Louisiana Transportation Research Center

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Evaluation of Bonded Concrete Overlays over Asphalt under Accelerated Loading

by

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16. Abstract

Bonded concrete overlay of asphalt (BCOA), previously known as ultra-thin whitetopping (UTW), has been widely used to repair aged asphalt concrete (AC) pavements with moderate distress in many states in the United States. Due to the increasing costs of roadway maintenance, Louisiana has a great interest in determining if the thin bonded concrete overlay (usually 2-6 in.) is a suitable and cost-effective alternative to the current practice of roadway maintenance. The objective of the study was to evaluate the structural performance and load carrying capacity of BCOA pavements and to characterize the influence of in-situ bond strength on the performance of BCOA pavements. In this study, three full-scale BCOA test sections with 6-in., 4-in., and 2-in. Portland cement concrete (PCC) over an aged asphalt pavement were tested under accelerated pavement test (APT) loading under a typical pavement condition in southern Louisiana. The aged asphalt pavement consists of 3-in. AC over 8.5-in. crushed stone and 10 in. cement treated subgrade. A heavy load simulation device – ATLaS30, equipped with a hydraulically-adjusted dual-tire wheel load, was used. Each section was trafficking-loaded to a failure (i.e., all the slabs in loading path were cracked) under alternated load magnitudes of 9 kips and 16 kips of the ATLaS dual-tire wheel load. It was found that the 6-in. PCC overlay had a superior load carrying capacity compared to the 4-in. and 2-in. concrete overlays. The predicted pavement lives for the 6-in., 4-in, and 2-in. BCOA sections were 8.9-, 3.5-, and 1.2- million ESALs, respectively. As expected, the majority of load-induced cracks were not at a slab corner but along the wheel path (or longitudinal direction), presumably because the accelerated load in this study was applied along the centerline of the slabs. The load-induced tensile strains (measured at bottom of the slabs) also revealed a longitudinal cracking potential. Several Non-Destructive Test (NDT) methods indicated that the crack initiation of a BCOA slab could be coupled with a possible debonding at the slab-asphalt interface. A trench cutting investigation further revealed that a good bond was established between the PCC and AC layer. A performance review and in-situ pull-off test (also known as bond test) of the BCOA slabs suggests that the main distresses, such as longitudinal and corner cracks, develop primarily as a result of debonding of the asphalt layer from the concrete overlay. Debonding, which reduces the contribution from the underlying asphalt layer, increases the stress in the concrete layer, leading to the development of cracks. Therefore, under what level the bond strength should be specified in a BCOA pavement design is still debatable. Based on the results, it is recommended that a 6-in. BCOA pavement may be used in a medium to high volume pavement design where heavy and overloaded trucks are abundant and a 4-in. BCOA may be suitable to be used in a pavement rehabilitation project with a medium volume traffic. A newly-developed SJPCP module in the Pavement ME software was employed to predict the performance of the BCOA sections of this study. The predicted results were discovered to be roughly comparable to the in-situ cracking performance of this study. Finally, a failure criterion in terms of fatigue cracking and bond strength was proposed and the corresponding construction cost savings when implementing BCOA pavement as a design option for a medium to high volume pavement were estimated.

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In this study, three full-scale BCOA test sections with 6-in., 4-in., and 2-in. Portland cement concrete (PCC) over an aged asphalt pavement were tested under accelerated pavement test (APT) loading under a typical pavement condition in southern Louisiana. The aged asphalt pavement consists of 3-in. AC over 8.5-in. crushed stone and 10-in. cement treated subgrade. A heavy load simulation device, ATLaS30, equipped with a hydraulically-adjusted dual-tire wheel load was used. Each section was trafficking-loaded to a failure (i.e., all the slabs in loading path were cracked) under alternated load magnitudes of 9 kips and 16 kips of the ATLaS dual-tire wheel load. It was found that the 6-in. PCC overlay had a superior load carrying capacity compared to the 4-in. and 2-in. concrete overlays. The predicted pavement lives for the 6-in., 4-in., and 2-in. BCOA sections were 8.9-, 3.5-, and 1.2- million ESALs, respectively. As expected, the majority of load-induced cracks were not at a slab corner but along the wheel path (or longitudinal direction), presumably because the accelerated load in this study was applied along the centerline of the slabs. The load-induced tensile strains (measured at bottom of the slabs) also revealed a longitudinal cracking potential. Several Non-Destructive Test (NDT) methods indicated that the crack initiation of a BCOA slab could be coupled with a possible debonding at the slab-asphalt interface. A trench cutting investigation further revealed that a good bond was established between the PCC and AC layer. A performance review and in-situ pull-off test (also known as bond test) of the BCOA slabs suggests that the main distresses, such as longitudinal and corner cracks, develop primarily as a result of debonding of the asphalt layer from the concrete overlay. Debonding, which reduces the contribution from the underlying asphalt layer, increases the stress in the concrete layer, leading to the development of cracks. Therefore, under what level the bond strength should be specified in a BCOA pavement design is still debatable.

Based on the results, it is recommended that a 6-in. BCOA pavement may be used in a medium- to high-volume pavement design where heavy and overloaded trucks are abundant and a 4-in. BCOA may be suitable to be used in a pavement rehabilitation project with a medium-volume traffic. A newly-developed SJPCP module in the Pavement ME software was employed to predict the performance of the BCOA sections of this study. The predicted results were discovered to be roughly comparable to the in-situ cracking performance of this study. Finally, a failure criterion in terms of fatigue cracking and bond strength was proposed and the corresponding construction cost savings when implementing BCOA pavement as a design option for a medium- to high-volume pavement were estimated.

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IMPLEMENTATION STATEMENT

The proven durability and cost-effective construction method of bonded concrete overlay over existing asphalt pavement has created a great deal of interest from many state and local transportation agencies. The accelerated pavement testing experiment of this study also demonstrated that a BCOA pavement can provide a cost-effective and durable pavement design option for medium to low-volume roads in Louisiana. In fact, the results showed that a 6-in. BCOA pavement may be used in a medium-to high-volume pavement design where heavy and overloaded trucks are abundant. The 4-in. BCOA may be suitable to be used in a pavement rehabilitation project with a medium-volume traffic. Currently, a typical medium-to high-volume roadway in Louisiana consists of an existing asphalt concrete layer over a PCC or cement-stabilized soil base. Due to the increasing costs of roadway maintenance, the Louisiana Department of Transportation and Development (DOTD) should consider a BCOA pavement as an alternative to the current practice of roadway maintenance. Therefore, the researchers recommend that DOTD consider implementing a BCOA pavement as a pavement design alternative in medium-to high-volume pavement design.

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INTRODUCTION

Bonded concrete overlay of asphalt (BCOA) is a pavement rehabilitation technique that involves the placement of a thin Portland Cement Concrete (PCC) overlay, over a distressed asphalt concrete (AC) pavement. Typically, the AC pavement is milled and cleaned which helps to create a bond between the existing AC pavement and the PCC overlay *[1-2]*. The bond between the two layers promotes composite action of the pavement section and as a result has a direct impact on the performance of the BCOA Pavements. Compared with unbonded overlays, bonded overlays have a sound bond between the overlay and the asphalt concrete (AC) layer. The bond is maintained through some proper construction techniques so that the composite action takes advantages of the structural capacity of the existing AC layer and correspondingly allows for a reduced thickness of the overlay layer. In general, the BCOA is usually categorized as ultra-thin (2 - 4 in.) and thin (4 - 8 in.) overlays in terms of the overlay thickness *[3]*. For BCOA pavements, saw-cutting square panels are typically recommended (i.e., the length and width of square panels in feet are limited to 1-1.5 times of the slab thickness in inches) in order to reduce the flexural and curling stresses in the overlay *[4-5]*.

Many studies have been carried out to investigate the performance of the BCOA under various conditions *[6-16]*. Sheehan et al. studied the performance of the concrete overlay on the AC layer and concluded that a good bond within the interface of the concrete and AC layer is essential for the performance of the BCOA *[2]*. In the study, the tensile stress at the bottom of the concrete layer under a partial bonding condition is 51 percent higher than that under a fully bonded condition. Newbolds concluded that the debonding of the BCOA is most likely the cause of the cracking and the debonding usually occurs prior to cracking *[7]*. Most of the cracks are corner breaks since the load was applied close to the saw cut joints, which caused the increased potential of debonding due to the higher corner/edge deflections *[4]*. It was also concluded that corner break is the primary distress when the saw cut joint is inside the wheelpath *[10]*. Coring results of the study indicate that a sound bonding is well maintained at midpanel while debonding often occurs at the edge of the panel *[4,10]*. Therefore, it is generally recommended that, if possible, longitudinal joints should be appropriately arranged so that they are not in the tire print.

Kim and Lee investigated the bonded stress at the interface through a finite element analysis *[8]*. It was found out that the normal tensile stress and horizontal shear stress at the interface may cause the debonding and therefore lead to the pavement distress. There are also some other existing studies focused on the performance of the BCOA with the joint sealing and dowel bars. Vandenbossche and Barman concluded that the sealing of the joints will extend the service life of the BCOA since the prevention of the water infiltration ensures a good bond *[11]*. The presence of dowel bars helps to mitigate faulting at joints and also has the benefit in maintaining the bond within the interface of the concrete overlay and AC layer.

Many methods for the BCOA design have been proposed in the past decades *[17-20]*. In general, considerations including the slab corner breaking, longitudinal cracking, temperature differential, and/or partial bonding were integrated into these empirical design methods to design the thickness of the BCOA. As the pavement design evolves from the empirical design to Mechanistic-Empirical design in recent years, Vandenbossche et al. developed a Mechanistic-Empirical design procedure, which has been recently implemented in the AASHTOWare Pavement ME software (Version 2.3.1) *[4,21]*.

The proven durability and cost-effective construction method of bonded concrete overlay over existing asphalt pavements has created a great deal of interests from many states and local transportation agencies. Currently, the typical medium to high volume roadway in Louisiana consists of an existing asphalt concrete layer over a crushed stone or cement-stabilized soil base. Due to the increasing costs of roadway maintenance, the Louisiana Department of Transportation and Development (DOTD) has a great interest in determining if the thin bonded concrete overlay (usually 2-6 in.) is a suitable and cost-effective alternative to the current practice of roadway maintenance.

LITERATURE REVIEW

A significant portion of US highway pavements are now in bad or poor condition and in need of repair. Various pavement rehabilitation alternatives have been developed and used for the rehabilitation of these deteriorated or partially-deteriorated pavements. Currently, the most common method of rehabilitating a deteriorated or partially-deteriorated pavement surface is through an AC overlay; however, high oil prices have caused designers and agencies to consider other methods. One alternative to the traditional AC overlay is a concrete overlay. Well designed and constructed concrete overlays can serve as cost-effective maintenance and rehabilitation solutions for almost any combination of existing pavement type and condition, desired service life, and anticipated traffic loading.

Reasons to consider a concrete overlay as a rehabilitation alternatives include the following *[5]*:

- May be appropriate for asphalt roads, streets, and intersections in fair or better structural condition with typical distresses such as rutting, shoving, slippage, and thermal cracking;
- Are generally 2-6 in. thick
- Rely on the existing asphalt pavement to provide additional load-carrying capacity, and bond to the existing asphalt pavement to form a monolithic section, thereby reducing stresses and deflections
- Add structural capacity where traffic loads have increased or are anticipated to increase
- Eliminate surface defects such as rutting and shoving
- Improve surface characteristics (friction, noise, and smoothness)
- Reduce urban heat island effect by increasing pavement surface albedo
- Low maintenance requirements
- Withstands heavy truck traffic
- Quick to construct
- Effective life-cycle costs
- Recyclable

The terms used for concrete overlays in the past (ultrathin whitetopping, conventional whitetopping, bonded overlays, unbonded overlays, etc.) have tended to confuse people. To avoid such confusion, recently all the concrete overlay types are considered to fall into two categories- the bonded concrete overlays and the unbonded concrete overlays. Figure 1 shows the various types of concrete overlay techniques.

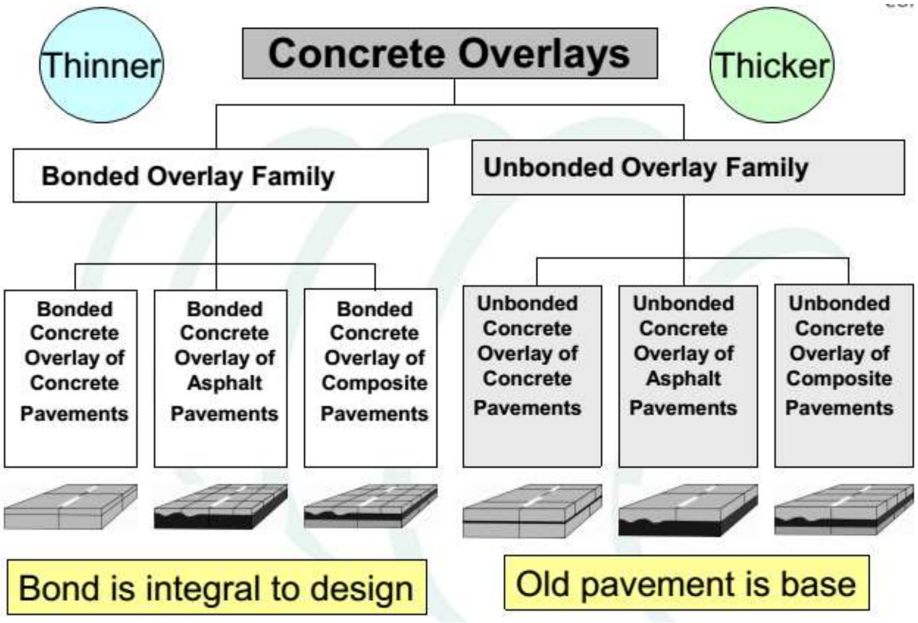


Figure 1
Types of concrete overlays

Bonded concrete overlays over existing concrete, asphalt, and composite pavements are used to restore the structural capacity and to correct surface defects of existing pavements that are in fair to good structural condition. These overlays commonly range between 2 and 6 in. in thickness and the average service life is around 15 to 20 years. The bond between the two layers promotes composite action of the pavement section and as a result has a direct impact on the performance of the pavement. This composite action allows for the reduced thickness in the overlay layer. Additionally, a short joint spacing is typically used, which reduces the flexural and curling stresses of the overlay and reduce debonding of concrete and asphalt at early ages *[5]*.

Unbonded concrete overlays over existing concrete, asphalt, and composite pavements are commonly used to add structural capacity to the existing severely distressed pavements. In this case, the existing pavement provides a foundation for the unbonded overlay that, in turn, serves as a new pavement. It does not require any bonding between the overlay and the underlying pavement. These unbonded overlays typically range between 4 and 11 in. in thickness and are the average service life is around 20 to 40 years *[5]*.

This study mainly focused on the performance of the bonded concrete overlays on asphalt (BCOA) pavements (previously known as ultra-thin whitetopping) shown in Figure 2.

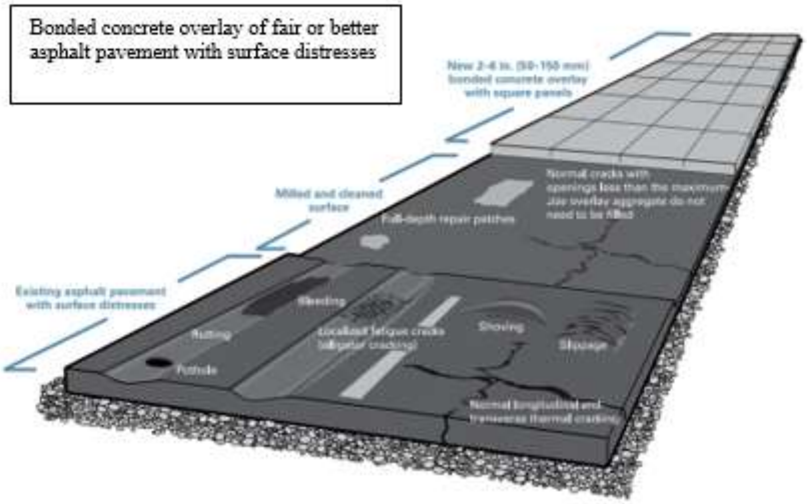


Figure 2
Bonded concrete overlay over asphalt pavement with surface distresses

Early work on use of thin BCOA can be traced back to the early 1980's in Denmark. The first BCOA was constructed in 1991 in the United States. Two test pavements were constructed in Louisville, Kentucky on an entrance road to a landfill with a thickness of 2-in. and 3.5-in. joint spacing were either 2 ft. or 6 ft. The authors reported that the test sections were a success. Following the success of the BCOA project in Kentucky, several other BCOA projects were conducted across the United States. All the projects constructed in the last few years have provided promising results for further implementation and analysis of BCOA as a rehabilitation technique for distressed asphalt pavements *[5]*. Following are some of the major consideration for the success of the BCOA pavements before construction:

- Milling of existing asphalt may be required to eliminate or reduce surface distortions of 2-in. or more and to help provide a good bond.
- Minimal spot repairs may be required.
- A minimum of 3-in. of asphalt should remain after milling.
- Asphalt surface should be sprinkled with water when the surface temperature exceeds 120ºF during overlay placement.
- A clean surface is critical to achieving an adequate bond between the overlay and the underlying asphalt.
- When feasible, design the longitudinal joints to be outside of the normal wheel paths.
- No notable stripping or delamination at tack lines exists in asphalt pavement to remain after milling.

According to the previous studies from different states, the performance of a BCOA pavement depends on the following factors *[5]:*

- Sufficient bond should exist between the concrete overlay and the AC. The bond actually results in composite, monolithic action of the pavement. This effectively shifts the neutral axis down in the pavement section thereby reducing the stress at the bottom of the concrete overlay to a level less than the concrete's strength (Figure 3).
- Shorter joint spacing or small panels. Smaller joint spacing helps to reduce the stresses generated by bending as well as curling and warping effects on the pavement due to temperature and moisture gradients. Figure 4 illustrates this theory.
- Sufficient thickness of the remaining asphalt. The thicker asphalt section carries more loads and helps the neutral axis to shift further down, thereby causing composite action.
- The critical load location may shift from the edge location to the corner location of the pavement, if the neutral axis moves low enough in the pavement section.
- The stiffness of the AC layer also affects the location of the critical loading. If the ratio of AC to concrete overlay stiffness is around 20 percent, the critical load location shifts from edge to the corner if the layers are fully bonded. If the bond is totally lost, the critical location is at the edge. Thus, both the edge and corner locations need to be evaluated during the BCOA design.

