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Feasibility of Using Accelerated Thin Bonded Concrete Overlay for CRCP Spalling Repair

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Abstract: A pilot trial under the Fully Optimized Road Maintenance (FORMAT) project of using thin bonded concrete overlay (BCO) for spalling repair was carried out in the Houston district on SH 146 near Baytown, Texas. In this paper, the practical considerations for the use of thin BCO in terms of the procedures and the material characteristics key to its success are presented, and the effectiveness of this treatment for spall damage in continuously reinforced concrete pavements (CRCPs) is assessed through varied field tests performed before and after the application. Also addressed is its feasibility relative to traffic control and user cost, existing pavement condition, and future maintenance factors as it is considered in the decision-making process of Strategic Analysis of Pavement Evaluation and Repair (SAPER) software. The results show that the application of the treatment combination (i.e. full depth repair, milling, and thin BCO) cost-effectively extended pavement life, improved load carrying ability with reduced user delay, and improved safety control and that it is an innovative and effective method of repair for CRCPs compared with other strategy alternatives.

***Key words**: Bonded overlay; Continuously reinforced concrete pavements (CRCPs); Repair; Spall.*

Introduction

The Fully Optimized Road Maintenance (FORMAT) project was proposed to enhance the efficiency and safety of the European road network by providing the means to reduce the number, duration, and size of repair operations for pavement maintenance purposes [1]. Hence, all aspects of the planning and execution of the pavement maintenance process are being optimized into a fully integrated usable set of pavement maintenance procedures. The work package 3 (WP3) — *Maintenance techniques* is one of the subjects of this extensive research effort and its objective is to identify and assess innovative maintenance techniques and procedures for maintaining concrete pavements that should reduce user delays and safety hazards through work zones.

Spalling is a distress type that plagues both jointed and continuously reinforced concrete pavements (CRCPs) - particularly in Texas where siliceous gravel aggregates have been extensively used in the Houston District for CRCP construction. Spalling related damage is expensive to repair and affects the ride quality giving a negative impression of the pavement's integrity to the traveling public. The Texas Department of Transportation (TxDOT) in the last 15 years has funded several research efforts addressing the mechanism and repair strategies on it.

Whiting et al. pointed out that the use of bonded concrete overlays (BCOs) began to increase significantly in the early 1970s, particularly in Iowa, Kansas, Minnesota, Missouri, South Dakota, and Texas [2]. For rehabilitation of concrete pavements, resurfacing with a BCO may provide significantly longer life and reduced maintenance costs [3]. In the past, problems with overlay delamination have made some agencies reluctant to use BCOs [4]. However, Delatte et al. pointed out that the use of BCOs can be expected to increase, particularly as the research becomes available to convince transportation officials that bond can be ensured [5]. In this study, in order to support the WP3 under the FORMAT project, a pilot trial of spalling repair was performed in Houston District on SH 146 near Baytown, Texas (TX). Over the period of weekends, an existing CRCP was closed to traffic, milled to a depth of 5cm (2inches) after full-depth repair (FDR) of deteriorated sections and then topped with a BCO which essentially restored the original line and grade prior to the opening. Furthermore, the effectiveness of the use of a BCO as a rehabilitation treatment for spalling damage in CRCPs was assessed through varied field tests performed before and after the application.

Strategic Analysis of Pavement Evaluation and Repair (SAPER) software Version 2.0 is an analysis tool developed on the behalf of the Federal Highway Administration (FHWA) to assist in the evaluation and selection of appropriate strategies for maintenance, rehabilitation, and reconstruction (MRR) of concrete pavements at the project level [6,7]. It provides a systematic and methodical approach for selecting appropriate MRR strategies of concrete pavement systems in terms of varied key decision factors. Through the decision making process (DMP), key factors that affect pavement repair type selection are considered including: (1) treatment type (pavement structure, functional condition, and traffic level), (2) traffic management (traffic control costs, non-agency costs, and corridor impact), (3) construction (constructability and time of construction), and (4) life-cycle costs, LCCs, (total construction, long-term maintenance, and salvage value) [8]. Therefore, it can be used to address the feasibility of using thin BCO for CRCP spalling repair in this pilot trial.

