Full-Depth Reclamation

Cost-Effective Rehabilitation Strategy for Low-Volume Roads

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Full-depth reclamation with or without various stabilizers has been successfully used as a rehabilitation strategy in California since 2001. Long-term field monitoring on a number of full-depth reclamation projects that use 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 this level of rehabilitation project. There has been growing interest in the use of full-depth reclamation with no stabilizer as a rehabilitation option for lower-volume roads 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 four full-depth reclamation 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 a set of tests in this accelerated loading study, which compared dry and wet performance of a pavement rehabilitated with full-depth reclamation without any stabilizer. The section performed well in terms of expected low-volume traffic (i.e., up to 500,000 equivalent single-axle wheel loads). Poorer performance under wet base course conditions emphasized the need for appropriate drainage on low-volume road structures. The findings indicate that full-depth reclamation with no stabilizer, followed by the placement of an appropriate surface treatment or thin asphalt concrete layer, is a potentially cost-effective rehabilitation strategy for distressed low-volume pavements.

Full-depth reclamation or 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. Full-depth reclamation 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.

The California Department of Transportation (Caltrans) built its first full-depth reclamation project with foamed asphalt combined with cement in 2001 in a 15-km (9.5-mi) pilot study on Route 20 in Colusa County. From early apparent advantages of this technology, Caltrans approved a University of California Pavement Research Center 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 full-depth reclamation projects are undertaken on pavements in this condition; this practice distinguishes California from many other states and countries that are investigating and using this rehabilitation strategy (*1*). Pavement technology in South Africa, Australia, and New Zealand, where much of the early research was undertaken on full-depth reclamation 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 (2 in.)] or aggregate surface treatment layers (chip seals) providing little or no structural integrity. Consequently, in those countries, the recycled material consists mostly of quality recycled natural aggregate, cracked cement-stabilized layers, or both; this practice was reflected in the 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, 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 of a number of projects (*1*). The project culminated in 2008 with the preparation of guidelines (*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, full-depth reclamation 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 full-depth reclamation projects, including cement and engineered emulsion. Full-depth reclamation without a stabilizer (i.e., pulverizing the old asphalt concrete layers and recompacting the material as a new unbound base course) has also been experimented with on lower-volume roads (Figure 1). There is also growing interest in using mechanistic design approaches in full-depth reclamation 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, 8*). This research entails monitoring additional field projects with the different strategies, laboratory testing, and accelerated load testing on an instrumented test track constructed with the four full-depth reclamation 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 comprehensive studies have been undertaken,

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(a) (b)

FIGURE 1 Low-volume road (*a*) before full-depth reclamation and (*b*) after full-depth reclamation.

with most research limited to field studies of one stabilization strategy on uninstrumented test sections, to laboratory testing, or to a combination (*7*).

Results from accelerated load tests conducted on full-depth reclamation with foamed asphalt and cement and full-depth reclamation with cement only were recently published (*9, 10*). This paper summarizes the results of a set of accelerated loading tests, comparing the performance of full-depth reclamation with no stabilizer under dry and wet conditions, with a view to using this approach for rehabilitation of distressed low-volume roads.

STUDY OBJECTIVES

The objective of the second phase of the California full-depth reclamation study is to develop comprehensive guidelines for the rehabilitation design of pavements with full-depth reclamation techniques. This objective is being achieved through the following tasks (*7, 8*):

1. A literature review on research related to the topic, with special emphasis on project selection, identifying the most suitable recycling strategy, 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 four-lane test track to compare full-depth reclamation with foamed asphalt and portland cement, portland cement only, and engineered asphalt emulsion stabilization against two sections with no stabilization in accelerated load tests. The two sections with no stabilization had different asphalt concrete surface layer thicknesses and represent typical lower-volume road pavement structures in the United States.
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.
6. Preparation of guidelines for full-depth recycling in California.

This paper provides a summary of the testing on the section with no stabilization with a thin 60-mm (2.5-in.) surface, as detailed in Tasks 3 and 4. 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 dry and wet test sections (*7, 8*). Comparisons of the performance of the sections with no stabilization with the performance of the full-depth reclamation with foamed asphalt and portland cement sections are published in earlier papers (*9, 10*).

LITERATURE REVIEW

Comprehensive literature reviews were conducted in both phases of the study (*1, 8*). More than 100 publications were reviewed, most of which documented project-level field tests, laboratory tests, or both. No published studies that compared field, laboratory, or accelerated load testing results of different full-depth reclamation strategies were found.