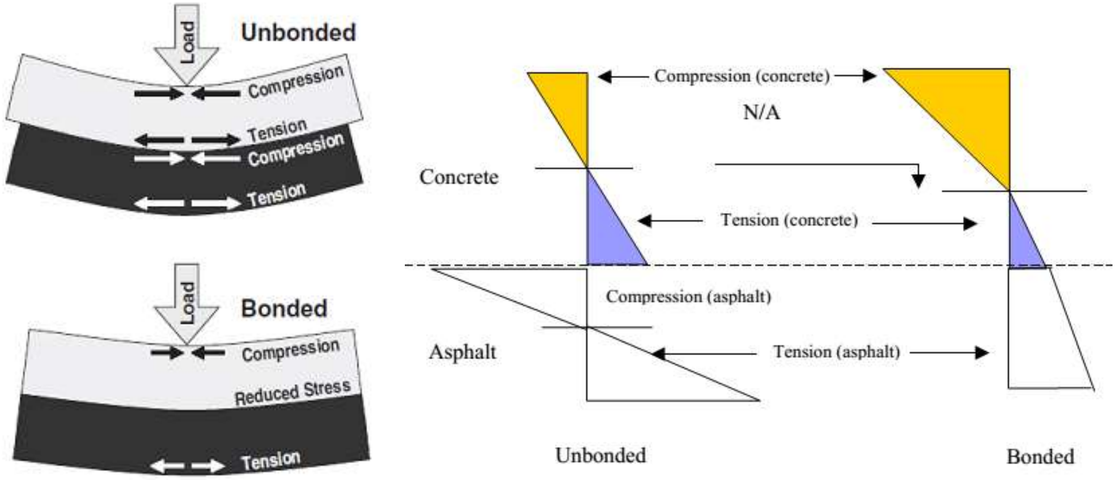


Figure 3
Stress distribution in bonded and unbonded concrete overlays

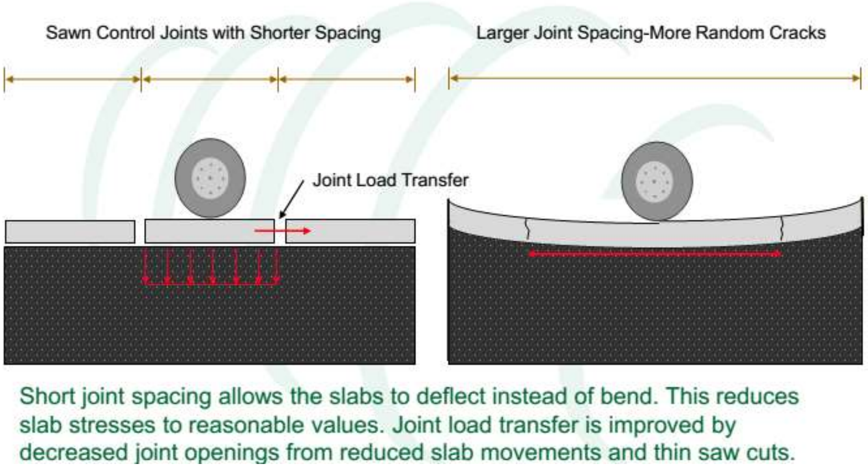


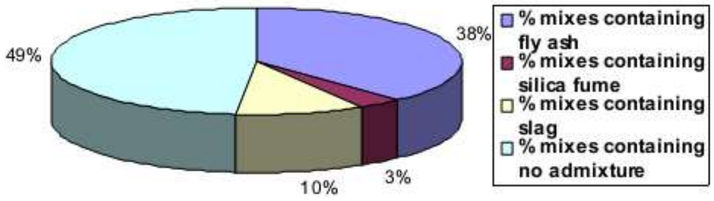
Figure 4
Effect of short joint spacing on performance of concrete overlay

Concrete Mix Design and Engineering Properties

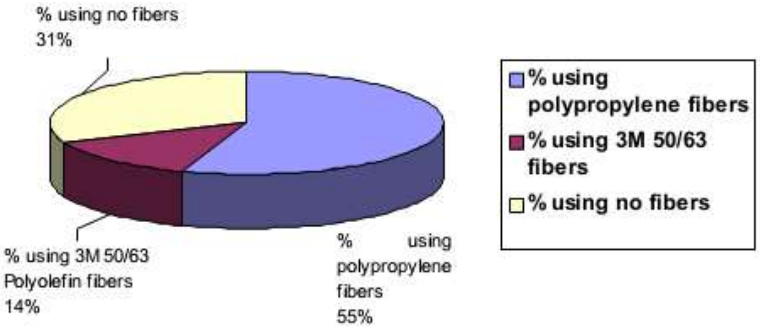
An effective mixture design is essential to the performance of a bonded concrete overlay. Conventional concrete mixtures are typically used for bonded concrete overlays. Each of the components used in a concrete mixture should be carefully selected so that the resulting mixture is dense, relatively impermeable, and resistant to both environmental effects and deleterious chemical reactions over the length of its service life.

The concrete mixture can be proportioned for rapid strength gain, minimum thermal expansion and contraction, and minimum shrinkage. Some states use rapid-strength concrete mixtures with a high cementitious material content. The typical mix is characterized by low water-cement ratio (< 0.40), and smaller top size aggregate (typically 0.75 in.). The slump requirement (2.5 in. - 4 in.) for construction and placing is achieved by the use of high range water reducers. For bonded concrete overlays, it is better to have a wet, sticky mixture than a dry one *[30]*.

The use of fibers also has been observed in many mixes. The fibers are believed to delay the crack propagation after the onset of a crack on the concrete surface. The two main fibers used are fibrillated Polypropylene fibers and Polyolefin fibers. The average compressive strengths achieved by the mixes were well above 17.25 MPa after 1 day and some of the mixes showed strengths of over 60 MPa after 28 days. The flexural strength of typical mixes was around 5 to 5.5 MPa after 28 days. Figure 5 shows the various use of mineral admixtures in the BCOA mixes *[31]*.



(a) Use of mineral admixtures in BCOA mixes



(b) Use of fibers in BCOA mixes

Figure 5
Use of mineral admixtures in BCOA mixes

Design of Bonded Concrete Overlays

Guidance for bonded concrete overlay design has been published by American CPA, FHWA, NCHRP, PCA and various state departments of transportation (CDOT, MnDOT, ICT, NJDOT etc.). Among all these design guidelines, ACPA is currently the recommended design method for BCOA pavements. The original design procedures for this overlay type were published by ACPA in 1998. ACPA developed a mechanistic procedure to design thinner (2 to 4-in.) bonded concrete overlays of asphalt pavements with smaller slab sizes. The ACPA procedure is based on calculating the fatigue damage in the slab for a corner loading condition, as well as limiting the fatigue damage at the bottom of the existing asphalt pavement at the transverse joint location. Temperature curling stresses are also considered in the critical pavement response. One limitation of this method is that it is based on the PCA beam fatigue model, which yields very conservative estimates. In 2004, ACPA refined its fatigue models to incorporate newer probabilistic methods into its pavement design procedures. Riley developed a modified ACPA method in 2006 that incorporated a new probabilistic concrete fatigue algorithm *[32]*. This modified method allows for inputting the existing asphalt pavement properties, accounts for the type and amount of structural fibers, and checks for a potential bond plane failure.

In January 2011, ACPA released a BCOA thickness design web application that incorporates the work by Riley. The ACPA BCOA is valid for a slab thickness of 3 to 6-in. and a maximum panel size of 6 ft. Shorter joint spacing (both transverse and longitudinal) are typically used for bonded overlays over asphalt pavements, such as 4-ft. by 4-ft. or 6-ft. by 6-ft. slabs for a 12-ft. wide lane. Updates in 2012 improved the fiber reinforcement input to the ACPA BCOA based on work by Roesler et al. *[14],* which used the residual strength ratio of the fiber reinforced concrete measured according to ASTM C1609-10. In 2012, the BCOA design tool was also upgraded to allow for structural designs in any climate zone in the U.S. by including site-specific effective temperature gradients *[21]* for approximately 200 cities.

Previous Studies

Many studies on the concrete overlay over asphalt pavements have been conducted in different states of the US and also in different countries. Several studies have been carried to investigating the performance and stress-strain characteristics of concrete overlay pavements, the bonding strength between concrete and asphalt layers, and the effect of temperature and degree of loading on the overlaid pavements, under both in situ conditions and accelerated research facility controlled-environment. Investigations have also been carried out to find the variation in the performances of plain concrete and concrete with admixture and fiber. Instrumentation gauges (e.g., concrete strain gauges and thermistors) have been used to monitor the strain and temperature behavior of the pavements. Finite element modeling was carried out to compare the predicted and observed stress behavior. The following list some of the recently-reviewed studies from the literature.

- The effect of underneath asphalt layer on concrete overlay was elaborately studied in Colorado *[2]*. They studied the effect of overlay on unprepared, milled and new asphalt layer. The use of concrete overlay on new AC was not recommended. Moreover, it was concluded that higher viscosity of the AC layer would prompt cracking in the pavement according to a study in Virginia. So, type, properties of existing AC layer along with joint spacing, and curing period play significant roles to achieve desired performance for concrete overlay. The use of tied concrete shoulder on thin concrete overlay was also emphasized.
- A study in Virginia revealed the impact of resilient versus permanent deformation on the concrete overlay *[6]*.
- A study has been conducted in Iowa for concrete overlays with higher variation in thickness (2-8 in.). They studied the variation of thickness, joint spacing concrete mix and surface preparation.

- The application of concrete overlay over airport runway has also been investigated in Tennessee and Missouri *[6]*. The stress-strain behavior for different weather conditions were also observed for the project in Tennessee. No significant difference was found.
- The pavement research facility of Indiana investigated the effect of different load ranges and temperature for plain and fiber mixed concrete *[7, 12]*. They found cracking only for high traffic loading under significant variation of temperature. The bonding between concrete and asphalt overlay was good.
- A project in Montana reported the failure of concrete overlay due to moisture sensitivity of asphalt layer. The other studies on the whitetopping in Montana have yielded in satisfactory cracking behavior of overlay along with improve in noise environment near intersections *[6]*.
- Cost benefit analysis shows the rate of increase in cost for concrete overlay is not proportional to thickness of the layer. There is an optimum amount of fiber for cost effective application of *overlay [6]*.
- Romanoschi et al. *[13]* studied the performance of thin concrete overlay over both rigid and flexible pavements. Cracking was visible on concrete overlay over rigid pavements. However, the bonding between the overlay and underneath layer was good in both of the cases. So, this cracking might be due to the loss of support beneath the transverse joints.
- The phenomenon of reflection cracking on concrete overlay by asphalt pavement was studied *[11]*. The stiffness of PCC and asphalt layer are determining factor behind this type of cracking.
- The performance of three BCOA sections in Louisiana were also studied, as shown in Table 1. The road function classifications for these sections were rural or urban principal arterials. The design average daily traffic (ADT) ranged from 8,200 to 53,100; and the 20-year projection equivalent single axle load (ESAL) ranged from 4,071,096 to 12,473,980 *[33]*. Figure 6 illustrates pictures of selected BCOA pavement sections.

Table 1

Louisiana BCOA projects

Route	Parish	Project Length (mile)	Function Classification	Design ADT	Truck Percentage (percent)	20-Year Projection ESAL	Existing Pavement after Milling	Traffic Opened Year
US167	Winn	1.0	Urban Principal Arterial	14,600	16	7,114,865	6” AC+ 12” Asphaltic Base	06/1999
US65	Concordia	1.6	Rural Principle Arterial	8,200	11	4,071,096	12” AC+8” PCC	10/2003
US90	Jefferson	0.3	Urban Principal Arterial	53,100	7	12,473,980	6.5”AC +5” Sandy Gravely Clay Base	02/2003

(a) UTW section on US167 after 13.5 years of service

(b) New constructed UTW section on US65 (*19*)

(c) UTW section on US65 after 9.4 years of service

(d) UTW section on US90 after 10.2 years of service

Figure 6

Louisiana BCOA pavement sections

All three BCOA sections had the same slab panel size of 4 ft. by 4 ft. with an overlay thickness of 4 in. The BCOA slabs were placed over existing flexible or composite pavements after milling 4-in. existing AC. The BCOA concrete mix design was required to achieve a minimum flexural strength of 700 psi in 28 days. The concrete slump was required to be less than or equal to 4-in. The concrete air content was 3 to 5 percent. Synthetic polypropylene fibers were added at a rate of 3 lb. per cubic yard of concrete. Saw cut joints were cut to a depth of 1/3 the pavement thickness. The performance survey date, corresponding pavement age, and predicted cumulative ESALs for each section can be found in Table 2 [33].

Table 2
Louisiana UTW project performance

No.	Route	Survey Date	Pavement Age (Year)	Predicted Cumulative ESALs
1	US 167	10/4/2000	1.3	421,030
		12/13/2003	4.5	1,480,134
		2/12/2005	5.7	1,885,981
		12/62006	7.5	2,504,081
		8/92008	9.2	3,097,873
		1/12/2011	11.6	3,953,819
		11/30/2012	13.5	4,645,995
2	US 65	4/5/2005	1.5	265,407
		2/27/2007	3.4	609,775
		10/26/2009	6.1	1,116,010
		2/5/2011	7.4	1,367,427
		2/28/2013	9.4	1,763,513
3	US 90	4/11/2003	0.2	113,302
		5/26/2005	2.3	1,312,054
		11/28/2007	4.8	2,771,867
		12/8/2008	5.9	3,425,636
		3/1/2011	8.1	4,755,258
		3/28/2013	10.2	6,052,101

OBJECTIVE

The overall objective of this research was to evaluate the structural performance and load carrying capacity of BCOA pavement structures with different PCC overlay thicknesses through accelerated pavement testing and document the experience of mix design and construction practice of PCC overlays for DOTD.

SCOPE

To achieve the objectives, an accelerated pavement testing experiment including three full-scale BCOA test sections were conducted in this research. The laboratory tests included the mixture design, unconfined compressive strength and flexural strength. In-situ pavement testing program consisted of falling weight deflectometer (FWD) deflection tests, pull-off test, surface texture and profile tests, temperature and load-induced pavement response measurements, crack mapping survey, and forensic trenching. Based on the APT results, potential benefits of using BCOA pavements were evaluated and guidelines were developed for BCOA pavements in Louisiana.

METHODOLOGY

Description of APT Test Sections

Pavement Structures

Three BCOA pavement test sections were constructed at the Pavement Research Facility (PRF) site in Port Allen, Louisiana, using normal highway construction equipment and procedures. Figure 7 presents the plan view and pavement layer thickness configurations of the test sections.

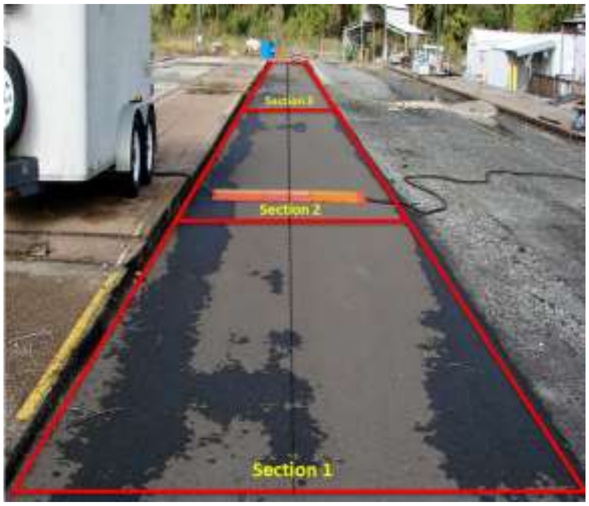
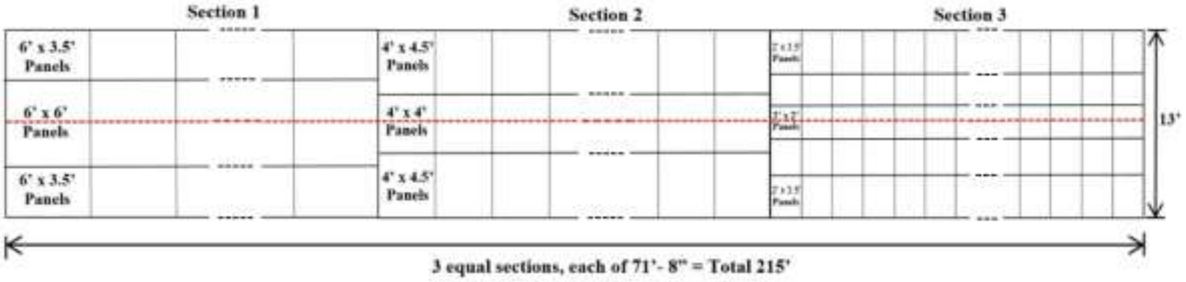


Figure 7
Existing AC test sections before overlay placement

As shown in Figure 8, each pavement section is 13 ft. wide and 72 ft. long. Saw-cut joints were prepared at a 2 × 2 ft., 4 × 4 ft. and 6 × 6 ft. panel spacing on the loading areas of the 2-in., 4-in. and 6-in. concrete overlays, respectively. The existing pavement consists of a 4-in. existing AC layer, an 8.5-in crushed stone layer over a 10-in. cement stabilized subgrade. One inch of the existing AC layer was milled and the milled surface was thoroughly cleaned before the placing of the concrete layer.



*Not to Scale

2, 4 or 6 in. PCC
3 in. existing AC
8.5 in. crushed stone
10 in. Cement treated subgrade
Subgrade

Figure 8

BCOA pavement test sections

Materials

The PCC mixes used in this study was designed at LTRC's concrete research lab. Cylindrical samples of PCC were prepared on site during the construction; cylinder PCC cores and saw-cut beams were prepared after the construction for the laboratory strength tests. All structural design material input parameters, such as compressive and flexural strength was determined. The 4 and 6-in. section was constructed using a Type B paving mixture and the LTRC concrete research lab developed the mix design to include fibers for the 2-in. section.

BCOA Mix Design

Mix Proportion Requirements for the 4-in. and 6-in. Pavement Sections:

- 525 pounds of total cementitious content
- 15 percent fly ash substitution on a pound for pound basis
- Following aggregate gradation (by volume) was used:
    - 35 percent crushed limestone
    - 25 percent pea gravel
    - 40 percent natural sand
- Water cement ratio = 0.50
- Minimum air-entraining agent (AEA) dosage rate
- Water reducer as required to achieve a 4-5 in. slump

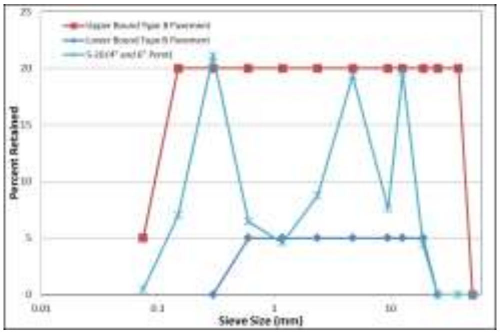


Figure 9

BCOA pavement gradation (6-in. and 4-in. section)

Mix Proportion Requirements for the 2-in. Pavement Section

- 600 pounds of total cementitious content
- 15 percent fly ash substitution on a pound for pound basis
- Following aggregate gradation (by volume) was used:
    - 50 percent #8 Crushed Stone
    - 50 percent natural sand
- Water cement ratio = 0.50
- Minimum air-entraining agent (AEA) dosage rate
- Water reducer, or superplasticizer, as required to achieve a 4-5 in. slump
- Strux 90/40, or equivalent, macro fiber dosed at 3 pounds per cubic yard (pcy)

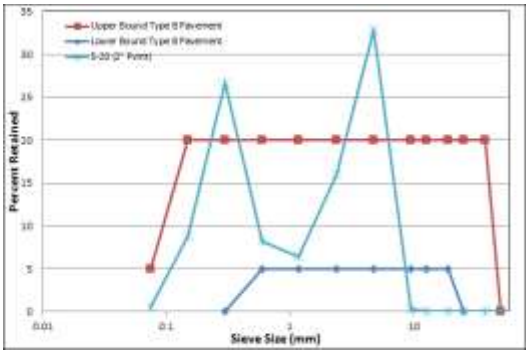


Figure 10
BCOA pavement gradation (2-in. section)

Construction of APT Test Sections

Pavement Evaluation and Pre-Overlay Repairs

An evaluation of the existing asphalt pavement is necessary to ensure it is structurally adequate to carry the anticipated traffic loads. The pavement test section was evaluated and it was determined that milling is required. Before the milling operation, areas with potholes, moderate to-severe cracking; or loss of base/subgrade support was identified to ensure the requirements of partial or full-depth spot repairs to provide uniform bonding and to achieve the desired load carrying capacity and long-term durability. The milled surface was also inspected for isolated pockets of deterioration that require further repairs.