In this paper, the practical application of this pilot trial including the procedures for application of the treatment and for traffic control,

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Table 1. Concrete Mix Proportion (1 Sack Batch).

Components	Coarse Aggregate	Water	Cement	Fine Aggregate	Steel Fiber
Weight (kg)	102.5	15.9	42.5	56.4	34

and the relevant characteristics of the materials applied to the BCO performance are described. The assessment of pavement condition before and after maintenance and the verification analysis from the SAPER are also performed.

Application of the Rehabilitation Treatment

The pilot site consisted of a 25.4cm (10inches) CRCP located on SH 146 in the Houston District near Baytown, TX. The pavement is over 18 years old, and average daily traffic volume is 36,500 vehicles. 15.2cm (6inches) cement treated base and 15.2cm (6inches) lime stabilized subgrade lay below the CRCP. Before rehabilitation, the pavement was experiencing spalling and cluster cracking at different severity levels. The whole rehabilitation project covered 4.4km (2.745miles) and the main steps in carrying out the spall repair included:

- FDR at 10 selected sections experiencing cracking and spalling at medium and high severity levels prior to placement of the overlay and the size of each section was 3.66 × 3.66m (12 × 12feet),
- Milling the pavement lanes to a depth of 5cm (2inches) to texture the surface and remove all surface contaminants,
- Cleaning the surface of milled lanes, and
- Applying a 5cm (2inches) BCO.

Traffic Control and Material Characteristics

Relative to work zone considerations, FDR is typically a short-term method of repair [9]. The work zone was delineated by use of advance warning and blocker trucks with flashing lights. Traffic cones were set at specified spacing to channelize the traffic lanes. As previously noted, construction of the BCO was done phase by phase over several weekends after the FDR work was completed. The work zone was again delineated similarly to the FDR work zone, where instead of traffic cones, directional I-beam barricades were used to enhance visibility during night time. A detour signal was also used during the operations.

One of the main advantages of a BCO is that the overlay can expedite construction, since it requires only a minimum number of operations [10]. To make this possible, a necessary condition that must be met is full bonding of the BCO to the underlying layer [11], which requires desirable materials characteristics. In this repair work, the design shear strength was 2758kPa (400psi) at age of 8 hours and 3103kPa (450psi) at age of 10 hours. Table 1 presents the main components of concrete for a sack batch. The design water-cement ratio for concrete overlay was 0.37, and the air content of the mixture was 2.2%. The use of air entrainment, a low water-cement ratio (0.37 in this application), and a low water content (15.88kg or 35lbs for 1 sack batch) resulted in higher strength and reduced shrinkage. Use of steel fiber also contributed to bonding improvement, and due to the randomly oriented steel fiber in cement matrix, a roughened surface is formed between the new and old concrete to provide significant mechanical interlocking and energy absorption capacity, and thus extremely high damage tolerance [12]. In addition, in this type of repair work, it was desirable to use a mixture with rapid strength gain characteristics. Hence, varied chemical admixtures were used to accelerate strength gain and placement of the concrete, including air entraining agent at the rate of 32.5cm^3 (1.1ounces) per 45.36kg (100lbs) of cement, Type B water reducer at the rate of 414cm^3 (14ounces) per 45.36kg (100lbs) of cement, Type C accelerator and Type F high range water reducer at both rates of 236.6cm^3 (8ounces) per 45.36kg (100lbs) of cement. Furthermore, a curing compound was applied after the placement of concrete, which also benefit improving concrete strength gain, while minimizing the shrinkage and thermal contraction of the concrete.

Work Zone and Time of Construction

During the milling and laydown operations, travel and time delay data relative to user costs was collected at various times. This data tended to suggest that, construction activities can have significant impact on the flow of traffic through the work zone [13]. Fig. 1 shows the different work zone conditions during different stages of

(a) During Paving.

(b) During Curing.

Fig. 1. Work Zone Condition of the Field.

Table 2. Work Zone and Time of Construction Data.

Constructior Activity	Time	Vehicle Speed (km/hr)		Work Zone Duration	
		Approaching	Work Zone	Hours per Day	No. of Days
FDR	Daytime, Weekend	72~97	64~72	9:00AM ~ 5 PM	1
Milling	Night	72~97	64~80	8:30PM ~ :30AM	1
Overlay	Daytime, Weekend	32~48	16	11:00AM ~ 4PM	1
Curing	Weekend	72~97	64~80	24 hours	2

construction. It can be seen that during concrete paving (shown in Fig. 1(a)) a long traffic queue was tended to build up, while after concrete paving (shown in Fig. 1(b)) the queue reduced but the vehicle speed was still low.

