FULL DEPTH RECLAMATION USING ENGINEERED EMULSION

CHAPTER 15

15.1 OVERVIEW

This guide has been prepared to provide guidance on project selection, materials, pavement structure design, and development of full depth reclamation with engineered emulsion (FDR-E) projects.

FDR-E transforms existing asphalt concrete (AC) pavement and underlying granular material into stabilized base for a new pavement surface layer. This guide is presented for an FDR-E project designed as part of a flexible pavement structure. If project parameters dictate a concrete surface is an effective strategy, design the rigid structure using the tables in Index 623.1 of the Highway Design Manual, using the thickness indicated in the tables for Class 2 aggregate base.

FDR-E addresses critical engineering and construction challenges associated with pavement rehabilitation. It allows for the reuse of existing in-situ materials to achieve a reliable and consistent strength component. FDR-E is more flexible, offers superior fatigue resistance, and is less prone to cracking.

FDR-E is considered a roadway rehabilitation strategy but may be suitable for pavement rehabilitation in limited locations as a highway maintenance (HM) or capital preventive maintenance (CAPM) project, if the headquarters pavement reviewer concurs that the amount of FDR-E meets the program or cost limitations for digouts. Refer to Chapter 9 of the Project Development Procedures Manual (PDPM), the HDM, and Design Information Bulletins (DIB) 79 and 81-01 for additional information.

15.1.1 Full Depth Reclamation Using Engineered emulsion

The FDR-E pavement rehabilitation process pulverizes the existing AC pavement and a portion of the underlying materials, and mixes the pulverized materials with engineered emulsion and water. Pulverization and mixing are usually performed in separate operations. The processed mixture is then graded, compacted, and cured.

Figure 15.1: FDR-E recycling train

FDR-E used in pavement rehabilitation offers benefits including:

- More flexible than other base course materials and chemical stabilizers, offers superior fatigue resistance, and is less prone to cracking
- Cost effective, in-place construction
- Increased structural capacity
- Reflection cracking mitigation (obliteration of existing cracking pattern)
- Cost effective corrections to profile, cross slope, and roughness
- Expedited construction and simplified staging with potentially less disruption to traffic
- No heating of engineered emulsion

FDR-E effectiveness is governed by (1) the nature of the base material underlying the pavement and the RAP to base ratio, (2) the proportion of engineered emulsion in the mix (engineered emulsion content), (3) moisture conditions, (4) the degree of compaction, (5) curing. Other factors having a direct impact on FDR-E are variability in materials, subgrade conditions, drainage, and construction practice.

For base-failure projects, FDR-E greatly improves constructability. Strategies that remove the existing failed pavement structure may create a situation where soft subgrade cannot support the weight of equipment. This necessitates bringing in material to stabilize the subgrade, such as fabric and rock, to give sufficient strength for a workable platform. FDR-E does not require removal of the pavement structure, which lessens issues of wetting the subgrade and unstabilizing areas that were in equilibrium. All the treatment is performed above the subgrade with low-pressure flotation tires. Once the material is treated and compacted, it immediately starts to cure.

15.1.2 Appropriate Applications

FDR-E can treat a variety of project conditions, but it is most cost effective as a pavement rehabilitation strategy indicated by (1) cracked surfaces requiring digouts of 20% or more by paving area, (2) a deflection study with 80th percentile deflections greater than 0.015 inch (see California Test 356), or (3) advanced pavement distress such as:

- Severe cracking (wider than ¼ inch)
- Continuous deep reflective cracking
- Alligator 'C'cracking (see Figure 15.2.2)
- Plastic deformation (shoving or rutting greater than ¾ inch)

FDR-E is effective for rough surfaces that require smoothing of bumps and dips to improve ride quality; and base deterioration due to fatigue, moisture intrusion, pumping, or other causes.

FDR-E also allows for reshaping of the finish grades. This is useful to address drainage issues, superlevation adjustments and conforms. After pulverization of the existing section, the pulverized materials and surface can be re-graded to new elevation requirements. This is not typically feasible with an overlay type of process where the designer is limited to using only the existing surface.

FDR-E can also enhance a pavement's structural capacity by providing additional stabilized base.

For pavement sections with geologic related (deep) issues, other strategies should be considered (see HDM Index 625.1 or 635.1(8)).

15.1.3 General Considerations

The following conditions and general items should be considered:

- Areas with drainage problems such as:
    - saturated subgrade or base layers
    - inadequate drainage systems to divert water away from the pavement structure
- Pavement structures with concrete, treated base, or a geosynthetic pavement interlayer (or fabric stress absorbing membrane). Lean concrete base (LCB) or cement treated base (CTB) layers may not suitable for FDR-E due to difficulty in pulverization. An indication of suitability is penetration by a dynamic cone penetrometer (DCP, see Section 15.3.2).
- Traffic volume, sufficient to produce construction delays exceeding 30 minutes under one-way traffic control (typically > 20,000 ADT). Higher volumes can be accommodated if detours are available.
- Truck traffic > 1,000 ADTT.
- Roadways with numerous shallow utilities or drainage facilities within 6 inches of the proposed FDR-E depth.
- Roadways with adequate structural capacity and good quality base, grades, and cross slopes despite a moderately cracked pavement surface with less than ½ inch crack widths.

If any of these conditions or various combinations exist, careful consideration should be made before selecting any pavement strategy. Mitigation may be feasible but will increase costs and could reduce the effectiveness of FDR-E or other rehabilitation strategies such as overlay, mill and fill, or remove and replace. Consult with the district materials engineer or Division of Maintenance Pavement Program for available pavement strategy alternatives.

15.2 Project Evaluation

A comprehensive project evaluation is important for understanding the existing pavement conditions, materials, and project surroundings. The findings are used to determine a rehabilitation strategy and, if selected, as input to the FDR-E engineered emulsion content determination, pavement structure design, and project specifications.

The three stages in a project evaluation include:

- Desktop study
- Preliminary field review and recommendations
- Detailed site investigation, testing, analysis, and recommendations

15.2.1 Desktop Study

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

- **Consult** the headquarters pavement advisor, district materials engineer, and district maintenance for input prior to any detailed analysis. Consider the funding program, expected design life, construction year, and traffic index. A flowchart to guide this decision is shown in Figure 15.2.1.
- **As-built plans** are available on the Caltrans intranet (http://drs.dot.ca.gov/falcon/websuite.shtml) to provide historical information about existing roadway features, including pavement structure design (layer thicknesses, types, materials, design life, traffic), drainage structures, etc.
- **Photo surveys** can be used to obtain an initial indication of the condition of the pavement, problem areas and localized failures, and project surroundings. Google maps (www.googlemaps.com) provides viewable photos of many state highways and other roadways. For Caltrans employees, the photolog is also available on the intranet.
- **Pavement Condition Report/ Pavement Management System** contains current and historical information on the pavement condition. Copies can be obtained from the district maintenance engineer, or the Pavement Program intranet site. Distress rating definitions are contained in the Pavement Condition Survey Pavement Evaluation Manual, also at the Pavement Program intranet site.
- **Traffic data** are used to determine the pavement structure design requirements and predict traffic growth or decline. Project data should be obtained from the district travel forecasting office but traffic counts are available from the Division of Traffic Operations 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 Concrete Pavement and Pavement Foundations or *http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/Climate.html*.

- **Maintenance records** from the area Maintenance Superintendent can identify problem areas along the project that may require additional investigation and pretreatment repair.
- **Maps**, Google Earth, Map Quest, and, for Caltrans employees, the interactive application CT Earth, are available.

When the reference information is gathered, it should be analyzed using the criteria in Section 15.1. If FDR-E is a viable strategy, a preliminary field review should be conducted.

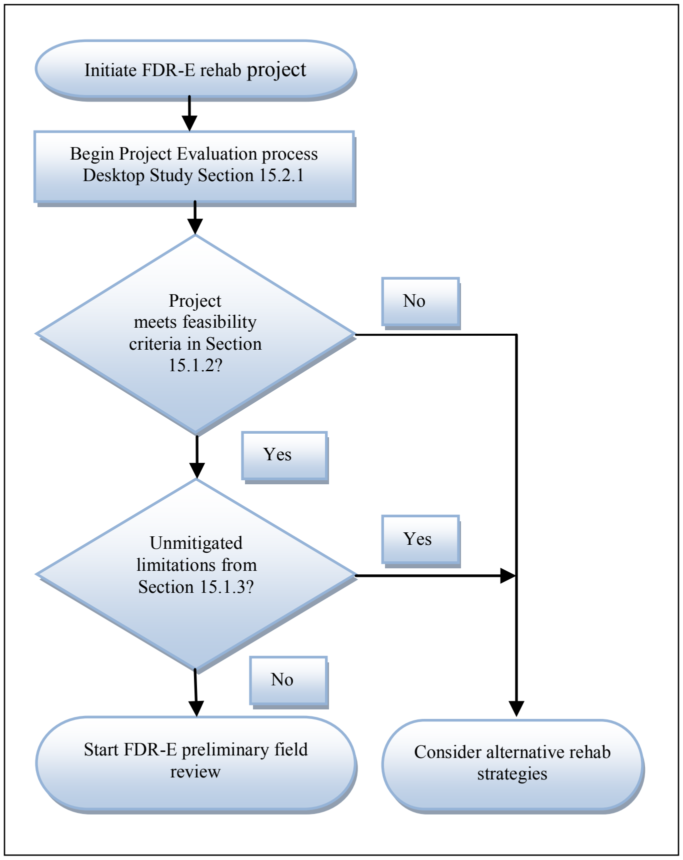


Figure 15.2.1: Project Evaluation Flowchart

15.2.2 Preliminary Field Review

A preliminary field review is needed to supplement data from the desktop study and assess whether FDR-E is suitable for a project. This preliminary review should be carried out as early as possible during project scoping, preferably during the rainy season when subgrade moisture and drainage issues can be assessed, to identify costs and maximize analysis time for FDR-E and alternative pavement strategies. Review and assessment of the project surroundings, pavement conditions, structural capacity, material properties, geometrics, traffic issues, constructability, and cost effectiveness should be conducted as part of the project evaluation process. Recommendations for proceeding with a more detailed study or investigating an alternative rehabilitation strategy should be included in the project initiation document (PSSR, PSR, etc.).