TEST TRACK DESIGN AND CONSTRUCTION

The test track for the accelerated load test was located at the University of California Pavement Research Center 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 (18 in.) of aggregate base, surfaced with 60 mm (2.4 in.) of conventional hot-mix asphalt underneath 60 mm of gap-graded rubberized asphalt concrete. This track was tested over 2 years (*11–13*). After testing was completed, the test track was recycled in place. Conventional full-depth reclamation procedures

(a)

(b)

FIGURE 2 Test track construction: (*a*) pulverization and mixing and (*b*) water addition and compaction.

were followed, with each of the four lanes of the test track subjected to a different stabilization strategy (*7*):

Lane 1, no stabilization;
Lane 2, engineered emulsion with no active filler;
Lane 3, foamed asphalt with portland cement; and
Lane 4, portland cement only.

Reclamation depth was set at 250 mm (10 in.) for all strategies, which is typical of reclamation depths on California rehabilitation projects [200 mm 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 one-half the length of the lane recycled with no stabilizer to quantify the differences in performance of the unstabilized base with different thicknesses of asphalt and to determine whether the performance of the unstabilized recycled base with thicker asphalt was similar to the performance of a stabilized base with thinner asphalt (*7, 8*). Conventional full-depth reclamation construction procedures were followed on the unstabilized section, with the recycler and connected water tanker making a single pass to pulverize and mix the material to optimum moisture content for compaction (Figure 2*a*). Compaction included initial rolling with a pad foot roller (Figure 2*b*), followed by vibrating smooth drum, and then rubber tired rollers. Final levels were achieved with a grader after initial rolling. Compaction was measured with a nuclear gauge. The test section was allowed to cure for 10 days before the asphalt was placed.

TEST TRACK INSTRUMENTATION AND MEASUREMENTS

The test section layout is shown in Figure 3. 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 (MDD), with linear variable differential transformers set at 60 mm (2.4 in.) (top of the recycled base), 310 mm (12.4 in.) (interface between recycled and existing layers), 480 mm (19.2 in.) (bottom of old aggregate base), 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, 8*).

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 (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 (*7, 8*).

ACCELERATED LOAD TESTING PROGRAM

Accelerated load testing on the two sections was carried out with a heavy vehicle simulator (HVS). All trafficking was conducted with a dual tire configuration in a wandering bidirectional mode; tire pressure was 720 kPa (104 pounds per square inch). Loading programs are summarized in Table 1 (*7, 8*).

Pavement temperature at the 50-mm (2-in.) depth was maintained at 30°C (± 4°C) (86°F ± 7°F) with an environmental chamber surrounding the equipment. This temperature was selected to assess both 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. In the wet test, the test section was soaked with water for 14 days before HVS testing to accelerate the onset of any potential moisture damage. A row of holes was drilled to the bottom of the asphalt concrete layer on the side of each test section to facilitate water ingress into the base. The holes were 25 mm (1.0 in.) in diameter, 250 mm (10 in.) from the edge of the HVS test section, and 250 mm (10 in.) apart. A wooden dam, 200 mm (8.0 in.) high and 300 mm (12 in.) from the edge of the test section, was then glued to the pavement with silicone to provide a head of water (Figure 4). The dam was kept full of water for the duration of the soaking period. During HVS testing, a constant flow of approximately 1.5 L (0.4 gal) of water per hour was maintained through irrigation tubes positioned in each hole in the asphalt layer to ensure that the base remained in a soaked condition. Excess water was allowed to flow across the surface to infiltrate any cracks in the asphalt concrete. This water was maintained at a temperature of 30°C ± 4°C (86°F ± 7°F) to prevent cooling of the pavement surface. This testing condition was considered to be an extreme worst case to illustrate the importance