Work zone user cost is also a function of work zone type, characteristics, duration, frequency, timing, and traffic operations [13]. It is also expected to be a function of the time when the work is carried out whether at night, day, or on weekends. Table 2 summarizes the work zone and time of construction data. The applications were all operated during night time or weekends, and the road was opened to traffic shortly after it has been overlaid, which minimized traffic disturbances and reduced associated user costs. Compared with same BCO application constructed during non-weekend periods, this constructed application during weekend period reduced the associated user cost by 13% based on the analysis from the SAPER software (although not elaborated here).

Assessment of Pavement Condition

In this section, various field tests performed before and after the application to assess the effectiveness of the use of a BCO as a MRR treatment for spalling damage in CRCPs, included:

- Pavement condition survey before the application,
- Falling weight deflectometer (FWD) testing at selected sections on the SH 146 prior to and after FDR, and
- Curing quality, maturity, and shear strength measurements at the interface of the BCO during the placement of the BCO.

Concrete cores were also taken to evaluate the in situ elastic modulus of the existing pavement.

Pavement Condition Survey before the Application

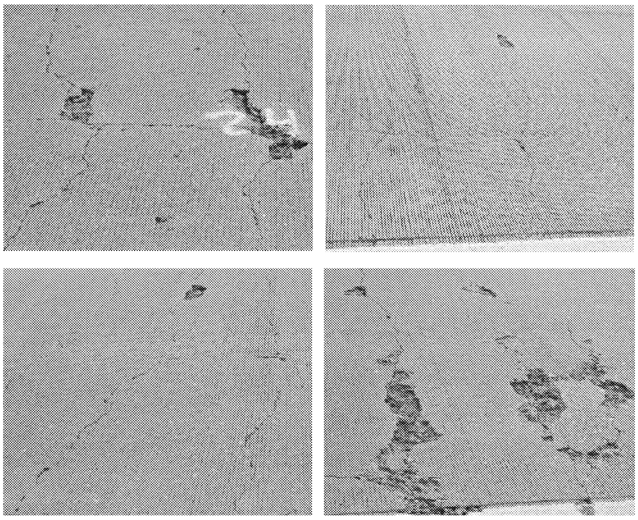
On January 23, 2004, the pavement condition survey was conducted on a 91.44-meter (300-foot) section of the pavement which included collecting crack spacings, punchouts, patches data etc. Fig. 2(a) provides a sample illustration of the existing pavement condition of SH 146. Within the surveyed length there were 98 transverse cracks, where the minimum crack spacing was 5cm (2inches), mean crack spacing was 94.2cm (37.1inches), and standard deviation of crack spacing was 52.8cm (20.8inches). The pavement experienced spalling along with transverse cracks at different severity levels, in addition to 4 punchouts at high severity level, 2 punchouts at low severity level, and 8 patches.

Pavement Condition Before and After FDR

FWD testing at selected sections on the SH 146 prior to and after FDR was conducted on January 16, 2004 and February 18, 2004, respectively, to evaluate the structural integrity of the pavement before and after the repair. During the testing process, slab deflection, load transfer efficiency (LTE), and pavement stiffness data was obtained. For the FWD testing prior to FDR, the load was applied on both upstream and downstream of 27 selected cracks at three different loading levels. For both cases, the testing was taken both in the outer wheel path and center of the slab. Concrete cores were extracted from the pavement and tested in the lab for elastic modulus data. The results indicated that the average elastic modulus of the existing CRCP was 32750MPa (4.75×10^{6}psi).

Table 3 summarizes the comparisons of structure condition prior to and after FDR. Basin area gives an indication of the deflection profiles measured using FWD, and is calculated from sensor deflections as:

$$\text{Area} = \{12/(2^*D_0)\}\{D_0+2[D_1+D_2+........D_{n-1}]+D_n\} \quad (1)$$



(a) Before FDR.

(b) After FDR.

Fig. 2. Pavement Conditions of the Test Section on SH-146.

