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Full-Depth Pavement Reclamation with Foamed Asphalt in California: Guidelines for Project Selection, Design, and Construction

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Partnered Pavement Research Program (PPRC) Strategic Plan Element 4.12: Development of Improved Mix and Structural Design and Construction Guidelines for Full-Depth Reclamation with Foamed Asphalt

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Abstract:

This document provides guidelines on full-depth reclamation using a combination of foamed asphalt and an active filler, typically portland cement or lime. The following aspects are discussed:

- Project selection
- Mix design
- Structural design
- Construction

The references provide a list of other commonly used guidelines.

Keywords:
Full-depth reclamation, Full-depth recycling, FDR, Deep in situ recycling, DISR, foamed asphalt, foamed bitumen

Proposals for implementation:

Related documents:

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DISCLAIMER

The contents of this guideline reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

The photographs used in this guideline are for illustrative purposes only and were taken on different full-depth reclamation projects in California. The California Department of Transportation and the University of California Pavement Research Center does not endorse the use of any specific equipment related to full-depth reclamation.

PROJECT OBJECTIVES

The objective of this project, titled "Development of Mix and Structural Design and Construction Guidelines for Full-Depth Reclamation of Cracked Asphalt Concrete as Stabilized or Unstabilized Bases," is to develop improved mix and structural design and construction guidelines for full-depth reclamation (FDR) of cracked hot-mix asphalt with foamed asphalt (FDR-FA). This project is Partnered Pavement Research Center Strategic Plan Element 4.12 (PPRC SPE 4.12).

This objective will be met after completion of six tasks:

1. Complete a literature survey, and technology and research scan.
2. Perform a mechanistic sensitivity analysis on potential pavement structures incorporating full-depth recycled layers using foamed asphalt.
3. Complete an assessment of Caltrans FDR-FA projects built to date based on available data.
4. Measure properties on Caltrans roads planned for rehabilitation using FDR-FA, assess construction, and monitor performance after rehabilitation.
5. Carry out laboratory testing to identify specimen preparation and test methods, and develop information for mix and structural designs and construction guidelines.
6. Prepare interim guidelines for project selection, mix design, structural design, and construction.

This document covers Task 6. The results of objectives 1 through 5 are included in a separate report.

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- The staff of Western Stabilization
- The staff of Durham Construction

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transport Officials
AB	Aggregate base
ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
CBR	California Bearing Ratio
CFIPR	Cold Foam In-place Recycling
CIR	Cold In-place Recycling
CMC	Compaction moisture content
CT	California Test
DCP	Dynamic Cone Penetrometer
DGAC	Dense-graded asphalt concrete
DISR	Deep in-situ recycling
DME	District Materials Engineer
DN	DCP Number
DSN	DCP Layer Structure Number
DSN_{800}	DCP Pavement Structure Number
LCA	Life-cycle Analysis
ESAL	Equivalent standard axle load
ER	Expansion ratio
FDR	Full-depth reclamation or full-depth recycling
FDR-FA	Full-depth reclamation using foamed asphalt
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GPR	Ground penetrating radar
HIR	Hot In-place Recycling
HMA	Hot-mix asphalt
ITS	Indirect tensile strength
MDD	Maximum dry density
MMC	Mixing moisture content
OMC	Optimum moisture content
PG	Performance grade
PPRC	Partnered Pavement Research Center
RAP	Recycled Asphalt Pavement
RHMA-G	Gap-graded rubberized hot-mix asphalt
SG	Subgrade
SPE	Strategic Plan Element
$\tau_{1/2}$	Foam half-life
TI	Traffic Index
TSR	Tensile strength retained
UCPRC	University of California Pavement Research Center

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO T-180	Standard method of test for moisture-density relations of soils using a 4.54-kg (10-lb) rammer and a 457-mm (18-in.) drop
AASHTO T-265	Laboratory determination of moisture of soils
AI MS2	Marshall method of mix design
CT 201	Method of soil and aggregate sample preparation
CT 202	Sieve analysis of fine and coarse aggregates
CT 204	Plasticity index of soils
CT 216	Method of test for relative compaction of untreated and treated soils and aggregates
CT 301	Resistance "R" Value of treated and untreated bases, subbases and basement soils (Stabilometer)
CT 304	Method of preparation of bituminous mixtures for testing
CT 356	Determining overlay requirements by pavement deflection measurements
CT 371	Resistance of compacted bituminous mixture to moisture induced damage

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
Symbol	**Convert From**	**Convert To**	**Symbol**	**Conversion**
LENGTH				
mm	millimeters	inches	in	mm x 0.039
m	meters	feet	ft	m x 3.28
km	kilometers	mile	mile	km x 1.609
AREA				
mm^2	square millimeters	square inches	in^2	mm^2 x 0.0016
m^2	square meters	square feet	ft^2	m^2 x 10.764
VOLUME				
m^3	cubic meters	cubic feet	ft^3	m^3 x 35.314
kg/m^3	kilograms/cubic meter	pounds/cubic feet	lb/ft^3	kg/m^3 x 0.062
L	liters	gallons	gal	L x 0.264
L/m^2	liters/square meter	gallons/square yard	gal/yd^2	L/m^2 x 0.221
MASS				
kg	kilograms	pounds	lb	kg x 2.202
TEMPERATURE (exact degrees)				
C	Celsius	Fahrenheit	F	°C x 1.8 + 32
FORCE and PRESSURE or STRESS				
N	newtons	poundforce	lbf	N x 0.225
kPa	kilopascals	poundforce/square inch	lbf/in^2	kPa x 0.145
*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)				

1 INTRODUCTION

1.1 Background

Full-depth reclamation/recycling/ (FDR), or deep in-situ recycling (DISR), of damaged hot-mix asphalt pavement with foamed asphalt and an active filler (e.g., portland cement or lime) to provide a stabilized base for a new hot-mix asphalt (HMA) wearing course, is a pavement rehabilitation strategy of increasing interest worldwide. The process, hereafter referred to by the acronym FDR-FA, provides a rapid on-grade method of rehabilitation that entails pulverizing the existing asphalt concrete pavement and a portion of the underlying granular base to a maximum depth of 12 in. (300 mm), whilst at the same time mixing-in the foamed asphalt, active filler and water, grading and compacting the recycled mixture, and overlaying the prepared surface with a new layer of hot mix asphalt (HMA). The procedure results in minimal traffic disruption and, most importantly, it reuses all the aggregates in the pavement, thereby minimizing the environmental impacts associated with extraction and transport of new aggregates.

The technology was introduced to the California Department of Transportation (Caltrans) in March 2000 and the Department's first 10 centerline mile (16 km) pilot study was completed in 2001 on State Route 20 in Colusa County. Since then, a number of roads have been rehabilitated in the state (Caltrans, county, and city) using this process. Most Caltrans FDR-FA projects are on pavements with thick, cracked HMA layers over a relatively thin, weak natural aggregate base. Recycling of this type of pavement structure distinguishes California practice from that of other states and countries investigating and using this technology. Pavement technology in South Africa and Australia, where considerable research on the topic has been undertaken, 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 hot-mix asphalt (<2 in. [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 is reflected in their research, experience, and guideline documentation. 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 differences between practices in California and elsewhere in the world generated sufficient interest for the initiation of a research project at the University of California Pavement Research Center (UCPRC) to monitor the performance of projects, and to carry out laboratory testing to identify any issues related to recycling thicker asphalt pavements. A report documenting this research study has been prepared *(1)*. The study found that FDR-FA is theoretically suited to the rehabilitation of any HMA pavement, the main limitation being whether the recycled layer is structurally adequate for the design traffic. This will be governed by the quality of the materials being recycled, the support provided by the underlying layers, variability in materials and subgrade conditions along the project, drainage, and the ability to construct the layer to the specified requirements. This guideline incorporates key findings from the research study that are applicable to project selection, mix design, structural design, and construction of FDR-FA projects in California.

1.2 Purpose of this Guideline

This document has been prepared to guide practitioners on project selection, mix design, structural design, and construction of FDR-FA projects in California. It provides information specific to California conditions not covered in the Highway Design Manual, specification documents, or other available design guides.

1.3 Terminology

A variety of terms are used for describing the recycling of pavements, including but not limited to full-depth reclamation or recycling (FDR), partial-depth reclamation or recycling (PDR), deep in-situ recycling (DISR), cold in-place recycling (CIR), and hot in-place recycling (HIR). Although studies have shown that a combination of foamed asphalt and active filler is required to achieve optimum results, most terminology excludes the active filler component. In this document, the terms "full-depth reclamation," abbreviated as FDR, and "full-depth reclamation with foamed asphalt," abbreviated as FDR-FA are used throughout for simplicity, although the term “foamed asphalt” generally implies foamed asphalt with an active filler. The term “cold foam in-place recycling” (CFIPR) is not used in this guideline as the term is considered misleading given that, although the pavement is not heated during the milling process, the asphalt binder used in the foaming process is very hot (i.e., between 300°F and 360°F [150°C and 180°C]).

The terminology in this guideline should not be confused with asphalt (or bitumen) stabilization or cementitious (e.g. cement, lime, fly-ash, etc) stabilization. The use of in-place recycling equipment to apply and mix a combination of the two types of additives results in a pavement layer that behaves differently than layers constructed with only asphalt or cementitious stabilization. Consequently, the use of design practices for either asphalt or only cementitious stabilization should **NOT** be used for FDR-FA. The basic characteristics of unstabilized and stabilized road-building materials are summarized in Figure 1.1.

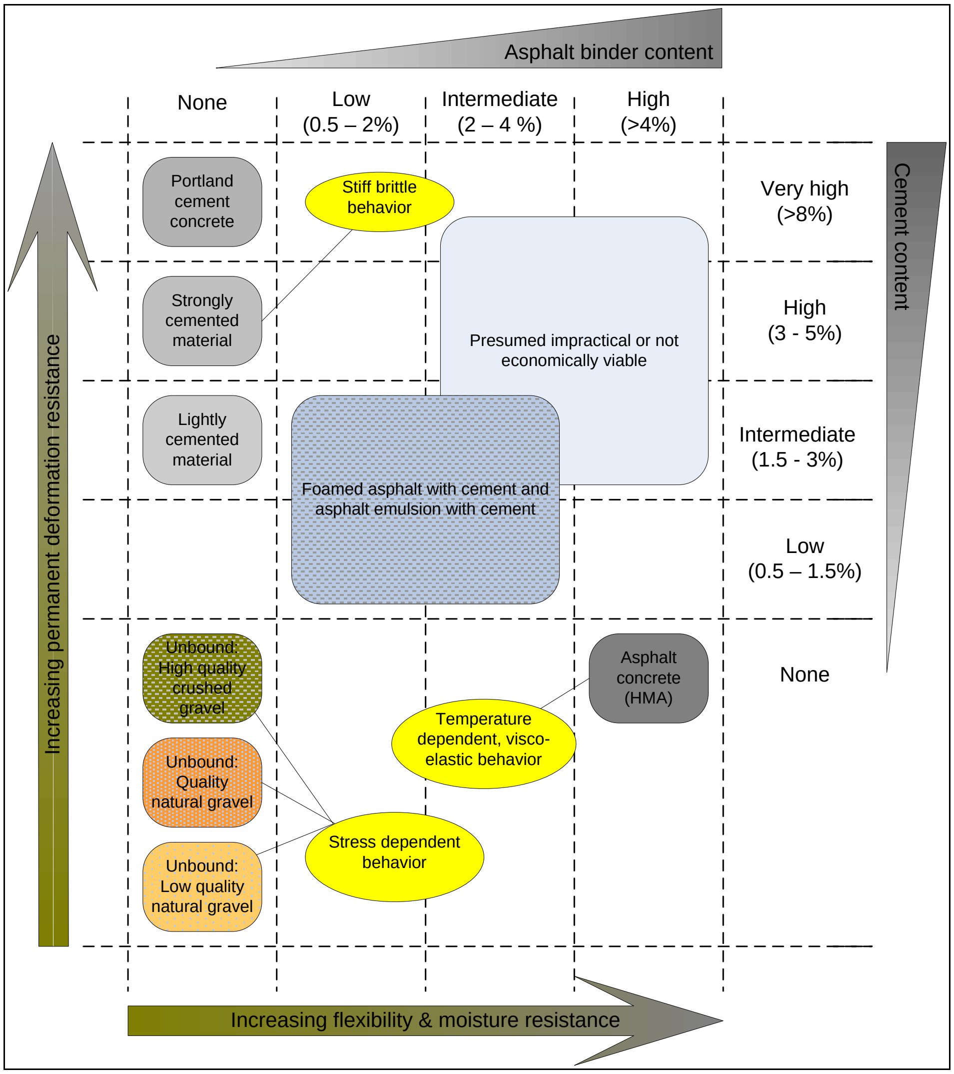


Figure 1.1: Basic characteristics of unstabilized and stabilized road-building materials *(2)*.

1.4 Guideline Structure

FDR-FA is **NOT** a miracle cure for the rehabilitation of severely distressed pavements and not all pavements in need of rehabilitation will be suited to the FDR-FA process. Project selection is therefore a very important part of the design process and satisfactory performance will be highly dependent on sound engineering judgment, sound pavement engineering principles, and quality construction. This guideline has been structured to guide Caltrans practitioners through the design and construction of an FDR-FA project, summarizing key issues through the following chapters:

- Chapter 2: Site investigation
- Chapters 3 and 4: Mix design
- Chapter 5 Structural design
- Chapter 6: Construction

Contract documentation (e.g. Proposal and Contract, Notice to Contractors, and Contract Special Provisions) is also a key issue, but is beyond the scope of this guideline and is not covered.

1.5 Other Published Guidelines

FDR-FA is being increasingly used worldwide to rehabilitate aging highway networks. Numerous reports, conference proceedings, and journal articles document the experiences of practitioners around the world. A number of organizations have prepared literature reviews on this documentation and therefore no literature review is provided in this guideline. Although numerous reports have been written, relatively few published guidelines with procedures for project selection, mix design, structural design, and construction are available. Currently available guidelines are briefly discussed below.

1.5.1 Wirtgen Manual (Germany)

The first edition of the *Wirtgen Cold Recycling Manual* was released in 1998. A revision of this document, which included updated recommendations based on experience around the world, was released in 2001. A second edition *(3)*, which includes a comprehensive overview of in-place recycling together with revised mix design and structural design procedures, was published in 2004. An electronic version of the guideline can be downloaded from the Wirtgen web site *(http://www.wirtgen.de/en/)*. Relevant parts of the Wirtgen Manual are referred to in this guideline, but the reader is encouraged to review the Wirtgen manual for additional insights into FDR-FA.

1.5.2 South Africa

Researchers in South Africa produced an interim technical guideline, *The Design and Use of Foamed Bitumen Treated Materials (2)*, in 2002 to guide practitioners in southern Africa. The document was based on limited experience and was intended as a placeholder while more comprehensive research was undertaken. A revised document, based on work undertaken since 2002, and covering both foamed bitumen and bitumen emulsion treatments has since been prepared and was released in May 2009 *(4)*. An electronic version of the new 2009 guideline can be downloaded from the South Africa Asphalt Academy web site *(http://www.asphaltacademy.co.za/Documents/TG2May09.pdf)*. Although the South African document focuses primarily on the recycling of thin surfacings/thick granular bases, relevant parts of it are referred to in this guideline. The reader is encouraged to review the South African guideline for additional insights into FDR-FA.

1.5.3 United States and Canada

Experiments and pilot projects using FDR-FA have been reported from a number of states in the United States and Canada, but no guidelines had been published at the time of preparing this document. Design procedures have generally followed the *Wirtgen Cold Recycling Manual (3)*. Some State Departments of Transportation have written interim project specifications and special provision documentation for individual projects. The Recycled Materials Resource Center (RMRC) at the University of New Hampshire has funded a number of FDR-FA projects, including a mix design specification using gyratory compaction *(5)* (submitted to AASHTO) and the determination of structural layer coefficients for FDR-FA projects *(6)*. These reports can be down loaded from the RMRC web site *(http://www.rmrc.unh.edu/research/).*

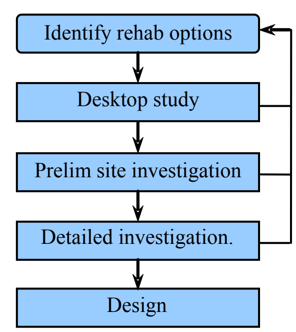
1.5.4 Other Countries

Although numerous reports and conference and journal papers have been written on FDR-FA projects in many countries, there does not appear to be any additional readily available comprehensive published guidelines to that described above, with most countries using the Wirtgen and/or South African guidelines. Many countries have, however, prepared project specifications and special provisions to supplement specification and contract documentation in accommodating FDR-FA.

2 PROJECT INVESTIGATION

2.1 Introduction

Research in California and the rest of the world has shown that the performance of FDR-FA projects is directly related to the materials in the pavement, the strength of the underlying layers, drainage, the mix and structural designs adopted, and the construction process followed. A comprehensive project investigation involving three phases is critical for understanding the existing pavement and surroundings, and collecting representative materials to test for the mix design. The findings are used to make an informed decision on the appropriateness of FDR-FA as a method of rehabilitation and, if selected, as input to the mix design, structural design, and project specifications. Early failures of rehabilitation projects are often caused by insufficient data gathering during the project investigation phase.



Stages in the project investigation

The three stages in a project investigation include:

1. Desktop study;
2. Preliminary site investigation, and
3. Detailed site investigation, testing and analysis.

2.2 Desktop Study

The desktop study is the first stage in the project investigation, which involves collecting all relevant information pertaining to the road including, but not limited to:

- **Investigation approval** needs to be obtained from the relevant headquarters program advisor and District Materials Engineer prior to any detailed investigation. Criteria used in making the decision to consider FDR-FA rehabilitation include the availability of program funding, the expected design life, construction start year, and traffic index *(7)*. A flowchart to guide this decision is shown in Figure 2.1.
- **As-built plans** are available online (http://drs.dot.ca.gov/falcon/websuite.shtml) for Department staff and are used to gain a basic understanding of the existing pavement structural design such as layer thickness, layer type, materials, drainage structures, design traffic, etc. This information will provide an initial indication of the pavement structure, road geometry, potential recycling depth, and whether additional aggregate base material is needed. The Department is currently developing a statewide Pavement Management System (PMS), which includes a Ground Penetrating Radar (GPR) survey of all state highways. In the future, these GPR traces and summaries could be used to supplement as-built plans. FDR-FA projects are generally uninfluenced by the geometric design (horizontal or vertical alignment) of the existing road, provided that adequate drainage can be ensured. Minor corrections in vertical alignment should be incorporated to improve safety and ride quality. Excess material should be used to add or widen shoulders to limit ingress of moisture to the wheelpaths.

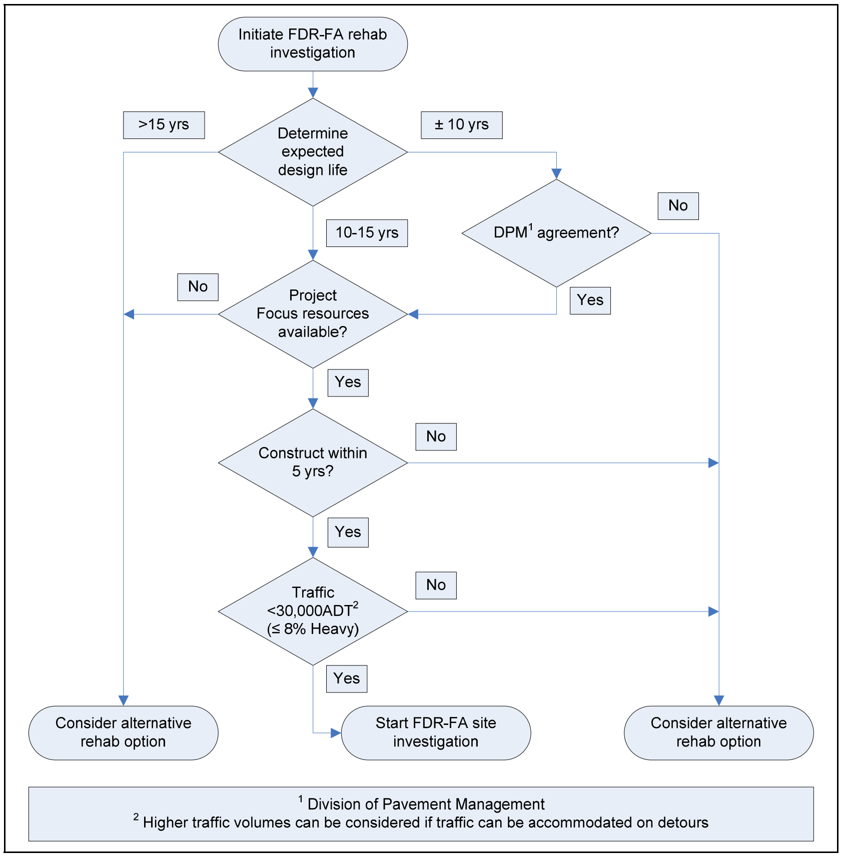


Figure 2.1: Flowchart for project investigation approval *(7)*.

- **Photolog**, which can be used to obtain an initial indication of the condition of the road and the presence of problem areas. Copies of the photolog can be obtained from the Office of Pavement Engineering, or *http://onramp.dot.ca.gov/photolog/*.
- **Pavement Condition Report**, which can be used to obtain additional information on the current condition of the road. Copies can be obtained from the Office of Pavement Engineering, or *http://onramp.dot.ca.gov/hq/maint/roadway_rehab/index.htm#pcr*.
- **Traffic data** are used to determine the structural design requirements of the pavement and understand traffic growth or decline. Data can be obtained from the Division of Traffic Operations or at *http://www.dot.ca.gov/hq/traffops/saferesr/trafdata/.*
- **Climate data** relevant to pavement design in California can be obtained from the Caltrans Office of Pavement Engineering or *http://www.dot.ca.gov/hq/esc/Translab/ope/Climate.html* and are used to identify precipitation type and intensity, typical minimum and maximum temperatures, and issues such as freeze-thaw. FDR-FA can be considered as a rehabilitation option in any climate in California. However, issues such as rainfall intensity, number of rain days, temperature, and freeze-thaw conditions will need to be understood in order to ensure the pavement and drainage system is designed and constructed appropriately.
- **Maintenance records**, obtained from the area Maintenance Superintendent, are used to identify problem areas on the road that may require additional investigation and pretreatment.
- **Maps** are available from *http://onramp.dot.ca.gov/hq/maint/roadway_rehab/gis/.*

- **Land-use plans** may be available from county or city planning departments and are used to identify potential traffic growth or a change in the type of vehicles using the road (e.g., increase in the number of trucks).

The output from the desktop study is a brief report detailing the following (example in Appendix A, Form 1):

- General project description, project identification, road description, program, and funding source.
- Record of headquarters' decision to proceed with the investigation if expected design life is less than 10 years.
- Existing pavement structure, including layer thicknesses and materials.
- General road condition.
- Current traffic.
- Climate.
- Potential problem areas.
- Fatal flaws that automatically exclude FDR-FA as a rehabilitation option (e.g., future plans for reconstruction or a new development, presence of a concrete layer underlying the HMA, utilities [e.g., gas or water pipelines] close to the surface of the road, etc.).

2.3 Preliminary Site Investigation

2.3.1 Introduction

The preliminary site visit is carried out by the District Materials Engineer (DME) and the area Maintenance Supervisor as a screening exercise to assess general project suitability for FDR-FA before a more detailed site investigation is carried out. This preliminary investigation should be carried out as early as possible during the project scope summary and preferably during the rainy season when subgrade moisture and drainage issues can be assessed. The investigation consists of a drive-through visual assessment in both directions and, in certain instances, subgrade material sampling, followed by preparation of a report (part of the Project Scope Summary Report [PSSR]) with recommendations for proceeding with a more detailed study or investigating an alternative rehabilitation strategy.