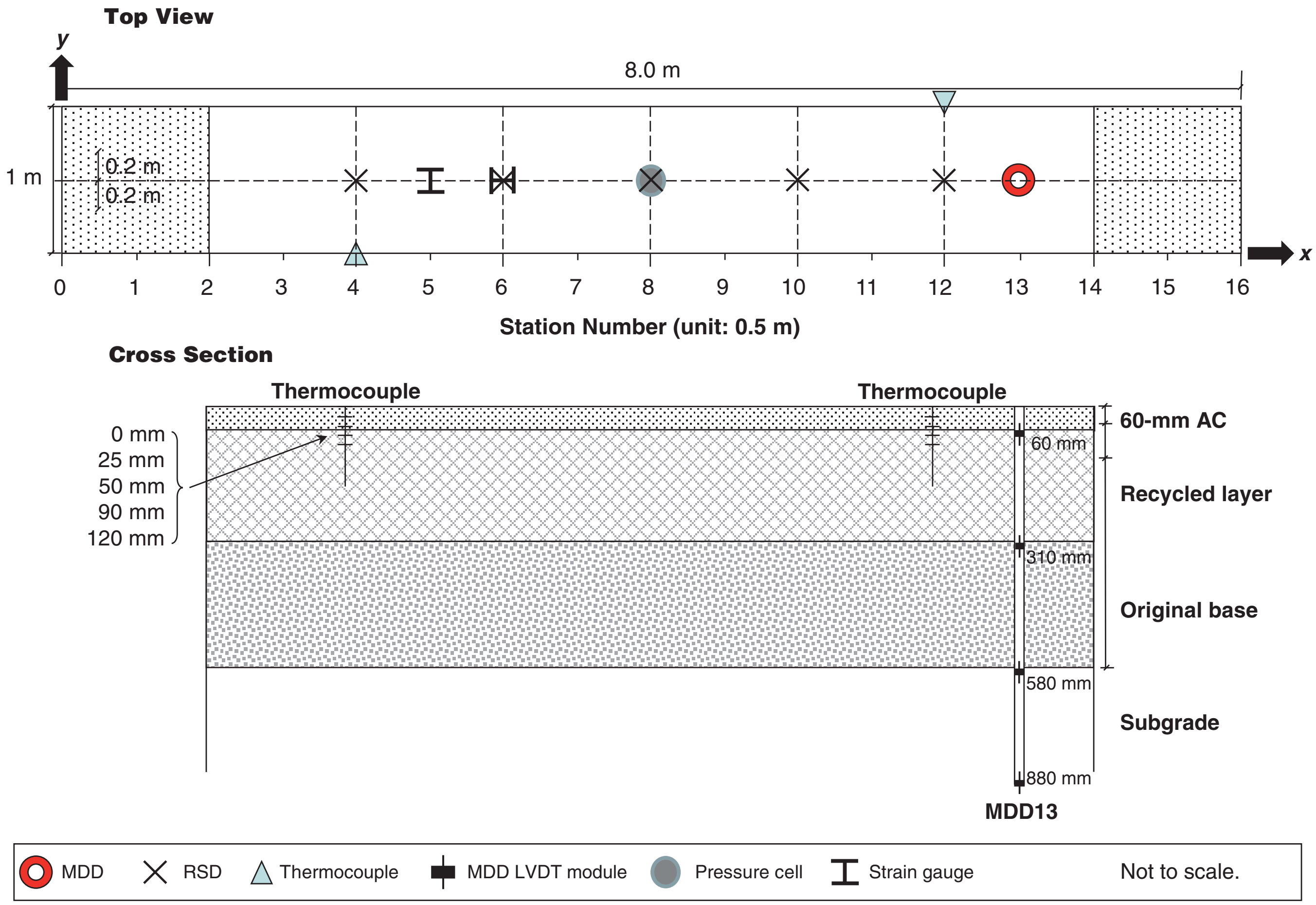


FIGURE 3 Test section layout (AC = asphalt concrete; LVDT = linear variable differential transformer).

of good drainage on rehabilitated low-volume roads; the importance of good drainage is often overlooked.

Failure criteria for the tests were set at an average maximum rut of 13 mm (~0.5 in.) or cracking of 2.5 m/m^2 (0.8 ft/ft^2), in line with Caltrans limits for these distresses.

TEST SECTION PERFORMANCE

Test section performance is summarized for the various measurements taken (*7, 8*). The dry section outperformed the wet section for all criteria measured, as expected. Apart from rutting, no surface distresses were observed on the dry section. Severe rutting and fatigue cracking, indicative of base failure, were observed on the wet section. Photographs of the two sections after testing are shown in Figure 5. Base and subgrade moisture contents did not vary significantly over the period of testing on the dry test, but increased significantly on the wet test, as expected.

Permanent Deformation on the Surface

Permanent surface deformation measured on the two sections is shown in Figure 6. (The average maximum rut is the measurement

TABLE 1 Loading Programs

Stage	Half-Axle Wheel Load (kN)	Number of Repetitions: Dry Test	Number of Repetitions: Wet Test	Rut Depth (mm): Dry Test	Rut Depth (mm): Wet Test	Cracking (m/m^2): Dry Test	Cracking (m/m^2): Wet Test
1	40	300,000	233,000	12.2	16.7	None	na
2	60	200,000	0	16.9	na	None	na
3	80	198,000	0	23.0	na	None	12.0
Total		713,000	233,000				
ESALs		5,052,104	233,000				
ESALs to failure		492,155	164,000				

NOTE: ESAL = equivalent standard single-axle wheel load, calculated by (axle load/18,000)$^{4.2}$; na = not applicable.

FIGURE 4 Presoak before testing.

from the bottom of the rut to the top of the displaced material on the side of the wheelpath, and permanent deformation is the measurement from the original surface to the bottom of the rut.)

