evaluate the effect of OGFC on top-down cracking;

1.4 Scope

This study will primarily focus on the identification of an appropriate evaluation method that allows for the characterization of the effect of bonded interface on top-down cracking and reflective cracking resistance and the effect of OGFC or other thin layers on top-down cracking. In order to develop testing protocols for composite specimen tests, two Superpave dense-graded mixtures were used to evaluate the possible damage to the dense-graded HMA induced during the composite specimen compaction process. One Superpave dense-graded mixture and two open-graded mixtures were used to produce composite specimens for test method development. Three types of interface bonding conditions were examined: the conventional tack coat, Novabond® polymer modified asphalt emulsion and trackless tack. For each interface type, only one application rate was examined, as recommended by manufacturers. For the effect of bonded interface on reflective cracking resistance, composite specimens consisting of dense-graded mixture placed on dense-graded mixture with two types of interfaces, and double Novachip® on concrete field cored composite specimens with 3 different
Novabond® application rates will be examined. All tests were conducted at one temperature (10°C), which has been determined to work well in prior fracture research at UF.

1.5 Research Approach

The approach taken for the development of an appropriate method for the evaluation of the effects of bonded interface on top-down and reflective cracking and OGFC on top-down cracking involved the following:

- **Literature review**: (1) Evaluation of pavement interface; (2) Top-down and reflective cracking mechanism; (3) Existing testing methods for composite specimen cracking resistance evaluation, with or without interface.

- **Test method development**: Develop a composite specimen testing method and associated data interpretation method for the evaluation of the effect of bonded interface on top-down and reflective cracking.

- **Conduct composite specimen testing**: To (1) evaluate the effect of different interface conditions on top-down cracking; (2) evaluate the effect of different interface conditions on reflective cracking; (3) evaluate the effect of OGFC on top-down cracking.

During the development of the appropriate testing method, finite element method analysis will be conducted to optimize the composite specimen geometry.
CHAPTER 2
LITERATURE REVIEW

2.1 Evaluation of Pavement Layer Interface

2.1.1 Background

Bonding agent is usually applied on existing clean asphalt or concrete surfaces to provide adhesive bond between existing pavement surface and newly constructed asphalt overlay. Three types of bonding agent will be evaluated in this work, conventional tack coat, polymer modified asphalt emulsion, and trackless tack.

Tack coat is the most commonly used bonding agent between pavement layers. According to ASTM D 8-02 Standard Terminology Relating to Materials for Road and Pavements, “Tack coat (bond coat) is an application of bituminous material to an existing relatively non absorptive surface to provide a thorough bond between old and new surfacing” (ASTM 2003). The tack material can be asphalt emulsion (slow, medium, and fast setting), cutback asphalt, high float emulsion, and polymer modified asphalt emulsion, and paving grade asphalt cement (Cross and Shrestha 2005; West et al. 2005; Wheat 2007). Since cutback asphalt contain volatile chemicals that evaporate into the atmosphere whereas emulsified asphalts evaporate water into the atmosphere, its usage has been greatly reduced (Texas Technical Advisory 2001). Several surveys indicated that anionic and cationic slow setting asphalt emulsions are the most widely used tack material (Chaignon and Roffe 2001; Mohammad et al. 2008; Santucci 2009). Paving grade asphalt cement is occasionally used for night work or work in cool weather or where multiple pavement layers are being placed and closure time is critical because it does not need any time to break, but they need to be heated for spray application (Cross and Shrestha 2005; Tack Coat Guidelines 2006; Santucci 2009).
Polymer modified asphalt emulsion has been widely used in ultrathin friction course (Russell et al. 2008; Kandhal and Lockett 1997; Cooper and Mohammad 2004), ultrathin bonded wearing course (Rurani 2007), bonded wearing course (MTAG 2007), and bonded friction course (Birgisson et al. 2006). In spite of the differences among ultrathin friction course, ultrathin bonded wearing course, bonded wearing course, and bonded friction course, all are developed from NovaChip® with different overlay mixtures and tack coat materials. NovaChip® is a paving process utilizing a single piece of equipment (spray-paver) to place a thin, gap graded HMA onto a relatively thick Novabond® membrane (polymer modified asphalt emulsion seal coat) (Kandhal and Lockett 1997; Russell et al. 2008). The polymer modified asphalt emulsion seals the existing pavement surface and produces high asphalt binder content at the interface of existing pavement surface, bonding the gap or open-graded mixture to the original pavement surface (MTAG 2007). The relatively thick nature of the polymer modified asphalt emulsion allows it to migrate upwards into the OGFC, filling voids in the aggregate and creating an interface of high cohesion.

Tracking or pickup occurs when the tack coat is picked up by the rubber tires of construction equipment and removed from the existing pavement surface. The survey conducted by Mohammad et al. (2008) indicated that 38% of the respondents required that the tack coat material should be completely set before haul trucks are allowed on it to reduce the tracking problem. At present, there are several ‘trackless’ tack products on the market (e.g., Blacklidge Emulsion, Inc. trackless tack and Ultrabond®, and NTSS-1HM emulsion trackless tack). Trackless tack can be driven over by haul trucks and paver without tracking.
2.1.2 Influencing Factors on Pavement Layer Interface Performance

It is generally believed that pavement layer interface characteristics between an existing pavement and an overlay are affected by several factors. These factors include the tack coat type, application rate, curing time, moisture, temperature, surface conditions, pavement structure, and testing method and loading conditions.

2.1.2.1 Tack coat type

Various types of materials, including asphalt emulsion, paving grade asphalt binder, cutback asphalt, and trackless tack, have been used as interface layer materials between AC layers, and between AC and PCC layers. Many studies have reported that paving grade asphalt binders, like PG64-22 and PG67-22, have higher shear strength compared to asphalt emulsions when they are used as interface layer materials between HMA layers (Buchanan and Woods 2004; Tayebali et al. 2004; West et al. 2005). The possible reason for this is attributed to the higher viscosity of paving grade asphalt binder. However, Tayebali et al. (2004) pointed out that asphalt emulsion CMS-2 performs better than PG 64-22 when they are used as interface materials between PCC and AC layers. This phenomenon was explained by slippage that occurred between PCC and AC layers because of the imperviousness of the PCC layer.

Latex modified asphalt emulsion (CRS-2L) has been reported to have better performance than unmodified asphalt emulsion (SS-1, CSS-1, SS-1h and SS-1L) and paving grade asphalt binder (PG64-22 and PG76-22M) at 130 °F; but statistical analysis indicated the latex modified asphalt emulsion is not significantly different from the same emulsion without latex (Mohammad et al. 2005).

Mohammad et al. (2009) indicated that trackless tack exhibited higher interface shear strength than asphalt emulsions CRS-1 and SS-1h at three application rates, 0.14
These results were directly related to the viscosity of the residual binder at 25°C; this supports the view of Tayebali et al. (2004). The non-tracking tack used by VDOT exhibited laboratory lower shear strength than asphalt emulsion CSS-1h and CRS-2 (McGhee and Clark 2009). However, the difference was attributed to the different interface layer materials and testing methods.

In order to evaluate the effect of interface conditions between AC overlay and PCC pavement on the overlay service life, the laboratory work performed by Leng et al. (2008) concluded that asphalt emulsion, SS-1hP, provided better interface shear strength than cut back asphalt, RC-70 at the same application rate; Accelerated Pavement Testing (APT) indicated that PG64-22 and SS-1hP have better rutting resistance than RC-70 when they are applied at the same residue application rate (Leng et al. 2009).

2.1.2.2 Application rate

Insufficient bond between pavement layers can result in a significant reduction in the shear strength in the pavement structure, thus making the whole pavement work in separate layers and leading to many pavement problems such as fatigue cracking, top down cracking, delamination, and slippage failure (Uzan et al. 1978; Tayebali et al. 2004; Tashman et al. 2006; Tashman et al. 2008). However, excessive bonding agent may reduce adhesion and aggregate interlock (Uzan et al. 1978), increase slippage between pavement layers (Tashman et al. 2008), reduce air void content of the overlay mixture because of the migration of bonding agent into the HMA mat during compaction (Mohammad et al. 2009).

Therefore, it is of great significance to estimate the optimum bonding agent application rate for different interface conditions. Optimum residue application rate has
been determined by Mohammad et al. (2002 and 2005) for modified asphalt emulsion CRS-2P and CRS-2L to be 0.02 gal/sy when it is applied between HMA layers and by Leng et al. (2008) for SS-1hP to be 0.04 gal/sy when it is applied between HMA and PCC.

The improvements of bond between pavement layers on the interface shear resistance are varied among the studies completed to date. Study by Tayebali et al. (2004) indicated that bonded surfaces have extremely high strengths compared to non-bonded surfaces. Specimens with no tack applied failed at the interface during the coring process and all three tack coat materials, SS-1h, CRS-1 and trackless tack, exhibited the higher shear strength at 0.16 gal/sy than at 0.03 and 0.06 gal/sy (Mohammad et al. 2009). Specimens with cationic emulsion interface at the rate of 150g/m² between HMA layers displayed much higher shear strength than those with no emulsion (Collop et al. 2010).

West et al. (2005) reported that for both CSS-1 and CRS-2 emulsions with three residue application rates, 0.02, 0.05 and 0.08 gal/sy, lower application rate generally displayed higher bond strength when they are applied between HMA layers consisting of 4.75 mm NMAS fine-graded mixture; however, application rate has little effect on bond strength when they are applied between HMA layers consisting of 19.0 mm NMAS coarse-graded mixture.

Some studies have concluded that the use of tack coat material does not necessarily result in an increase in interlayer shear strength. Sholar et al. (2002) reported that the shear strength increase slightly as the tack coat application rate was increased; but the strengths essentially equalized regardless of the application rates.
after weeks of traffic for pavements consisting of a 12.5 mm fine graded Superpave mixture over a 12.5 mm fine graded Superpave mixture. Non-destructive defection tests on pavements consisting of tack coat at three different application rates, 0.056, 0.046 and 0.04 gal/sy, indicated that the effectiveness of tack coat on pavement strength is not significant at 95% confidence level (Mrawira and Yin 2006). It should be noted that even though the use of tack coat at pavement layer interface does not increase the shear strength, the benefit of tack coat material against watering of the surface and thermal aging must not be ignored (Raab and Partl 2004).

2.1.2.3 Curing time

There was no complete agreement in the literature concerning the curing time of tack coat. Some studies and guidelines suggest that tack coat should be cured before laying the new asphalt overlay (Hot Mix Asphalt Paving Handbook 2000; Texas Technical Advisory 2001; Flexible Pavement of Ohio 2001). It has been reported that interface shear strength increased with longer curing time (Hachiya and Sato 1997; Canestrari et al. 2005; Chen et al. 2008). However, some studies concluded that curing time has little effect on the interface shear strength (Tashman et al. 2006; Tashman et al. 2008). Study by Buchanan and Woods (2004) indicated that three emulsions (SS-1, CSS-1 and CRS-2) with three application rates (0.05, 0.09, and 0.13 gal/sy) exhibited highest tensile and torque-shear strength at low application rates when emulsions are not fully broken, and highest tensile and torque-shear strength at the application rate of 0.09 gal/sy after emulsion are fully cured.

2.1.2.4 Temperature

It is well known that asphalt mixture is a temperature susceptible material; thus it is expected that temperature has a significant effect on the shear strength between
pavement layers. Studies with various testing temperatures have all concluded that the interface shear strength increased as the testing temperature decreased (Deysarkar and Tandon 2005; West et al. 2005; Canestrari and Santagata 2005; Yang et al. 2007; Leng et al. 2008; Collop et al. 2010). However, this relationship may not hold true as the temperature approaches the glass temperature of the HMA and / or tack coat (Leng et al. 2008).

Average bond strength measured by NCAT Bond Strength Device is 2.3 times greater at 50ºF compared to 77ºF and it is 6 times greater at 77ºF compared to 140ºF (West et al. 2005). Shear reaction modulus defined as nominal shear modulus divided by composite specimen thickness increases as the temperature decreases in the temperature range of 10 ºC to 30ºC (Collop et al. 2010).

According to Canestrari et al. (2005), the shear strength between pavement layers consists of residual friction, dilatancy, the inner cohesion of layer materials, and adhesion given by interface material. At a higher temperature, different interface treatments will provide similar interface shear strength because the interface material adhesion becomes relatively insignificant and the interface shear resistance is mainly related to the layers characteristics, like surface roughness (Canestrari et al. 2005; West et al. 2005). Thus the effect of interface friction is expected to be more evident at higher temperature and the effect of normal pressure will be more notable at higher temperature. In the filed, interface shear resistance appears to be lowest during hot days.
It is interesting to note that increasing the temperature of the original pavement before placing the overlay can increase the shear strength at the interface (Abd and Easa 2002).

2.1.2.5 Surface conditions

Existing pavement surface conditions, like surface roughness, cleanliness, and wetness have a significant effect on the interface shear resistance between pavement layers. It is generally recommended that tack coat materials should be applied on a dry and clean pavement surface (Hot Mix Asphalt Paving Handbook 2000; Flexible Pavement of Ohio 2001; Texas Technical Advisory 2001; Cross and Shrestha 2005). This requirement was confirmed by studies of Hachiya and Sato (1997), Collop et al. (2003) and McGhee and Clark (2009) in which interface shear resistance reduction is found for dirty pavement surfaces even when extra tack coat materials are applied. On the other hand, Kruntcheva et al. (2006) found that a dry and clean interface with no tack coat has similar properties to the same interface with a standard quantity of tack coat.

However, it is interesting to note that in the study by Mohammad et al. (2009), dusty conditions exhibited higher interface strength than clean conditions especially when tested with a confining pressure. This likely resulted from the higher viscosity of the dust and asphalt mastic than the neat residual asphalt.

It has been reported that the micro and macro texture of the lower pavement surfaces appears to play a significant role in interface bonding when it comes to contact surface roughness (Mrawira and Damude 1999). Roughness characteristics measured by Computer Tomography indicated that higher macro-texture (higher roughness) leads to an increase in interface shear resistance (Santagata et al. 2008).
It has been reported that pavement milling provided a better bond at the interface between the existing pavement and the new HMA overlay due to the rough longitudinal grooving on the lower pavement surface created during the milling process (West et al. 2005; Tashman et al. 2008). For milled surfaces, the bond strength at the interface between existing pavement and the overlay is not affected by the application of tack coat materials; in other words, tack coat was not effective at increasing the interface shear resistance for composite pavements with milled lower layer (Sholar et al. 2002; Tashman et al. 2006; Tashman et al. 2008; McGhee and Clark 2009). This indicated that the application of tack coat materials on milled pavement surfaces was not necessary. Study by Cooley (1999) pointed out that grooved pavement (from milling operation) in conjunction with the melting of the asphalt within the loose milling materials (left by the lightly sweeping of the milled surface) by heat of the overlay mixture would create a bond between milled pavement surface and overlay.