Milling and Surface Cleaning

Most surface distresses were removed through milling. For this study, 1-in. of asphalt was milled based on the types and severity of distresses on the old pavement test section. Following the milling, the asphalt surface was cleaned to ensure adequate bonding between the existing asphalt surface and the new concrete overlay. Adequate bonding is very important to the performance of this type of overlay. Cleaning was accomplished by first sweeping the asphalt surface, then cleaning with compressed air.

Concrete Overlay Placement and Curing

Once the surface of the existing asphalt pavement was prepared, paving was accomplished using fixed form construction technique. Before the concrete placement, water trapped in the milled surface was blown off with compressed air.

Curing is especially critical on a bonded concrete overlay because its high surface area-to-volume ratio makes the thin concrete overlay more susceptible to rapid moisture loss. Within 30 minutes of placing the overlay, curing compound was applied at the standard rate.

Joint Sawing

Timely joint sawing is necessary to prevent random cracking. Lightweight early-entry saws were used to allow the sawing crew to get on the pavement as soon as possible. Saw-cut joints were prepared at a 2 × 2 ft., 4 × 4 ft. and 6 × 6 ft. panel spacing on the loading areas of the 2-in., 4-in., and 6-in. concrete overlays, respectively to a depth of one-third the slab thickness.

(a) Milled asphalt

(b) Pouring of concrete

(c) Placement of concrete

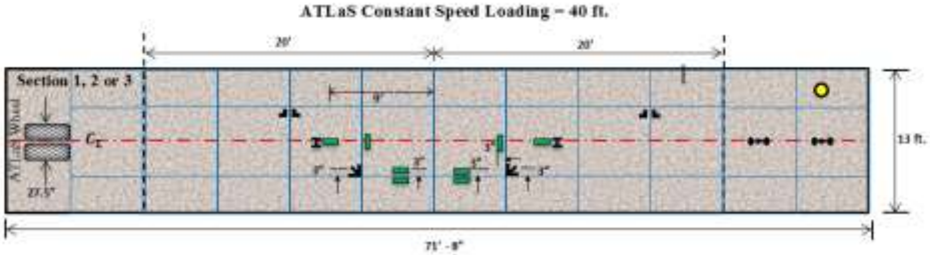
(d) Levelling

(f) Broom finish (g) Curing

Figure 11
Construction of BCOA test sections

Instrumentation

Instrumentation devices were installed during and after the construction of PCC overlay test sections. The instrumentation layout for each test section proposed in this study is depicted in Figure 12. In general, four different types of strain gauges were used to measure the strains at midslab, edge and corner of the PCC slab under wheel loading at different depths. The strain gauges were, concrete strain gauge (Tokyo Sokki PML-60-2L), interface strain gauge (WFLM-60-11-2LT), surface strain gauge (Tokyo Sokki PL-120-11), and corner strain gauge (PLR-60-11). The concrete strain gauge was embedded in concrete at various depths in the slab, both transversely as well as longitudinally. The longitudinal gauges were installed at the center of the slab, near longitudinal joint and adjacent slab. The gauges were located 0.5 in. from the bottom of the overlay and about 0.5 in. from the top of the overlay. The transverse gauges were installed at the center of the slab near the transverse joint at similar depths. The output from these strain gauges were helpful to predict the fatigue damage of the concrete overlay. The interface strain gauge were installed at the top of the existing AC just under the concrete embedded gauge. These gauges were used to predict the strain at the bottom of concrete overlay to calculate the fatigue life. The corner strain gauge consisting of three fixed gauges together aligned in the transverse, longitudinal, and an inclined 45-degree angle axis were installed at the corner of the slab. The gauges rosette were located 0.5 in. from the bottom of the overlay and about 0.5 in. from the top of the overlay. The output from these gauges were useful to analyze the fatigue and corner cracking.



(a) Plan View

(c) Typical Cross Section

(b) Legends

Figure 12
Instrumentation plans for each test section

Tokyo Sokki PML 60. The purpose of embedded strain sensors is to measure the dynamic strain responses at the bottom of the PCC layer in the center of the wheelpath under moving loads.

Installation:

- Prior to installation, the functionality of each strain gauge was checked and manufacturer provided calibration was used for the experiment.
- The locations of the strain gauge on the test sections was marked with respect to a fixed reference point.
- Precautions were taken during construction of PCC layer to minimize disturbance of gauges.
- After construction, the location, elevation and functionality of each strain gauge was confirmed to check the survival.

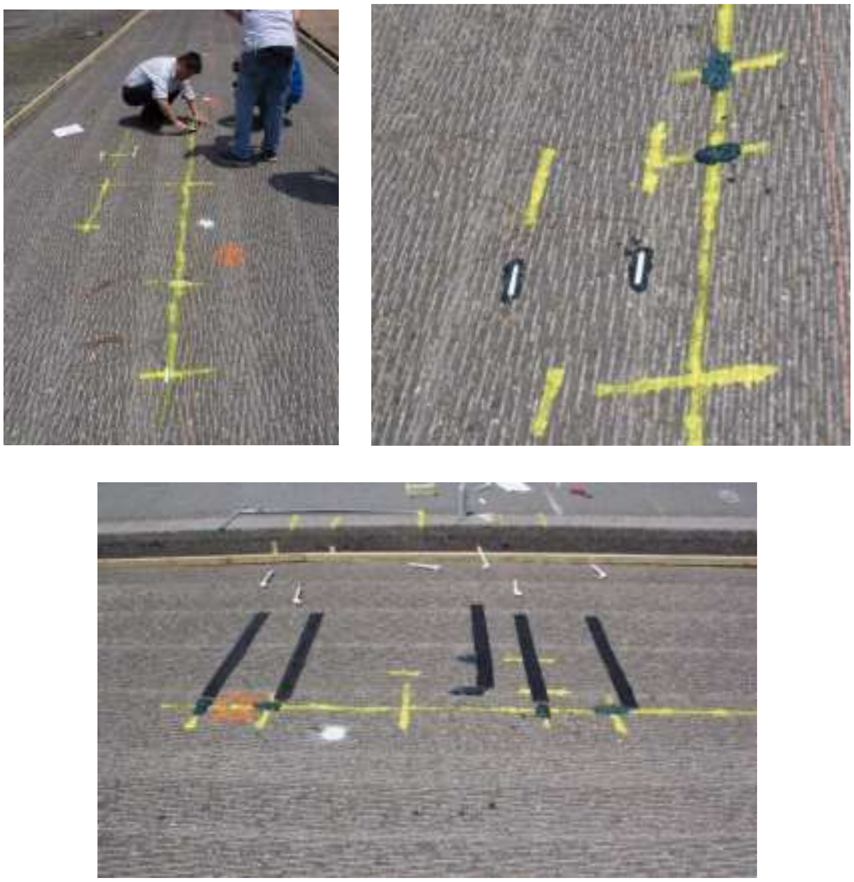


Figure 13
Instrumentation of BCOA test sections

Data Acquisition Systems

National Instruments (NI) DAQ hardware was utilized to collect data from strain gauges. Data acquisition and archiving requires appropriate software configured for each experimental setup. For this experiment, data was collected using NI LabVIEW ver. 12. Built in pre-processing signal filtering in the data acquisition hardware and software helped to produce a clean signal. However, electronic noise was encountered while examining the data. A 10-point moving average of data points was used to get clean signals by eliminating the noise. The raw data files were saved into separate folders and subfolders according to the test date, dual tire load, repetition, section number, and data type.

Accelerated Loading Experiment

APT Loading Device

A heavy vehicle load simulation device (ATLaS30) was used for the accelerated loading of BCOA test sections in this experiment. As shown in Figure 14, the ATLaS30 device is 65 ft. long, 7 ft. high, and 10 ft. wide, constructed around two parallel steel I-beams. The ATLaS30 wheel assembly models one-half of a single axle and is designed to apply a dual-tire load up to 30,000 lbf by hydraulic cylinders; see Figure 14. With a computer-controlled loading system, the weight and movement of traffic is simulated repetitively over a 40-ft. long loading area in bi-directional mode at a top speed of 6 mi/hr. By increasing the magnitude of load and running the device for 24 hours a day, it is possible to condense 20 years of loading into a period of only one month. An incremental loading sequence (e.g., 9 and 16kips) of the ATLaS30 dual tire load is expected to be applied in order to fail each BCOA pavement section in fatigue cracking within a reasonable time frame.

Figure 14
The ATLaS30 device

Failure Criteria and Loading History

Figure 15 shows in situ failure conditions of each BCOA test section tested in this study. Overall, one and half million-load repetitions (i.e., 750,000 of 9-kip and 750,000 of 16-kip) were applied on the 6-in. BOCA section; 560,000 repetitions (i.e., 310,000 of 9-kip and 250,000 of 16-kip) were loaded on the 4-in. sections; and 210,000 repetitions (i.e., 130,000 of 9-kip and 80,000 of 16-kip) were added on the 2-in. section. According to the 1993 AASHTO design method, such amounts of load repetitions are equivalent to 8.9-, 3.5-, and 1.2- million ESALs for the 6-in., 4-in. and 2-in. BCOA sections, respectively. In the end of loading, all the BCOA pavement test sections were found to have reached to a cracking failure. This was evidenced by the fact that all slabs under loading have developed at least one load-induced crack in either longitudinal, transverse, or corner directions. The measured cracking areas were 51 percent, 54 percent and 59 percent for the 6-in., 4-in. and 2-in. sections, respectively.

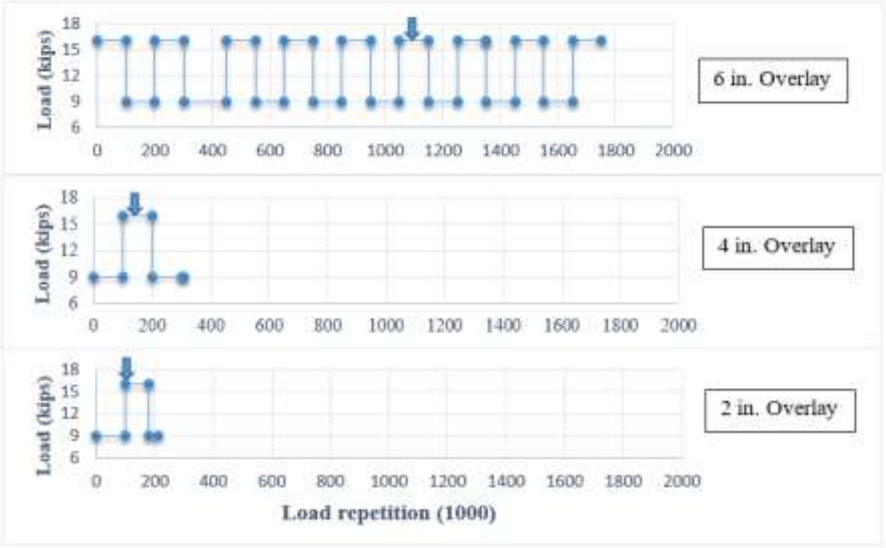


Figure 15
Loading sequence of the pavement test sections

In this study, the predicted ESAL numbers were computed using an equivalent axle load factor (EALF) multiply by the corresponding number of load repetitions under a certain ATLaS30 axle load. The EALFs for different ATLaS30 axle loads were estimated based on the AASHTO's rigid pavement equations as follows *[22]:*

$$\log(EALF) = 4.62\log(18+1) - 4.62\log(L_x + L_2) + 3.28 log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad (1)$$

$$G_t = \log(\frac{4.5-p_t}{4.5-1.5}) \quad (2)$$

$$\beta_x = 1.00 + \frac{3.63(L_x+L_2)^{5.20}}{(D+1)^{8.46}L_2^{3.52}} \quad (3)$$

where, L_x is the load in kip on different axles;
L_2 is the axle code, 1 for single axle, 2 for tandem axles, and 3 for tridem axles;
p_t is the terminal serviceability, which indicates the pavement conditions to be considered as failures;
D is the slab thickness in inches.

Field Measurements and Non-Destructive Testing

During and After Construction

The Falling Weight Deflectometer (FWD) deflection test and density measurements were performed on the completed surfaces of all base and subgrade layers during the construction. Shortly after the construction, a suite of in- situ tests were performed on the finished BCOA surfaces, including walking profiler, Light FWD (LFWD), falling weight deflectometer (FWD) and Pull off Test. A Dynatest 8002 FWD was used in this experiment with nine sensors spaced at 0 in., 8 in., 12 in., 18 in., 24 in., 36 in., 48 in., 60 in., and 72 in. from the center of the load plate. Figure 16 shows a picture of each in-situ tests used. In addition, an ARRB Walking Profiler G2 was used to measure the centerline profilers of the finished BCOA surfaces. A software named "ProVAL" was used to convert a measured longitudinal profile into the International Roughness Index (IRI) number for each BCOA pavement section tested *[23]*.

In-Situ Measurements

In-situ tests including the FWD, LFWD, walking profiler and in-situ pull-off bond strength test were conducted at different locations along the pavement test section on both loaded and unloaded areas; see Figure 16. A post mortem evaluation on failed BCOA pavement sections was also performed at the end of APT testing by taking out field cores and trenches.

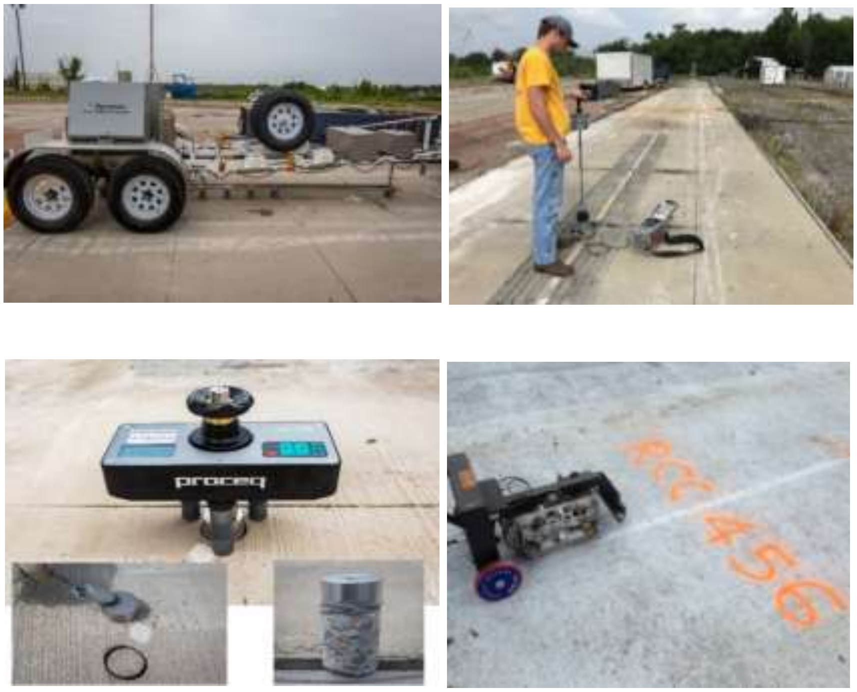


Figure 16

In-situ test devices

Data Analysis Techniques

The data analysis of this study include the processing of NDT deflection data, evaluation of instrumentation results, modeling BCOA pavement structure and fatigue analysis, and prediction of BCOA pavement cracking performance. The analysis procedures and software used in this study are: ELMOD 6, ProVal 3.0, BCOA-ME, and AASHTO PavementME.

DISCUSSION OF RESULTS

The results presented for discussion were obtained from both laboratory and APT measurements, including the mixture strengths, moisture-density curves, NDT, instrumentation data, surface crack mapping, and forensic trenches on failed BCOA test sections.

Results from Laboratory Tests

BCOA Laboratory Results

Compressive Strengths. Figure 17 shows the compressive strength results for all lab-produced mixtures tested. The target strength for the mixture was set at 4000 psi at 28 days of age. The results show that all mixtures meet the required 4000 psi as early as 7 days of age.

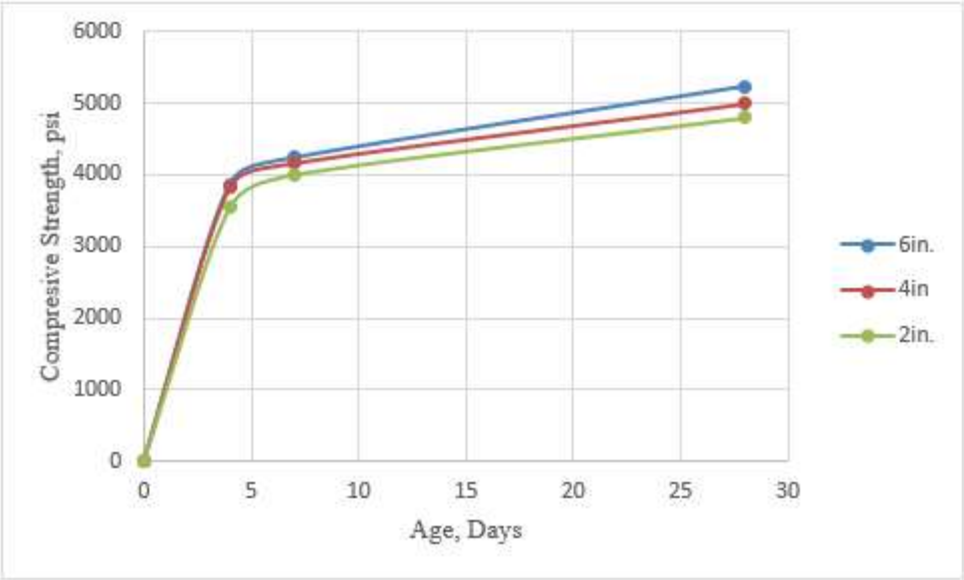


Figure 17
Compressive strengths of BCOA pavements

Flexural Strength. An average flexural strength of the laboratory prepared beam samples at 28 days was 688 psi. It should be pointed out that all the cylindrical samples and field cores achieved the adequate strength requirements for this experiment.