Significantly more rutting was noted on the wet test than the dry test, as expected. The terminal average maximum rut of 13 mm was recorded on the dry section after 335,000 wheel repetitions [300,000 repetitions at 40 kN (9,000 lb) half-axle wheel loads and 35,000 repetitions at 60 kN (13,500 lb)], which equates to about 500,000 equivalent single-axle wheel loads (ESALs) (see Table 1). On the wet test, the terminal rut was reached after 165,000 40-kN wheel repetitions (equal to about 165,000 ESALs). Testing continued on the dry section to collect additional data at the higher load levels. A contour plot of the surface deformation is shown in Figure 7. Rutting on the dry test appeared to be predominantly downward compression or densification, with very little displaced material on the edges of the wheelpath. On the wet test, both downward compression and displacement were observed, indicative of base failure (see Figure 5).

Permanent Deformation in 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 8 (AB indicates the top of the existing aggregate base and bottom of the recycled layer) for the dry test only. The MDD failed during the wet test because of loss of contact with the layer as a result of the soaked conditions. The MDD measurements were consistent with the laser profilometer measurements. Most of the deformation occurred in the recycled base.

(a) (b)

FIGURE 5 Dry and wet test sections after HVS testing.

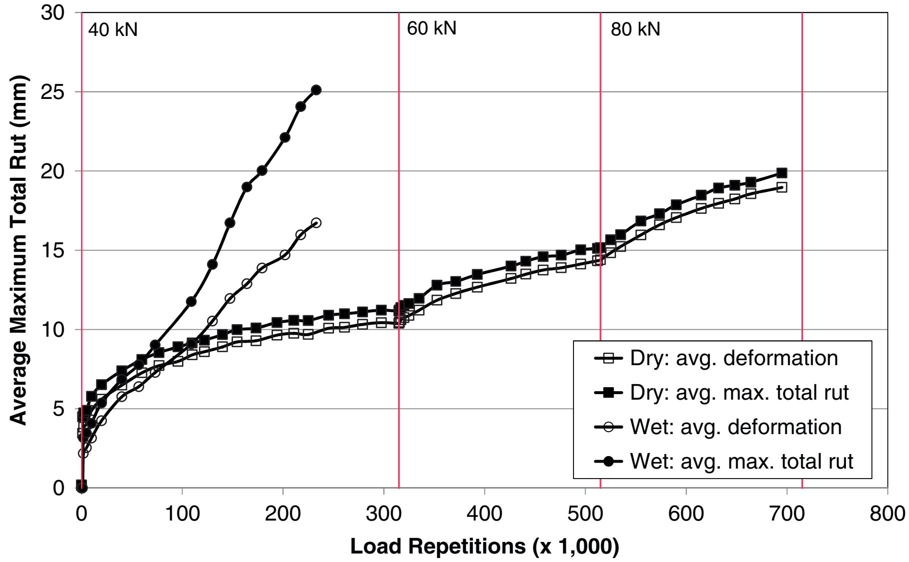


FIGURE 6 Surface permanent deformation (avg. = average; max. = maximum).

Tensile Strain at Bottom of Asphalt Concrete Layer

Figure 9 shows the comparison of peak traffic–induced tensile strain at the bottom of the asphalt concrete layer for the dry test. No data were collected during the wet test because of the soaked conditions. Longitudinal strain remained fairly constant throughout the test, apart 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 with a slight decrease thereafter until the load was changed to 60 kN; this result suggests gradual layer stiffening from densification caused by the HVS trafficking. Strains increased after the load change but then showed similar decreasing trends; the decreasing trends indicated continued densification under loading. No surface distresses associated with the change in strain measurements in the recycled layer were noted during testing.

Vertical Pressure at Top of Recycled Base

Figure 10 shows the comparison of traffic-induced vertical pressure at the top of the recycled base layer for the dry test. As with the other tests, no data were collected during the wet test because of the soaked