For pavements with HMA overlay placed on PCC slab, the texture of the PCC surface affects not only the interface shear resistance but also the overlay rutting. Among the four types of concrete surface textures evaluated by Leng et al. (2008), including smooth, transverse tining, longitudinal tining and milling, milled PCC surface exhibited the highest interface shear strength. At low tack coat application rate, the tined PCC surface provided higher interface shear strength than smooth surface; however, at optimum tack coat application rate, smooth surface has better bonding than the tined surface at intermediate temperature without normal forces applied. The reason is that at low application rate, the interlock between tined PCC and HMA overlay is dominant in spite of less contact area between the two surfaces. In the following field work, Leng et
al. (2009) reported that milled surfaces showed lower rutting than smooth and transverse tinting surfaces. Interfaces between AC and AC provide better shear strength than interfaces between AC and PCC due to the absorption of emulsion into the underlying AC layer (Tayebali et al. 2004).

As far as the effect of wetness on the interface shear resistance, Sholar et al. (2002) showed that water applied to the tack coated surface reduced the shear strength of the specimens compared to those without water applied; Raab and Partl (2004) indicated that for specimens without tack coat, the watering of the surface has a negative influence on the adhesion. However, Mohammad et al. (2009) reported that water sprayed on tack coated surfaces prior to HMA overlay placement has no significant effect on the bond strength because a small amount of water can be flashed away by the hot HMA mat and it has no consequential effects on the tack coat quality.

2.1.2.6 Pavement materials and structure

Since the pavement layer interface is the surface where two pavement layers come into contact, it is well recognized that the materials in contact play a key role on the interface properties. Kruntcheva et al. (2006) concluded that the interface properties depend on the type of materials in contact rather than on the amount of tack coat applied and/or the interface conditions. Abd and Easa (2002) also concluded that the interface shear resistance is strongly affected by the types of materials in contact.

Through the comparison between specimens from laboratory and in situ, Canestrari et al. (2005) reported that air voids content is closely related to the inner cohesion of the mixture. Generally, it is believed that interface shear resistance will increase with increasing mixture density. This was confirmed by the conclusion drew by Kruntcheva et al. (2006); materials requiring more compaction time will create better
bond at the interface. Ponniah et al. (2006) also stated that for composite specimens with HMA mixture for both top and lower layers, the application of tack coat has no significant effect on the interface shear strength when the top layer is compacted to 125 gyrations, whereas the tack coat will increase the interface shear strength by 10% when the top layer is only compacted to 75 gyrations.

Fine-graded, smaller NMAS mixture has been reported to have better interface shear strength than coarse-graded, larger NMAS mixture (West et al. 2005; Leng et al. 2008). The interface cohesion of tack coat between different specimens decreases in the order of between dense-graded mixture and dense-graded mixture, between porous mixture and dense-graded mixture, between porous mixture and SMA mixture (Chen et al. 2008). Sholar et al. (2002) also concluded that tack coat at the application rate of 0.02 gal/sy has no effect on the interface shear strength between 12.5mm coarse graded Superpave mixture and 19.0mm coarse graded Superpave mixture.

Raab and Partl (2004) reported the negative influence of thermal ageing of the composite specimen on the interface shear strength. As far as construction practices, West et al. (2005) pointed out those cores taken from within the wheelpath and those from between wheelpaths showed no significant difference in bond strength; and those cores from sections paved with Novachip® spreader showed significantly higher bond strength than those paved with normal paving equipment due the avoidance of tack coat material tracking during Novachip® paving process. Mohammad et al. (2002) reported that monolithic mixture has higher shear strength than specimens jointed at the interface. Analytical analysis indicated that thicker overlay can reduce the interface shear stress (Hachiya and Sato 1997; Tayebali et al. 2004).
2.1.2.7 Testing methods and loading conditions

Interface shear strength has been reported to increase with the increasing normal pressure applied on the specimen (Uzan et al. 1978; Mohammad et al. 2005; West et al. 2005). The effect of normal pressure is expected to be more pronounced at higher temperature because the effect of friction is more evident at higher temperature. However, Romanoschi and Metcalf (2001) concluded that shear strength values are not affected by the normal stress levels applied on the interface with tack coat, but they are affected for the interface without tack coat. Interlayer reaction tangential modulus defined by Canestrari et al. (2005) as initial slope of the stress-displacement curve increases proportionally with normal stress.

Interface shear strength was also reported to increase with higher shear loading rate (Leng et al. 2008; Mohammad et al. 2009), the application of horizontal load (Tayebali et al. 2004), and the application of confinement on specimens during testing (Mohammad et al. 2009).

Raab and Partl (2004) indicated that interface shear strength measured by layer parallel static direct shear test can not describe the effect of tack coats under dynamic loading. Repeated loading tests performed by Collop et al. (2010) showed that a higher fatigue life and greater sensitivity to shear stress level at the lower temperature; for instance, reduction of the stress level by a factor of approximately 1.9 increases the life by a factor of approximately 15. Collop et al. (2010) also evaluated two different loading rates (180°/min and 600 N m/ min); the nominal shear strength measured at 180°/min is approximately 1.9 times higher than that measured at 600 N m/ min.

Specimens prepared in the laboratory with no tack coat exhibited substantial shear strength (Uzan et al. 1978; Mohammad et al. 2005; Kruntcheva et al. 2006); however
field cores without tack coat applied at the interface have been reported to de-bond at the interface (Tayebali et al. 2004; West et al. 2005). Muench and Moomaw (2009) pointed out that the non-uniform application rate, torsional/normal forces created by the coring equipment, and compaction by construction equipment might have contributed the de-bonding.

Three different tests, UTEP pull-off test, FDOT shear tester, and torque bond test, evaluated by Tashman et al. (2008) generally showed different results.

2.1.3 Effects of Bonding Conditions on Pavement Performance

A good bond between pavement layers can ensure the pavement system act as a uniform composite layer and more effectively transfer the external load into the subgrade and distribute the loading over a larger area, thus reduce the potential of pavement distress. On the other hand, poor bonding or debonding can cause slippage and reduce the shear strength between pavement layers, thus reducing the load transferring capability and leading to pavement distress, like cracking, rutting, shoving, and pothole. Debonding has been reported to be caused by either poor tack coat between layers or water infiltration due to distress or inadequate compaction (Muench and Moomaw 2009)

Early fatigue cracking has been reported to be related to debonding through layer elastic analysis (Shahin et al. 1986; Willis and Timm 2006) and field test section results (Harvey et al. 1997; Willis and Timm 2006). Analytical analysis by Shahin et al. (1986), Willis and Timm (2006), Ziari and Khabiri (2007), and Hu et al. (2010) indicated that compressive strains on subgrade surface increased substantially with increasing slippage, leading to higher subgrade rutting. Through field test section investigation,
Leng et al. (2009) reported that test sections with higher interface shear strength exhibited lower MHA overlay surface rutting.

Study by Shahin et al. (1986) indicated that maximum tensile strain is located at the bottom surface of the original asphalt layer if pavement layers are fully bonded at the interface. However, if debonding occurs at the interface, the overlay and the underlying structural layer will respond individually, leading to greater interface stress (Buchanan and Woods 2004; Ziari and Khabiri 2007), tensile stress at the bottom of the overlay (Shahin et al. 1986; Hu et al. 2010) and critical stress shifted to the bottom of the overlay and is far more critical compared to complete bond (Ameri et al. 1990). The stress distribution in the pavement system is shown in Figure 2-1 for fully bonded and fully slipped pavement layers (Gomba et al. 2005). Only a small amount of debonding is able to produce strains in the pavement approaching to those with full debonding (Shahin et al. 1986). Kruntcheva et al. (2005) reported a 20 to 35% reduction in pavement life due to debonding.

Figure 2-1. Stress distribution for fully bonded (left) and fully slipped (right) pavement system (after Gomba et al. 2005)

Meanwhile, in absence of interface bond, tensile stress at the bottom of the overlay induces a compressive stress at the top surface of the underlying asphalt layer. This allows the occurrence of relative movement between the overlay and the underlying layer at the interface, leading to weaker bond and more slippage (Shahin et
al. 1986) and larger octahedral shear stress due to less confining stress (Ameri et al. 1990).

Analytical analysis indicated that the presence of horizontal force, in the form of acceleration and braking, caused an increase in the interface shear stress (Shahin et al. 1986; Ameri et al. 1990; Hachiya and Sato 1997). It is interesting to note that when debonding occurs, normal acceleration (less than 1.5 m/s²) has no significant effect on the AC layer mechanistic response, whereas deceleration can cause dramatic changes in the maximum shear strains at the surface of the pavement structure even at the deceleration rate of 1.5 m/s² (Hu et al. 2010).

Chen (2010) reported a premature pavement overlay failure only 1 day after it was opened to traffic due to the loss of interface bonding. Dynamic cone penetrometer results confirmed that the slippage cracks were not linked to weak base or subgrade.

Heavy Vehicle Simulator (HVS) testing performed on full scale accelerated pavements with bonded and unbonded interfaces showed a 10 to 45 fold increase in the estimated loading (ESALs) for the bonded pavement sections over the unbonded sections (Santucci 2009).

2.1.4 Summary

The effect of interface materials on pavement layer interface shear strength has been the focus of most of the research work to date. However, some analytical and field section research has indicated that the interface conditions play a key role on the stress and strain distribution in the pavement system, especially in surface layers for pavements with overlays (and thus the pavement service life). Research directly related to the effect of interface conditions on pavement cracking performance is necessary to evaluate the interface conditions on pavement performance.
2.2 Top-down and Reflective Cracking Mechanism

2.2.1 Top-down Cracking Mechanism

Top-down cracking is a pavement deterioration mechanism where cracks initiate at the pavement surface and propagate downward with time. It has been widely reported in the United States of America (Roque et al. 1990; Uhlmeyer et al. 2000; Svasdisant et al. 2002), as well as in Europe (Gerritsen et al. 1987; Dauzats et al. 1987; Nunn et al. 1998; De Freitas et al. 2003), Japan (Matsuno et al. 1992), and other countries (Wambura et al. 1999; Emery 2006; Raju et al. 2008). However, this failure mode can not be explained by the traditional fatigue mechanisms in which the maximum tensile stresses and strains always occur at the bottom of the asphalt structure layer when the pavement system is subjected to external loading on the pavement surface.

Of the many mechanisms identified to date, it is well accepted that the critical near surface stresses and strains induced by non-uniform contact stresses between the tire and the pavement surface may cause top-down cracking. Research work by Myers (2000) indicated that surface cracking appears to be initiated by critical tensile stresses induced by non-uniform contact stress between the ribs of radial truck tires and the pavement surface. However, Jacobs (1995) points out that the maximum tensile stresses occur at the edge of a bias ply truck tire on the pavement surface. The difference as explained by Myers (2000) was caused by the different stress states induced by different tire structures; and the radial and wide base tires are potentially more detrimental to pavement surface distress than bias ply tires. Analytical studied by Molenaar (1984) and Gerritsen et al. (1987) concluded that high surface tensile strains induced at the edge of the tire are the cause of top-down cracking. Nunn et al. (1998) indicated that surface initiated cracking was due to horizontal tensile stresses generated
by truck tires at the pavement surface. Groenendijk (1998) also indicated that the combined influence of the non-uniform tensile contact stress and the AC mixture aging could result in critical tensile stress at the pavement surface rather than at the bottom.

Since asphalt mixture is a temperature susceptible material; temperature has significant effects on the engineering characteristics of the asphalt pavement. Dauzats et al. (1987) reported that thermal stresses could initiate top-down cracking after a number of repeated temperature cycles and it will further propagate under traffic loading. Roque et al. (1990) studied the top-down cracking potential in asphalt pavements due to thermal and load-induced stresses and concluded that it is the combination of thermal and load-induced stresses that may induce top-down cracking. Schorsch et al. (2003) reported that nighttime temperatures produce the highest magnitude of surface tensile stress.

However, OGFC mixtures may be the ‘first front’ in resisting top-down cracking. For pavements surfaced with OGFC, it is recognized that more sever aging can occur in the OGFC due to its higher air voids in combination with their direct exposure to UV radiation and heat. Aging will increase the binder stiffness and brittleness with a corresponding effect on the mixture. Asphalt binder aging has been attributed to be the major cause of top-down cracking in many studies such as Hugo et al. (1985) in South Africa, Gerritsen et al. (1987) in Netherlands, Matsuno et al. (1992) in Japan, Wambura et al. (1999) in Kenya, and Svasdisant et al. (2002) in Michigan.

Stiffness gradients induced by temperature gradients along the depth of the pavement, asphalt mixture age-hardening and pavement cooling rate have also been linked to top-down cracking (Roque et al. 1988; Rowe et al. 2001). In addition,
construction quality has been identified as a significant contributor to the top-down cracking (Gerritsen et al. 1987; Schorsch et al. 2003; De Freitas et al. 2005).

2.2.2 Reflective Cracking Mechanism

Reflective cracking is the phenomenon when a crack reflects up into and through the new pavement overlay just above the discontinuities in the old pavement. It has been observed in nearly all types of overlays, but it is most common in AC overlays placed on rigid pavements (Mukhtar and Dempsey 1996).

The most recognized driving force of reflective cracking is the horizontal movement concentrated at the cracks and joints in the existing pavement, as represented in Figure 2-2. Because of the bond between overlay and existing pavement, tensile stress is induced in the HMA overlay directly above the crack and joint. This horizontal movement is introduced by the daily temperature change. Cracking occurs when the induced tensile stress exceeds the breaking strength of overlay mixture. Reflective cracking caused by this mechanism initiates at the bottom of the overlay just above the cracks and joints. A large daily temperature drop with a low temperature at the end of the cooling cycle creates the most critical reflective cracking condition (Bozkurt and Buttlar 2002). The HMA overlay contraction due to low temperature will increase the resistance to the joint opening and create additional tensile stress in the overlay.

The temperature drop in the evening creates a temperature gradient with lower temperature in the upper portion of PCC slab and higher temperature in the lower portion of PCC slab. This temperature gradient causes the upper portion to contract more than that of the lower portion, causing the upward curling of PCC slabs. This
upward curl initiates cracking from the HMA overlay surface where more severe overlay mixture age hardening occurs (Nesnas and Nunn 2004; Von Quintus et al. 2010).

Moving traffic loads can cause differential vertical movement of the PCC slab across the cracks and joints in the PCC slab. This differential vertical movement can be caused by the development of voids beneath the PCC slab at the cracks and joints, or poor PCC slab support, or poor load transfer (Bennert 2010; Von Quintus et al. 2010). These vertical movements create bending and/or shear stresses in the HMA overlay near the cracks and joints, and eventually reflective cracking.

