# Comparison of Full-Depth Reclamation with Portland Cement and Full-Depth Reclamation with No Stabilizer in Accelerated Loading Test

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**Full-depth reclamation (FDR) with or without various stabilizers has been successfully used as a rehabilitation strategy in California since 2001. Long-term field monitoring on several FDR projects that used foamed asphalt with portland cement as the stabilizer combined with a comprehensive laboratory study resulted in the preparation of guidelines and specification language for this rehabilitation strategy in 2008. However, the design criteria were essentially empirical, in line with California design procedures for a rehabilitation project of this level. Recently, interest has grown in the use of cement, engineered emulsion, and no-stabilizer FDR 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 including accelerated load testing on an instrumented test track constructed with these four FDR strategies to gather data for developing performance models that could be included in mechanistic–empirical rehabilitation design procedures. This paper summarizes results of the second set of tests in this accelerated loading study, which compared no-stabilizer and portland cement strategies. The portland cement stabilized section outperformed the unstabilized section in all measured aspects. The most notable observation was in relation to rutting performance; the unstabilized section reached a terminal rut depth of 13 mm after approximately 490,000 equivalent standard axle loads were applied, compared with the cement section, which had a rut depth of only 3.0 mm after more than 43.3 million equivalent standard axle loads. No cracking was observed on either section at the end of testing. Advantages of using portland cement over unstabilized pulverized material are clearly evident from the results.**

Full-depth reclamation or full-depth recycling (FDR), 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 with foamed asphalt combined with cement in 2001 in a 15-km (9.5-mi) pilot study on Route 20 in Colusa County. On the basis of 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 (*1*). Most Caltrans FDR projects are undertaken on pavements in this condition; that fact 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 (FDR-FA), typically relies on good quality granular material or cement-treated base and subbase layers for the primary load-carrying capacity of the pavement The thin asphalt concrete [<50 mm (2 in.)] or aggregate surface treatment layers (chip seals) used provide little or no structural integrity; consequently, in those countries the recycled material consists mostly of good quality recycled natural aggregate, cracked cement-stabilized layers, or both. That fact was accordingly reflected in their research, experience, and guideline documentation at the time the California study was initiated (*2–5*). Practice in Europe has been intermediate between that of California and South Africa; the recycled material generally consists 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 (*1*). The project culminated in 2008 with the preparation of a guideline document and specification language (*6*). The design criteria were essentially empirical, in line with California design procedures for a rehabilitation project of this level. Since the completion of this phase of the research, FDR-FA has been widely used as a rehabilitation strategy in the state.

Recently, interest has been growing in the use of other stabilizers in FDR projects, including portland cement (FDR-PC) and engineered emulsion (FDR-EE). FDR without a stabilizer (FDR-NS) (i.e., pulverizing the old asphalt concrete layers and recompacting the material as a new unbound base course) has also been experimented with. 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 (*7*).

This research study entails monitoring 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. A comprehensive literature review on local and international research on the topic found that no similar published studies have been undertaken, with most research limited to field studies on uninstrumented test sections, laboratory testing, or both (*7*).

Results from the first two accelerated load tests conducted on the FDR section with no stabilizer (FDR-NS) and the FDR with foamed asphalt and cement (FDR-FA) were recently published (*8*). This paper summarizes the results of the second set of accelerated loading tests conducted on the FDR with portland cement (FDR-PC). The results of the FDR-NS testing are included for performance comparison.

## STUDY AND PAPER 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 FDR techniques. This objective is being achieved through the following tasks (*7*):

1. Literature review on research related to the topic, with special emphasis on selecting projects, identifying the most suitable recycling strategy, and identifying 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 FDR with foamed asphalt and cement, portland cement, and engineered asphalt emulsion stabilization against two sections with no stabilization in accelerated load tests (with the two sections with no stabilizer having different asphalt concrete surface layer thicknesses);
4. Accelerated load testing of each recycling strategy;
5. Laboratory testing to refine mix-design procedures and identify suitable criteria for mechanistic–empirical design procedures and performance models; and
6. Preparation of guidelines for full-depth recycling in California.

The objective of this paper is to provide a summary of Tasks 3 and 4 above. The paper includes a summary of the test track design and construction, test track instrumentation and measurements, accelerated load testing criteria, and results of accelerated load tests on the FDR-NS and FDR-PC test sections (*7*).

## 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 (361 ft) long and 16 m (53 ft) wide, was originally constructed to assess the performance of seven warm-mix asphalt technologies in rubber modified asphalt concrete. The test track consisted of 450 mm (1.5 ft) of aggregate base (AB), surfaced with 60 mm (0.2 ft) of conventional hot-mix asphalt underneath 60 mm of gap-graded rubberized asphalt concrete. This track was tested during a period of 2 years (*9–11*). After testing was complete, the test track was recycled in place. Conventional FDR procedures were followed; each of the four lanes of the test track were subjected to a different stabilization strategy (*7*):

Lane 1. No stabilization, called FDR-NS in this paper;
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 (10 in.) for all strategies, which is typical of milling depths on California rehabilitation projects [200 to 300 mm (8 to 12 in.)]. 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 performance similar 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 to determine optimal stabilizer contents in line with current Caltrans stabilized base design requirements. The mix designs can be summarized as follows (*7*):

- 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 (*7*):

- 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 a 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 for 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. Some water was added to raise the moisture content to a level suitable for compaction. Compaction and finishing followed the same process as for the unstabilized section.
- On the portland cement section, the cement was first spread onto the existing pavement (Figure 1*a*) 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 (Figure 1*b*). This process was followed by compaction and finishing with the same process as for 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

(a)

(b)

FIGURE 1 FDR-PC test track construction: (*a*) spreading cement and (*b*) water addition and mixing.