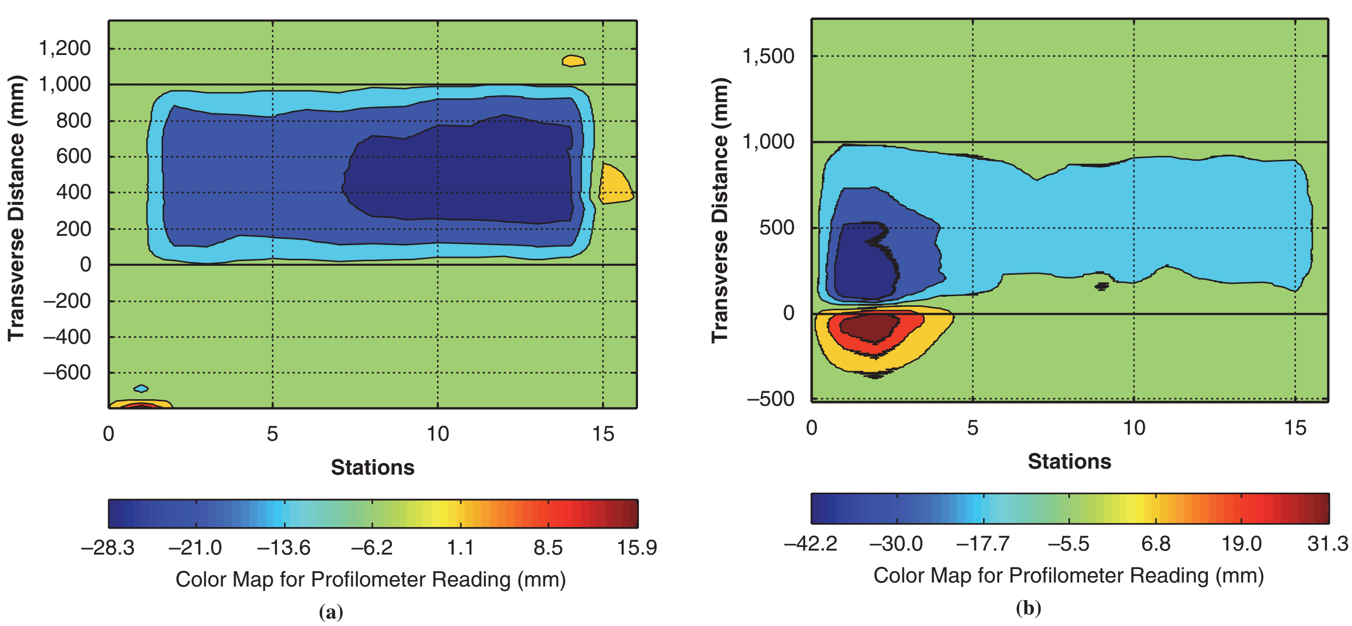


FIGURE 7 Contour plots of surface permanent deformation (negative is downward deformation): (*a*) dry test, end of test (713,000 load repetitions); and (*b*) wet test, end of test (233,000 load repetitions).

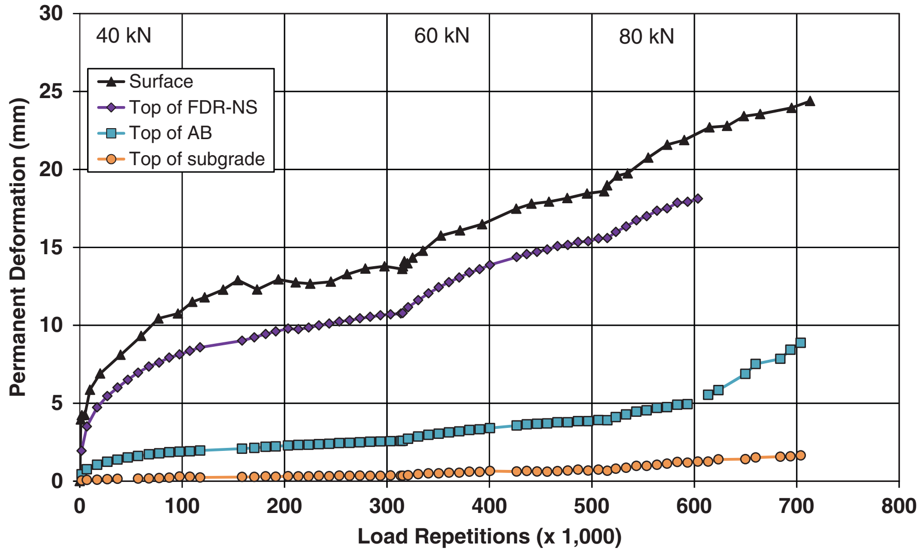


FIGURE 8 Permanent deformation in surface and underlying layers (dry test only) (FDR-NS = full-depth reclamation with no stabilizer; AB = aggregate base).

