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Accelerated Loading Evaluation of Foamed Asphalt Treated RAP Layers in Pavement Performance

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Abstract: An accelerated pavement testing (APT) experiment was conducted to evaluate field performance of foamed asphalt-treated reclaimed asphalt pavement (RAP) layers used in a flexible pavement structure under typical southern Louisiana highway conditions. The APT experiment consisted of three full-scale flexible pavement sections with different base layers: a regular good-performing crushed stone base and two foamed asphalt-treated RAP bases containing different RAP percentages. Laboratory test results indicated that the two foamed asphalt RAP materials exhibited the higher potential of moisture susceptibility, had less resilient moduli, and were more prone to permanent deformation than the crushed stone base material considered. The APT results showed that the foamed asphalt base test sections had excellent early performance, but both failed by a suddenly sharp increase in permanent deformation when the APT load level was increased. A shakedown analysis revealed that the foamed asphalt treated RAP base materials could have lower shakedown stress thresholds than that of the crushed stone under a moisture-rich road condition. Finally, forensic investigation indicated that one foamed asphalt base failed mainly due to its severe moisture susceptibility, while the other experienced both mositure and over-asphalting problems.

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***Key words**: APT; Foamed asphalt; Pavement performance; RAP; Stone base.*

Introduction

The use of foamed asphalt in pavement stabilization was first developed in 1957 in Iowa as a method to stabilize marginal local aggregates such as gravel, sand, and loess with controlled asphalt foam produced by introducing saturated steam into heated asphalt bitumen [1]. The foaming process later became more practical and less expensive when modified by adding cold water rather than steam into the hot bitumen [2]. The foamed asphalt base stabilization now has become a common method used in the full-depth reclamation and cold-in-place recycling of roadway rehabilitation. In a foamed asphalt mixture design, the percentage of aggregate material passing No. 200 sieve and the asphalt content are generally considered to be the two most important factors [1, 3-4]. Research studies also demonstrated the feasibility of using salvaged material to produce a foamed, recycled mixture with or without virgin materials [2, 4-5]. It is generally accepted that the foamed asphalt base provides a quick construction method and has an increase in strength over unbound materials, lower cost than reconstruction, and improved durability and material resistance to moisture infiltration [6].

Due to the lack of locally produced high-quality stone base materials, the Louisiana Department of Transportation and Development (LADOTD) continuously seeks for alternative base materials in lieu of crushed stone used for roadway construction. In 2005, LADOTD established two experimental base sections in a continuously reinforced concrete pavement project to evaluate the potential use of foamed asphalt-treated recycled asphalt pavement (RAP) material in Louisiana highways. The two foamed asphalt treated RAP materials (one with 100% RAP and the other with 75% RAP and 25% recycled Portland cement concrete) both showed having a higher initial in-situ stiffness and structure numbers than a crushed limestone base layer (i.e., a control base) tested immediately after the construction [7]. The Maine Department of Transportation recently published a report on using foamed asphalt as a stabilizing agent in a full depth reclamation project [8]. The first five-year performance results (i.e., rut depth, cracking, IRI, and structural number) indicated that a foamed section containing 3-in. hot mix asphalt (HMA) and 8-in. foamed asphalt stabilized full-depth reclamation base performed slightly better than a regular section without foamed asphalt treatment. The cracking data also showed that the foamed section had significantly less amount of cracking than the regular section during the first four years; however, the transverse, longitudinal, and load cracking on the foamed section increased to about the same level as the regular section during the fifth year. The reason for such a rapid cracking increase in the fifth year was not investigated [8].

Initially satisfactory performance of using a foamed asphalt stabilized base material has been widely reported in many studies [1-2, 9-10]. However, its long-term performance is not widely known or available. A warranty project in Texas reported that a foamed asphalt-treated base material was found to possess a severe moisture susceptibility problem that directly caused the premature pavement failure (i.e., structural distresses, including alligator cracking and deep rutting) as found in that project during its first three-year warranty period [11].

To evaluate long-term field performance and obtain direct knowledge of using foamed asphalt-treated RAP base layers in a flexible pavement structure under typical southern Louisiana

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highway conditions, an accelerated pavement testing (APT) experiment was recently conducted at the Louisiana Transportation Research Center (LTRC).

APT Experimental Design

Test Sections and Instrumentation

Normal construction procedure was followed to construct test sections for this APT experiment. Fig. 1 presents pavement structures of test sections considered. Each test section is 13-ft. wide and 107.5-ft. long. As shown in the figure, all sections consist of a 2.0-in. HMA wearing course, an 8.5-in. base course, and a 12-in. cement-treated subbase layer over an A-6 embankment subgrade. A good-performing, ¾ -in. Superpave HMA mixture, typically used as a wearing course for intermediate/high volume pavements in Louisiana [12], was selected as the surface layer of test sections. The subbase layer is an in-place 8 percent (by volume) cement-treated A-6 soil. The details of different base materials will be presented in the subsequent section.

Fig. 1 also shows the field instrumentation layout of each test section. For each test section, two Geokon 3500 pressure cells were embedded at two depths directly along the centerline: one at the bottom of the base layer and the other on top of the subgrade. One multi-depth deflectometer (MDD) with six potentiometers (deformation measurement sensors) was installed on each test section at a distance of 4.5 ft. away from the pressure cell location along the centerline. More details about those instrumentation devices can be found elsewhere [13].