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 multidepth deflectometer, with linear variable differential transformers set at 60 mm (2.4 in.) (top of recycled base), 310 mm (12.2 in.) (interface between recycled and existing layers), 480 mm (18.9 in.) (bottom of old AB), and 750 mm (30 in.) (subgrade). Pavement temperatures were measured with thermocouples on the surface and at 25-mm (1-in.) intervals to a depth of 150 mm (6 in.) (*7*).

In addition to the embedded instrumentation, surface deflections were measured with an electronic Benkelman beam (road surface deflectometer) and the surface profile was measured with a laser profilometer. Falling weight deflectometer measurements were taken on each section before and after testing to evaluate changes in stiffness

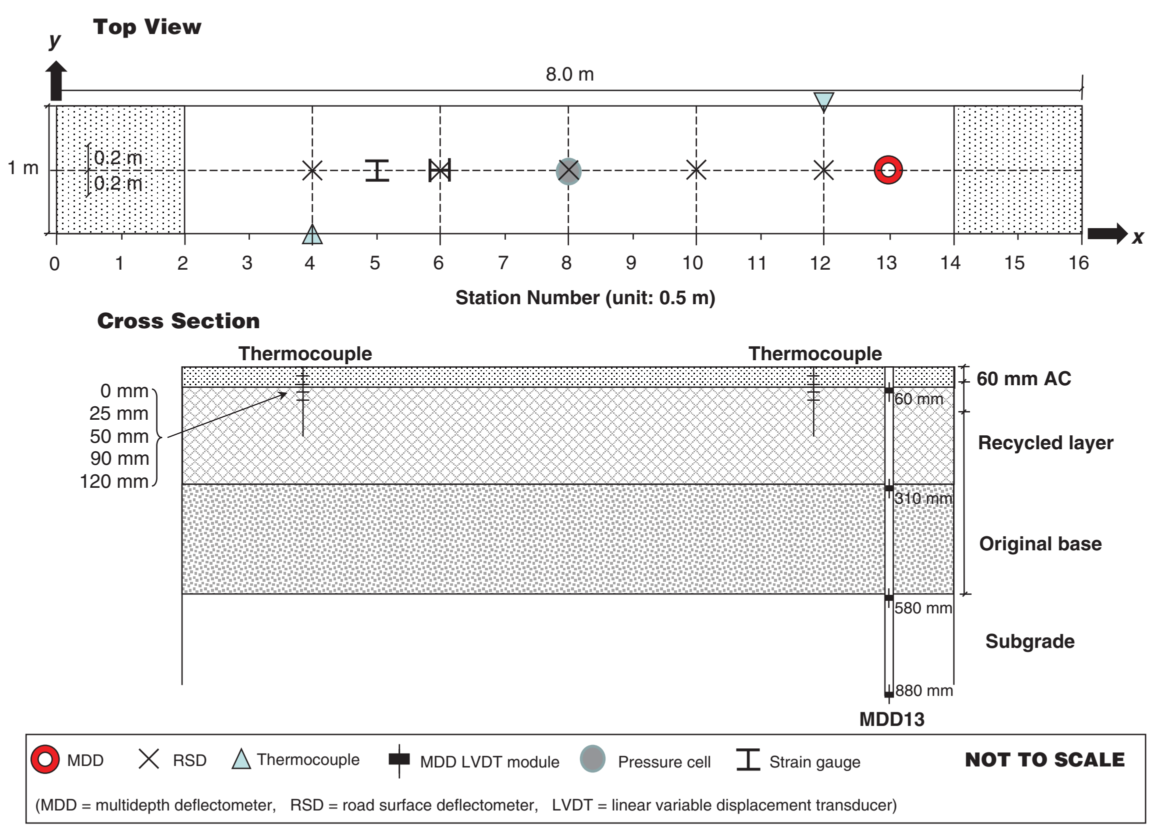


FIGURE 2 Test section layout (AC = asphalt concrete).

TABLE 1 Loading Program

| Phase | Half-Axle Wheel Load (kN) | Number of Repetitions | | Rut Depth (mm) | | Cracking (m/m$^2$) | |
|---|---|---|---|---|---|---|---|
| | | FDR-NS[a] | FDR-PC[b] | FDR-NS | FDR-PC | FDR-NS | FDR-PC |
| 1 | 40 | 300,000 | 300,000 | 12.2 | 1.3 | None | None |
| 2 | 60 | 200,000 | 200,000 | 16.9 | 1.5 | None | None |
| 3 | 80 | 198,000 | 250,000 | 23.0 | 1.7 | None | None |
| 4 | 100 | — | 795,565 | — | 3.0 | — | None |

NOTE: — = not tested.
[a]Total = 713,000; equivalent standard axle loads (ESALs) calculated by (axle load/18,000)$^{4.2}$ = 5,052,104; ESALs to failure = 492,155.
[b]Total = 1,560,565; ESALs = 43,334,874; ESALs did not fail.

