Comparison of Full-Depth Reclamation with Foamed Asphalt and Full-Depth Reclamation with No Stabilizer in Accelerated Loading Test

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Full-depth reclamation (FDR) with foamed asphalt has been successfully used as a rehabilitation strategy in California since 2001. Long-term field monitoring on several projects and a comprehensive laboratory study resulted in the preparation of guidelines and specification language in 2008. However, the design criteria were essentially empirical, in line with California design procedures for this level of rehabilitation project. Recently, there has been growing interest in the use of cement, engineered emulsion, and no-stabilizer full-depth reclamation strategies in addition to foamed asphalt and in the use of mechanistic design in rehabilitation projects. Consequently, the research initiative was extended to a second phase to include accelerated load testing on an instrumented test track constructed with these four FDR strategies to gather data for the development of performance models that can be included in mechanistic–empirical rehabilitation design procedures. This paper summarizes the results of the first two tests in this accelerated loading study, which compared no stabilizer and foamed asphalt–cement strategies. The foamed asphalt section outperformed the unstabilized section in all measured aspects. The most notable observation was in rutting performance: the unstabilized section reached a terminal rut depth of 13 mm after approximately 490,000 equivalent standard-axle loads had been applied, compared with the foamed asphalt and cement section, which had a rut depth of only 4.3 mm after more than 17.7 million equivalent standard-axle loads. No cracking was observed on either section. The advantages of using foamed asphalt with cement over unstabilized pulverized material are clearly evident from the results.

Full-depth reclamation (FDR) and recycling, or deep in situ recycling, of damaged asphalt concrete pavement to provide an improved base for a new asphalt concrete wearing course is a pavement rehabilitation strategy of increasing interest worldwide. FDR offers a rapid rehabilitation process, with minimal disruption to traffic. Most important, it reuses the aggregates already in the pavement, thereby minimizing the environmental and social impacts associated with extraction and transport of new aggregates.

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The California Department of Transportation (Caltrans) built its first FDR project using foamed asphalt and cement in 2001 in a 15-km pilot study on Route 20 in Colusa County. On the basis of the early apparent advantages of using this technology, Caltrans approved a University of California Pavement Research Center (UCPRC) study in 2004 to investigate the use of this technology under California pavement, material, traffic, and environmental conditions, with a special focus on the rehabilitation of thick, severely cracked asphalt pavements. Most Caltrans FDR projects are undertaken on pavements with thick, cracked asphalt concrete layers, which distinguishes California practice from that of many other states and countries investigating and using this rehabilitation strategy. Pavement technology in South Africa and Australia, where much of the early research was undertaken on FDR with foamed asphalt, typically relies on good-quality granular material or cement-treated base and subbase layers for the primary load-carrying capacity of the pavement, with the thin asphalt concrete (<50 mm) or aggregate surface treatment layers (chip seals) providing little or no structural integrity. Consequently, in those countries the recycled material consists mostly of recycled natural aggregate and cracked cement-stabilized layers, which was accordingly reflected in their research, experience, and guideline documentation at the time at which the California study was initiated (*1–4*). Practice in Europe has been intermediate between that of California and South Africa, with the recycled material generally consisting of a mix of asphalt bound and natural aggregate materials.

The first phase of research focused on foamed asphalt and included a comprehensive laboratory study and long-term field performance monitoring on a number of projects (*5*). The project culminated in 2008 with the preparation of a guideline document (*6*) and specification language. The design criteria were essentially empirical, in line with California design procedures for this level of rehabilitation project. Since the completion of this phase of the research, FDR with foamed asphalt has been widely used as a rehabilitation strategy in the state.

Recently, there has been growing interest in the use of other stabilizers in FDR projects, including cement and engineered emulsion. FDR without a stabilizer (i.e., pulverizing the old asphalt concrete layers and recompacting the material as a new unbound base course) has also been studied. There is also growing interest in using mechanistic design approaches in FDR projects. Consequently, the California research initiative was extended to a second phase to include the additional stabilization strategies and to investigate the development of mechanistic–empirical performance models for them. This research study entails monitoring of additional field projects with the different strategies, laboratory testing, and accelerated load testing on an instrumented test track constructed with the four FDR strategies. Data collected during this research will be used for the development of performance models that can be included in mechanistic–empirical rehabilitation design procedures. This paper summarizes the first two accelerated load tests, conducted on the FDR section with no stabilizer and the FDR section with foamed asphalt and cement.

STUDY OBJECTIVES

The objective of the second phase of the California FDR study is to develop a comprehensive guideline for the rehabilitation design of pavements using full-depth reclamation techniques. This objective is being achieved through the following tasks:

1. A literature review on research related to the topic, with special emphasis on project selection, identifying the most suitable recycling strategy, the most suitable stabilizer or stabilizer combination, mix design, empirical and mechanistic–empirical pavement design, equipment, construction guidelines, construction specifications, and accelerated and long-term performance, with special emphasis on cracking behavior, rutting, freeze–thaw, moisture sensitivity, and densification under traffic.
2. Long-term monitoring of field experiments to assess stiffness, cracking, rutting and densification, freeze–thaw, moisture sensitivity, and other observed distresses.
3. Construction of a test track to compare full-depth cement, foamed asphalt with cement, and engineered asphalt emulsion stabilization against two sections with no stabilization in accelerated load tests. The two sections with no stabilizer have different asphalt concrete surface layer thicknesses.
4. Laboratory testing to refine mix design procedures and identify suitable criteria for mechanistic–empirical design procedures and performance models.
5. Preparation of guidelines for full-depth recycling in California.