Table 3. Pavement Structure Condition Comparison.

	Average Deflection Basin Area (cm)	Average LTE (%)	Average RRS (cm)
Prior to FDR	103.4	76.7	95.3
After FDR	108.1	99.22	99.6

where,

Area = basin area,

D_i = measured sensor deflection, and

n = number of sensor (at 0.3m or 12inches spacing) on one side of load plate minus one.

Each deflection reading is normalized with respect to the maximum deflection D_0, and all the measured basin areas are averaged to determine a mean basin area. The LTE was calculated by Eq. (2).

$$LTE = \Delta L / \Delta A \times 100\ \% \qquad (2)$$

where,

ΔL = deflection on the unloaded side of the crack, and

ΔA = deflection on the loaded side of the crack.

The radius of relative stiffness (RRS) which used to characterize the effective stiffness at the joint is obtained, and theoretically determined by the following equation:

$$RRS = \left[\frac{Eh^3}{12(1-\nu^2)k}\right]^{\frac{1}{4}} \qquad (3)$$

where

E = concrete modulus of elasticity,

h = concrete slab thickness,

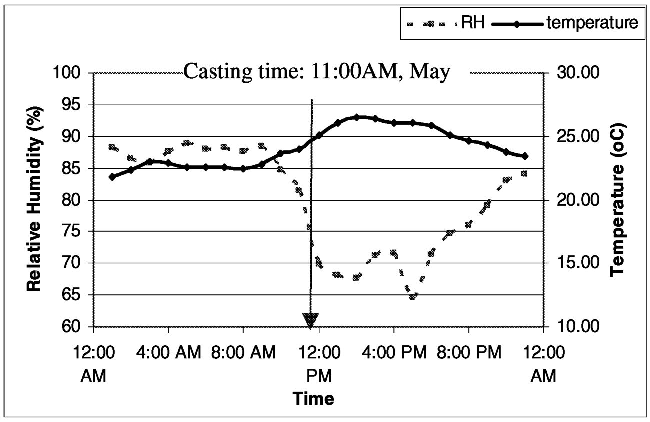
ν = Poisson's ratio, and

k = Foundation modulus

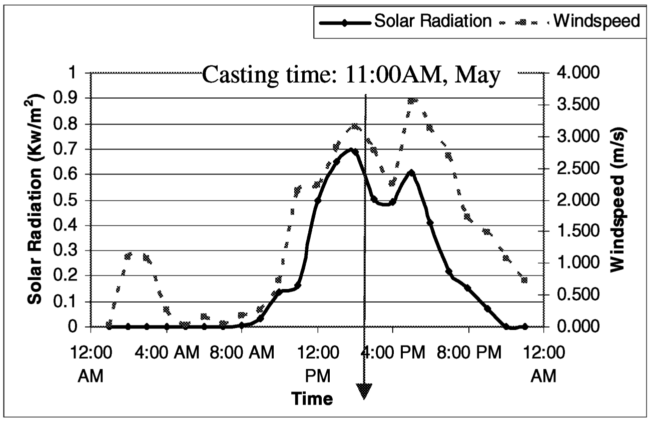
Based on the relationship between the basin area and the RRS [14] and Eq. (3), the average RRS was back-calculated by the use of the ISLAB software [15]. It can be seen that the values of deflection basin area, LTE, and RRS increased at different degrees after FDR, which indicated that FDR effectively restores the structural integrity of a deteriorated pavement. The high average LTE after FDR (99.22%) also showed that the pavement after FDR was structurally sound and was an appropriate candidate for a BCO rehabilitation. In addition, comparing the pavement condition before and after FDR (Fig. 2(a) and 2(b)), it is obvious that FDR addressed deteriorated transverse cracks, joint spalling, blowup, and punchouts, and improved the rideability of the pavement. One more advantage of applying FDR before BCO placement was that it eliminated the formation of secondary joint cracking [4], which was associated with the delamination in the BCOs.

Tests during BCO Construction

Previous research [16] has pointed out that delamination of BCOs is an early-age problem. As noted in the same reference, debonding was even located in a BCO within 24 hours following placement. Hence, the behavior of BCOs at early ages is very critical. In this study, tests including curing quality, maturity, and shear strength measurements at the interface of the BCO were conducted during the placement of the BCO to evaluate the possibility of delamination development after applying BCO.