Table 3
Laboratory flexural strength of field samples at 28 days

Age: 28day	6in.	4in.	2in.
Sample1	685	707	651
Sample2	715	774	658
Sample3	669	725	609
Avg.	690	735	639
StDev.	23.4	34.7	26.5
CoV.	3.4	4.7	4.1

Results from BCOA APT Test Sections

Overall BCOA Pavement Performance

In the end of the APT loading test, all the BCOA pavement test sections (6, 4 and 2 in.) were found to have reached their respectively pavement service lives, evidenced by the extensive surface cracks (above 50 percent area cracked) and significant surface roughness as shown in Figure 18. Since there are limited slabs (8 for the 6-in. section, 12 for the 4-in. section and 24 for 2-in. section) the percentage of cracking slabs of all the slabs in the wheel path may not fully reveal the development of the cracking under the accelerated load. In addition, the IRI results imply that the pavement may still be capable of bearing more load repetitions even at a 100 percent slab cracking. For this experiment, a test section was considered to have failed when 50 percent of the trafficked area of a section developed visible cracks (e.g., longitudinal, transverse, and corner cracks) more than 1 ft/ft^2. The percent cracking area in the wheel path was calculated as shown in equation (1). In equation (1), the width of the wheel path is assumed as 3-ft. and the cracking is assumed to be 1-ft. wide. Based on the equation, the percentages of the cracking area in the test sections at the end of the loading repetitions are 51 percent, 54 percent and 59 percent for the 6-in., 4-in. and 2-in. section, respectively.

$$\text{Percent cracking area} = \text{Cracking length in the wheel path} \times 1 \text{ ft.} / (\text{lane length} \times 3 \text{ ft.}) \quad (1)$$

6-in. Section **4-in. Section** **2-in. Section**

Figure 18
Visual distresses of BCOA pavement test sections

Cracking Performance

The majority of the cracks in this study were not corner cracks as observed in several previous studies but the bottom-up longitudinal ones. The main reason is that the accelerated loading was applied along the centerline of the slab and therefore the tireprint was relatively far away from the longitudinal joints. As shown in Figure 19, the 4-in. and 2-in. section did demonstrate a portion of corner cracks due to the shorter joint. Comparing the three BCOA sections, it was noticed that the longitudinal cracking was propagated within both the tireprints on the 4-in. and 2-in. section while only in one of the tireprints on the 6-in. section. This phenomenon may be caused by the short joint spacing (4 ft. and 2 ft.) of the 4-in. and 2-in. section. For the 4-in. and 2-in. section with the 4-ft. and 2-ft. joint spacing respectively, after the generation of a longitudinal cracking in one of the tireprints, the other tireprint became the potential occurrence location of the bottom-up longitudinal cracking. Since the short joints are the weak spots of the BCOA, it is wise to prevent the saw-cut joints directly appearing in the middle of the wheelpath.

FWD backcalculated subgrade moduli (M_r) before applying any loads at different stations were also plotted on a vertical axis to the left side in Figure 19. The weaker subgrade portion under the loading area caused a higher tensile stress under the slab than did the stronger subgrade portion All the BCOA pavement test sections initially cracked at the weaker subgrade support and also heavily cracked on those locations.

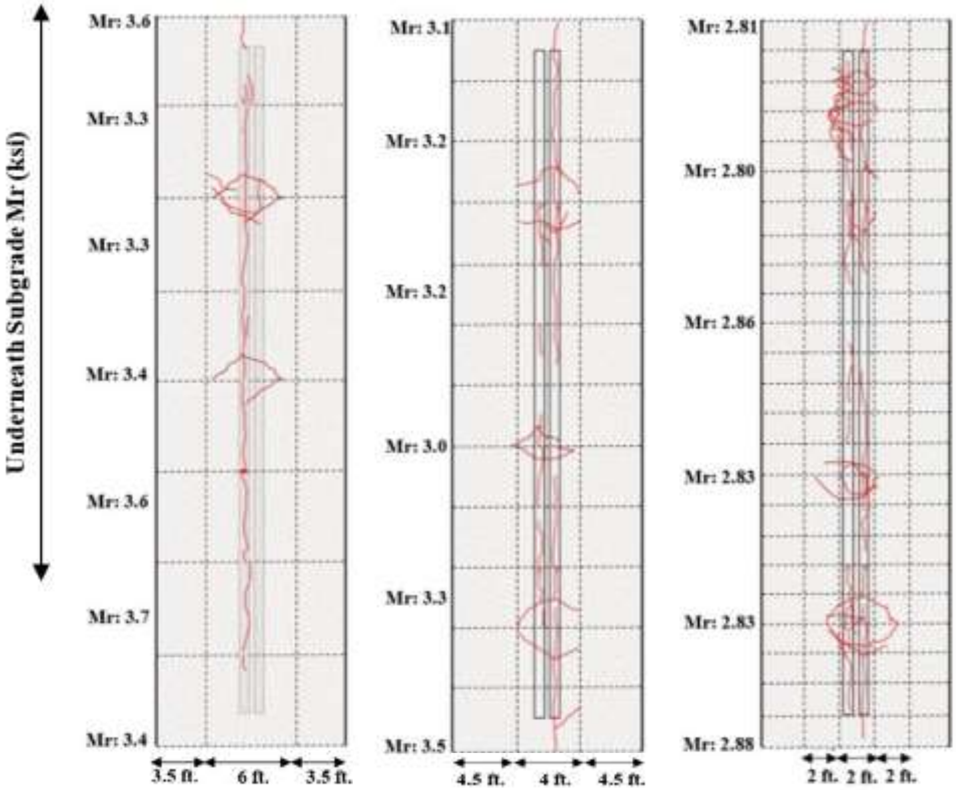


Figure 19
Cracking mechanism of BCOA pavement test section

Load-Induced Strains

The pre-installed strain gauges in the slab as shown in Figure 20 captured the load-induced tensile strains in the slab with the increase of load repetitions. Overall, the measured strains were constant before the occurrence of the cracking and debonding area except showing temperature variations. With the increase of the load repetitions, the strain gauges gradually became dysfunctional due to the deterioration of the slab. Figure 20 shows the average strain measured by each functional strain gauges. Strain gauge A1 measured the longitudinal strain (which could cause a potential of a bottom-up transverse crack in the slab) at the bottom of the slab and A2 measured the transverse strain (which could cause a potential for a bottom-up longitudinal crack in the slab) at the bottom of the slab. Clearly, the strain gauge A2 measured the most critical transverse strain underneath a saw-cut joint. Therefore, the transverse strain was much higher than the longitudinal one at the locations of A1 and A2. A higher transverse strain indicates a longitudinal cracking potential, which resulted in the cracking pattern as appeared in Figures 19. The strain gauges A4 and A5, which were installed adjacent to each other, showed much lower longitudinal strain readings as compared with others at the bottom of saw-cut joints. A3 captured the transverse strain on the top of the slab edge under the accelerated load. The strain may cause the top-down fatigue cracking in the longitudinal saw-cut joint parallel to the traffic direction. Similar response was observed for all three pavement test sections.

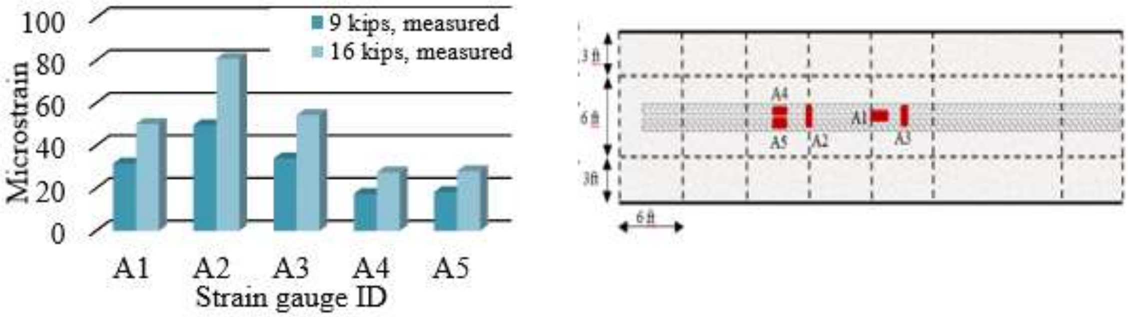


Figure 20

Average strains in the slab

FWD Results

A Dynatest FWD was used in this experiment with nine sensors spaced at 0 in., 8 in., 12 in., 18 in., 24 in., 36 in., 48 in., 60 in. and 72 in. from the center of the load plate. Four FWD load levels: 9,000, 12,000, 15,000 and 25,000 lb. were used on the finished surfaces of BCOA test sections and on the milled AC layer before placing the PCC layer to determine the surface deflections and pavement stiffness. The FWD test was also conducted at the end of the pavement life to determine a change in pavement stiffness with load repetition. The results were also used to identify potential void location under the PCC layer. ELMOD 6 was used in this study for the backcalculation and void detection of the BOCA pavement structure. Because of the difficulty to use the FWD test under the ATLaS30 loading device, LFWD tests were also conducted at different load repetition along the pavement test sections. Figure 21 shows the location of the chainage station for the FWD tests and LFWD testing locations.

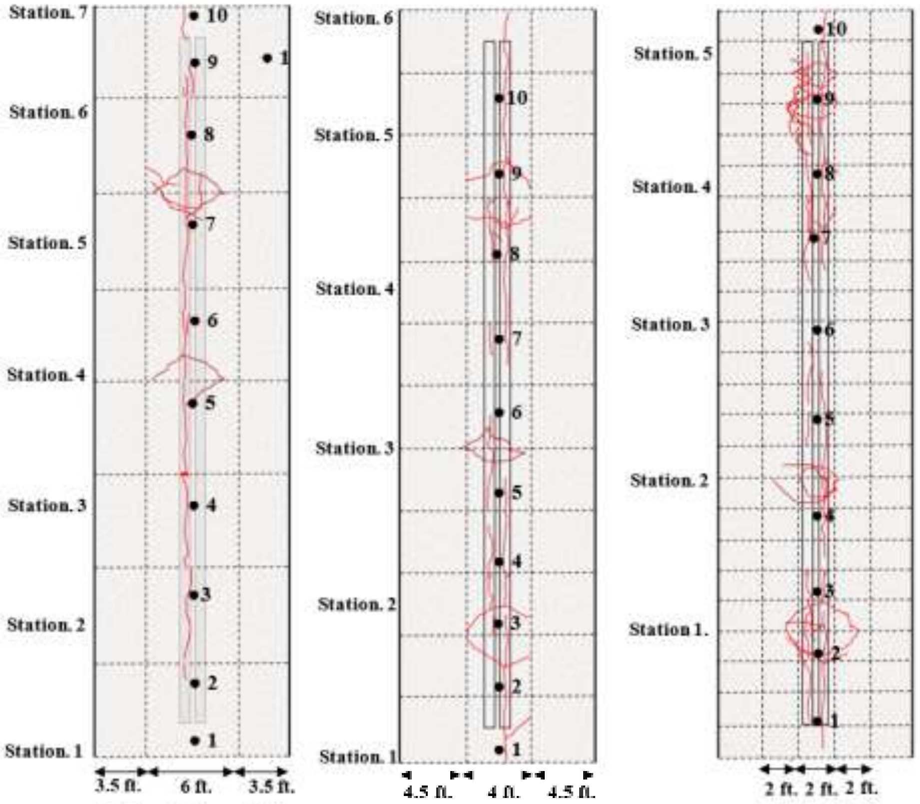
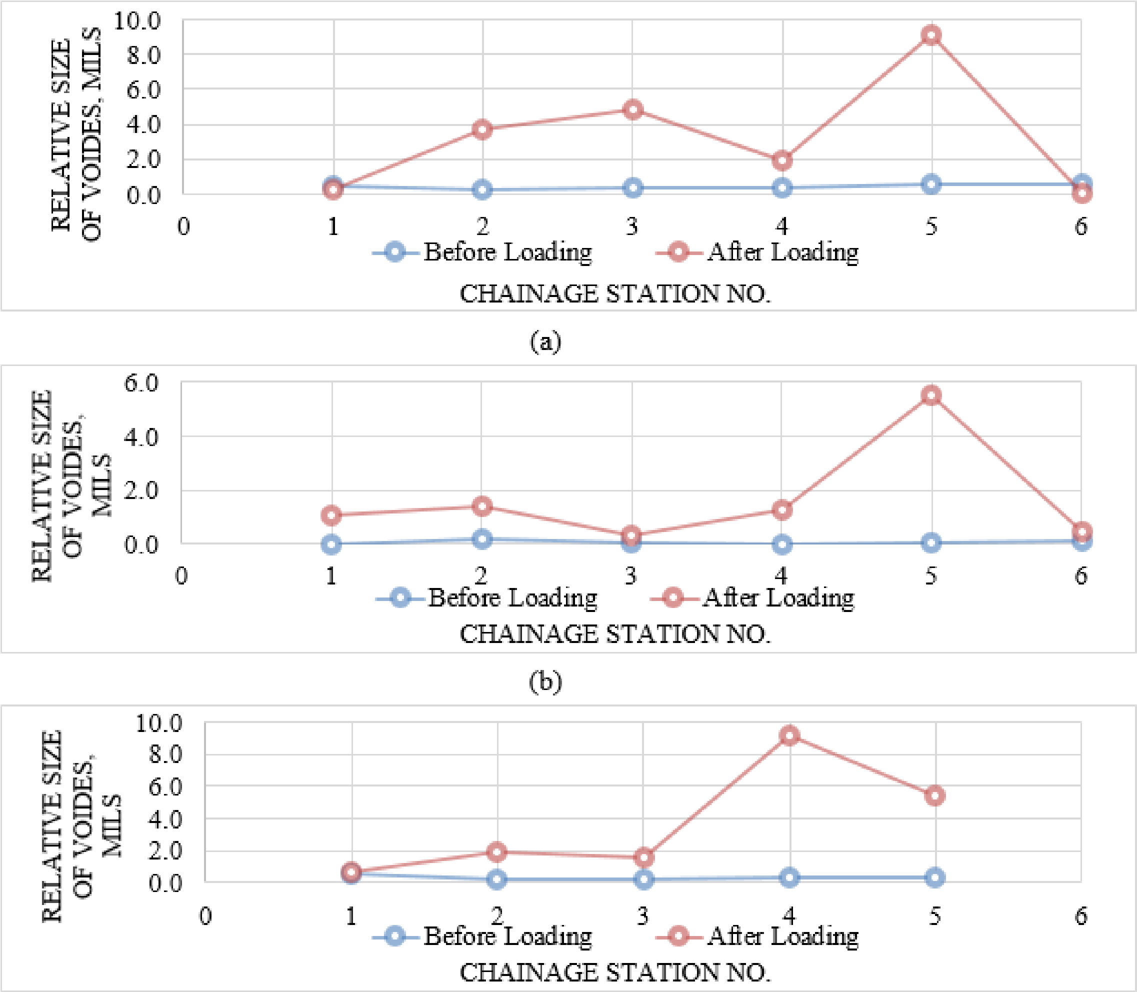


Figure 21

FWD chainage station and LFWD test locations

Voids are generally created below slab corners due to pumping and erosion of subbase/subgrade material from repeated loading cycles. In this study, the data from the FWD drops at four different loads was used to plot edge deflections against the applied load for each station to assess the potential for voids. The best-fit line of the data points should go through the origin if the pavement response is linear. However, the pavement deflections respond nonlinearly when voids exist. When voids are present, a deflection occurs with a minimal applied load until the slab comes in complete contact with the base layer. According to other research studies, an intercept of the y-axis greater than 2 mils may be an indication of the existence of voids *[29]*. The intercept values from the load versus deflection plots for the FWD tests performed in 6, 4, and 2-in. BCOA pavements is summarized in Figure 22. As shown in the figure, the y-intercepts for all the sections were below 2 mils before applying any loads on the pavement. However, there are some possible void locations were observed after the load is applied on the pavement test sections. This voids or the existence of loss of support also comply with the cracking mechanism. For the 6-in. section, locations 2, 3, and 5 shows potential voids or loss of support. For the 4-in. section, locations 5 shows potential voids or loss of support and for the 2-in. section location 4 and 5 shows potential voids or loss of support. Forensic investigation at those locations also revealed the existence of voids underneath the PCC layer.



(a)

(b)

(c)

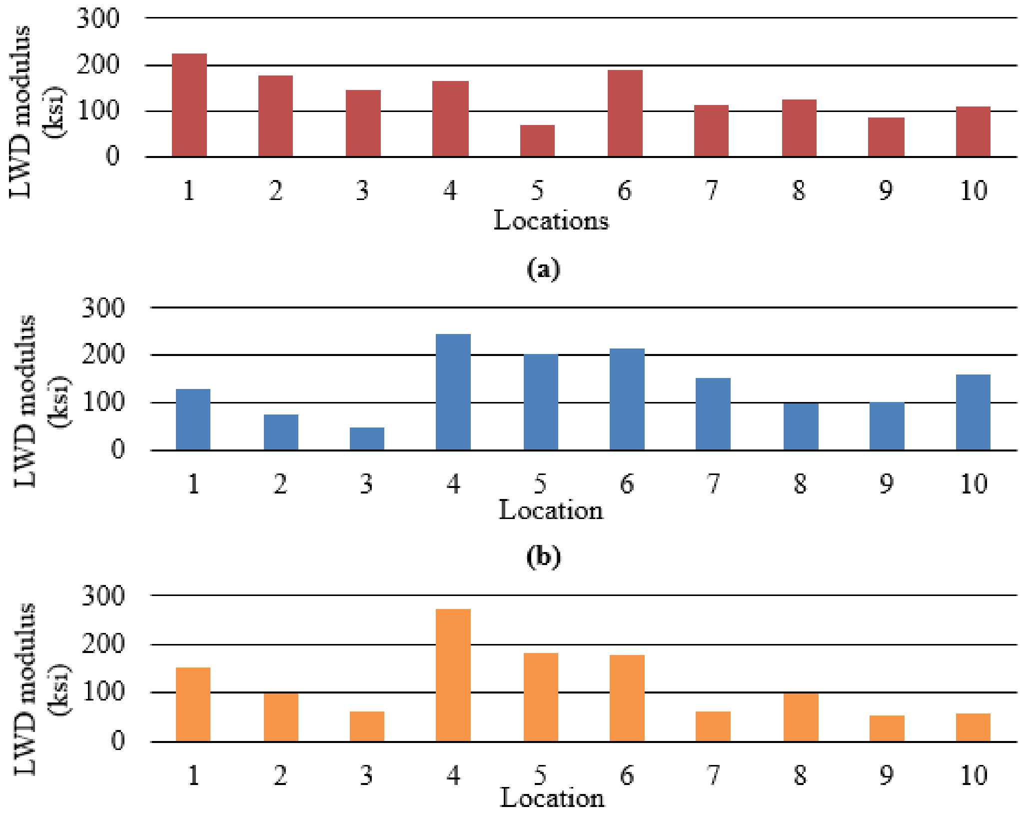
Figure 22
Y-intercepts from void detection test results

In addition to the voids identification, the change in modulus of the PCC layer were also investigated from the FWD test results at different chainage stations. The results are shown in Table 4. The modulus of the PCC layer decreased significantly at the cracked location. Based on the FWD results, the 6-in. severely cracked slab is in between station 4 and 5 where the FWD backcalculated moduli also decreased significantly. Similar findings were also observed on the 4-in. and 2-in. sections.

Table 4
Backcalculated PCC modulus at different station along the BCOA pavement sections

PCC Backcalculated Modulus, E (ksi)			
6-in. BCOA	Before Loading	After Loading	Reduction in E percent
Station 1	4804	3266	32.02
Station 2	3288	923	71.93
Station 3	3687	921	75.02
Station 4	4405	463	89.50
Station 5	2730	701	74.32
Station 6	5268	4454	15.44
4-in. BCOA	Before Loading	After Loading	Reduction in E percent
Station 1	2309	1816	21.35
Station 2	5475	1560	71.50
Station 3	4422	2994	32.29
Station 4	4829	525	89.13
Station 5	4351	35	99.19
Station 6	6283	2824	55.05
2-in. BCOA	Before Loading	After Loading	Reduction in E percent
Station 1	3320	882	73.43
Station 2	2948	574	80.53
Station 3	3666	784	78.61
Station 4	1912	81	95.76
Station 5	3558	100	97.19

Figure 23 shows the average moduli determined by the LFWD device on the 6-in., 4-in. and 2-in. slab at different load repetitions. It was observed that the pavement moduli generally decreased after the development of the cracks and those close to the joints were even lower. The locations with relatively low moduli, such as locations 5 and 7 for 6-in., location 3, 8 and 9 for 4-in. and location 3,7 and 9 for 2-in. pavement test sections experienced debonding as indicated in Figure 23. It is noticed that a pavement modulus less than 60 ksi determined by the LFWD test may indicate the debonding of the BCOA with a typical pavement structure as demonstrated in the figure.