This paper discusses the results of the first two accelerated load tests listed in Task 3.

TEST TRACK DESIGN AND CONSTRUCTION

The test track for the accelerated load test was located at the UCPRC in Davis, California. The test track, which is 110 m long and 16 m wide, was originally constructed to assess the performance of seven warm-mix asphalt technologies in rubber-modified asphalt concrete. The test track consisted of 400 mm of aggregate base, surfaced with 60 mm of conventional hot-mix asphalt underneath 60 mm of gap-graded rubberized asphalt concrete. This track was tested over a period of 2 years (*7–9*). After completion of testing, the test track was recycled in place. Conventional full-depth reclamation procedures were followed, with each of the four lanes of the test track subjected to a different stabilization strategy:

Lane 1. No stabilization (FDR-NS),
Lane 2. Engineered emulsion with no active filler (FDR-EE),
Lane 3. Foamed asphalt with cement (FDR-FA), and
Lane 4. Portland cement (FDR-PC).

Milling depth was set at 250 mm for all strategies, which is typical of milling depths on California rehabilitation projects (range, 200 to 300 mm). A 60-mm-thick conventional dense-graded asphalt concrete overlay was placed over the full track. An additional 60-mm layer of asphalt concrete was placed over half the length of Lane 1 (no stabilizer) to quantify the differences in performance of the unstabilized base with different thicknesses of asphalt and to determine whether the unstabilized recycled base with thicker asphalt provided similar performance to a stabilized base with thinner asphalt. It also allowed the collection of data for life-cycle cost and environmental life-cycle analyses. Mix designs were undertaken by the UCPRC in consultation with the California–Nevada Cement Association and manufacturers of engineered emulsions. The mix designs can be summarized as follows:

- Engineered emulsion: 5% by mass of aggregate,
- Foamed asphalt: 3% asphalt and 1.5% cement by mass of aggregate, and
- Portland cement: 5% cement by mass of aggregate.

Conventional FDR construction procedures were followed:

- On the unstabilized section, the recycler and connected water tanker made a single pass to pulverize and mix the material to optimum moisture content for compaction, which included initial rolling with a pad foot roller, followed by vibrating smooth drum, and rubber tired rollers. Final levels were achieved with a grader after initial rolling. Compaction was measured with a nuclear gauge.
- On the engineered emulsion section, the recycling train (binder tanker and recycler) made a single pass. No additional compaction water was added. Compaction and finishing followed the same process as the unstabilized section.
- On the foamed asphalt section, cement was first spread onto the pavement, after which the recycling train (binder tanker, recycler, and water tanker) made a single pass (Figure 1*a*). Some water was added to raise the moisture content to a suitable level for compaction. Compaction and finishing followed the same process as the unstabilized section (Figure 1*b*).
- On the cement section, the cement was first spread onto the existing pavement and then pulverized to the predetermined depth without the addition of any water. A second pass of the recycler with a water tanker added water and remixed the material. This procedure was followed by compaction and finishing using the same process as the unstabilized section.
- The test sections were allowed to cure for 10 days before the asphalt was placed. The FDR-FA and FDR-PC sections were kept moist during the curing period. The FDR-EE section was not watered.

The test section layout is shown in Figure 2. Each accelerated load test section was instrumented with two strain gauges (transverse and longitudinal positions) on top of the base, one pressure cell (embedded to be level with the top of the base), and a multi-depth deflectometer (MDD), with linear variable differential transformers (LVDTs) set at 60 mm (top of the recycled base), 310 mm (interface between recycled and existing layers), 480 mm (bottom of old base), and 750 mm (subgrade). Pavement temperatures were measured with thermocouples on the surface and at 25-mm intervals to a depth of 150 mm. In addition to the embedded instrumentation, surface deflections were measured with an electronic Benkelman beam (road surface deflectometer, RSD) and surface profile was measured with a laser profilometer. Falling weight deflectometer

(a) (b)

FIGURE 1 FDR-FA test track construction.

(FWD) measurements were taken on each section before and after testing to evaluate changes in stiffness caused by traffic and moisture content in the underlying layers. Moisture contents were taken from cores and augured material from the core holes (to subgrade depth) before and after each test.

ACCELERATED LOAD TESTING PROGRAM

Accelerated load testing on the two sections was carried out with a heavy vehicle simulator (HVS). Identical loading programs were followed and are summarized in Table 1. Pavement temperature at 50-mm depth was maintained at 30°C (± 4°C) using an environmental chamber surrounding the equipment. The chamber also kept the sections dry. All trafficking was conducted with a dual-tire configuration (720-kPa tire pressure) in a wandering bidirectional mode. Failure criteria were set at 13-mm average maximum rut or 2.5 m/m^2 of cracking, or both.

Loading on the FDR-FA section was terminated after 1 million load repetitions in the interest of completing the project within the project time and financial constraints.

TEST SECTION PERFORMANCE

Test section performance is summarized below for the various measurements taken. The FDR-FA section outperformed the FDR-NS section for all criteria measured, as expected. Apart from rutting, no surface distresses were observed on either section. No surface cracking was observed on either section. Base and subgrade moisture contents were similar for both sections and did not vary significantly over the period of testing.