(a) Relative Humidity and Temperature vs. Time



(b) Solar Radiation and Wind Speed vs. Time

Fig. 3. Weather Data Collection During Paving.

During its early age, the pavement is most susceptible to thermal changes, drying winds, and to other adverse environmental conditions. Therefore, climatic factors significantly affect the development of delaminations, spalling, and other distresses in BCO systems at an early age [17, 18]. A weather station was used to collect weather data in the field that consisted of relative humidity, temperature, solar radiation, wind direction, and wind speed. Fig. 3(a) and 3(b) record the trends of relative humidity, temperature, solar radiation, and wind speed as a function of time from 1am to 11pm on May 8th 2004, respectively. Relative humidity showed an inverse relationship with temperature, i.e. higher temperature associated with lower relative humidity. Solar radiation level reached the highest value at 2pm, where the wind speed showed a big variation with the time.

Maturity, Curing Quality, and Setting Time

The concrete maturity at the interface between the old and new concrete is critical to the bonding at the interface. Maturity was based on both temperature and moisture available at the interface, which require the use of moisture meters and thermometers. Time of setting was also determined and correlated to maturity. Moisture

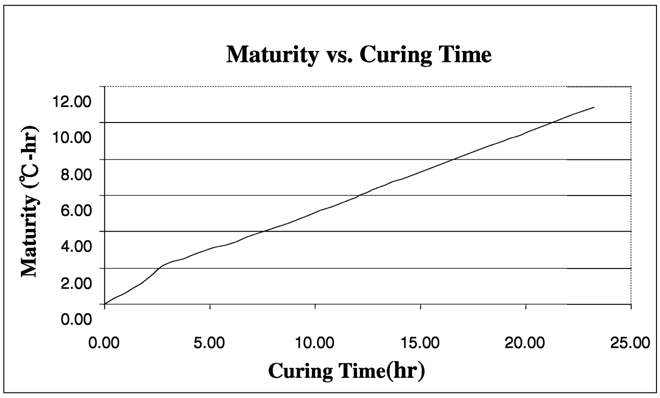
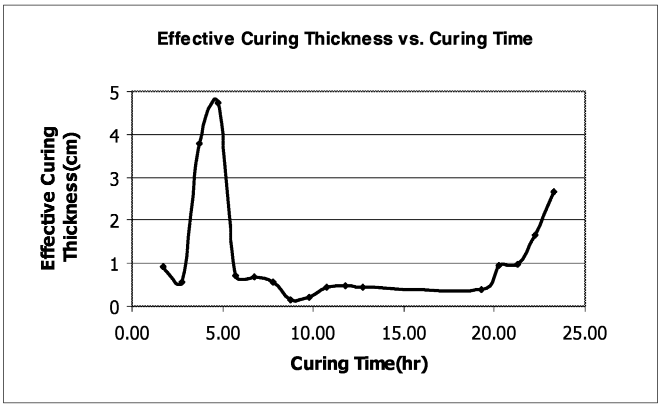
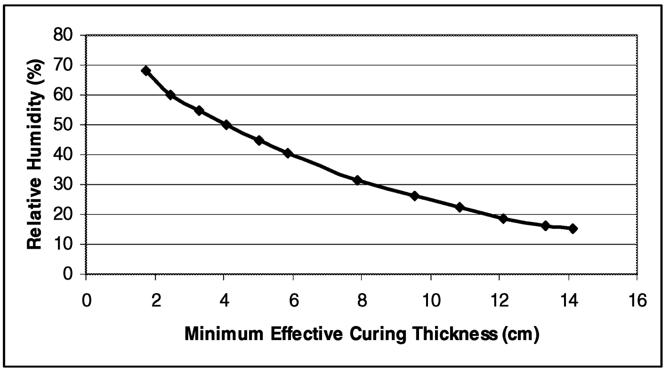


Fig. 4. Maturity vs. Curing Time of Concrete.



(a) ECT vs. Curing Time.



(b) Relative Humidity vs. Minimum ECT.

Fig. 5. Effective Curing Thickness of Concrete.

readings were useful to assess the quality of the curing. The development of maturity with curing time by the Nurse-Saul formulation [18] is shown in Fig. 4. It can be seen that the maturity increased with curing time.