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 (*7*).

## 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 (*7*). Pavement temperature at a depth of 50 mm (2 in.) was maintained at 30°C (±4°C) (86°F ± 7°F) by using an environmental chamber surrounding the equipment. This temperature was selected to assess rutting and cracking potential in the recycled layer under typical pavement conditions. Lower or higher asphalt temperatures could have led to premature cracking or rutting failure of the asphalt concrete, respectively. The chamber also kept the sections dry. All trafficking was conducted with a dual-tire configuration [720 kPa (104 psi) tire pressure] in a wandering bidirectional mode. Failure criteria were set at 13 mm (~0.5 in.) average maximum rut, or 2.5 m/m$^2$ (0.8 ft/ft$^2$) of cracking, or both, in line with Caltrans limits for these distresses. Loading on the FDR-PC section was terminated after 1.56 million load repetitions in the interests of completing the project within the project time and financial constraints.

## TEST SECTION PERFORMANCE

Test section performance is summarized below in regard to the various measurements taken (*7*). The FDR-PC 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 of the sections. Base and subgrade moisture contents were similar for both sections and did not vary significantly during the testing period.

### Permanent Deformation on 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, and permanent deformation being the measurement from the original surface to the bottom of the rut) measured on the two sections is shown in Figure 3.

Significantly more rutting was noted on the FDR-NS section compared with the FDR-PC 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 (9,000 lb) half-axle wheel load and 35,000 at 60 kN (13,500 lb)], which equates to 492,155 equivalent single-axle loads (ESALs) (see Table 1). Testing continued on the

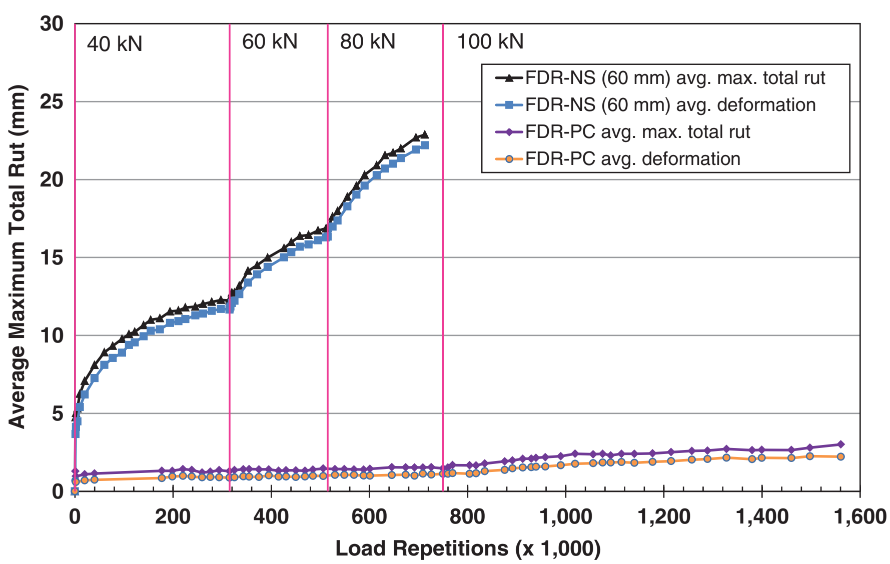


FIGURE 3 Permanent surface deformation (avg. max. = average maximum).