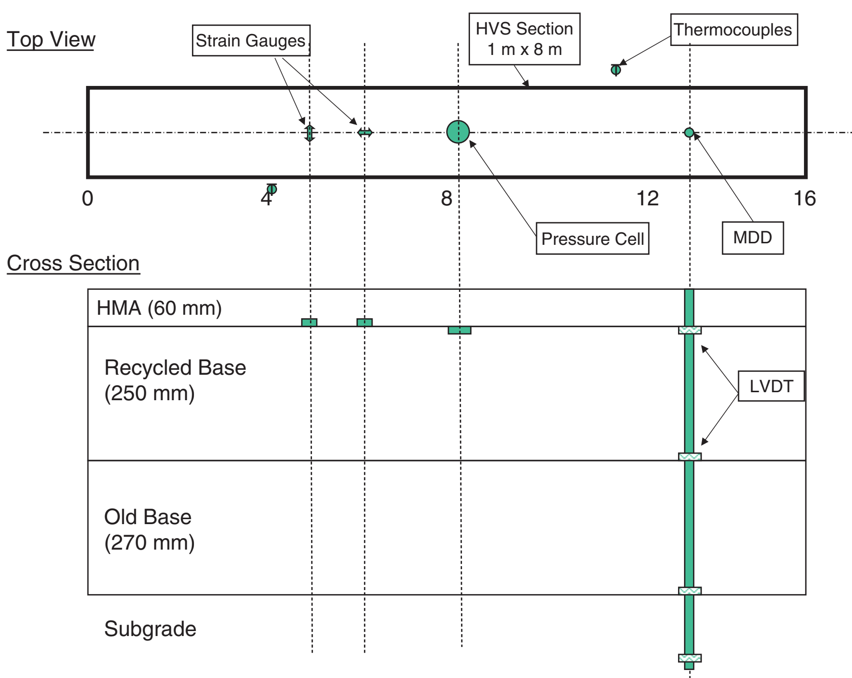


FIGURE 2 Test section layout.

TABLE 1 Loading Program

Phase	Half Axle Wheel Load (kN)	Number of Repetitions		Rut Depth (mm)		Cracking (m/m^2)	
		FDR-NS	FDR-FA	FDR-NS	FDR-FA	FDR-NS	FDR-FA
1	40	300,000	300,000	12.2	1.7	None	None
2	60	200,000	200,000	16.9	2.3	None	None
3	80	165,000	250,000	22.0	3.2	None	None
4	100	na	250,000	na	4.3	na	None
Total		665,000	1,000,000	na	na	na	na
ESALs		4,430,591	17,772,552	na	na	na	na
ESALs to failure		492,155	Did not fail	na	na	na	na

NOTE: na = not applicable; ESALs calculated by (axle load/18,000)$^{4.2}$.

Permanent Deformation on the Surface

Permanent surface deformation (average maximum rut being the measurement from the bottom of the rut to the top of the displaced material on the side of the wheelpath) measured on the two sections is shown in Figure 3. Significantly more rutting was noted on the FDR-NS section compared with the FDR-FA section. The terminal average maximum rut of 13 mm was recorded on the FDR-NS section after 335,000 wheel repetitions (300,000 at 40-kN half-axle wheel load and 35,000 at 60 kN), which equates to 492,155 equivalent standard-axle wheel loads (ESALs, see Table 1). The average maximum rut recorded on the FDR-FA section after 1 million load repetitions (equivalent to 17,772,552 ESALs) was about 4.5 mm. The FDR-NS section was also load sensitive, with each load change resulting in an embedment phase and increased rut rate per load repetition. Performance on the FDR-FA section did not appear to be load sensitive. A contour plot of the surface deformation is shown in Figure 4. Rutting on both sections appeared to be predominantly downward compression and densification, with very little displaced material on the edges of the wheelpath.

Permanent Deformation in the Underlying Layers

Permanent deformation in the underlying layers, recorded with MDDs compared with the surface layer (recorded with a laser profilometer) is shown in Figure 5. Some LVDT failures occurred under trafficking and consequently a full set of data could not be collected. The MDD measurements were consistent with the laser profilometer measurements. On the FDR-NS section, most of the deformation occurred in the recycled base. Because of the LVDT failure on the FDR-FA section, it is not clear where the limited permanent deformation occurred, but it is likely to have been distributed between the surfacing and top of the recycled layer. A forensic investigation will be undertaken on completion of all testing.

Tensile Strain at the Bottom of the Asphalt Concrete Layer

Figure 6 shows the comparison of peak traffic-induced tensile strain at the bottom of the asphalt concrete layer for both sections. Longitudinal strain remained fairly constant throughout the test, apart

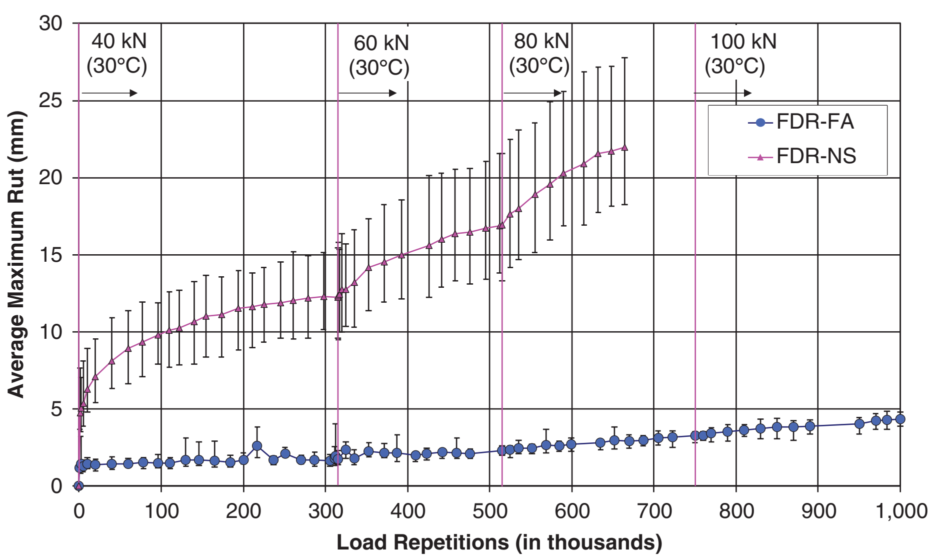


FIGURE 3 Surface permanent deformation.