Base Materials

As shown in Fig. 1, three base layers were considered: a crushed limestone base on section 4-2B and two foamed asphalt (FA) treated RAP bases on sections 4-3A and 4-3B. The crushed limestone base of 4-2B is a regular LADOTD Class-II base course with a specified gradation listed in Table 1 [12].

The foamed asphalt mixture design was followed the Wirtgen Cold Recycling Manual [10]. The FA base mixture of section 4-3A consists of 48.6 percent RAP, 48.6 percent recycled soil cement, and 2.8 percent PG 58-22 asphalt binder (hereafter called as FA/50RAP/50SC), whereas, the FA base of 4-3B contains 97.5 percent RAP and 2.5 percent PG 58-22 binder (hereafter called FA/100RAP). The gradation of RAP material is presented in Table 1. The optimum water content and maximum dry unit weight for the RAP was found to be 8.6 percent and 118 kN/m3, respectively. Table 2 presents a summary for the foamed asphalt mixture design. It may be seen from the table that both treated materials seems to possess a relatively low indirect tensile strength (ITS) strength value. The FA/50RAP/50SC mixture even had a lower retained ITS than that of the FA/100RAP, indicating more prone to moisture susceptibility. In addition, the design air voids for FA/50RAP/50SC and FA/100RAP materials were 20.3 percent and 15.3 percent, respectively.

APT Loading and Field Measurements

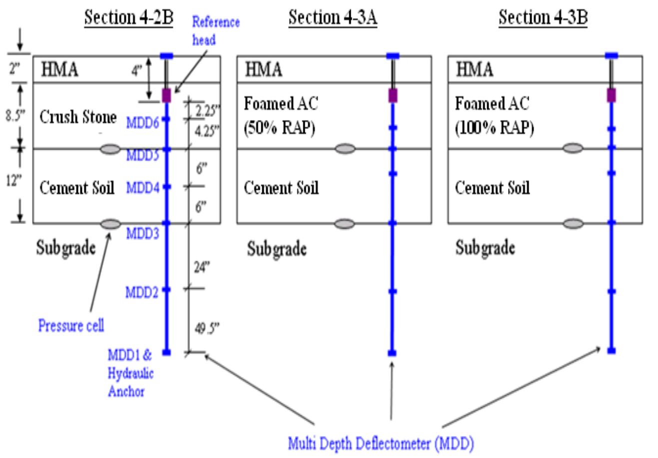


Fig. 1. Pavement Structures of APT Test Sections (1 in. = 2.54 mm).

Table 1. Gradation Requirements for RAP and Crushed Stone Base.

U.S. Sieve	RAP	Crushed Stone Base	
	Percent Passing	LADOTD Specification	Percent Passing
1½ in.	100	100	100
1 in.	100	90~100	97
¾ in.	100	70~100	88
½ in	97		74
3/8 in	87		67
# 4	65	35~65	50
# 8	51		36
# 16	42		26
# 30	35		20
# 50	22		15
#200	9	5~12	11

Table 2. Design Data for Foamed Asphalt RAP.

Property	FA/100RAP	FA/50RAP/50SC
Asphalt Cement Type	PG58-22	PG58-22
Design Asphalt Cement (%)	2.5	2.8
Indirect Tensile Strength (ITS) - Dry, psi	53.0	46.7
ITS - Wet, psi	50.0	38.4
Retained ITS (%)	94.5	82.4
Selected Moisture Content (%)	6	8
Bulk Relative Density (lb/ft3)	124.8	117.3
Air Voids (%)	15.3	20.3

Note: 1 in. = 2.54 mm, 1psi = 6.89 kPa, and 1 lb/ft^3 = 0.157 kN/m^3.

An Australia-designed Accelerated Loading Facility (ALF) device was used in this study. The device is equipped with a wheel assembly of dual tires and simulates one half of a single axle loading. The wheel load is adjustable from 9,750 lb to 18,950 lb [13]. The beginning wheel load for this experiment weighs 9,750-lb. Two steel load plates (2,300-lb each) were added subsequently to the load assembly to expedite the pavement deterioration immediately after 175,000 and 225,000 load repetitions, respectively. In addition, a 7.5-in. traffic wander was considered during the wheel loading.

A test section shall be considered to have failed when meets either of the following failure criteria, whichever comes first: the average rut depth of 0.5 in. within the trafficked area, or visible cracks (e.g. longitudinal, transverse, and alligator cracks) of more than 1.5 ft/ft2 within 50 percent of the trafficked area.

Field instrumentation data (i.e., MDD and pressure cell readings) was collected at the end of every 8,500 ALF load repetitions. Non-destructive deflection tests including Dynaflect and falling weight deflectometer (FWD) were performed at 8 stations along the centerline of ALF loading path at the end of every 25,000 load repetitions. Note that the Dynaflect deflection results were used to estimate pavement structural number (SN) values [14], whereas, the FWD data were input to backcalculate the layer moduli.

Discussion of Results

Results presented for discussion included those from laboratory tests, field non-destructive deflection measurements, instrument responses to vehicular loading, surface distress survey, and forensic investigation on failed pavement structures.