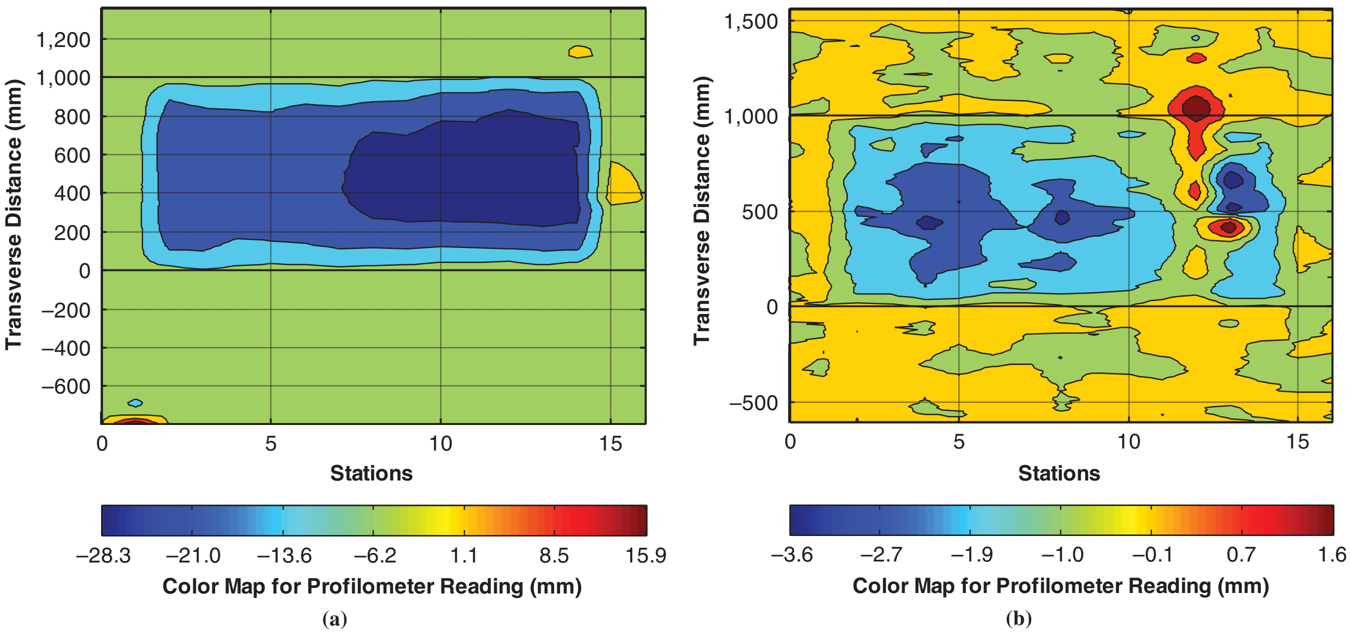


FIGURE 4 Contour plots of surface permanent deformation (negative is downward deformation): (*a*) FDR-NS, end of test (713,000 load repetitions), and (*b*) FDR-PC, end of test (1,560,565 load repetitions).

FDR-NS section to collect additional data at the higher load levels. Average maximum rut recorded on the FDR-PC section after 1.56 million load repetitions (equivalent to 43,334,874 ESALs) was about 3.0 mm (0.12 in.). 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-PC 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 Underlying Layers

Permanent deformation in the underlying layers, recorded with multidepth deflectometers, compared with the surface layer (recorded with a laser profilometer) is shown in Figure 5 (AB indicates top of the existing AB and bottom of recycled layer.). The multidepth deflectometer measurements were consistent with the laser profilometer measurements. On the FDR-NS section, most of the deformation occurred in the recycled base. Very little deformation was measured on the FDR-PC section, with small contributions (<1.0 mm) attributed

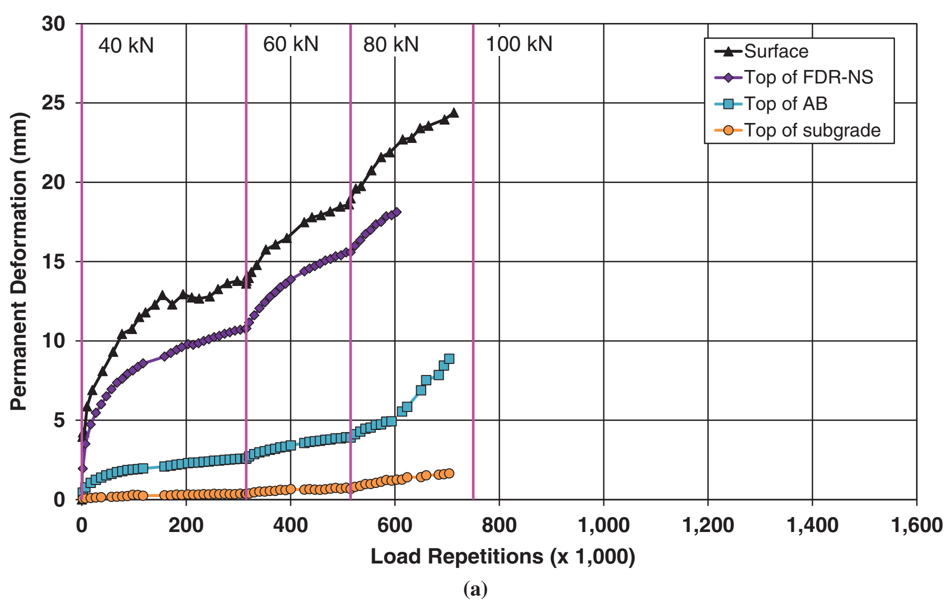


FIGURE 5 Permanent deformation in surface and underlying layers: (*a*) FDR-NS.

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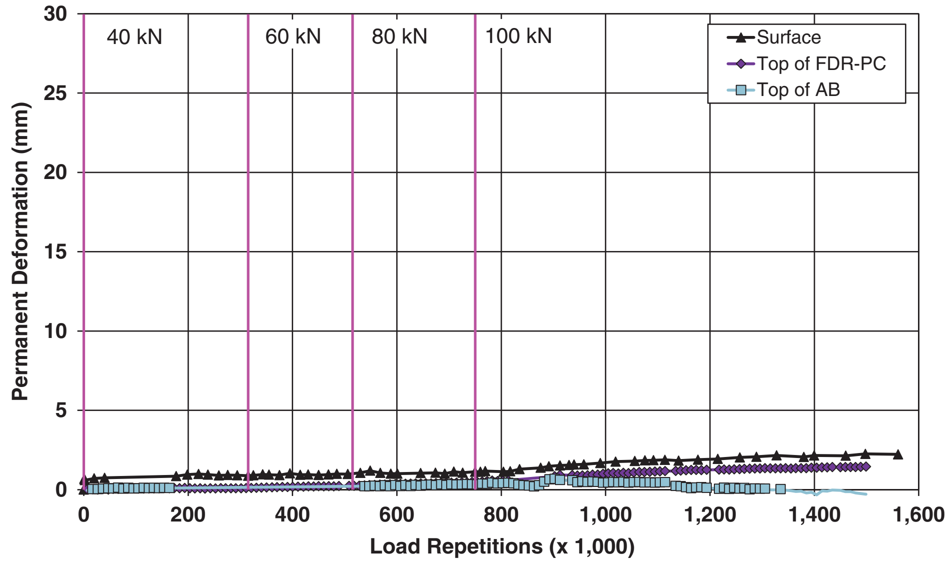