Visual Assessment

The visual assessment should identify the existing pavement failure modes and any specific reasons why FDR-E may not be a suitable rehabilitation option. The Maintenance Supervisor should have knowledge of problem areas and the frequency and extent of maintenance work.

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 for:

- Type, severity, and extent of alligator cracking or pumping (extensive fatigue cracking and pumping of fines through the cracks usually indicates 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?)
- Road height above natural ground level and presence of an existing granular base layer (roads at or below natural ground level, without drainage systems, will usually have drainage problems
- Drainage design efficiency (i.e., road shape, side drains, culverts, etc.)
- Land use immediately adjacent to the road (irrigated agricultural lands and the use of side drains for irrigation purposes may lead to moisture related pavement structure problems)
- Locations of natural water sources and adjacent roadway impacts

The primary cause of pavement failure (e.g., age, increased traffic loading, overloading, inadequate structural design or layer thicknesses, lack of existing base material, poor drainage, weak subgrade, etc.) should be noted. Observations should be recorded on an appropriate worksheet (example in Appendix F, Form 2).

Preliminary Recommendations

Recommendations summarizing the initial project evaluation from the desktop study and preliminary field review should be prepared and attached to the project initiation document. Include 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-E or to consider an alternative method of rehabilitation. A template for preliminary recommendations is provided in Appendix F, Form 3. The recommendations should contain:

- General project description, project identification, road description, program, and funding source.
- Existing pavement structure, including layer thicknesses and materials
- General description of existing pavement condition
- Current traffic data
- Climate region
- Potential problem areas and mitigation
- Life-cycle cost analysis of alternative pavement strategies
- Analysis recommendations. Include features that make FDR-E a viable strategy, may limit effectiveness, or fatal flaws that exclude FDR-E as a rehabilitation option.

15.2.3 Detailed Site Investigation

The detailed site investigation is carried out by district materials staff during project design to gather additional pavement and materials information and verify FDR-E is a suitable strategy for the project location. Investigations can be done any time of year, but during the wet season is preferable since construction activities are minimal and drainage problems are readily identified.

The detailed site investigation should include:

- Pavement Evaluation
    - Distress assessment
    - Digouts and failure cause
    - Drainage systems
- Existing Pavement Structure Assessment (Section 15.3)
    - Coring or ground penetrating radar (GPR) survey (Section 15.3.1—Surface Layer Thickness)
    - Deflection (falling weight deflectometer: FWD) and DCP testing (Section 15.3.2—Subgrade Analysis)
    - Sampling location recommendation for contractor mix design and material properties assessment (Section 15.3.4)
    - Material sampling
    - Laboratory Testing (Section 15.3.4)
- Analysis summary and recommendation (Section 15.5)

Inadequate site investigations can lead to misapplication of FDR-E and premature failures associated with unidentified areas of weak subgrade materials, inadequate drainage, and material variability.

Pavement Evaluation

The pavement evaluation should supplement the visual assessment during the preliminary field review (Section 15.2.2) and identify the existing modes of failure and any specific reasons why FDR-E may not be the optimum rehabilitation strategy. Information should be captured on a form (Appendix F, Form 4) and summary sheet (Appendix F, Form 5).

Procedure

The following tasks need to be completed during the pavement evaluation. Problem areas and potential solutions should be identified on the summary sheet:

1. Assess the distress type, severity, extent (percentage of project length), and failure modes. Emphasize cracking, rutting, and pumping. Large areas of loose AC in areas of severe alligator cracking may influence the consistency of the reclaimed material (oversized chunks). Pumping often indicates weak support conditions. Deep, wide ruts are often an indication of weak subgrade and insufficient pavement structure. These areas may require additional investigation, such as test pits, coring, DCP, or FWD.
2. 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.).
3. 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 ditches and culverts are:
        - Blocked by erosion or agricultural activity
        - Used for agricultural irrigation water flows
    - Plow furrows run perpendicular or towards the road

- Water flows into the pavement structure from access roads and driveways

Blocked ditch and culvert.

Side ditch used for irrigation water.

Plow furrows perpendicular to road.

Irrigation water sprays on the road.

Access road drainage problems (note digout).

Severe alligator cracking.

Figure 15.2.2: Example Pavement Evaluation Features

4. Assess areas that are performing adequately to apply mix design and determine upper limits of unconfined compressive strength with mix design proportions

15.3 Existing Pavement Structure Assessment

15.3.1 Surface Layer Thickness

Coring can be used to obtain an indication of surface layer thicknesses and variability within the project limits. While coring data is limited to an intermittent sampling interval, project trends can often be identified from the resulting pavement profile and information from local maintenance personnel.

Test pits can also be considered. See section 15.6.1 for information on test pits.

Ground penetrating radar (GPR) can provide a continuous evaluation of pavement layer thickness and also identify the location of underground utilities. Network level GPR surveys are available through the pavement management system under the Division of Maintenance Pavement Program and project specific GPR surveys can be arranged through the Office of Roadway Materials Testing in Materials Engineering and Testing Services (METS). If a GPR survey is undertaken, limited coring will still be required to verify the data and conduct DCP testing described in Section 15.3.2.

Coring Procedure

The following procedure should be used for coring:

1. Core once every 1,500 ft in the center of the lane (minimum 4 inch diameter) and alternate between lanes.
2. Core in additional problem areas identified during the pavement evaluation and where differences in pavement design or construction are apparent, such as digouts.
3. Conduct a DCP test after removing the core to analyze variability in subgrade strength and validate FWD measurements (see Section 15.3.2). DCP measurements should be taken in each core hole to check variability in subgrade strength and to validate FWD measurements.
4. Measure each core and record the AC thickness and any special characteristics (e.g., layers with rubberized asphalt, stripping, the presence of interlayers, thin areas, digouts, adhesion to the base, etc.). An example core log is provided in Appendix F (Form 6).
5. Photograph the core against a tape measure (Figure 15.3)
6. After measurement, backfill the core hole.

Figure 15.3: Core (4” diameter)

Core thicknesses should be entered into a spreadsheet to calculate the average and standard deviation. A high standard deviation indicates that thickness varies along the section. Thicknesses should be plotted to identify areas above and below the average thickness. If the average AC thickness is greater than 0.90 foot, consideration should be given to cold planing to establish an acceptable FDR-E depth for pavement rehabilitation projects. A thick AC layer may also indicate areas with weak subgrade, inadequate base, or ongoing maintenance problems that may require a thicker FDR-E layer than basic pavement rehabilitation.

15.3.2 Subgrade Analysis

When materials samples are collected, carefully assess and document the following features:

1. **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.
2. **Layer thickness.** Measure the thickness of each layer and calculate averages. This data will be used to determine the FDR-E depth, verify as-built information, correlate with the DCP determined layer thicknesses, and to determine whether supplementary aggregate is required.
3. **AC assessment.** Inspect each layer of AC to identify the presence of fabrics, or other materials that may influence the FDR-E operation.
4. **Base layer assessment.** Inspect the base to assess material type, gradation, presence of large aggregate, and signs of contamination from the subgrade (pumping) or severe moisture fluctuations (mottling). Moisture problems will typically be associated with high subgrade deflection modulus values and DCP penetration rates.
5. **Subgrade assessment.** Inspect the subgrade to identify moisture condition, plasticity, signs of fluctuating moisture conditions (mottling), shearing (slickenslides), inadequate support for the overlying layer (punching of aggregate), and any other problems that could influence FDR-E effectiveness.

The primary purpose of analyzing the subgrade using an FWD and DCP is to evaluate the stiffness of materials below the anticipated FDR-E depth (typically the base or subbase and subgrade), locate weak areas that require special treatment before or during recycling, and identify suitable locations for mix design materials sampling (although locations will not be specified) (Section 15.3.4).

Falling Weight Deflectometer (FWD)

California Test 356 is used to determine overlay requirements from pavement deflection measurements. To obtain deflection measurements for subgrade analysis during FDR-E site investigation, follow CT 356, Method A with the following modifications:

- Testing should ideally be carried out at the end of the rainy season, when subgrade moisture is likely to be highest.
- The lane with the worst existing pavement condition should be tested unless each lane is designed separately, in which case both lanes should be tested.
- Use core thicknesses to determine the pavement structure profile and conduct DCP analysis (see below).
- Use a calibrated FWD unit capable of applying impact loads of 9,000 lb on a standard 12 inch diameter plate and measuring pavement deflection at a distance of 24 ± 1.0 inch from the plate center.