Laboratory Test Results

Resilient Modulus Test

Laboratory repeated loading triaxial (RLT) tests were used to determine the resilient moduli (M_r) of base materials considered in this study [15]. All laboratory test samples were remolded from material collected in the field and compacted in the laboratory at their in situ conditions and the Mr tests were performed at an ambient temperature of 25±1^o. Fig. 2 presents the resilient moduli results varied with bulk stress (σ_b) and confining stress (σ_c) for the crushed stone and two foamed asphalt base materials of this study. As shown in Fig. 2, the M_r of crushed stone increased as either σ_b or σ_c increased. This observation indicates that an increase in the σ_b would increase frictional resistance among crushed stone particles and an increase of σ_c would decrease material dilatational properties. Fig. 2 further indicates that the resilient properties of the two foamed asphalt-treated RAP materials were slightly different from the crushed stone. When buck stress σ_b is less than 20 psi (138 kPa) and confining stress σ_c is constant, the M_r values for both foamed asphalt RAP materials would increase as the increase of σ_b. However, when σ_b becomes greater than 20 psi, those M_r values tended to decrease as the σ_b increases. This may be attributed to the decrease in friction among the foamed-asphalt treated RAP particles because of the smooth asphalt coating around them, especially under high σ_b levels. Meantime, as the confining pressure increases, the M_r of foamed-asphalt treated RAP increases. Such a behavior is similar to that of a crushed stone. Overall, the evaluated crushed stone material showed higher M_r values than both foamed- asphalt treated RAP materials.

Permanent Deformation Test.

The permanent deformation test is another RLT test [13]. The test consists of conditioning the samples in the same procedure used in the resilient modulus tests, followed by applying 10,000 load cycles at a constant confining pressure of 5 psi and a peak cyclic stress of 15 psi for base materials. The test acquires loads and vertical deformations continuously throughout the 10,000 cycles. The total strain, resilient strain, and permanent strain for each load cycle are then computed. The permanent strain curves of crushed stone and foamed asphalt RAP materials tested in this study are shown in Fig. 3. The crushed stone material exhibited an initial accelerated rate of permanent strain with the increase of load repetitions and then reached a steady stage. While the FA/50RAP/50SC accumulated slightly higher permanent strain than the crushed stone material, the FA/100RAP accumulated the largest permanent strain among all the base materials evaluated. The permanent strain curve with the number of load cycles of FA/100RAP increased at an accelerated rate and without showing any steady strain. This implies that treating RAP material with foamed asphalt appears to degrade the

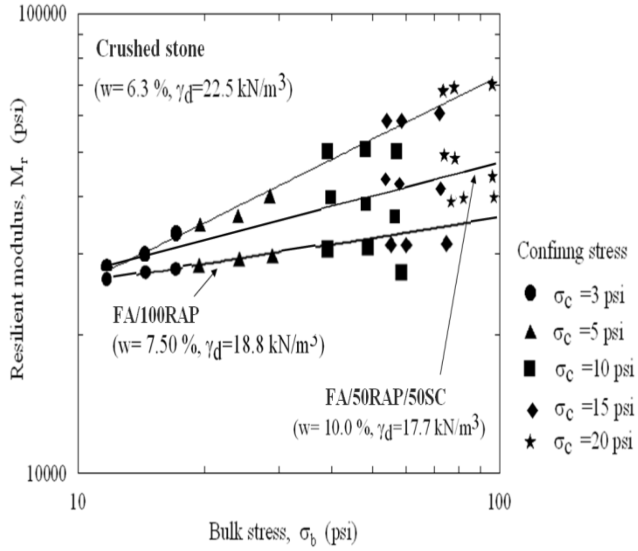


Fig. 2. Resilient Modulus of Base Materials (1 psi = 6.89 kPa).

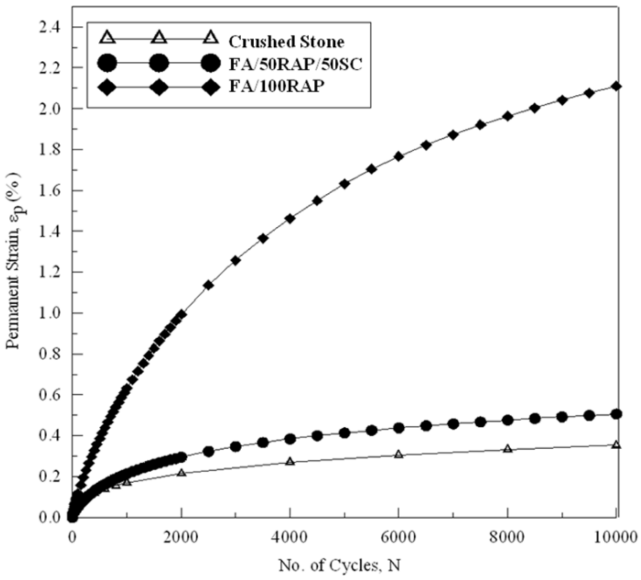


Fig. 3. Permanent Strain Curves for RAP Materials.

permanent deformation resistance properties under repeated loading.