(c)

Figure 23

LFWD test results (a) 6-in. (b) 4-in. (c) 2-in.

Bond Strength Characteristics

Evaluations of the BCOA pavements were based on an assessment of how well the overlays are bonded to the AC layer and how well they increase the stiffness of the pavement. The bonding between the overlay and the existing pavement is very important to prevent early distresses and to make the pavement behave as a monolithic structure to withstand the curling and loading stresses. In order to quantify the bonding quality of bonded concrete overlay, many highway agencies have developed individual bond strength criterion. American Concrete Pavement Association (ACPA) suggests 200 psi of shear strength between the overlay and the existing pavement *(22)*. In case of Canadian Standard, the required bond strength is defined by the shear strength 130 psi *(23)*. Sprinkel and Ozyidirim defines bond strength criterion by tensile strength as follows:

- ≥ 300 psi, excellent
- 250 to 299 psi, very good
- 200 to 249 psi, good

- 100 to 199 psi, fair
- 0 to 99 psi, poor

However, in their study, the tensile bond strength between concrete overlay over concrete structure varied between 200 to 300 psi but for concrete overlay over asphalt varied between 20 to 115 psi *[24]*.

The bonding condition is reported to be critical for BCOA field performance *[7-14]*. The bonding condition will change with time and traffic repetitions due to cumulative damage. On the other hand, debonding changes the fundamental design assumption of BCOA pavement and will result in the structural failure. Figure 24 shows the significant tensile stress increase at different frictional coefficient from 1 for fully bonded to 0 for debounded PCC/AC interface conditions for 4-in., 6-in., and 8-in. slab thickness, based on FE modeling *[34]*. This result also indicates that the most obvious tensile stress increase happens when the frictional coefficient reduced from 1 to 0.75. The thinner the slab, the more significant the tensile stress increases.

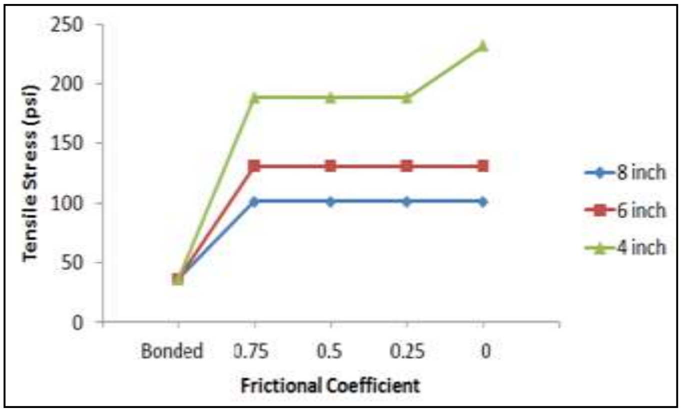


Figure 24

Change in tensile stress with respect to interface frictional coefficient

In this study, the in-situ bond strength was investigated in terms of BCOA pavement performance by evaluating the bond strengths measured by direct tensile test (pull-off test) of ASTM C-1853 standard *[25]*. Eight cores, 2-in. in diameter were tested from each overlay test section at different locations from both the loaded and unloaded areas. The cores were drilled below the asphalt layer, and metal caps were epoxied onto the drilled surfaces. The specimens were pulled in direct tension using PROCEQ tensile bond tester to provide an indication of tensile bond strength and failure mode; see figure 25. The core location were selected based on the in-situ measurement and observed distresses in the BCOA pavement test section. All the bond strength tests revealed failure type B, which is the debonding between concrete overlay and AC layer. The results from the bond strength were shown in Table 5.

Table 5

Tensile bond strength of BCOA pavement test sections

	6-in. BCOA Bond Strength (psi)		**4-in. BCOA Bond Strength (psi)**		**2-in. BCOA Bond Strength (psi)**	
Core Location	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
1	97.2	104.4	95.7	116.1	124.7	197.3
2	62.4	101.5	0*	66.72	88.5	95.7
3	98.6	132.0	92.8	166.8	0.00	117.5
4	42.1	113.1	42.1	102.9	0.00	131.9
Average	**75.1**	**112.8**	**57.7**	**113.13**	**53.3**	**135.6**
Percent Reduction in Bond Strength	**33.4**		**49.1**		**60.7**	

** The core came out with the drill bit unbonded*

Figure 25

Tensile pull-off bond strength test

According to the Sprinkel and Ozyidirim criterion, the average in-situ tensile bond strength at unloaded location, all the BCOA falls in a fair condition, whereas the bond strength at the loaded locations, the BCOA falls under poor bond condition. However, the bond strength test results from the unloaded areas cannot be considered as the true initial bond strength for the BCOA pavement test sections. Because, the pull-off test was conducted after 2 years of overlay placement and the bond strength was affected by the differential movements between substrate and overlay due to temperature and shrinkage. Therefore, the true initial bond strength would be higher than the measured bond strength at the unloaded area. The bond strength at the unloaded area (assuming initial condition) for the 6-in. and 4-in. BCOA section found to be similar; whereas, the 2-in. BCOA section has a higher bond strength, which could be due to the fibers in the mixture. The reduction in bond strength also indicates the effect of interface bond strength on the BCOA pavement performance. The 6-in. and 4-in. sections developed less severe cracking distresses. Therefore, the load carrying capacity is greater than expected.

Forensic Trench-Cutting

A post mortem transverse trench slab (4 ft. x 1 ft.) was cut on a failure area of each test section after the APT testing. Figure 26 shows the trench slabs obtained. In general, the following observations were made from the trenching cutting:

- The majority of longitudinal cracks under the wheel path are bottom-up cracking. In addition, all sections showed voids underneath the PCC layer and complied with the FWD test result.
- It also revealed that the saw cutting joints were cracked through along the PCC slab thickness at the end of APT loading.
- The trench slabs from all the BCOA sections came out in tact having PCC bonded with the asphalt layer. This indicates that all the BCOA section had a good bond strength with the underlying AC layer and also supports the bond strength results found from the tensile pull off test.

Figure 26

Forensic trenches of BCOA pavement sections

Several researchers reported that the shear strength between the overlay and existing pavement is 2 to 3 times higher than tensile bond strength *[24, 26]*. For this experiment, considering the shear strength is 2 times higher than the tensile bond strength will also meet the ACPA bond strength standard.

International Roughness Index (IRI)

To measure the IRI, the longitudinal profiling was carried out by a walking profiler on the left tireprint, the centerline, and the right of the tireprint and the corresponding average IRIs were determined by the ProVAL software (Version 3.61), as shown in Table 6. For the 6-in. slab, the IRI has significantly increased on the left tire print due to the longitudinal cracks observed along the left tire print only. The IRIs also increased significantly on the 4-in. and 2-in. sections along the loaded area due to longitudinal, transverse and corner cracking.

Table 6

BCOA pavement test section IRI before and after APT loading

Section	**IRI**				**ΔIRI**		
	Load repetition (×1000)	**left**	**center**	**right**	**left**	**center**	**right**
6-in.	0	137	145	169			
	1,750	296	148	203	159	3	34
4-in	0	155	159	150			
	310	242	261	263	87	102	113
2-in.	0	292	202	211			
	210	452	446	435	160	244	225

PERFORMANCE PREDICTED BY PAVEMENT ME SOFTWARE

The recently developed Short Joint Portland Concrete Pavement (SJPCP) module in the current Pavement ME software (Version 2.3.1) was employed to predict the performance of the BCOA sections in this study. The predicted results were compared with the in-situ performance of the BCOA sections to evaluate the competency of the SJPCP module as a BCOA design tool for Louisiana. However, the SJPCP cannot design for a 2-in. BCOA pavements. Thus only the 6-in. and 4-in. BCOA pavement sections were evaluated for the performance prediction. In the SJPCP module, the bottom-up longitudinal fatigue cracking is determined as a percentage of slabs with longitudinal cracks of the total slabs in the wheel paths and the failure criterion is chosen as 15 percent of slabs with longitudinal cracks of the total slabs in the wheel paths.

SJPCP Inputs

Layer moduli of the 4-in. and 6-in. sections were back-calculated based on the FWD results (Table 7). The layers of the cement treated subgrade and the natural subgrade were considered as an equivalent subgrade in the back-calculation. Table 7 also summarizes the material inputs in the Pavement ME software. Software default values were input for other material input parameters.

Table 7
Material Property Inputs Used in Pavement ME

Layers	Resilient modulus (ksi)	Flexural strength (psi)	Layer thickness (in.)	PG grade	Joint spacing (ft.)	Input level
PCC	4,000	750	4 or 6	-	5* or 6	3
AC	820	-	3	70-22	-	3
Crushed stone base	26	-	-	-	-	-
Subgrade	23					

** Minimum joint spacing in the Pavement ME software.*

An XML file, in which single axle loads of 18 kips and 32 kips were stored alternately, was imported in the Pavement ME software to simulate the accelerated load repetitions applied in this study. Two-way AADTT was chosen as 3,300 so that the monthly one-way load repetition is approximately 100,000, which is the alternated load repetition applied in each load stage. Default values were chosen for other parameters. The climate station of Baton

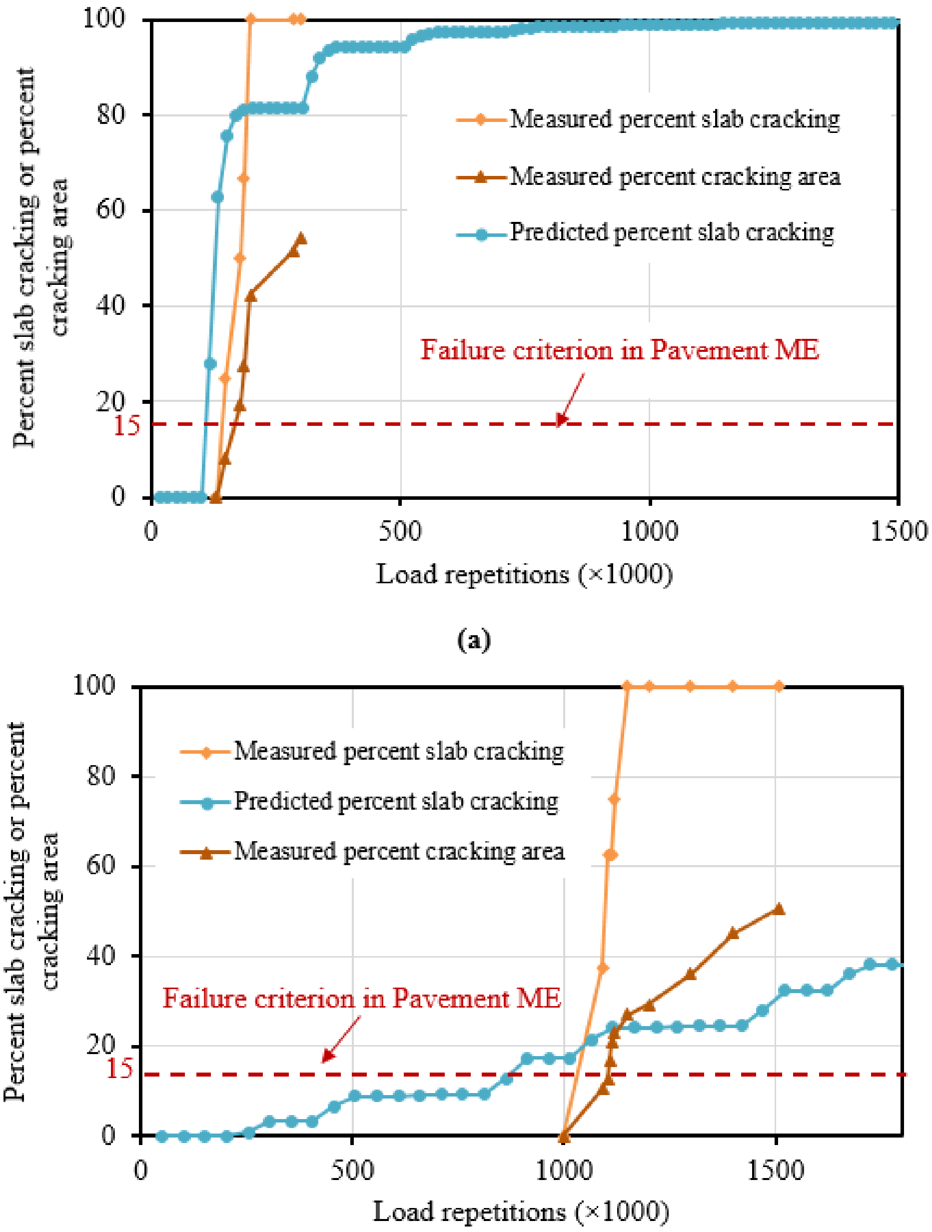
Rouge, LA, was chosen to simulate the climate condition of the test sections.

Comparison of the Predicted and Measured Performance

Figure 27 show the comparison of the measured and predicted slab cracking. In terms of the failure criterion of the 15 percent cracking slab, the measured and predicted performance roughly match with each other. However, the failure modes of the in-situ pavement sections and Pavement ME model reveal some significant differences.

After the cracking initiation, both the 4-in. and 6-in. sections demonstrated a drastic propagation of the cracking. The initiation of the cracking might be caused by the fatigue damage mode, which is usually described by an empirical function of the stress ratio (concrete flexural stress/modulus of rapture). The propagation of the cracking, however, might subject to the damage modes of fracture mechanics. In the Pavement ME models, the percentage of cracking slabs was only dominated by an empirical fatigue equation, which is the function of the stress ratio. Due to the high stress ratio in the 4-in. slab, the predicted percentage of cracking slabs increased drastically under a 16 kips load. Since the stress ratio is relatively low in the 6-in. slab, the predicted result grew slowly along the increase of the load repetition.

Since there are limited slabs (12 for the 4-in. section and 8 for the 6-in. section) in the test sections of this study, the percentage of cracking slabs of all the slabs in the wheel path may not fully reveal the development of the cracking under the accelerated load. In addition, the IRI results imply that the pavement may still be capable of bearing more load repetitions even at a 100 percent slab cracking. Therefore, the percentages of the cracking area in the test sections were calculated and presented in Figure 27 as well. As indicated in the figures, at the end of the loading repetitions, the 4-in. section and the 6-in. section had 54 percent and 50 percent of the cracking area, respectively.



(a)

(b)

Figure 27

Comparison of the measured and predicted percent slab cracking of: (a) 4-in. section and (b) 6-in. section

For each pavement test section, the percent slab cracked and the percent area cracked was calculated at different load repetition. The measured percent slab cracked was then compared with the predicted ESAL based on the PavementME outputs. The measured versus predicted slabs cracked in terms of ESAL was shown in Table 8 at the end of pavement life.

Table 8
Pavement life in terms of ESALs

BCOA-Thickness	Percent Slabs Cracked (15 percent)		Percent Area Cracked (50 percent)
	Predicted ESAL (millions)	Measured ESAL (millions)	Measured ESAL (millions)
6-in.	4.9	6.5	8.9
4-in.	0.4	1.0	3.5
2-in.	NA	0.3	1.2

Figure 28 shows the measured ESALs of the BCOA pavement sections in terms of pavement thickness.

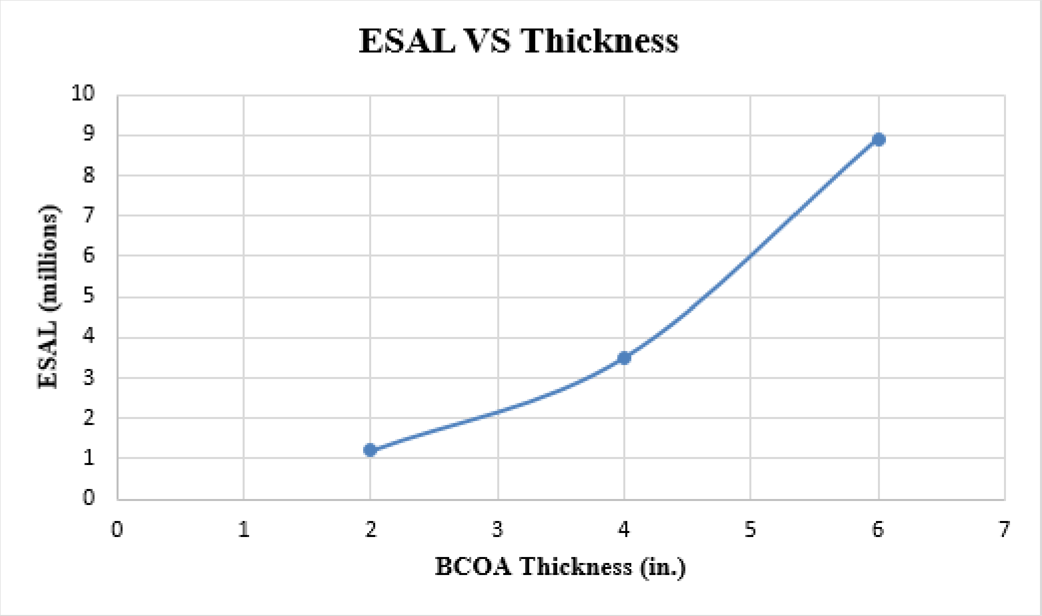


Figure 28
BCOA Pavement test section performance in terms of ESALs

COST-BENEFIT ANALYSIS

BCOA rehabilitation is more cost-effective than AC overlay when the pavement design life is longer and takes into consideration not only initial construction costs, but also the maintenance and users costs. The cost related to user delays can be much higher for an AC overlay compared to a BCOA pavement, which requires less maintenance and fewer rehabilitation activities *[5]*. A study from Purdue University established that a 2-in. BCOA has a life expectancy of 25 years and becomes cost-effective at only 17 years when compared with a 4-in. AC overlay *[5]*. Experience from Colorado showed that there is a 1 percent difference in construction cost between thin BCOA and AC overlays, so both options are considered to be similar when only initial construction cost is analyzed. But the difference between these two alternatives was more than 11 percent if maintenance costs were taken into consideration *[5]*. A study from Minnesota shows that a 6-in. BCOA costs 50 percent more than a 3-in. AC overlay, and lasts twice the pavement life compared to an AC overlay.

Construction Cost Analysis of BCOA and Equivalent AC Overlay

To quantify cost benefits from using a BCOA pavement in lieu of a AC overlay alternative, a construction cost analysis was performed on different pavement structure alternatives for medium and medium to high volume roadways.

Medium Volume Roadway

For a design life of 20 years with a 9500 Two-Way Average Daily Traffic (ADT) and 2 percent growth rate, the estimated total ESALs is 2.5 million. As outlined in Figure 29, alternative A contains a pavement structure similar to test section-2 (i.e., 4-in. BCOA and 3-in. old AC over a 8.5-in. crushed stone and subgrade); whereas, alternative B has a similar base and subgrade structure as alternative A but uses a 6.5-in. AC overlay as the surface layer. According to the 1993 AASHTO design guide, the pavement structure of the alternative B would be expected to have a pavement life of 2.5 million of flexible ESAL, when the layer coefficients of a new AC, old AC and a crushed stone layers are assumed to be 0.44, 0.22 and 0.14, respectively. According to total number of accelerated load repetition to failure on section 2, the total estimated flexible ESALs based on the 1993 flexible pavement equivalent load factors (EALF) would be 2.5 million and total estimated rigid ESALs based on the 1993 rigid pavement equivalent load factors (EALF) would be 3.5 million. That means, considering the flexible ESALs, the pavement life of the alternative B is expected to have a similar pavement life compared to the alternative A. Both the alternatives will meet the design life for medium volume roadways.