- Conduct tests between the wheelpaths to minimize the effects of severe wheelpath cracking on the seating of the FWD load and sensors.
- Use a test interval of 200 ft to obtain 21 deflection measurements per lane-mi. Testing productivity will be approximately 2.0 lane-mi/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. Areas of interest identified during the pavement evaluation should be tested in addition to measurements at the regular interval.
- Analyze FWD test results according to the procedures in Appendix B and assess all areas with stiffness less than 6,500 psi or R-value < 20. Likely reasons for low strength should be identified (e.g., drainage problems, subgrade materials, etc.).

Dynamic Cone Penetrometer (DCP)

Use a standard DCP with 60° cone and a 1500 ft test interval for DCP measurements. DCP testing should coincide with the removal of cores, discussed in Section 15.3.1. In areas of suspected high variability in underlying materials, such as cut and fill transitions, changes in moisture condition, soil or vegetation type, or failed or repaired areas, more frequent measurements (every 300 to 500 ft) 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. Measure the penetration after every five blows up to a depth of 800 mm (31.5 in.) An example is provided in Appendix F Form 7. Analyze DCP results according to the procedures in Appendix C.

If historical R-value information based on actual test data is not available, subgrade material samples should be collected from the edge of the road to determine plasticity and R-value (see Section 15.3.3). Sampling intervals should take into account potential variability based on experience and geologic, geographic, topographic, and hydrologic changes throughout the project limits. Samples should be collected from alternate sides of the road as close to the edge of the road as possible, without including base, subbase, or other imported material. Sampling depth should be from 1 to 2 feet and a minimum of 65 lb of subgrade should be collected.

15.3.3 Laboratory Testing

Standard materials tests (Table 15.3) are required to characterize the existing pavement structure and subgrade to determine the viability of FDR-E as a project strategy. Additional indicator tests are carried out by the contractor during the mix design (Section 15.6). If the AC layer is thicker than 0.90 foot, the sample should be scalped to obtain the correct proportion of AC and underlying material based on the preliminary pavement structure design. If any of the following minimums are not met, add sufficient supplementary aggregate (preferably RAP) to the design to improve the engineering properties (see Section 15.5.2) or select a strategy other than FDR-E:

Table 15.3: Material Test Minimum Targets

Material/Layer	Sample Size (lbs)	Grading (CT 202)	Plasticity (CT 204)	R-value[3] (CT 301)
Exist AC + underlying material[1]	65	passing #200 ≤ 20%	PI < 6	-
Base[2]	65	-	PI < 6	-
Subgrade	65	-	PI < 40	5

[1]Sample and blend proportionally according to the preliminary design FDR-E depth. Minimum 2” underlying material.
[2]Layer may not be present.
[3]If mechanistic-empirical analysis is used for pavement structure design, R-value testing is not required for base or subgrade characterization.

The minimum targets in Table 15.3 should be interpreted carefully. If the percent passing the no. 200 sieve is 20 percent or more, FDR-E need not necessarily be rejected as a strategy. However, FDR-E will not treat clay as cementitious additives will, and will require a higher engineered emulsion content to coat fine particles effectively. Consider lowering the FDR-E gravel equivalency to 1.3 for this condition. Subgrade material with a low R-value (between 5 and 20) may be adequate for FDR-E or other pavement strategies, but could also require special design considerations. If the existing pavement structure has a base layer, subgrade plasticity is less critical than for non-engineered sections where native material is underlying the existing AC surface layer and will be blended into FDR-E material.

15.3.4 Material Sampling Site Recommendation

The contractor is responsible for coring and sampling material for the FDR-E mix design, according to the criteria in Section 15.6, after a project is awarded. As part of the Materials Information Handout included in the bid package, the District Materials Engineer is responsible for presenting the results of the project evaluation and recommending the minimum number of materials sampling sites required for the contractor to adequately characterize material variability throughout the project length. Potential locations can be noted for the project records but should not be provided as recommendations to the contractor due to liability issues.

Each FDR-E project should have at least two materials sampling sites, but more may be indicated by variability in surface layer thickness or materials, subgrade analysis results (FWD or DCP), or changes in geologic, geographic, topographic, and hydrologic features throughout the project limits.

15.4 ANALYSIS SUMMARY

The detailed site investigation should be summarized, documented, and included in the Materials Information Handout to support a final recommendation on the use of FDR-E or an alternative rehabilitation strategy. An example form is shown in Appendix F, Form 8 and the flow chart in Figure 15.4 can be used to guide the decision process.

Improvement of weak subgrade must be considered in the pavement structure recommendation, whether or not FDR-E is determined to be a viable strategy. FDR-E design features that can mitigate weak subgrade include:

- Add Class 2 AB to subgrade prior to FDR-E
- Remove and replace poor material
- Increase overlay thickness
- Enhance drainage features

- Stabilize subgrade with lime or cement (FDR-E equipment), or subgrade enhancement geosynthetics (SEG)

15.5 MATERIALS

15.5.1 Cement

Cement is recommended to be used in all FDR-E projects. A nominal amount (0.5 – 1.0%) will expedite the curing process. However, cement is not considered in the mix design or gradation testing.

Cement must be Type II or Type V portland cement specified in ASTM C 150/150M.

Cement should be added to the roadbed after pulverizing and shaping. Mixing should occur within 30 minutes of spreading and all grading and compaction should be completed within 2 hours. Weather conditions will affect this work window.

15.5.2 Supplementary Aggregate

If the material characterization indicates a poorly graded or plastic material (Table 15.3), supplementary aggregate or a fine material such as crusher dust may be added to improve the FDR-E material characteristics and thicken the base layer. Other alternatives include increasing the FDR-E depth or cement content can be increased. More commonly, supplementary aggregate may be needed to provide additional material for shoulder widening, profile, or cross slope corrections.

Supplementary aggregate must comply with the quality characteristics for Class 2 Aggregate Bases, but the gradation is not specified.

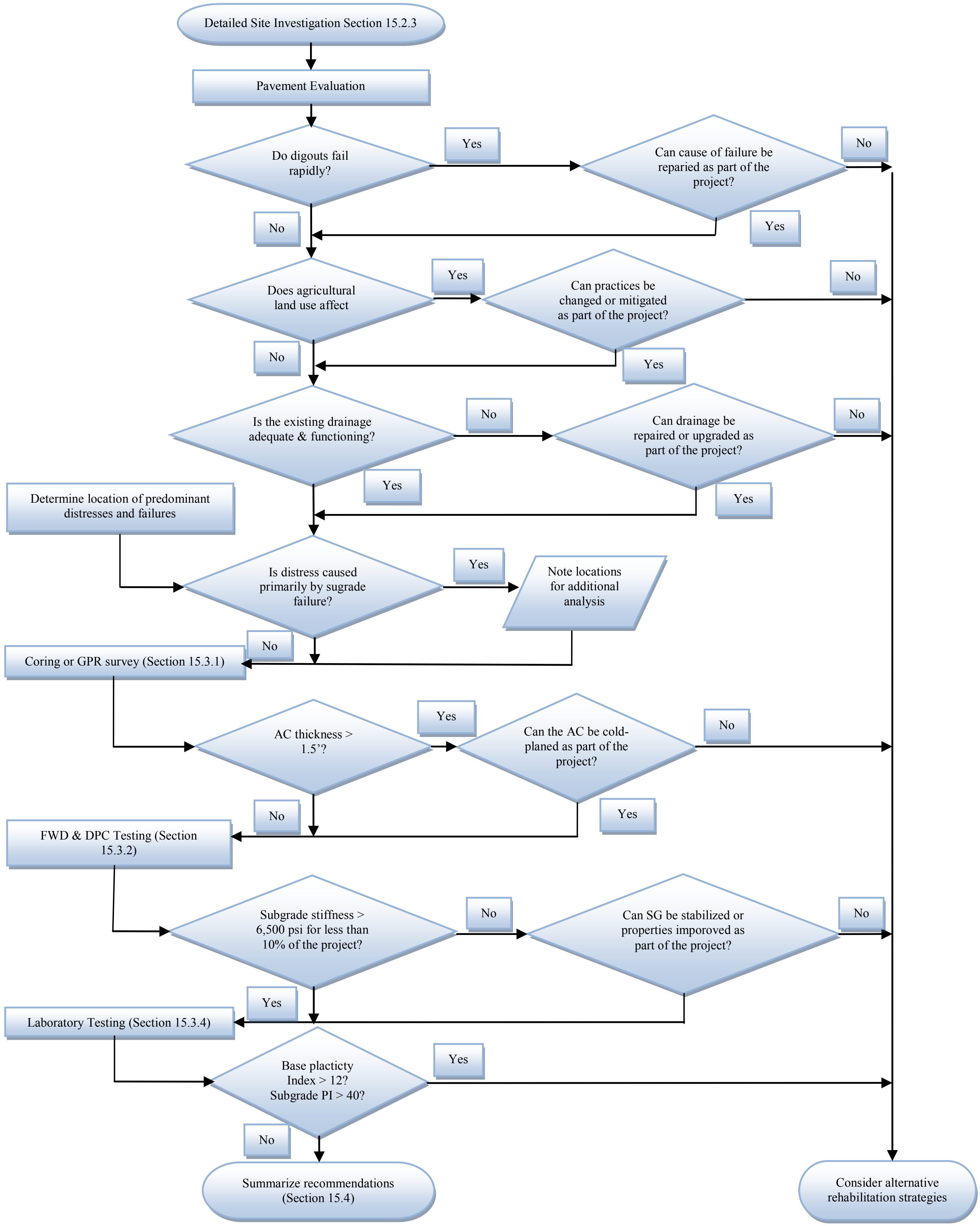


Figure 15.4: Detailed site investigation decision process.