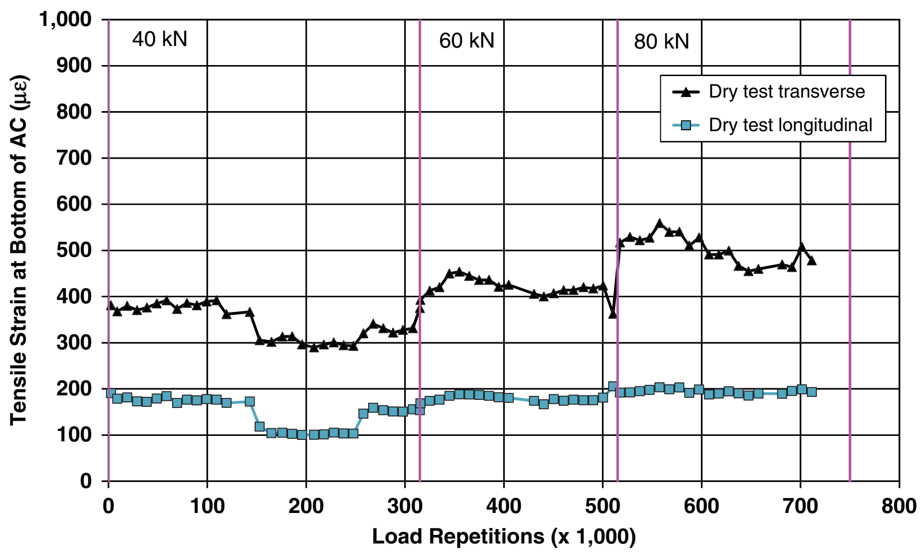


FIGURE 9 Tensile strain at bottom of asphalt concrete layers.

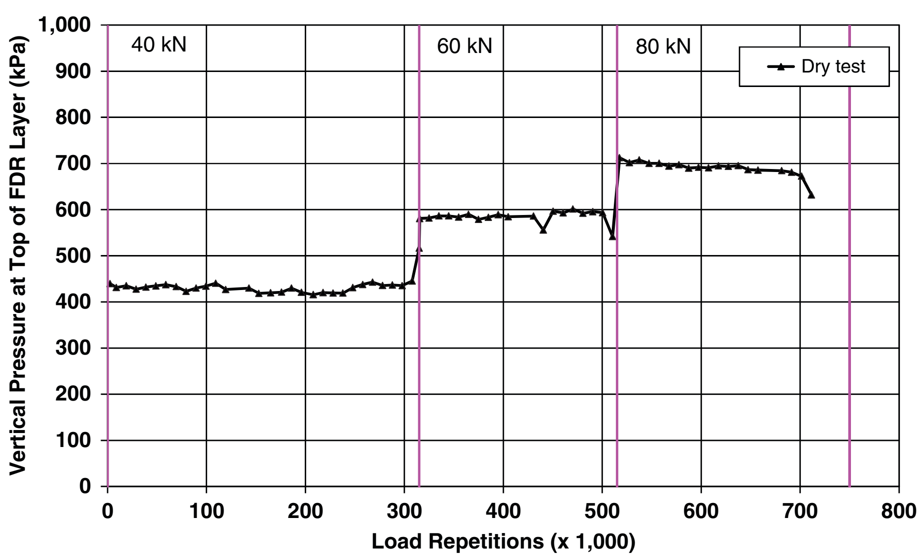


FIGURE 10 Traffic-induced vertical pressure at top of recycled layer.

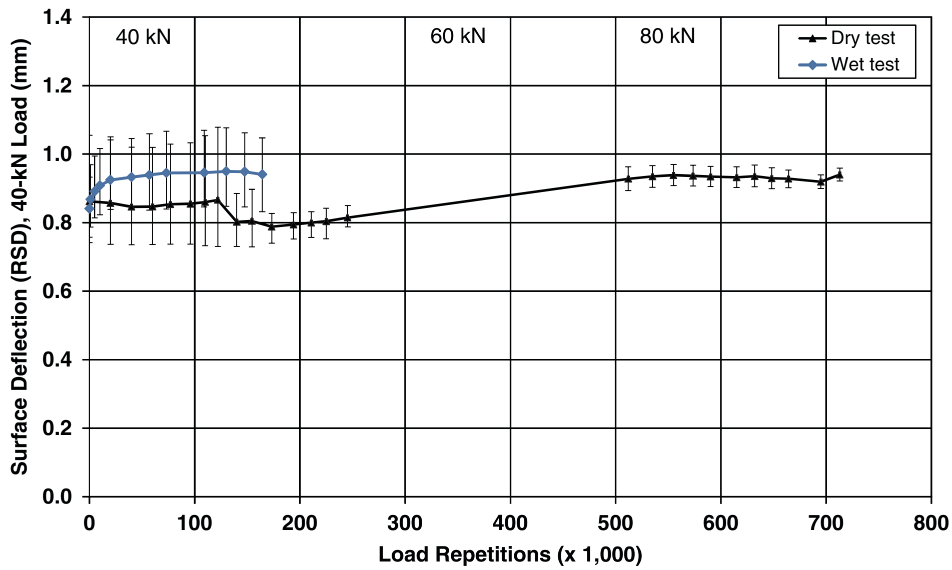


FIGURE 11 Surface deflection measured with RSD.

conditions. Pressure readings were stable but sensitive to load change for the duration of the dry test.