(b)

FIGURE 5 *(continued)* **Permanent deformation in surface and underlying layers: (*b*) FDR-PC.**

to each layer. The multidepth deflectometer module in the subgrade of the FDR-PC section was damaged during testing. Since no deformation was recorded in the recycled or underlying AB layers, it was concluded that no deformation occurred in the subgrade.

## Tensile Strain at Bottom of 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 on both sections, apart from a small decrease on the FDR-NS section 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. Strains were generally low on the FDR-PC section, this finding being attributed to the very stiff recycled layer underneath the strain gauges. Longitudinal strains were slightly higher than the transverse strains and increased after each load change. The longitudinal strains also showed some variability after the load change to 100 kN (22,500 lb), which was attributed to a combination of temperature changes and their effect on microcracks under the strain gauge, related to damage in the layer caused by the heavier loads. Transverse strains remained constant throughout the first three loading cycles [40 kN, 60 kN, and 80 kN (9,000, 13,500, and 18,000 lb)], but increased slightly after

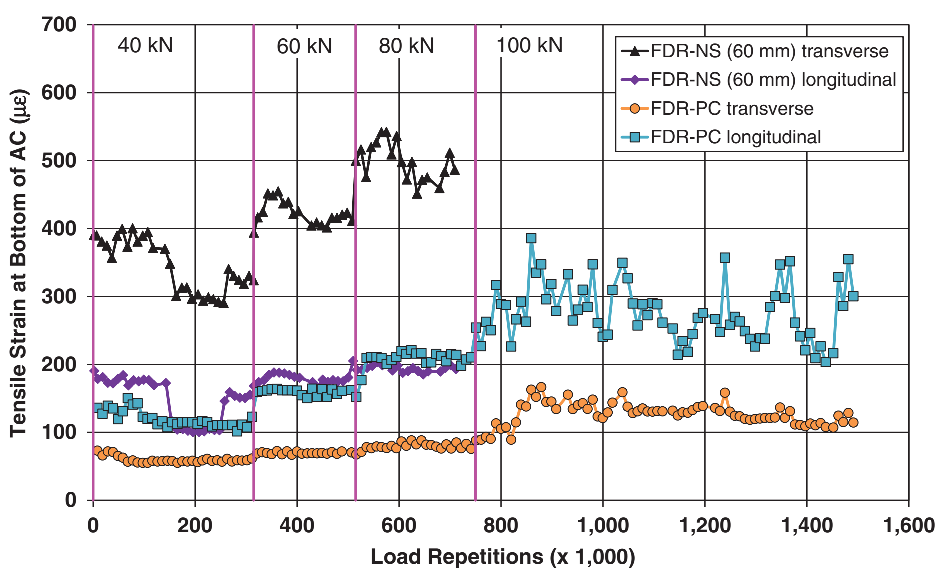



FIGURE 6 **Tensile strain at bottom of asphalt concrete (AC) layers.**

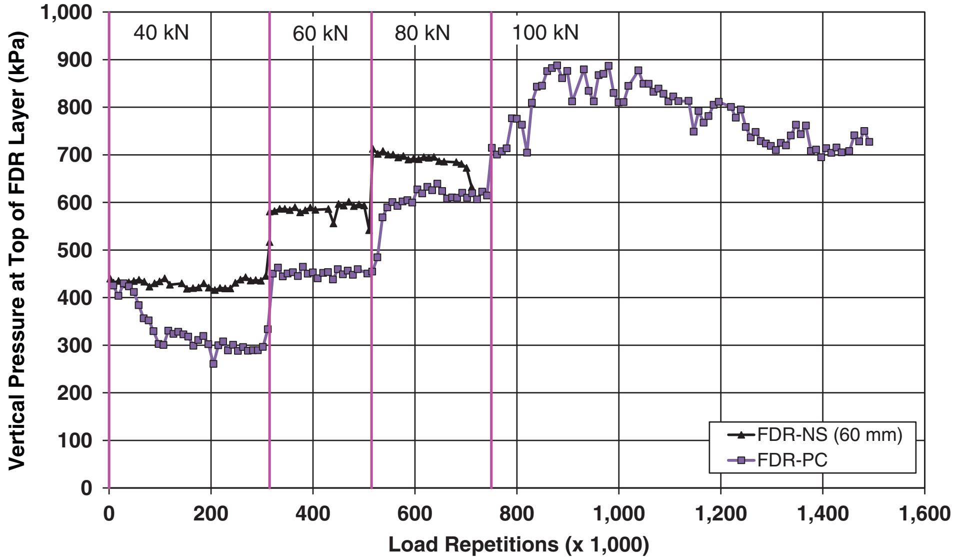



FIGURE 7 Traffic-induced vertical pressure at top of recycled layers.