15.6 MIX DESIGN

A key component of the FDR-E process is carried out by the Contractor to assess the properties and variability of the sampled materials, and optimize the engineered emulsion content and application rate. The cost and effort involved in optimizing the engineered emulsion content are small in terms of the overall project costs, minimizing the risk of premature failure, and maximizing the benefits from extending the useful life of the road.

Engineered emulsion content is determined in the laboratory as the amount of engineered emulsion needed to achieve the design criteria. The criteria are:

Table 15.4 FDR-E Properties

Property Criteria	Type I [a]	Type II [b]
Short-term strength test, 1 hour – modified cohesiometer, AASHTO T 246, g/25 mm of width [c]	180 min	175 min
Indirect tensile strength (ITS), ASTM D 4867, 25 degrees C, psi [d]	40 min	35 min
Conditioned ITS, ASTM D 4867, psi	25 min	20 min
Resilient modulus, ASTM D 7369, 25 degrees C, psi x 1,000	300 min	240 min

[a] For mixtures containing < 8 percent passing no. 200 sieve.
[b] For mixtures containing ≥ 8 percent passing no. 200 sieve.
[c] Use a Hveem cohesiometer apparatus with the following exceptions:

1. Capability of testing 150 mm diameter specimens
2. Shot flow rate of 2,700 ± 50 g/minute
3. Cure each specimen at each emulsion content for 60 ± 5 minutes at 25 degrees C and 10 to 70 percent humidity after compacting and before testing

[d] Prepare specimens with Superpave Gyratory Compactor under AASHTO T 312 at 30 gyrations.

The procedure for designing a flexible pavement structure using FDR-E is described in section 15.7.

The FDR-E engineered emulsion content determination process includes:

- Material sampling by coring and pavement layer analysis (Section 15.6.1)
- Optimization of the engineered emulsion content through laboratory measurements of ITS, resilient modulus, and short-term strength

15.6.1 Materials Sampling

The Contractor typically takes materials samples for the mix design by taking cores. The cores also provide a cross section of the pavement layers and subgrade, and an indication of subgrade moisture conditions. The project specifications will indicate the minimum number of materials sampling locations for the Contractor, based on District core evaluation. While District cores are to make an assessment of applicability of FDR-E, determine a pavement thickness profile, verify DCP and FWD data, and sample materials for determining a starting engineered emulsion content, Contractor cores are intended for material collection for laboratory mix design testing and to assess the variability in the subgrade to determine the number of mix designs required. For longer projects with variable terrain and pavement structures, materials sampling sites should be specified (without identifying locations).

Approximately 500 lbs of existing AC and underlying material is required for testing, but actual amounts will vary based on the extent of testing and existing section thicknesses.

For projects where preliminary investigation indicates problem areas or where weak subgrade is present, the District can consider test pits. Test pits should also be considered whenever information shown in as-built plans or other records of pavement structure materials indicate variability. If required, a test pit is dug by cutting at least 1 sq ft of existing pavement and excavating the underlying material. The excavation should be at least as deep as the anticipated pulverization depth and may go deeper if the underlying material is inconsistent or subgrade samples are needed. Larger and more representative sample materials can be obtained from pits relative to cores since all layers of the pavement structure can be examined (Figure 14) and extracted, but are potentially more disruptive to traffic as they take longer to complete and are more destructive to the existing roadway than cores.

Figure 14. Test pit excavation

For test pits, a cold milling machine can be used to excavate the AC and at least the top 2.0 inches of base material to ensure that representative samples are collected, or a portable crusher with a movable jaw can be used to process samples and simulate FDR-E grading for laboratory testing.

15.6.2 Mix Design Testing

FDR-E must meet specified minimums (see SSP) for the following design criteria:

- Short term strength determined under AASHTO T 246
- Indirect tensile strength (ITS) determined under ASTM D 4867 with specimens prepared with a Superpave Gyratory Compactor under AASHTO T 312
- Resilient modulus determined under ASTM D 7369

Additional sampling and testing by the Contractor to refine engineered emulsion content is encouraged.

The following general procedure is followed:

1. Determine the grading of FDR-E
2. Determine the moisture content required
3. Determine the optimal engineered emulsion content to achieve the minimum design criteria.
4. Determine the engineered emulsion spread rate in gal/sq yd

15.7 FDR-E Pavement Structure Design For Flexible Pavements

For Caltrans projects, the pavement designer determines the depth of the FDR layer from the pavement profile determined by coring and DCP during the detailed site investigation.

The gravel factor (Gf) used in FDR-E design is 1.4 for Type II. The gravel factor may be increased to 1.5 for Type I if certain material conditions are known or can be anticipated (Table 15.5). FDR-E must comply with the criteria in Table 15.4.

Table 15.5 FDR-E Gravel Factors

Material Quality		G_f
Type I:	Low fines (passing no. 200 < 8%) RAP > 50%.	1.5
Type II:	High Fines (8% ≤ passing no. 200 ≤ 20%) FDR-E: RAP < 50%,	1.4

The Contractor samples and tests materials, and provides a mix design with an engineered emulsion content that achieves the target strengths and resilient modulus. The Contractor will be responsible for proposing varying engineered emulsion contents over the length of the project, considering the variability of the material, limits of the specifications, and ease of construction.

Although FDR-E is a process for rehabilitation of an existing road, the design process is similar to that for a new pavement since the pavement structure is being reconstructed from the base up, with the FDR-E forming a new base for the new pavement layer.

Mechanistic-empirical analysis procedures can also be used for FDR-E pavement structure design. For more information, contact the Office of Asphalt Pavement in the Division of Maintenance Pavement Program.

15.7.1 Design Life and Traffic Index (TI)

If subgrade support is adequate, the expected design life of the pavement structure is related to the FDR-E depth and the type and thickness of the new flexible surface layer. FDR-E projects should be designed with a minimum pavement design life of 20 years, unless a life-cycle cost analysis indicates a 40-year pavement design life is more cost effective (HDM Topic 612).

Pavement design requires knowledge of anticipated traffic volumes and loading, which help determine the pavement structure requirements. Contact the district traffic forecasting office and refer to HDM Topic 614 for procedures to determine the traffic index for the required design life.

15.7.2 FDR-E Depth

Depth and material consistency can be achieved when FDR-E production takes place in a continuous manner. The FDR-E depth should be at least 0.10 foot more than the existing flexible surface layer thickness. The pulverizing teeth must extend into the existing base to prevent excessive wear and lost productivity. An advantage of FDR-E is that the depth may be increased to provide additional GE from the base layer, reducing the required flexible pavement layer thickness and material costs.

The typical FDR-E section thickness ranges from 6 to 10 inches. If analysis of the subgrade during the detailed site investigation indicates extensive areas of weak material, a more extensive investigation and design process would likely be necessary. It may be possible to bridge areas of weak subgrade with thicker FDR sections.

Depending on the grade control requirements (e.g., curb and gutter), it may be necessary to remove some material after pulverization to achieve the designed HMA thickness. However, it is also important to maintain the FDR-E design depth, so pulverizing to a depth exceeding the design depth may be necessary. Alternatively, cold planing the pavement surface prior to FDR-E pulverization to attain the designed FDR-E depth to leave room for the HMA layer is an option, but the percentage of RAP should be maximizes in FDR-E material.

15.8 SPECIAL CONSIDERATIONS

15.8.1 Volumetric Change

The FDR-E process alters gradation and alters the density of existing roadway materials as it is transformed into compacted base material. Even without adding new material, compacted FDR-E material typically swells from 5 to 10% relative to the original material. Excess material must be accounted for in the project design and may be used as embankment fill or to increase the actual FDR-E layer thickness (use design depth for pavement structure calculations), correct profile and cross slope, or widen sections. If more material is required for the design, supplemental aggregate is usually mixed into the FDR-E after pulverization.

15.8.2 FDR-E Area

The width and crown of the roadway to be reclaimed dictates the number of passes to cover the full width. Drums are typically 8 feet wide but can vary in width from 6 to 14 feet. Several passes will normally be required to pulverize the roadway. If the roadway is crowned, the FDR-E equipment should not straddle the crown; this is to ensure uniform treatment depth and consistency in the FDR-E material.

FDR-E should proceed from the outside of the roadway towards the centerline to maintain a reference to the profile elevation. The first pass uses the full width of the drum. In subsequent passes, the treatment width will be reduced by a minimum overlap of 4 inches. If the FDR-E depth is more than 12 inches or the FDR-E material is coarse, the overlap width should be increased. Overlapped FDR-E material should not be treated with engineered emulsion on more than 1 pass.