2.3.2 Visual Assessment

The visual assessment is carried out to identify the modes of failure of the existing pavement and to identify any specific reasons why FDR-FA may not be a suitable rehabilitation option. The Maintenance Supervisor will have knowledge of problem areas and the frequency and extent of maintenance efforts. The assessment should include a determination of whether distress is confined to the surface (i.e., environmental or traffic) or whether the distress was caused by structural inadequacy or a related cause, such as poor drainage. This can be achieved by studying the pavement and adjacent area and estimating:

- The type, severity, and extent of cracking and any pumping (extensive alligator cracking and pumping of fines through the cracks usually indicates subgrade problems);
- Rut depth, shape, and extent (deep, wide ruts usually indicate subgrade problems);
- Extent of maintenance (especially digouts) and the condition relative to the service life of maintained areas (i.e., are the digouts failing within one year?);
- The height of the road above natural ground level and presence of an existing granular base layer (roads level or below natural ground level, without kerbs and pipes, will usually have drainage problems;
- Efficiency of the drainage design (i.e., road shape, side drains, culverts, etc.); and
- Land use immediately adjacent to the road (irrigated agricultural lands and the use of side drains for irrigation purposes may lead to moisture related problems).

The primary cause of pavement failure (e.g., age, increased traffic loading, overloading, inadequate structural design/design thickness, poor drainage, weak subgrade, etc.) should be noted.

Observations should be recorded on an appropriate worksheet (example in Appendix A, Form 2).

2.3.3 Subgrade Material Sampling and Testing

In instances where there appears to be no base or the road profile is low (i.e., the road is level or even below the natural surrounding area) subgrade material samples should be collected from the edge of the road to determine the Atterberg Limits (CT 204 i.e. plasticity index). Samples should be collected from alternate sides of the road at 2.0-mi (3.0-km) intervals. Sample holes should be as close to the edge of the road as possible, while ensuring that base and subbase gravels are not included in the sample. Sampling depth should be between 12 in. and 20 in. (300 mm and 500 mm) and a minimum of 20 lb (10 kg) should be collected.

2.3.4 Preliminary Site Investigation Report

A preliminary site investigation report, which forms part of the PSSR, should be prepared that includes a brief description of the project, a summary of the observations, and a recommendation on whether to proceed with a detailed site investigation for FDR-FA or to consider an alternative method of rehabilitation. An example of a preliminary site investigation report template is provided in Appendix A (Form 3). The flowchart shown in Figure 2.2 can be used to assist with the decision whether to proceed with a detailed site investigation.

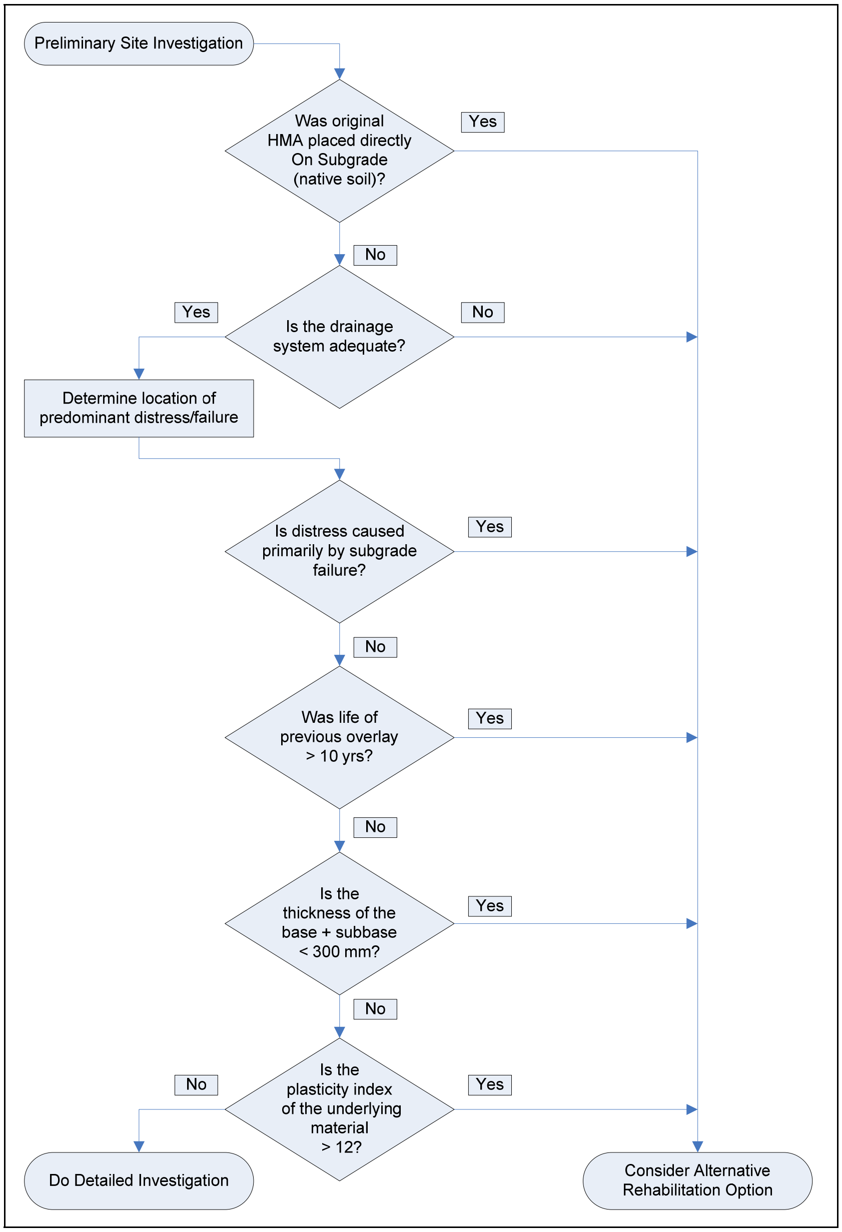


Figure 2.2: Flowchart for preliminary site investigation decision making. (Notes: 300 mm = 12 in).

Projects where FDR-FA can be excluded at the preliminary site investigation stage include, but are not limited to:

- HMA layers have been placed directly onto the subgrade (i.e. native soils) or on a very thin (less than 4.0–in. [100-mm] oiled gravel over weak subgrade (e.g., plasticity index in the material under the HMA is higher than 12 and fines content [< 75 micron] is greater than 20 percent). The road will typically have severe cracking and possibly pumping and rutting in the wheel paths. The level of the road above the surrounding natural ground level will be small.
- There are insufficient side drains and culverts to divert water away from the base during normal rainfall events.

- Distresses in the pavement are caused primarily by subgrade failures rather than surface or aggregate base failures.
- Extensive deep patching (digouts) are evident over more than 25 percent of the road, and records show that these areas require additional attention during or after each rainy season.

2.3.5 Record of Decision

A record of decision (i.e., continue with a detailed site investigation or consider an alternative rehabilitation method) should be recorded in the project file.

2.3.6 Caltrans Headquarters Notification

The Pavement Management Program, Office of Engineering and Specification Development in the Headquarters Division of Maintenance should be notified if the decision to proceed with a detailed site investigation on FDR-FA is made. This office will provide information on program funding, provide assistance with determining expected design life and provide the latest specification language for FDR-FA projects.

2.4 Detailed Site Investigation

2.4.1 Introduction

The detailed site investigation is carried out to gather pavement and site condition information and to sample materials for mix design testing, the results of which will be used to assist in determining the best rehabilitation design for the specific conditions. Inadequate site investigations can lead to premature failures associated with overlooked problems such as areas of weak subgrade materials, inadequate drainage, and material variability. The investigation is typically undertaken by a team selected by the DME and assisted by staff from the area maintenance office. Investigations can be undertaken anytime of year, but are best done during the wet season when construction activities are minimal and wet season problems can be readily identified. The detailed site investigation should include:

- Subgrade stiffness assessment (deflection and Dynamic Cone Penetrometer survey [Sections 2.4.2 and 2.4.5]).
- Visual assessment of the pavement, drainage system, and adjacent areas (Section 2.4.3)
- Pavement layer thickness assessment (coring and/or ground penetrating radar survey [Section 2.4.4]).
- Pavement layer thickness and property assessment (test pits [Section 2.4.6])
- Material sampling (Section 2.4.7).
- Indicator tests (Section 2.4.8).
- Analysis summary and recommendation (Section 2.4.9).
- Life-cycle cost analysis (Section 2.4.10)

2.4.2 Subgrade Stiffness Assessment: Falling Weight Deflectometer

The primary purpose of the subgrade assessment with the Falling Weight Deflectometer (FWD) is to evaluate the stiffness of pavement materials below the anticipated recycling depth (typically the subbase and/or subgrade), identify weak areas that require special treatment before recycling, identify areas where specific attention should be given during the visual assessment, and identify suitable locations where test pits should be excavated.

The subgrade assessment should be undertaken with a calibrated FWD unit that is capable of applying impact loads of 40 kN (8,800 lb) on a standard plate (300 mm [12 in.] in diameter), and measuring pavement deflection at a distance of 600 mm ± 25 mm (24 in. ± 1.0 in.) from the center of the loading plate.

The purpose and method of FWD testing for a site investigation are different from California Test 356 (*Determining Overlay Requirements by Pavement Deflection Measurements*). This method should not be followed; however, relevant sections in the method (e.g., Section B: Equipment; Section C: Background Data and Selection of Test Sites; and Section G: Safety and Health) can still be used as general references.

<u>FWD Testing Procedure</u>

The following should be considered when planning FWD measurements:

- Testing should be carried out at the end of the rainy season, when subgrade moisture is likely to be highest.
- The lane with the worst existing condition should be tested unless each lane is designed separately, in which case both lanes should be tested.
- A test interval of 65 ft (20 m) is recommended, which allows for a testing productivity of approximately 0.6 lane-mi/hr (1.0 lane-km/hr). Longer test intervals can be adopted if there are constraints such as traffic or limited closure schedules; however, this increases the risk of missing weaker sections.
- Testing should be carried out between the wheelpaths to minimize the effects of severe wheelpath cracking on the seating of the FWD load and sensors.

<u>Analysis of FWD Results</u>

Site evaluation often involves testing pavements with severe alligator cracking, which violates the continuity assumption for modulus backcalculation based on FWD data. Pavement layer modulus backcalculation is therefore inappropriate in these instances. However, valuable information can still be gathered on the properties of the subgrade using a simple method to approximate the modulus from the deflection measured by one of the FWD sensors. The Boussinesq's equation for this calculation is shown below (Equation 3.1):

$$E_{def}(r) = \frac{(1-\upsilon^2)\times P}{\pi \times r \times d} \qquad \textbf{(3.1)}$$

where: E_{def} = deflection modulus;
P = the applied load;
v = Poisson's ratio, generally using 0.35;
r = the distance from the load center to the measured deflection;
d = measured deflection at r.

For a layered pavement structure the calculated deflection modulus is a function of the distance (r) at which the deflection is measured. For typical FDR-FA structures in California, the deflection modulus ($E_{def}(r)$) at 600 mm (24 in.) from the load center (i.e. r = 600 mm [24 in.]; i.e. distance to the fifth FWD sensor) is a reasonable indicator of subgrade modulus (i.e., $E_{def^\circ}(600\text{ mm}) \approx E_{SG}$). The calculated deflection modulus $E_{def^\circ}(600\text{ mm})$ is not significantly affected by the condition of the surface layers, and thus no temperature correction is necessary. If certain constraints prevent adjusting the location of the sensor to 600 mm (24 in.) from the load center, a tolerance of ± 25 mm (1.0 in.) is allowed. When calculating E_{def}, the measured distance between the sensor and the load center should be used.

Results of the analysis should be plotted against postmile or station on a graph (example in Figure 2.3). The graph can be used to identify problem subgrade or drainage areas. The following criteria (summarized in Table 2.1) should be used in interpreting the deflection data from the 600 mm (24 in.) sensor (load normalized to 566 kPa [82 psi], or 40 kN [8,800 lb]):

- If the calculated deflection modulus E_{def} (600 mm) is greater than 45 MPa (6,530 psi) (equivalent to a 0.37 mm [15 mils] deflection measured by the 600 mm [24 in.] sensor), the subgrade should not require any specific improvement.
- If the calculated deflection modulus E_{def} (600 mm) is between 45 MPa and 25 MPa (3,630 psi) (equivalent to between 0.37 mm and 1.25 mm [15 and 49 mils] deflection measured by the 600 mm sensor), subgrade-related problems are likely and corrective action should be taken prior to recycling of the pavement. This could include, but is not limited to, excavation and replacement of the weak material, reinforcement, raising the embankment, and/or provision of additional drainage.
- If the calculated deflection modulus E_{def} (600 mm) is less than 25 MPa (equivalent to more than 1.25 mm [49 mils] deflection measured by the 600 mm sensor), a more detailed survey should be undertaken and appropriate actions or other reconstruction options considered.

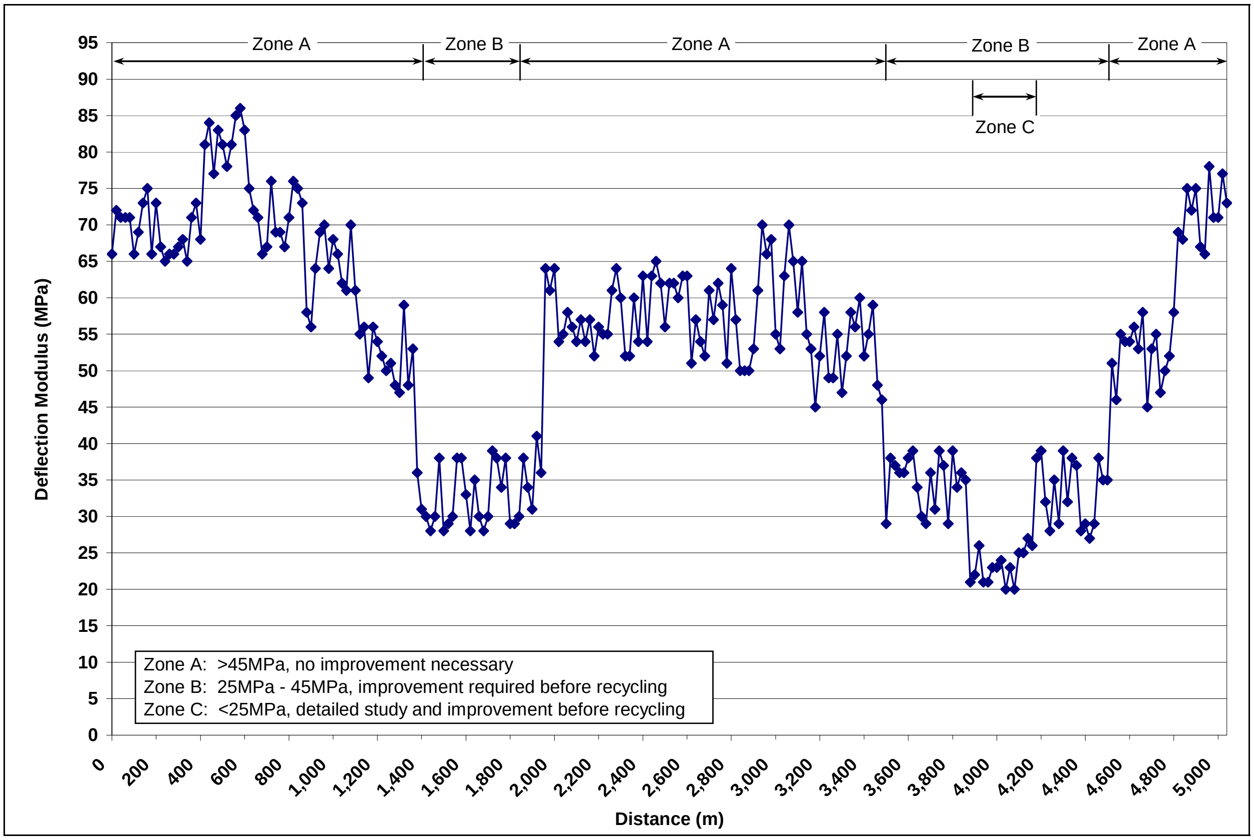


Figure 2.3: Example FWD analysis.

Table 2.1: Criteria for Assessing FWD Deflections

Deflection					
> 45 MPa	**< 0.37 mm**	**25 – 45 MPa**	**0.37 – 1.25 mm**	**< 25 MPa**	**> 1.25 mm**
>6,530 psi	< 15 mils	3,630 – 6,530 psi	15 – 49 mils	< 3,630 psi	> 49 mils
No improvement necessary		Subgrade improvement required prior to recycling		Subgrade improvement required after more detailed survey.	

2.4.3 Visual Assessment

The visual assessment is undertaken to identify the modes of failure of the existing pavement and to identify any specific reasons why FDR-FA will not be a suitable rehabilitation option, the same as for the visual assessment in the preliminary site investigation (Section 2.3.2). However, in this stage the visual assessment is usually done by foot or bicycle to allow a more thorough inspection.

<u>Visual Assessment Procedure and Analysis</u>

The following tasks need to be completed during the visual assessment:

- Assess the modes of distress (primarily cracking [fatigue and thermal], rutting, and pumping), together with an estimate of the extent of each distress as a percentage of the project length. Information should be captured on a form (example in Appendix A, Form 4) and summary sheet (example in Appendix A, Form 5). The presence of large areas of loose hot-mix asphalt blocks in areas of severe alligator cracking may influence the consistency of the recycled material (i.e., oversize material). Pumping through the cracks often indicates weak support conditions. Deep, wide ruts are often an indication of weak subgrade and insufficient pavement structure.

- Assess the extent and condition of existing digouts, with special attention given to areas where digouts are failing again at regular intervals. The causes of failure in these areas should be identified and documented (e.g., drainage problems, change in subgrade materials, etc.). In most instances, recycling alone will not correct these problems.
- Assess all areas with FWD-determined subgrade strengths less than 45 MPa (i.e., Zone B and Zone C from Section 2.4.2). Likely reasons for low strength should be identified (e.g., drainage problems, change in subgrade materials, etc.).
- Assess the condition of drainage systems (i.e., side drains, and culverts) and problem areas associated with inadequate drainage, including but not limited to areas where:
  - Side drains and culverts have been blocked by agricultural activity (Figure 2.4).
  - Side drains are used for moving irrigation water (Figure 2.5).
  - Plough furrows run perpendicular or at an angle to the road (Figure 2.6).
  - Irrigation water contacts the road (Figure 2.7).
  - Water flows into the roadway from access roads and driveways (Figure 2.8).

Problem areas should be identified on the summary sheet and options to correct the problems should be noted.

Figure 2.4: Blocked side drain and culvert.

Figure 2.5: Side drain used for irrigation water.

Figure 2.6: Plough furrows perpendicular to road.

Figure 2.7: Irrigation water sprays on the road.

Figure 2.8: Access road drainage problems (note digout).

- Identify test pit, core and Dynamic Cone Penetrometer (DCP) locations as follows:
  - At least one test pit should be excavated in each uniform section identified during the subgrade strength assessment (see Section 2.4.2). In longer uniform sections, a test pit should be excavated at least every 3.0 mi (5.0 km). Additional test pits should be excavated in problem areas (example Zone B and Zone C in Figure 2.3) to determine appropriate corrective action.
  - Three cores (centerline and wheelpaths) should be taken per test pit location to check variability in surface layer thickness over the width of the road, and at least one additional core should be taken every 1,500 ft (500 m) to check thickness variability along the project (see Section 2.4.4). Additional cores can be taken in problem areas if required.
  - DCP measurements should be taken in each core hole (see Section 2.4.5) to check variability in subgrade strength and to validate FWD measurements.
- Identify any other factors that may influence recycling, including but not limited to:
  - Overhanging trees, overhead power lines, or trees planted close to the road that may interfere with the recycling equipment.

- Presence of known services (e.g., pipelines, cables, etc.) within the potential recycling depth.

Potential conflicts should be noted on the summary sheet.

2.4.4 Pavement Layer Thickness Assessment

Ground Penetrating Radar (GPR) and/or coring can be used to obtain a reliable indication of pavement layer thickness and thickness variability along the test section. GPR can also be used to identify the location of underground services and will provide a continuous evaluation of pavement layer thickness along the section, while coring is limited to an intermittent evaluation depending on sampling interval. If a GPR survey is undertaken, limited coring will still be required to verify the GPR data and provide an access point for the Dynamic Cone Penetrometer (DCP) survey described in Section 2.4.5.

Testing Procedure

GPR surveys should be arranged through the Office of Flexible Pavement Materials in the Division of Materials Engineering and Testing Services. GPR testing procedures are not discussed in this document. The following procedure should be used for coring:

- Remove at least one 4.0 in. (100 mm) core from the outer wheel path every 1,500 ft (500 m) to check surface layer thickness. Alternate between lanes.
- Take additional cores in problem areas identified during the visual assessment and subgrade strength assessment and where differences in pavement design/construction are apparent.
- Carry out a DCP test after the core has been removed and before the core hole is filled (see Section 2.4.5).
- Measure each core and record the thickness of the HMA. Record any special characteristics (e.g., layers with rubberized asphalt, stripping, the presence of fabrics or geogrids, thin areas, cores in digouts, adhesion to the base, etc.). An example core log is provided in Appendix A (Form 6). The core can be photographed against a measure tape for later analysis and record purposes if required.
- Cores can be discarded after measurement unless required for other purposes.

Layer Thickness Analysis

GPR analysis will be undertaken by the Office of Flexible Pavement Materials in the Division of Materials Engineering and Testing Services. A summary plot of the layer thicknesses and locations of any utility services will be provided.

Core thicknesses should be entered into a spreadsheet and the average and standard deviation calculated. Thickness should be plotted to identify areas that are above and below the average thickness (example in Figure 2.9). A high standard deviation will indicate that thickness varies along the section.

If the average HMA thickness is greater than 10.0 in. (250 mm) consideration should be given to premilling it to a thickness of between 8.0 in. and 10.0 in (200 mm to 250 mm), with the millings salvaged as recycled asphalt pavement (RAP) for use in new HMA.

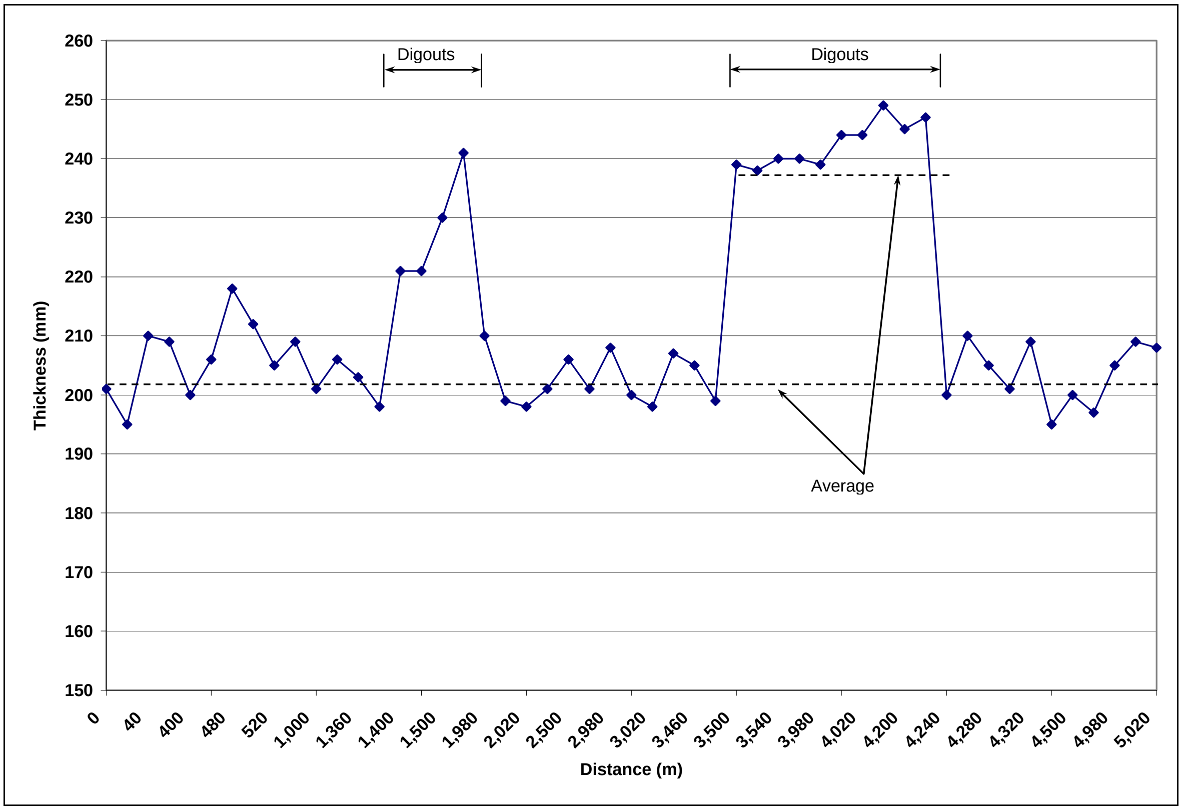


Figure 2.9: Example layer thickness analysis.