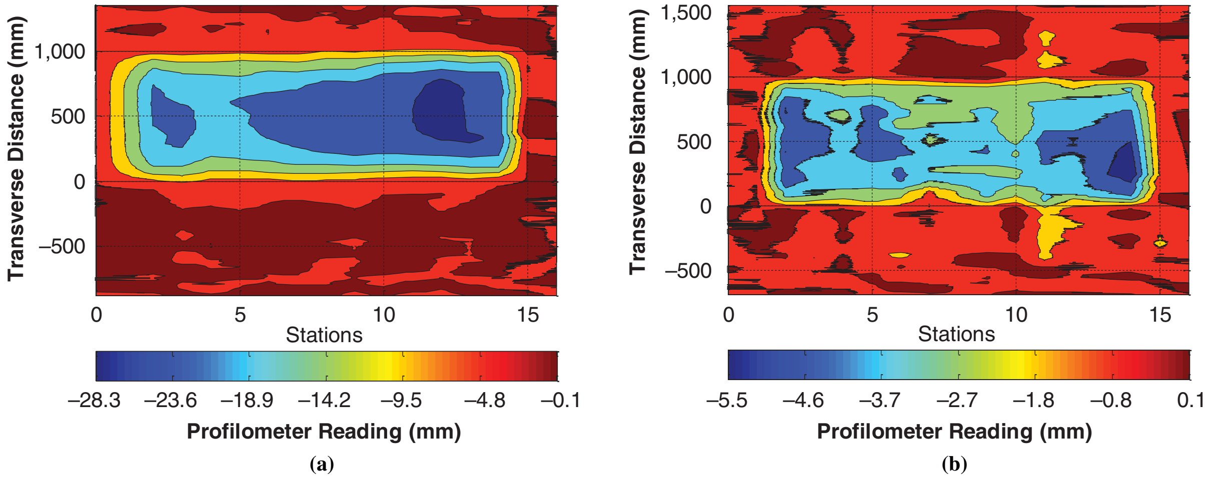


FIGURE 4 Contour plots of surface permanent deformation for (*a*) FDR-NS Section 672HB with 0.713 million repetitions and (*b*) FDR-FA Section 673HB with 1 million repetitions (negative is downward deformation).