the load change to 100 kN, indicating that some damage (e.g., microcracks) had resulted from the heavier loading. However, transverse strain did not continue to increase, indicating that the integrity of the layer was not deteriorating at the time the testing was halted. 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 Top of 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-PC sections. Pressure readings were stable and sensitive to load change for the duration of the FDR-NS test and for most of the FDR-PC test. Initial pressure dropped considerably on the FDR-PC section, which was unexpected given that layer elastic theory would suggest higher pressures considering the much higher stiffness of the FDR-PC section. This anomaly could be attributed to movement of the gauge. After the first load change, the pressure readings appeared to stabilize and increases were consistent with later load changes. Variability and a reduction in recorded pressures after the load change to 100 kN was attributed to problems with the instrument at the higher load levels.

## Surface Deflection Measured with Road Surface Deflectometer

Figure 8 compares elastic surface deflections measured with a road surface deflectometer on the two sections under a 40-kN half-axle load. Road surface deflectometer measurements were taken under a creep-speed load and will not be the same as those recorded under the trafficking load. Deflections were notably higher on the FDR-NS

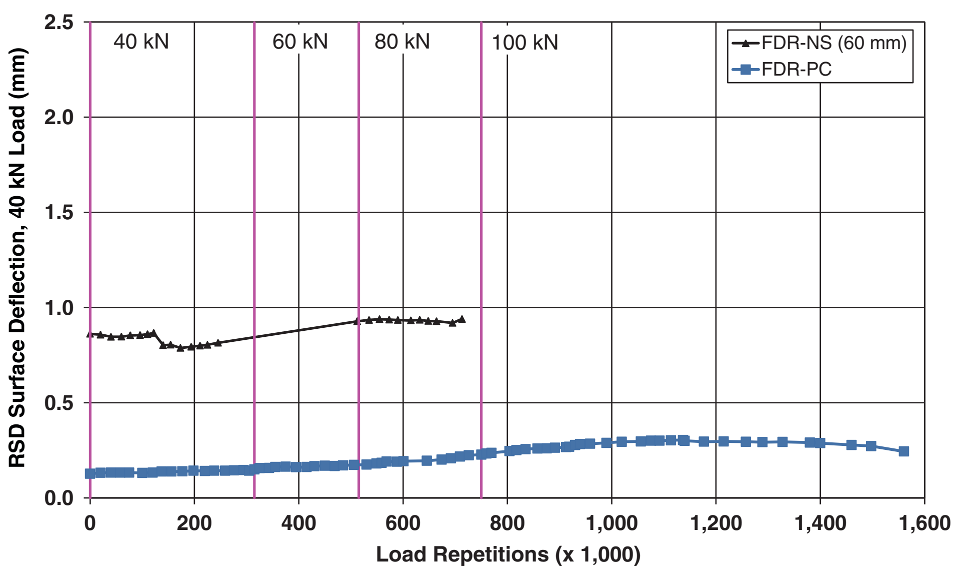
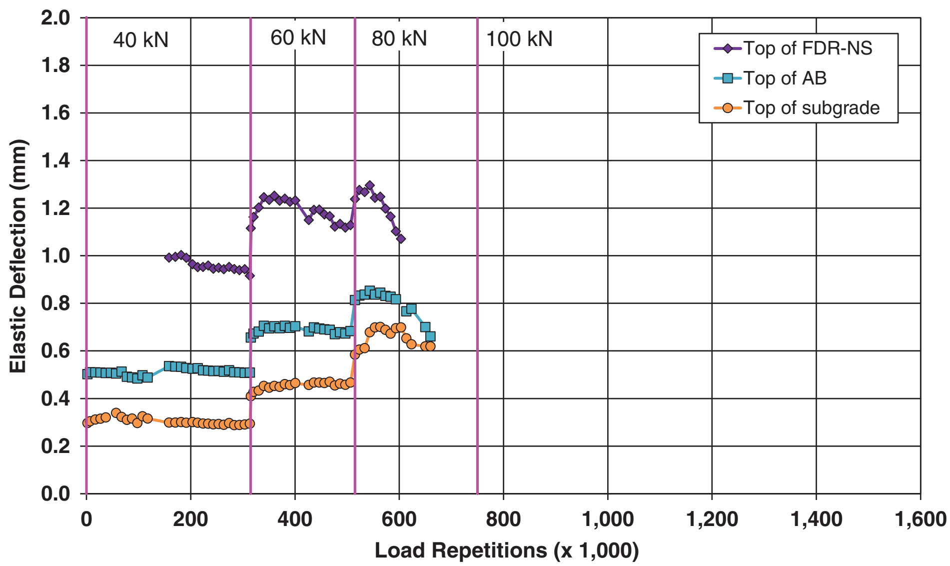



FIGURE 8 Surface deflection measured with road surface deflectometer (RSD).