2.4.5 Subgrade Assessment: Dynamic Cone Penetrometer (DCP)

The primary purpose of the DCP subgrade assessment is to further evaluate the stiffness and moisture content of pavement materials below the anticipated recycling depth (typically the subbase and or subgrade) to identify weak areas that require special treatment before recycling. A standard DCP with 60° cone (Appendix B) is used for this assessment.

<u>Testing Procedure</u>

The recommended test interval for DCP measurements is 1,500 ft. (500 m) and should coincide with the removal of cores, discussed in Section 2.4.4. In areas of suspected high variability in underlying materials, or areas where repeated repairs have been necessary, more frequent measurements should be taken to better understand the pavement structure and layer thicknesses. DCP measurements can be taken inside the core hole, although care must be taken when interpreting the results as water used to cool the core bit will soften the upper layer of material under the surfacing, giving an unrealistically low shear strength for the upper layer. If a more accurate stiffness of the upper layer of material is required, DCP measurements should be made through drill holes or a dry core hole (cooled with compressed air). Penetration should be measured after every five blows up to a depth of 800 mm (31.5 in.) (Form 7 in Appendix A).

Analysis of DCP Results

DCP results are typically analyzed in terms of the DCP Number (DN), the DCP Layer Structure Number (DSN), and the DCP Pavement Structure Number (DSN_{800}). Hot-mix asphalt layers are excluded from the evaluation.

- The DCP Number (DN) is the DCP rate of penetration in millimeters (mm) per hammer blow (mm/blow). This provides an indication of the relative shear strength of the material at the depth where it was calculated. This shear strength will typically reduce with increasing depth, and if the DN is plotted against depth distinct jumps are often apparent. The points of each jump can be used to estimate the pavement layer thickness. Empirical relationships have been developed in a number of countries to relate the penetration rate to the effective layer stiffness and to California Bearing Ratio (CBR). No documented comprehensive studies have been undertaken to relate DN to R-value *(8)*. Although these relationships provide useful indications that can be combined with FWD measurements and visual assessments to identify and evaluate potential problem areas, the stiffness and CBR values obtained should be regarded as **approximate estimates** only. An example of a relationship between stiffness and penetration rate, developed in South Africa, is defined below (Equation 3.2). A summary of DN ranges and corresponding stiffnesses is provided in Table 2.2.

  $$E_{eff} = 10^{3.05-1.066(Log(DN))} \qquad \textbf{(3.2)}$$

  where: E_{eff} is the effective elastic modulus

- The DCP Layer Structure Number (DSN) is the total number of hammer blows needed to penetrate a pavement layer. It provides an indication of the relative structural contribution of a particular layer.
- The DCP Pavement Structure Number (DSN_{800}) is defined as the total number of blows needed to penetrate 800 mm (31.5 in) into the pavement structure. It provides an indication of the overall pavement strength of the layers underlying the hot-mix asphalt.

Table 2.2: Example Relationship between DN and Stiffness

DN Range (mm/blow)	Approx CBR Range* (%)	Stiffness* (MPa)*	Equivalent FWD Deflection Modulus Zone*
< 4	>70	> 258	A
4 – 5	50 – 70	204 – 258	A
5 – 8	30 – 50	124 – 204	A
8 – 14	30 – 15	68 – 124	A
14 – 19	10 – 15	48 – 68	A
19 – 25	7 – 10	37 – 49	B
25 – 30	< 7	30 – 37	B
30 – 35	-	26 – 30	B
> 35	-	< 26	C
* Values are approximate only and should be used with caution and only as a guide.			

DCP Numbers should be entered into a spreadsheet and an average and standard deviation calculated. Results should be plotted similar to the FWD analysis (Figure 2.10) to refine the delineation of uniform sections and identify potential problem areas.

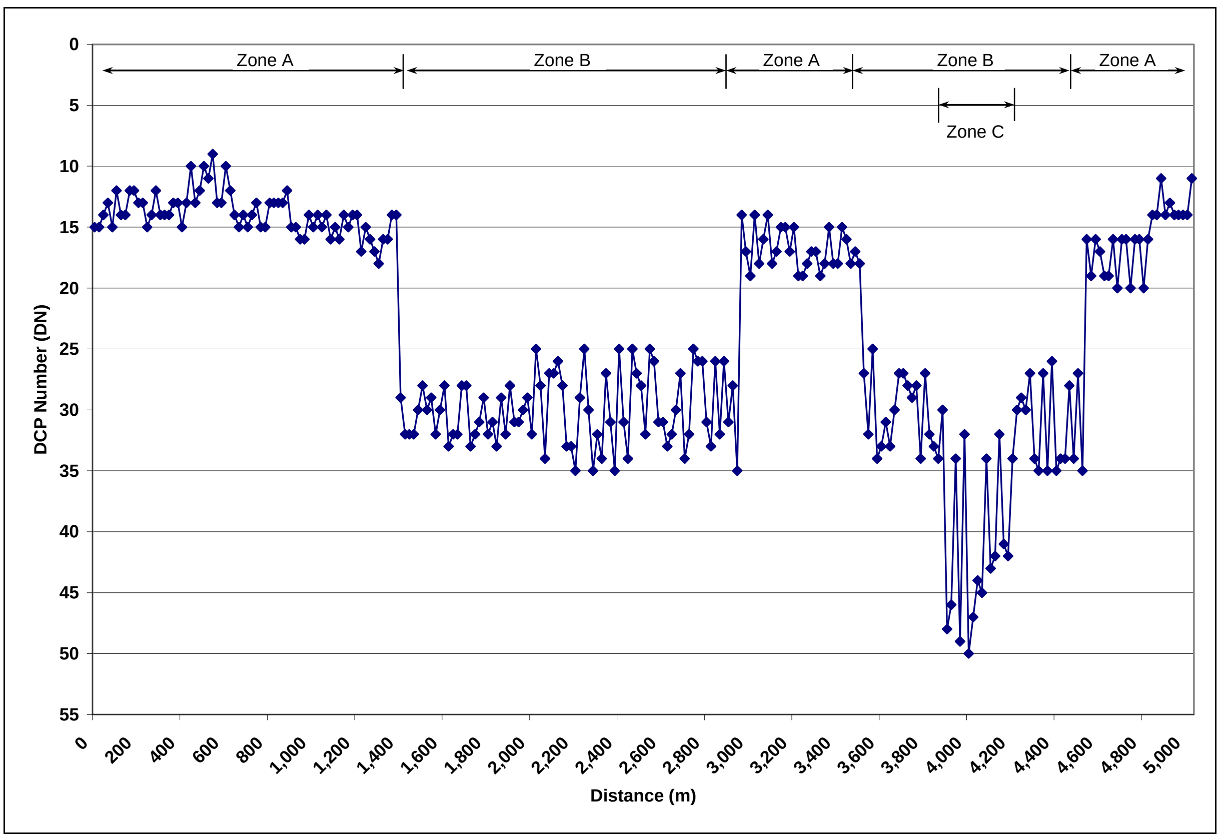


Figure 2.10: Example DCP Number analysis.

2.4.6 Pavement Layer Assessment from Test Pits

Pavement layers are assessed by excavating test pits, which serve a number of purposes, including providing a cross section of the pavement layers and subgrade, an indication of subgrade moisture

conditions, and a source of material for laboratory mix designs. One test pit should be excavated in each uniform section identified during the subgrade strength assessment (see Section 2.4.2). In longer uniform sections, a test pit should be excavated at least every 3.0 mi (5.0 km). Additional test pits should be excavated in problem areas (example Zone B and Zone C in Figure 2.3 and Figure 2.10) to determine appropriate corrective action, and in areas of obvious change (cut-to-fill transition, reconstructed areas, etc.).

Pavement Layer Excavation

Test pits are excavated across the outer wheelpath. Dimensions of the test pit are approximately 3.5 ft x 3.5 ft. x 3.5 ft (1.0 m x 1.0 m x 1.0 m), which will provide sufficient material for laboratory mix design purposes. Excavation of the asphalt and top 2.0 in. (50 mm) of the base material is best undertaken with a cold milling machine (Figure 2.11) to ensure that representative samples are collected (slabs of hot-mix asphalt removed from the test pit and crushed in the laboratory may not provide representative aggregate grading and shape, both of which influence mix behavior and consequently also the mix design). The hot-mix asphalt and top 2.0 in. (50 mm) of the underlying material (i.e. total of 10 in. to 12 in. [250 mm to 300 mm]) will be used for the mix design and should be separated from the rest of the material excavated (Figure 2.12).

Figure 2.11: Test pit excavation with milling machine.

Figure 2.12: Layer samples.

Pavement Layer Assessment and Analysis

When the test pit has been excavated, clean the test pit face and delineate the individual layers with string. Carefully inspect the test pit face and assess and document the following (Appendix A, Form 8):

- **Layer moisture contents**. Remove a sample of material from each of the underlying layers and place in a sealed container immediately after excavation for moisture content determination. This will be used to refine the DCP analyses and to establish a mixing moisture content range for recycling operations.
- **Layer thickness.** Measure each layer thickness across the test pit face and calculate an average thickness. This will be used to determine the recycling depth, to verify the as-built documentation, to verify the DCP determined layer thicknesses, and to decide whether additional gravel needs to be imported. A minimum combined hot-mix asphalt and base layer (Class 2 aggregate base or cement-treated base) of between 8.0 in. and 10.0 in. (200 mm and 250 mm) is preferred for FDR-FA projects, provided that the road has adequate drainage.
- **Hot-mix asphalt assessment.** Inspect each layer of hot-mix asphalt to identify the presence of rubber, fabrics, or other materials that may influence the recycling operation. The thickness of the hot-mix asphalt should not exceed 10.0 in. (250 mm) unless premilling of the asphalt is possible.
- **Base-course assessment.** Inspect the base-course to assess material type, gradation, presence of large aggregate, and plasticity range, and to identify signs of contamination from the subgrade (pumping) and/or evidence of severe moisture fluctuations (mottling). Moisture problems will typically be associated with high subgrade deflection modulus values.
- **Subgrade assessment.** Inspect the subgrade to identify moisture condition, signs of fluctuating moisture conditions (mottling), signs of shearing (slickenslides), inadequate support for the overlying layer (punching of aggregate), and any other problems that could influence the decision to recycle.

2.4.7 Material Sampling

Representative material samples are required for the laboratory mix design determination and should be collected during the excavation of the test pits. Suggested sample quantities are listed in Table 2.3. Sample bags must be clearly labeled, and include test pit location and layer description.

Table 2.3: Suggested Test Pit Material Sample Sizes

Material/Layer	Sample Size	
	lbs	kg
Old HMA + top 2.0 in. (50 mm) of underlying material.	950	450
Base-course (or first underlying layer)	110	50
Subbase (or second underlying layer)[1]	110	50
Selected layer (or third underlying layer)[1]	110	50
Subgrade	110	50

[1] Layer may not be present.

2.4.8 Indicator Tests

Standard indicator tests (Table 2.4) are required to characterize the imported and subgrade materials to determine whether to proceed with the detailed design. Additional indicator tests are carried out in the mix design phase (see Chapter 3). Note that the grading analysis of the hot-mix asphalt and top 2.0 in. (50 mm) of the underlying material should be undertaken on the equivalent of about 10.0 in (250 mm) of material. If the hot-mix asphalt layer is thicker than 10.0 in. a sufficient proportion of the sample should be scalped to obtain the correct proportion of hot-mix asphalt and underlying material.

Table 2.4: Indicator Tests on Test Pit Materials

Material/Layer	Grading (CT 202)	Atterberg Limits (CT 204)	R-Value (CT 301)
Old HMA + top 2.0 in. (50 mm) of underlying material[1].	✓	-	-
Base-course (or first underlying layer)	✓	✓	-
Subbase (or second underlying layer)[2]	✓	✓	-
Subgrade	-	✓	✓

[1] Maximum equivalent of 10.0 in. of HMA. [2] Layer may not be present. [3] 200 mm – 250 mm

Indicator Test Result Analysis

The indicator test results are used to determine whether the available materials are suitable for recycling. If any of the following conditions apply, additional aggregate base material will need to be imported, which will influence the design, cost, and construction of the project.

- The blend of hot-mix asphalt millings and base material has a fines content (percentage passing #200 [0.075 mm] sieve) of more than 15 percent.
- The plasticity index of any of the underlying layers exceeds 12 percent.
- The R-value of the subgrade material is too low to achieve a reliable and economical structural design.

2.4.9 Analysis Summary

The analyses of each of the components of the project investigation study should be summarized in the form of a checklist described below (example in Appendix A, Form 9). This will be used to make a final recommendation on the use of FDR-FA to rehabilitate the road, or to consider an alternative rehabilitation method. The flow chart in Figure 2.13 can be used to guide the process.

- **FWD and DCP analysis.**
  - What percentage of the project falls into each of the three categories? Ideally, less than 10 percent of the road should have a calculated subgrade modulus of less than 45 MPa.
  - The implications of improving weaker areas will need to be considered when making a decision.
- **Visual and test pit assessment.**
  - What is the extent of subgrade and/or drainage problems on the project, do digout repairs fail again after the rainy season, and are roadside activities (e.g., irrigation) influencing road performance?
  - The implications of improving areas with weak subgrade and/or constructing additional drainage infrastructure will need to be considered when making a decision.
- **Layer thickness assessment.**
  - On thinner pavement, is there sufficient material to recycle?
  - On thicker pavement, will pre-milling be required; and if so can the recycled material be used in other projects (e.g., in hot-mix asphalt or as aggregate base)?

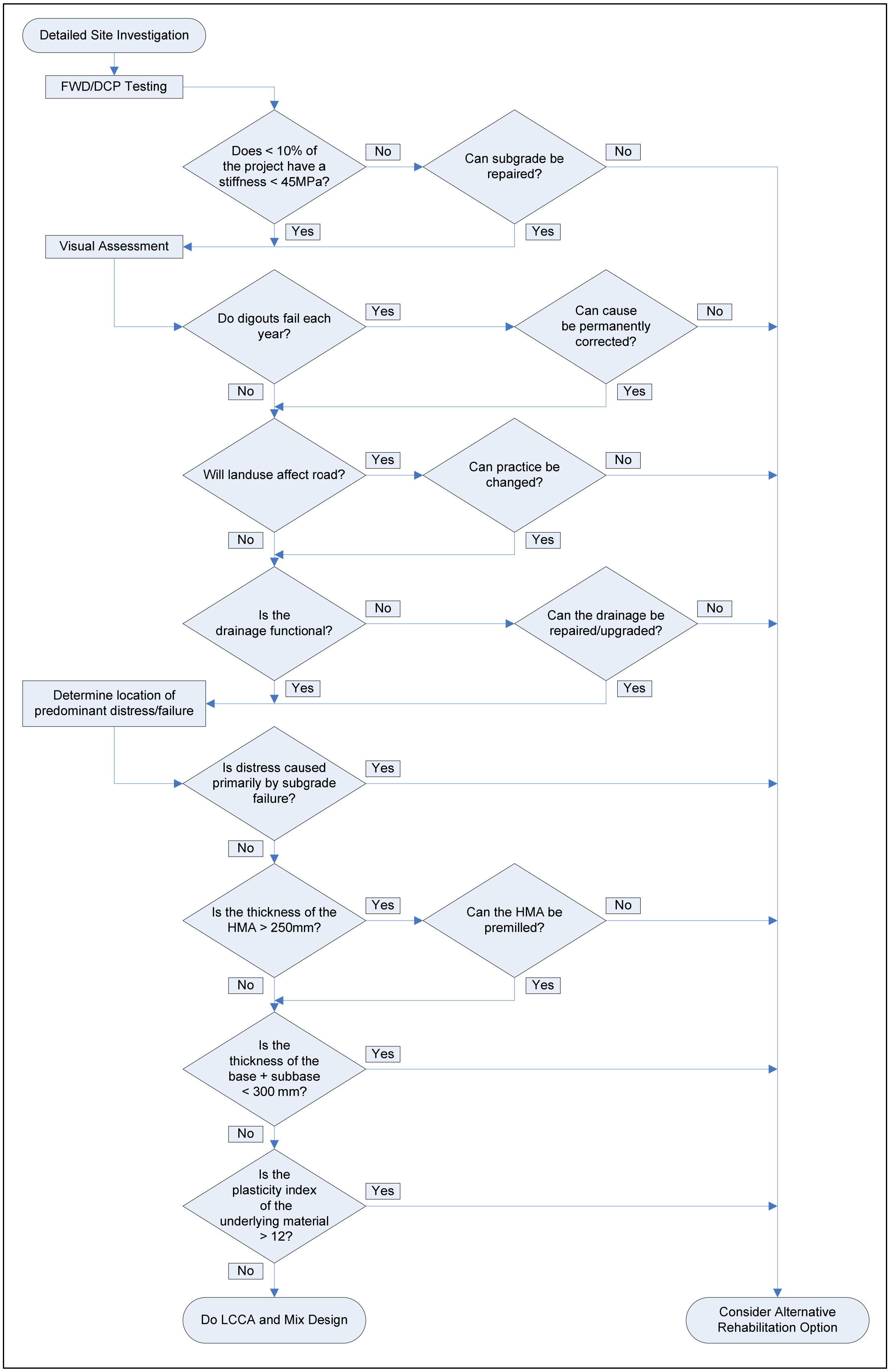


Figure 2.13: Flowchart for detailed site investigation decision making. (Notes: 250 mm = 10 in, 300 mm = 12 in).

2.4.10 Life-Cycle Cost Analysis and Life-Cycle Analysis

A life-cycle cost analysis, using the Caltrans *Life-Cycle Cost Analysis Procedures Manual* and software program *(9)*, should be used to quantify the economic benefits of using FDR-FA to rehabilitate the road compared to other approaches.

Life Cycle Assessment (LCA) is the comparison of the environmental impact of one rehabilitation strategy versus another, similar to the cost comparisons performed in LCCA. Caltrans does not have a requirement to perform LCA or a standard process, however, analysis of these factors may be desirable for some projects. Typical elements of an LCA would be comparison of the quantities of virgin aggregate used, the quantities of HMA, and the mileage of trucks hauling in new material and removing milled material. Until more formal procedures are developed for LCA, it is important to compare quantities of same items. It is expected that assessment of environmental impacts will become more important and will be considered with cost as a criterion in the future.

2.5 Project Investigation Report

A brief project investigation report should be prepared on completion of the detailed site investigation as part of the Project Study Report (PSR). The report should include the following:

- Project details
- The desktop study report (Section 2.2).
- The preliminary site investigation report (Section 2.3.4).
- Headquarters Office of Engineering and Specification Development acknowledgement.
- FWD analysis, showing uniform sections and potential problem areas (Section 2.4.2).
- Visual assessment summary (Section 2.4.3).
- Layer thickness analysis (Section 2.4.4).
- DCP Number analysis (Section 2.4.5).
- Test pit assessment (Section 2.4.6).
- Material sample inventory (Section 2.4.7).
- Indicator test results (Section 2.4.8).
- Analysis checklist (Section 2.4.9).
- Life-cycle cost analysis summary (Section 2.4.10).
- Recommendation. Engineering judgment, based on the findings of a risk assessment, life-cycle cost analysis, and life-cycle assessment should be used together with results of the project investigation to make a recommendation on proceeding with rehabilitation using FDR-FA, or to consider an alternative rehabilitation process.

2.5.1 Record of Decision

A record of decision (i.e., continue with mix and structural design or consider alternative rehabilitation method) should be recorded in the project file.

3 MIX DESIGN: LEVEL-1 TESTING

3.1 Introduction

Mix design is a key component of the FDR-FA design and is carried out to assess the properties and variability of the sampled materials, to identify the best available binder, to determine optimum foamed asphalt and active filler application rates, and to gain an understanding of expected performance of the road after rehabilitation. **The cost and effort involved in optimizing the mix design are inconsequential in terms of the overall costs of the project, minimizing the risk of premature failure and maximizing the benefits of extending the useful life of the road.**

Two levels of mix-design testing are discussed in this guideline: *Level-1* and *Level-2*.

- The Level-1 mix design procedure should be followed by design engineers and practitioners with limited or no experience of the FDR-FA process, and by design engineers and practitioners who have experience with FDR-FA but not with the materials being assessed. Level-1 testing should also be followed on higher risk projects (e.g., roads with heavy truck traffic [Traffic Index values between 10 and 12] and roads with specific problems identified during the project investigation). Level-1 testing requires a minimum of 72 Indirect Tensile Strength tests.
- The Level-2 mix design procedure (see Chapter 4) can be followed by design engineers and practitioners who have experience with previous FDR-FA projects and are confident in selecting appropriate target asphalt binder contents, active filler type, and target active filler contents. Level-2 testing requires a minimum of 36 Indirect Tensile Strength tests.

3.2 Overview of California FDR-FA Mix Design Procedure

The key features of the mix design procedure covered in this guideline include:

- All mix designs use a foamed asphalt/active filler combination.
- Foamed asphalt and active fillers serve different purposes in the stabilization process, and their application rates are based on separate tests and different criteria.
- The stabilized layer is not a purely asphalt-stabilized or cementitious-stabilized layer (i.e. cement or lime), but rather a “hybrid” with unique properties.
- A single strength test method, namely the indirect tensile strength (ITS) test, is used.
- Two sets of ITS tests are carried out, each with its own curing procedure. One set represents conditions during earlier opening to traffic; the second set assesses longer-term performance considerations.
- Material evaluation is primarily focused on the strength of water-soaked specimens.
- The range of asphalt binder and active filler contents tested is narrower than that in other guidelines, but more emphasis is placed on assessing and controlling variation in mix properties induced by variability in the parent materials and inevitable inconsistencies in laboratory testing.
- Additional testing to refine/optimize the mix design is encouraged.

A typical mix design procedure for FDR-FA applications involves the following eight required tasks and one optional task, each one of which determines the value of one specific design variable from laboratory testing and analysis of the results.

1. Determine the grading of the pulverized material (Section 3.4.1).
2. Select the active filler type(s) (Section 3.4.2).
3. Determine the compaction curve of the pulverized material (Section 3.4.3).
4. Select the asphalt binder and determine the foaming parameters (Section 3.4.4).
5. Determine the mixing moisture content (MMC) (Section 3.4.5).
6. Determine the asphalt binder content (Section 3.4.6).
7. Determine the active filler content (Section 3.4.7).
8. Determine the reference density for field compaction (Section 3.4.8).
9. Determine the tensile strength retained and temperature sensitivity of the mix design (optional) (Section 3.4.9).

Materials typically vary along the length of a project. An initial indication of material variability will be obtained from the assessment of cores and test pits. More than one mix design may need to be determined if there is considerable variation between the materials.