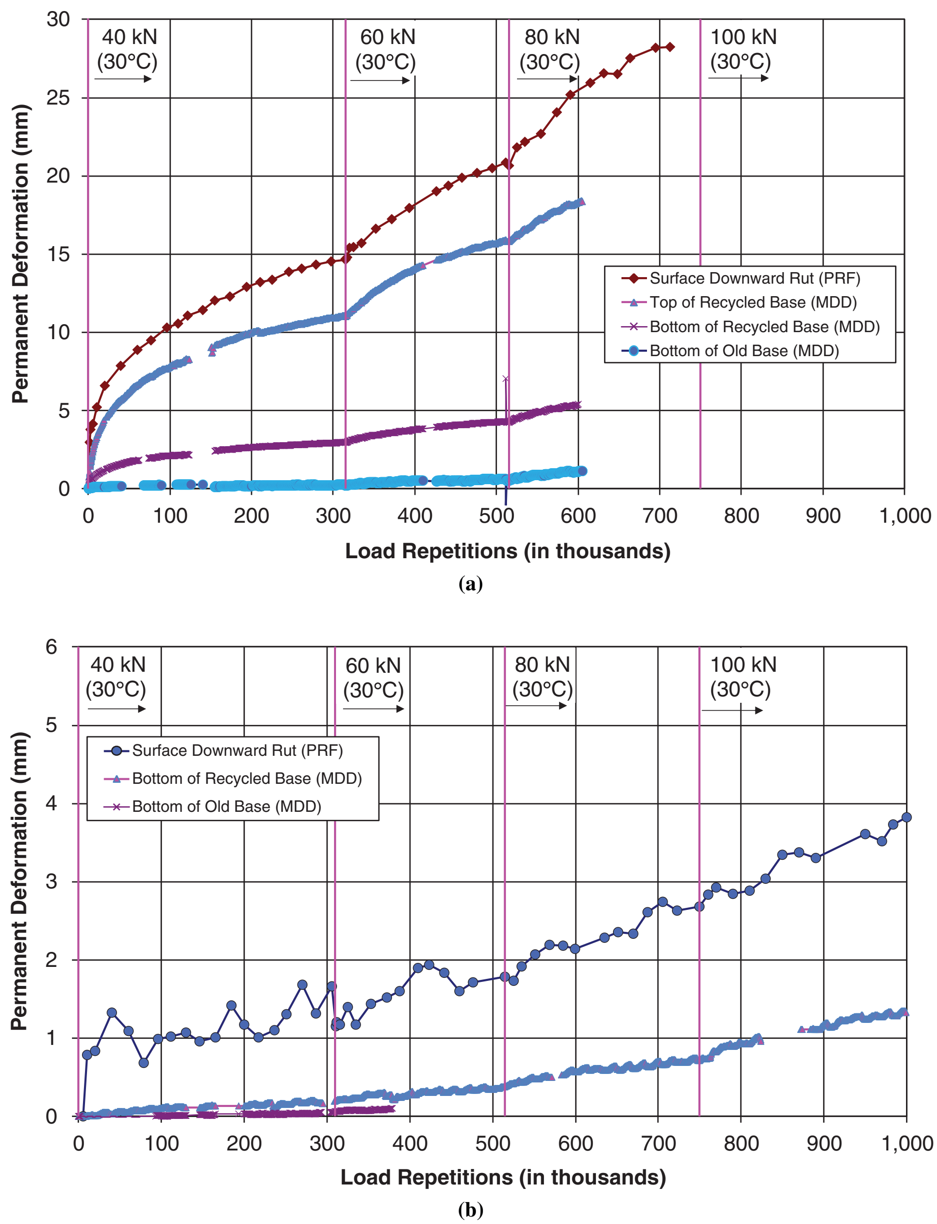


FIGURE 5 Permanent deformation in surface and underlying layers: (*a*) FDR-NS and (*b*) FDR-FA (PRF = profilometer; different *y*-axis scales.)

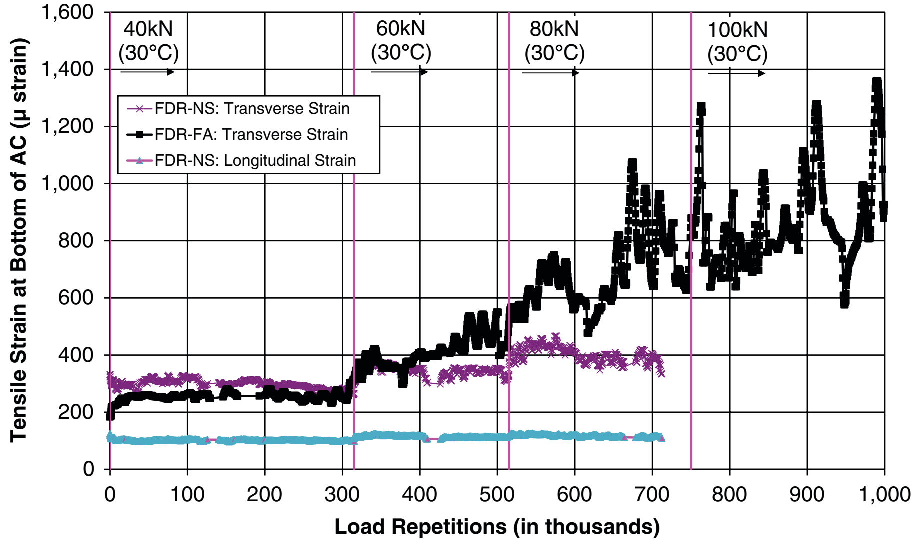


FIGURE 6 Tensile strain at the bottom of asphalt concrete layers.

from a small decrease during the first 20,000 load repetitions and some small spikes when the wheel load was increased. The figure indicates relatively constant transverse strain readings for the first 200,000 load repetitions for the FDR-NS section, with a slight decrease thereafter until the first load change, suggesting gradual layer stiffening resulting from densification caused by the HVS trafficking. Strains increased after each load change but then showed similar decreasing trends, indicating continued densification under loading. On the FDR-FA section, initial transverse strains were similar to those recorded on the FDR-NS section during the first part of the testing, apart from a sharp increase in the first 20,000 load repetitions, attributed to initial breakdown of the cement bonds. After the wheel load increases, transverse strain in the FDR-FA section continued to increase over time, suggesting further weakening of the structure (probably attributed to microcracking in the recycled base) caused by trafficking. Variability in the strain measurements was attributed to a combination of temperature changes and their effect on microcracks under the strain gauge. No surface distresses associated with the increase in strain measurements in the recycled layer were noted during the course of the study.

Vertical Pressure at the Top of the Recycled Base

Figure 7 shows the comparison of traffic-induced vertical pressure at the top of the recycled base layer for the FDR-NS and FDR-FA sections. Pressure readings were stable and sensitive to load change for the duration of the FDR-NS test and for most of the FDR-FA test. Initial pressure was higher on the FDR-FA section compared with the FDR-NS section, which was expected on the basis of