Loaded Wheel Tracking Test

To capture rutting performance under both dry and submerged conditions, two types of loaded wheel tracking (LWT) tests: Hamburg Type Wheel Tracking and Asphalt Pavement Analyzer (APA) were conducted on slab samples fabricated from the foamed asphalt treated base materials used in the APT experiment. The Hamburg test is considered as a torture test that produces damage by rolling a 71.1 kg (158 lb) steel wheel across the surface of a slab that is submerged in water for 20,000 passes. The APA device simulates actual road conditions by rolling a metal wheel over a rubber hose pressurized at 100 psi for 8000 cycles. The APA test was conducted under dry conditions at 104 and 122°F, while the Hamburg test was performed with a submerged water temperature of 40°C (104°F). Fig. 4 presents the average rut depths obtained from the results of those tests. It is noted that the rut depths increased with increasing the temperature. At the same testing temperature, the foamed asphalt-treated RAP materials accumulated much higher rut depth under the wet condition in the Hamburg Type Wheel Tracking test compared to the dry condition in the APA test. Such results clearly indicate that both foamed asphalt RAP materials possess potential moisture susceptibility problems. Furthermore, it may be also noticed from Fig. 4 that the FA/50RAP/50SC material tends to exhibit much greater moisture susceptibility than FA/100RAP material.

ALF Loading Results

All three test sections had a rutting failure according to the failure criteria set for this experiment. Some severe localized cracks were observed on all sections after the APT test. It should be noted that those localized cracks directly resulted from large surface depression developed nearby. Fig. 5 presents the average measured rut depths with the number of load repetitions for the three sections tested. As shown in the figure, for the first 175,000 load repetitions when the load level was at 9,750-lb, it is apparent that the two foamed asphalt base sections (4-3A and 4-3B) performed similarly as or even slightly better than the stone section. The mean rut depth at 175,000 repetitions was 0.12-in. for the FA/50RAP/50SC section, 0.24-in. for both the FA/100RAP and stone sections. Subsequently, as the load levels increased, both foamed asphalt sections exhibited a significantly higher rutting accumulation rate than the stone section. In the end, the FA/50RAP/50SC section (4-3A) reached the rutting limit (i.e. an average rut depth of 0.5-in.) at 228,000 repetitions, whereas, the FA/100RAP section (4-3B) reached at 230,000 repetitions, and the stone section (4-2B) reached at 282,000 repetitions. If the ALF repetitions are converted into the 18,000-lb Equivalent Single Axle Load (ESAL) numbers based on the fourth power law [16], the corresponding ESAL numbers for sections 4-2B, 4-3A and 4-3B would be 786,000, 411,000 and 356,000, respectively. Obviously, the stone base section performed better than both foamed asphalt base sections in this study.

NDT Test Results

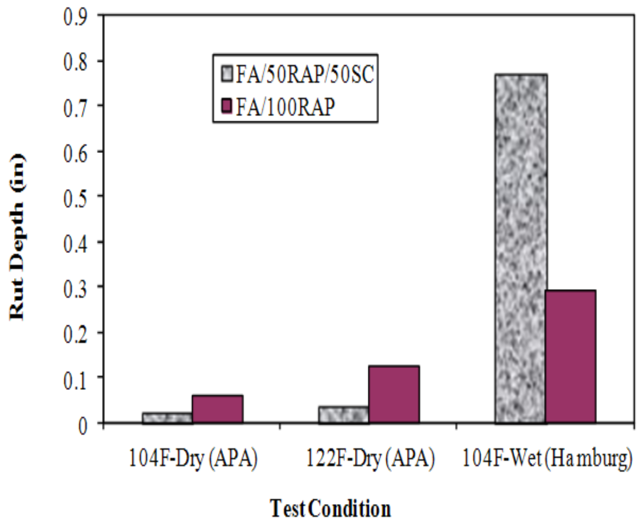


Fig. 4. Results of Loaded Wheel Tracking Tests (1 in. = 2.54 mm).

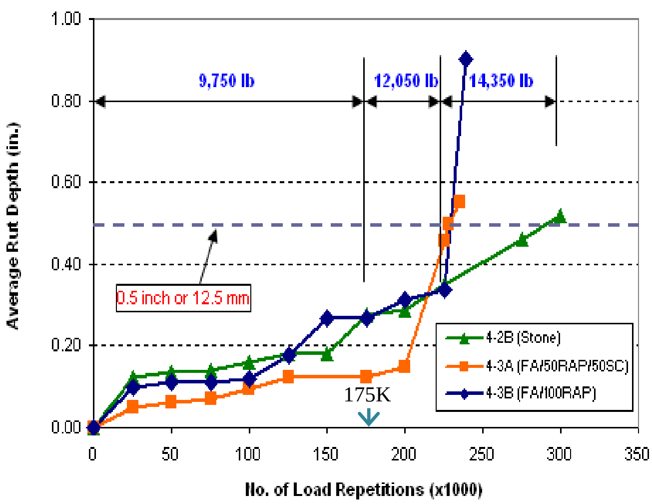
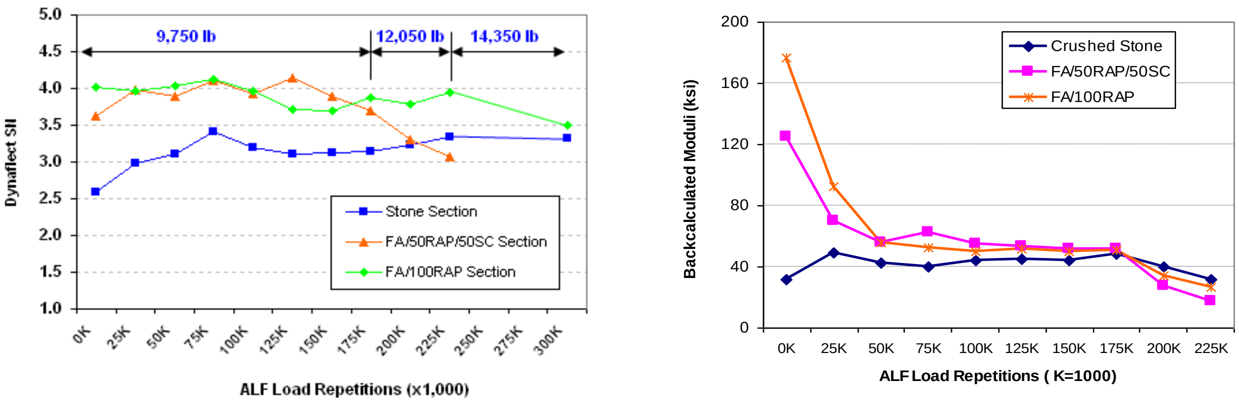