3.3 Test Methods and Material Requirements

The test methods and material requirements for mix design testing are summarized in Table 3.1. Appropriate measures should be taken (i.e., sufficient splitting, sieving, and batching, etc.) following Caltrans procedures to ensure that the pulverized material used for all the tasks has consistent properties. Apart from the grading analysis, all testing should be carried out on material that passes the 3/4 in. (19 mm) sieve.

Table 3.1: Test Methods and Material Requirements for Mix Design Testing

Parameter	Test Method	Number of ITS Tests	Quantity of Material Required		
			Description	lbs	kg
Pulverized material grading	CT 202	-	Aggregate[1]	45	20
Pulverized material compaction curve	AASHTO T-180[2]	-	Aggregate	80	35
Foaming characteristics	See Section 3.4.4	-	Binder	110	50
Mixing moisture content	See Section 3.4.5	-	Aggregate	70	30
Asphalt binder content	See Section 3.4.6	48	Aggregate	175	80
Active filler content	See Section 3.4.7	24	Aggregate	90	40
Reference density	See Section 3.4.8	-	Aggregate	30	15
Tensile strength ratio[3]	See Section 3.4.9	12	Aggregate	35	20
Temperature sensitivity[3]	See Section 3.4.9	12	Aggregate	45	20
	Total ITS tests[4]	72[4]	Tot agg	570[5]	260[5]

[1] Aggregate is full-depth pulverized material, including the underlying base, subbase, and/or subgrade (native) material.
[2] Method D (see Section 3.4.3 for justification for using this method over CT 216).
[3] Optional. [4] Excludes optional tests. [5] Includes optional tests.

The following general issues also need to be considered in preparing for the mix design testing:

- Pulverized materials sampled from the field will contain varying amounts of moisture. All sampled materials should therefore be sufficiently dried following CT 201 (Section D) in a forced draft oven (maximum 140°F [60°C]) to obtain a relatively consistent moisture content prior to the start of any testing. Complete material separation on the #4 (4.75 mm) sieve and a free-flowing condition in the portion passing this sieve is considered satisfactory. The residual moisture content after drying and the moisture loss from evaporation during foamed asphalt mix preparation will need to be determined to ensure that the correct quantities of water are added in each test and that the specified mixing moisture content can be obtained.

- Customized laboratory foaming equipment (e.g., Wirtgen WLB-10 and the associated mixer) are required to undertake an FDR-FA mix design. A twin shaft pug mill mixer is recommended as the material agitation provides a reasonable exposure of the fines to the foamed asphalt spray, and is considered to be generally representative of the mixing action in full-scale recycling projects. The mixer used should have:
  - A capacity of between 22 lb and 55 lb (10 kg and 25 kg).
  - The capability to receive foamed asphalt sprays directly from the spray nozzle.
  - Sufficient power to completely agitate the material during mixing.

Aggregate Mixer

- Aggregate and ambient temperatures should be controlled and recorded during mixing and prior to compaction. Ambient temperatures should be maintained at approximately 77°F (25°C). Aggregate temperatures should be maintained in a range of 68°F to 77°F (20°C to 25°C), which typically requires the pulverized material to be preheated to around 86°F (30°C), depending on the ambient temperature. The mix temperature immediately before foamed asphalt spraying should be measured and recorded.

3.4 Testing, Analysis, and Reporting

3.4.1 Pulverized Material Grading

Testing

Grading of the pulverized material (a representative sample of all the layers that will be recycled) should follow standard Caltrans testing procedures (CT 202).

Analysis

The material grading of the full-depth pulverized material, including the underlying base, subbase, and/or native material should conform to the requirements for Class 2 Aggregate Base (1½ in. [37.5 mm] maximum) in the Caltrans Specifications, with the exception of the fines content (i.e., material passing the #200 [0.075 mm] sieve), which should be between 5.0 and 12 percent (Table 3.2). The fines content does not include the active filler.

Grading test results should be interpreted as follows:

- In the unlikely event of the fines content being below 5.0 percent, extra non-plastic fines (in addition to the active filler) may be required. This can be achieved by increasing the recycling depth to incorporate more fines from the underlying layer, or by importing non-plastic fines from another source and spreading them on the road surface prior to recycling.

- If the fines content is between 12 and 15 percent, recycling can proceed; however, a higher binder content may be required to ensure that the fine particles are adequately coated.
- If the fines content is between 15 and 20 percent, consideration should be given to decreasing the recycling depth to reduce the quantity of fines from the underlying layers. Alternatively, additional testing can be carried out to determine whether the required soaked indirect tensile strengths can be achieved. Binder contents will probably need to be increased.
- Projects with fines contents higher than 20 percent should not be considered for FDR-FA rehabilitation, given that very high binder contents will be required and soaked indirect tensile strengths will usually be too low for satisfactory performance.

Table 3.2: Recommended Grading for FDR-FA Materials

Sieve Size		Percent Passing 1.5 in. (37.5 mm) Maximum	
US	Metric	Operating Range	Contract Compliance
2	50	100	100
1½	37.5	90 – 100	87 – 100
1	25	-	-
¾	19	50 – 85	45 – 90
#4	4.75	25 – 45	20 – 50
#30	0.6	10 – 25	6 – 29
#200	0.075	5 – 12	5 – 15

<u>Reporting</u>

Document the test results on a summary sheet (example in Appendix A, Form 10).

3.4.2 Active Filler Selection

At least 1.0 percent active filler (portland cement or hydrated lime) should be used in all FDR-FA projects to provide some initial strength for early opening to traffic. Portland cement should be used as the active filler in the mix design if the aggregates in the pulverized material are predominantly of acid crystalline (e.g., granite), high silica (e.g., quartzitic), or arenaceous (e.g., sandstone) origin. Mix design testing with both portland cement and hydrated lime is recommended for materials of basic crystalline (e.g., basalt and andesite), argillaceous (e.g., shale), and carbonate (e.g., limestone) origin until sufficient experience is gained on FDR-FA projects with these materials. If the design engineer has local experience with specific active fillers on the materials being assessed, only one active filler need be tested. Record the choice of active filler(s) on the results summary sheet (Form 10 in Appendix A).

3.4.3 Pulverized Material Compaction Curve

<u>Testing</u>

Determination of the compaction curve for the pulverized material (representative sample of all the layers that will be included in the recycling process) must follow the AASHTO T-180 (Method D) test method.

Caltrans CT 216 is not recommended as this test is designed for quality control during construction and is not sufficiently accurate for determining maximum dry density and optimum moisture content for mix design laboratory tests.

The selected active filler is added to the material at a rate of 1.0 percent portland cement or 2.0 percent hydrated lime. Five samples, each approximately 15 lb (7.0 kg), are required for this test.

Note that AASHTO T-180 allows breaking compacted specimens and reusing the material. This practice is not appropriate for FDR-FA mix design.

Analysis and Reporting

Document the optimum moisture content (OMC) and maximum dry density (MDD) of the full-depth pulverized material with active filler on the results summary sheet (Form 10 in Appendix A). The OMC will be used as the starting moisture content for determining the mixing moisture content (Section 3.4.5).

3.4.4 Asphalt Binder Selection and Foaming Parameters

General Issues

California uses the Performance Graded (PG) system as the primary asphalt binder specification system for pavement applications. Although the current PG grade binder selection guide for hot-mix asphalt is used for selecting an appropriate asphalt binder grade for a specific climatic region in the state, it cannot be used as an indicator of suitability of a specific binder for foamed asphalt applications. Instead, the selection of asphalt binders that are suitable for foamed asphalt applications should be primarily based on the binder foaming characteristics (half-life and expansion ratio). Although asphalt binder types are typically identified by the refinery and PG grade, there is no guarantee that the foaming characteristics will always be the same, given that different crude oil sources are used and that antifoaming additives may be added for safer transportation. Design engineers must ensure that the asphalt binder used for the laboratory mix design process is representative of the binder that will be used throughout the entire project. Foaming characteristics should also be checked each day during construction to monitor conformance with the mix design.

Research *(1)* has shown that the foaming characteristics of the binders available in California vary. The research also showed that asphalt binders with better foaming characteristics yielded better performance. A range of available binders should therefore be considered during mix design testing, and final selection should be based on optimized performance, rather than price. Higher prices (i.e., higher transportation costs to bring in a better binder) are often offset by lower application rates and improved compaction and strengths. A simple cost-benefit calculation can be carried out to determine whether it is appropriate to transport a better binder.

Definition of Foam Expansion Ratio and Half-Life

Asphalt foam (asphalt binder in the foamed state) is usually characterized by its expansion ratio (ER) and half-life.

Expansion ratio (ER) is a measure of the viscosity of the foam and will determine how well it will disperse in the mix. It is calculated as the ratio of the maximum volume of foam relative to its original volume.

Half-life is a measure of the stability of the foam and provides and indication of the rate of collapse of the foam. It is important to note that two distinct methods of calculating the half-life are used by practitioners:

- *Method 1*: Half-life is the time measured in seconds for foamed asphalt to subside to half of the maximum volume **from the maximum volume**.
- *Method 2*: Half-life is the time measured in seconds for foamed asphalt to subside to half of the maximum volume **from the time the foam nozzle shuts off**.

***Method 2* must be followed for FDR-FA mix design in California.** (*Method 2* is preferred, given that the accurate determination of the point at which the foam reaches its maximum volume [required in *Method 1*] is difficult, and that the foam is both stable and workable in the time period between the foam nozzle shutting off [at 0 seconds] and the foam reaching its peak volume.)

Testing

Testing must follow the procedures prescribed in the laboratory foam apparatus operating manual. At least 90 lb (40 kg) of binder is required to fully characterize the foaming characteristics of an asphalt binder type. Binder should be preheated before testing.

Asphalt binder temperature and foaming water ratio (the ratio between the water injection rate and the asphalt discharge flow rate) are the two variables considered in asphalt foaming. For each asphalt type, a total of 16 combinations should be tested. This is based on a factorial of four asphalt temperatures (300°F, 320°F, 340°F, and 360°F [150ºC, 160ºC, 170ºC, and 180ºC]) and four foaming water ratio levels (2.0, 3.0, 4.0, and 5.0 percent).

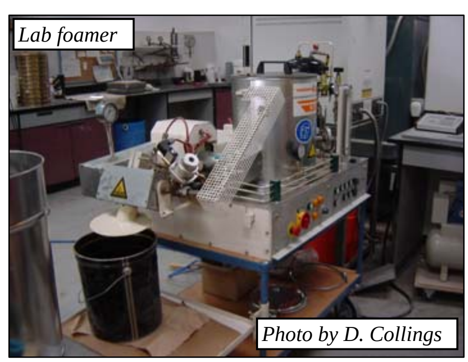

Lab foamer

Photo by D. Collings

The average of three replicate sprays is recorded. Experience has shown that precise control of the asphalt temperature is difficult and therefore a tolerance for temperature variation, typically ± 4°F (2ºC), should be specified.

Analysis

Record the test results for foaming characteristics on an appropriate form (example in Appendix A, Form 11). Two principles of foaming characteristics are often referred to in the literature:

- For a given foaming water ratio, increasing the asphalt temperature results in higher expansion ratios and longer half-life, and
- For a given asphalt temperature, increasing the foaming water ratio results in higher expansion ratios, but shorter half-life.

Research in California *(1)* has shown that these principles are not necessarily true for the binders available in the state and test results should therefore not be extrapolated based on these two "rules". Instead, additional tests at foaming water ratios or asphalt temperatures should be carried out if required.

The results of foaming characteristics testing are used to select the most appropriate asphalt binder type (source and PG grade) and to identify an acceptable working range of asphalt temperature and foaming water ratio for this particular binder. The minimum foaming characteristics for projects in California are:

- Expansion ratio: 10 (i.e. 10 time the original volume)
- Half-life (using *Method 2*): 12 seconds.

In principle any binder type that meets these requirements can be used for FDR-FA applications. However, binder dispersion in the aggregate improves with increasing expansion ratio and half-life, and better binder dispersion leads to better material properties.

If more than one of the asphalt binders meets the above minimum requirement, it is recommended that the choice be made using the following criteria:

- If two asphalt binders both meet the minimum requirements but one has a higher expansion ratio and the other has a longer half-life ($\tau_{1/2}$), then the product of the expansion rate and half-life is used to select the binder. Use the asphalt binder with the highest value of the product of the two parameters.
  - Example
    Asphalt A has ER = 20 and $\tau_{1/2}$ = 12 seconds and *Asphalt B* has ER = 15 and $\tau_{1/2}$ = 20 seconds.
    Asphalt A has expansion ratio/half-life product of 20 x 12 = 240
    Asphalt B has expansion ratio/half-life product of 15 x 20 = 300
    Asphalt B should therefore be selected.
- If two asphalt binders both meet the minimum requirements, select the binder with the least variation in expansion ratio and half-life over the range of temperatures. Stability in expansion ratio

and half-life across a range of temperatures implies that the foam will be more tolerant of changes in aggregate temperature and ambient temperature, and the control of field foaming parameters will be easier.

- If two asphalt binders both meet the minimum requirements and both have similar stability, select the binder with the lower viscosity.
- Selection of the asphalt binder based on cost-benefit is difficult given the limited current understanding of the longer-term performance of FDR-FA pavements and the absence of comparative tests. However, some indication of performance will be gained during the mix design testing, and design engineers/contractors should use engineering judgment in specifying a "better" binder at slightly higher cost if the benefits (i.e., lower application rate, improved strengths, working in colder ambient temperatures, etc.) are obvious. In these instances, justifications for the decision should be documented.

Once the asphalt type is selected, the optimum asphalt temperature and foaming water ratio are determined for the mix design testing. If an optimum combination of expansion ratio and half-life is not obvious, the combination should be adjusted so that the product of the two values is maximized. Finally, an acceptable range of asphalt temperatures and foaming water ratios for construction should be determined. This range is defined as the selected temperature, ±10°F (5ºC), and selected optimum foaming water ratio, ±0.5 percent.

Reporting

Record the selected asphalt binder, alternative asphalt binder (if applicable), optimal expansion ratio and half-life, target asphalt temperature and foaming water ratio, and acceptable range of asphalt temperature and foaming water ratio on the results summary sheet (Form 10 in Appendix A).

3.4.5 Mixing Moisture Content Determination

General Issues

The mixing moisture content (MMC) of a foamed asphalt mix is defined as the moisture content in the pulverized material when foamed asphalt is injected.

In the procedure described in this chapter, MMC is practically the same as the compaction moisture content (CMC). MMC and CMC influence the foamed asphalt mix properties in terms of asphalt dispersion and compaction behavior of the material (i.e., density for a given compaction method). The dispersed asphalt can potentially act as a compaction aid and hence the optimum moisture content (OMC) for a foamed asphalt mix to achieve maximum density is generally not the same as the OMC of the parent pulverized material.

Testing

There is currently no standard test method for determining the MMC for foamed asphalt mixes, as this is typically dependent on the laboratory asphalt foaming unit and mixer used. A suggested method and example is provided below, in which the MMC is determined by undertaking a simple sensitivity analysis using the following procedure:

- Prepare four samples (15 lb [7.0 kg] each) of pulverized material.
- Place the material in the mixer, add the selected active filler at the approximate target rate (actual rates will be determined in a later task), and begin agitation. The material should be thoroughly mixed.
- Add sufficient water to meet the following four target mixing moisture contents (note that some moisture will already be present in the material).
  - OMC of the pulverized material determined in Section 3.4.3
  - OMC of the pulverized material minus 1.0 percent
  - OMC of the pulverized material minus 2.0 percent
  - OMC of the pulverized material minus 3.0 percent
- Spray foamed asphalt onto the material following the procedure specified in the laboratory foam device manual. Set the foamed asphalt content to an equivalent of 3.0 percent of the mass of the dry material (actual rates will be determined in a later task). Set the asphalt temperature and foaming water ratio to the values determined in Section 3.4.4.
- Compact the material according to AASHTO T-180 (Method D), and measure the moisture content following AASHTO T-265 (see Section 3.4.3).
- Select the MMC that yields the highest dry density of the foamed asphalt mix and record the result on the summary results sheet (Form 10 in Appendix A). Determine the percentage of OMC. (Experience has shown that MMC values are typically between 75 and 90 percent of the OMC of the pulverized material.)

3.4.6 Asphalt Binder Content Determination

General Issues

Although the final mix design will include both asphalt binder and an active filler, it is important to accurately determine the contents of each separately. In this task, the optimum asphalt binder content is determined, with no active filler added. It should be noted that the old asphalt in the recycled material is *not* factored into the binder content, as the cold recycling temperatures are significantly below the minimum temperatures required to soften the old asphalt sufficiently for it to act as a binder.

Experience has shown there is a high variation in test results between replicate specimens from the same batch of mix, and between replicate batches of mixes. Therefore, at least two batches of mix per asphalt content and at least six replicate specimens per batch must be prepared and tested to obtain a reliable indication of performance.

Asphalt Binder Application Rates

Research *(1)* has shown that optimum asphalt binder contents on recycling projects are usually dependent on the fines content of the recycled material (i.e., increasing binder content with increasing fines content), but are likely to be in the vicinity of 3.0 percent by mass of the dry pulverized material. However, a sensitivity analysis should be carried out around this binder content to ensure that optimum results are achieved. An untreated control and three asphalt binder contents (2.0, 3.0, and 4.0 percent) are therefore tested in this sensitivity analysis. Engineering judgment or a second round of testing can be used to optimize the binder content to half-percentages (i.e., 2.5 or 3.5 percent) if required.

Mix Preparation, Curing, and Conditioning

The mix is prepared as follows:

- Prepare eight samples (25 lb [10 kg] each) of pulverized material, sufficient for testing an untreated control and three asphalt binder contents, each with a replicate. Do not add active filler.
- Place the prepared material into the mixer and begin agitation.
- Add sufficient water to achieve the MMC determined in Section 3.4.5 and mix thoroughly. To accomplish this, keep the mixer running for approximately five minutes to allow the moisture content to equilibrate.
- Spray the specified foamed asphalt content onto the pulverized material (skip this step for the untreated control).
- Seal the prepared mix in a suitable container.
- From each batch, prepare six specimens with a diameter of 4 in. (100 mm) and a height of 2.5 in. (63.5 mm), complying with the specimen preparation procedure described in the Asphalt Institute's Mix Design Methods for Asphalt Concrete (MS-2) (Marshall Method of Mix Design). Seventy-five compaction hammer blows are applied on each face of a specimen. All compaction must be completed within eight hours of the mixes being prepared.
- Extrude the specimens from the mold immediately after compaction and cure in a forced draft oven at 105°F (40ºC) for 72 hours.
- After curing, remove the specimens from the oven and place in a water bath for 24 hours. Water temperature should be between 68°F and 77°F (20ºC and 25ºC). Water depth should be 4.0 in. (100 mm) above the specimen surface. Specimens must not be stacked.
- After soaking, remove the specimens from the water and allow them to drain for 60 minutes and equilibrate to the room temperature. Ambient temperature should be 77°F ± 4°F (25°C±2ºC). Specimens should be covered with a damp cloth to prevent excess evaporation. Care should be taken at all times to prevent damage to the specimens.

Testing

The specimens are evaluated using an indirect tensile strength test. Testing should follow California Test 371 (CT 371): *Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced*

Damage. A displacement controlled loading rate of 2.0 in. (50 mm) per minute is used (Sections J.2 and J.3 in the method). The tensile strength is calculated based on Section K of the method.

<u>Analysis and Reporting</u>

The indirect tensile strength test results are analyzed as follows:

ITS Test
Photo by D. Collings

- For each batch of mix, calculate the average strength of the replicate specimens. If a specimen disintegrates during soaking (possible for untreated control specimens), assume a strength of 1.5 psi (10 kPa).
- Assess the variability of the strength for each mix by calculating the standard deviation for the specimens within the batch. Two of the six replicate specimens prepared for each mix can be excluded from the calculation if the specimens have been damaged by soaking or handling. If the standard deviation of the strength is more than 15 percent of the average strength (i.e., coefficient of variation is greater than 15 percent), then the results for this mix should be rejected and the test repeated.
- Assess the variability between the two batches at the same asphalt binder content. For each asphalt content level, the difference between the average strengths of the two replicate batches should be less than 15 percent of the combined average strength if the two mixes were both prepared on the same day, or less than 20 percent if prepared on two separate days. If these limits are exceeded, new specimens should be prepared and tested.
- Calculate the average strengths for each asphalt content level from the average of the two replicate batches.
- Determine the soaked strength improvement ($ITS_{imp@n\%}$) by calculating the difference between the soaked strength of each mix and that of the untreated control mix (ITS_C) as follows:
  - For 2.0 percent asphalt binder content, $ITS_{imp@2\%} = ITS_{2\%} – ITS_C$
  - For 3.0 percent asphalt binder content, $ITS_{imp@3\%} = ITS_{3\%} – ITS_C$
  - For 4.0 percent asphalt binder content, $ITS_{imp@4\%} = ITS_{4\%} – ITS_C$
- Determine the optimum asphalt binder content using the following criteria (Figure 3.1 provides a visual summary of the process):
  - If $ITS_{imp@3\%} > 15$ psi (100 kPa), then use 3.0 percent as the default asphalt content.
  - If $ITS_{imp@3\%} < 15$ psi (100 kPa) and $ITS_{imp@4\%} > 15$ psi (100 kPa), then use 4.0 percent as the design asphalt content.
  - If $ITS_{imp@3\%} > 15$ psi (100 kPa) and $ITS_{imp@4\%} > 1.25 \times ITS_{imp@3\%}$ then 4.0 percent can be used as an alternative design asphalt content, as shown in the “Optional Decision” part of Figure 3.1. The design engineer should determine the final value according to experience and other criteria (e.g., likelihood of fines content between 12 and 15 percent).
  - If $ITS_{imp@2\%} > 15$ psi (100 kPa) and $ITS_{imp@2\%} > 0.8 \times ITS_{imp@3\%}$, then 2.0 percent can be used as an alternative design asphalt content as shown in the “Optional Decision” part of Figure 3.1. The design engineer should determine the final binder content according to experience and other criteria.

- If $ITS_{imp@4\%}$ < 15 psi (100 kPa) then the material should be considered as unsuitable for FDR-FA. The recycled source material will need to be modified, or an alternative rehabilitation strategy should be investigated.

- Record the selected binder content on the summary sheet (Form 10 in Appendix A).

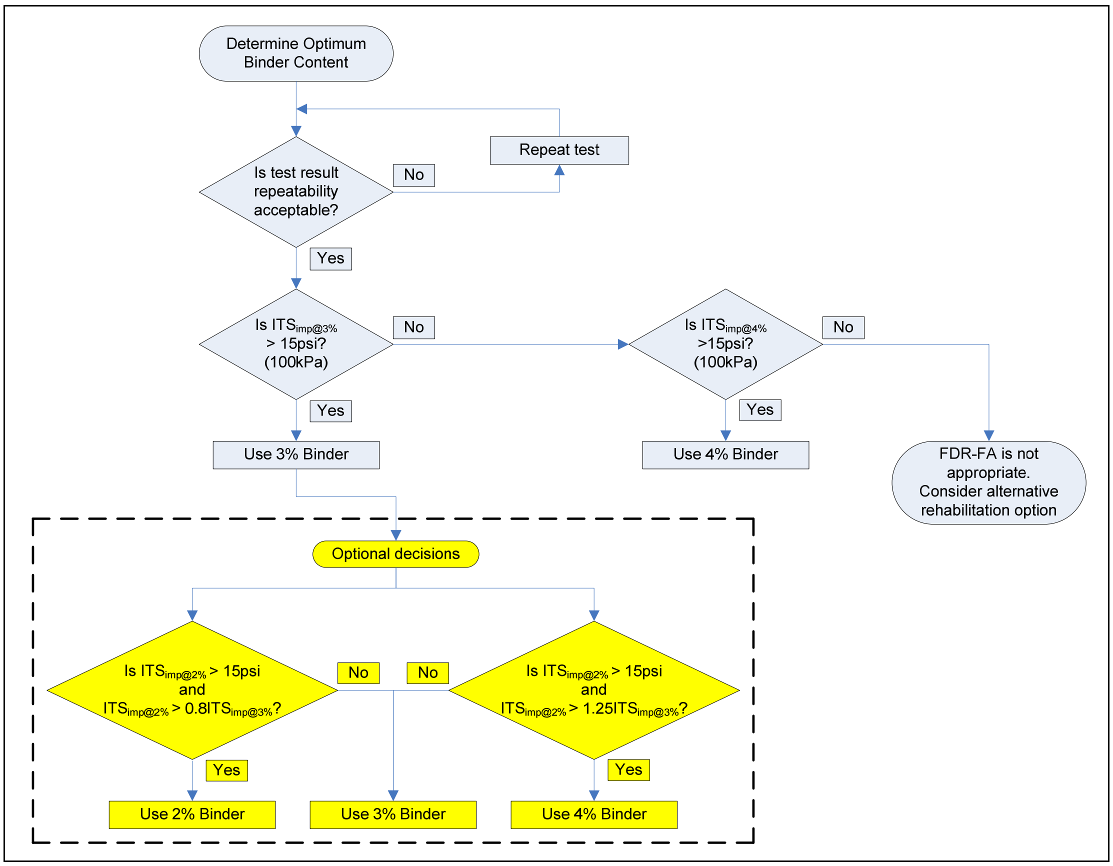


Figure 3.1: Summary for determining optimum asphalt binder content.