Alternative A Alternative B

Figure 29

Pavement alternatives used in cost-benefit analysis

The construction costs of two pavement alternatives are listed in Table 9. The unit prices in the table were determined from the previous construction costs and APT experiments. The quantities were calculated based on a 13-ft. wide lane for one mile long.

Table 9

Initial construction costs

Alternative A

Materials	Unit Prices ($)	Quantity	Construction Costs($)
4-in. BCOA	$110 per yd^3	847.4 yd^3	93,215.00
Milling & Surface Preparation	$0.15 per yd^2	7626.7 yd^2	1,144.00
Total Initial Construction Costs			$94,359.00

Alternative B

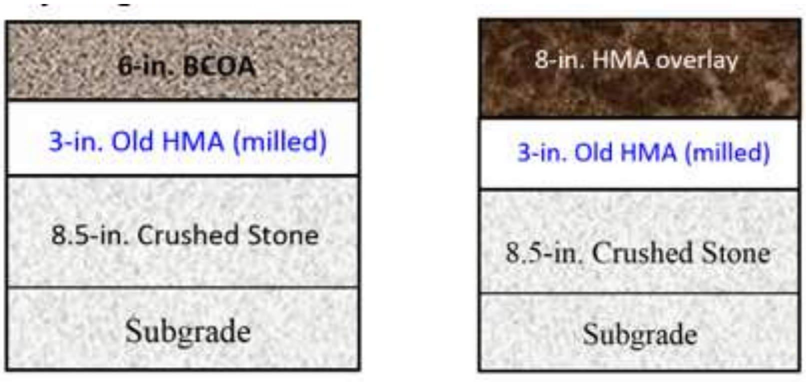
Materials	Unit Prices ($)	Quantity	Construction Costs($)
6.5-in. AC overlay	$80 per ton	2695.6 ton	215,644.00
Milling & Surface Preparation	$0.15 per yd^2	7626.7 yd^2	1,144.00
Total Initial Construction Costs			$216,788.00

The estimated construction costs for Alternatives A and B were $94,359 and $216,788 respectively. Therefore, by using a 4-in BCOA in lieu of a 6.5-in. AC overlay for low volume roadways, the estimated cost benefits would be $122,429, per lane mile. Applying the estimated cost benefits to a typical two lane, 10-mile long roadway project, and the use of a

4-in BCOA in lieu of a 6.5-in AC overlay results in a total construction cost savings up to $2,448,580.

Medium- High Volume Roadway

For a design life of 20 years with a 15,000 two-way Average Daily Traffic (ADT) and 2 percent growth rate, the estimated total ESALs for a medium volume roadway is 7.5 million. As outlined in Figure 30, alternative A contains a pavement structure similar to test section-1 (i.e., 6-in. BCOA and 3-in. old AC over a 8.5-in. crushed stone and subgrade); whereas, alternative B has a similar base and subgrade structure as alternative A, but uses a 8-in. AC overlay as the surface layer. Based on the pavement design concept, both the alternatives will have the similar pavement life and can withstand 7.5 million flexible ESALs for a medium to high volume roadway design.



Alternative A Alternative B

Figure 30
Pavement alternatives used in cost-benefit analysis

The construction costs of two pavement alternatives are listed in Table 10. The unit prices in the table were determined from the previous construction costs and APT experiments. The quantities were calculated based on a 13-ft. wide lane for one mile long.

Table 10
Initial construction costs

Alternative A			
Materials	Unit Prices ($)	Quantity	Construction Costs($)
6-in. BCOA	$110 per yd^3	1272.0 yd^3	139,920.00
Milling & Surface Preparation	$0.15 per yd^2	7626.7 yd^2	1,144.00
Total Initial Construction Costs			$141,064.00
Alternative B			
Materials	Unit Prices ($)	Quantity	Construction Costs($)
8-in. AC overlay	$80 per ton	3318.0 ton	265,440.00
Milling & Surface Preparation	$0.15 per yd^2	7626.7 yd^2	1,144.00
Total Initial Construction Costs			$266,584.00

The estimated construction costs for Alternatives A and B were $141,064and $266,584 respectively. Therefore, by using a 6-in BCOA in lieu of an 8-in. AC overlay, the estimated cost benefits would be $125,520, per lane mile. Applying the estimated cost benefits to a typical two lane, 10-mile long roadway project, the use of a 6-in BCOA in lieu of a 8-in AC overlay results in a total construction cost savings up to $2,510,400.

Life-Cycle Cost Analysis

To further demonstrate the benefit of using BCOA in lieu of an asphalt overlay in pavement rehabilitation, a 20-year life-cycle cost analysis (LCCA) was performed based on the APT test results in this study. Since a typical flexible pavement structure for a low-volume road in Louisiana consists of a 3.5-in. HMA layer and an 8.5-in. base over a treated soil subgrade, two pavement rehabilitation alternatives based on the geometry and existing pavement of the APT sections were considered in the LCCA, as shown in Figure 31.

As can be seen in Figure 31, the alternative A contains a same pavement structure as Section 2 used in this experiment (i.e., 4-in. BCOA built over an existing asphalt pavement of 3-in. old HMA plus an 8.5-in. crushed stone base); whereas, the alternative B has a similar existing pavement structure as the alternative A but uses a 4-in. HMA overlay as the surface layer instead.

Alternative A Alternative B

Figure 31
Pavement alternatives used in life-cycle cost analysis

According to the 1993 AASHTO design guide, the predicted pavement design life of the alternative B would be 1.26 million of 18-kip equivalent single axle loads (ESALs). This was estimated based upon the difference between the initial present serviceability index and the design terminal serviceability (ΔPSI) of 1.7 and the layer coefficients for a new, aged HMA and crushed stone layer were 0.44, 0.22 and 0.14, respectively. In analysis of an initial annual traffic of 115,000 ESALs with an annual growth rate of 2 percent, a 10-year cumulative ESALs would be 1,259,218. This indicates that the alternative B would have an approximate 10 years of pavement design life before a need of rehabilitation (e.g. an asphalt overlay resurfacing). On the other hand, the Alternative A with an estimated pavement life of 3.5 million ESALs (Table 8) would last longer than 20 years of the design traffic without requiring any rehabilitation or resurfacing activities. In this study, a typical resurfacing rehabilitation activity of milling 2-in. of the existing HMA layer followed by a 4-in. HMA overlay was considered at the end of the pavement design life (i.e., 10 years for the Alternative B). During a 20-year pavement design analysis, a resurfacing rehabilitation in every 10-year and a preventive maintenance (i.e., a chip seal or micro-surfacing) in every 5-year was assumed for the alternative B; whereas, no resurfacing rehabilitation was needed for the alternative A except recommending some joint-and-crack sealing in every 10-year of trafficking. Based on a 20-year LCCA for a mile long 13-ft wide pavement lane, using the alternative of 4-in. BCOA in lieu of a 4-in. HMA overlay could result in the savings in terms of net present value (NPV) up to $135,621 and $155,052, respectively, when considering a chip seal or micro-surfacing as preventive maintenance strategy in the analysis of Alternative B. More details of the LCCA analysis can be found in Appendix E. Moreover, BCOA reduced the requirement for yearly maintenance thereby consuming fewer raw materials over the pavement life-cycle. Although not specifically quantified, there were also savings through the elimination of yearly constructions zones which impede traffic, generate additional vehicle emissions and delay users.

Cost-Benefit Analysis of BCOA Thickness in terms of Long-Term Performance

The costs analysis of two BCOA pavement alternatives in terms of thickness can also be useful in term of implementing at the medium to high volume roadways. To compare the cost in terms of pavement life it has been calculated that a medium volume roadway with 9500 two-way Average Daily Traffic (ADT), 50 percent directional distribution factor, 100 percent design lane factor, 2 percent growth rate and 10 percent trucks the estimated total ESALs of 9 million will last for approximately 24 years and 3.5 million ESALs will last for approximately 11 years. Based on the performance analysis of this study, the 6-in. BCOA is expected to last for 24 years and the 4-in. BCOA is expected to last for 11 years for a medium volume roadway. The cost/per lane/year is $5830 and $8474 for a 6-in. BCOA and 4-in. BCOA respectively. Considering the pavement type and expected pavement life the 6in. BCOA can be cost effective over a 4-in. BCOA section for a medium to high volume roadway. The 4-in. BCOA would be more appropriate for the low to medium volume roadways. Table 11 shows the cost comparison of different BCOA thickness in terms of pavement performance.

Table 11

Cost of BCOA Pavements in terms of pavement thickness and pavement performance

BCOA Thickness	Cost_ $/yd3	Quantity yd3)	Total Cost_$	ESAL (millions)	Expected Design life (years)	Cost$/ per lane/year
6	110	1272.0	139920	8.9	24	5830
4	110	847.4	93215	3.5	11	8474
2	110	423.7	46607	1.2	5	9321

CONCLUSIONS

In this study, three BCOA pavement sections with the thickness of 6-in., 4-in., and 2-in. were tested under the accelerated loading. The following observations and conclusions were drawn:

- Crack was first noticed on the 6-in. BCOA section after 1,090,000 load repetitions under the combination loads of 550,000 passes of 9-kips and 540,000 passes of 16-kips. On the other hand, cracks started to show on the 4-in. and 2-in. BCOA sections only after 130,000 load repetitions (100,000 9-kips + 30,000 16-kips) and 110,000 load repetitions (100,000 9-kips + 10,000 16-kips), respectively. This indicates that a 6-in. PCC overlay had a superior load carrying capacity compared to the 4-in. and 2-in. concrete overlays tested in this study.
- The predicted pavement lives for the 6-in., 4-in, and 2-in. BCOA sections were 8.9-, 3.5-, and 1.2- million ESALs, respectively. The 6 in. and 4 in. sections developed less severe cracking distresses. Therefore, the load carrying capacity of this pavements is greater than expected.
- The 6-in. BCOA pavement may be used in a medium to high volume pavement design where heavy and overloaded trucks are abundant. The 4-in. BCOA may be suitable to be used in a pavement rehabilitation project with a low to medium volume traffic. However, the 2-in. BCOA section did not perform well in this experiment. No recommendation could be made.
- Fair to good bond strengths were found on all BCOA sections. The bond strength reduced with number of load repetition and potential debonding were also detected at the bottom of the PCC layer. A trench cutting investigation revealed that a good bonding was achieved on all the BCOA section. The 2-in. section had a higher initial bond strength due to fiber content. The 6-in section performed significantly better than the 2- and 4-in. sections evaluated due to the lower reduction in bond strength. Currently there is no specification for bond strength on BCOA pavement performance. Based on this experiment, it is recommended that the bond strength should be considered in the fatigue analysis for BCOA pavement sections and to predict the interface bonding failure.
- In terms of the failure criterion of 15 percent cracking slabs of all the slabs in the wheel path, the performance predicted by Pavement ME is comparable to the in-situ performance of the BCOA sections in this study. However, the failure modes of the in-situ pavement sections and Pavement ME model reveal some significant differences. Pavement ME under predicts the BCOA design life in terms of failure criterion of 15 percent cracking slabs. Based on this study, it can be recommended that a higher percent slabs cracked can be considered instead of 15 percent slabs cracked as a failure criterion to overcome the PavementME under design prediction.

RECOMMENDATIONS

The following recommendations can be made based on the APT study:

- A slab panel size should not be more than half the lane width, which would result in a greatly reduced number of wheel loads on the slab corners as well as reduced joint forming and sealing costs. It will also reduce the loss of contact friction or debonding at the interface near the slab corner.
- A bond strength criterion can be specified to determine the BCOA pavement performance and the interface bonding failure.
- A higher percent slab cracked can be recommended as a failure criterion for fatigue cracking instead of 15 percent slabs cracked for BCOA pavement design to overcome the PavementME under design prediction.
- Based on the cost benefit analysis and BCOA pavement performance it is recommended that a 6-in. BCOA pavement may be used in a medium to high volume pavement design where heavy and overloaded trucks are abundant and a 4-in. BCOA may be suitable to be used in a pavement rehabilitation project with a medium volume traffic.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
APT	Accelerated Pavement Testing
BCOA	Bonded Concrete Overlay of Asphalt
CDOT	Colorado Department of Transportation
DOTD	Department of Transportation and Development
FHWA	Federal Highway Administration
ft.	Feet
FWD	Falling Weight Deflectometer
ICT	Illinois Center for Transportation
in.	Inch
JDMD	Joint Deflection Measurement Device
JMF	Job Mix Formula
LFWD	Light Falling Weight Deflectometer
LTRC	Louisiana Transportation Research Center
LVDT	Linear Variable Differential Transformer
mm	Millimeter
MnDOT	Minnesota Department of Transportation
NJDOT	New Jersey Department of Transportation
PCA	Portland Cement Association
PCC	Portland Cement Concrete
SA	Single Axle
TA	Tandem Axle
TDR	Time Domain Reflectometer
UCS	Unconfined Compressive Strength
USACE	United States Army Corps of Engineering

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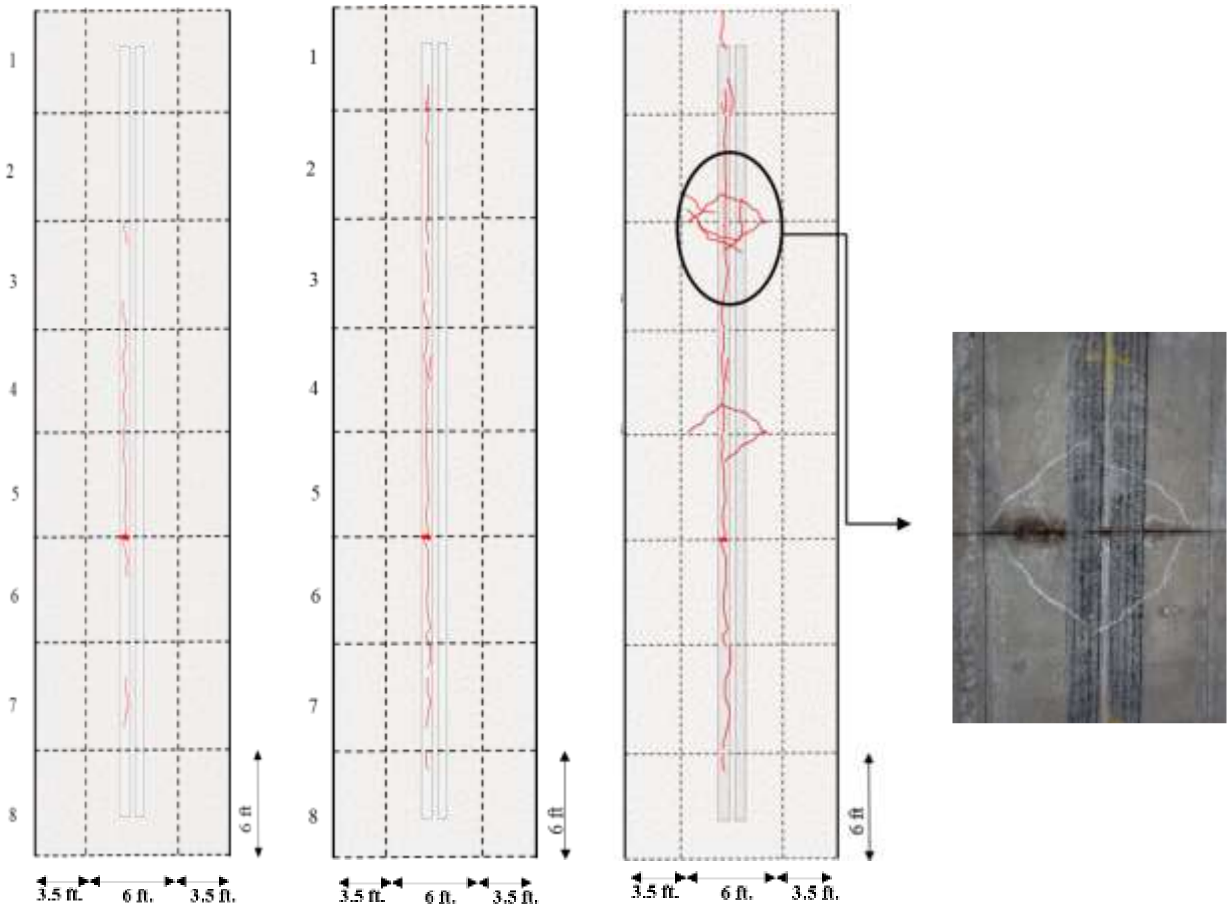
APPENDIX A

Fatigue Crack Propagation with No. of Load Repetition

Sections 1 (6-in. BCOA)

A total of one and half million-load repetitions (i.e., 750,000 of 9-kip and 750,000 of 16-kip) were applied on the 6-in. BOCA section and the estimated ESALs to the fatigue failure was 8.9 million. Figure 32 shows the cracking development under different load repetitions observed on section 1 (6-in. BCOA). The crack was imitated in longitudinal direction initially followed by corner cracks.

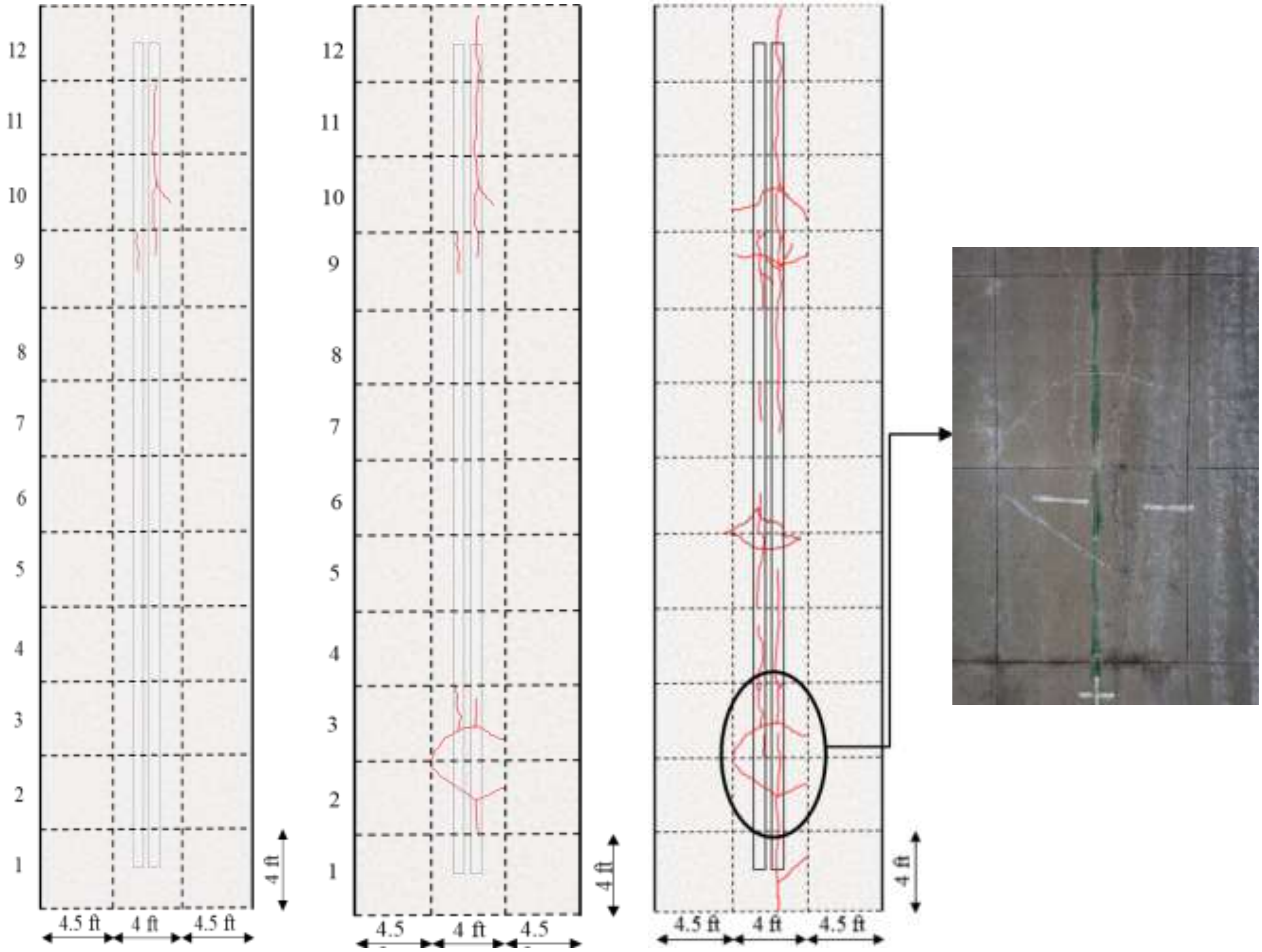


(a) (b) (c)

Figure 32
Crack mapping of the 6-in. BCOA section at a load repetition of: (a) 1,100,000; (b) 1,500,000; and (c) 1,700,000

Sections 2 (4-in. BCOA)

A total of 560,000 repetitions (i.e., 310,000 of 9-kip and 250,000 of 16-kip) were loaded on the 4-in. sections and the estimated ESALs to the fatigue failure was 3.5 million. Figure 33 shows the cracking development under different load repetitions observed on section 2 (4-in. BCOA). The crack was imitated in longitudinal direction initially followed by corner cracks.