Fig. 5. Measured Rut Depths on Test Sections (1 in. = 2.54 mm & 1 lb = 0.454 kg).

Dynaflect Results

Fig. 6(a) presents ALF load induced progression of the average SN values for the three test sections evaluated. A higher SN value indicates greater structural capacity of a pavement. An initial increase in the SN values during the first 75,000 ALF passes or so may be attributed to the post construction densification of pavement layers and the corresponding material strength gains due to the curing. As expected, the overall SN values generally displayed a slightly decreasing trend (due to pavement deterioration) with the increase of load repetitions.

As shown in Fig. 6(a), prior to 175,000 loading repetitions, both foamed asphalt sections had higher SN values than the stone section (4-2B). After 175,000 repetitions, the SN for the FA/50RAP/50SC section (4-3A) began to decrease rapidly and eventually became lower than that of the stone section. Furthermore, due to the increase of ALF load levels, the SN for the FA/100RAP section also showed a sharper decrease after 225,000 repetitions. However, the change in



(a) Dynaflect SN Results (b) FWD Backcalculated Base Moduli

Fig. 6. Deflection Test Results (1 in. = 2.54 mm & 1 lb = 0.454 kg).

SN values for the stone section seems to be not as sensitive to the changes of ALF load levels, see Fig. 6(a). In general, the SN changes observed in Fig. 6(a) matched well with the rutting measurement curves shown in Fig. 5.

Fig. 6(b) presents the FWD backcalculated moduli for the three base materials. As shown in the figure, the moduli for both foamed asphalt materials decreased rapidly as the load repetitions increased. However, the stone base used in section 4-2B seemed not very sensitive to the load repetitions, whose moduli varied slightly with the increase of load repetitions. It is noted that both foamed asphalt bases had a higher backcalculated modulus than the stone base up to 175,000 load repetitions, Fig. 6(b). The rapid decrease in backcalculated modului of those foamed asphalt materials, although partially due to the temperature effect, might be explained by internal material damages due to the load and environmentally effects (e.g. the moisture).

Instrument Responses to ALF Wheel Loading

It was observed during the ALF loading that all embedded instrumentation gages started malfunctioning when a certain cumulative pavement distress (e.g., rutting) at the gage installation locations reached to a severe level. As a result, the pressure cell measured vertical stresses up to 175,000 load repetitions were considered reasonable and used in the analysis.

Statistical summary results showed that the average vertical stresses developed at the bottom of base layers were 18.6-, 10.2- and 9.6- psi for the stone base section (4-2B), the FA/50RAP/50SC section, and the FA/110RAP section, respectively. Meanwhile, the corresponding average stress values on the top of subgrades were 0.7-, 0.4 and 0.3- psi, respectively. This indicates that a higher vertical stress distribution generally existed within the stone section (4-2B) than those within the two foamed asphalt sections under the ALF load of 9,750-lb during the first 175,000 repetitions. It further confirmed the FWD backcalculated base modulus results as showed in Fig. 6(b). Unfortunately, no further comparison could be made after 175,000 repetitions.

Fig. 7 presents MDD measured permanent deformations versus the number of load repetitions for individual pavement layers of the three APT test sections. As expected, significantly large amounts of permanent deformation were observed on all three base layers of test sections. However, the load-deformation curves differed significantly from one to the other. The crushed stone base (Fig. 7(a)) was found to develop significantly large permanent deformation during the first 25,000 ALF repetitions, and then the rate of deformation started to slow down and showed a decreasing trend till the end of the MDD measurements of 175,000 ALF passes. On the other hand, both foamed asphalt base layers initially developed very small amounts of permanent deformation. The rate of deformation rate started to take off at 175,000 ALF load repetitions on section 4-3A and at 100,000 repetitions on section 4-3B. It is evident that both foamed asphalt base layers experienced significant strength breakdown during the loading and the MDD results confirmed the overall rutting results as shown in Fig. 5.