Figure 2-2. Reflective cracking in HMA overlay of PCC base (after Von Quintus et al. 2010)

**2.2.3 Summary**

This review of the literature indicates that the interface conditions will affect the pavement material properties near the interface for both top-down and reflective cracking, the stress distribution in the overlay (like OGFC) for top-down cracking, and the stress distribution near the crack tip for reflective cracking. A good bond at the interface can help dissipate the stresses built up near the interface and increase the
fracture resistance of the material near the interface. Since OGFC mixtures may be the ‘first front’ in resisting top-down cracking, it is also of significant importance to evaluate the effect of OGFC on pavement top-down cracking performance. It can be concluded that composite specimen testing is needed for the evaluation of cracking initiation and propagation through the interface.

2.3 Testing Methods for Pavement Layer Interface Evaluation

2.3.1 Interface Shear Resistance Testing

2.3.1.1 ASTRA test set-up

ASTRA Test device, a direct shear box, similar to the device usually used in soil mechanics, was developed under Anocona Shear Testing Research and Analysis (ASTRA) program (Canestrari et al. 2005). The basic test configuration is schematically shown in Figure 2-3. It can accommodate both prismatic (maximum square cross-section area 100 ×100 mm²) and cylindrical specimens (diameters from 94 to 100 mm). The mixture influences on shear resistance are eliminated by holding two half-boxes on the mixture with an unconfined interlayer shear zone in the center. A normal load is applied with a lever and weight system; a horizontal load is applied with a driving motor and measured by a load cell. Shear force, horizontal and vertical displacement are recorded during the test.

To evaluate the interlayer shear resistance, the test is performed at the horizontal displacement loading rate of 2.5mm/min under two temperatures, 20ºC and 40ºC. Composite specimens consisting of two types of dense-graded hot mixes (AC16 and AC 11), compliant with Italian technical standards, were prepared from both field trial section and laboratory. Three types of interface treatment methods were evaluated, without tack coat, with conventional cationic emulsion, and with polymer modified
cationic emulsion. For both the latter two treatment methods, 300g/m² residue application rate was used. Short curing time (tested after 2 to 3 weeks) and medium curing time (tested after 7 to 8 weeks) were evaluated under 20°C.

Figure 2-3. Configuration of the ASTRA test device (after Canestrari et al. 2005)

Application of different normal load on the same testing configuration allows the construction of peak envelope that represents the interlayer failure criterion like Coulomb failure law. Test results indicated that tack coat does have an effect on the interlayer shear resistance under low temperature (20°C), but it is more related to the layer characteristics under higher temperature (40°C).

2.3.1.2 Double shear test

Double shear test (DST) was originally developed by Diakhate et al. (2006) to study the shear fatigue behavior of tack coats. Since this device can not apply either oligocyclic or monotonic tests beyond fatigue, a more versatile device was considered. Diakhate et al. (2011) optimized both the specimen and device geometries to obtain a relatively pure shear loading at the interface.
DST in the laboratory involves a specimen consisting of three layers bonded two-by-two with the same tack coat, as shown in Figure 2-4. The two side layers (AC #1 and AC #3) are fixed during the test, and the center layer (AC #2) is subjected to either monotonic or repeated loading. Diakhate et al. (2011) evaluated two types of interface conditions, with and without tack coat, at a frequency of 10 Hz under load control. Specimens have to be conditioned in the climatic chamber for at least 6 h before testing. Two temperatures (10 °C and 20 °C) were evaluated. The cyclic test was set to automatically stop whenever the measured load exceeds the setting value by 20%.

![Figure 2-4. Schematic of the double shear test (after Diakhate et al. 2011)](image)

The results showed that at 10 °C, the absence of tack coat results in a decrease in bonding fatigue performance. It should also be noted that the relationship between applied stress and the number of loading cycles to failure can be expressed by a power law.
2.3.1.3 FDOT shear tester

FDOT shear tester was developed to quantify the bond strength of the tack coat that had been wetted by rain (Sholar et al. 2002). This simple direct shear device can operate in the Materials Testing System (MTS) as shown in Figure 2-5.

The six-inch nominal diameter specimen can be either roadway cores or laboratory produced specimens. A 3/16 inches gap between the shearing platens is chosen to reduce the effects of skewness, and bending due to the cantilever effect of the unsupported edges during shearing. The strain controlled load is applied at a displacement rate of 2 in/min, which can be easily achieved on Marshall apparatus. Specimens have to be conditioned at 77°F for at least 2 hours prior to testing. The field cores are oriented in the shearing plates so that the loading direction is parallel to the traffic direction marked on the specimen.

Test results from field projects indicated that rainwater has a negative effect on the shear strength of the specimens. Tack coat application rate within the range of 0.02 to
0.08 gal/sy had a slight effect on the shear strength. The gradations of the asphalt mixtures bonded by the tack coat played a critical role the shear resistance.

2.3.1.4 Layer-Parallel Direct Shear (LPDS) test

LPDS test device (See Figure 2-6) is an EMPA modified version the Leutner test developed in Germany in the late 1970s (Raab and Partl 2004; Canestrar et al. 2005; Raab and Partl 2008; Santagata et al. 2008). This test is performed without the application of normal load. One part of the specimen is laid on a circular U-bearing and held by a semicircular pneumatic clamp; the other part remains suspended. An interface shear zone, a 5 mm gap, is introduced between the yoke and the pneumatic clamp. The test uses 150±2 mm diameter or prismatic (150 mm×130 mm) specimens comprising at least two layers; it is usually performed at the displacement rate of 50±2 mm/min through semicircular yoke under 20±1°C temperature. The test returns a shear force-shear displacement curve that can be used to determine the maximum shear stress and shear reaction modulus.

Figure 2-6. Schematic view of the LPDS test device with pneumatic clamping (after Raab and Partl 2008)
2.3.1.5 Leutner test

Leutner test was developed in the late 1970s for evaluation of pavement layer interface using simplified direct shear test (Collop et al. 2009; Sutanto 2010). The test is performed on 150±2 mm diameter specimens encompassing at least two layers from either field cores or laboratory produced specimens as shown in Figure 2-7. To make sure good contact between the specimen and the load device, the layer thickness has to be at least 70 mm and 25 mm for lower layer and upper layer, respectively. A constant shear displacement rate across the pavement layer interface was applied without any normal force applied. The test is normally conducted at the displacement rate of 50 mm/min at 20±1°C. The displacement rate 50 mm/min allow the test to be performed in Marshall or CBR load devices. The disadvantage of this test is that non-uniform shear stresses are induced on the interface. A 5 mm gap was introduced into the shear plane on the standard Leutner test to reduce the edge damage caused by misalignment and irregular interface.

Figure 2-7. Photograph and schematic diagram of Leutner load frame (after Collop et al. 2009)
Collop et al. (2009) pointed that the average shear strength from field cores tends to be higher for the surfacing/binder course interface than the binder course/base interface. The average pavement layer interface shear strength from field cores increases as the class of the road increases.

### 2.3.1.6 Shear fatigue test

Shear fatigue test was developed to evaluate the pavement layer interface shear fatigue behavior under the repetitive mechanical action of the traffic loading (Romanoschi and Metcalf 2001). Normal and shear stresses are applied simultaneously on the specimen; the longitudinal axis of the specimen was tilted 25.5° to the vertical so that the shear stress at the interface is half the normal stress, as shown in Figure 2-8.

A vertical load with a minimum value of 10% of the maximum at the frequency of 5Hz was applied on the specimen. 0.2 s loading period with 0.05 s pulse was used to simulate the vehicle speed at 50 km/h. Four vertical load levels at 4, 6, 8, and 10 kN were used, introducing normal stress of 0.5, 0.75, 1.0, and 1.25 MPa at the interface. The elastic and permanent deformations at the interface in normal and tangential directions are recorded for each loading cycle. The number of loading cycles leading to an increase of permanent shear displacement of 1mm was used to evaluate the fatigue properties of the layer interface. The results from this study indicated that interface with a tack coat exhibited a longer life than that without tack coat.

### 2.3.1.7 Superpave Shear Tester

The Superpave Shear Tester (SST) was developed as part of SHRP research to measure mixture properties that can be used to characterize a HMA mixture’s resistance to permanent deformation (Witczak et al. 2004). Vertical, horizontal, and
confining loads can be simultaneously applied on the specimens. The environmental chamber can maintain temperature in the range of 0ºC (14ºF) to 80ºC (176ºF).

Figure 2-8. Schematic of shear fatigue test (after Romanoschi and Metcalf 2001)

A shearing mold, consisting of two parts, was specially designed for the shearing test using the Superpave Shear Tester as shown in Figure 2-9 (Mohammad et al. 2002; Mohammad et al. 2005). Each part has a 150 mm (5.9 inch.) diameter and 50.8 mm (2 in.) deep cylindrical groove in it for holding the specimen during testing. The applied horizontal and vertical loads, specimen deformation (in the axial, horizontal and vertical direction) can be recorded during testing.

This shearing test was performed in a load controlled manner at a constant rate of 222.5 N/min (50 lb/min). The test arrangement (SST environmental chamber with test mold in it) was shown in Figure 2-10.
Among the evaluated tack coat materials (PG 64-22, PG 76-22M, CRS-2P, CRS-2L, CSS-1, SS-1H, SS-1L, SS-1), CRS-2P and CRS-2L provided significantly higher interface shear strengths (Mohammad et al., 2005). For each of the tack coat material, optimum residue application rate was determined. The interface shear resistance increases with increasing vertical stress.

Figure 2-9. Design shear mold (left) and mold with a sample inside (right) (after Mohammad et al. 2005)

Figure 2-10. Test arrangement for the shearing test (after Mohammad et al. 2005)

2.3.1.8 Torque bond test

Torque bond test was originally developed in Sweden for in-situ pavement layer interface conditions evaluation (Walsh and Williams 2001). It has been adopted in UK to
measure interface properties between thin surface layer and underlying structural layer. A torque is applied manually at the top of the core, introducing a twisting shear failure at the layer interface. A 100 mm diameter coring specimen is used to limit the required magnitude of moment within the range of manual application.

The manual torque bond testing procedure in UK (UK Guidelines 2000) requires the test to be performed at a constant torque rate so that the failure can occur in (60±30) seconds. To avoid the difficulty in controlling the torque rate, a constant torque rate of 600 N m/min was used by synchronizing the torque dial gauge in the torque wrench with the second hand of an analogue clock (Choi et al. 2005). Since the moment is applied by twisting the top of the core with torque wrench, the stiffness and thickness of the adjacent pavement layers plays an important role on the interface shear resistance. An automatic laboratory-based torque bond test was developed by Collop et al. (2010) to investigate the two different loading rates (600 N m/min and 180º/min) that were used in the manual torque bond test. This testing setup is shown in Figure 2-11.

The testing equipment consists of an environmental chamber with a range between -5ºC and 40ºC, a 100kN servo hydraulic actuator, an axially mounted load cell and a Linear Variable Differential Transformer (LVDT). The hydraulic actuator testing machine can apply either compressive or tensile load under static or repeated loading conditions. Specimens with 100mm in diameter and 10mm in thickness cylindrical metal platens glued to the top and bottom have to be conditioned in the environmental chamber for at least 5 hours prior to testing.

Collop et al. (2010) prepared double-layered cylindrical specimens for interface condition evaluation. The top layer was an 11mm Asphalt Concrete mixture, 30mm thick
and the bottom layer was a 16mm Asphalt Concrete mixture, 50mm thick. Three interface conditions, no bitumen emulsion, a modified bitumen emulsion, and a cationic bitumen emulsion. Both modified bitumen emulsion and cationic bitumen emulsion has a 150g/m² residue bitumen application rate. The shear strength is calculated using the following equation,

\[ \tau^N = \frac{2T}{\pi R^3} \]

Where \( \tau^N \) is the nominal shear strength, \( T \) is the peak torque and \( R \) is the specimen radius.

Test results reported by Collop et al. (2010) indicated that shear strength increased with deceasing temperature. And specimens with no emulsion at the interface showed the lowest shear strengths. The material compliance of both upper and lower mixture has a relatively small effect on the rotation and shear reaction modulus of the interface unless the shear stiffness of the mixture is very low and/ or the thickness is very larger.

Figure 2-11. Photograph and schematic diagram of the automatic torque equipment (after Collop et al. 2010)
2.3.1.9 UTEP Pull-Off Device (UPOD)

In order to remove the effect of pavement layer surface, like surface roughness, UPOD was performed in tension (pull-off) rather than shear mode (Deysarkar 2004). It measures the tensile strength of the tack coat before the overlay is placed. The instrument weighs about 23 lbs and can be easily leveled with the pivoting feet as shown in Figure 2-12. It has a weight key (40 lbs) on the top, providing the stability during placement of loads. A drive torque wrench is used to the pull the plate up or down from the tack-coated surface. 3M double-sided tape is attached between the aluminum contact plate and moisture bearing foam to make sure that the device conforms to the rough surface.

UPOD is placed on the tack coated pavement after a specified period of set time. The torque wrench is rotated clockwise until the contact plate is firmly set on the tack-coated pavement. After the 40 lbs load has been applied on the weight key for 10 minutes, the load is then removed and the torque wrench is rotated in the counterclockwise direction to detach the contact plate from the tack-coated pavement surface. The torque required to detach the contact plate from the pavement is recorded and converted to the strength using a calibration factor.

For the equipment used by Deysarkar (2004), the following calibration factor was obtained:

\[ F = 0.6571 \times T \]

Where T is the torque in in-lb and F is the load in lbs.

In the laboratory work conducted by Deysarkar (2004), the following parameters were evaluated: six types of tack coat: CSS-1h, CSS-1, SS-1h, SS-1, PG64-22, and RC-250; three temperatures: 140, 93 and 50°F; three set times: 30, 45, and 60 minutes;
0.04 gal/sy residue application rate. Test results indicated that the emulsion strength depends on the application rate, set time and test temperature.

![UTEP pull-off device test set-up](image)

Figure 2-12. UTEP pull-off device test set-up (after Deysarkar and Tandon 2004)

### 2.3.1.10 Wedge splitting test

Wedge splitting test was developed in 1986 to replace the pull-off test for adhesive tensile strength measurement because the pull-off test only returns the adhesive tensile strength and the results are extensive scattered (Tschegg et al. 1995). From the load-displacement curve recorded during testing, the slope of the curve that describes the elastic properties, the notched-bar tensile strength following the adhesive tensile strength, and the fracture energy and crack resistance, respectively, can be obtained (Tschegg et al. 2007).
Specimens were prepared with a rectangular groove introduced at the interface and a starter notch placed in the interface at the bottom of the groove. The schematic view of the test is shown in Figure 2-13. The vertical load $F_M$ applied by the machine is transmitted by the slender wedge to a high horizontal force $F_H$ and a small vertical force $F_V$ during testing. The horizontal displacement in the plane of the splitting force $F_H$ measures the crack mouth opening displacement. The splitting force $F_H$ can be calculated from the measured vertical force $F_V$. Notched-bar tensile strength and fracture work (or specific fracture work) can be obtained from the $F_H – \text{CMOD}$ curve.