3.4.7 Active Filler Content Determination

General Issues

Active filler is added primarily to provide early strength to support traffic as well as faster dry back of the compacted layer. This task determines the optimum active filler content in the mix. The active filler content should always be less than the asphalt binder content.

Limited research *(1)* has shown that optimum portland cement contents on FDR-FA projects in California are likely to be between 1.0 and 2.0 percent by mass of the dry pulverized material. Only limited research has been carried out on the use of hydrated lime in California FDR-FA projects and, to date, no optimum limits have been established. Portland cement contents higher than 2.0 percent should not be considered because of the risk of creating a stabilized material that will be prone to shrinkage cracking. There is some concern about cracking associated with the use of portland cement contents higher than 1.0 percent. However, research *(1)* on a limited number of material types showed that portland cement at rates of up to 2.0 percent in combination with foamed asphalt cement did not behave in the same manner as material treated with 2.0 percent cement and no foamed asphalt (i.e., similar to a Type A cement-treated base material). Laboratory specimens with 2.0 percent portland cement and varying quantities of asphalt binder up to 4.0 percent showed no evidence of shrinkage. These findings, along with limited microscope analysis, support the conclusion that performance of materials with a combination of the two additives is different from the performance with either of the additives alone, and that portland cement contents of up to 2.0 percent can be considered, provided that appropriate material assessments are undertaken.

Active Filler Application Rates

Portland cement contents of 1.0, 1.5, and 2.0 percent and/or hydrated lime contents of 2.0, 2.5, and 3.0 percent by mass of the dry material are used as a starting point together with an untreated control (i.e., asphalt binder with no active filler). Active filler contents must not exceed the asphalt binder content determined in Section 3.4.6.

If the test results indicate that both active fillers provide satisfactory performance, the design engineer should select according to cost, availability, and local experience.

Mix Preparation, Curing, and Conditioning

One mix, using one active filler type, is prepared as follows. The procedure should be repeated if more than one active filler is considered:

- Prepare four samples (22 lb [10 kg] each) of pulverized material, sufficient for testing the untreated control and three active filler contents, each with a replicate.
- Place the material in the mixer and add the active filler at the predetermined rates. Mix thoroughly.
- For each sample, add sufficient water to achieve the MMC determined in Section 3.4.5 and mix thoroughly.
- Spray the specified foamed asphalt content (determined in Section 3.4.6) onto the pulverized material.
- Seal the prepared mix in a suitable container.
- Prepare six specimens as described in Section 3.4.6. All compaction must be completed within 60 minutes of the mixes being prepared.
- Extrude the specimens from the mold immediately after compaction and place each one in a tightly sealed plastic bag. Store the bags in a temperature-controlled room at 77°F (25°C) for 24 hours. Do not open the bags until immediately before testing. No further conditioning or soaking is required.

Testing

Remove the specimens from the bag immediately prior to testing. Testing must be carried out within 24 hours ± 1 hour after preparation of the mix and specimens should be tested in the same sequence as preparation. Testing follows California Test 371 (CT 371) as described in Section 3.4.6.

Analysis and Reporting

The indirect tensile strength test results are analyzed as follows:

- Calculate the average strength of the replicate specimens for each batch of mix.
- Assess the variability within each mix as described in Section 3.4.6. Prepare a new mix and repeat the testing if the variability is higher than the specified criterion.
- Calculate the average strengths for each active filler content level.
- Determine the strength improvement ($ITS_{imp@n\%}$) by calculating the difference between the strength of each mix and that of the untreated control mix (ITS_C) as follows (note that only portland cement contents are shown):
  - For 1.0 percent portland cement, $ITS_{imp@1\%} = ITS_{1\%} - ITS_C$
  - For 1.5 percent portland cement, $ITS_{imp@1.5\%} = ITS_{1.5\%} - ITS_C$
  - For 2.0 percent portland cement, $ITS_{imp@2\%} = ITS_{2\%} - ITS_C$
- Select the optimum active filler content using the following criteria:
  - Select the lowest active filler content that yields a strength improvement higher than 30 psi (200 kPa) as the default active filler content.
  - Select a higher active filler content only if:
    - Significant additional strength improvement can be achieved compared to the default active filler content (i.e., 25 percent more strength improvement with 0.5 percent higher active filler content), and
    - The engineer is confident that shrinkage cracking is not a concern at the higher active filler content.
  - If $ITS_{imp@2\%} < 30$ psi (200 kPa) for portland cement treatment, then this active filler is unlikely to be effective and an alternative active filler should be considered. Portland cement contents higher than 2.0 percent should not be considered.
- Document the proposed active filler content on the summary sheet.

3.4.8 Reference Density for Field Compaction

The reference dry density for field compaction control is based on the laboratory density of the selected mix design, and is determined as follows.

Mix Preparation and Testing

- Prepare two samples of pulverized material, at least 15 lb (7.0 kg) each.
- Place the material in the mixer and add the active filler at the predetermined rate. Mix thoroughly.
- For each sample, add sufficient water to achieve the MMC determined in Section 3.4.5 and mix thoroughly.

- Spray the specified foamed asphalt content (determined in Section 3.4.6) onto the pulverized material.
- Seal the prepared mix in a suitable container.
- Compact the material according to Method D in AASHTO T-180, and determine the dry density. Measure the moisture content of the prepared mix following AASHTO T-265. Use this measured moisture content to calculate the dry density (not the target mixing moisture content).

Analysis and Reporting

Analyze the results as follows:

- If the difference between the measured moisture content of either sample and the target MMC is more than 1.0 percent, reject the results of the problem sample(s) and prepare and test a new sample.
- If the relative difference between dry densities determined for the two samples is higher than 3.0 percent, discard the results of both samples and prepare and test new samples.
- Report the average dry density of the two accepted samples as the reference dry density for field compaction control.

3.4.9 Tensile Strength Retained and Temperature Sensitivity Assessment (Optional)

General Issues

The mix design procedure described in this guideline is based on assessing potential field performance under worst-case scenarios (i.e., moisture contents in the FDR-FA base increase in the wet season). The tensile strength retained (TSR, difference in strength of unsoaked and soaked specimens) is therefore not used as a design criterion. However, the TSR can provide an indication of potential moisture sensitivity to a design engineer familiar with the materials being assessed.

The mix design procedure described in this guideline is performed at standard laboratory temperatures (i.e., approximately 77°F [25°C]). However, dispersion of foamed asphalt in the pulverized material is dependent on the expansion ratio and half-life, which in turn are dependent on the ambient and aggregate temperatures (i.e., the expansion ratio and half-life decrease with decreasing ambient and aggregate temperatures). It is generally accepted that recycling should not begin until the surface and ambient temperatures are both 60°F (15°C) or higher if the expansion ratio and half-life are 10 times and 12 seconds respectively. If higher values for expansion ratio and half life than these minimums are obtained, lower start temperatures can be considered, provided that adequate binder dispersion and sufficient material strengths can be achieved. An optional temperature sensitivity test can therefore be included in the mix design if lower construction temperatures are anticipated and/or the minimum expansion ratio and half-life of the selected asphalt binder are exceeded.

Tensile Strength Retained: Mix Preparation, Curing, and Conditioning

The mix for determining the TSR is prepared as follows:

- Prepare one sample (36 lb [16 kg]) of pulverized material, sufficient for one TSR test (i.e., 12 specimens).
- Place the material in the mixer and add the active filler at the predetermined rates. Mix thoroughly.
- For each sample, add sufficient water to achieve the MMC determined in Section 3.4.5, and mix thoroughly.
- Spray the specified foamed asphalt content (determined in Section 3.4.6) onto the pulverized material.
- Seal the prepared mix in a suitable container.
- Prepare 12 specimens as described in Section 3.4.6. All compaction must be completed as soon as possible after mixing, preferably within 60 minutes, although 120 minutes is acceptable given the time required to prepare and compact specimens.
- Extrude and cure the specimens as described in Section 3.4.6. Soak six of the specimens as described in Section 3.4.6. Place the remaining six specimens on a drying rack.

Tensile Strength Retained: Testing

The soaked and unsoaked specimens are evaluated using an ITS test as described in Section 3.4.6.

Tensile Strength Retained: Analysis and Reporting

Determine the tensile strength retained (TSR) using the following formula (Equation 3.1):

TSR = (average soaked strength/average unsoaked strength) x 100 **(3.1)**

The tensile strength retained should be at least 50 percent. Document the TSR on the summary sheet (Appendix A, Form 10).

Temperature Sensitivity: Mix Preparation, Curing, Conditioning and Testing

The mix for assessing temperature sensitivity is prepared as follows. No active filler is used in the test since the influence of temperature on binder dispersion is of primary interest.

- Prepare two samples (22 lb [10 kg] each) of pulverized material, sufficient for testing of two different aggregate mixing temperatures.
- Cool one of the samples to 10°F (5°C) below the minimum expected surface temperature during recycling for the proposed project. This temperature should not be less than 40°F (5°C). Warm the other sample to 86°F (30°C) (i.e., 10°F [5°C] above room temperature).
- Place the material in the mixer. Do not add any active filler.
- For each sample, add sufficient water to achieve the MMC determined in Section 3.4.5, and mix thoroughly.
- Spray the specified foamed asphalt content (determined in Section 3.4.6) onto the pulverized material.

- Seal the prepared mix in a suitable container.
- Prepare six specimens per temperature as described in Section 3.4.6.
- Extrude, cure, soak, and test the specimens as described in Section 3.4.6.

Temperature Sensitivity: Analysis and Reporting

Compare the average strengths of the two mixes. Recycling on the project can be started at the lower temperature provided that:

- The ITS values are at least 15 psi (100 kPa) higher than the average ITS of the control specimens tested during determination of the optimum asphalt binder content (Section 3.4.6), and
- The Design Engineer is confident that any reduction in strength compared to that obtained from the mix prepared at the control temperature (i.e., 77°F [25°C]) will not influence construction or later performance.

Tests can be repeated if desired with a softer binder or a binder with a higher expansion ratio/half-life to identify the least sensitive mix.

Document the minimum recycling temperature on the summary sheet (Appendix A, Form 10).

3.5 Mix Design Report

Prepare a summary report with tables and plots of all results and a summary of the following key parameters:

- Fines content
- Plasticity index
- MDD and OMC of the pulverized material
- Selected asphalt binder and source refinery
- Acceptable ranges of foaming parameters (i.e., expansion ratio and half-life of selected binder)
- Asphalt binder content
- Selected active filler
- Active filler content
- Reference density for field compaction
- Proposed MMC for construction

The report should also provide details on how the designer plans to deal with variable fines content (e.g., asphalt binder content range) and areas with marginal plasticity index.

4 MIX DESIGN: LEVEL-2 TESTING

4.1 Introduction

The Level-2 mix design procedure discussed in this chapter should only be followed by practitioners who have experience from previous FDR-FA projects and are confident in selecting appropriate target asphalt binder contents, active filler type, and target active filler contents. If the practitioner has any concerns with respect to unfamiliarity of the materials or binder, or if the project has any associated risk, the Level-1 mix design procedure should be followed.

The Level-2 mix design procedure includes the same eight tasks followed in the Level-1 procedure. However, testing is focused on assessing the applicability of predetermined values selected based on experience, rather than using the sensitivity analysis approach followed in Level-1 mix designs.

4.2 Test Methods and Material Requirements

Test methods and material requirements for mix design testing are summarized in Table 4.1. Appropriate measures should be taken (i.e., sufficient splitting, sieving, batching, and drying, etc.) to ensure that the pulverized material used for all the tasks has consistent properties. Apart from the grading analysis, all testing should be carried out on material that passes the 3/4 in. (19 mm) sieve.

Table 4.1: Test Methods and Material Requirements for Mix Design Testing

Parameter	Test Method	Number of ITS Tests	Quantity of Material Required		
			Description	lbs	kg
Pulverized material grading	CT 202	-	Aggregate[1]	45	20
Pulverized material compaction curve	AASHTO T-180[2]	-	Aggregate	80	35
Foaming characteristics	See Section 3.4.4	-	Binder	110	50
Mixing moisture content[3]	See Section 3.4.5	-	Aggregate	70	30
Asphalt binder content	See Section 3.4.6	24	Aggregate	90	40
Active filler content	See Section 3.4.7	12	Aggregate	45	20
Reference density	See Section 3.4.8	-	Aggregate	30	15
Tensile strength ratio[3]	See Section 3.4.9	12	Aggregate	35	20
Temperature sensitivty[3]	See Section 3.4.9	12	Aggregate	45	20
	Total ITS tests[4]	36[4]	Tot agg	440[5]	200[5]

[1] Aggregate is full-depth pulverized material, including the underlying base, subbase, and/or native material.
[2] Method D (see Section 3.4.3 for justification for using this method over CT 216).
[3] Optional [4] Excludes optional tests [5] Includes optional tests

4.3 Testing, Analysis, and Reporting

4.3.1 Pulverized Material Grading

Testing, analysis, and reporting for this task are the same as that for Level-1 testing (see Section 3.4.1).

4.3.2 Active Filler Selection

Active filler selection in the Level-2 procedure is typically based on previous experience.

4.3.3 Pulverized Material Compaction Curve

Testing, analysis, and reporting for this task are the same as that for Level-1 testing (see Section 3.4.3). The typical active filler rate used on previous projects can be used.

4.3.4 Asphalt Binder Selection and Foaming Parameters

If the design engineer is satisfied with the foaming characteristics (i.e., expansion ratio and half-life) of the binder from a particular refinery and there have been only minor variations in the characteristics and foaming properties over time on previous projects, then additional binder selection testing is not required. However, the expansion ratio and half-life at the predetermined foaming parameters will still need to be checked. If the same values are not obtained, new optimal foaming parameters must be determined following the Level-1 procedure.

If a new binder is being evaluated then the testing, analysis, and reporting procedures described for Level-1 testing must be followed (see Section 3.4.4).

4.3.5 Mixing Moisture Content Determination

Experience has shown that mixing moisture content (MMC) values are typically between 75 and 90 percent of the optimum moisture content (OMC) of the pulverized material. If the design engineer's experience indicates that a consistent MMC is common for materials in the District, then that MMC can be used for preparing materials for assessing asphalt binder and active filler contents. If experience indicates that the MMC varies for different materials in the District, then the testing, analysis, and reporting procedures for Level-1 mix designs should be followed (see Section 3.4.5).

4.3.6 Asphalt Binder Content Determination

The asphalt binder is a significant cost component of any FDR-FA project, and in most instances the design engineer will want to optimize the binder content used. In this case, the Level-1 procedure should be followed (see Section 3.4.6). However, on certain projects with similar materials, a study of the construction records has shown that the asphalt binder contents were the same or very similar for the different projects. In these instances, the design engineer can reduce the number of tests to initially assess one binder content against an untreated control. If the results are consistent with previous testing on other projects, then the same binder content can be used on the new project. If inconsistent results are obtained, additional testing should be undertaken.

The same test procedure described in Section 3.4.6 should be followed. The results should be analyzed as follows:

- If the average ITS of the specimens at the predetermined rate is more than 15 psi (100 kPa) higher than that of the untreated control specimens, and the results are consistent with experience, then use this binder content.
- If the value is lower than 15 psi (100 kPa), then increase the asphalt binder content by between 0.5 and 1.0 percent based on engineering judgment, and do a second set of tests. The asphalt binder content should not exceed 4.0 percent.
- If the average ITS of the specimens prepared with the higher binder content is more than 15 psi (100 kPa) higher that of the untreated control specimens, then use the higher binder content. If the value is still lower than 15 psi (100 kPa), the material is probably not suitable for FDR-FA and an alternative rehabilitation approach should be considered.

Report results as for Level-1 testing.

4.3.7 Active Filler Content Determination

Active filler also has a considerable influence on the cost of an FDR-FA project, and the design engineer will probably also want to optimize the active filler content used. In this case, it is recommended that the Level-1 procedure be followed (see Section 3.4.7), although sufficient experience with materials in the District will probably preclude testing with more than one filler type. In a similar manner to determining the optimum asphalt binder content, the design engineer can reduce the number of tests to initially assess one active filler content against an untreated control. If the results are consistent with previous testing, then the same active filler content can be used on the new project. If inconsistent results are obtained, additional testing should be undertaken.

The same test procedure described in Section 3.4.7 should be followed. Analyze the results as follows:

- If the average ITS of the specimens at the predetermined rate is more than 30 psi (200 kPa) higher than that of the untreated control specimens, and the results are consistent with experience, then this active filler content can be used.
- If the value is lower than 30 psi (200 kPa), then increase the active filler content by between 0.5 and 1.0 percent based on engineering judgment, and test a second set of specimens. Portland cement contents must not exceed 2.0 percent and the active filler content (either portland cement or lime) must not be higher than the asphalt binder content.

- Use the higher active filler content if the average ITS of the specimens prepared with the higher active filler content is more than 30 psi (200 kPa) higher than that of the untreated control specimens and the Design Engineer is satisfied that shrinkage cracking will not occur. If the value is still lower than 30 psi (200 kPa), then assess an alternative active filler following the Level-1 procedure. Alternatively, a different rehabilitation strategy should be investigated.

Report results as for Level-1 testing.

4.3.8 Reference Density for Field Compaction

Testing, analysis, and reporting for this task are the same as that for Level-1 testing (see Section 3.4.8).

4.3.9 Tensile Strength Retained and Temperature Sensitivity Assessment (Optional)

Testing, analysis, and reporting for this task are the same as that for Level-1 testing (see Section 3.4.9).

4.4 Mix Design Report

Reporting for Level-2 mix designs is the same as that for Level-1 (see Section 3.5). Design parameters selected based on engineering judgment and experience should be highlighted, explained, and justified in the report. The report should also provide details on how the designer plans to deal with variable fines content (e.g., asphalt binder content range) and areas with marginal plasticity index.

5 STRUCTURAL DESIGN

5.1 Introduction

Rehabilitation projects incorporating an FDR-FA layer can be designed using empirical or mechanistic-empirical procedures. However, given that very little long-term performance data has been collected from FDR-FA projects in California, and that only limited testing is carried out during the mix design phase, mechanistic-empirical designs are not considered appropriate at this time. Additional information on mechanistic-empirical design of FDR-FA pavements can be found in the literature *(1,3)*.

5.2 Proposed Design Method

The California empirical design method for flexible pavements can be used for the structural design of FDR-FA projects. The "Engineering Procedures for New and Reconstruction Projects" (Topic 633 in the *Caltrans Highway Design Manual [HDM])* should be followed. The procedure in "Engineering Procedures for Flexible Pavement and Roadway Rehabilitation" (Topic 635 of the HDM) is not appropriate.

Design parameters in the procedure include the California R-value of the subgrade, the Traffic Index (TI) for the pavement design life, and the gravel factors (G_f) for the engineered pavement materials. The design procedure should follow the current Caltrans protocol.

A gravel factor of 1.4 should be used for foamed asphalt–treated materials *(1)*.

5.2.1 Surfacing

Any surfacing can be applied on an FDR-FA layer, provided that it meets the design requirements. International experience has shown that hot-mix asphalt provides the most durable surface. Chip seals have been used in a number of countries with varying success, provided that an appropriate chip seal design process is followed. However, experience has shown that FDR-FA layers often have higher-than-acceptable ball-penetration layers values after construction, which typically results in punching of the chip seal surfacing stone into the recycled layer and associated bleeding of the surfacing binder. The problem is exacerbated during high temperatures. It is therefore recommended that only hot-mix asphalt with a minimum thickness of 2.0 in. (50 mm) be used as the surface layer on FDR-FA projects in California.

5.2.2 Pavement Structure Design Example

The following is an example of a pavement structure design based on the *Caltrans Highway Design Manual.* The existing road has an average asphalt thickness of 8.0 in. (200 mm) over 8.0 in. (200 mm) of Class 2 aggregate base over subgrade. Input data are summarized in Table 5.1.

Table 5.1: Input Data for Pavement Structure Design Example

Input	Value (US)	Value (Metric)
Traffic index (TI)	10.0	10.0
R-value of subgrade	30	30
Recycle depth	10.0 in	250 mm
Remaining aggregate base	6.0 in	150 mm
Gravel factor of recycled material (GF_{FDR})	1.4	1.4

The pavement structure design calculations are summarized in Table 5.2.

Table 5.2: Calculations for Pavement Structure Design Example

Parameter	Value (US)
Gravel equivalent of pavement (GE_{Total})	GE_{Total} = 0.032(10.0)(100-30) = 2.24 ft
Gravel equivalent of aggregate base (GE_{AB})	GE_{AB} = 0.50(1.1) = 0.55 ft
Gravel equivalent of recycled material (GE_{FDR})	GE_{FDR} = 0.83(1.4) = 1.16 ft
Gravel equivalent for HMA (GE_{HMA})	GE_{HMA} = 2.24 – 0.55 – 1.16 = 0.53 ft
HMA thickness from Table 633.1 in HDM	0.3 ft of HMA = GE_{HMA} of 0.54 ft
Parameter	**Value (Metric)**
Gravel equivalent of pavement (GE_{Total})	GE_{Total} = 0.975(10.0)(100-30) = 683 mm
Gravel equivalent of aggregate base (GE_{AB})	GE_{AB} = 150(1.1) = 165 mm
Gravel equivalent of recycled material (GE_{FDR})	GE_{FDR} = 250(1.4) = 350 mm
Gravel equivalent for HMA (GE_{HMA})	GE_{HMA} = 683 – 165 – 350 = 168 mm
HMA thickness from Table 633.1 in HDM	90 mm of HMA = GE_{HMA} of 161 mm

Based on the calculations, the proposed layer thicknesses for this example are summarized in Table 5.3

Table 5.3: Proposed Layer Thicknesses for Pavement Structure Design Example

Layer	Value (US)	Value (Metric)
Hot-mix asphalt	0.30 ft	90 mm
FDR-FA	0.83 ft	250 mm
Subbase (existing layer)	0.50 ft	150 mm

5.3 Alternative Design Methods

Alternative design methods for FDR-FA pavements can be found in the literature *(3,6)*.

6 CONSTRUCTION

6.1 Introduction

As with any road construction project, the quality of the construction on FDR-FA projects is critical to ensure that the pavement will perform satisfactorily over its design life. The recycling and mixing of the foamed asphalt and active filler components are intricate processes that require the correct equipment, an experienced crew, and careful logistical planning. This chapter highlights key issues with respect to construction procedures that should be followed when rehabilitating roads using an FDR-FA process.