Other factors to consider are obstructions adjoining the edge of pavement such as curb and gutter, dike, guard rail, concrete barrier, or retaining walls. For dikes, curb and gutter, or utility manholes, the recycling train should be able to treat the roadway up to the face or edge. For taller obstructions, the adjacent roadway will have to be removed using another method. The treatment area should include the entire cross section of the pavement structure from edge of pavement to edge of pavement.

15.8.3 Underlying Unsuitable Material

Although often it cannot be identified until commencement of construction operations, the potential for unsuitable material below the FDR-E depth should be considered during the detailed site investigation. Areas exhibiting drainage problems, pumping, rutting, severe cracking, or moisture intrusion may indicate deteriorated base or subgrade that is unsuitable for pavement construction. Analysis of abnormally high deflections or DCP penetration rates generally indicate weak underlying layers (see Appendices B and C). Localized areas of unsuitable material should be removed, disposed, and replaced with excess FDR-E material or new Class 2 AB.

If weak material is widespread throughout the project limits, the pavement structure should be strengthened and any moisture or drainage issues addressed. Alternatives include increasing the FDR-E depth, importing Class 2 AB, and subgrade stabilization. FDR-E material requires support from underlying layers to achieve compaction and design strength. If mitigation cannot be attained, alternative rehabilitation or reconstruction strategies should be considered.

15.8.4 Constructability

FDR-E pavement structure designs should account for significant variations in controlling parameters such as subgrade R-values or existing pavement structure layers and thicknesses in a consistent manner. For ease of construction, design parameters such as engineered emulsion content, depth, area, and overlay thickness should not vary more frequently than 1-mile long segments. Transverse variations in the design cross section should take into account equipment width (see Section 15.8.2) and other considerations.

As with all in-place recycling operations, control over material uniformity is largely dependent on site conditions. Field adjustments to parameters such as production and application rates will be necessary during construction as indicated by changes to in-situ conditions or QC/QA test results. Large clumps of RAP greater than 3 inches in diameter are detrimental to FDR-E material and should be removed prior to final grading and compaction. If the existing pavement surface has extensive fatigue cracking, the FDR-E machine's forward speed should be slowed to ensure adequate gradation. The particle distribution should be 100% smaller than 3 inches with 85 to 100% passing the 1½ inch sieve.

Conflicting utilities, including valves and access points, must be referenced and lowered at least 6 inches below the FDR-E depth or worked around. If utility depths have not been confirmed by field inspection, potholing, or GPR, the design FDR-E depth should be at least 12 inches above the approximate utility depth.

Maintaining moisture content to the mix design requirement is important to ensure complete coating. The roadbed should be pulverized, shaped, and either adding water or allowing to dry to the mix design moisture content before adding cement and emulsion.

After mixing the engineered emulsion, the Contractor should immediately compact. As the engineered emulsion "breaks," water will escape and the FDR-E will become stiffer. Before opening to traffic, the Contractor should proof-roll the FDR-E surface for deformations using a 2-axle, fully loaded 2,000 gal capacity water truck. Do not allow traffic on these areas until material dries and stabilizes or until corrective action is taken. Verify relative compaction for areas that display movement.

The Contractor should apply asphaltic emulsion after proof rolling and before opening to traffic.

The FDR-E surface should be recompacted within 48 to 72 hours of initial compaction and before smoothness testing. This secondary compaction will ensure voids created by water escaping from the emulsion are compacted.

Paving with HMA should not commence until the FDR-E at mid layer has a moisture content of 2.5 percent of dry material.

15.8.5 Traffic Handling

FDR-E is best suited for moderate to low volume roadways (see Section 15.1.3). Since FDR-E surfaces are exposed to traffic during construction, high traffic volumes prior to paving can cause raveling. Accordingly, FDR-E operations require reduced work zone speeds as determined by the district traffic operations office. For two-lane conventional highways, a pilot car should be used to escort vehicles through the work zone during FDR-E operations.

Traffic and Contractor equipment should be allowed on the finished surface before paving. The Contractor proof-rolls the surface with a loaded water truck before opening to traffic.

Temporary striping must use bid Item 120159 Temporary Traffic Stripe (Paint) since floppy markers and tape will not adhere to the finished FDR-E surface.

15.9 PLANS, SPECIFICATIONS, AND ESTIMATING

15.9.1 Plans

The plans for a FDR-E project are analogous to a project using common roadway rehabilitation strategies. The layout plans should show the existing roadway and the limits of FDR-E (width and length). The typical cross sections should clearly show the cross slope, width, and depth of the existing pavement layers, new FDR-E base layer, and new flexible pavement layers. If survey data is not available and superelevation diagrams are not provided, indicate "match existing" cross slope and the contractor will reference the existing profile along the roadway centerline.

If existing roadway grades are consistent, they can be maintained and surveyed slope stake information may not be necessary. More commonly, existing flexible pavement structures exhibit undulations and uneven settlement. When pulverization and grading precede engineered emulsion application, the FDR-E operation offers a rare opportunity to correct these defects and properly construct and finish the roadway surface. It is much more cost effective to adjust the grade of FDR-E material with extra grading or imported AB than to grade the finished surface using additional HMA (grinding or trimming FDR-E should be avoided to maintain the design thickness). Any design changes to profile, cross slope, and superelevation should be indicated in the plans so the contractor can account for additional grading or material handling. If the finished surface is leveled with HMA, include Item 390145 HMA (leveling), which is paved separately from the HMA surface to improve final compaction and smoothness and does not include geometric changes.

The construction details should include conforming transverse tapers where the FDR-E pavement structure ties into existing or new roadway. Quantity sheets should include the stationing and corresponding FDR-E areas and additive amounts in the roadway items table. Appendix D contains example plan sheets for an FDR-E project.

15.9.2 Specifications

Standard special provision (SSP) 30-5 is used for FDR-E. The specification addresses a number of material and equipment requirements, construction methods, inspection, quality control and quality assurance (QC/QA), acceptance requirements, measurement, and payment. The SSP requires the contractor to determine FDR-E engineered emulsion content based on adequate characterization of the existing materials and make any adjustments due to material variability in the field based on results of QC testing for 1,000 square yard lots. The Department performs periodic QA testing to ensure accuracy and compliance.

15.9.3 Estimating

The estimation process for FDR-E cost must take into account several project specific features such as location, length, schedule, geometrics, traffic handling, as well as FDR-E depth and area. There are multiple items associated with FDR-E which need to be estimated:

Table 14.9A: Estimating Unit Costs

Item Code	Item Description	Unit	Estimate Basis	*Historical Item*
305000	Full Depth Reclamation-Engineered emulsion	sqyd	reclaimed pavement area	*N-A*
	Engineered Emulsion (Full Depth Reclamation-Engineered Emulsion)	Ton	5% of dry unit weight of pulverized material	*N-A*
305100	Cement (Full Depth Reclamation-Engineered emulsion)	Ton	0.5 to 1 % of dry unit weight of pulverized material	*N-A*
305400	Mix Design (Full Depth Reclamation-Engineered emulsion)	LS		*N-A*
305300	Asphaltic Emulsion (Full Depth Reclamation-Engineered emulsion)	ton	0.08 gal/sq yd residual rate	*N-A*
305200	Supplementary aggregate (Full Depth Reclamation-Engineered emulsion)	ton	If necessary, determined by DME	*N-A*
120159	Temporary Traffic Stripe (Paint)	LF	Total length of each stripe for each stage	*No change*
390145	HMA (leveling)	ton	Percentage of total HMA	*390107 AC (leveling)*
066670	Payment Adjustment for Price Index Fluctuation	LS	Change in asphaltic emulsion cost from asphalt price index	*No change*

Typical project mobilization costs for FDR-E equipment run under $10,000, keeping the process cost effective for smaller projects and areas. Historical cost data for a limited number of FDR projects is available on the intranet from the Unit Cost Database (see Appendix E) for some items. Among other considerations, analysis of historical costs must consider that past FDR projects were located primarily in the North Region and used an nSSP with different item codes, design, materials, and QC/ QA requirements:

- Contractor-performed FDR-E mix designs are a new requirement so historical cost data is not yet available. The FDR-E mix design item is based on a lump sum that includes work for material sampling, lab testing, and 1.5 days traffic control.
- Material quantities for FDR-E are based on the preliminary investigations or experience, by dry unit weight of FDR-E, and the processed volume of FDR-E material.
- Supplementary aggregate is only required if recommended by the DME or if necessary for widening, profile, or cross slope requirements. Historical data can be used for estimating but note that payment should be based on tonnage since spreading and grading is included in the FDR-E item.

Measurement and Payment

Item 305000 “Full Depth Reclamation-Engineered Emulsion” is measured and paid for by the square yard based on the theoretical FDR-E area and includes all labor, materials, tools, equipment, and testing related to the FDR-E operation, and preparation of the existing roadway. The roadbed dimensions to be reclaimed should be shown on the typical sections, layout plans, and quantity sheets to clearly indicate the work limits.

Engineered emulsion is a separate item and not included in the item for FDR-E. The Contractors will bid on a engineered emulsion content that is a specified percentage of a dry unit weight, which the District determines. After award, if the submitted mix design indicates a different engineered emulsion content, the cost of the engineered emulsion material will be deducted or added to the payment.