![Figure 2-13. Schematic view of the wedge splitting test (after Tschegg et al. 2007)](image)

Three different pretreatments of the milled asphalt concrete surface, no pretreatment, cement grout, and cement grout plus dispersion, were evaluated by Tschegg et al. (2007). The prismatic specimen dimensions are 100 mm×120 mm×140 mm (70 mm asphalt + 70 mm concrete). Tests were performed at horizontal splitting speed 0.5 mm (0.02 inch.)/ min under -10, 0, 10, 22°C. The results indicate that no pretreatment leads to the highest cracking resistance. The tensile strength and the specific fracture energy show a completely different behavior as a function of
temperature; the tensile strength decreases with increasing temperature whereas the specific fracture energy reaches the maximum in the medium temperature range.

2.3.2 Interlayer Cracking Resistance Testing

2.3.2.1 TTI overlay tester

TTI overlay tester was developed in the 1970s to simulate the opening and closing of joints or cracks and it was used to evaluate reflective crack initiation and propagation of the overlay materials (Cleveland et al. 2002; Zhou and Scullion 2004; Chowdhury et al. 2009). The test instrument, as shown in Figure 2-14, features two steel blocks, one is fixed and the other slides horizontally to simulate the tensile and compressive stresses induced in the old pavement as a result of cyclic changes in temperature (Pickett and Lytton 1993).

![Figure 2-14. Schematic diagram of TTI overlay tester (after Zhou and Scullion 2004)](image)

The original overlay tester has two different specimen dimensions: the small one is 15 inch (375 mm) long by 3 inch (75 mm) wide with variable height; the large one is 20 inch (500 mm) long by 6 inch (150 mm) wide with variable height. It has been successfully used to evaluate the effectiveness of different geosynthetic materials on mitigating reflective cracking (Pickett and Lytton 1993; Cleveland et al. 2002; Chowdhury et al. 2009). One of the disadvantages reported in previous work is the large
specimen size. The specimen size was reduced to 6 inch (150 mm) long by 3 inch (75 mm) wide with the height of 1.5 inch (38 mm) in the upgraded overlay tester in 2003 (Zhou and Scullion 2004).

The specimens required for the upgraded overlay tester can be prepared either from Superpave Gyratory Compactor or from field cores. Typically, the test is performed at 25°C at the loading rate of one cycle per 10 sec with a maximum displacement of 0.025 inch (0.64 mm), as shown in Figure 2-15. This displacement is approximately equal to the displacement experienced by PCC pavements with a 4.5 m joint or crack spacing undergoing 14°C temperature changes (Zhou and Scullion 2004). The validation work by Zhou and Scullion (2004) showed that the upgraded tester is repeatable and can effectively differentiate the reflective cracking resistance of different asphalt mixtures.

Figure 2-15. Typical displacement used in overlay tester (after Zhou and Scullion 2004)

Four large specimens (18 inch long by 6 inch wide) were taken from each of the test sections with different geosynthetic products interlayer at all three test locations and three small specimens (6 inch long by 3 inch) were taken from each of the test sections with different geosynthetic products interlayer at one location. The bottom part of the
specimens was trimmed to obtain a smooth, flat surface with a uniform thickness of leveling layer. The top part was not disturbed. For a given test section, small and large specimens were trimmed to the same thickness.

The small specimen sizes always exhibited failure due to separation at the geosynthetic interlayer. The large specimen occasionally exhibited similar failure mechanism. On average, the geosynthetic products have significant improvement in reflective cracking resistance of the composite specimens. The small overlay tester was not appropriate for evaluating the specimens with geosynthetic interlayer whereas the large overlay tester can be used for the geosynthetic interlayer reflective cracking resistance on composite specimens.

2.3.2.2 Interlayer Stress Absorbing Composite (ISAC) system testing equipment

ISAC is a composite material of a low stiffness geotextile, viscoelastic membrane layer, and a high stiffness geotextile (Mukhtar and Dempsey 1996). It was introduced between the old PCC slab and new AC overlay to stop the upward propagation of a crack into the overlay and reinforce the overlay. The equipment as shown in Figure 2-16 was introduced to measure the effectiveness of ISAC on reflective cracking resistance.

The composite specimen consisted of two 3.75 feet long by 6 inch wide by 5 inch thick PCC slab, ISAC interlayer, and 2.5 inch thick AC overlay on top of the PCC slab. The joint opening between the slabs was ¼ inch. The specimen was conditioned to 30°F prior to be cycled back and forth by the hydraulic ram over a distance of 0.063 in at the rate of 0.0016 inch/min. The induced force from hydraulic ram and the relative movement between the two box sections were recorded. Test results indicated that the ISAC vastly outperformed the AC overlay without ISAC.
2.3.2.3 Beam tests

Kim et al. (1999) developed a beam specimen testing technique to evaluate the performance of selected modified and/or reinforced asphalt mixtures under mode I (bending) fatigue fracture. The test arrangement is shown in Figure 2-17. The composite specimen consisted of a dense-graded asphalt mixture as an overlay on top of a concrete block with reinforcing interlayer at the bottom of the asphalt mixture. The asphalt mixture specimen was bonded to the concrete block with tack coat; the concrete block has a 10mm gap cut 2/3 the depth from the top and an arbitrarily broken crack in the lower 1/3 depth. The dimensions of the specimens are 340 mm (13.39 inch) long by 120 mm (4.72 inch) wide by 50 mm (1.97 inch) thick, and 340 mm (13.39 inch) long by 120 mm (4.72 inch) wide by 120 mm (4.72 inch) thick for asphalt mixture and concrete.

Figure 2-16. Schematic diagram of ISAC system testing equipment (after Mukhtar and Dempsey 1996)
block respectively. Repeated square loads are applied on the top center of the beam at 10 Hz using a hydraulic loading device. A circular loading plate with rubber pad attached to its bottom was used to simulate the tire contact. The maximum pressure of 100 psi (5.4 kN load) was used; and a sitting load of 0.196-kN was applied. The specimen has to be conditioned to 20°C in the environmental chamber prior to testing. Horizontal expansion of the asphalt mixture and visualized vertical crack length versus number of loading cycles were recorded.

Figure 2-17. Test arrangement (after Kim et al. 1999)

Brown et al. (2001) developed a ‘semi-continuous’ support system to more closely simulate the field conditions as a combination of bending in the specimen and continuity of support. The schematic diagram of the test is shown in Figure 2-18. The reinforcement was placed 30 mm above the base layer. A 12 mm thick rubber layer was used to provide the support for the composite specimen over the steel base. The base layer has a gap cut 1/3 depth from the bottom. The tests were carried out at 20°C and 5
Hz under 5.5 kN load. Crack propagation reduction was observed in the test for specimens with reinforcement even though there is a significant scatter in results.

Figure 2-18. Schematic diagram of the testing set-up (after Brown et al. 2001)

Khodaii. A et al. (2009) introduced an experimental program to evaluate the effects of geosynthetic reinforcement on the reflective cracking resistance improvement in asphalt overlays. The schematic diagram of the test setup is shown in Figure 2-19. The three-layered pavement structure consisted of asphalt overlay, existing pavement, and resilient subgrade modeled with neoprene rubber. Repeated square loads are applied on the top center of the beam at 10 Hz. A maximum pressure of 100 psi (6.79 kN load on 112 mm diameter loading plate) was used; and a sitting load of 0.196-kN was applied. The specimens have to be conditioned in the environmental chamber at least 2 h before tested at either 20ºC or 60ºC. The existing pavement has a 10 mm, 15 mm or 20 mm gap cut 2/3 the depth from the top. Results indicate that the geogrid inclusion in the asphalt overlay leads to a significant increase in overlay reflective cracking
resistance. And the geogrid is most effective when it is placed at the one-third depth from the overlay bottom.

![Schematic diagram of the test setup (after Khodaii et al. 2009)](image)

**Figure 2-19. Schematic diagram of the test setup (after Khodaii et al. 2009)**

**2.3.3 Summary**

The tests available for pavement layer interface evaluation are mainly focused on the interface shear resistance and most of them are performed in monotonic mode, which is not representative of the pavement interface loading conditions under traffic. On the other hand, tests used to evaluate the cracking resistance of the interlayer materials require large specimens; they are relatively difficult to fabricate in the laboratory and more difficult to get from the field. Thus a test needs to be developed for the pavement interface cracking performance evaluation using 150 mm diameter specimens which can be easily produced in the laboratory or obtained from field cores.
CHAPTER 3  
COMPOSITE SPECIMEN PREPARATION AND EVALUATION 

3.1 Composite Specimen Preparation

An appropriate composite specimen with bonding agent applied at the interface is needed to evaluate the effect of pavement layer interface on cracking performance. In the laboratory, it can be prepared by compacting loose overlay material, like open-graded mixture, on top of the pre-compacted lower layer material using Superpave Gyratory Compactor (SGC). Bonding agents, like conventional tack coat or Novabond®, can be applied to the base material surface before placing the overlay mixture.

The following procedures were followed:

- Compact dense-graded mixture using SGC to desired air voids as the base material. Dense-graded mixture was designed according to Superpave™ volumetric mix design method.

- Slice compacted dense-graded mixture specimen to the desired dense-graded mixture thickness to be used in the composite specimen, as shown in Figure 3-1.

- Apply conventional tack coat or Novabond® to the cut side of the dense-graded mixture. The amount of binder or emulsion should correspond to the anticipated field application rate; the calculation is illustrated in Appendix A. For a hot binder tack material, preheat the silicone rubber mold (Figure 3-2) in a 135°C (275°F) oven for 7±2 minutes. Pour the hot binder into the appropriate size silicone rubber mold based on the specimen size to be prepared; a 150mm diameter silicone rubber mold was used in this study. Place the silicone rubber mold on a level shelf in the 135°C (275°F) oven for 10±2 minutes to allow the binder to self level. Remove the mold from the oven, place on a level surface and allow the mold to cool to room temperature. For an emulsion tack material, pour the emulsion into the appropriate size room temperature silicone rubber mold. Place the mold on a level shelf in a 60°C (140°F) oven and allow the emulsion to set to a constant weight. Remove the mold from the oven, place on a level surface and allow the mold to cool to room temperature.

- With the silicone rubber mold sitting on a level surface, place compacted dense-graded mixture in the silicone rubber mold, as shown in Figure 3-3. Allow the weight of the specimen to remain on the silicone rubber mold for at least 5 minutes. Transfer the compacted specimen with the silicone rubber mold to a freezer. Remove the compacted specimen with the attached mold after at least 15 minutes in the freezer. Invert the specimen to where the silicone rubber mold is on
top the specimen. Slowly remove the mold from the dense-graded mixture surface. Allow the specimen to warm to room temperature while sitting undisturbed. The dense-graded base materials with applied conventional tack coat and Novabond® are shown in Figure 3-4.

Figure 3-1. Half sliced specimen

Figure 3-2. Silicone rubber mold on level shelf
• Heat SGC compaction mold and top mold plate in the oven at the required compaction temperature for at least 30 minutes prior to compaction.
• Push the SGC compaction mold along the edge surface of the compacted room temperature specimen sitting on a level surface after removing the ring holding rotating base from falling off the compaction mold (see Figure 3-5). Place a room temperature base plate and a paper disk underneath the compacted dense-graded mixture in the compaction mold.

• Place desired weight of open-graded mixture into the compaction mold on top of the base material. A paper disk was placed on top of the mixture followed by the top mold plate. Compaction mold was loaded and the compaction was initiated. The amount of open-graded mixture was calculated based on the relationship among mixture maximum specific gravity, air void content, and desired height of open-graded mixture in the composite specimen after compaction. This calculation is illustrated in Appendix B.

• After compaction, remove the mold from the gyratory compactor. Extrude the compacted composite specimen from the mold after an appropriate cooling period (around 10 minutes). Compacted specimen is shown in Figure 3-6.

Figure 3-5. Compacted base material being pushed into SGC compaction mold
3.2 Evaluation of the Effect of Overlay Compaction on the Integrity of Lower Layer

Since additional compaction was introduced to the compacted dense-graded mixture in the composite specimen preparation process, Superpave IDT tests were performed to evaluate the possible damage to the dense-graded HMA induced during the overlay compaction process.

3.2.1 Materials and Testing Methods

A dense-graded mixture commonly used by the FDOT and identified as Dense-GA-Granite was selected as the base material for this evaluation. Its aggregate was made up of four components: coarse aggregate, fine aggregate, screenings, and sand. Its gradation is shown in Table 3-1. This mixture was designed according to the Superpave volumetric mix design method. Design asphalt contents for the mixture was
determined such that each mixture had 4% air voids at \(N_{\text{design}} = 75\) gyrations. PG 67-22 asphalt was used for the mixture. A total of nine dense-graded Gyratory specimens were prepared. Table 3-2 shows the bulk specific gravity of the prepared specimen. A Superpave mixture available in the lab was used as overlay mixture (2000 grams per specimen) to evaluate the additional compaction on the integrity of the underlying base material.

The following tests and analyses were performed:

- Dense-graded mixtures were designed according to the Superpave™ volumetric mix design method. 4500 grams of aggregate were prepared for each mixture. Asphalt content was 4.8%. A total of nine specimens were prepared.

- Compacted dense-graded mixture specimens were cut in half. Nine of them were used for Superpave IDT control test, while the other nine were used for recompaction evaluation.

- Tack coat was applied on the cut side of dense-graded specimens. The reason that the cut side was selected was that the mixture was more uniformly compacted than that of the uncut side. The tack coat was applied in form of pure asphalt (AC-20) to save time on emulsified asphalt setting. The reason that AC-20 was used was that the viscosity of AC-20 corresponded to the residual asphalt of the emulsion commonly used in Florida.

- 2000 grams of Superpave mixture available in the lab were placed on top of each of the nine half cut dense-graded specimens. Three were compacted to 50 gyrations, three to 100 gyrations and three to 150 gyrations. The ring holding the rotating base was taken off the gyratory compaction mold so the prepared dense-graded specimen could be easily pushed back into the mold from the bottom.

- Three groups of Superpave IDT tests were performed on no re-compaction (control) and re-compacted specimens, respectively. Each group had three specimens. A total of 18 IDT tests were performed. All tests were performed at 10°C.

### 3.2.2 Analysis of Test Result

Superpave IDT test results are summarized in table 3-3. The results show that additional compaction appeared to have slightly improved the specimen strength. However, student’s t-tests show that the differences between control and recompaction
for m-value, D₁, Sᵥ, Mᵣ, FE, DCSE, ER, were not statistically significant; in other words, no damage was induced by the additional compaction process.