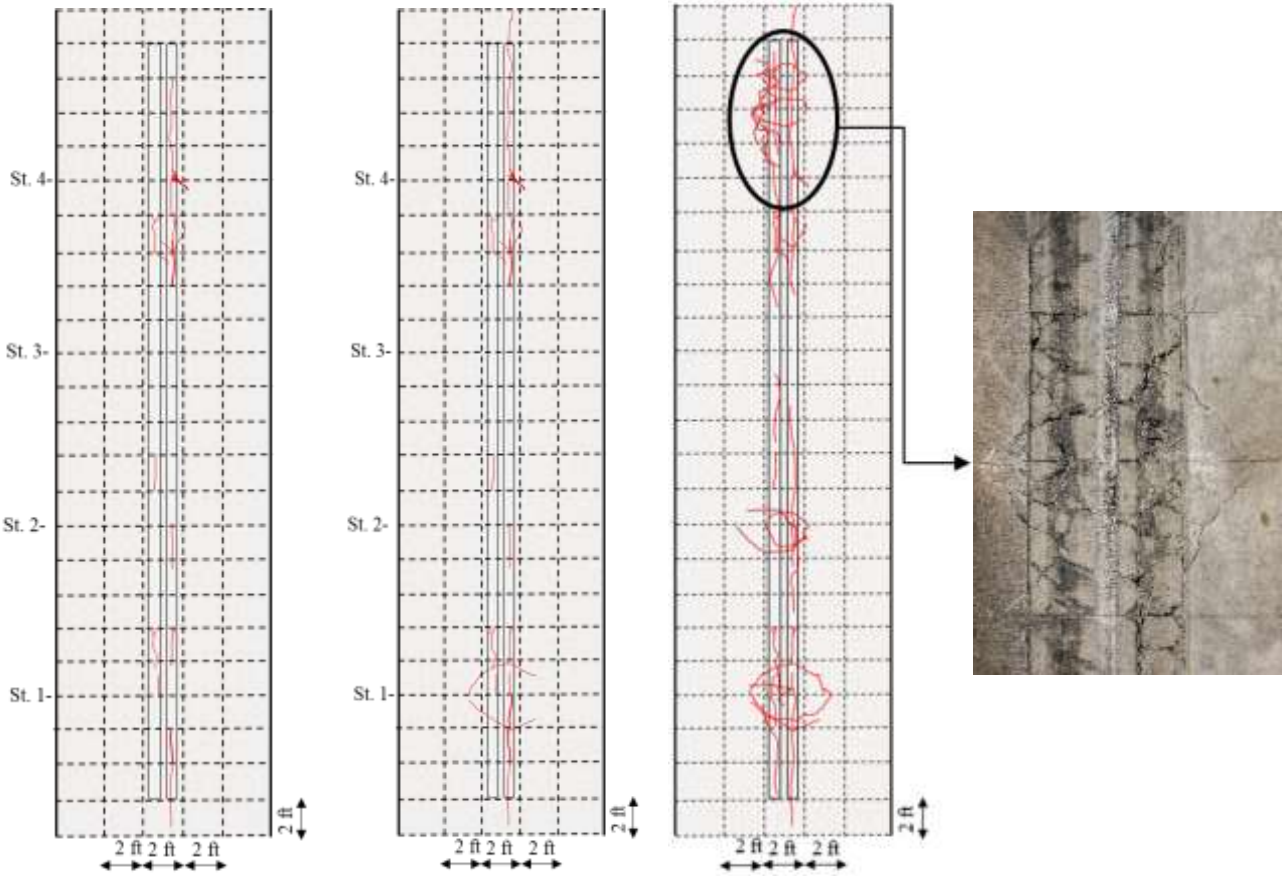


(a) (b) (c)

Figure 33
Crack mapping of the 4-in. BCOA section at a load repetition of: (a) 200,000; (b) 350,000; and (c) 550,000

Sections 3 (2-in. BCOA)

A total of 210,000 repetitions (i.e., 130,000 of 9-kip and 80,000 of 16-kip) were added on the 2-in. section and the estimated ESALs to the fatigue failure was 1.2 million. Figure 34 shows the cracking development under different load repetitions observed on section 3 (2-in. BCOA). Corner cracks developed first and severe localized failure observed.



(a) (b) (c)

Figure 34
Crack mapping of the 2-in. BCOA section at a load repetition of: (a) 150,000; (b) 180,000; and (c) 200,000

APPENDIX B

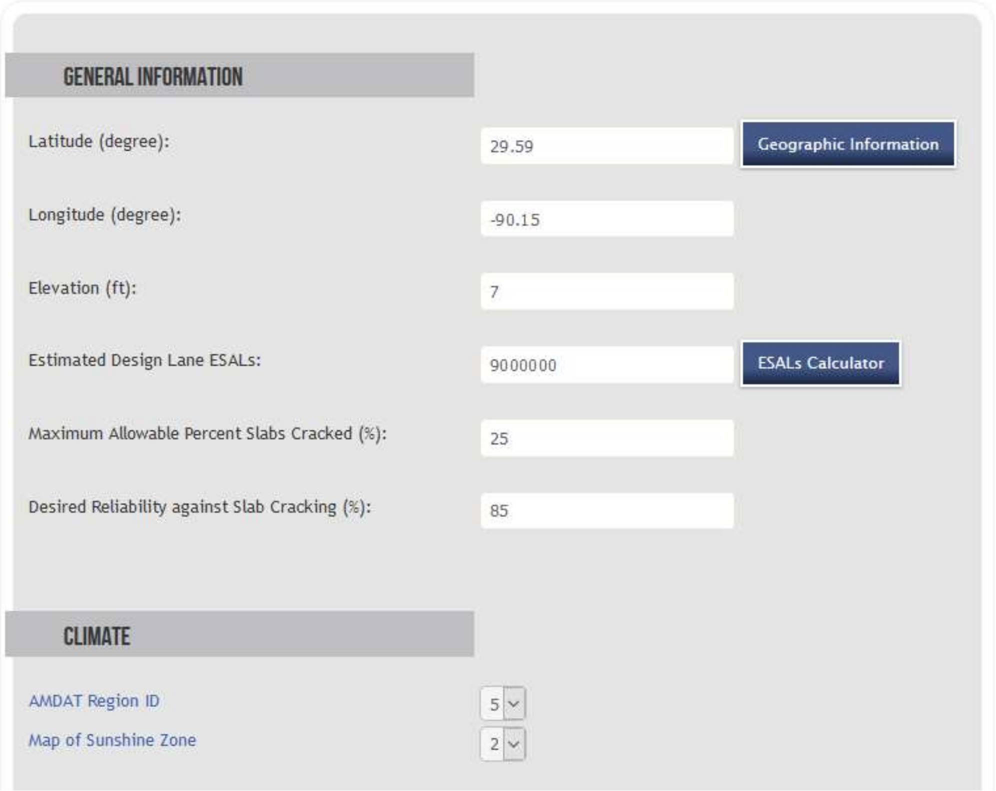
BCOA-ME Design Example

The BCOA ME design software developed by University of Pittsburgh was evaluated for a 6-in. BCOA section. According to the BCOA ME software, a 6-in. BCOA section can carry 9 million ESALs for a medium to high volume roadways. The Design procedure is shown below.

Step 1

Define geographic information for weather data and Design ESAL (9 million for this example)

(Last updated: 4/21/2015)



GENERAL INFORMATION

Latitude (degree):	29.59
Longitude (degree):	-90.15
Elevation (ft):	7
Estimated Design Lane ESALs:	9000000
Maximum Allowable Percent Slabs Cracked (%):	25
Desired Reliability against Slab Cracking (%):	85

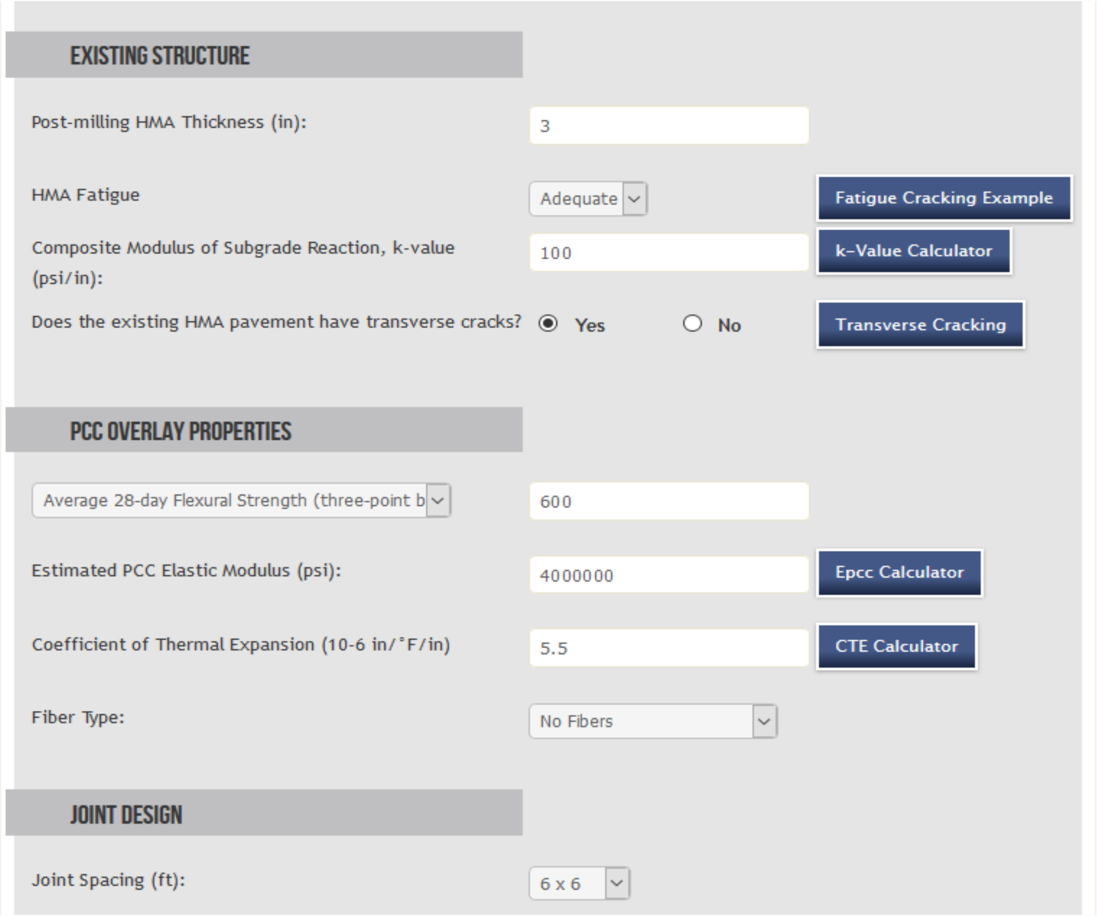
CLIMATE

AMDAT Region ID	5
Map of Sunshine Zone	2

Step 2

Define Pavement Structure, Material Properties and Joint Spacing.

Following are the values chosen for this example.



EXISTING STRUCTURE

Post-milling HMA Thickness (in):	3
HMA Fatigue	Adequate
Composite Modulus of Subgrade Reaction, k-value (psi/in):	100
Does the existing HMA pavement have transverse cracks?	● Yes ○ No

PCC OVERLAY PROPERTIES

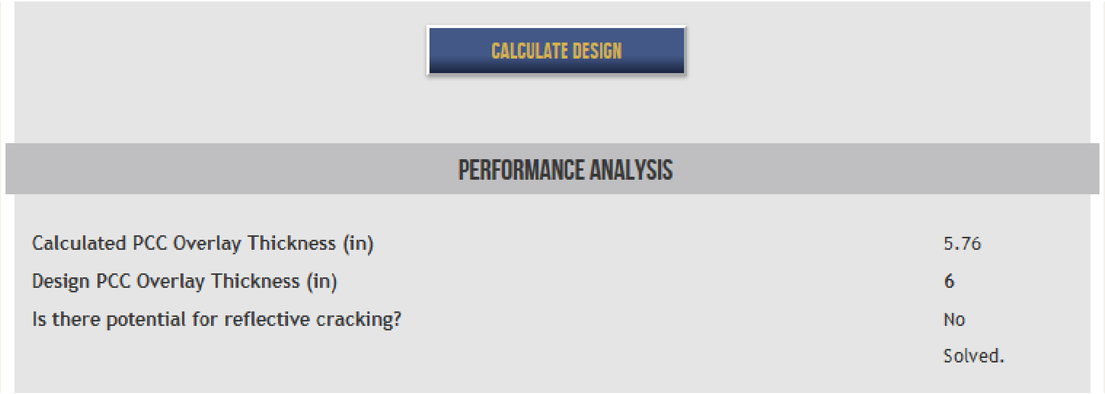
Average 28-day Flexural Strength (three-point b	600
Estimated PCC Elastic Modulus (psi):	4000000
Coefficient of Thermal Expansion (10-6 in/°F/in)	5.5
Fiber Type:	No Fibers

JOINT DESIGN

Joint Spacing (ft):	6 x 6

Step 3

Calculate Design and Performance Analysis.



PERFORMANCE ANALYSIS

Calculated PCC Overlay Thickness (in)	5.76
Design PCC Overlay Thickness (in)	6
Is there potential for reflective cracking?	No
	Solved.

APPENDIX C

Tensile Bond Strength Test (Pull-off Test)

Principle

In the **BOND-TEST,** a disc is bonded to a prepared testing surface and the disc is pulled off after a partial core has been cut around the disc (extreme left in following figure). The pull-off force, *F,* is divided by the cross-sectional area of the partial core to obtain the pull-off strength *fp*:

$$f_p = \frac{4F}{\pi d^2}$$

Where, *d* is the diameter of the partial core.

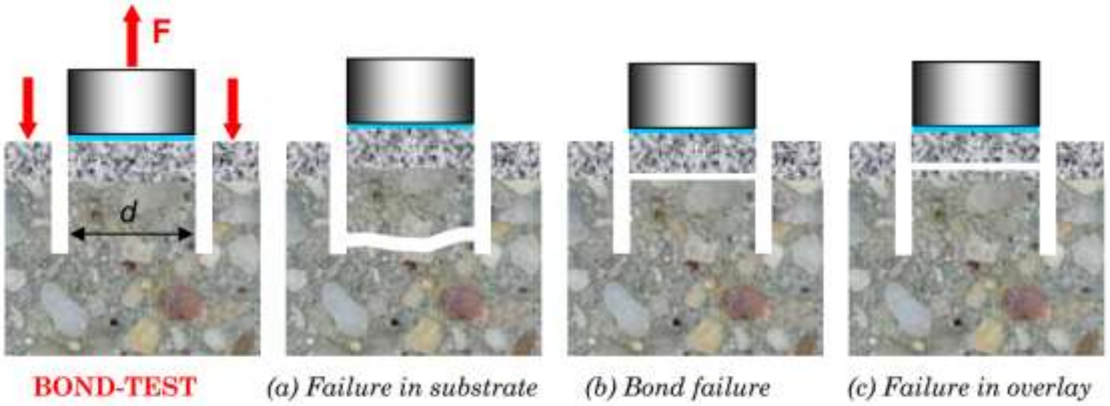


Figure 35
Tensile bond strength test failure modes

The bond test procedure:

- Partial coring and Surface planning
- Bonding the disc
- Pull off
- Define failure type

Figure 36
Tensile bond strength test on BCOA sections

The output from the bond strength test results are as follows.