Effective curing thickness (ECT) can be described as the equivalent layer of concrete that would provide the same degree of curing as the curing medium. The thicker the effective curing thickness is, the larger the difference in humidity between the surface and immediately above the surface and the better the curing quality, which suggests ECT can be used as an indicator of curing quality [18]. Fig. 5(a) illustrates the trend of ECT with curing time.

It can be seen that ECT increased during a few hours after concrete placement when bleeding was underway, and then decreased afterward. From Fig. 3(b), it can be seen that the ambient relative humidity varied from 65% to 75% during 5 to 9 hours after placement. Correspondingly, from Fig. 5(b) which illustrates the minimum required ECTs under different relative humidity based on the authors' previous research, the required ECT should range from 1.3 to 2.0cm (0.5inch to 0.8inch) to ensure adequate bond at the interface between the old and new concrete. However, Fig. 5(a) shows that the actual ECT during this period was less than 1cm which indicates that this period was very critical to the concrete performance.

Time of setting of concrete mixture was determined by penetration resistance (RS) test based on ASTM Standard C 403M -97 [19]. Fig. 6 is the plot of the penetration RS versus maturity. The RS increased with the increase of maturity. The initial and setting time were determined as the times when the penetration resistance equaled 3447kPa (500psi) and 27579kPa (4000psi), respectively, while in Fig. 6, the associated maturity values were 70 and 118^{o}C-hrs. The initial and final setting time were obtained by using the linear regression relation between the logarithms of penetration resistance and elapsed time, and the values were 115 and 180mins, respectively. Obviously, the use of chemical admixtures in the mixture resulted in the accelerated setting of the concrete. Fig. 7 illustrates the increase of concrete modulus of new overlay with time. It can be seen that the concrete modulus increased very fast within a few hours after casting, and then increased at a slower rate.

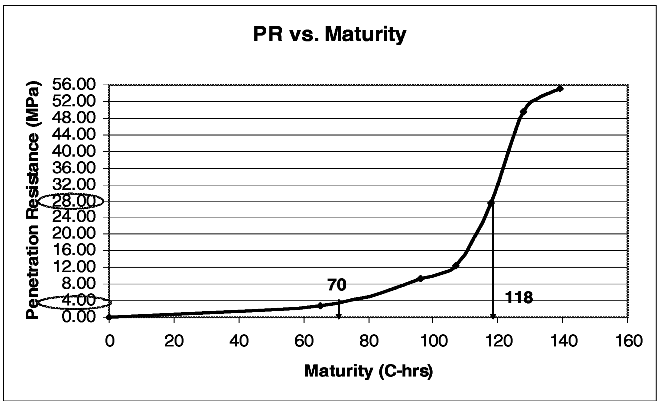


Fig. 6. Penetration Test Results of Concrete.

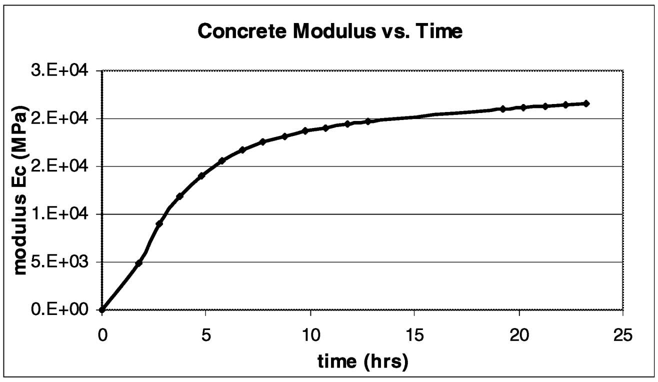
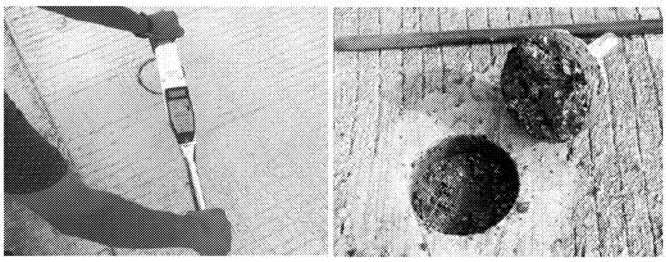
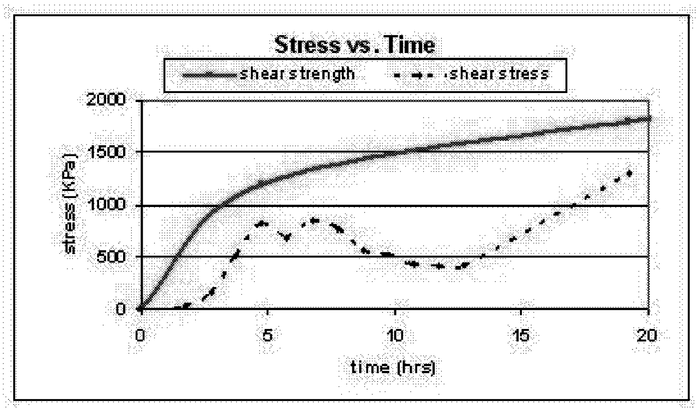