The difference among the permanent deformation development of the three base materials may be explained by the Shakedown Theory [17]. The Shakedown Theory indicates that most pavement materials are stress-dependent and have a self-specified threshold stress level called the "shakedown load". When limiting the stress level in a pavement material below its threshold stress, it will eventually respond in a resilient (elastic/shakedown) manner as the load repetitions increase. On the other hand, when continuously increasing the stress level and passing its threshold stress, the material will first go to plastic creep stage and eventually to a stage of incremental collapse. The shakedown analysis indicated that both foamed asphalt treated RAP base materials seemed to have a lower shakedown threshold stress than the crushed stone base. It was due to the increase of the ALF load levels after the 175,000 repetitions that caused pavement base stresses to be higher than the shakedown threshold stresses of the two foamed asphalt treated RAP base materials. This eventually resulted in a sudden rutting failure for the two foamed asphalt test sections. Since both foamed asphalt base materials had an excellent early performance up to 175,000 repetitions when the load level was at 9,750-lb, the shakedown analysis also suggested that, as long as the traffic induced stress level was kept below their corresponding threshold stresses (as shown in the case when the ALF load was at a 9,750-lb level), both foamed asphalt base materials would have continuously performed similarly to or better than the stone base.

Failure Analysis of Foamed Asphalt Base Materials

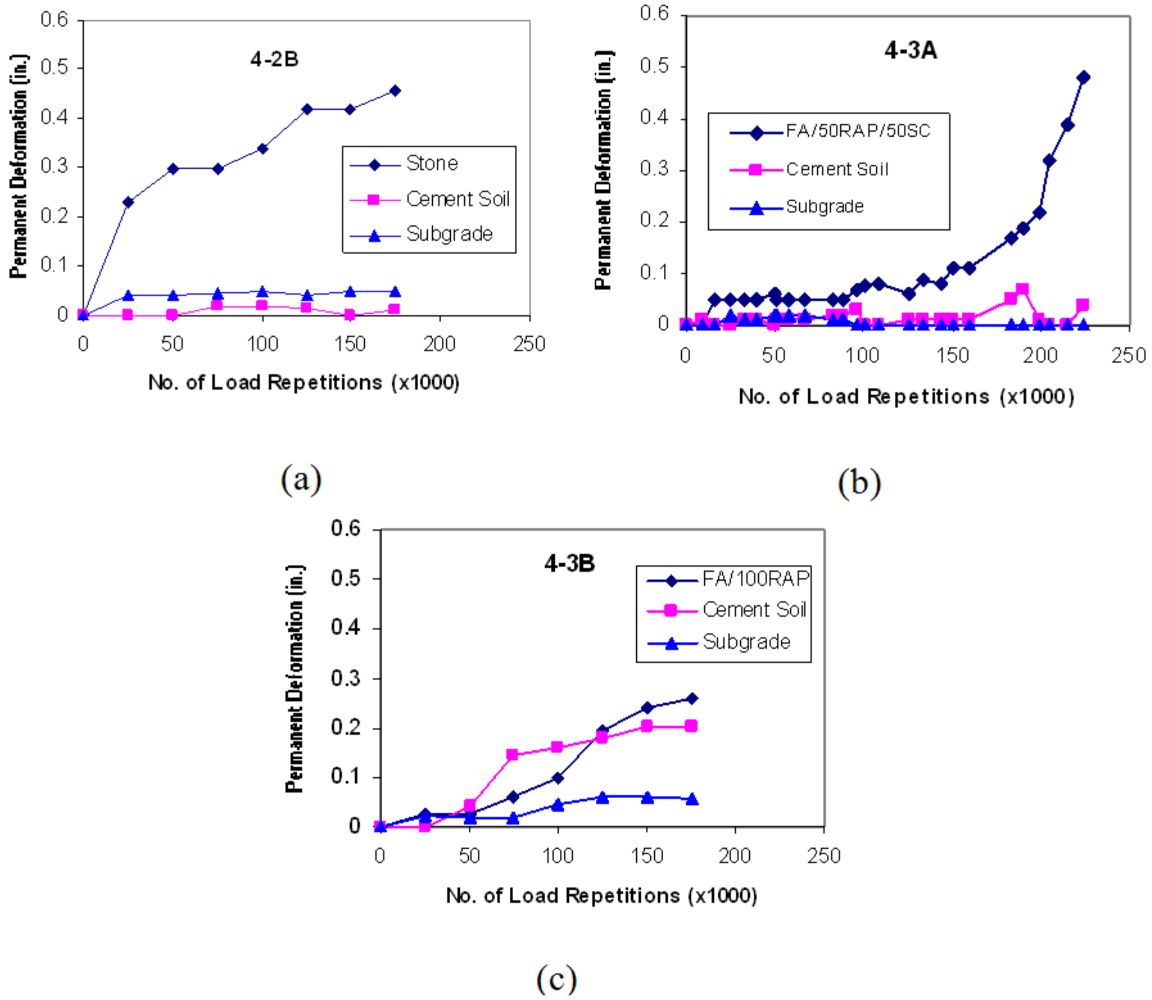
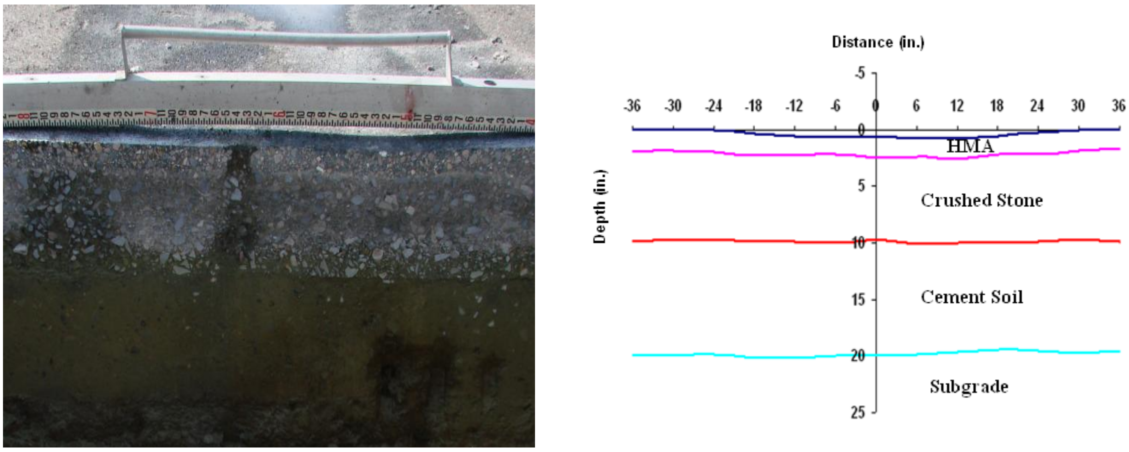