Table 3-1. Dense-graded mixture aggregate gradation

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<th>Percent Passing</th>
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</tr>
<tr>
<td>3/4&quot;</td>
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<tr>
<td># 100</td>
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<td># 200</td>
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Table 3-2. Bulk specific gravity

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<th>6</th>
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<td>Bulk Specific Gravity</td>
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<td>2.44</td>
<td>2.45</td>
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Table 3-3 Superpave IDT test results

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<tr>
<th>Project Name</th>
<th>50 Gyraations</th>
<th>100 Gyraations</th>
<th>150 Gyraations</th>
<th>Control 1</th>
<th>Control 2</th>
<th>Control 3</th>
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<tr>
<td>m-value</td>
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<td>D₁ (GPa)</td>
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<td>5.26E-07</td>
<td>1.03E-06</td>
<td>4.17E-07</td>
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<td>Sᵥ (GPa)</td>
<td>2.77</td>
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<td>3</td>
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<td>Mᵣ (Gpa)</td>
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<td>13.4</td>
<td>11.21</td>
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<td>FE (kJ/m³)</td>
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<td>5.1</td>
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<td>2.9</td>
<td>4.8</td>
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<td>3.2</td>
<td>2.8</td>
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<td>a</td>
<td>4.46E-08</td>
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<td>2.458</td>
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<tr>
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<td>1.35</td>
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<td>1.29E-08</td>
<td>1.84E-08</td>
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<td>1.51E-08</td>
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</tbody>
</table>
Damage rate was defined as creep rate, which is one of the most critical parameters affecting mixture performance; the damage rates presented in table 3-3 was calculated using equation 3-1.

\[
\frac{dD(t)}{d(t)} = \varepsilon_{cr} = mD^{1/2}t^{-1}, \text{ where } t = 1000
\]  

(3-1)

The damage rates calculated from equation (3-1) show that there is some improvement in damage resistance. However, careful examination of the results indicated that some measurements were clearly unreliable and appeared to be affected by problems with the gages. Only measurements that were clearly reliable were included in the analysis and presented in Figures 3-7 through 3-11.

![Figure 3-7. Creep compliance versus time for no re-compaction replicate 1](image)
Figure 3-8. Creep compliance versus time for no re-compaction replicate 2

Figure 3-9. Creep compliance versus time for 50 additional gyrations
Figure 3-10. Creep compliance versus time for 100 additional gyrations

Figure 3-11. Creep compliance versus time for 150 additional gyrations

The creep rates recalculated using only reliable measurements are presented in Table 3-4 and Figure 3-12.
Table 3-4. Damage rate recalculation

<table>
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<tr>
<td>150 gyrations</td>
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</table>

The data in Table 3-4 and Figure 3-12 show that additional compaction had no effect on the integrity of the dense-graded mixture.

Figure 3-12. Re-calculated creep rates for no re-compaction and re-compacted specimens
3.3 Summary

The additional compaction of Superpave mixture or OGFC has no effect on the integrity the bottom dense-graded mixture. Therefore, the method presented here appears suitable to prepare appropriate specimens for composite specimen tests.
CHAPTER 4
DEVELOPMENT OF COMPOSITE SPECIMEN TENSION TEST

4.1 Background

As mentioned in the literature review, pavement layer interface plays a significant role on the stress distribution in the overlay for both top-down and reflective cracking and the pavement material properties near the interface when polymer modified asphalt emulsion is used as the bonding agent. One possible way to evaluate the interface conditions on cracking performance is to perform direct tension tests on composite specimens. The newly developed Dog-Bone Direct Tension test (DBDT, Koh 2009) has been successfully used to measure the tensile properties of the dense and open graded mixture. However, careful examination indicated that although DBDT is ideal for uniform specimens composed of a single mixture, it is not suitable in its current form for tests on composite specimens. The dog-bone specimen results in excessively non-uniform and complex stress states once composite specimens are introduced. As dog-bone specimen is suitable for evaluation of cracks propagating inwards to the specimen center but not suitable for evaluation of cracks propagating downwards from overlay to base material. Therefore, it was decided that a modified specimen geometry and loading configuration was needed to properly evaluate the interface conditions on cracking performance.

4.2 Prototype Composite Specimen Tension Test System

Based on thorough analysis of the available testing systems and consideration of the research goals, a composite specimen interface cracking (CSIC) test was conceived, as shown in Figure 4-1. In this composite specimen test system, the crack is expected to initiate from the open-graded mixture side (with the help of a stress
concentrator) and propagate through the interface and into the dense-graded mixture. This crack initiation and propagation process can also be used to simulate reflective cracking if the stress concentrator is located on the base material side. The various devices used for and procedures followed in the composite specimen fabrication are presented in the following sections.

Figure 4-1. Prototype of composite specimen tension test
4.2.1 Slicing, Cutting and Grooving of Composite Specimen

The following procedures were followed:

- Slice the top and bottom of the compacted composite specimen to obtain the desired thickness for both open-graded and dense-graded mixtures. Diamond-tip saw used for slicing is shown in Figure 4-2. A sliced composite specimen is shown in Figure 4-3.

- Cut the sliced specimen to desired width (3.5 inch was selected). The diamond saw used for cutting is shown in Figure 4-4. The straight cut composite specimen is shown in Figure 4-5.

- Two specimens were held together by a clamp to core through both OGFC surfaces and obtain one semicircular groove (stress concentrator) on each specimen. The core drill bit diameter is ¾ inch. The coring setup is shown in Figure 4-6. The composite specimen with groove is shown in Figure 4-7.

Figure 4-2. Diamond-tip saw used for specimen slicing
Figure 4-3. Sliced composite specimen

Figure 4-4. Diamond-tip saw used for composite specimen cutting
Figure 4-5. Composite specimen after cutting

Figure 4-6. Composite specimen stress concentrator drilling setup
4.2.2 Sanding, Gluing, and Gage Points Attachment of Composite Specimen

The following procedure was followed:

- In order to make sure the loading head and specimen curved end surface made solid contact, loose materials (i.e. mastic) were sanded off until aggregates were fully exposed. The spindle sander used for this purpose and sanded specimen are shown in Figure 4-8.

- Four brass gage points (5/16-inch diameter by 1/8-inch thick) were affixed with epoxy to each side of the specimen. The locations of the gage points are shown in Figure 4-9.

- Both the loading head inner surfaces and specimen curved end surfaces need to be uniformly coated with epoxy and the voids on the curved end surfaces need to be filled with epoxy before joining them together. The epoxy used was LOCTITE® Hysol® Product E-20HP epoxy. It takes about 6 hours for this epoxy to get about 90% of its full strength on aluminum at 25°C. The loading heads and epoxy used are shown in Figure 4-10.
Figure 4-8. Spindle sander and sanded specimen

Figure 4-9. Strain gage distributions on the composite specimen
4.3 Monotonic Strength Tests on Asymmetrical Composite Specimens

Since monotonic strength test has been successfully used to determine strength and fracture energy for specimens with a single mixture, the loading rate applied in DBDT for single dense-graded mixture, 25 mm/min was selected for preliminary testing. All tests were performed at 10°C.

4.3.1 Materials

The dense-graded mixture used for composite specimen was the same as in section 3.2.1. Oolitic limestone FC-5 (open-graded friction courses) was used for top layer of the composite specimen. Its aggregate gradation is shown in Table 4-1. The asphalt binder used for oolitic limestone FC-5 was ARB-12; namely PG67-22 with 12% ground tire rubber and 0.4% mineral fiber by weight of the mixture.

The compacted composite specimen consisted of 1 inch dense-graded mixture and 1 3/8 inch open-graded mixture with approximately 15% air voids. The open-graded
mixture has natural compacted surfaces without slicing. The amount of each component of open-graded mixture needed was 78.4 grams of ARB-12 and 1147.0 grams of aggregate with 6.4% binder content. For initial testing to evaluate the effectiveness of this specimen geometry, neither tack coat nor Novabond® was introduced to the interface between open-graded mixture and dense-graded mixture.

Table 4-1. Oolitic limestone FC-5 mixture aggregate gradation

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<td># 100</td>
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<td># 200</td>
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</tbody>
</table>

4.3.2 Monotonic Strength Test at 25 mm/min

While the ¾ inch diameter diamond-tip coring bit was being made, an attempt was made to cut the groove as a stress concentrator using a diamond saw as shown in Figure 4-11. Five cuts were made to form the groove. The specimen with diamond saw cut groove is shown in Figure 4-12.

Test results of 3 composite specimens prepared as described above showed that the newly introduced groove successfully concentrated the stress in middle of the specimen on the OGFC side. This indicated that the diamond-tip coring approach can be used to form an effective groove when a diamond-tip coring bit is not available. The cracks in the specimen are shown in Figure 4-13.
Figure 4-11. Geometry of the five cuts to form the groove

Figure 4-12. Prepared composite specimen with diamond saw cut groove
Figure 4-13. Cracks in the specimen at loading rate of 25 mm/min
Typical displacements at a loading rate of 25 mm/min are shown in two consecutive parts for two sets of gages in Figures 4-14 and 4-15.

Figure 4-14. Strain gage displacement at loading rate of 25 mm/min

Figure 4-15. Strain gage displacement at loading rate of 25 mm/min
The strain gage displacement Figures 4-14 and 4-15 did show that specimens start to crack from the open-graded mixture side and propagate all the way through the dense-graded side. All tests were completed in 4 seconds. Unfortunately, these results indicated that it is almost impossible to identify the instant of crack initiation. This monotonic loading rate 25mm/min was determined to be too fast for testing to evaluate interface effects.

4.3.3 Monotonic Strength Test at 2.5 mm/min and 0.25 mm/min

Since loading rate at 25 mm/min was determined to be too fast, loading rates were reduced to 2.5 mm/min and 0.25 mm/min on specimens with ¾ inch diameter semi-circular groove. Tests performed on three specimens at a loading rate of 2.5 mm/min showed that all composite specimens broke from the open-graded mixture side; but 2 of them broke near the loading heads while only one of them broke at the center. The cracks in composite specimen are shown in Figure 4-16.

Cracks near loading head
Cracks at the center
Figure 4-16. Cracks in the specimen at loading rate of 2.5 mm/min
Typical displacements at loading rate of 2.5 mm/min are shown in Figures 4-17 and 4-18.

**Figure 4-17.** Strain gage displacement at loading rate 2.5 mm/min-broke near the end

**Figure 4-18.** Strain gage displacement at loading rate 2.5 mm/min-broke at the center
Figures 4-17 and 4-18 clearly indicate that composite specimens broke from the open-graded mixture side. However, it took around twice longer for the specimen that broke at the center to fail than the specimen that broke near the loading heads to fail. This is because the rough surface of open-graded mixture forms natural stress concentrators; in some cases, these natural stress concentrators work more effectively than the cored groove stress concentrators, especially near the loading heads where end-effects further concentrated stresses.

Loading rates were further reduced to 0.25 mm/min on specimens with cored groove. Interestingly, test results showed that all composite specimens broke from the dense-graded mixture side near the loading heads. The cracks in composite specimen are shown in Figure 4-19. Typical displacements at loading rate 0.25 mm/min are shown in Figure 4-20.

![Figure 4-19. Cracks in the specimen at loading rate of 0.25mm/min](image)

The reason that the specimens broke at the dense-graded side instead of the open-graded side is that at this slow loading rate, the stiffer, lower compliance dense-
graded mixtures attract more stress, while at the same time dissipate less stress during testing, while open-graded mixtures with the lower stiffness and higher strain tolerance have higher capacity to release part of the input energy used to damage the material. Therefore, the composite specimens failed once the strain limit of dense-graded mixture was reached.

Figure 4-20. Strain gages displacement at loading rate of 0.25mm/min

4.3.4 Conclusion for Asymmetric Monotonic Strength Tests

Tests performed on composite specimens at the loading rate of 25 mm/min, 2.5 mm/min, and 0.25 mm/min show that this monotonic strength test is not a good choice for interface evaluation because either the testing time is too short to identify the crack initiation point or because composite specimen broke from the dense-graded mixture side, even though stress concentrators were introduced on the open-graded mixture side.
4.4 Repeated Loading Test on Asymmetrical Composite Specimens

Based on the results presented above, it seems clear that a simple monotonic strength test, which is appropriate to determine strength and fracture energy in single mixture specimens, is not suitable for composite specimens. Therefore, repeated loading tests on asymmetrical composite specimen were attempted. All tests were performed at 10°C.

4.4.1 Repeated Loading Test on Asymmetrical Composite Specimen with 1 inch Dense-graded Mixture Layer

Repeated loading approach involved a repeated haversine load of one-tenth second duration followed by nine-tenth second rest period. Based on previous research experience, a peak load of 1200-lb peak load was selected for preliminary tests. The repeated loading schematic diagram is shown in Figure 4-21.

![Repeated loading schematic diagram](image)

Figure 4-21. Repeated loading schematic diagram

4.4.1.1 Materials

The dense-graded mixture for composite specimen tests was the same as that used in section 3.2.1. The open-graded mixture used for the top layer was the same as
that used in section 4.3.1. The composite specimen configuration was the same as that in section 4.3.1 except that a ¾ inch diameter semi-circular groove was used instead of diamond saw cut groove. Neither conventional tack coat nor Novabond® was introduced to the interface between open-graded mixture and dense-graded mixture.

4.4.1.2 Analysis of results

Initial trials showed the composite specimen broke near the loading head instead of through the groove, as shown in Figure 4-22. The failure occurred near the loading head partly because of end effects, and partly because of low compaction density near the end and a large amount of air voids on the rough open-graded mixture surface forming natural stress concentrators. It appears that these natural stress concentrators were more effective than the drilled groove to initiate cracks. The comparison between newly compacted open-graded mixture surfaces and cut surfaces are shown in Figures 4-23 and 4-24.

Since composite specimens tend to fail near the loading head because the higher air voids on open-graded mixture surface, which might more effectively concentrate stresses than the groove, slicing off the rough surface to have a uniform surface like in Figure 4-24 was attempted. Tests on composite specimen with the top 3/8 inch sliced off show the crack initiated from the groove bottom. Failed specimen is shown in Figure 4-25.

Typical total recoverable deformations for OGFC and dense-graded mixture are shown in Figure 4-26; total or instantaneous recoverable deformation from repeated loading test is a measure of resilient modulus and increase in recoverable deformation is a measure of damage induced in the specimen.
Figure 4-22. Composite specimen broke near the end

Figure 4-23. Compacted open-graded mixture surface with rough surface
Figure 4-24. Compacted open-graded mixture surface after rough surface sliced

Figure 4-25. Composite specimen with top 3/8 inch rough surface sliced off
During this repeated loading process, damage started to accumulate in open-graded mixture right after loading; but little or no damage was induced in dense-graded mixture until cracks prorogated into it. This damage feature can be used to evaluate the effect of different types of interface materials, like conventional tack coat and Novabond®. For specimens with same geometry and external load but with different interface conditions, difference in the number of loading cycles to failure is direct measurement of interface condition effect on cracking performance.