Surface Deflection Measured with RSD

Figure 11 compares elastic surface deflections measured with an 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. Deflections were higher on the wet test, as expected, with a relatively large increase at the beginning of the test, before stabilizing. Toward the end of the test, deflections could not be measured on the areas of severe deformation. Deflection on the dry test continued to increase with increasing wheel load, as expected. The increase was constant, indicating that no significant damage had occurred in the asphalt concrete layer when trafficking was stopped.

Elastic Deflection in Underlying Layers

Figure 12 shows the history of in-depth elastic deflections, measured by the linear variable differential transformers in the MDD in the dry test. These readings are consistent with the surface deflections measured with RSD shown in Figure 11. Variation between the two sets of readings was attributed to the different locations of the instru-

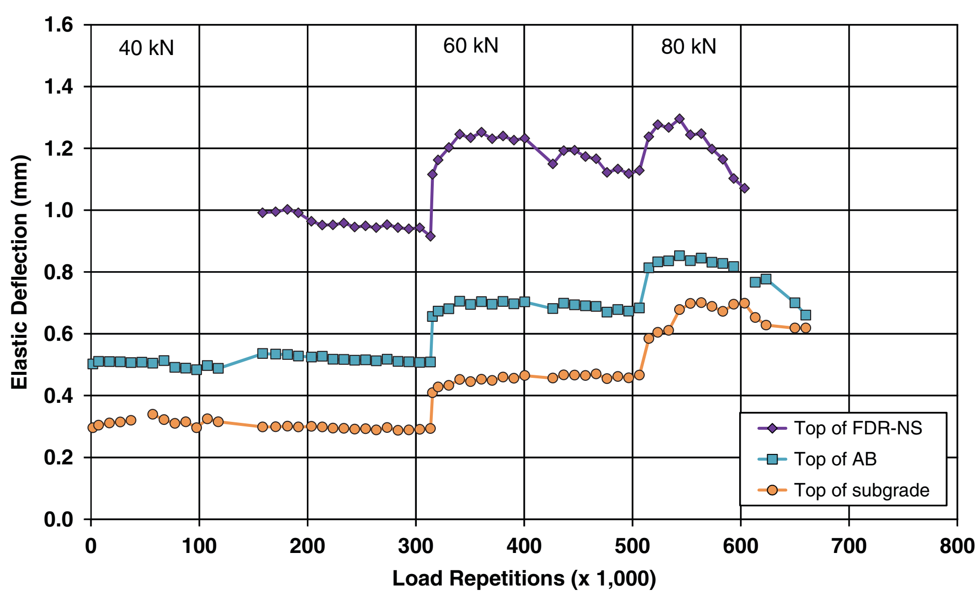
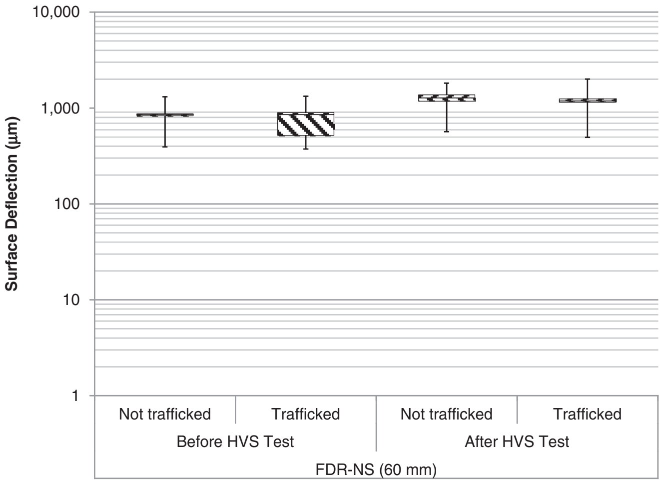
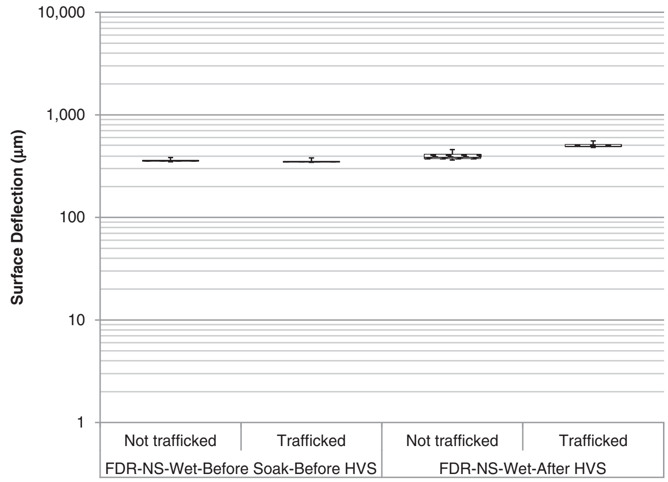


FIGURE 12 Elastic deflection in underlying layers (from MDD, dry test only).