Supplementary aggregate are measured and paid for by ton.

Supplemental Work

Due to the difficulty in identifying underlying unsuitable material (see Section 15.8.3), a supplemental work item for roadway excavation to remove and dispose of the material should be included in the estimate if unsuitable material has been identified, is difficult to accurately quantify, or is otherwise likely to be present on a project. Any unsuitable material that has already been identified and located should be quantified and estimated as a roadway item and not included in supplemental work.

Section 9-1.07 of the Standard Specifications requires payment adjustment for asphalt materials when the statewide crude oil price index fluctuates by more than 5 percent between the time of the bid and the month the material is placed. Include supplemental work Item 066670 "Payment Adjustment for Price Index Fluctuation" to fund this cost.

Working Days

Due to the wide array of equipment available and varying roadway distress addressed using FDR-E, it is difficult to suggest a single expected production rate. Daily production rates may vary on average from 4,750 yd^2 to 9,500 yd^2 based on the interaction of variables such as existing pavement structure, distress, FDR-E depth, area, gradation, and grading. Assume the Contractor will pulverize and grade before applying engineered emulsion (as opposed to injecting engineered emulsion while the pavement is initially pulverized). The experience level of the general and subcontractors with the FDR-E process is also a factor. If the subcontractor uses multiple recyclers, production will be increased, but grading and compacting typically constrain construction productivity and are usually the general contractor's responsibility. Daily paving operations typically consist of two lifts over half a mile. Table 15.9B provides a general guide for estimating FDR-E production rates:

Table 15.9B: Daily FDR-E Production

	Existing AC Thickness (in.)	**FDR-E Depth[1] (in.)**	**Alligator Cracking (extent)**	**Profile/Cross Slope Corrections**	**Daily Production Rate (yd^2)**
Range	Thick (7-9 inches)	Deep (8-10 inches)	Continuous (85-100%)	Numerous	**4700**
	Medium (5-7 inches)	Medium (6-8 inches)	Nearly continuous (50-85%)	Some	**7100**
	Thin (3-5 inches)	Shallow (4-6 inches)	None to intermittent (0-50%)	Minor	**9500**

Materials Information Handout

It is important to compile and provide a Materials Information Handout that includes the documentation of the investigative work performed.

REFERENCES

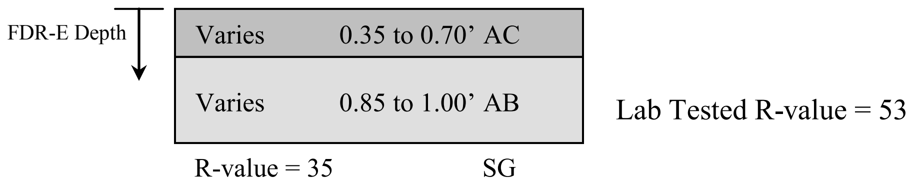
1. **Recommended Construction Guidelines for Full Depth Reclamation (FDR) Using Bituminous Stabilization**, 2011. Annapolis, MD. Asphalt Recycling and Reclaiming Association
2. **Wirtgen Cold Recycling Manual.** 2004. Windhagen, Germany: Wirtgen GmbH.
3. MALLICK, R. B., Kandhal, P. S., Brown, E. R., Bradbury, R. L., and Kearney, E. J. 2002. **Development of a Rational and Practical Mix Design System for Full Depth Reclaimed (FDR) Mixes.** Durham, NH: Recycled Materials Resource Center.
4. **Geotechnical Aspect of Pavements**, FHWA NHI-05-037, May 2006.
5. JONES, D. and Harvey, J. 2005. **Relationship Between DCP, Stiffness, Shear Strength and R-value.** Davis and Berkeley, CA: University of California Pavement Research Center. (Technical Memorandum: UCPRC-TM-2005-12).
6. **Life-Cycle Cost Analysis Procedures Manual.** 2013. Sacramento, CA: State of California, Department of Transportation, Division of Maintenance, Pavement Program.
7. **California Manual on Uniform Traffic Control Devices .** 2012. Sacramento, CA: State of California, Department of Transportation.
8. **Flexible Pavement Rehabilitation Using Pulverization.** 2008. Sacramento, CA: State of California, Department of Transportation.
9. JONES, D., Rahim A., Saadeh S., and Harvey, J. May, 2010. **Guidelines for the Stabilization of Subgrade Soils In California.**

APPENDIX A: FDR-E FLEXIBLE PAVEMENT STRUCTURE DESIGN EXAMPLE

GIVEN PROJECT:

Description	2-lane, rural conventional highway
Traffic Index	TI_{20} = 10.5
Length	4.3 miles
Width (EP to EP)	28 ft

Existing Pavement Structure:



DETERMINE: FDR-E Pavement Structure Design:

- Minimum design FDR-E depth
- Estimated excess FDR-E material quantity
- FDR-E layer thickness
- HMA overlay thickness

SOLUTION: (1) Calculate the minimum FDR-E depth

For a single depth pavement structure design throughout the project, the **maximum existing AC thickness governs the minimum design FDR-E depth**:

With max existing AC thickness = 0.70 ft →

Min. design FDR-E depth = 0.80 ft

(2) Estimate the excess FDR-E material

<u>From Section 15.8.1:</u> *Compacted FDR-E material swells by 5-10%*

Assume swell factor = 7%

FDR-E material volume = (4.3 miles)(5280ft/mi)(28ft)(0.80ft)

= 508,570 ft^3

Excess FDR-E material = 7%(508,570 ft^3)

Est. excess FDR-E material = 35,600 ft^3 = 1,319 yd^3

> **<u>Optional</u>:** This quantity can be considered roadway excavation or used to increase the actual thickness of the FDR-E layer, correct profile or cross slope, level existing surface undulations, or widen the roadway. FDR-E material can also be used as embankment. **<u>Do not</u>** include estimates of excess material in pavement structure design calculations.

FDR-E thickness increase = (swell factor)(min designFDR-E depth)

= 7%(0.80 ft) + 0.80 ft

Actual FDR-E layer thickness = 0.85 ft

(3) **Calculate the total required gravel equivalent**

$$GE_{Total} = GE_{HMA} + GE_{FDR\text{-}E} + GE_{AB}$$

<u>From HDM Index 633.1, for a 20-year design:</u>

$$GE_{Total} = 0.0032(TI_{20})(100 – R_{SG})$$

$$GE_{Total} = 0.0032(10.5)(100 – 35)$$

$$GE_{Total} = 2.18 \text{ ft}$$

(4) **Calculate GE of each pavement structure layer**

Assume Type II FDR-E

Gravel factor = 1.4

$$Thickness = \frac{GE}{Gf}$$

$GE_{FDR\text{-}E}$ = (design thickness)(G_f) = (0.80)(1.4)

$GE_{FDR\text{-}E}$ = 1.12

To determine the GE of the remaining AB, average the existing thicknesses from the pavement structure profile:

$$Average\ Existing\ AC\ Thickness = \frac{0.35 + 0.70}{2} = 0.525\ ft$$

$$Average\ Existing\ AB\ Thickness = \frac{0.85 + 1.00}{2} = 0.925\ ft$$

$FDR\text{-}E\ Depth = 0.80$ ft

$Average\ Remaining\ AB\ Thickness = 0.525 + 0.925 – 0.80$
$= 0.65$ ft

Using conservative approach, use Gf_{AB} = 1.0

GE_{AB} = 0.65 x 1.0

GE_{AB} = 0.65

The GE required for the HMA layer is:

$GE_{HMA} = GE_{Total} - GE_{FDR\text{-}E} - GE_{AB}$

$GE_{HMA} = 2.28 - 1.12 - 0.65$

→ $GE_{HMA} = 0.51$

5 Determine the HMA thickness

From HDM Table 633.1:

With $TI_{20} = 10.5$ → $G_{f\,(HMA)} = 1.71$

$$Thickness = \frac{GE}{Gf} = \frac{0.51}{1.71}$$

= 0.298 ft

From HDM Index 633.1(1)(d):

Round up to the nearest 0.05 ft increment

Actual HMA Thickness = 0.30 ft

APPENDIX B: FWD ANALYSIS

The following analysis procedures are intended for use with deflection measurements obtained using a falling weight deflectometer (FWD) under CT 356 modified by Section 15.3.2 to evaluate the stiffness of underlying layers and identify areas of weak subgrade.