Fig. 7. MDD Measured Permanent Deformation at Each Section (1 in. = 2.54 mm).

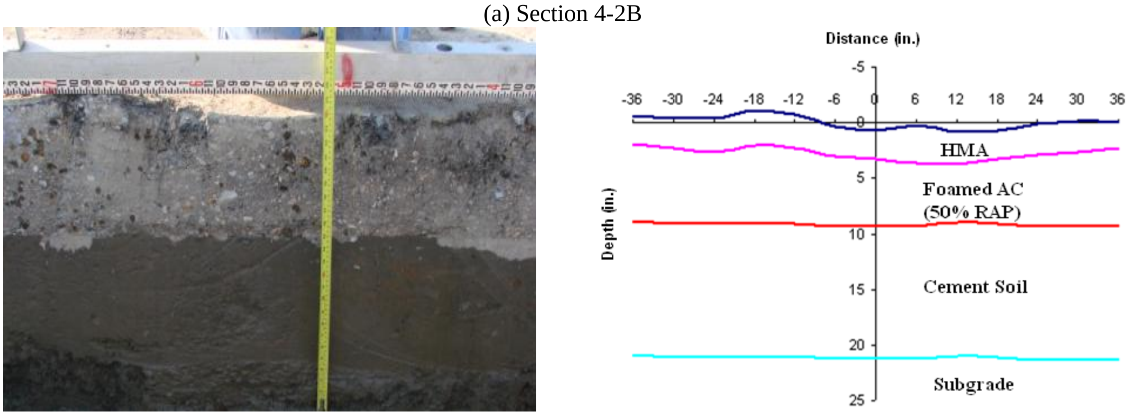
Fig. 8 presents results of post-mortem trenches saw-cut at a severely-distressed station on each test section. As shown in Fig. 8(a), the transverse rutting profile of section 4-2B (the stone base section) primarily resulted from further densification (depression below the original surface) of the HMA and crushed stone materials under the load. However, the rutted profiles on the foamed asphalt sections (Fig. 8(b) and 8(c)) included not only the densification but also heave deformation (permanent deformation above the original surface). The heave deformation was generally found rooting from the base layers of sections 4-3A and 4-3B, indicating both foamed asphalt treated base materials had a shear failure under the increased ALF load levels. Obviously, such shear failures are associated with insufficient shear strength, which further demonstrates that both foamed asphalt treated RAP base layers should have a lower shakedown load threshold than that for the crushed stone base in 4-2B.

It is believed that the insufficient shear strength and low shake-down threshold are largely associated with low water resistance of the foamed asphalt RAP materials. Laboratory LWT rut tests showed that both foamed asphalt materials exhibited low water resistance when tested in a submerged condition and the FA/50RAP/50SC material exhibited even greater moisture susceptibility than the FA/100RAP material. The FA/100RAP mixture consisted of 48.6 percent RAP, 48.6 percent recycled soil cement, and a design air void of 20.3 percent. Such a high design air void plus high percentage of recycled soil cement material had potentially produced a weak structural skeleton for the FA/50RAP/50SC mixture (i.e. too much soil particles); thus, only 2.8 percent foamed asphalt content seemed not able to bond the weak aggregate skeleton effectively (which can cause the water susceptibility problem). Consequently, when high load-induced stresses transformed to this material under a moisture rich pavement condition, it lost its strength and started to develop a shear failure.