**Total Recoverable Deformation for OGFC and Dense-Graded Mixture**

![Graph showing total recoverable deformation for OGFC and dense-graded mixture](image)

**Figure 4-26.** Total recoverable deformation for OGFC and dense-graded mixture

4.4.2 Repeated Loading Test on Asymmetrical Composite Specimen with 3 inch Dense-graded Mixture Layer

The success of composite specimen with ¾ inch diameter semi-circular groove introduced on OGFC surface under repeated loading make it possible to evaluate the effect of interface conditions on stress redistribution in OGFC and dense-graded layer near the interface and on cracking retardation from OGFC layer into dense-graded
layer. Considering the fracture process involves crack initiation, stable crack propagation and unstable crack propagation, dense-graded mixture thickness in composite specimen was increased to 3 inch from the original 1 inch to make sure that the cracking is still in stable crack propagation range in order to evaluate the effect of interface; otherwise the effect of interface may be overshadowed by the unstable crack propagation period. In order to identify the crack tip once the crack propagates from the OGFC through the interface to the dense-graded mixture, strain gages in dense-graded mixture were placed near the interface as shown in Figure 4-27.

![Figure 4-27. Strain gage distributions on specimen with 3 inch dense-graded mixture](image)

### 4.4.2.1 Materials

The dense-graded mixture used for composite specimen was the same as that used in section 3.2.1. The open-graded mixture used for the top layer was the same as that used in section 4.3.1. The composite specimen configuration was the same as that in section 4.4.2 except that dense-graded mixture thickness was increased to 3 inch.
Tack coat and Novabond® were applied on the dense-graded surface at the application rate of 0.045 gal/sy and 0.3 gal/sy, respectively.

4.4.2.2 Analysis of results

Since the composite specimen thickness was increased to 4 inches, external load was increased up to 2850 lbs (from 1200 lbs for 2 inch thick specimen) to reduce the number of loading cycles to fail the specimens. Typical total recoverable deformations for OGFC and dense-graded mixture are shown in Figures 4-28 and 4-29 for tack coat and Novabond® interface, respectively.

Both Figures 4-28 and 4-29 indicate that damage was accumulating in dense-graded mixture even though the damage rate is lower than that in OGFC for thick specimens; the reason is that 3 inch thick dense-graded mixture is carrying a larger portion of the external load than the 1 inch thick dense-graded mixture composite specimen. It took more loading cycles for specimen with tack coat interface than specimen with Novabond® interface to fail; actually, specimens with Novabond® interface were expected to fail after many more loading cycles. This idea of increasing dense-graded mixture thickness to keep interface in stable crack propagation region was proved to be inappropriate because OGFC and dense-graded are accumulating damage at the same time; premature failure in the underlying HMA layer can be addressed by introducing a more effective stress concentrator, like a rectangular groove, to concentrate high enough stress in OGFC so that dense-graded damage is caused by crack propagation rather than external load during the loading process.
Figure 4-28. Total recoverable deformation for OGFC and dense-graded mixture with tack coat interface (3 inch dense-graded mixture layer).

Figure 4-29. Total recoverable deformation for OGFC and dense-graded mixture with Novabond® interface (3 inch dense-graded mixture layer).
4.4.3 Repeated Loading Test on Asymmetrical Composite Specimen with Rectangular Groove

Rectangular groove was introduced on OGFC surface in composite specimen with dense-graded mixture thickness reduced back to 1 inch, as shown in Figure 4-30. The groove is 3/8 inch deep and 5 diamond-tip saw cuts wide along the external load pulling direction.

4.4.3.1 Materials

The dense-graded mixture used for composite specimen was the same as in section 3.2.1. Nova Scotia-granite FC-5 (open-graded friction courses) instead of oolitic limestone FC-5 was used for top layer of the composite specimen. Its aggregate gradation is shown in Table 5-4. The asphalt binder used is ARB-12. The compacted composite specimen consisted of 1 inch dense-graded mixture and 1 3/8 inch open-graded mixture with 20% air voids. The top 3/8 inch OGFC was sliced off. The amount of each component of open-graded mixture needed was 83.8 grams of ARB-12 and 1313.2 grams of aggregate with 6.0% binder content. Conventional tack coat and Novabond® were applied on dense-graded surface at the application rate of 0.045 gal/sy and 0.3 gal/sy, respectively.
Table 4-2. Nova scotia-granite FC-5 mixture aggregate gradation

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4.4.3.2 Analysis of results

Tests on 4 samples of composite specimen with tack coat interface and 3 samples of composite specimen with Novabond® interface were performed. Because the rectangular groove was used, external load was reduced to 720lbs. Tests results are shown in Figures 4-31 through 4-34. Samples are denoted as: CST1, CST2, CST3, CST4, CSN1, CSN2, CSN3, with letters CS denoting composite specimen, the letter T denoting tack coat interface, and N denoting Novabond® interface.

Figures 4-31 to 4-34 indicate huge variations from sample to sample for both composite specimens with tack coat interface and Novabond® interface. Specimen CST1 and CST3 failed shortly after loading; but specimen CST2 and CST4 failed by slowly accumulated damage. It took relatively the same amount of time for CST2, and CST4 and CN3 to fail; this indicates that the effect of Novabond® interface was overshadowed somehow.
Figure 4-31. Total recoverable deformation for OGFC with tack coat interface (rectangular groove)

Figure 4-32. Total recoverable deformation for dense-graded with tack coat interface (rectangular groove)
Jones (1980) pointed out that it is impossible to pull on an asymmetric composite specimen without at the same time bending and/or twisting the composite specimen.
This huge variation was determined to be caused by rectangular stress concentration and the bending of composite specimen.

4.5 Repeated Loading Test on Symmetrical Composite Specimen

In order to mitigate bending induced during pulling on asymmetric composite specimen, two single composite specimens were bonded together at the open-graded mixture surface to create a symmetrical composite specimen as shown in Figure 4-35. All tests were performed at 10°C.

4.5.1 Materials and Testing Method

The dense-graded mixture used for composite specimen was the same as that used in section 3.2.1. Nova Scotia-granite FC-5 (open-graded friction courses) was used for the top layer of the composite specimen. The asphalt binder used was ARB-12. The compacted composite specimen consisted of 1inch dense-graded mixture and 1cinch open-graded mixture with 23% air voids. The natural voids on the compacted OGFC surface were used as stress concentrators to initiate crack. The amount of each component of open-graded mixture needed was 50.6 grams of ARB-12 and 792.3 grams of aggregate with 6.0% binder content. Tack coat and Novabond® were applied on dense-graded specimen surface at an application rate of 0.045 gal/sy and 0.3 gal/sy, respectively.

The composite specimens were bonded together with one spacer throughout the whole symmetric plane except 1 inch wide at the center. This 1 inch open space created a gap between two asymmetric composite specimens and functioned as a stress concentrator. Repeated loading (Figure 4-21) was applied using a peak load of 2500 lbs.
Both fiber glass and cardboard were tried as spacers. The cracking surfaces are presented in Figure 4-36.

Figure 4-35. Symmetrical composite specimen

Because of the brittleness of the fiber glass, the composite specimen broke right along the edge of the fiber glass; while the composite specimen with cardboard spacer broke along the natural weak path. Thus cardboard was selected as the spacer material.

Figure 4-36. Cracking surfaces for fiber glass (left) and cardboard (right) spacer
4.5.2 Alignment System for Composite Specimen Preparation

One of the issues encountered in composite specimen preparation was the alignment of the composite specimen and loading heads. Poor alignment not only makes the testing setup difficult but also introduces bending in the specimen. Two pieces of steel angles were mounted on two diagonal corners of the loading heads to enforce good alignment. Loading heads assembled with two steel angles are shown in Figure 4-37.

![Figure 4-37. Loading heads with two steel angles](image)

4.5.3 Results of Symmetrical Composite Specimen

Two symmetrical composite specimens for tack coat and Novabond® interface each were tested and the results are shown in Figure 4-38. Samples are denoted as: CSST1, CSST2, CSSN1, and CSSN2 with letters CSS denoting composite specimen with symmetrical configuration, the letter T denoting tack coat interface, and N denoting Novabond® interface. Four extensometers were positioned at the center of each of the
symmetrical composite specimen’s four surfaces with gage H1 and H2 mounted on the interface and gage V1 and V2 mounted on dense-graded mixture surface. The results shown in Figure 4-38 are the average results of gage H1 and H2, and gage V1 and V2.

Figure 4-38. Total recoverable deformation for symmetrical composite specimen

The results clearly show that the crack did initiate from the stress concentrator in the open-graded mixture, propagated through the interface and eventually failed the specimen. The repeatability of the test results was greatly improved for composite specimens with both conventional tack coat and Novabond® interface with the help of this alignment system and symmetrical specimen configuration as compared to asymmetric composite specimen. However, the effect of the interface conditions was not identified because the entire composite specimen was being subjected to tensile load with the loading head glued to both the open-graded and dense-graded mixture. This loading configuration led to most of the external load being applied to the dense-
graded mixture because of its higher stiffness. It can be concluded that the effect of the interface conditions was overwhelmed by this loading configuration.

4.6 Monotonic Partial Loading on Symmetric Composite Specimen

The results from section 4.3 to 4.5 indicate that the effect of interface conditions on the composite specimen cracking performance is overshadowed when the composite specimen behavior is dominated by the dense-graded mixture. One possible way to reduce this dense-graded mixture dominance behavior is to decrease the load carried by the dense-graded mixture by loading the OGFC mixture part only. The following two sections deal with the optimum composite specimen geometry and test results of the new loading configuration. All tests were performed at 10°C.

4.6.1 Optimum Geometry of Symmetric Composite Specimen for Partial Loading

Three dimensional finite element method (FEM) analyses were performed to determine the optimum diameter and constraint conditions of the symmetric composite specimens. The material properties of each component of the composite specimen, including OGFC, dense-graded mixture, and loading head are shown in Table 4-3. The sketch of half composite specimen (symmetric to OGFC surface) is shown in Figure 4-39. Since the desirable stress distribution is that the stress is dominant on the OGFC mixture rather than on the dense-graded mixture under tensile loading conditions, the stresses in the direction of external loading (x direction in the model) were checked.

<table>
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<th>OGFC</th>
<th>Dense-Graded</th>
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<td>Modulus (psi)</td>
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<td>1.01E6</td>
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<td>Poisson's ratio</td>
<td>0.2</td>
<td>0.35</td>
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</table>
Composite specimen diameters in the range of 3 inch to 6 inch were analyzed. The 3 inch diameter was selected for practical reasons, such as easy handling and the smallest available strain gage length. The 6 inch diameter was selected because this is typically the largest composite specimen that can be fabricated or cored. Three constraint conditions were considered: 1) only OGFC is loaded; 2) OGFC plus half dense-graded mixture are loaded; 3) both OGFC and dense-graded mixture are loaded. The composite specimen is 1.5 inch wide with 1 inch thick OGFC and 1 inch dense-graded mixture.

The diameter effect of the composite specimen on the stress distribution in external loading (x direction in the model) under 1000 psi tensile stress is shown in Figure 4-40, whereas the effect of constraint conditions is shown in Figure 4-41.

It can be concluded from this FEM analysis that the stresses carried by OGFC increase as compared with the stresses carried by dense-graded mixture when the composite specimen diameter and/or the loading area are reduced.
Figure 4-40. Effect of composite specimen diameter on stress distribution

Figure 4-41. Effect of constraint condition on stress distribution
4.6.2 Analysis of Results

The materials used for this evaluation were the same as that used in section 4.5.1 except that the compacted OGFC layer was 1.5 inch thick and sliced down to 1 inch thick to remove the rough surface. Tack coat and Novabond® were applied on dense-graded surface at the application rate of 0.045 gal/sy and 0.3 gal/sy, respectively. Based on the results of the FEM analysis, the final specimen geometry was determined to be 1.5 inch wide by 2 in thick for 3 in diameter. This 3 in diameter composite specimen was obtained by coring of the 6 in laboratory prepared composite specimen, as in Figure 4-42.

Following the composite specimen preparation procedure stated in section 4.2 and 4.5, the final specimen is shown in Figure 4-43. One new set of loading heads with 3 inch diameter and 2 inch width was fabricated for the 3 inch diameter specimen, as shown in Figure 4-44. The digital image correlation system (Birgisson et al. 2009) was tried for the strain field measurement instead of the traditional strain gage measurement.

Because of the time consuming issue involved with repeated loading tests, monotonic loading at the rate of 0.025 mm/min was applied to reduce the testing time. This slow loading rate was expected to allow the interface material to have enough time to dissipate the stress and/or reduce the stress transmitted through the interface. The low quality of the pictures taken during this test run led to no valuable strain field information. The failed composite specimen is shown in Figure 4-45.

The failure mode shown in Figure 4-45 indicated that the crack did start from the bottom of the groove, but the shear stress induced in OGFC reached its failure limit before the tensile stress induced near the interface could drive the crack from OGFC.
through the interface and into the dense-graded mixture. It can be concluded that when
the composite specimen was only loaded on OGFC section, specimens were failed
because of the low shear strength of OGFC.

Figure 4-42. Schematic diagram of the 3 inch diameter specimen coring

Figure 4-43. Prepared 3 inch diameter symmetrical composite specimen
Figure 4-44. Loading heads, alignment bar, and shim blocks

Figure 4-45. Failure mode for composite specimen under monotonic partial loading
4.7 Monotonic Internal Loading on Symmetric Composite Specimen

Based on the results from section 4.6, it was determined that on the composite specimen, from inside the stress concentration groove, even more favorable tensile stress distribution to initiate and drive the crack to propagate across the interface could be achieved by internally loading (expanding). The loading system shown in Figure 4-46, involving a split cylinder placed inside the stress concentrating hole, was conceived and designed. All tests were performed at 10°C.

4.7.1 Materials and Loading Assembly

The materials used for this evaluation was the same as that used in section 4.6. Conventional tack coat and Novabond® were applied on dense-graded specimen surface at an application rate of 0.045 gal/sy and 0.3 gal/sy, respectively. The composite specimen geometry is the same as in section 4.6. Since the composite specimen was intended to be loaded from within the stress concentrator, a new of loading assembly was fabricated as shown in Figure 4-46. This loading assembly consists of one set of loading heads, two pins, two cross bars (split cylinders through which the load is applied) and four clevises that form two sets of loading yokes. The crossbar is a ¾ in diameter half cylinder bar; its size is the same as that of the stress concentration groove.

4.7.2 Analysis of Results

Monotonic loading at a rate of 0.025 mm/min was applied on the loading head to pull the composite specimen apart from the stress concentration groove, as shown in Figure 4-47. Strain field measurements are not available because of the low image qualities for the digital image correlation system. The failed specimens are presented in Figures 4-48 and 4-49 for conventional tack coat and Novabond® interface, respectively.
Figure 4-46. Loading assembly for internal loading

The results shown in Figures 4-48 and 4-49 indicate that the crack initiated from the bottom of the groove and propagated towards the interface. It should be noted that the crack propagated into the dense-graded mixture for the specimen with conventional tack coat interface (Figure 4-48) whereas the crack propagated along the plane of maximum shear stress for the specimen with Novabond® interface (Figure 4-49). For the specimen with conventional tack coat interface, after the crack propagated through the interface, bending was introduced in the OGFC mixture near the composite specimen symmetrical plane because of the constraint from dense-graded mixture. The tensile stress induced by this bending behavior reached the tensile strength limit of OGFC before the tensile stress induced in the dense-graded mixture exceeds its limit, which led to the final failure of the composite specimen with conventional tack coat
interface. On the other hand, for the specimen with Novabond® interface, which introduced a higher fracture resistant material at the interface, the crack also started from the bottom of the groove but propagated along the plane of maximum shear stress.