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 not appropriate in these instances but valuable information about the subgrade properties can be obtained by approximating the modulus from the measured deflection using the following Boussinesq's equation (Equation B.1):

$$E_r = \frac{(1-v^2)\times P}{\pi \times r \times d} \quad \textbf{(B.1)}$$

where: E_r = deflection modulus at distance r (psi)

P = the applied load (lbs)

v = Poisson's ratio, generally using 0.35

r = the distance from the load center to the measured deflection (inches)

d = measured deflection at distance r (inches)

For a layered pavement structure the calculated deflection modulus (E_r) is a function of the distance from the load center (r) at which the deflection is measured. Typically, the deflection modulus at r = 24 ± 1.0 in. (distance to the fifth FWD sensor) is approximately equivalent to the subgrade modulus ($E_{24} \approx E_{SG}$). Consider:

To calculate E_r, use the measured distance between the sensor and the load center.
No temperature correction is necessary since the calculated deflection modulus E_{24} is not significantly affected by the surface layer condition,

Results of the analysis should be plotted against postmile or station on a graph (Figure B.1). The graph can be used to identify problem subgrade or drainage areas. The following criteria (Table B.1) should be used to interpret the deflection data from the 24 in. sensor with the load normalized to 9,000 lb:

Table B.1: Deflection Criteria for Assessing Subgrade

$d_{(24)}$*	E_r*	Subgrade Zone (Figure B.1)[1]	Conclusion	Potential Corrective Actions
< 15 mils	>6,500 psi	A	SG sufficient	None
15 – 49 mils	3,600 – 6,500 psi	B	May need to improve SG prior to FDR-E	None, soil stabilization, geosynthetic reinforcement, remove and replace, raise profile, address drainage, thicker pavement structure
> 49 mils	< 3,600 psi	C	Improve SG prior to FDR-E or other strategy	Conduct more detailed survey and consider corrective actions or other rehab/ reconstruction strategies
*Values are only an approximate guide				

APPENDIX B: FWD ANALYSIS

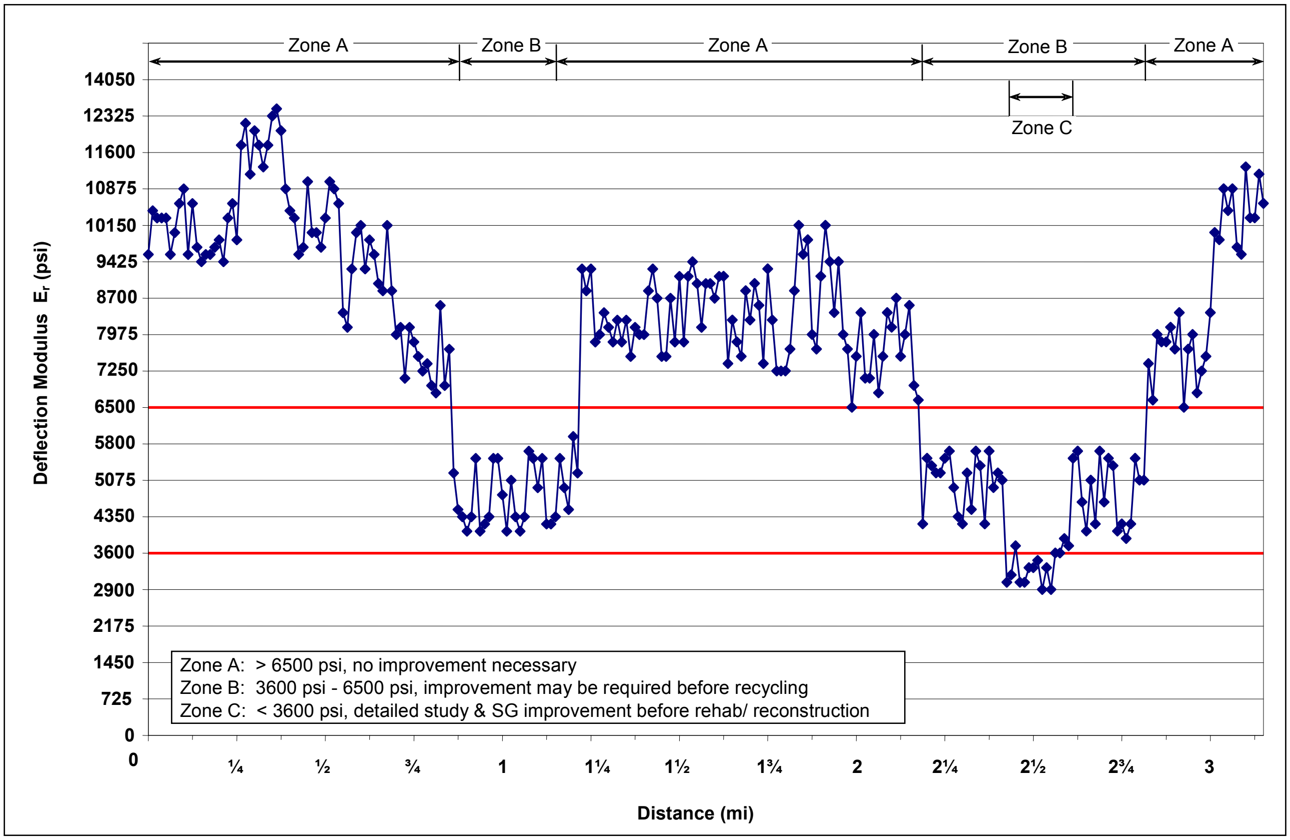


Figure B.1: Example FWD analysis.

Ideally, Zone B + Zone C < 10% total project length.

If Zone B + Zone C > 10% total project length, FDR-E can still be considered as a rehabilitation strategy. As with other alternatives, the service life may be reduced and additional design features should be included to mitigate poor subgrade material (see Section 14.3).

APPENDIX C: DCP ANALYSIS

Dynamic cone penetrometer (DCP) results are typically analyzed in terms of the DCP Number (DN) to provide a relative indication of layer shear strength and thickness. AC layers are excluded from the evaluation. The DCP layer Structure Number (DSN) and the DCP Pavement Structure Number (DSN_{800}) can also be used to assess pavement structures but are not covered in this guidance.

Calculate the DCP Number (DN) as 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. If the DN is plotted against depth, distinct jumps are often apparent. The points of each jump can be used to indicate changes in material type, properties, or moisture conditions and to estimate underlying layer thicknesses.

> No comprehensive studies have been documented to relate DN to R-value, but empirical relationships have been developed to relate the penetration rate to the effective layer stiffness and California Bearing Ratio (CBR) *(***Error! Reference source not found.***)*. These relationships provide useful indicators that can be combined with FWD measurements and visual assessments to identify and evaluate potential problem areas, but resulting stiffness and CBR values should be considered **approximate estimates** only.

Calculate the effective elastic modulus. An example relationship between stiffness and penetration rate developed in South Africa is given below (Equation C.1) and a summary of DN ranges, corresponding stiffnesses, and subgrade zone is provided in Table C.1.

$$E_{eff} = 145.04 \times 10^{3.05-1.066(Log(DN))} \quad \textbf{(C.1)}$$

where: E_{eff} is the effective elastic modulus (psi)

Table C.1: Approximate Relationship between DN, CBR & E_{eff}

DN Range (mm/blow)	CBR Range[1] (%)	E_{eff}[1] (psi)	R-value[1,2]	Subgrade Zone (Figure C.1)[1]	Subgrade Description
< 4 4 – 5 5 – 8 8 – 14 14 – 19	>70 50 – 70 30 – 50 30 – 15 10 – 15	>37400 29600 – 37400 18000 – 29600 9900 – 18000 6500 – 9900	>80 75 – 80 65 – 75 50 – 65 42 – 50	A	Relatively strong
19 – 25 25 – 30 30 – 35	7 – 10 3 – 7 1 – 3	5400 – 6500 4350 – 5400 3600 – 4350	35 – 42 18 – 35 1 – 18	B	Marginal strength
> 35	< 1	< 3600	< 1	C	Weak, potentially wet

[1]Values are only an approximate guide. Use with caution as there is no published correlation between DN and R-value.
[2]From Huang 1993 based on CBR comparison to R-value through laboratory testing. Not developed from DCP and R-value analysis. Not verified for use in California. R-value < 50 appears to be too high for rate of DCP penetration.

Plot DN over the project length and calculate the average and standard deviation to help identify uniform sections and potential problem areas (Figure C.1):