6.2 Key Issues for Construction of FDR-FA Pavements

Key issues for construction of FDR-FA pavements are discussed under the following headings:

- Contractor experience (Section 6.2.1)
- Traffic accommodation (Section 6.2.2)
- Pre-milling (Section 6.2.3)
- Importing new material (Section 6.2.4)
- Equipment inventory (Section 6.2.5)
- Recycling train crew responsibilities (Section 6.2.6)
- Recycling train setup (Section 0)
- Test strip (Section 6.2.8)
- Ambient and pavement temperatures (Section 6.2.9)
- Asphalt binder checks (Section 6.2.10)
- Recycling plan (Section 6.2.11)
- Active filler spread rate (Section 6.2.12)
- Asphalt binder content (Section 6.2.13)
- Recycling depth and recycled material consistency (Section 6.2.14)
- Lateral joints (Section 6.2.15)
- Compaction moisture (Section 6.2.16)
- Initial compaction (Section 6.2.17)
- Final grades and final compaction (Section 6.2.18)
- Curing (Section 6.2.19)
- Trafficking (Section 6.2.20)
- Surfacing (Section 6.2.21)
- Drainage (Section 6.2.22)
- Quality control (Section 6.2.23)

6.2.1 Contractor Experience

A limited number of FDR-FA projects have been constructed in California. Although the contractors who own the equipment and undertake the recycling/foamed asphalt work have experience in the process, they often subcontract to prime contractors who may have little or no experience with the process. It is therefore important for the prime contractors to be trained in the process before work begins, specifically on the components that differ from conventional construction/rehabilitation that are detailed below. As with any construction project, the safety of workers and the public is very important and all crew members should be fully trained on all safety issues, especially in handling the high temperature asphalt binder.

6.2.2 Traffic Accommodation

FDR-FA has less impact on traffic than most other rehabilitation/reconstruction options. On two lane roads, typically one lane is recycled at a time, allowing controlled traffic to use the remaining half of the road. Provided that the recommended foamed asphalt/active filler combination has been used, the recycled layer can be opened to traffic within a few hours after final compaction. Appropriate traffic control measures must be implemented *(e.g., Reference 10)*.

Traffic Accommodation on FDR-FA Construction

6.2.3 Pre-Milling

Pre-milling and removal of the recycled asphalt pavement (RAP) may be required if the existing hot-mix asphalt is too thick (i.e., typically thicker than 10 in. [250 mm]), or if precise surface levels need to be maintained (e.g., in urban areas). The need for pre-milling will be determined during the project investigation. Standard milling equipment and procedures should be used for this process. Pre-milling should be completed before recycling operations begin. Traffic can drive on the pre-milled surface with appropriate traffic control and information. Pre-milling should not be confused with pre-pulverization, which is discussed in Section 6.2.8.

6.2.4 Importing New Material

Additional aggregate base material may be called for in the rehabilitation design to correct grades, increase layer thickness, and/or improve the bearing capacity of the pavement structure. In such instances, material meeting the specified requirements should be spread to the required thickness on top of the existing road surface, shaped to the required cross-slope, watered, and then compacted to the specified density. This operation should be completed before recycling operations begin. The compacted surface can be trafficked at low speeds if necessary, provided that the surface is watered to prevent raveling and to control dust.

6.2.5 Equipment Inventory

Rehabilitation/reconstruction using FDR-FA requires specialized equipment in addition to that used for the construction of conventional aggregate and hot-mix asphalt pavement layers. The recycling train (Figure 6.1), which consists of the recycling machine, asphalt binder tanker (in front of and "pushed" by the recycling machine), and water tanker (behind and towed by the recycling machine), is a fundamental component of the equipment inventory. The water tanker can be replaced by a slurry applicator (Figure 6.2), which applies the active filler as a slurry at the mixing moisture content through the recycler.

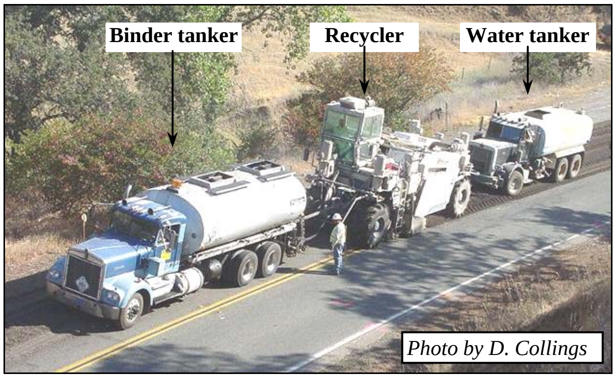


Figure 6.1: Recycling train (binder tanker, recycling machine, and water tanker).

Figure 6.2: Slurry applicator.

The remaining equipment requirements are similar to those for conventional aggregate basecourse construction and include:

- Active filler spreader (Figure 6.3) if a slurry applicator is not used. Active filler needs to be spread accurately and evenly ahead of the recycling train. Most recyclers do not shift material appreciably in the horizontal plane, making accurate spreading an important factor.

Figure 6.3: Active filler spreader.

- Rollers
  - One vibrating padfoot (sheepsfoot) roller with a blade per recycling train (Figure 6.5). The required weight of the roller will depend on the thickness and material grading of the layer being recycled and, to a certain extent, the support conditions under the recycled layer. Guide weights for different layer thicknesses are summarized in Table 6.1 and Figure 6.4. Care should be taken to ensure that punching of the recycled material into the subgrade does not occur when heavy rollers (> 18 tons) are used. The specified density must be achievable throughout the thickness of the reclaimed layer.
  - One smooth-drum roller between 10 and 12 tons depending on the thickness of the layer (Figure 6.6).
- One pneumatic-tired roller (PTR) for layer finishing (Figure 6.7).
- Grader. A standard grader is used for final shaping and leveling (Figure 6.8).
- Water tanker. An additional standard water tanker is used for correcting moisture content after initial compaction with the padfoot roller has been completed, as well as for dust control and wetting of the final surface. A second water tanker may be needed to transport water for refilling the water tanker in the recycling train.

Table 6.1: Recommended Primary Roller Weights for Different FDR-FA Layer Thicknesses *(3)*

Compacted Layer Thickness (in)	Compacted Layer Thickness (mm)	Static Weight (tons)
< 6	< 150	12
6 – 8	150 – 200	15
8 – 10	200 – 250	18
10 – 12	250 – 300	20[1]
> 12	> 300	25[1]

[1] Care should be taken to ensure that punching of the recycled material into the subgrade does not occur when heavy rollers are used.

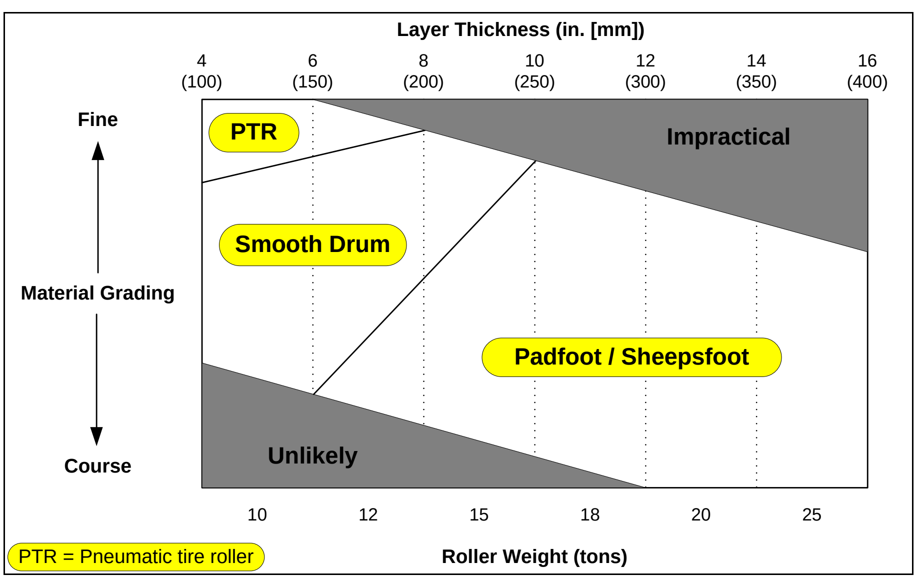


Figure 6.4: Primary roller selection guide *(3)*.

Figure 6.5: Padfoot roller.

Figure 6.6: Smooth-drum roller.

Figure 6.7: Pneumatic-tired roller (PTR).

Figure 6.8: Grader.

- Loader. A loader is used for moving excess materials from the roadway and clearing aggregate and asphalt concrete spills into drainage courses (Figure 6.9).
- Mechanical broom. This is used to sweep loose material from the surface prior to opening to traffic and prior to placing the hot-mix asphalt surface (Figure 6.10).

Figure 6.9: Loader.

Figure 6.10: Mechanical broom.

6.2.6 Recycling Train Crew Responsibilities

The recycling train crew must understand and be able to fulfill their responsibilities, which include but are not necessarily limited to:

Pipeline Marker

- Checking for marked and unmarked services, power lines, culverts, overhanging branches, etc., that may influence the recycling train.
- Checking couplings between the tankers and recycler.
- Checking that binder and water contents are correct at all times.
- Checking that binder temperatures in the tanker are within the acceptable range.
- Checking that expansion ratio and half-life meet or exceed the design requirements before commencing operations each day and at each tanker change.
- Checking that active filler has been evenly spread at the required rate for a sufficient distance ahead of the recycling train (i.e., the recycling train will never need to stop while active filler is being spread). Checks should also ensure that spread active filler is not being blown away by wind or passing traffic.
- Marking guides to ensure that adequate overlaps are included in each recycling pass.
- Checking that the speed of advance does not exceed the specified rate (typically between 18 ft/min and 33 ft/min [7.0 m/min and 9.0 m/min]).
- Ensuring that an **experienced** technician is always present behind the recycling machine to check:
  - Depth of cut on both sides of the recycler (Figure 6.11).

Figure 6.11: Checking recycling depth.

  - Material characteristics, material consistency, and mixing moisture content, and suggesting adjustments of asphalt binder and/or mixing moisture content to the Resident Engineer and recycler operator (Figure 6.12).
  - Presence of unfoamed binder (stringers and globules) and adherence of binder to the recycler tires, and stopping the recycling train if problems with the foaming equipment are apparent (Figure 6.13 and Figure 6.14).

Figure 6.12: Checking material consistency.

Figure 6.13: Unfoamed binder in recycled material.

Figure 6.14: Binder adherence to recycler tires.

- For oversize material, recycling depth, and other issues that may influence the quality of the finished pavement.
- Proximity of the padfoot roller (i.e., never further than 300 ft (100 m) behind the recycling train), and stopping the recycling train if this roller falls too far behind.
- For leaks and spills while the recycling train is standing to ensure that no soft spots will be left in the pavement that may form potholes at a later date.

- That appropriate safety procedures are followed during recycling, especially during the change-over of asphalt binder tankers, and working between the recycler, tankers, and rollers.

NOTE: Crew working on and around the recycling train should be cautious at all times. The monitoring of milling depth and recycled material behind the recycler are particularly dangerous exercises.

6.2.7 Recycling Train Setup

Apart from the standard start-up procedures specified in the equipment operating procedures and manuals, a number of preliminary checks should be completed before commencing operations each day. The procedures are quick and simple to carry out and should become routine practice at the start of every shift. Checks include:

- The recycler operator is familiar with the day plan and has all relevant data including asphalt binder contents, mixing moisture contents, and recycling depths.
- Operators and drivers of all ancillary machines and vehicles have a clear understanding of their responsibilities and what they are expected to do to ensure that the recycling operation is successful.
- Daily maintenance and inspections have been completed on all machines and equipment to be used in the recycling operation.
- Recycler settings (drum speed, breaker bar, rear door pressure, etc.) are correct and that the rubber flap fitted to the base of the front door of the milling chamber has been lifted to prevent redistribution of the prespread active filler.
- All nozzles are open and that there are no blockages in the system.
- Temperatures of the asphalt binder, air, road surface, and spread active filler have been measured.
- Sufficient quantities of asphalt binder, active filler, and water are available or are scheduled for delivery to complete the day’s planned activities.
- Feed pipes are correctly connected and leak-free, valves are open, and air has been bled from the system.
- The recycler has been warmed up to operating temperatures.

6.2.8 Test Strip

A single-lane test strip at least 1,500 ft (500 m) should be constructed on the first production day at the start point of each project prior to starting full-scale operations. The test strip is constructed to check that:

- The correct equipment is available and in sound working condition, and that crews are adequately trained.
- The recycling machine can produce an acceptable grading throughout the predetermined recycling depth, that no oversize chunks remain in the processed material, and that the specified recycling depth, measured against the adjacent unrecycled material, is appropriate (Figure 6.15). Grading should be checked against the mix-design grading (pulverize a short distance at the start without the addition of any stabilizer). Depending on the type of recycling equipment, grading can be changed by adjusting the recycling drum speed, the forward speed of the recycler, the position of the breaker

bar in front of the milling and mixing chamber, and/or by adjusting the rear door of the mixing chamber. These adjustments should be assessed to determine minimum and maximum production speeds for the recycling train.

Figure 6.15: Checking recycling depth and grading.

- The binder delivery temperature is within specification and the expansion ratio and half-life of the binder meet or exceed the mix-design requirements.
- The moisture content of the in-situ material has been correctly estimated and that mixing and compaction moisture contents have been correctly calculated, and can be met by the recycling machine.
- The active filler can be accurately and uniformly spread at the correct rate (Figure 6.16) and that there is no significant overlap, which could lead to localized cracking due to higher than design active filler contents.

Figure 6.16: Checking active filler spread rate.

- The recycled material with foamed asphalt and active filler appears adequately processed prior to compaction, that there is no unfoamed binder (globules or stringers) in the mix (Figure 6.13), and that no binder or treated material adheres to the recycler tires (Figure 6.14).

- The compaction equipment operators understand the differences between compacting natural aggregate and FDR-FA material, know the correct procedure for compacting FDR-FA material (see Sections 6.2.17 and 6.2.18), and can keep up with the recycling train.
- The specified density can be achieved at the top and bottom of the recycled layer.
- The correct bulking factor has been calculated and that the correct quantity of material is bladed from the road after initial compaction to ensure that final levels can be achieved.
- The desired surface finish and levels can be achieved.
- The surface can be broomed without disintegration (Figure 6.17 and Figure 6.18).

Figure 6.17: Unacceptable surface after final compaction.

Figure 6.18: Good quality surface after final compaction.

Materials should be sampled behind the recycling machine (before initial compaction) for determination of indirect tensile strength (CT 304 and CT 371). Results after curing and soaking must be comparable to the results obtained during mix design testing.

The Resident Engineer must approve the test strip before the contractor can proceed with the project. If any project requirements (e.g., gradation, moisture content, active filler spread rate, relative compaction, etc.) cannot be met, the section should be reworked until it complies with the specifications. Any adjustments to the process (e.g., change in asphalt binder content, active filler content, recycling depth, mixing moisture content, etc.) must be agreed on between the contractor and the Resident Engineer before a second test strip is constructed.

Pre-Pulverization

Pre-pulverization (Figure 6.19) of the material prior to stabilizing should not be considered on FDR-FA projects in California. Experience in the state to date has shown that an appropriate gradation cannot be achieved with two passes of the recycling machine and that excessive fines are often produced. Good quality recycling and mixing should not be sacrificed to achieve higher production rates.

Figure 6.19: Pre-pulverization on FDR-FA project

Target Density for Recycled Layers

Achieving optimal density during compaction of the recycled layer is critical to ensuring that the required structural capacity of the layer is obtained, thereby limiting the likelihood of permanent deformation of the layer and/or fatigue of the asphalt surfacing under traffic. Density requirements are usually specified in terms of a percentage of a reference density, typically the maximum dry density (MDD) determined in the laboratory during the project investigation. Caltrans specifications require a density of at least 97 percent (determined according to CT 231) of the laboratory-determined density (AASHTO T-180/ CT 216) for FDR-FA layers.

There are a number of potential problems when using a reference density specification, including:

- The precision of nuclear density gauges can be influenced by the presence of bitumen in the recycled layer. Erroneous measurements can therefore be obtained and some form of calibration of gauges on the test strip (e.g., with a sand-cone replacement test) may be required.
- The material properties on typical rehabilitation projects vary along the length of the project. Consequently, the density of the material will also change. Differences of a few percent can be the difference between accepting and rejecting a section of the road, and/or between over- and under-

compaction. To overcome this problem, a representative reference density will need to be determined by carrying out a moisture-density relationship test on a sample collected from every location where the field density is measured. This will significantly increase the number of laboratory tests and could result in reworking completed layers, since test results are only available after a minimum of 24 hours.

- The support of the underlying layers has a significant influence on the ability of the contractor to compact the recycled layer, with strong support providing a stiff platform for compaction of the FDR-FA material (i.e., an anvil effect). Varying and weak subgrade support, common in some areas of California, leads to difficulty in achieving optimal compaction.

As an alternative to using a reference density, some practitioners are now specifying a "refusal density" as the target. Refusal density can be defined as the maximum density that can be achieved on a material under the prevailing field conditions (i.e., material properties and support conditions). This can be assessed using two methods, or a combination of the two methods. Standard quality control procedures must still be followed. The two methods are:

1. Complete a short test strip at regular intervals along the project, during which a nuclear density gauge reading is taken after each roller pass. Stop rolling if the same density is recorded for two consecutive passes. The number of passes required to achieve this density is then used for that particular production run. The minimum required density must still be achieved.
2. Use an "intelligent compaction" system fitted to the roller. These systems incorporate a "compactometer" on the vibrating drum to measure "rebound acceleration," which is a measure of the response of the material to an impulse (vibration). This provides an indication of the density of the material. These measurements in combination with a GPS locator allow multiple measurements taken at the same location to be compared. Results are displayed in the cab, allowing the roller operator to continuously monitor density development at every location. When successive passes of the roller show no further increase in density, the refusal density has been achieved and the roller can move forward to compact the next section of work.

Satisfactory results have been achieved using a refusal density compaction specification provided that the correct equipment is used, appropriate procedures are followed, changes in material properties are monitored, and the moisture content of the material being compacted is in the required range relative to the optimum moisture content of the material.

6.2.9 Ambient and Pavement Temperatures

Dispersion of the foamed asphalt through the recycled material is dependent on the temperature of the aggregate and fines particles, with dispersion improving with increasing temperature of both. The following considerations with regard to temperature are important:

- Recycling should not begin until the ambient temperature is above 50°F (10°C) and the temperatures of the road surface and pre-spread active filler are both equal to or above 60°F (15°C) (see Figure 6.20 through Figure 6.23).
- The surface temperature requirement can be relaxed (to 50°F [10°C]) if mix design testing indicates that satisfactory dispersion and strengths can be achieved at the lower temperatures (see Section 3.4.9). Binders with high expansion ratio and half-life are typically required to meet these requirements.

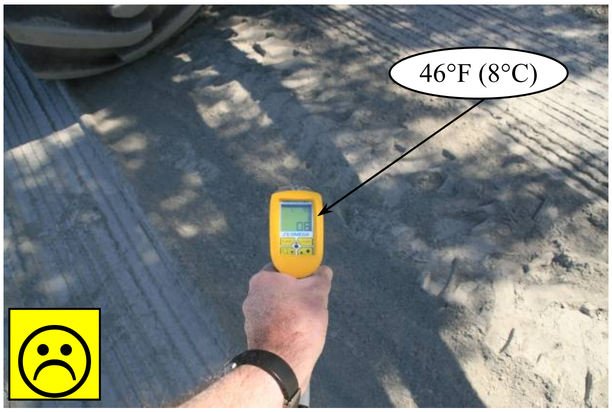


Figure 6.20: Portland cement temperature prior to recycling (cold).

Figure 6.21: Recycled material (cold, poor dispersion).

Figure 6.22: Portland cement temperature prior to recycling (warm).

Figure 6.23: Recycled material (warm, good dispersion).

6.2.10 Asphalt Binder Checks

A series of asphalt binder checks needs to be made throughout the construction process as follows:

Binder Tanker Thermometer

- The delivery paperwork for each tanker must be checked to ensure that the correct binder grade has been delivered and that the source has not been changed.
- The asphalt binder temperature must be checked prior to connecting to the recycler. This temperature should be

determined from a sample collected in a bucket from the outlet or from the hatch on top of the tank. Tank thermometers, if installed, should not be trusted. Binder below the specified temperatures (i.e., mix-design temperature) or above 375°F (190°C) must be returned to the refinery.

- Keeping a small sample of the binder from each tanker for reference purposes is recommended.
- Check the asphalt binder expansion ratio and half-life after each tanker change (Figure 6.24) by taking a sample from the dedicated test nozzle on the recycler.

Figure 6.24: Checking expansion ratio and half-life.

6.2.11 Recycling Plan

A number of factors influence the way in which the road will be recycled. The number of recycling passes will depend primarily on the road width, while the cross-slope influences the positioning of longitudinal joints between adjacent passes. The following should be considered when preparing the recycling plan:

- On most recycling projects, the width of the recycled cut will usually be less than the road or lane width and more than one pass will be required to recycle the full width, resulting in a series of longitudinal joints between adjacent passes. The location of longitudinal joints should be between the wheelpaths of any lane. Crowned roads should be treated in half-widths to maintain road shape and achieve a uniform depth of recycling across the crown. An exampled recycling plan for a two-lane highway is shown in Figure 6.25.

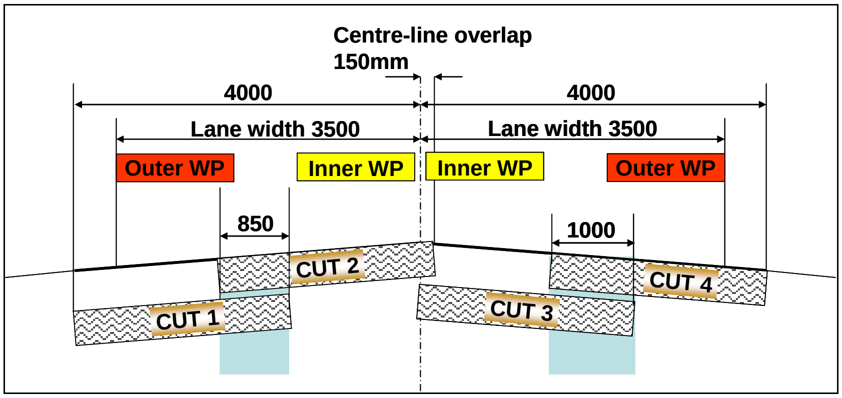


Figure 6.25: Example recycling plan for a two-lane highway.

- Overlaps are required along the full length of each joint to achieve continuity between adjacent cuts. Overlaps are typically between 4.0 in. and 6.0 in. (100 mm and 150 mm), but should be increased if the thickness of the recycled layer exceeds 12 in. (300 mm), or the material is very coarse. The width of overlap should also be increased if cementitious active filler is being used and the planned pass will overlap a pass constructed more than 12 hours earlier. When planning the recycling operation, it should be noted that only the first cut will recycle virgin material over the full drum width, and thereafter, the effective width of all subsequent cuts will be reduced by the width of overlap. The binder and water nozzle(s) in the overlap area should be switched off to prevent over-application of binder and water. Cement must not be spread in the overlap area.
- Guides should be painted on the road to assist the recycler operator with maintaining correct overlaps (Figure 6.26).
- The use of two recycling trains is preferable on most projects to limit time lost when repositioning the recycling train on half-width projects and to limit problems associated with overlaps and longitudinal joints (Figure 6.27).
- Where possible, steep gradients should be recycled by working downhill to ensure that the required production speeds are maintained. Equipment operators should ensure that sufficient head is maintained over the outlet valves on the binder and water tankers, especially when working on gradients.

Figure 6.26: Marking directional guides for recycling train.

Figure 6.27: Tandem recycling train.