It can be concluded that the final failure was caused by the bending behavior for the specimen with conventional tack coat interface and by shear for the specimen with Novabond® interface.

Figure 4-47. Test setup for internal loading
Figure 4-48. Failure mode for composite specimen with tack coat interface

Figure 4-49. Failure mode for composite specimen with Novabond® interface
4.8 Monotonic Internal Loading on Symmetric Composite Specimen with Carbon Fiber Sheet Reinforcement

The internal loading configuration successfully forced the crack to initiate at the stress concentrator and OGFC. However, the secondary bending and shear stresses resulting after crack initiation caused the crack to change paths to go through the OGFC in conventional tack coat interface and shear failure with the Novabond® interface. In order for the crack to continue propagating into the dense-graded mixture, the composite specimen curved end surface was reinforced with carbon fiber to minimize or eliminate the potential for failure in bending or shear through the OGFC. All tests were performed at 10°C.

4.8.1 Materials and Specimen Preparation

The materials used for this evaluation was the same as that used in section 4.6. Tack coat and Novabond® were applied on dense-graded specimen surface at an application rate of 0.045 gal/sy and 0.3 gal/sy, respectively. The composite specimen geometry is the same as in section 4.6.

Carbon fiber sheet was glued to the curved end surface of the composite specimen using Hardman double/bubble® regular setting epoxy, as shown in Figure 4-50. This very low-viscosity epoxy cures to a light color (almost colorless) solid. The specimen curved end surface with glued carbon fiber sheet is shown in Figure 4-51.

4.8.2 Analysis of Results

Monotonic loading at the rate of 0.025 mm/min was applied on curved end surface reinforced composite specimen for both tack coat and Novabond® interface. The typical failure mode of the composite specimen is shown in Figure 4-52 and the load-displacement curve is shown in Figure 4-53.
Figure 4-52 clearly showed that the crack propagated through the interface and into the dense-graded mixture when the reinforcement was used. However, Figure 4-53 indicated that not much difference was seen between specimen with conventional tack coat interface and Novabond® interface in terms of fracture energy. For the specimen with tack coat interface, the load reached the peak after the crack tip propagated into the dense-graded mixture. For the specimen with Novabond® interface, even after the crack tip propagated into the dense-graded mixture, the OGFC part with Novabond® materials still held together and the external effort was overcoming both the OGFC and dense-graded mixture, which explained why the peak load for specimen with Novabond® interface was lower than specimen with tack coat interface.

Figure 4-50. Composite specimen curved end surface, epoxy, and carbon fiber sheet
Figure 4-51. Composite specimen curved end surface with glued carbon fiber sheet

Figure 4-52. Failure mode of composite specimen with curved end surface reinforced
4.9 Repeated Internal Loading on Symmetric Composite Specimen

The successful elimination of bending and/or shear failure through the OGFC with the carbon fiber sheet reinforcement led to the desired composite specimen failure mode, which is characterized by the crack propagating through the dense-graded mixture. However, the composite specimen fracture energy was not sensitive to the interface conditions and failure occurred on one side of the specimen only. The reason appears to be that the Novabond® interface materials can not release the stress accumulated near the interface under monotonic loading.

4.9.1 Materials and Loading Configuration

The materials used for this evaluation was the same as that in section 4.6. Conventional tack coat and Novabond® were applied on dense-graded surface at the
application rate of 0.045 gal/sy and 0.3 gal/sy, respectively. Composite specimen curved end surfaces were reinforced with carbon fiber sheet.

The 6-inch diameter composite specimen has the advantage of easy fabrication and long shear path as compared to 3 inch diameter specimen. Thus, the composite specimen geometry is the same as in section 4.6 except that the specimen diameter was increased back to 6 inch, which can be easily obtained from gyratory compaction or field coring.

4.9.2 Analysis of Results

The resting period in the repeated loading approach can provide the stress release time for interface materials and balance the damage accumulated on the two sides of symmetrical plane. The repeated loading mode shown in Figure 4-21 was applied. Based on previous research and FEM modeling results, 570 lbs peak load was tried. All tests were performed at 10°C. Three specimens with tack coat and Novabond® interface each were prepared and tested. The typical failure mode is shown in Figure 4-54 and the number of loading cycles for specimen failure is shown in Figure 4-55.

Figure 4-54 shows that the crack initiated from the groove and propagated through the interface and into the dense-graded mixture, which caused the final failure on both sides of the composite specimen. The testing configuration successfully identified the benefit of Novabond®, which enhanced the cracking resistance of the composite specimen as shown in Figure 4-55.

The results presented in this section indicate that this testing configuration and mode of loading appears be appropriate to evaluate the interface conditions on composite specimen for top-down cracking. It can also be used for reflective cracking if
the existing cracked pavement layer rather than overlay is glued together at the symmetrical plane.

Figure 4-54. Failure mode for composite specimen under repeated internal loading

![Image of failure mode](image)

Figure 4-55. Number of cycles to failure of Novabond® and conventional tack

![Bar chart showing number of cycles to failure](chart)

Figure 4-55. Number of cycles to failure of Novabond® and conventional tack
CHAPTER 5
DATA COLLECTION AND INTERPRETATION METHOD

The test method developed in the Chapter 4 showed excellent potential for the evaluation of interface bond condition effect on top-down and reflective cracking. However, although the number of loading cycles to specimen breaking can be used as a parameter to differentiate different interface conditions, it does not provide information regarding cracking initiation and propagation. Local deformation measurement, like strain gage measurement, was used for the identification of crack initiation and the crack propagation near the interface.

5.1 Data Collection Method

In order to fully capture the characteristics of the repeated loading shown in Figure 4-21, previous research experience indicated that at least 500 points of data per second have to be acquired. A typical repeated loading at the rate of 512 points per second versus time plot is shown in Figure 5-1.

The fact that the applied load has to be low enough to allow the interface materials to relax during the resting period and thus dissipate the accumulated stress near the interface leads to considerably long testing time as compared to monotonic strength test. If the data, including four strain gages, external load, displacement and the corresponding time, are acquired at the rate of 512 points per second as shown in Figure 5-1 for the entire testing period, which may be as long as 18 hours as shown in Figure 4-55, the amount of collected data will surpass the processing capability of the computer available in the laboratory. Fortunately, not all of the data during the entire testing period are necessary for crack initiation and propagation evaluation; data points
where abrupt strain gage deformation occurs are sufficient to characterize the damage accumulation in the composite specimen.

During the test, frequency data acquired at the rate of 5 points per second were plotted versus time to identify sudden changes in strain gage deformation as an indication of local damage evolution. Once this sudden change occurs, or whenever desired, the operator recorded a burst of data for 6 consecutive loading cycles at a rate of 512 data points per second to calculate the specimen’s total recoverable deformation. The data points acquired for recoverable deformation calculation was shown in Figure 5-2.

Total recoverable deformation, including both the instantaneous recoverable and the time-dependent recoverable deformation during the unloading and rest-period portion of each loading, as defined in Figure 5-3, was calculated. The results at each acquired data point are the four strain gage total recoverable deformations, and peak load as an average of 6 consecutive loading cycles. It should be noted that the data format of these 6 consecutive loading cycles is the same as that of the data used to calculate total resilient modulus in Superpave IDT test.

5.2 Data Interpretation Method

5.2.1 Data Interpretation Method

As stated in section 4.9, the total number of loading cycle it took for the composite specimen to break is a straightforward cracking resistance comparison parameter for specimens with different interface conditions under the same magnitude of loading. However, this parameter provides only the fracture resistance of the whole specimen without any information regarding the damage evolution in the specimen.
Figure 5-1. Typical repeated loading versus time

Figure 5-2. Data points recorded for recoverable deformation calculation
Figure 5-3. Total recoverable deformation definition

It has been well recognized that damage induced in the specimen can be measured by stiffness reduction in the specimen. Because of the complicated stress distribution in composite specimen under repeated loading, the stiffness calculation is not practical for routine evaluation. However, the easily obtained total recoverable deformation of strain gage measurement which is inversely related to the specimen’s stiffness was calculated to facilitate comparison of the specimen’s behavior and performance throughout the test. The typical total recoverable deformation versus time is presented in Figure 5-4. The total recoverable deformation versus time curve can be divided into three stages: the initial stage, which is known to involve changes in temperature and local damage adjacent to the loading yokes; the second stage, which involves steady-state damage; and the final stage, when the crack propagates rapidly.
and the specimen breaks. Damage rate is defined as the slope of the steady state of total recoverable deformation progression curve shown in Figure 5-4.

![Figure 5-4. Typical total recoverable deformation](image)

### 5.2.2 Damage Rate as a Differentiation Parameter

For the tests mentioned in section 4.9, strain gage deformations are measured for total recoverable deformation calculation. The distance between the gage point center and interface is \( \frac{1}{4} \) inch for both gages in OGFC and in dense-graded mixture as shown in Figure 4-54. Because of the specimen to specimen variation, total recoverable deformation was normalized to the intercept of the steady state line to total recoverable deformation axis as shown in Figure 5-4 (cycled). Normalized total recoverable deformation for strain gage measurement in OGFC is shown in Figure 5-5.
Figure 5-5. Normalized total recoverable deformation

Figure 5-5 clearly indicates that damage rate can indentify the effect of different interface material on the damage development inside composite specimen. The lower damage rate developed in composite specimen with Novabond® interface is consistent with the fact that specimens with Novabond® interface can resist more loading cycles to failure when compared to specimens with tack coat interface.

It can be concluded that the damage rate as defined in this section can be used to evaluate the damage evolution for different interface materials. It is an additional evaluation parameter besides the number of loading cycles to failure that does not require long testing time for evaluation.
CHAPTER 6
INTERFACE CRACKING PERFORMANCE EVALUATION

A good bond at the interface can help dissipate the stresses near the interface and increase the resistance to fracture through the interface. Composite specimens with polymer modified asphalt emulsion applied at the interface are expected to have better cracking performance compared to specimens with conventional tack coat materials. Therefore, the effect of interface materials on both top-down and reflective cracking performance will be evaluated in this chapter. Since OGFC mixtures may be the ‘first front’ in resisting top-down cracking, it is also of great importance to evaluate the effect of OGFC on pavement top-down cracking resistance. All tests were performed at 10°C.

6.1 Effects of Interface on Top-down Cracking

In this section, the effects of three types of interface materials, conventional tack coat, Novabond® from Road Science, LLC and trackless tack, on top-down cracking were evaluated. Except for interface materials, the asphalt and aggregate used for composite specimen production, specimen geometry and loading configuration and magnitude are the same as stated in section 4.9. All damage rate results were obtained from strain gage measurements at the same location with respect to each composite specimen as shown in Figure 6-1.

6.1.1 Effects of Novabond® on Top-down Cracking

As part of the test method development, the effect of Novabond® interface on composite specimen cracking performance in terms of the number of cycles to failure was reported in section 4.9 as shown in Figure 4-55. The effect of Novabond® interface on damage rate as compared to conventional tack coat interface is shown in Figure 6-2.
The typical cracking surfaces for specimens with Novabond® and conventional tack coat interface are presented in Figure 6-3.

Figure 4-55 together with Figure 6-2 clearly indicated that specimens with Novabond® interface outperformed the specimen with conventional tack coat in terms of cracking resistance. The reason appears to be the stress relief capability of the Novabond® material and the higher polymer modified asphalt emulsion concentration near the interface as shown in Figure 6-3.

![Figure 6-1. Stain gage distribution on composite specimen](image)

**6.1.2 Effects of Trackless Tack on Top-down Cracking**

Since the trackless tack evaluated in this section is a non-emulsified trackless tack coat material, it has to be distributed at a temperature of around 350°F. The primary advantage of this product is that it cools to touch in 20 to 30 seconds and can be driven over by haul trucks and paver without tracking. It can be applied at very thick residue rates up to 0.18 gal/sy as compared to 0.03 gal/sy residue rate for conventional tack coat used for current FC-5.
The effects of trackless tack on cracking performance were evaluated at two residue application rates, 0.2 gal/sy and 0.13 gal/sy. This 0.2 gal/sy residue was
selected to match the residue application rate of the Novabond® interface used in section 6.1.1, whereas 0.13 gal/sy was the residue application rate used by FDOT. The emulsion and residue application rates used in this section for Novabond®, conventional tack coat and trackless tack are summarized in Table 6-1. Three composite specimens were produced for each application rate.

Table 6-1. Novabond®, conventional tack and trackless tack application rate

<table>
<thead>
<tr>
<th>Type</th>
<th>Novabond (AC-20 residue)</th>
<th>Conventional Tack (AC-20 residue)</th>
<th>Trackless Tack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion Application Rate (gal/sy)</td>
<td>0.3</td>
<td>0.045</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Residue Application Rate (gal/sy)</td>
<td>0.2</td>
<td>0.025</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The effect of trackless tack interface on composite specimen cracking performance in terms of the number of cycles to failure is shown in Figure 6-4. The effect of trackless tack interface on damage rate as compared to conventional tack coat interface is presented in Figure 6-5. The typical cracking surfaces of specimens with trackless tack interface are presented in Figure 6-6.

The results presented in Figures 6-4 and 6-5 indicated that the trackless tack interface has a negative effect on the cracking resistance of the composite specimens as compared to the specimens with conventional tack coat interface. This finding is contrary to the presumption that this thick trackless tack application rate can increase the cracking performance of composite specimen. The reason appears to be that the brittleness of trackless tack led to the reduction of fracture resistance of specimens with

130
trackless tack interface. The dry cracking surfaces shown in Figure 6-5 seem to confirm this conclusion when compared to Figure 6-3.

Figure 6-4. Number of cycles to failure of trackless tack and conventional tack

Figure 6-5. Damage rate of trackless tack and conventional tack
6.2 Effects of Interface on Reflective Cracking

In this section, the effects of two types of interface materials, conventional tack coat and Novabond® from Road Science, LLC, on reflective cracking were evaluated. Tests were performed on composite specimens produced in the laboratory by Road Science and field cores obtained from I-70/Broadway avenue exit project in St. Louis. All tests were performed at 10°C.