APPENDIX C: DCP ANALYSIS

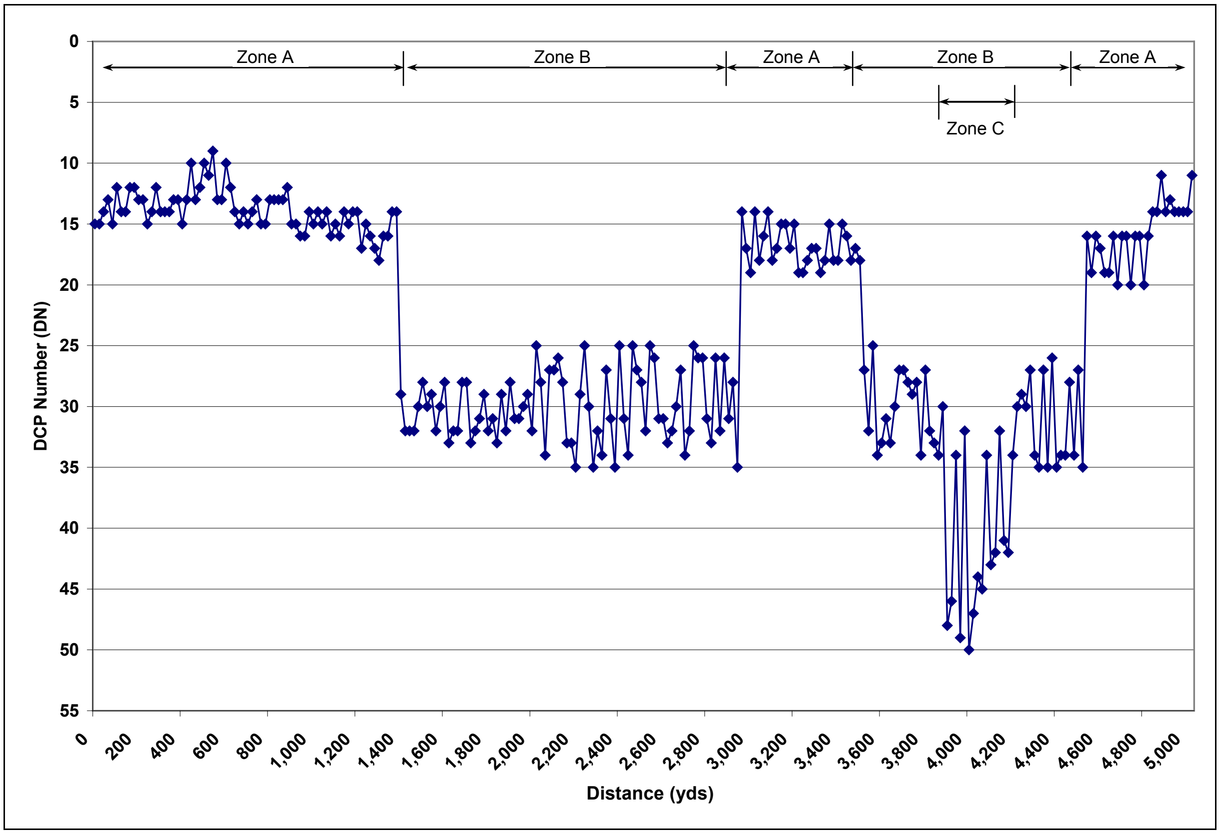


Figure C.1: Example DCP Number analysis.

Categorize the data relative to a subgrade zone. For the example in Figure C.1, eight uniform sections can be identified and divided into three different zones: A, B, and C.

Zone A can be considered reasonably strong for subgrade material. Zone B has marginal strength, and Zone C is very weak, indicating potentially wet, clay soils

As with FWD analysis, ideally Zone B + Zone C < 10% total project length.

If Zone B + Zone C > 10% total project length, FDR-E can still be considered as a rehabilitation strategy. As with other alternatives, the service life may be reduced and additional design features should be included to mitigate poor subgrade material (see Section 14.3)

APPENDIX D: ONLINE RESOURCES

Information	Internet Address
Highway Design Manual (HDM)	http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
Design Information Bulletins (DIB)	http://www.dot.ca.gov/hq/oppd/dib/dibprg.htm
Project Development Procedures Manual	http://www.dot.ca.gov/hq/oppd/pdpm/pdpmn.htm
Traffic Data	http://www.dot.ca.gov/hq/traffops/saferesr/trafdata/
Life-Cycle Cost Analysis	http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/LCCA_index.html
Office of Roadway Materials Testing (ORMT-METS)	http://www.dot.ca.gov/hq/esc/Translab/ofpm/index.htm
Pavement Management Program	http://www.dot.ca.gov/hq/maint/Pavement/Pavement_Program/index.html
Standard Specifications (2010)	http://www/hq/esc/oe/specifications/std_specs/2010_StdSpecs/

APPENDIX E: EXAMPLE FORMS

The following example forms are provided in this appendix:

FDR-E Project Evaluation: Desktop Study
FDR-E Preliminary Field Review
FDR-E Project Evaluation: Preliminary Recommendations
FDR-E Detailed Site Investigation: Visual Assessment
FDR-E Detailed Site Investigation: Visual Assessment Summary
FDR-E Detailed Site Investigation: Core Log
FDR-E Detailed Site Investigation: DCP Assessment
FDR-E Project Evaluation: Detailed Site Investigation Analysis Summary

1 FDR-E Project Evaluation: Desktop Study

Project Name or Description:					
Dist-Co-Rte:		**Beg PM:**		**Date:**	
EA/ Project ID:		**End PM:**		**Prepared By:**	
Record of HQ Decision Approving Investigation:					
Program:			**Funding Source:**		
Traffic:					
Climate:					

Existing Pavement Structure

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-E Project Evaluation: Preliminary Field Review

Project Name or Description:									
Dist-Co-Rte:			**Beg PM:**					**Date:**	
EA/ Project ID:			**End PM:**					**Reviewer:**	

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. Granular base	Yes		No						
7. Height above natural ground									
8. Drainage	Adequate		Irrigation						
9.									
10.									
11.									
12.									
14.									
14.									
15.									
Samples taken?	Yes		No		Purpose				
Fatal flaws?	Yes		No		Reason				

3	FDR-E Project Evaluation: Preliminary Recommendations				
Project Name or Description:					
Dist-Co-Rte:		**Beg PM:**		**Date:**	
EA/ Project ID:		**End PM:**		**Prepared By:**	

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

Continue with detailed investigation	Yes		No		Reason	

4 FDR-E Detailed Site Investigation: Pavement Evaluation

Project Name or Description:					
Dist-Co-Rte:		**Beg PM:**		**Date:**	
EA/ Project ID:		**End PM:**		**Prepared By:**	

Surface Assessment

Surface type	

	Degree Slight Severe						Extent <5 >80					Length	Width	Number	Location
Bleeding/flushing															
Raveling															

Structural Assessment

	Degree Slight Severe						Extent <5 >80					Narrow (% area)	Wide (% area)	Position	Location
Cracks - block															
Cracks - longitudinal															
Cracks - transverse															
Cracks - alligator															
Pumping															
Rutting															
Undulation/settlement															
Edge cracking															
												Small	Medium	Large	Location /Number
Patching/digouts															
Potholes															
Delamination															

Functional Assessment

	Degree Good Poor					Influencing Factors									
Riding quality						Potholes		Patching		Undulation		Corrugation		Fatigue	
Surface drainage															
Side drainage															

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

5 FDR-E Detailed Site Investigation: Pavement Evaluation Summary

Project Name or Description:					
Dist-Co-Rte:		**Beg PM:**		**Date:**	
EA/ Project ID:		**End PM:**		**Prepared By:**	

Distress/problem	% Area	**Yes**	**No**	**Influence FDR-E decision?**
Patching/digouts				
Alligator Cracking				
Pumping				
Rutting				
Undulation/settlement				
Adjacent irrigation				
Other				
Cause of failure requiring digout				
Cause of low strength areas in FWD survey				

Drainage systems	Side drains	OK				
	Culverts	OK				

Notes	**Photographs**
	1
	2
	3
	4
	5
	6
	7
	8
	9
	10
	11
	12

6 FDR-E Detailed Site Investigation: Core Log

Project Name or Description:					
Dist-Co-Rte:		**Beg PM:**		**Date:**	
EA/ Project ID:		**End PM:**		**Prepared By:**	

Core Number	**PM**			**Location/ Offset**					**Observations**
		Lane Direction	**Lane Number**	**CL**	**LTWP**	**BWP**	**RTWP**	**ETW**	

NB/SB/EB/WB - Lane direction | RTWP – Outer wheelpath | LTWP – Inner wheelpath | BWP – Between wheelpath | CL - Centerline

7 FDR-E Detailed Site Investigation: DCP Assessment

Project Name or Description:								
Dist-Co-Rte:			Beg PM:			Date:		
EA/ Project ID:			End PM:			Prepared By:		
Core No./ PM			Core # or PM			Core # or PM		
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
140	330	530	140	330	530	140	330	530
145	335	535	145	335	535	145	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-E Project Evaluation: Detailed Site Investigation Analysis Summary

Project Name or Description:					
Dist-Co-Rte:		**Beg PM:**		**Date:**	
EA/ Project ID:		**End PM:**		**Prepared By:**	

Task	**Parameter**	**Yes**	**No**
Visual assessment	Subgrade moisture problems are not evident		
	Weak subgrade caused < 10% of pavement distress		
	If >10%, can weak areas be strengthened as part of project?		
	Digout areas did not fail again rapidly (i.e., after rainy season).		
	If failed, can problem areas be strengthened as part of project?		
	Drainage is effective and functional.		
	If not effective, can problem drainage areas be corrected as part of project?		
	Surrounding land use and terrain does not influence pavement.		
	If influenced, can land use practices be mitigated?		
Layer thickness	Base and subbase thickness > 12”		
	If underlying base < 12”, can Class 2 AB be added to FDR-E to increase structural capacity of base layer?		
	0.20’ < AC thickness < 0.90’.		
	If AC > 0.90’, can it be cold planed?		
Subgrade Analysis (FWD & DCP)	Subgrade failure <10% of project area.		
	Less than 10% of the road has a subgrade modulus of < 6500 psi.		
	If > 10%, can weak areas be strengthened as part of project?		
Laboratory tests	Blend of RAP and underlying material passing #200 < 15%		
	Underlying base material plasticity index < 12		
	Base strength sufficient for pavement structure		
	Subgrade plasticity index < 12		
	Subgrade R-value > 20, or sufficient for pavement structure		
	If R-value < 20, can Class 2 AB be added to FDR-E to increase structural capacity of base layer?		
Recommendation	**FDR-E is an appropriate rehabilitation option**		
Test Pits	Minimum number of sampling locations to characterize project material for mix design		
Justification			