Fig.7. Concrete Modulus Development with Time.



(a) Shear Strength Testing



(b) Interfacial Shear Stress and Strength

Fig. 8. Shear Strength Test of Concrete.

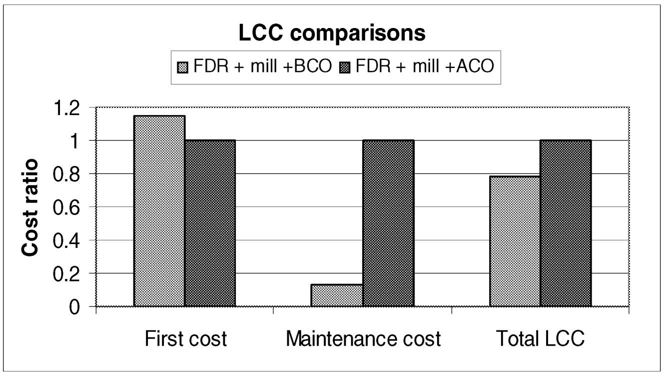


Fig. 9. LCC Comparisons between Two Repair Strategies.

Developments of Concrete Modulus and Shear Strength at the Interface

Tensile bond pulloff test is generally used to determine the bond strength between the new overlay and old concrete slab. However, two problems were encountered in coring for pulloff tests. It was very difficult to core deeply enough to drill past the interface without binding the core barrel or damaging the core or interface. It was also difficult to attach the steel cap to the core [5]. Therefore, shear strength test was conducted to evaluate the bonding between the overlay and old concrete slab. A torsional test device (torque wrench) shown in Fig. 8(a) was applied to debond the new concrete from the old concrete [20]. When the torque wrench was slowly rotated, the torque was delivered to the interface between the overlay and old concrete slab. The torque values at different curing time were collected, and the torsional shear strengths were calculated from the maximum value of the torque when the overlay interface fails and the reading of the torque reached its maximum value by Eq. (4):

$$\tau_{\max} = \frac{M}{J}\frac{d}{2} \tag{4}$$

where,

M = the torque,

d = the diameter of the cylindrical overlay segment, and

J = the polar moment of inertia.

The associated shear stress was determined as the product of drying shrinkage and concrete modulus assuming the new concrete is completely restrained against movement by the underlying concrete. The shear stress and strength with respect to the time were depicted in Fig. 8(b), which shows the shear strength increased greatly with the increase of the time. The shear stress varied with the time and also during the critical period discussed before (5 to 9 hours after casting) and two small peak values of the shear stress were observed. However, at any time period, the shear stress didn't reach the shear strength, which indicated that there was no delamination at the interface till 20 hours after casting.

SAPER Analysis

In order to evaluate the effectiveness of the BCO application in this instance (FDR, 5cm (2inches) milling and 5cm (2inches) BCO) to CRCP, a verification analysis was performed by the SAPER software, which computerizes the MRR strategy selection DMP through four primary steps which involved for the overall MRR selection process: Basic Project Data, Pavement Evaluation and Testing, Suitable Pavement Treatments, and Preferred Pavement Treatment [21]. The treatment combination of FDR and asphalt concrete overlay (ACO) is commonly recommended for CRCP repair through MRR strategy selection DMP [14]. Therefore, another treatment alternative: FDR, 5cm (2inches) milling and 5cm (2inches) ACO was chosen for comparison while keeping same other conditions. The details of analysis are not elaborated but the results are summarized and briefly discussed.