6.2.1 Effects of Novabond® on Reflective Cracking

Six composite specimens for each of the two types of interface, 0.1 gal/sy diluted conventional tack coat and 0.2 gal/sy Novabond®, were prepared by Road Science in their laboratory. The specimens consisted of two dense-graded layers. The geometry and strain gage distribution of prepared testing specimen are shown in Figure 6-7.
Tests were performed under the loading mode stated in section 4.9 with 570lbs peak load. Tests results are presented in Figure 6-8 for number of loading cycles to failure and Figure 6-9 for damage rate.
Figure 6-9. Damage rate of Novabond® and diluted conventional tack

Specimens with 0.2 gal/sy Novabond® and 0.1 gal/sy diluted conventional tack interface exhibited almost the same fracture resistance. After careful examination of the cracking surfaces as shown in Figure 6-10, the similarity in cracking performance between specimens with Novabond® and conventional tack interface might be explained by the fact the low voids content of dense-graded mixture does not allow the migration of Novabond® upwards into the mixture like in OGFC but is rather partly squeezed out from the interface. It should also be noted that dense-graded mixture has higher fracture energy than OGFC, which leads to shorter time for Novabond® to have an effect (after crack propagated to the interface) for specimen consisting of two layers of dense-graded mixture.
6.2.2 Effects of Novabond® on Reflective Cracking on Specimens with Teflon Spacer

Six specimens for each of the two types of interface, 0.1 gal/sy diluted conventional tack coat and 0.2 gal/sy Novabond®, were prepared by Road Science in the same way as in section 6.2.1 except that a teflon spacer was introduced to more effectively concentrate stress. The prepared composite specimen with teflon spacer is shown in Figure 6-11. The geometry and strain gage distribution of test specimens were the same as in section 6.2.1.

![Figure 6-10. Cracking surfaces of specimens with Novabond® and diluted conventional tack interface](image)

Half the load used in section 6.2.1, 280 lbs, was applied because of the teflon spacer stress concentrator. Specimens with Novabond® and conventional tack coat failed in 103 to 125 hours. Careful examination of the strain gage deformations indicated that the specimens were not uniformly loaded, which made the results
unreliable. Therefore, the results with 280lbs peak load were not included in the following analysis.

Figure 6-11. Composite specimen with teflon spacer

Peak load was increased to 430 and 520 lbs to reduce the testing time. Tests results are presented in Figure 6-12 for loading cycles to failure and Figure 6-13 for damage rate. Results presented in Figures 6-12 and 6-13 indicate that specimens with Novabond® interface exhibited higher fracture resistance than specimens with conventional tack coat interface. These results also indicate that Novabond® applied at the interface took effect right from the loading moment with the introduction of teflon spacer as stress concentrator, which leads to better cracking performance for specimens with Novabond® interface even with the possibility of being partially squeezed out.
Figure 6-12. Number of cycles to failure of Novabond® and diluted conventional tack for specimens with teflon spacer.

Figure 6-13. Damage rate of Novabond® and diluted conventional tack for specimens with teflon spacer.
6.2.3 Effects of Novabond on Double Novachip® Reflective Cracking

Six cored specimens, double Novachip® on top of PCC base, were taken from 3 different sections, each with different Novabond® emulsion application rate. As stated earlier, the specimens were cores from the I-70/Broadway Avenue exit project in St. Louis. Typical double Novachip® composite specimen is shown in Figure 6-14. There were two passes of a gap graded Novachip® mixture with approximately ¾ inch thick per pass. The details of Novabond® application rates for each section are presented in Table 6-2. The actual lift thickness measurements are exhibited in Table 6-3, in which composite specimens are denoted by section number and test number (for instance s1t1 meaning section 1 test 1).

The peak load used in section 6.1, 570lbs, was first tried on composite specimen s1t2. The specimen failed very quickly after loading, around 700 seconds. The results of specimen s1t2 were not included in the following analysis. Around half of the load used in section 6.1, 270 lbs, was used on the rest of the specimens.

For section 2 specimens, an unsuccessful attempt was made to introduce a crack in the concrete groove in specimen s2t2. Damage was introduced in the specimen while cracks were initiated by force with visible crushed concrete at the bottom of the groove. The results of specimen s2t2 were not included in the following analysis.

For section 3, specimen s3t1 was broken by accident. Visibly less binder (drier) on top layer was observed on all three composite specimens of section 3 as shown in Figure 6-15. This was probably caused by construction problems. Results of specimens from section 3 were therefore not included in the following analysis.
Figure 6-14. Double Novachip® composite specimen

Table 6-2. Novabond® application rate of double Novachip®

<table>
<thead>
<tr>
<th>Number</th>
<th>Lift 1(gal/sy)</th>
<th>Lift 2(gal/sy)</th>
<th>Total(gal/sy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
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<td>0.211</td>
<td>0.4</td>
</tr>
<tr>
<td>Section 2</td>
<td>0.308</td>
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</tr>
<tr>
<td>Section 3</td>
<td>0.299</td>
<td>0.398</td>
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</table>

Tests results are presented in Figure 6-16 for number of loading cycles to failure and Figure 6-17 for damage rate. Damage rate results were obtained from strain gage measurement as shown in Figure 6-14. In Figures 6-16 and 6-17, low rate are results for section 1 and high rate are results for section 2. Test results indicated that section 1 with lower Novabond® application rate underperformed relative to section 2 with higher Novabond® application rate.
Table 6-3. Double Novachip® lift thickness

<table>
<thead>
<tr>
<th>Number</th>
<th>Lift 1 (mm)</th>
<th>Lift 2 (mm)</th>
<th>Concrete (mm)</th>
<th>Total (mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>17.50</td>
<td>14.61</td>
<td>49.61</td>
</tr>
<tr>
<td>1-1a</td>
<td>17.10</td>
<td>17.29</td>
<td>18.16</td>
<td>52.55</td>
</tr>
<tr>
<td>1-1b</td>
<td>19.32</td>
<td>21.02</td>
<td>15.46</td>
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<tr>
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<td>11.98</td>
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<tr>
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<td>15.52</td>
<td>50.38</td>
</tr>
<tr>
<td>3-3b</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6-15. Cracking surfaces of double Novachip® composite specimen
It should be noted that the ½ inch thick concrete might cause local effects at the bottom of the concrete groove as shown in Figure 6-18. In the future, concrete thickness should be increased in order to reduce this local effect.

Figure 6-16. Number of cycles to failure for double Novachip® specimen

Figure 6-17. Damage rate of double Novachip® specimen
6.3 Effects of OGFC on Top-down Cracking

Because of its low fracture resistance, OGFC may increase the susceptibility to top-down cracking failure for pavements. Test specimens consist of only dense-graded mixture with no interface. The typical all dense-graded mixture specimen is shown in Figure 6-19. Tests were performed under the same condition as in section 6.1.1. Their results are compared with those from composite specimens (OGFC compacted on dense graded) with conventional tack coat interface as shown in section 6.1.1.

Tests results are presented in Figure 6-20 for loading cycles to failure and Figure 6-21 for damage rate. Results indicate that to some extent OGFC reduce cracking resistance for pavements with OGFC overlay relative to pavements without OGFC.
Figure 6-19. All dense-graded mixture specimen

<table>
<thead>
<tr>
<th>Test</th>
<th>No. of Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test1</td>
<td>Test2</td>
</tr>
<tr>
<td>20000</td>
<td>25000</td>
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</tbody>
</table>

Figure 6-20. Number of cycles to failure of OGFC on dense with conventional tack interface and all dense-graded
Figure 6-21. Damage rate of OGFC on dense with conventional tack interface and all dense-graded.
7.1 Summary and Conclusions

A composite specimen interface cracking (CSIC) test system was developed in this research to evaluate the effects of pavement layer interface characteristics on cracking performance. During the developing process, a composite specimen with interface preparation method was first conceived and evaluated; and the following variables were evaluated: loading mode including monotonic and repeated; composite specimen thickness including 1 inch and 3 inch dense-graded mixture; stress concentrator type including rectangular and cylindrical; composite specimen geometry including asymmetric and symmetric and specimen diameter; loading position including specimen curved end surface and within the stress concentrator; composite specimen curved end surface reinforcement. Three types of interface conditions on top-down cracking, two types of interface conditions on reflective cracking, and the effect of OGFC on top-down cracking were evaluated. Some of the findings associated with this development and testing are as follows,

- The additional compaction of Superpave mixture or OGFC had a negligible effect on the integrity the bottom dense-graded mixture. If there is any, the effect would be the improvement in damage resistant.

- As compared with monotonic loading, repeated loading with resting period allows the interface materials to dissipate the accumulated stress and thus differentiate the effects of interface conditions on cracking.

- For asymmetric composite specimen under monotonic loading, the attempt to keep interface in stable crack propagation region by increasing lower layer thickness from 1 inch to 3 inch was proved to be ineffective because damage was accumulating in both composite specimen layers.

- Greater specimen to specimen variability was caused by rectangular stress concentrator and asymmetric specimen as compared to cylindrical stress concentrator to symmetric specimen, respectively.
More favorable stress state was achieved by reducing the specimen diameter and loading head width; however it led to specimen shear failure in OGFC. Shear failure was eliminated by loading within the stress concentrator; however this led to specimen bending failure, which was eliminated by use of carbon fiber reinforcement on specimen curved end surface.

Repeated loading applied within the 6 inch diameter specimen stress concentrator with edge surface reinforcement successfully propagated cracks through the interface and effectively identified the effects of interface on cracking performance.

For top-down cracking performance, as compared with conventional tack coat, Novabond® increased the number of cycles to failure and reduced the damage rate; on the other hand, trackless tack reduced the number of cycles to failure and increased the damage rate.

For reflective cracking performance, as compared with conventional tack coat, Novabond® increased the number of cycles to failure and reduced the damage rate for composite specimen with teflon spacer, which consisted of dense-graded mixture on dense-graded mixture, whereas no difference was observed for specimens without teflon spacer.

For reflective cracking performance, higher application rate of Novabond® showed larger number of cycles to failure and lower damage rate for composite specimens consisting of double Novachip® on Portland cement concrete.

For the effects of OGFC on top-down cracking, as compared with all dense-graded mixture specimens, composite specimens with OGFC on top of dense-graded mixture exhibited less number of cycles to failure and higher damage rate.

After comprehensive evaluation of the effects of different layer interface conditions on top-down and reflective cracking, and the effect of OGFC on top-down cracking, the following conclusions can be drawn,

- The CSIC test method developed in this study can be used to evaluate the relative effects of pavement layer interface characteristics on cracking performance.
- Polymer modified asphalt emulsion, like Novabond®, increases the top-down cracking performance of composite specimen by increasing the cracking resistance of materials near the interface and by dissipating the stress accumulated at the interface. It should be pointed out that the effectiveness of interface conditions is closely related to its brittleness. Trackless tack had a negative effect on the top-down cracking performance.
- Polymer modified asphalt emulsion, like Novabond®, increases the reflective cracking performance of composite specimen when compared with conventional...
tack coat. Novabond® interface application rate plays an important role on the cracking resistance.

- OGFC applied on top of dense-graded mixture to some extent reduces the cracking resistance of composite specimen with conventional tack coat interface as compared with specimens without OGFC. In order to maintain the cracking performance of pavements with OGFC overlay, polymer modified asphalt emulsion needs to be applied at the interface.

### 7.2 Recommendations

Based on the studies completed, the following items are recommended for further research:

- Experimental road test on the effects of interface conditions on both top-down and reflective cracking performance needs to be conducted and evaluated.

- The effects of interface conditions on cracking performance for different composite specimen combination, including both top and lower layer material type and gradation, need to be evaluated. Optimum interface condition, i.e., application rate, needs to be identified.

- A thorough analysis of the total recoverable deformation versus time curve should be performed to identify the crack initiation and propagation stages in the specimen and thus the fracture resistance of OGFC. It can be used as an approach to measure the properties of thin OGFC or other thin layers within the composite specimen.

- Besides the cracking performance of interface as stated in this study, the interface bonding condition between pavement layers also has an important effect on the pavement performance. Literature review indicates that a new bond test (under repeated loading) needs to be developed based on the test method identified in this study.

- Age hardening has a significant effect on the cracking performance of asphalt concrete mixture and the interface materials. An age conditioning procedure needs to be developed for composite specimen, including heat, ultraviolet and water. Laboratory aged composite specimen properties can be compared with field coring composite specimen.
APPENDIX A
THE AMOUNT OF INTERFACE MATERIAL CALCULATION

Cross section area of the SGC specimen:

\[ A = \pi r^2 = \pi \times 7.5^2 = 176.71 \text{ cm}^2 \]

1 yard^2 = 8361.27 cm^2; 1 gallon = 3785.41 cm^3;
1 gallon / yd^2 = 3785.41 cm^3 / 8361.27 cm^2 = 0.453 cm^3 / cm^2.

The amount of asphalt emulsion applied,

\[ \text{mass} = \text{application rate} \times 0.453 \times 176.71 \times P_b. \]

Specific gravity \( P_b \) of asphalt emulsion is around 1.0. For instance, the application rate is 0.045 gallon / yd^2 for open-graded friction course overlay according to 2010 FDOT Standard Specifications for Road and Bridge Construction Section 300.

The amount of asphalt emulsion applied,

\[ \text{mass} = 80.05 \times 0.045 \times 1.0 = 3.6 \text{ grams}. \]

If paving grade binder is used, it should be adjusted from the amount of asphalt emulsion corresponding to the residue rate.
APPENDIX B
THE AMOUNT OF OVERLAY MATERIAL CALCULATION

Assume compacted overlay material’s height is $H_{\text{overlay}}$, air void content is $AC_{\text{overlay}}$, maximum specific gravity is $Gmm_{\text{overlay}}$, mass of overlay mixture is $M_{\text{overlay}}$, Gyratory compaction mold inner diameter is $D$, base material height is $H_{\text{base}}$,

$$M_{\text{overlay}} = V_{\text{asphalt-aggregate}} \times Gmm_{\text{overlay}}$$

$$= \pi \times (D / 2)^2 \times H_{\text{overlay}} \times (1 - AC_{\text{overlay}}) \times Gmm_{\text{overlay}}.$$

This compaction is based on the compacted specimen height, $H_{\text{overlay}} + H_{\text{base}}$, but not the number of gyrations.
LIST OF REFERENCES


Texas Technical Advisory (2001). “Proper use of tack coat,” Technical Advisory 2001-1, Construction and Bridge Divisions, Texas Department of Transportation, Austin, TX.


BIOGRAPHICAL SKETCH

Yu Chen was born in Siyang, Jiangsu Province, People’s Republic of China in 1981. He received a Bachelor of Science degree in civil engineering from Chang’An University in 2003.

In August 2003, Yu Chen started a Master of Engineering program in civil engineering at Chang’An. After finishing his master’s degree, Yu Chen came to the United States in 2006. He joined the Ph.D. program of the materials group at the University of Florida and worked as a graduate research assistant with his doctoral advisor, Dr. Reynaldo Roque. After completing his Ph.D., he plans to work in academia, government agencies, or private companies in civil engineering.