(a)



(b)

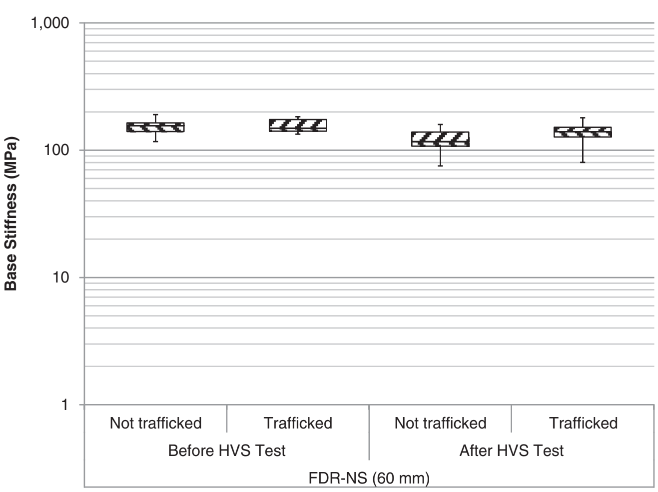
FIGURE 13 Elastic deflection in recycled layers and in subgrade (from FWD).

ments and to the wheel speeds during measurement. (MDD data are collected at trafficking speed, whereas RSD data are collected at creep speed.) Deflections measured at the top of the recycled base decreased with the increasing number of load repetitions; this result suggests some stiffening in the recycled layer, attributed to densification under HVS trafficking.

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., 4 m (~13 ft) on either end of the 8-m (~13-ft) test section] at 500-mm (19.7-in.) intervals. Two sets of tests were undertaken on each day to obtain a temperature range. On the wet test after HVS trafficking, measurements could not be taken on approximately one-half of the test section because of the severe deformation (see Figure 5). Results are summarized in Figure 13. The results differed slightly from the RSD measurements in that deflection on the wet test was slightly lower than on the dry test. This result was attributed in part to measurements being taken only on the stronger part of the wet test (i.e., less deformation). The wet test was also conducted 13 months after the dry test. Consequently, the asphalt concrete would have been subjected to additional aging and was therefore likely stiffer, providing additional confinement to the underlying recycled base layer.

The recycled layer stiffnesses were backcalculated from the deflection measurements with the CalBack software package. Results are summarized in Figure 14. The stiffnesses of the recycled layers in both tests were low and did not change significantly [about 30 MPa (4.4 kips per square inch)] after trafficking. The stiffness of the recycled layer in the wet test was slightly higher than that in the dry test. This result was attributed to the same reasons cited previously for deflection.



(a)

(b)

FIGURE 14 Backcalculated stiffness in recycled layers (from FWD).

SUMMARY AND CONCLUSIONS

This paper reviews and summarizes the results of two tests from a larger accelerated loading study that investigated the performance of pavements rehabilitated with full-depth reclamation. The two tests focused on low-volume road applications for which no stabilizer was added during the pavement recycling. Testing was done under wet and dry conditions. In the wet test, conditions represented a worst-case scenario to illustrate the importance of ensuring that appropriate drainage measures are considered during design, construction, and operation of the rehabilitated road. The dry test outperformed the wet test in all aspects that were measured, as expected. Key results include the following:

- A terminal rut depth of 13 mm (~0.5 in.) was recorded on the dry test after approximately 500,000 ESALs had been applied, compared with 13 mm on the wet test after just 165,000 ESALs had been applied. Rutting on the dry test appeared to be predominantly downward compression or densification, with very little displaced material on the edges of the wheelpath. On the wet test, both downward compression and displacement were observed, indicative of base failure. Permanent deformation in the recycled layers was consistent with the surface measurements.
- No cracking was observed on the dry test. Severe deformation and fatigue cracking (average of 12 m/m^2 at the end of the test) were observed on the wet test during and after trafficking.
- Measured and backcalculated stiffnesses were similar on both tests. However, deflections on the most damaged area of the wet test could not be tested; deflections of this area would have influenced the results.

Testing under dry conditions (i.e., with the base at an appropriate equilibrium moisture content) indicated that full-depth reclamation without the addition of a stabilizer, followed by the placement of an appropriate surface treatment or thin asphalt concrete layer, is an appropriate, sustainable, and potentially cost-effective rehabilitation strategy for distressed low-volume roads with a design life of up to about 500,000 ESALs. Poor performance during testing under extreme wet conditions illustrated the importance of taking appropriate measures to ensure that the recycled base remains dry during the design service life of the pavement (i.e., making sure that good drainage is provided along the length of the road). The results of this research are being used to prepare guidelines on full-depth reclamation in California, which will include mechanistic–empirical design criteria and parameters.

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