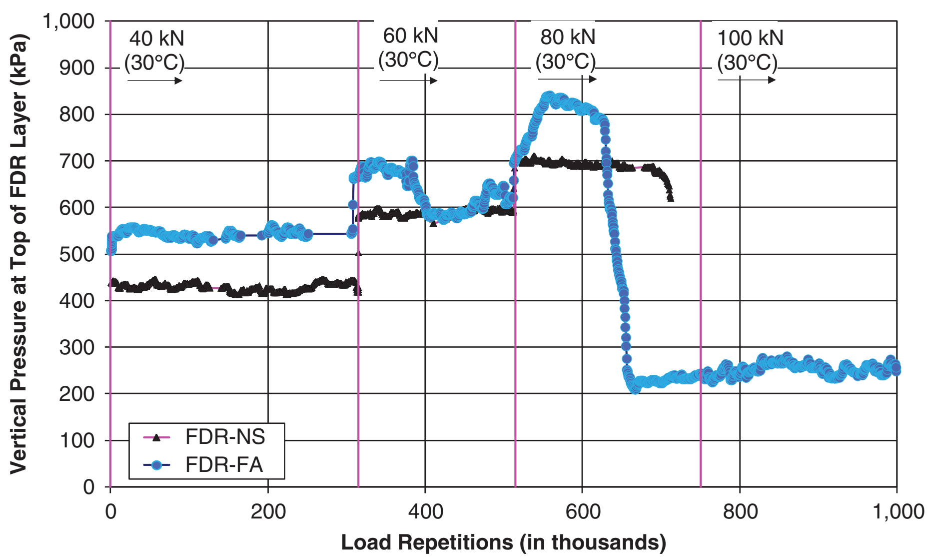


FIGURE 7 Traffic-induced vertical pressure at the top of recycled layers.

layer elastic theory and considering the much higher stiffness of the FDR-FA section. Increases in recorded pressures occurred after the first two load changes on both sections, as expected. A rapid increase followed by a significant drop in pressure was recorded on the FDR-FA section between 520,000 and 620,000 load repetitions. The reason for this occurrence is unclear, but it is assumed that the instrumentation was either damaged or support conditions under the pressure cell changed.

Elastic Deflection in the Underlying Layers

Figure 8 shows the history of in-depth elastic deflections, measured by the LVDTs in the MDDs, for the FDR-NS and FDR-FA sections. These readings are consistent with the surface deflections measured with the RSD shown in Figure 9. Variation between the two sets of readings was attributed to the different locations of the instruments. On the FDR-NS section, deflections measured at the top of the recycled base decreased with the increasing number of load repetitions, suggesting some stiffening in the recycled layer, attributed to HVS trafficking. On the FDR-FA section, there was a consistent increase in vertical deflections measured at the different depths, suggesting a decrease in overall stiffness of the pavement structure over the duration of the test.

Surface Deflection Measured with RSD

Figure 9 compares elastic surface deflections measured with a RSD on the two sections under a 40-kN half-axle load. Note that RSD measurements were taken under a creep-speed load and will not be the same as those recorded under the trafficking load.

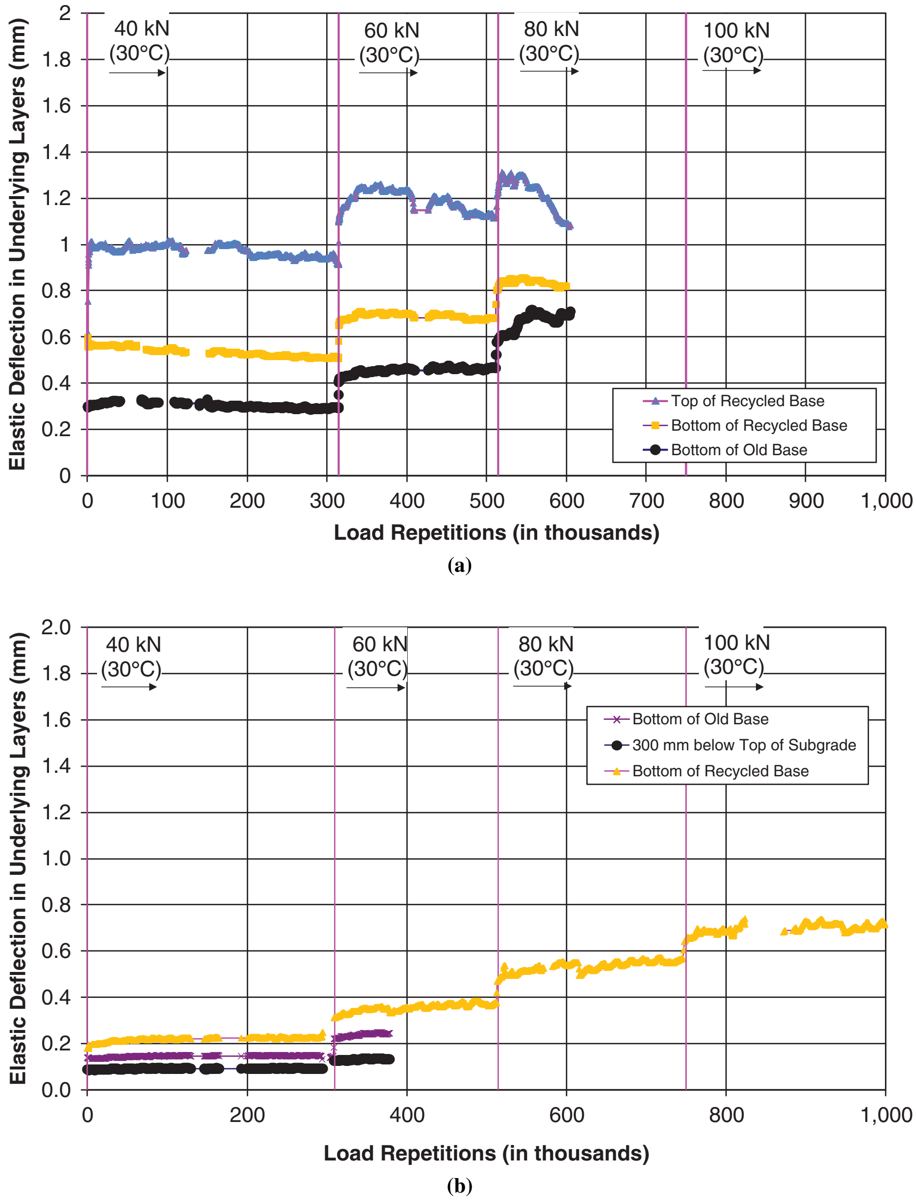


FIGURE 8 Elastic deflection in underlying layers measured with MDD: (*a*) FDR-NS and (*b*) FDR-FA.