The comparison of LCCs ratio is illustrated in Fig. 9. It can be seen that the first construction cost of the BCO was higher than that of the ACO by 15%. However, due to frequent maintenances within the analysis period the ACO showed much higher maintenance cost than the BCO, which resulted in the higher LCC.

Table 4 lists the summary from the SAPER analysis, where the numbers represent the rating values for evaluation attributes. The details of the rating system on a scale of 0 to 10 to synthesize and account for a variety of factors through the DMP are presented by Liu et al. and Zollinger et al. [6, 14]. Suitable treatment combinations were identified based on the combination of (1) overall treated pavement rating, (2) life extension rating, (3) first cost rating, and (4) time of construction rating. Both treatment combinations provided good overall pavement condition and life extension to the pavement system but the higher first construction cost of the BCO led to its lower first cost rating. Assuming same work zone and time of construction data for both applications, same rating values of construction time were given to these two treatments.

Table 4. SAPER Analysis Summary.

	Evaluation Attributes	FDR, Mill, and BCO	FDR, Mill, and ACO	Evaluation
Strategy Suitability Summary	Overall Treated Condition	9.18	9.18	Both rating values are greater than 5. Both are suitable.
	Life Extension	10.00	10.00	
	First Cost	7.00	9.00	
	Time of Construction	6.00	6.00	
	Overall Rating	8.65	8.85	
Preferred Strategy Summary	LCC	9.00	7.00	BCO shows higher overall rating and it's the preferred strategy.
	User Cost	7.00	7.00	
	Corridor Impact	6.50	6.30	
	Constructability	6.60	7.00	
	Overall Rating	7.52	6.86	

The weighted overall ratings considering these four attributes were 8.65 and 8.85 for the BCO and ACO, respectively. Compared with the criteria suitability (i.e. if the overall rating of the strategy exceeds 5, it is suitable), these two combinations were considered to be suitable and worthy of LCC consideration. The selection of the preferred strategy was accomplished in a similar manner, and each of the suitable treatment combinations was evaluated with respect to (1) LCCs, (2) non-agency cost, (3) corridor impact, and (4) constructability. Lower LCC of the BCO led to its higher LCC rating. Again, same work zone and time of construction data resulted in same user cost ratings of these two treatment combinations. The BCO showed a little higher rating of corridor impact than the ACO due to its lower air pollution during construction. However, it showed a little lower rating of constructability than the ACO due to its greater requirements for contractor experience, capability, and availability to execute the work to be carried out in the project. The final overall rating of the BCO was higher than that of the ACO, and it was identified as the preferred strategy.

Conclusion

In this paper, the application of a BCO to a CRCP on SH 146 in Houston District was presented. Application procedures including FDR, milling, and overlay placement associated with material characteristics as well as work zone and time of construction information were described. The pavement condition prior to and after application were assessed through a variety of field tests such as FWD testing before and after FDR, curing quality, maturity, and interfacial shear strength during the overlay program. The SAPER software was also used to evaluate the effectiveness of this application.

The improvement of pavement LTE after FDR indicates that adequate pre-overlay repair (i.e. FDR) effectively restores the rideability and structural integrity of a spalled pavement. Pavement milling before applying the overlay created effective surface texture to ensure the development of an intimate bond between the overlay and the existing pavement. Both of these pre-treatments relieved the formation of delamination in the BCO. The tests conducting during overlay construction shows that the application provides good bonding condition at the interface between the overlay and the existing pavement. In addition, the concrete material applied and construction characteristics lead to an overlay with quick curing and strength development, minimized traffic interference, and reduced user costs. The comparison with the other treatment alternative through the SAPER analysis also verified its effectiveness.

In a summary, the treatment combination (i.e. pre-overlay repair, surface preparation, and BCO) cost-effectively extended pavement life, improved riding quality and load carrying ability, thereby protecting infrastructure investment. It is an innovative and effective method of spalling repair for CRCPs, and it is recommended as a feasible strategy for CRCPs over other alternatives.

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