6.2.12 Active Filler Spread Rate

Active filler should be evenly spread on top of the road surface ahead of the recycling train. The following considerations are important:

- Even spread rates of the active filler are critical since the lateral mixing ability of recycling machines is not as effective as the vertical mixing. Concentrations of filler during spreading could lead to localized excesses, which could lead to localized shrinkage cracking in the recycled base. Overlaps of active filler are not permitted for the same reason.
- Some recyclers have a tendency to form a windrow ahead and on the sides of the mixing chamber that can lead to excesses of active filler at the joins. Spillages from the side of the mixing chamber of the recycler may lead to these windrows being covered by fine material and are consequently difficult to detect (Figure 6.28). These windrows need to be raked level before the next pass of the recycler.
- Spread distances must be reduced in windy conditions or if there is a possibility that the recycling train will need to stop for an extended period (e.g., waiting for asphalt binder delivery).
- Spread rates must be checked at least once per application run.
- Any water spraying for dust control, compaction, etc., in adjacent lanes must not contact the active filler under any circumstances.

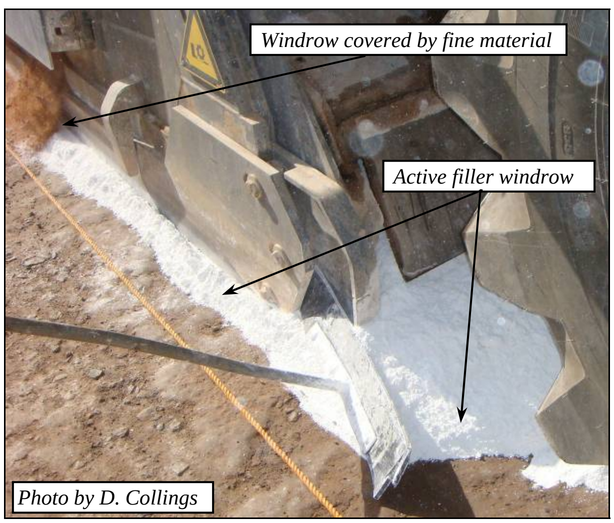


Figure 6.28: Excess active filler on joints.

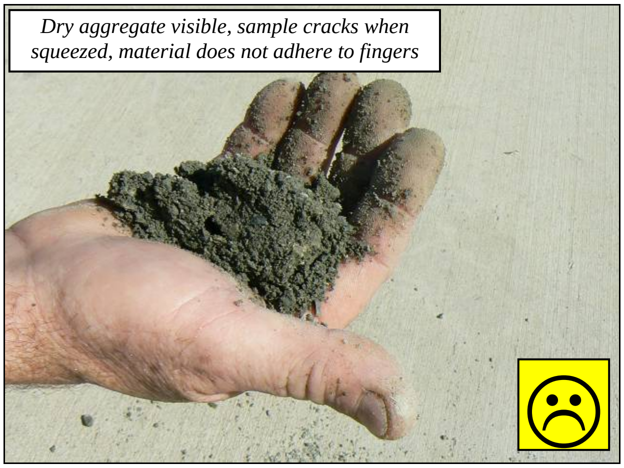
6.2.13 Asphalt Binder Content

Asphalt binder content cannot be easily checked in the processed material due to the presence of old asphalt in the recycled material. Binder contents therefore need to be monitored through recycler instrumentation and through checks of delivered quantities (weigh bridge documentation from the refinery) against the area of roadway recycled. Project designs and specifications typically allow for minor adjustments to the asphalt binder content and mixing moisture content to accommodate variation in materials. The Resident Engineer should be notified of any changes in binder content and the reasons for them.

6.2.14 Recycling Depth and Recycled Material Consistency

Monitoring of recycling depth and recycled material consistency by the recycling crew (and checked by the Resident Engineer) is critical because of the variability in materials, moisture content, and layer thickness in the old pavement. The following considerations are important:

- Check recycling depth with a T-bar at least every 300 ft (100 m) (Figure 6.15). Measurements can be taken in the space behind the recycler and in front of the water tanker, or immediately behind the water tanker, but before the first pass of the padfoot roller. Using a shovel, scrape a furrow across the recycled path every 1,500 ft (500 m) to assess recycling depth and consistency of the material throughout the layer. Backfill the trench before initial compaction. Feedback on the depth should be provided to the recycler operator for appropriate adjustments. If the recycling depth is less than the specified depth, stop the recycling train and rework the section to the correct depth. New asphalt binder and active filler should not be added during the rework, however, the compaction moisture content may need to be supplemented.
- Check overlaps at least every 300 ft (100 m) at the same time as the recycling depth checks. If a strip of unrecycled material is encountered between two recycling paths, stop the recycling trains and rework the strip. Asphalt binder will need to be sprayed over the strip of unrecycled material but not over the remaining material.
- Check material consistency continuously behind the recycler. The presence of asphalt stringers and globules in the freshly recycled material and/or on the recycler tires indicates a problem with the recycler settings, and the recycling train should be immediately stopped for corrections (Figure 6.12 through Figure 6.14). The consistency of the color of the material immediately behind the recycler also usually indicates whether or not the machine is set up correctly. A gradual change in color across the width normally indicates that one end of the drum is lower than the other. A lighter appearance indicates dilution (under-application of water and asphalt binder) caused by the drum penetrating beyond the specified depth. A darker color indicates an over-application due to the drum not penetrating to the required depth. Binder application consistency can also be checked with a temperature gun. A variation in the temperature across the recycled material immediately behind the recycler usually also indicates inconsistent binder application (higher temperatures indicate higher binder application rates).
- Check moisture content together with the material consistency using a “squeeze test” (a handful of material, when squeezed in the hand, should not exude water [too wet], or crumble [too dry] when released [Figure 6.29 and Figure 6.30]). The squeeze test also provides a good indication of asphalt binder dispersion: large sticky spots of asphalt remaining on the hand after squeezing the material into a ball indicates poorly dispersed asphalt binder, while evenly distributed tiny “pinpricks” of binder indicates good dispersion (Figure 6.31). The ball should also be held between the thumb and index finger and pressure gently applied on opposite sides to gauge the cohesiveness of the material. The ball should deform before falling apart. The face of the broken ball should be inspected for asphalt dispersion. If no asphalt can be seen, the mix is perfect. The presence of asphalt globules indicates a poor mix.



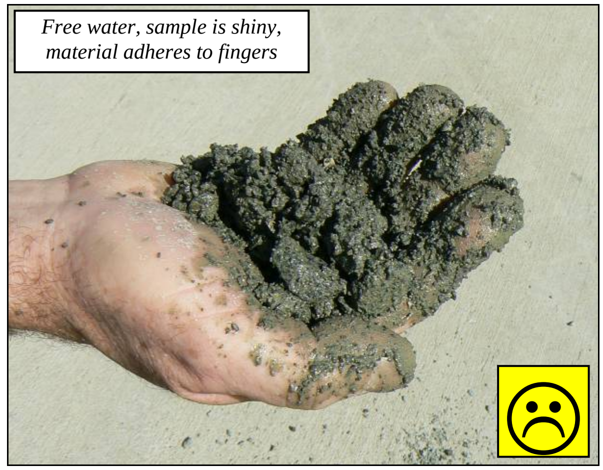


Figure 6.29: Moisture content checks (too dry and too wet).

Figure 6.30: Moisture content checks (good).

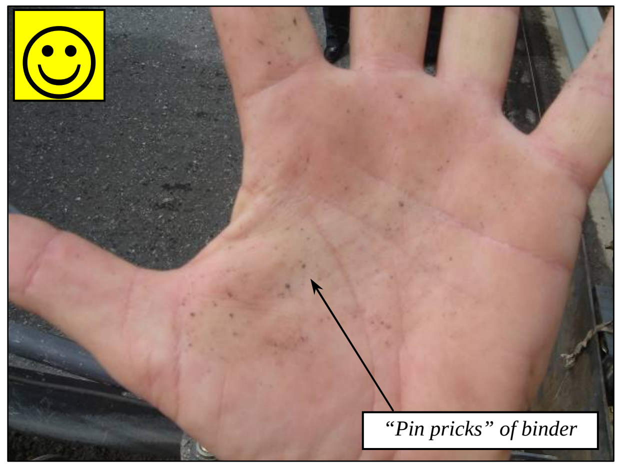


Figure 6.31: Asphalt binder dispersion check (good).

- Take a material sample every 90 to 120 minutes (approximately every 1,800 ft to 3,000 ft [600 m to 1,000 m], or a minimum of five samples per day) behind each recycling train before compaction with the padfoot roller. Sample material through the full recycling depth. This material will be used to check grading, moisture content, and indirect tensile strength as required by the specifications. Store moisture samples in an air-tight container, and start tests within four hours of the sample being taken. Record the location of each sample.
- Send the results of laboratory tests to the Resident Engineer as soon as they are available. Adjustments, approved by the Resident Engineer, should be made to the binder contents and mixing moisture contents based on these results. The Resident Engineer will also use the results to decide whether any particular section requires reworking in line with the specifications.

6.2.15 Lateral Joints

Lateral joints are discontinuities across the width of cut that are formed each time the recycling operation stops and starts (e.g., tanker changes, breakdowns, compaction problems, end of daily production). Most problems encountered result from over- or underapplication of asphalt binder and/or water at the joint, and/or material segregation when the recycling machine is idling with the drum rotating in the milled material (Figure 6.32). Problems can be minimized by:

- Limiting the number of production stoppages.
- Following correct start-up procedures. Bleeding of air from the asphalt binder and water supply lines is especially important. Failure to do this can result in short sections of roadway being recycled with incorrect quantities of binder and/or water.
- Enriching the joint area by reversing the recycling train by the diameter of the milling drum (approximately 5.0 ft [1.5 m]) back into the previously recycled material, thereby ensuring that all material is treated across the effective width of the joint. Before moving forward again, the operator should apply full power and accelerate immediately to the specified operating speed.
- Lifting the drum completely off the road while idling.

Figure 6.32: Material segregation during idling.

6.2.16 Compaction Moisture

Compaction moisture is critical to ensure that optimal density is achieved. In most instances, additional water will be required in addition to the in situ moisture and foaming water to reach the optimal mixing moisture content. The following considerations are important:

- The compaction water must be mixed with the material in the mixing chamber of the recycler, using water supplied by the towed tanker.
- Water must not be sprayed onto the uncompacted material using a separate water tanker and grader to mix, or during compaction with the padfoot roller under any circumstances (Figure 6.33), as poor dispersion and an unsatisfactory mix will be obtained. Water spraying behind the recycler without grader mixing is also unacceptable as the compaction water will not penetrate to the lower levels of the layer.

- Water can be sprayed onto the surface after completion of initial compaction with the padfoot roller (i.e., during compaction with the smooth-drum and pneumatic-tired rollers).

Figure 6.33: Water application between recycling train and roller before initial compaction.

6.2.17 Initial Compaction

Initial (or primary) compaction must be undertaken prior to any leveling, or other work with the grader, using a vibrating padfoot (sheepsfoot) roller. The following considerations are important:

- One padfoot roller must be used per recycling train. If more than one is used, they should be the same make and model, with same amplitude and vibration settings.
- Use high amplitude vibration to achieve maximum penetration of compactive effort.
- Do not let roller speed exceed 2.0 mph (3.0 km/h) or 165 ft/min (50 m/min).
- Initial compaction on FDR-FA layers is different than that on conventional aggregate bases. Although the material exiting the recycler is in a loose state, the rear wheels of the recycler and all the wheels of the water tanker run on this material, resulting in compaction of the loose material in the equipment wheelpaths (Figure 6.34). The in-place density of this compacted material is at least 10 percent higher than that of the adjacent uncompacted material. It is therefore imperative that the material between the wheelpaths first be compacted to at least the same density as that in the wheelpaths before any additional processing is initiated. **Grading prior to initial compaction, or failure to compact this material in an appropriate sequence will result in a permanent density differential, which could lead to premature failure (rutting) in the wheelpaths.**
- The first pass of the padfoot roller should proceed down the center of the recycling train wheelpaths, ensuring that the drum of the roller bridges the wheelpaths (Figure 6.35). At the end of the run (i.e., when the roller catches up with the recycling train), the blade should be lowered and the roller reversed back down the same path while dragging material into the padfoot impressions and wheelpaths of the recycling train. The material between the wheelpaths should now be level with and of a similar density to that in the wheelpaths. A conventional rolling pattern can then be followed to obtain uniform compaction of the recycled material. The blade should be used on each reverse pass to fill in the padfoot impressions (Figure 6.36).

Figure 6.34: Differential compaction in recycling train wheelpaths.

Figure 6.35: First padfoot roller pass.

Figure 6.36: Using the blade to redistribute material in padfoot impressions.

- As more roller passes are applied, the increasing compactive effort results in increased density in the lower regions of the recycled layer, which increases the resistance to penetration of the individual pads on the roller, allowing the roller to “walk out” of the material. Only minor indentations, which can be skimmed by the grader during leveling, should be left on the surface after completion of initial compaction with the padfoot roller (Figure 6.37 and Figure 6.38).
- If the recycler works at about 24.0 ft/min (8.0 m/min), the padfoot roller, which typically operates at 165 ft/min (50 m/min) can make five unidirectional passes while keeping pace with the recycling train. If more than five passes are required to achieve the density requirements, the speed of the recycling train will need to be reduced, or an additional roller used. If a second roller is used (i.e., two rollers if one recycling train is used and three rollers if two recycling trains are used), it should be the same make and model as the first, with the same vibration settings. If the roller falls too far behind the recycling train (i.e., typically more than 150 ft [50 m], or when the material dries out and the specified density cannot be achieved throughout the layer [Figure 6.39 through Figure 6.41]), the train must be stopped until the roller catches up.
- The cutting of final levels and final compaction should not interfere with initial compaction (Figure 6.42) (**i.e., initial compaction must be completed before the grader begins cutting final levels**).

Figure 6.37: First padfoot roller pass impressions.

Figure 6.38: Padfoot impressions after multiple passes.

Figure 6.39: Desirable initial compaction procedure.

Figure 6.40: Primary compactor too far behind recycling train.

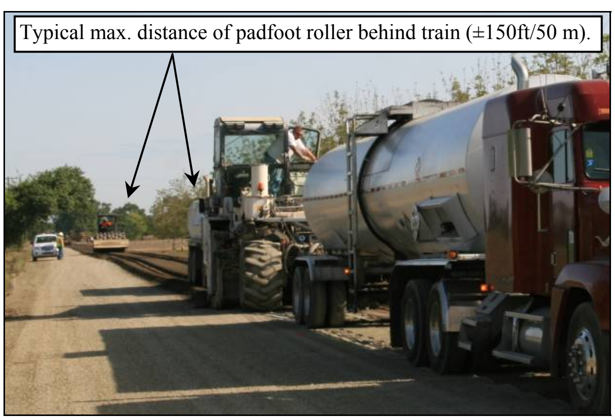


Figure 6.41: Typical maximum distance of padfoot roller behind recycling train.

Figure 6.42: Final leveling and compaction interfering with initial compaction.

- The use of low amplitude vibration or using a roller with insufficient static mass during initial compaction will result in densification of the material in the upper horizon of the layer, forming a bridge of compacted material over a layer of relatively loose material. This loose material will eventually densify under traffic, resulting in settlement and consequently rutting of the pavement.

- Rollers must be correctly selected during test strip construction and quality control of density must be rigorously carried out to ensure that the specified density is obtained throughout the recycled layer.

6.2.18 Final Grades and Final Compaction

Final grading and compaction should follow initial compaction as quickly as possible. The following considerations are important:

- The processes followed for final grading and compaction are similar to those for standard aggregate base. Although this work is not necessarily carried out immediately behind the padfoot roller, every effort should be made to complete it as soon as possible after initial compaction because the asphalt binder and active filler sets up relatively quickly and becomes more difficult to work, resulting in rougher final surfaces.
- Final grades should be cut with the grader after initial compaction is complete (i.e., only minor padfoot impressions remain) (Figure 6.43).

Figure 6.43: Shaping and final levels with the grader.

- Some drying out of the material can be expected in between completion of initial compaction and start of final compaction. Therefore sufficient water should be sprayed onto the surface prior to grading and final rolling to prevent segregation (Figure 6.44), the formation of laminations (Figure 6.45), and to ensure that optimum density is achieved in the upper horizon of the layer.
- Excess material is usually bladed to the side of the road and used for shoulder backfill, or collected and transported for minor corrections along the grade.
- Final compaction is undertaken with a smooth-drum vibrating roller, followed by pneumatic-tired roller. The smooth-drum roller should follow the grader to compact the upper horizon of the recycled layer (Figure 6.46). A low amplitude vibration should be used and care should be taken not to "overcompact" the material, which will result in aggregate breakdown, and/or instability and loss of density.

Figure 6.44: Segregation after grading. **Figure 6.45: Laminations after grading.**

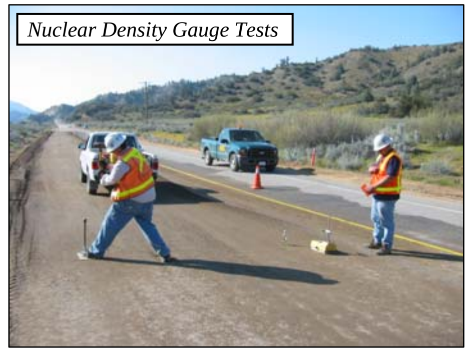
Figure 6.46: Smooth-drum roller behind grader.

- The pneumatic-tired roller is used to obtain a tightly-knit surface finish. This is achieved by spraying water onto the surface followed by rolling (Figure 6.47). Sufficient passes should be applied with the pneumatic-tired roller to achieve the required surface finish. The surface should not be overwatered, as this can lead to segregation of the surface material, laminations, and/or weak spots.

Figure 6.47: Final rolling with pneumatic-tired rollers.

- If the recycled layer will be opened to traffic prior to surfacing, consideration should be given to using a highly diluted asphalt emulsion (30 percent residual bitumen) in the water spraying ahead of the pneumatic-tired roller. This will prevent raveling of the surface, limit the generation of dust, and provide a good surface for the subsequent hot-mix asphalt layer to adhere to.

Compaction Quality Control


Nuclear Density Gauge Tests

Compaction must meet the specification and/or special project provision requirements. This typically requires a nuclear density gauge measurement (CT 231 checked against the laboratory determined density [CT 216]) for every 1,000 yd^2 (1,000 m^2) recycled by each recycling train. Take measurements at three heights within the recycled layer at each point, as follows:

- One-third of layer thickness – 1.0 in. (25 mm) (i.e., bottom third of the recycled layer)
- Two-thirds of layer thickness – 1.0 in. (25 mm) (i.e., middle of the layer)
- Layer thickness – 1.0 in. (25 mm) (i.e., top third of the layer)

Each measurement must meet the specified density. If the specified density is not reached, the rejected section will need to be reworked. A small quantity of foamed asphalt (typically between 0.5 and 1.0 percent) together with a recalculated water content will need to be added to ensure that the correct compaction can be achieved.

Recycled Layer Thickness Quality Control

Thickness quality control is usually determined from cores. Specifications typically call for a core at the same point as the nuclear density gauge measurement described above. Core holes should be filled with rapid-strength concrete. Areas with deficient thickness are typically corrected with hot-mix asphalt according to the requirements of the specification.

Width and Levels Quality Control

Final width and grades should be checked for conformance with design and specification requirements.

6.2.19 Curing

An FDR-FA layer will only gain full strength once the compaction moisture has evaporated. The following issues need to be considered in deciding when surfacing will be scheduled:

- Curing of the asphalt binder component requires that the layer be left to dry back to between 30 and 50 percent of the optimum moisture content before the wearing course (or other overlying layer) is placed. Once the recycled layer is surfaced very little evaporation will take place. Failure to allow this period will result in the foamed asphalt not drying to the required design strengths.

- The small quantities of active filler (portland cement or lime) added during recycling are included to provide early strength to the layer. This early strength gain permits the recycled layer to be opened to traffic after the completion of work each day, and provides sufficient bearing capacity during the slower strength gain of the foamed asphalt. The active filler component of the FDR-FA layer does not need to be cured as a portland cement or lime-treated layer and it should not be expected to perform or behave like one in the longer term.
- If dilute asphalt emulsion was sprayed onto the surface during or after the final rolling, little or no further water spraying will be necessary in the period between final rolling and placement of the surfacing. Occasional watering may be necessary to keep the surface tightly bound. If dilute asphalt emulsion was not sprayed, the surface will need to be regularly watered to prevent raveling and to control dust. Watering must be controlled to ensure that:


Water Spraying for Dust Control

  - The surface does not erode, especially on gradients and super elevations;
  - Slippery conditions are not created;
  - The surface does not rut; and
  - The rate of dry-back of the foamed asphalt layer is not retarded.

6.2.20 Opening to Traffic

The addition of small quantities of active filler (portland cement or lime) will provide some early strength to open the recycled layer to traffic after each day's production. The following considerations with regard to opening to traffic are important:


Sweeping Prior Opening to Traffic

- Prior to opening to traffic, the surface must be broomed to remove any loose material and, if required, temporary markings should be painted onto the surface. Pop-up lane delineators and other forms of adhesive marker do not adhere to the FDR-FA surface and should not be used.
- Appropriate traffic control and signage requirements must be adhered to at all times.
- Despite the use of active filler, the recycled layer will still be susceptible to damage by traffic, specifically permanent deformation. If possible, the use of the road by heavy truck traffic should be limited until the wearing course has been placed. Traffic controls must also be carefully planned to ensure that traffic waiting at the Stop/Go control points do not stand on a section of recycled pavement that is less than 24 hours (and preferably 48 hours) old.
- In the period between final rolling and placement of the surfacing, the road must be carefully monitored each day to identify problem areas that will need to be repaired before surfacing. The cause of any problems observed should be identified. Potential problems could include:

- Raveling, usually caused by low asphalt binder contents, insufficient watering, or excessive blading of the surface after compaction.
- Cracking, usually caused by rapid drying of the layer, contamination of the recycled layer with plastic fines, higher-than-design contents of active filler, under- or overwatering, and/or inadequate compaction.
- Rutting, usually caused by inadequate compaction or overwetting of the surface.

6.2.21 Surfacing

Surfacings should not be placed on the recycled layer until the material has dried back to between 30 and 50 percent of the optimum moisture content (see Section 6.2.19).

The Resident Engineer should carefully inspect the project prior to giving his/her approval to place the surfacing. All problems areas must be repaired ,and all loose material broomed from the surface (the broom should not cause the surface to ravel). Surfacing must not be placed onto a raveled surface (Figure 6.48).

Figure 6.48: Unacceptable and acceptable surfaces prior to placement of wearing course.

6.2.22 Drainage

FDR-FA pavements, like all other pavements, are moisture sensitive and adequate drainage is imperative to ensure good performance throughout the design life of the road. The following need to be checked during construction and before the project is closed:

- Adequate crossfall has been provided along the length of the project to ensure that water can drain off the road and that no localized ponding will occur in low spots.
- Side drains and drain turnouts have been cleared to ensure that water can drain away from the road and will not pond close to the structure. This is particularly important on roads that do not have wide shoulders.
- Culverts have been checked for blockages and all excess construction material cleared from inlets and outlets (Figure 6.49) and that water will not pond near outlets.

- Irrigation channels and ditches have been checked to ensure that they do not interfere with the road drainage.

Figure 6.49: Blocked drains after construction.