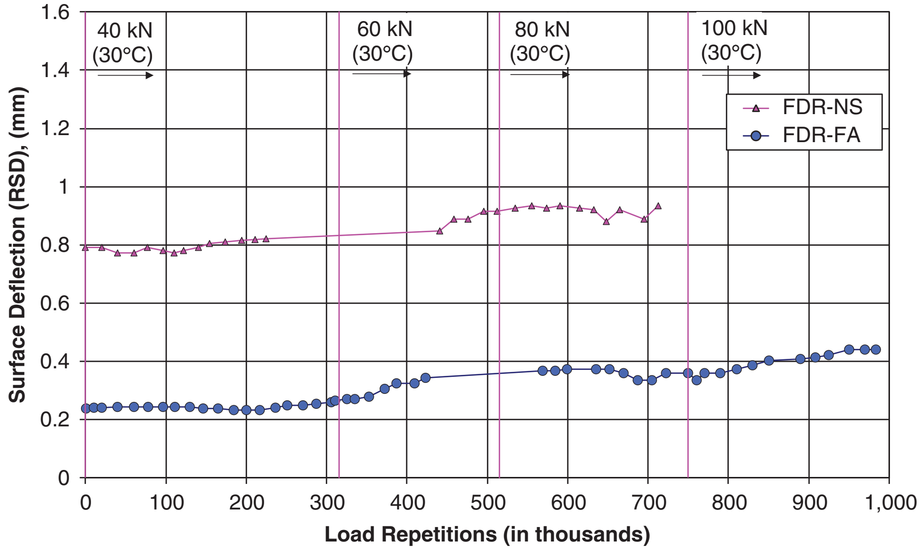


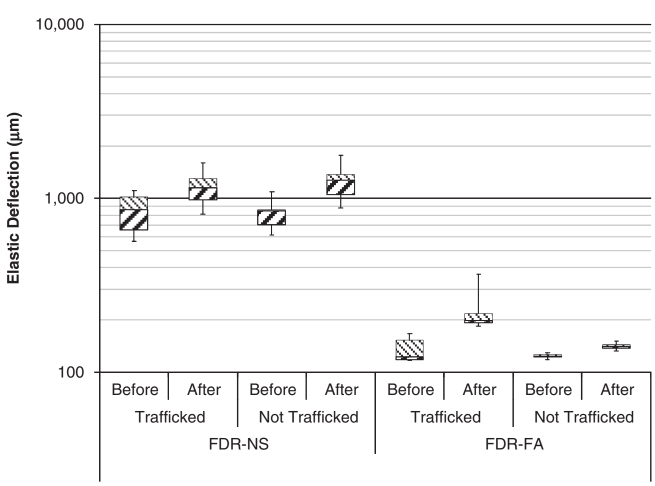
FIGURE 9 Surface deflection measured with RSD.

Deflections were notably higher on the FDR-NS section, as expected. Slight increases in absolute surface deflection were recorded on both sections over the duration of the tests. The amount of increase was similar for both sections after 665,000 load repetitions (~0.13 mm), when testing on the FDR-NS section was stopped. Deflection continued to increase at a constant rate on the FDR-FA section, indicating that no significant damage had occurred in the asphalt concrete layer when trafficking was stopped. There were no significant changes in deflection measurements after the load changes.

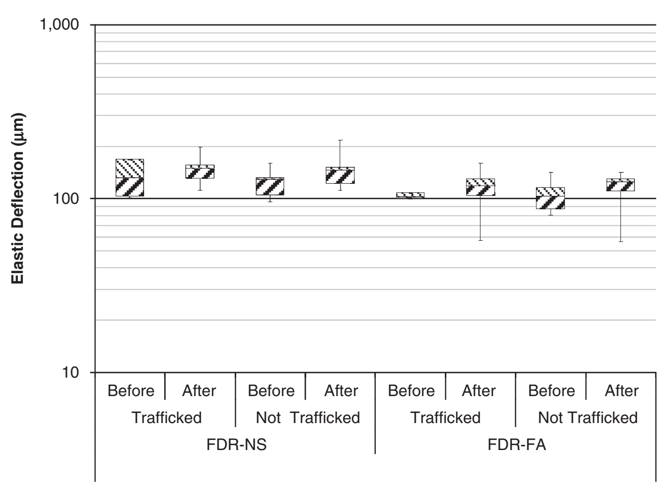
FWD Measurements Before and After Testing

FWD testing was conducted on each section before and after HVS testing to evaluate the change in stiffness caused by trafficking. Testing was undertaken on both the trafficked and adjacent untrafficked areas (i.e., 5 m on either end of the 8-m test section) at 500-mm intervals. Two sets of tests were undertaken on each day to obtain a temperature range. Results are summarized in Figure 10. The results were consistent with the RSD measurements discussed in the previous section, with both sections showing higher deflections on the surface after completion of trafficking. The average surface deflection on the FDR-NS section increased by 190 µm after trafficking, compared with an increase of 40 µm on the FDR-FA section. Deflections in the subgrade did not appear to change during the course of testing and were similar on both sections.