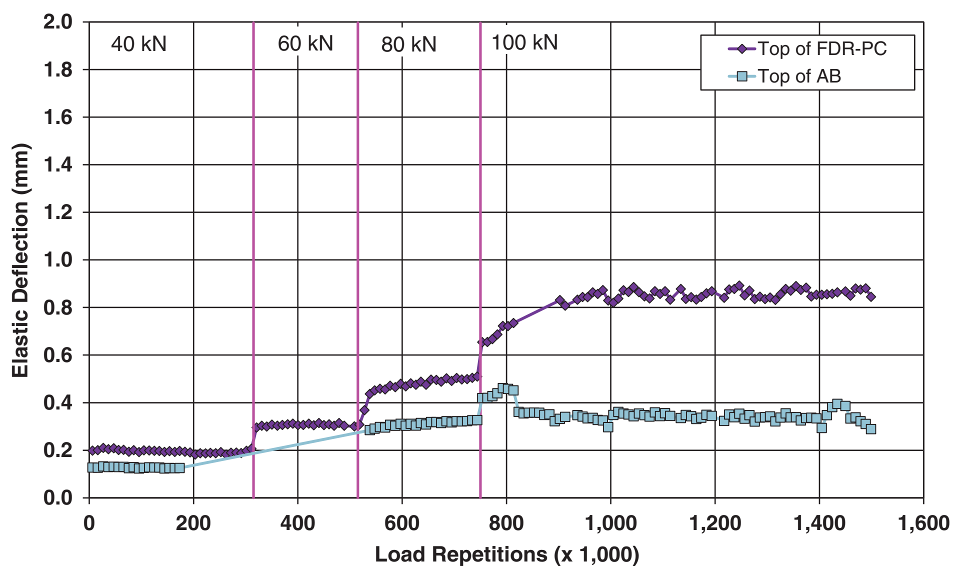
section, as expected. Slight increases in absolute surface deflection were recorded on both sections for the duration of the tests. The amount of increase was similar for both sections after 665,000 load repetitions (~0.13 mm) when testing on the FDR-NS section was stopped. Deflection continued to increase at a constant rate on the FDR-PC 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.

## Elastic Deflection in Underlying Layers

Figure 9 shows the history of in-depth elastic deflections, measured by the linear variable differential transformers in the multidepth deflectometers, for the FDR-NS and FDR-PC sections. These readings are consistent with the surface deflections measured with the road surface deflectometer shown in Figure 8. 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-PC section, there was a consistent increase in vertical deflections measured at the different depths up to about 1 million load repetitions, suggesting a decrease in overall stiffness of the pavement structure for the duration of the test consistent with the breakdown of cement bonds and resultant microcracking. Thereafter, deflections remained relatively constant.




(a)




(b)

FIGURE 9 Elastic deflection in underlying layers (multidepth deflectometer): (*a*) FDR-NS and (*b*) FDR-PC.

### Falling Weight Deflectometer Measurements Before and After Testing

Falling weight deflectometer testing was conducted on each section before and after HVS testing to evaluate the change in stiffness caused by trafficking. Testing was undertaken on the trafficked and adjacent untrafficked areas [i.e., 4 m (~13 ft) on either end of the 8-m (~26-ft) test section] at 500-mm (19.7-in.) 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 road surface deflectometer measurements discussed in the previous section, with average surface deflection on the FDR-NS section increasing by 450 microns after trafficking, compared with an increase of about 10 microns on the FDR-PC 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 with the CalBack software package. Results are summarized in Figure 11. The stiffness of the unstabilized recycled layer was very low and did not decrease significantly [about 30 MPa (4.4 kips per square inch (ksi)] after trafficking. The stiffness of the FDR-PC 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 [~7,000 MPa (1,015 ksi)] in stiffness of the recycled layer after trafficking, which was attributed to the breaking of the cement bonds under loading and consequent damage in the form of microcracking. However, the FDR-PC layer stiffness was still significantly higher compared with the recycled layer in the FDR-NS section after completion of trafficking [~6,000 MPa (870 ksi) compared with ~150 MPa (22 ksi)] despite the significantly higher number of equivalent standard axle loads applied on the FDR-PC section.

## SUMMARY AND CONCLUSIONS

Full-depth reclamation (FDR) with foamed asphalt has been successfully used as a rehabilitation strategy in California since 2001. Long-term field monitoring on a number of 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 a rehabilitation project of this level. Recently, interest has been growing in the use of portland cement, engineered emulsion, and no-stabilizer FDR 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 including 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 two tests in this accelerated loading study, which compared no-stabilizer and portland cement strategies under the same 60-mm asphalt concrete surfacing layer. The portland cement section outperformed the unstabilized section in all measured aspects, with results similar to those measured on the test section with foamed asphalt in combination with cement (*8*). Key results include the following:

- A terminal rut depth of 13 mm (~0.5 in.) was recorded on the FDR-NS section after approximately 490,000 equivalent standard axle loads had been applied, compared with only 3.0 mm (0.12 in.) on the portland cement section after more than 43.3 million equivalent standard axle loads had been applied. Testing was halted on the FDR-PC 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.