6.2.23 Quality Control

Quality control must be carried out according to the requirements in the standard specifications and project special provisions. Key quality control issues include, but are not limited to:

- Start-up procedures, including machine warm-up and air bleeding, and containment of spills during asphalt binder tanker changes and water tanker refills (see Section 0). Start-up procedures should follow equipment operating manuals.
- Ambient and road surface temperatures (see Section 6.2.9).
- Asphalt binder delivery information, temperature, expansion ratio, and half-life (see Section 6.2.10).
- Active filler content and spread rate accuracy (see Section 6.2.12).
- Asphalt binder content (see Section 6.2.13).
- Recycling depth, overlaps, and joints (see Sections 6.2.14 and 6.2.15).
- Consistency of recycled material, mixing moisture content, and dispersion of the foamed asphalt (see Section 6.2.14).
- Compaction moisture content (see Section 6.2.16).
- Distance of the padfoot compactor behind the recycling train (see Section 6.2.17).
- Density after compaction and relative compaction (see Section 6.2.18).
- Final levels and final widths (see Section 6.2.18).
- Layer thickness after compaction (see Section 6.2.18).
- Layer strength after compaction (see Section 6.2.14).
- Surface condition prior to placement of the wearing course (see Section 6.2.21).

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APPENDIX A: EXAMPLE FORMS

The following example forms are provided in this appendix:

1. FDR-FA Project Investigation: Desktop Study
2. FDR-FA Site Investigation: Initial Visual Assessment
3. FDR-FA Project Investigation: Preliminary Report
4. FDR-FA Site Investigation: Visual Assessment
5. FDR-FA Site Investigation: Visual Assessment Summary
6. FDR-FA Site Investigation: Core Log
7. FDR-FA Site Investigation: DCP Assessment
8. FDR-FA Site Investigation: Test Pit Assessment
9. FDR-FA Project Investigation: Analysis
10. FDR-FA Mix Design: Summary Worksheet
11. FDR-FA Mix Design: Foam Characteristics

1 FDR-FA Project Investigation: Desktop Study

Project Number and Description:					
District:		**County:**		**Date:**	
Road No:		**Post Mile:**	**to**	**Assessor:**	
Record of HQ Decision Approving Investigation:					
Program:			**Funding Source:**		
Traffic:					
Climate:					

Pavement Design from As-Built

Layer	Description	Thickness	Material
1			
2			
3			
4			
5			
6			

General condition:	
Potential problems:	1
	2
	3
	4
	5
	6
	7
	8
	9
	10
Fatal flaws:	

Continue with preliminary investigation?	**Yes**		**No**	

2 FDR-FA Site Investigation: Initial Visual Assessment

Project Number and Description:					
District:		**County:**		**Date:**	
Road No:		**Post Mile**	to	**Operator:**	

Observation									Comments
1. Crack type and extent	Alligator		Thermal		Longitudinal		Extent	%	
2. Pumping	From cracks		From other				Extent	%	
3. Rut depth and extent	Depth		Surface		Structural		Extent	%	
4. Maintenance	Digouts		Digout failure				Extent	%	
5. Cause of failures	Age		Traffic		Structural		Drainage		
6. Gravel base	Yes		No						
7. Height above natural ground									
8. Drainage	Adequate		Irrigation						
9.									
10.									
11.									
12.									
13.									
14.									
15.									

Samples taken?	Yes		No		Purpose	
Fatal flaws?	Yes		No		Reason	

3	FDR-FA Project Investigation: Preliminary Report					
Project Number and Description:						
District:		**County:**			**Date:**	
Road No:		**Post Mile**		**to**	**Operator:**	

Observation					Comments
1. Is there sufficient material to recycle?	Yes		No		
2. Is there sufficient structural support/layer thickness?	Yes		No		
3. Is the drainage adequate / can the drainage be improved?	Yes		No		
4. Are failures limited to the surface and base?	Yes		No		
5. Do digouts exceed 25% of the pavement surface?	Yes		No		
6. Is the PI of the underlying layers <12%?	Yes		No		
7. Are there any specific reasons why FDR-FA should not be used?	Yes		No		

8. Other notes:

Continue with detailed investigation	Yes		No		Reason	

4 FDR-FA Site Investigation: Visual Assessment

Project Number and Description:					
District:		**County:**		**Date:**	
Road No.:		**Post Mile:**	to	**Assessor:**	

Surfacing Assessment

Surfacing type	

	Degree Slight					Severe	Extent <5				>80	Length	Width	Number	Location
Mechanical failure	0	1	2	3	4	5	1	2	3	4	5				
Other surface failure	0	1	2	3	4	5	1	2	3	4	5				
Bleeding/flushing	0	1	2	3	4	5	1	2	3	4	5				
Raveling	0	1	2	3	4	5	1	2	3	4	5				
Binder condition	0	1	2	3	4	5	1	2	3	4	5				

Structural Assessment

	Degree Slight					Severe	Extent <5				>80	Narrow (% area)	Wide (% area)	Position	Location
Cracks - block	0	1	2	3	4	5	1	2	3	4	5				
Cracks - longitudinal	0	1	2	3	4	5	1	2	3	4	5				
Cracks transverse	0	1	2	3	4	5	1	2	3	4	5				
Cracks - alligator	0	1	2	3	4	5	1	2	3	4	5				
Pumping	0	1	2	3	4	5	1	2	3	4	5				
Rutting	0	1	2	3	4	5	1	2	3	4	5				
Undulation/settlement	0	1	2	3	4	5	1	2	3	4	5				
Edgebreak	0	1	2	3	4	5	1	2	3	4	5	Number	Diameter		
Potholes	0	1	2	3	4	5	1	2	3	4	5				
Delamination	0	1	2	3	4	5	1	2	3	4	5				
												Small	Medium	Large	Location
Patching/digouts	0	1	2	3	4	5	1	2	3	4	5				

Functional Assessment

	Degree Good				Poor	Influencing Factors									
Riding quality	1	2	3	4	5	Potholes		Patching		Undulation		Corrugation		Fatigue	
Surface drainage	1	2	3	4	5										
Side drainage	✓	✗													

Notes	**Photographs**
	1
	2
	3
	4
	5
	6
	7
	8

5 FDR-FA Site Investigation: Visual Assessment Summary

Project Number and Description:					
District:		County:		Date:	
Road No.:		Post Mile:	to	Assessor:	

Distress/problem	% Area	Influence FDR-FA decision?				
Surface problems		Yes		No		
Cracking		Yes		No		
Pumping		Yes		No		
Rutting		Yes		No		
Undulation/settlement		Yes		No		
Patching/digouts		Yes		No		
Drainage		Yes		No		
Vegetation		Yes		No		
Services		Yes		No		
Cause of failure requiring digout						
Cause of low strength areas in FWD survey						

Side drainage						
Side drainage	Side drains	Good		Bad		
	Culverts	Good		Bad		
	Irrigation	Good		Bad		

Notes	Photographs
	1
	2
	3
	4
	5
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	12

6 FDR-FA Site Investigation: Core Log

Project Number and Description					
District:		County:		Date:	
Road No.:		Post Mile	to	Operator:	

Core Number	Lane		Position					Observations
	NB/EB	SB/WB	Edge	OWP	BWP	IWP	CL	

NB/EB/SB/WB - Lane direction	OWP – Outer wheelpath	IWP – Inner wheelpath	BWP – Between wheelpath	CL - Centerline

7 FDR-FA Site Investigation: DCP Assessment

Project Number and Description								
District			**County**			**Date**		
Road No.			**Post Mile**	to		**Assessor**		
Position			**Position**			**Position**		
0			0			0		
5	205	405	5	205	405	5	205	405
10	210	410	10	210	410	10	210	410
15	215	415	15	215	415	15	215	415
20	220	420	20	220	420	20	220	420
25	225	425	25	225	425	25	225	425
30	230	430	30	230	430	30	230	430
35	235	435	35	235	435	35	235	435
40	240	440	40	240	440	40	240	440
45	245	445	45	245	445	45	245	445
50	250	450	50	250	450	50	250	450
55	255	455	55	255	455	55	255	455
60	260	460	60	260	460	60	260	460
65	265	465	65	265	465	65	265	465
70	270	470	70	270	470	70	270	470
75	275	475	75	275	475	75	275	475
80	280	480	80	280	480	80	280	480
85	285	485	85	285	485	85	285	485
90	290	490	90	290	490	90	290	490
95	295	495	95	295	495	95	295	495
100	300	500	100	300	500	100	300	500
105	305	505	105	305	505	105	305	505
110	310	510	110	310	510	110	310	510
115	315	515	115	315	515	115	315	515
120	320	520	120	320	520	120	320	520
125	325	525	125	325	525	125	325	525
130	330	530	130	330	530	130	330	530
135	335	535	135	335	535	135	335	535
140	340	540	140	340	540	140	340	540
145	345	545	145	345	545	145	345	545
150	350	550	150	350	550	150	350	550
155	355	555	155	355	555	155	355	555
160	360	560	160	360	560	160	360	560
165	365	565	165	365	565	165	365	565
170	370	570	170	370	570	170	370	570
175	375	575	175	375	575	175	375	575
180	380	580	180	380	580	180	380	580
185	385	585	185	385	585	185	385	585
190	390	590	190	390	590	190	390	590
195	395	595	195	395	595	195	395	595
200	400	600	200	400	600	200	400	600

8 FDR-FA Site Investigation: Test Pit Assessment

Project Number and Description:					
District:		**County:**		**Date:**	
Road No.:		**Post Mile:**	**to**	**Assessor:**	
Pit Number:		**Post Mile:**		**Position:**	

Layer Thickness

Layer	Present	Average	Thickest	Thinnest	Comments
Hot-mix asphalt					
Base					
Subbase 1					
Selected 2					
Selected					
Other					

Hot-mix Asphalt Layer

Problems	Rubber?		Fabric?		Geogrid?		Other?	
Notes								

Granular Layers

Problems	Grading?		Oversize?		Plasticity?		Rutting?	
	Moisture?		Pumping?		Mottling?		Other?	
Notes								

Subgrade

Problems	Punching?		Plasticity?		Silt?		Rutting?	
	S/slides?		Moisture?		Mottling?		Other?	
Notes								

Samples

Moisture	HMA		Base 1		Base 2		Subgrade	
Material	HMA		Base 1		Subbase		Subgrade	

Notes	Photographs
	1
	2
	3

9 FDR-FA Project Investigation: Analysis

Project Number and Description:					
District:		**County:**		**Date:**	
Road No.:		**Post Mile:**	**to**	**Assessor:**	

Task	Parameter				
FWD and DCP	Less than 10% of the road has a subgrade modulus of <45 MPa.	Yes		No	
	If > 10%, can weak areas be strengthened as part of project?	Yes		No	
Visual assessment	Subgrade failure appears to be <10% of project area.	Yes		No	
	If >10%, can weak areas be strengthened as part of project?	Yes		No	
	Digout areas did not fail again after 12 months (i.e., after wet season).	Yes		No	
	If failed, can problem areas be strengthened as part of project?	Yes		No	
	Drainage is effective.	Yes		No	
	If not effective, can problem areas be corrected as part of project?	Yes		No	
	Land use does not influence pavement.	Yes		No	
	If influenced, can land use practices be changed?	Yes		No	
Layer thickness	Base and subbase thickness > 12 in. (300 mm)	Yes		No	
	If <300 mm, can additional material be imported as part of project?	Yes		No	
	Hot-mix asphalt thickness >2 in. and <10 in. (>50 mm and <250 mm)	Yes		No	
	If HMA >10 in., can hot-mix asphalt be pre-milled as part of project?	Yes		No	
Test pit assessment	Presence of reinforcing layers and rubber will not influence recycling?	Yes		No	
	Pavement distress is not caused by weak subgrade	Yes		No	
	Subgrade moisture problems are not evident	Yes		No	
Indicator tests	PI of underlying materials are <12	Yes		No	
	Blend of asphalt millings and underlying material has fines content <15%	Yes		No	
	R-value of subgrade is sufficient for pavement structure	Yes		No	
	If R-value is low, can base material be imported as part of project?	Yes		No	
Recommendation	FDR-FA is appropriate rehabilitation option	Yes		No	

Justification for recommendation

10 FDR-FA Mix Design: Summary Worksheet

Project Number and Description:							
District:		**County:**			**Date:**		
Road No.:		**Post Mile:**	**to**		**Assessor:**		
Grading	**Sieve**		**Required**	**Actual**	**Comply?**		
	50	2.0	100		Yes		No
	37.5	1.5	90 – 100		Yes		No
	25	1.0	-		Yes		No
	19	0.75	50 – 85		Yes		No
	4.75	#4	25 – 45		Yes		No
	0.6		10 – 25		Yes		No
	0.075	#200	5 – 12		Yes		No
	If P0.075 < 5%, what is proposed action?						
	If P0.075 < 5%, what is proposed action?						
	Continue mix design?				Yes		No
Binder Selection	Selected binder				Alternate binder		
	Test		**Required**	**Actual**	**Comply?**		
	Expansion ratio				Yes		No
	Half-life				Yes		No
	Selected foam temperature				Foam temp range		
	Selected foaming water ratio				Foaming water range		
Active filler	Active filler type			1		2	
MDD/OMC	MDD		OMC		MMC		
Binder content	Content				ITS @ selected content		
	ITS Control				ITS improvement		
Active filler	Type				Source		
	Content				ITS @ selected content		
	ITS Control				ITS improvement		
Ref density	Reference density						
TSR	Wet ITS		Dry ITS		TSR		
Temperature	Min recycling temp						

11 FDR-FA Mix Design: Foam Characteristics

Project Number and Description				
Foaming Water Ratio (%)	**Asphalt Temperature (Tolerance ±2ºC [±4°F])**			
	150°C (302°F)	**160°C (320°F)**	**170°C (338°F)**	**180°C (356°F)**
Binder 1				
Supplier		**Refinery**		**PG Grade**
	Expansion Ratio			
2				
3				
4				
5				
	Half-Life			
2				
3				
4				
5				
Max product (ER* $\tau_{1/2}$)				
Binder 2				
Supplier		**Refinery**		**PG Grade**
	Expansion Ratio			
2				
3				
4				
5				
	Half-Life			
2				
3				
4				
5				
Max product (ER* $\tau_{1/2}$)				
Binder 3				
Supplier		**Refinery**		**PG Grade**
	Expansion Ratio			
2				
3				
4				
5				
	Half-Life			
2				
3				
4				
5				
Max product (ER* $\tau_{1/2}$)				

Notes
Expansion ratio and half-life are reported as an average of three tests.
Product (ER* $\tau_{1/2}$) is the highest value for each column.

APPENDIX B: DYNAMIC CONE PENETROMETER

The Dynamic Cone Penetrometer (DCP) is a simple tool consisting of a steel rod with a conical, hardened steel tip that is driven into the road pavement using a drop hammer of standard mass (8.0 kg [17.6 lb]) (Figure B.1). The penetration rate, measured in mm/blow, provides an indication of the in-situ strength of the material in the different pavement layers. DCP probes are normally driven to a depth of 800 mm, or deeper with heavier pavement structures. This enables a profile to be compiled indicating in-situ properties relative to depth.

DCP measurements correlate well with the California Bearing Ratio (CBR) in fine and sandy materials (and reasonably well for coarse granular materials) at in situ density and moisture content. Correlations with Unconfined Compressive Strength (UCS) in lightly cemented materials have also been developed. DCP results may also be used as an indicator of the elastic modulus of the materials in the pavement at in-situ conditions.

DCP investigations require a series of tests for improved reliability since the coefficient of variation is often relatively high. These measurements should therefore be analyzed statistically to obtain the relevant percentile value (the twentieth percentile is typically used for lower traffic volume roads and the fifth percentile for higher traffic volume roads).

The results of a DCP survey are useful for indicating the thickness of layers of uniform strength within the pavement structure. Computer programs are available for analyzing the penetration data to indicate in situ CBR, UCS, layer thickness, and elastic moduli, as shown in Figure B.2.

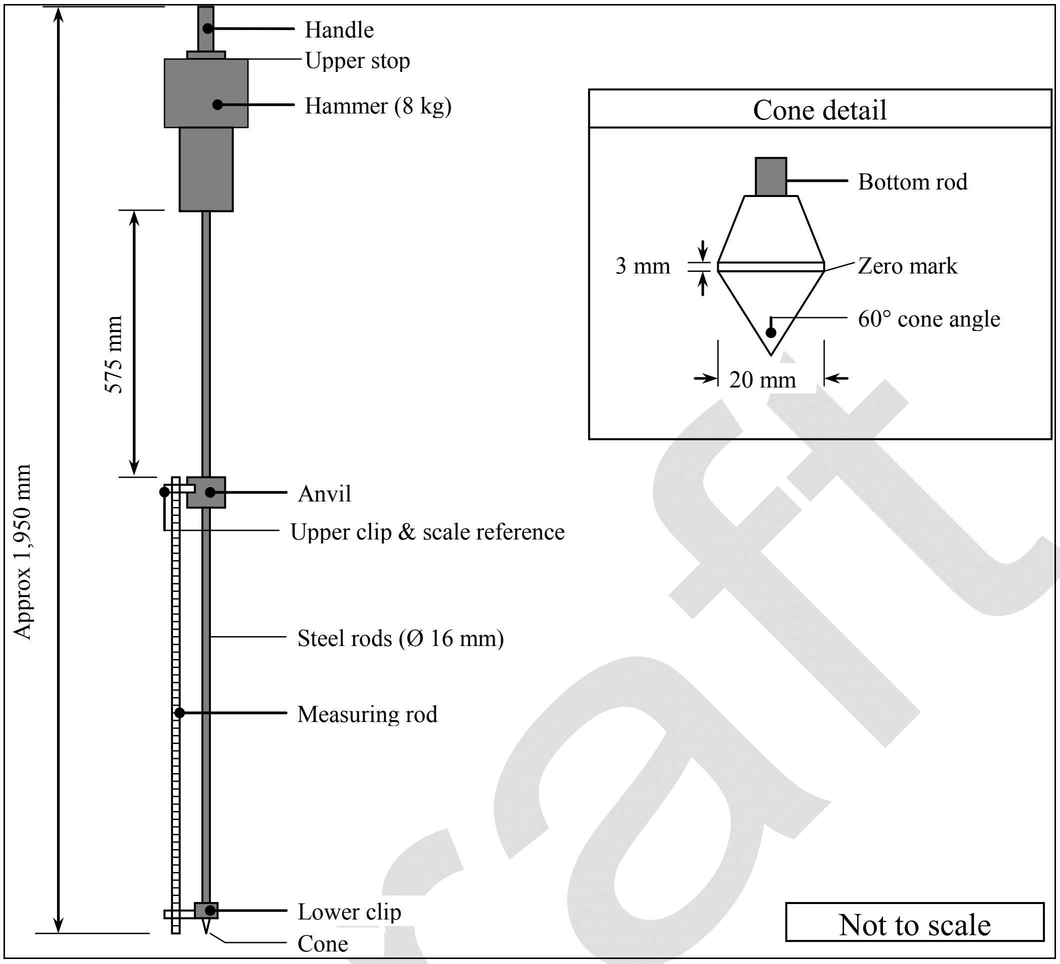

Figure B.1: Dynamic Cone Penetrometer (DCP).

DCP summary

Area : RFS
Road : MB Road Distance : 4.00 km
Structure Number (DSN_{800}) : 193
B = 38 A = 4767

Moisture : Moist
Position : Section
Base Type : Cemented
Category VI: Poorly balanced deep structure (PBD)

Category : 0
Test Date : 03/24/07
Struct. Cap. (E80s) : $1.392x10^6$

User defined layer summary

From-To (mm)	Avg.DN (mm/blow)	Std.Dev. (mm/blow)	CBR (%)	Range 5% - 95%	UCS (kPa)	Range 5% - 95%	E-Mod (MPa)	Range 5% - 95%
0-150	2.17	0.85	153	50- 346	1257	473- 2573	490	194- 1447
150-410	4.86	3.11	55	11- 310	511	121- 2338	208	53- 1180
410-800	22.69	2.93	8	5- 12	91	64- 132	41	29- 58

Redefined layer summary

From-To (mm)	Avg.DN (mm/blow)	Std.Dev. (mm/blow)	CBR (%)	Range 5% - 95%	UCS (kPa)	Range 5% - 95%	E-Mod (MPa)	Range 5% - 95%
0-284	2.03	0.62	166	68- 316	1351	616- 2375	525	249- 1217
284-408	9.66	2.87	23	10- 61	237	110- 559	100	49- 227
408-800	22.72	2.93	8	5- 12	91	64- 132	41	29- 57

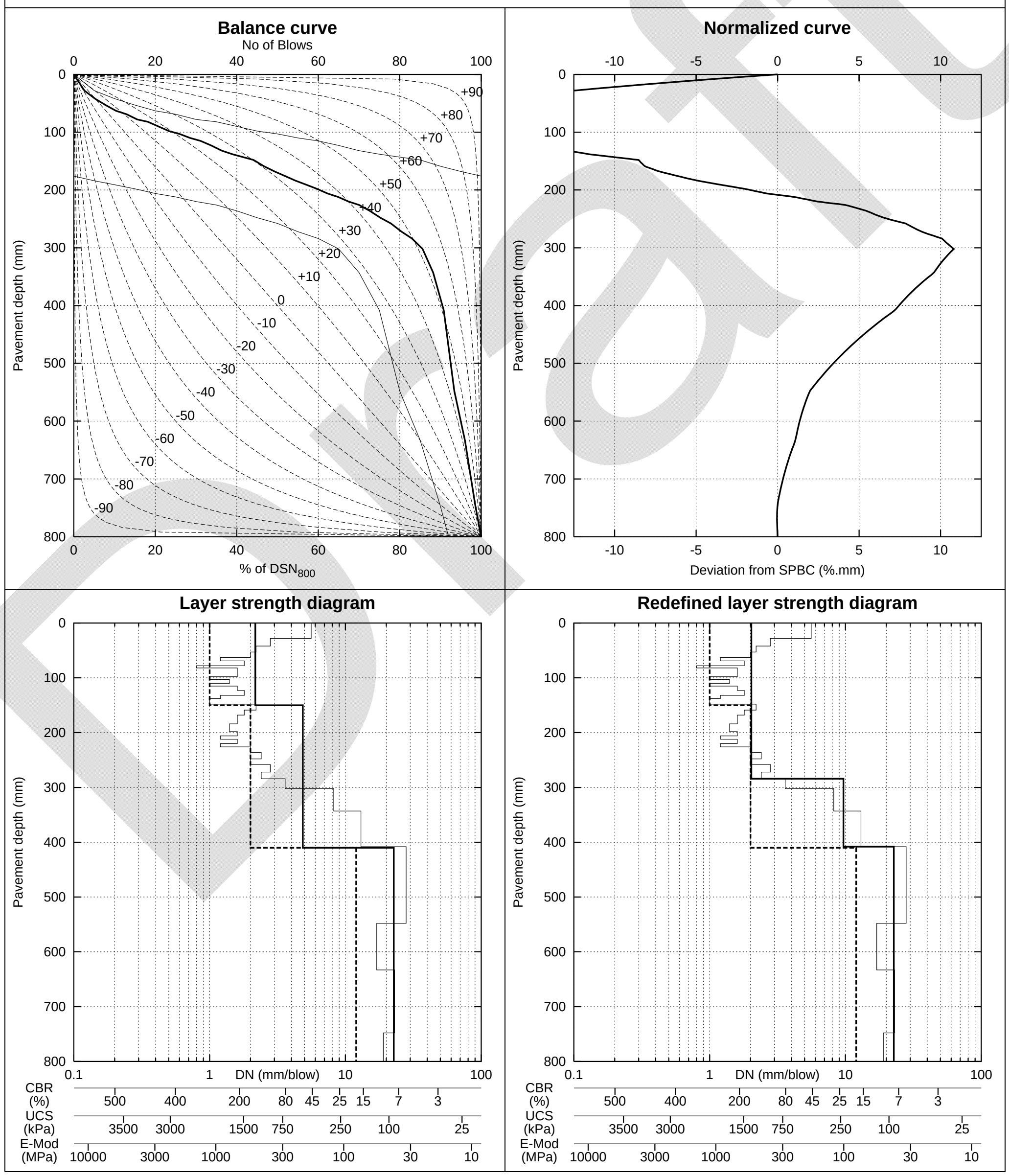

Figure B.2: Plots of DCP data.