The recycled layer stiffnesses were backcalculated from the deflection measurements using the CalBack software package. Results are summarized in Figure 11. The stiffness of the unstabilized recycled layer was very low and did not decrease



(a)



(b)

FIGURE 10 Elastic deflection measured with FWD: (*a*) recycled surface layers determined from D1 sensor and (*b*) subgrade determined from D6 sensor, 925 mm from D1 sensor.

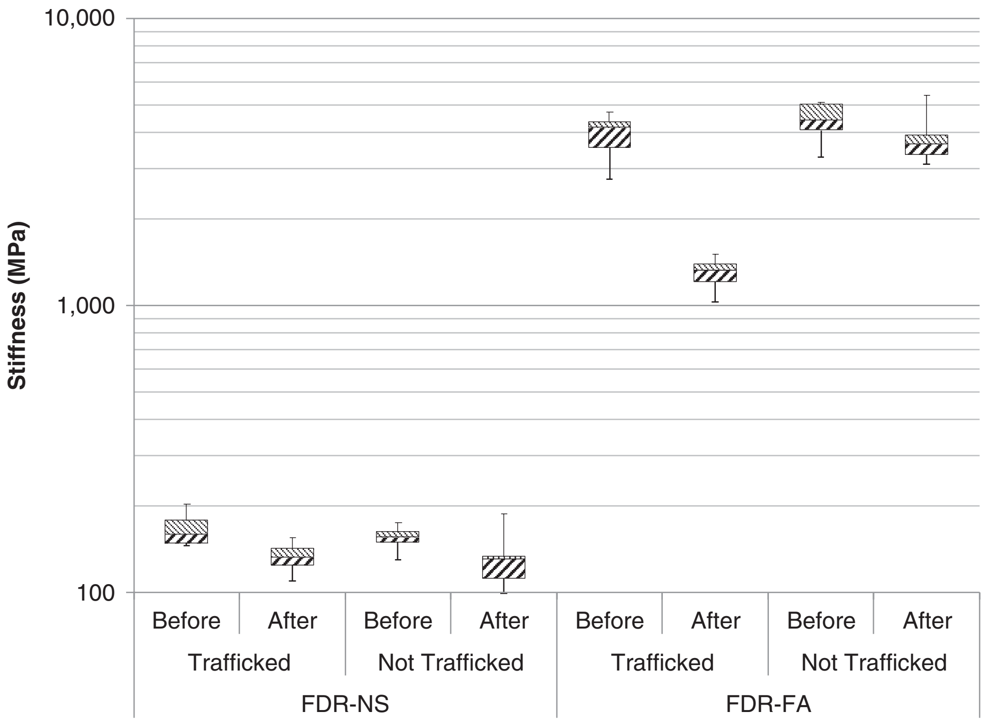


FIGURE 11 Backcalculated stiffness in recycled layers (from FWD).

significantly (about 30 MPa) after trafficking. The stiffness of the foamed asphalt–cement layer was orders of magnitude stiffer than the unstabilized layer, consistent with data collected on a range of field projects. There was a notable drop (~2,600 MPa) in stiffness of the recycled layer after trafficking, which was attributed to some breaking of the cement bonds under loading and consequent microcracking. However, stiffnesses were still significantly higher compared with the untrafficked section after completion of trafficking, despite the significantly higher number of ESALs applied.

SUMMARY AND CONCLUSIONS

FDR-FA has been successfully used as a rehabilitation strategy in California since 2001. Long-term field monitoring on several projects combined with a comprehensive laboratory study resulted in the preparation of guidelines and specification language in 2008. However, the design criteria were essentially empirical, in line with California design procedures for this level of rehabilitation project. Recently, there has been growing interest in the use of cement, engineered emulsion, and no-stabilizer full-depth reclamation strategies in addition to foamed asphalt and in the use of mechanistic design in a greater range of rehabilitation projects. Consequently, the research initiative was extended to a second phase to include accelerated load testing on an instrumented test track constructed with these four FDR strategies to gather data for the development of performance models that can be included in mechanistic–empirical rehabilitation design procedures. This paper summarizes the results of the first two tests in this accelerated loading study, which compared no stabilizer and foamed asphalt with cement strategies under the same 60-mm asphalt concrete surfacing layer. The foamed asphalt section outperformed the unstabilized section in all aspects that were measured. Key results include the following:

- A terminal rut depth of 13 mm was recorded on the FDR-NS section after approximately 490,000 ESALs had been applied, compared with only 4.3 mm on the FDR-FA section after more than 17.7 million ESALs had been applied. Testing was halted on the FDR-FA section at this point in the interest of testing the other sections within the time and financial constraints of the project. Permanent deformation in the recycled layers was consistent with the surface measurements.
- Measured and backcalculated stiffnesses were significantly higher on the FDR-FA section compared with the FDR-NS section. Although the stiffness dropped considerably in the recycled layer on the FDR-FA section after trafficking, it was still orders of magnitude higher than that on the FDR-NS section, despite having been subjected to 17 million more ESALs.
- Elastic deflection at the bottom of the FDR-FA layer after completion of testing (17.7 million ESALs) was approximately the same as that at the bottom of the FDR-NS layer after 490,000 ESALs. The rate of change in deflection was, however, slightly higher on the FDR-FA section, which is consistent with stabilized layers containing cement.
- No cracking was observed on either section.

The advantages of using foamed asphalt with cement over unstabilized pulverized material are clearly evident from the results.

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