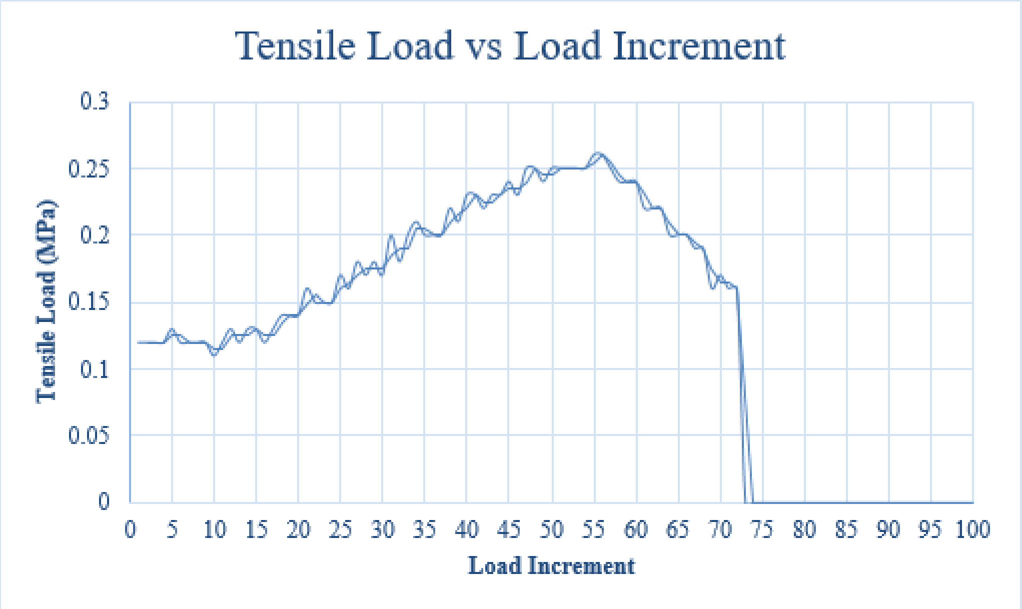


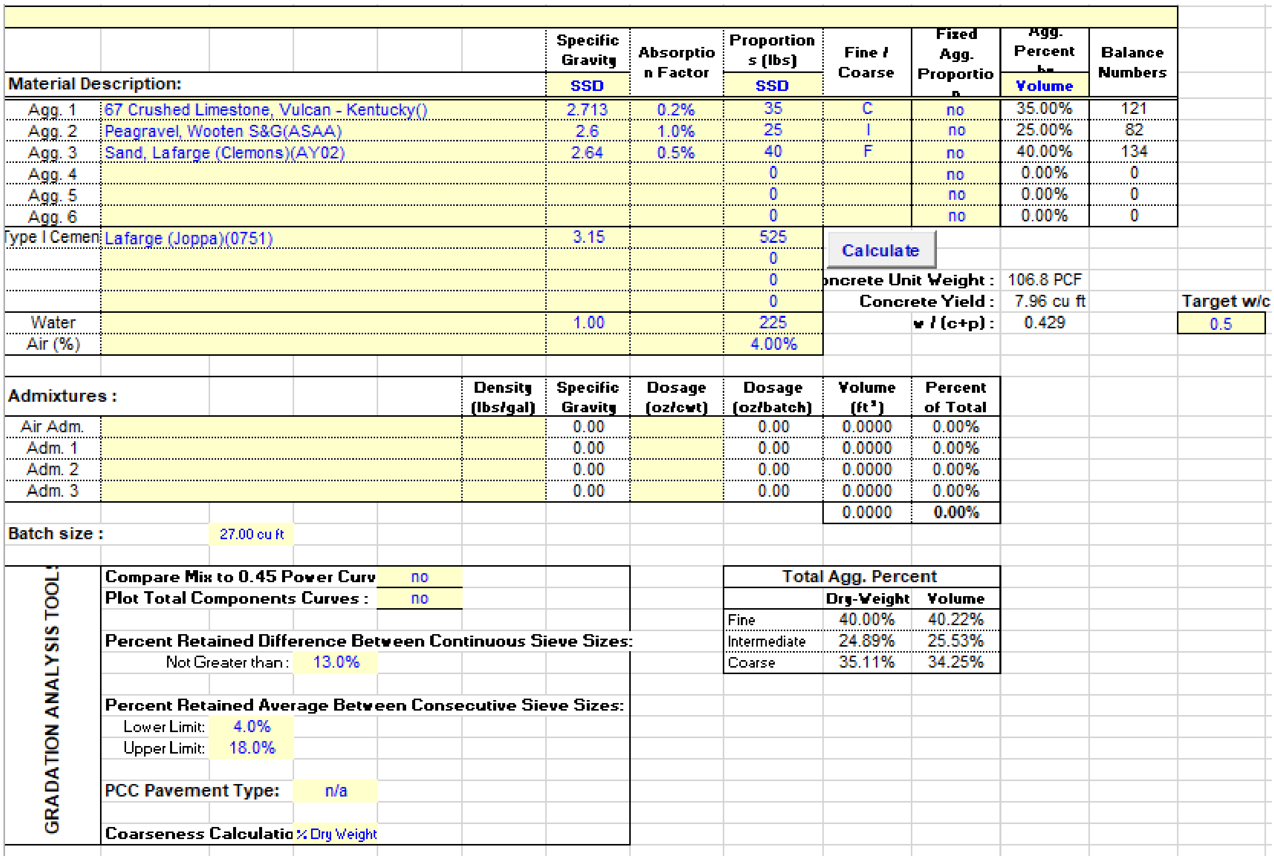
Figure 37
Tensile load versus load increment under bond strength test

Table 12
Output results from bond strength test on BCOA section

Peak Load	0.26 MPa
Peak Load Time	8.6 s
Tear-off Time	11.5 s
Effective Load Rate	0.013 Mpa/s
Load Rate	0.035 Mpa/s
Load Limit	8.15 Mpa
Test Disc Area	1963 mm2
Test Disc Diameter	50.0 mm
Failure type	B

APPENDIX D

BCOA Mix Design Details



Material Description:		Specific Gravity SSD	Absorptio n Factor	Proportion s (lbs) SSD	Fine / Coarse	Fixed Agg. Proportio	Agg. Percent Volume	Balance Numbers
Agg. 1	67 Crushed Limestone, Vulcan - Kentucky()	2.713	0.2%	35	C	no	35.00%	121
Agg. 2	Peagravel, Wooten S&G(ASAA)	2.6	1.0%	25	I	no	25.00%	82
Agg. 3	Sand, Lafarge (Clemons)(AY02)	2.64	0.5%	40	F	no	40.00%	134
Agg. 4				0		no	0.00%	0
Agg. 5				0		no	0.00%	0
Agg. 6				0		no	0.00%	0
Type I Cemen	Lafarge (Joppa)(0751)	3.15		525				
				0				
				0				
				0				
Water		1.00		225				
Air (%)				4.00%				

Calculate

ncrete Unit Weight : 106.8 PCF

Concrete Yield : 7.96 cu ft

w / (c+p) : 0.429

Target w/c 0.5

Admixtures :		Density (lbs/gal)	Specific Gravity	Dosage (oz/cwt)	Dosage (oz/batch)	Volume (ft³)	Percent of Total
Air Adm.			0.00		0.00	0.0000	0.00%
Adm. 1			0.00		0.00	0.0000	0.00%
Adm. 2			0.00		0.00	0.0000	0.00%
Adm. 3			0.00		0.00	0.0000	0.00%
						0.0000	0.00%

Batch size : 27.00 cu ft

GRADATION ANALYSIS TOOL

Compare Mix to 0.45 Power Curv no

Plot Total Components Curves : no

Percent Retained Difference Between Continuous Sieve Sizes:

Not Greater than : 13.0%

Percent Retained Average Between Consecutive Sieve Sizes:

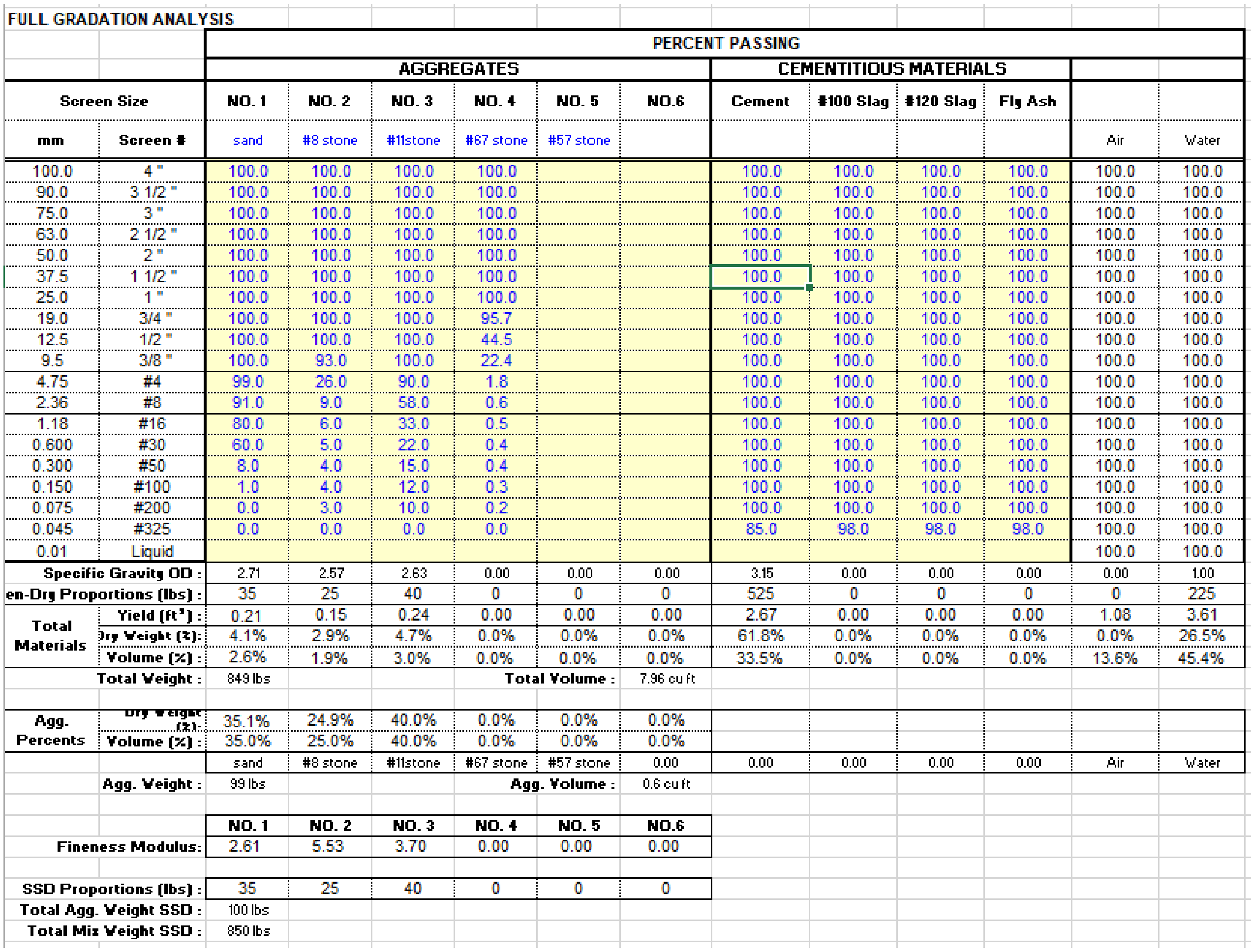
Lower Limit: 4.0%

Upper Limit: 18.0%

PCC Pavement Type: n/a

Coarseness Calculatio % Dry Weight

Total Agg. Percent	Dry-Weight	Volume
Fine	40.00%	40.22%
Intermediate	24.89%	25.53%
Coarse	35.11%	34.25%



FULL GRADATION ANALYSIS

		PERCENT PASSING											
		AGGREGATES						CEMENTITIOUS MATERIALS					
Screen Size		NO. 1	NO. 2	NO. 3	NO. 4	NO. 5	NO.6	Cement	#100 Slag	#120 Slag	Fly Ash		
mm	Screen #	sand	#8 stone	#11stone	#67 stone	#57 stone						Air	Water
100.0	4 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
90.0	3 1/2 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
75.0	3 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
63.0	2 1/2 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
50.0	2 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
37.5	1 1/2 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
25.0	1 "	100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0	100.0
19.0	3/4 "	100.0	100.0	100.0	95.7			100.0	100.0	100.0	100.0	100.0	100.0
12.5	1/2 "	100.0	100.0	100.0	44.5			100.0	100.0	100.0	100.0	100.0	100.0
9.5	3/8 "	100.0	93.0	100.0	22.4			100.0	100.0	100.0	100.0	100.0	100.0
4.75	#4	99.0	26.0	90.0	1.8			100.0	100.0	100.0	100.0	100.0	100.0
2.36	#8	91.0	9.0	58.0	0.6			100.0	100.0	100.0	100.0	100.0	100.0
1.18	#16	80.0	6.0	33.0	0.5			100.0	100.0	100.0	100.0	100.0	100.0
0.600	#30	60.0	5.0	22.0	0.4			100.0	100.0	100.0	100.0	100.0	100.0
0.300	#50	8.0	4.0	15.0	0.4			100.0	100.0	100.0	100.0	100.0	100.0
0.150	#100	1.0	4.0	12.0	0.3			100.0	100.0	100.0	100.0	100.0	100.0
0.075	#200	0.0	3.0	10.0	0.2			100.0	100.0	100.0	100.0	100.0	100.0
0.045	#325	0.0	0.0	0.0	0.0			85.0	98.0	98.0	98.0	100.0	100.0
0.01	Liquid											100.0	100.0
Specific Gravity OD :		2.71	2.57	2.63	0.00	0.00	0.00	3.15	0.00	0.00	0.00	0.00	1.00
en-Dry Proportions (lbs) :		35	25	40	0	0	0	525	0	0	0	0	225
Total Materials	Yield (ft³) :	0.21	0.15	0.24	0.00	0.00	0.00	2.67	0.00	0.00	0.00	1.08	3.61
	Dry Weight (%):	4.1%	2.9%	4.7%	0.0%	0.0%	0.0%	61.8%	0.0%	0.0%	0.0%	0.0%	26.5%
	Volume (%) :	2.6%	1.9%	3.0%	0.0%	0.0%	0.0%	33.5%	0.0%	0.0%	0.0%	13.6%	45.4%
	Total Weight :	849 lbs				Total Volume :	7.96 cu ft						
Agg. Percents	Dry Weight (%):	35.1%	24.9%	40.0%	0.0%	0.0%	0.0%						
	Volume (%) :	35.0%	25.0%	40.0%	0.0%	0.0%	0.0%						
		sand	#8 stone	#11stone	#67 stone	#57 stone	0.00	0.00	0.00	0.00	0.00	Air	Water
	Agg. Weight :	99 lbs				Agg. Volume :	0.6 cu ft						
		NO. 1	NO. 2	NO. 3	NO. 4	NO. 5	NO.6						
Fineness Modulus:		2.61	5.53	3.70	0.00	0.00	0.00						
SSD Proportions (lbs) :		35	25	40	0	0	0						
Total Agg. Weight SSD :		100 lbs											
Total Mix Weight SSD :		850 lbs											

COMBINED GRADATIONS

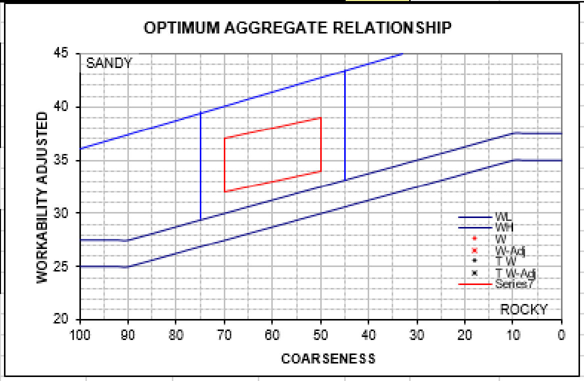
	AGGREGATES				OTAL COMPONENTS		ARGET AGGREGATE		LIMITS				
									Lower	Upper		% Retained Average Calculatio	% Retained Average Check
Screen #	% Pass.	% Retained	13.0% Check	13.0% Calculatio	% Pass.	% Retained	% Pass.	% Retained	% Pass.	% Pass.			
4 "	100.0	0.0			0.0	0.0	100.0	0.0	100.0	100.0	Q		
3 1/2 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
3 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
2 1/2 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
2 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
1 1/2 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
1 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
3/4 "	100.0	0.0		0.0	0.0	0.0	100.0	0.0	100.0	100.0		0.0	
1/2 "	100.0	0.0		0.0	0.0	0.0	96.5	3.5	93.0	100.0		0.0	
3/8 "	98.2	1.8		1.8	0.0	0.0	90.5	6.0	85.0	96.0		0.9	
#4	77.2	21.0	-	22.8	0.0	0.0	68.0	22.5	58.0	78.0	I	11.4	-
#8	57.4	19.8	-	40.8	0.0	0.0	47.0	21.0	41.0	53.0		20.4	FAIL
#16	42.8	14.6	-	34.4	0.0	0.0	37.0	10.0	32.0	42.0	W	17.2	-
#30	31.1	11.7	-	26.3	0.0	0.0	24.5	12.5	19.0	30.0		13.2	-
#50	9.8	21.3	-	33.0	0.0	0.0	11.5	13.0	8.0	15.0		16.5	-
#100	6.1	3.7	-	25.0	0.0	0.0	3.0	8.5	1.0	5.0		12.5	-
#200	4.7	1.4		5.1	0.0	0.0	1.0	2.0		2.0		2.6	FAIL
#325	0.0	4.7		6.1	0.0	0.0	0.0	1.0				3.1	
Pan	0.0	0.0			0.0	0.0							

Mix Workability Properties

Q =	1.8	Coarseness Factor =	4.2
I =	40.8	Workability Adjusted =	56.3
W =	57.4	Percent Mortar =	100.0
		Fineness Modulus =	3.77

Target Mix Workability Properties

Q =	9.5	Coarseness Factor =	17.9
I =	43.5	Workability Adjusted =	46.0
W =	47.0		
		Fineness Modulus =	4.19



APPENDIX E

Life Cycle Cost Analysis

A life-cycle cost assessment was conducted to determine the long-term economic benefits of BCOA pavement. Table 13 shows the initial construction cost for both pavement alternatives shown in Figure 31.

Table 13

Initial construction costs

Alternative A			
Materials	Unit Prices ($)	Quantity	Construction Costs($)
4-in. BCOA	$110 per yd^3	847.4 yd^3	93,215.00
Milling & Surface Preparation	$0.15 per yd^2	7626.7 yd^2	1,144.00
Total Initial Construction Costs			$94,359.00

Alternative B			
Materials	Unit Prices ($)	Quantity	Construction Costs($)
4-in. AC overlay	$80 per ton	1658.8 ton	132,704.00
Milling & Surface Preparation	$0.15 per yd^2	7626.7 yd^2	1,144.00
Total Initial Construction Costs			$133,848.00

Calculation:

Project length: 1 mile=5280 ft.=1760 yd.

Lane width: 13 ft.=4.333 yd.

Pavement area: 1760*4.333=7626.7 yd^2

4in. BCOA volume: 7626.7*0.1111=847.4 yd^3

HMA density=145 pcf

4-in. HMA volume in Ton=5280*13*0.3333*145/2000=1658.8 Ton

During a 20-year design life period, a resurfacing maintenance was carried out every 10-year intervals followed by a preventive maintenance every 5 years for the alternative B. On the other hand, no resurfacing maintenance was required for alternative-A except joint and crack sealing. A 20 year cost comparison of BCOA and AC overlay for 1 mile 13 ft. wide pavement is provided in Table 13. According to a previous study, Louisiana's preventive maintenance program involves the use of chip seal and micro-surfacing and the preventive maintenance cycle is about 5-7 years according to the Pavement Condition Index (PCI). For the cost benefit analysis, both chip seal and micro-surfacing maintenance strategy has been considered at a 5-year interval and the unit cost has been selected based on previous studies *[34]*.

Table 14
Life Cycle Cost Comparison

Year	BCOA	Net Present Value	AC Overlay Strategy 1 (Chip Seal)	Net Present Value	AC Overlay Strategy 2 (Micro-Surfacing)	Net Present Value
1 (Initial Cost)	94,359	94,359	133,848	133,848	133,848	133,848
5	0	0	10,297	8,463	24,406	20,060
10	12,540	8,472	133,848	90,423	133,848	90,423
15	0	0	10,297	5,718	24,406	13,552
20	0	0	0	0	0	0
Total NPV		**102,831**		**238,452**		**257,883**
Savings				**135,621**		**155,052**

Calculations:

AC Maintenance and Rehabilitation Strategy 1:

Chip seal

Unit cost= \$1.35/yd^2

Total cost=\$1.35*7626.7= \$10,297

AC Maintenance and Rehabilitation Strategy 2:

Micro-Surfacing

Unit cost= \$3.20/yd^2

Total cost=\$3.20*7626.7= \$24,406

BCOA Maintenance and Rehabilitation Strategy:

Joint sealing unit cost= \$1.5/ft.

With a half the slab width panels, total joint length= 16,720 ft.

Considering 50% joints need to be sealed,

Total cost=\$1.5*16720*0.5= \$12,540

The Net Present Value (NPV) represents the discounted monetary value of expected net benefits, and was calculated using the following formula:

$$\text{NPV= Initial Cost} + \sum_{k=1}^{n} (Rehab\ Cost)_k \left(\frac{1}{(1+i)^n}\right)$$

Where,

i=discount rate

n=year of expenditure

According to FHWA guidelines, a 4% discount rate was used for this study to reflect the true time value of money with no inflation premium *[35]*.

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