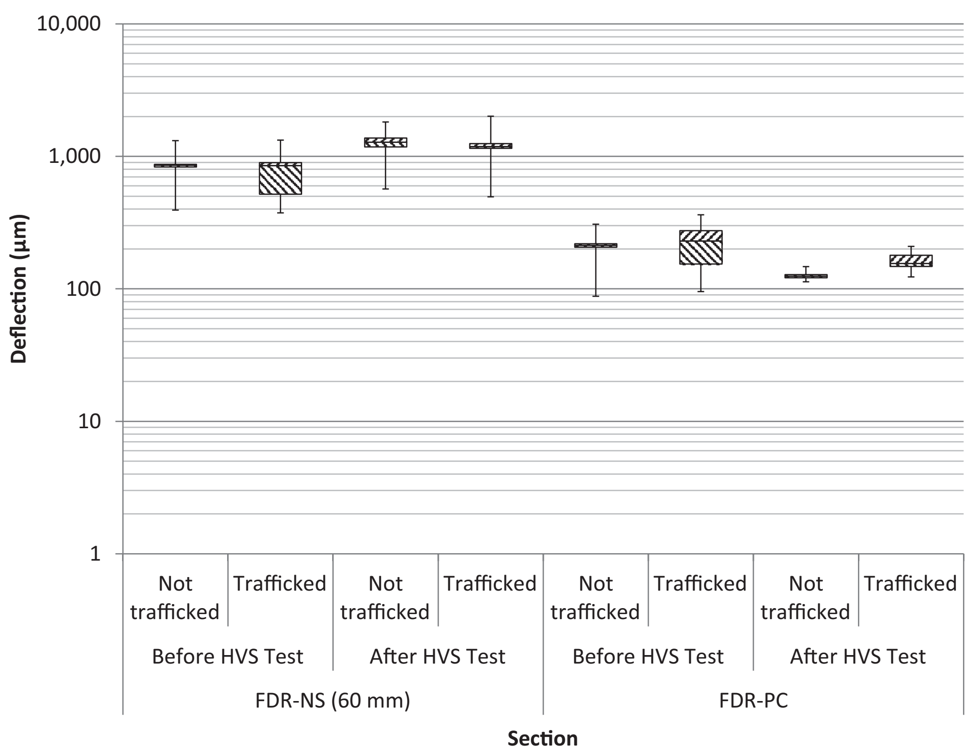



FIGURE 10 Elastic deflection in recycled layers and in subgrade (from falling weight deflectometer).

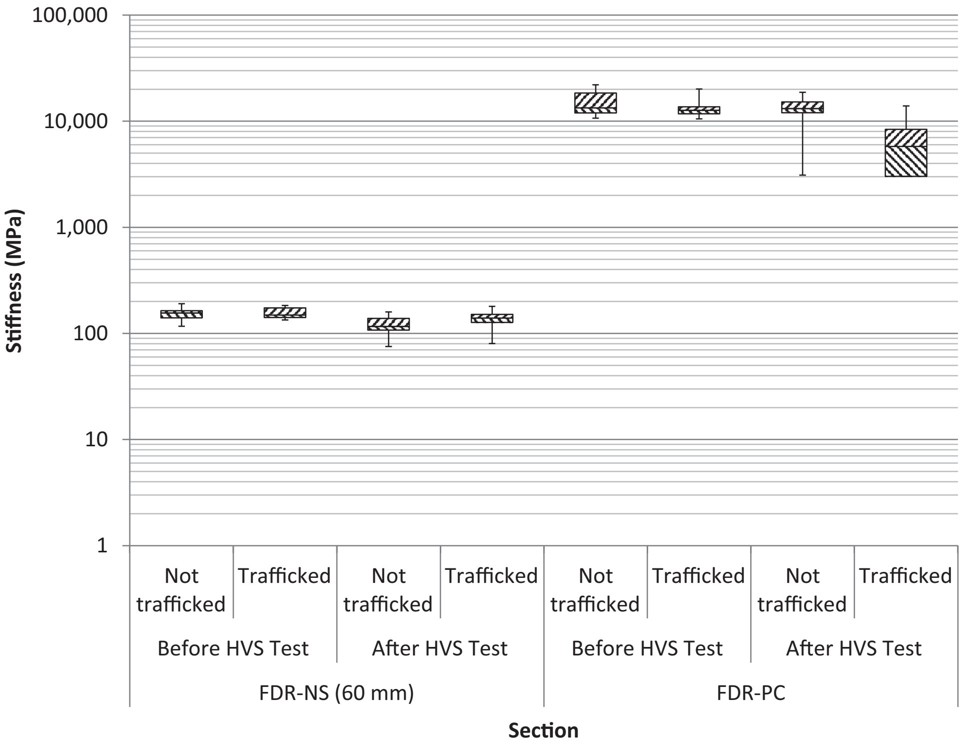



**FIGURE 11 Backcalculated stiffness in recycled layers (from falling weight deflectometer).**

- Measured and backcalculated stiffnesses were significantly higher on the FDR-PC section compared with the FDR-NS section. Although the stiffness dropped considerably in the recycled layer on the FDR-PC section after trafficking, it was still orders of magnitude higher than that on the FDR-NS section, despite having been subjected to more than 37 million additional ESALs.
- Elastic deflection at the bottom of the FDR-PC layer after completion of testing (43.3 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-PC section, which is consistent with stabilized layers containing cement.
- No cracking was observed on either section.

The advantages of using portland cement over unstabilized pulverized material are clearly evident from the results. The results also support the continuation of this study to develop mechanistic–empirical design criteria and parameters for FDR and the use of FDR as an appropriate rehabilitation strategy for cracked asphalt pavements.

## ACKNOWLEDGMENT

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