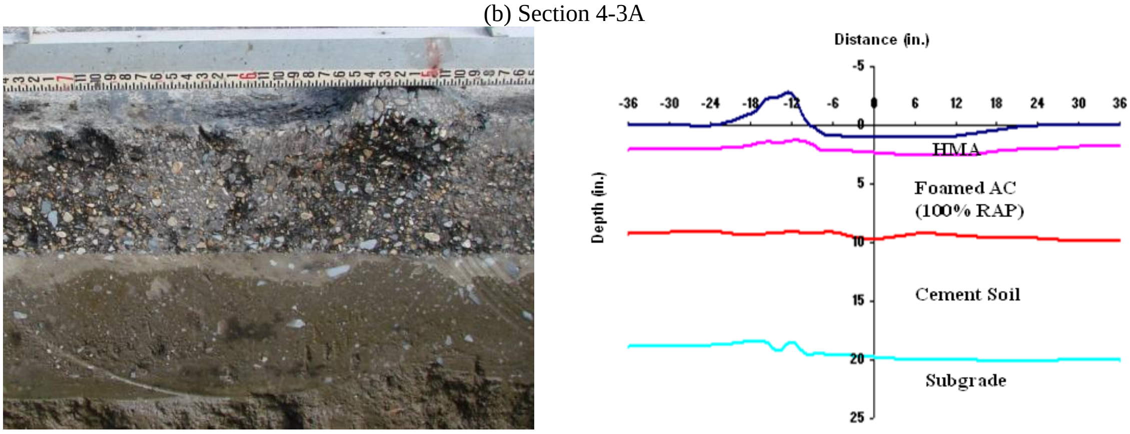
On the other hand, the trench profiles also revealed that the cement soil and subgrade layers on the FA/100RAP section (4-3B) did show some permanent deformation development. This observation is consistent with the MDD results in Fig. 7(c). Several months after construction, small droplets of asphalt binder material seeped up through the surface of section 4-3B (with FA/100RAP base). The initially spotted asphalt droplets, as shown in Fig. 9(a), became much more noticeable during the APT testing, and eventually caused significant surface distresses on section 4-3B (Fig. 9(b)). The FA/100RAP mixture contained 97.5 percent RAP and 2.5 percent foamed asphalt with a design air void of 15.3 percent. The



(a) Section 4-2B



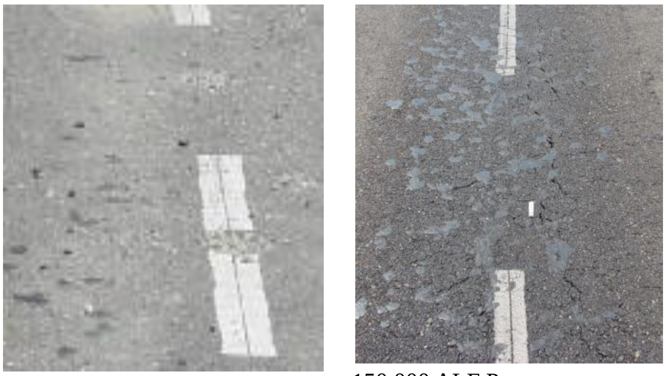
(b) Section 4-3A



(c) Section 4-3B

Fig. 8. Post-Mortem Trench Results (1 in. = 2.54 mm).

droplet binder material that had bled through the surface could be the aged foamed asphalt binder, or RAP binder, or a MC-250 cutback asphalt prime coat (applied at a rate of 0.25 gallons per square yard in the construction record), which indicated a possible over-asphalting problem for the FA/100RAP mixture design. Under the daily temperature change (especially during a summer), the free asphalt materials started to seep up through the top HMA layer. Such "seep-up" action not only caused a cosmetic problem, but also created many tiny crack paths inside the HMA mixture. Therefore, free surface moistures could have entered into the FA/100RAP base layer through those cracks, which gradually weaken the strength of the base material and thus cause a premature shear failure.



Before ALF Loading 150,000 ALF Passes

Fig. 9. Asphalt Droplets on Section 4-3B.

Summary and Conclusions

Based on this study, the following observations and conclusions may be drawn:

- Both foamed asphalt treated RAP materials tested in this study were found to be susceptible to moisture. The moisture susceptibility could be directly resulted from improper foamed asphalt mixture design. Problems associated with the foamed asphalt RAP mixture design included the weak aggregate skeleton, high air voids, insufficient bond between binder and recycled soil cement, and over-asphalting. More research on how to improve water susceptibility in a foamed asphalt mixture design using the RAP and other salvage recycled materials is still warranted.
- Both foamed asphalt treated RAP materials showed excellent early performance under a 9,750-lb. dual-tire ALF load, which simulates one half of a single axle of 19,500 lbs. According to the Shakedown Theory, if keeping the traffic induced stress level below the corresponding shakedown threshold stresses, both foamed asphalt base materials would have continuously performed similarly to or better than the stone base considered.
- A cost analysis showed that the unit cost for construction of an 8.5-in. foamed asphalt treated RAP base would be $5.39 per square yard when RAP materials are closely available, while the average construction cost for an 8.5-in. imported crushed stone base in Louisiana would be approximately $7.50 per square yard. Due to the excellent early performance under the 9,750 lb ALF load and the potential cost benefit, the foamed asphalt RAP mixtures evaluated in this study may be suitable to use as a base course material for the low volume roads in Louisiana, where the percentage of heavy truck traffic is relatively low and the environment is relatively dry (or have a good drainage system).

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