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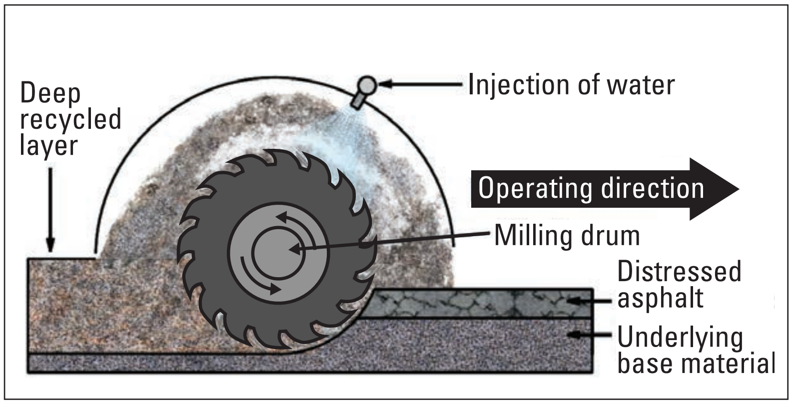
Guide to
FULL-DEPTH RECLAMATION (FDR)
with Cement



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16. Abstract

As the nation's infrastructure ages, agencies at all levels are tasked with maintaining and rehabilitating their infrastructure. Sustainable engineering technologies in pavement rehabilitation, such as full-depth reclamation (FDR), could be the answer for agencies in their quest to provide taxpayers with high-quality infrastructure while being good stewards of public funds. Full-depth reclamation of asphalt pavement is a rehabilitation method that involves recycling an existing asphalt pavement and its underlying layer(s) into a new base layer. The FDR process begins with using a road reclaimer to pulverize an existing asphalt pavement and a portion of the underlying base, subbase, and/or subgrade. Usually the pulverized material is uniformly blended with an additional stabilizing material such as portland cement to provide an upgraded, homogeneous material. Finally, the stabilized material is compacted in place with rollers. The result is a stiff, stabilized base that is ready for a new rigid or flexible surface course. This guide introduces the FDR with cement process and discusses issues related to project selection, design, construction, and testing/quality control.

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GUIDE TO FULL-DEPTH RECLAMATION (FDR) WITH CEMENT

[March 2017]
January 2019

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About This Guide

This *Guide to Full-Depth Reclamation (FDR) with Cement* is a product of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University's Institute for Transportation, with funding from the Portland Cement Association. The guide provides a concise discussion of all aspects of selecting, designing, and constructing a reclaimed, cement-stabilized asphalt base in preparation for a new pavement surface layer.

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Note that much of the information in this document is based on two excellent resources: the Portland Cement Association's *Guide to Full-Depth Reclamation (FDR) with Cement* (Luhr et al. 2014) and the Asphalt Recycling and Reclaiming Association's *Basic Asphalt Recycling Manual* (ARRA 2015).

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Contents

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Figures, continued

Chapter 7

Chapter 8

Tables

Chapter 1

Chapter 2

Chapter 4

Chapter 5

Chapter 7

Chapter 8

Chapter 1

Introduction

As the nation's infrastructure ages, agencies at all levels are tasked with maintaining and rehabilitating their infrastructure. While budgets are shrinking, construction costs are increasing; it is becoming more costly to completely remove and replace existing pavements. In addition, as sustainable construction practices come to the forefront, agencies want to recapitalize their investments in decades-old pavements by reusing existing materials on site in a cost-effective manner. Sustainable engineering technologies in pavement rehabilitation, such as full-depth reclamation (FDR), could be the answer for agencies in their quest to provide taxpayers with high-quality infrastructure while being good stewards of public funds.

What is FDR?

Full-depth reclamation of asphalt pavement, also referred to as FDR, is a rehabilitation method that involves recycling an existing asphalt pavement and its underlying layer(s) into a new base layer. As shown in Figure 1.1, the FDR process begins with using a road reclaimer to pulverize an existing asphalt pavement and a portion of the underlying base, subbase, and/or subgrade. Usually the pulverized material is uniformly blended with an additional stabilizing material such as portland cement to provide an upgraded, homogeneous material. Finally, the stabilized material is compacted in place with rollers. The result is a stiff, stabilized base that is ready for a new rigid or flexible surface course.

Benefits of FDR

Full-depth reclamation has numerous benefits, including the following:

- Cost-effectiveness
- Increased structural capacity
- Increased durability (compared to granular base materials)
- Opportunity to improve roadway geometry
- Shortened construction schedule and improved staging
- Early opening to traffic
- Reduced impacts on the community during construction
- Reduced carbon footprint

By using in-place materials, FDR does not require the existing pavement to be removed from the site, unless a small amount of material must be removed to retain the existing elevation. Full-depth reclamation also reduces the amount of new material to be hauled to the site compared with methods that require granular material to be trucked to the site. By limiting the effort involved in removing and disposing of existing material and in hauling and placing new material, FDR saves time and money, minimizing hauling and labor costs compared with remove-and-replace construction methods. See Table 1.1 (adapted from Luhr et al. 2014).

Full-depth reclamation with cement increases the structural capacity of the new roadway by providing a stronger and more consistent base. The pulverized, stabilized, and compacted pavement and subsurface layers become a new roadway base with an improved structural capacity. With a cement-stabilized FDR base, the thickness of the new surface course can be decreased.

The strong uniform support provided by FDR with cement results in reduced stresses on the subgrade, particularly when the surface course is asphalt (Figure 1.2). (In fact, a thinner cement-stabilized FDR layer can reduce subgrade stresses more than a thicker untreated aggregate base layer.) Subgrade failures, potholes, and road roughness are thus reduced. The slab-like characteristics and beam strength of cement-stabilized FDR bases are unmatched by granular bases, which can fail when aggregate interlock is lost.

In addition, compared to an unstabilized granular base, the stiffer base reduces deflections due to traffic loads, resulting in lower strains in an asphalt surface (Figure 1.3). This delays the onset of surface distresses, such as fatigue cracking, and extends pavement life.

Figure 1.1. Road reclaimer performing FDR of an asphalt roadway

Table 1.1 Comparison of Pavement Rehabilitation Strategies

Solution	Advantages	Disadvantages
Thick structural overlay	• Provides new pavement structure • Fast construction • Only moderate traffic disruption	• Large quantity of material must be imported • Old base/subgrade may still need improvement • High cost alternative • Elevation change can present problems for existing curb and gutter and overhead clearance
Removal and replacement	• Provides new pavement structure • Failed base and subgrade are eliminated • Existing road profile/elevation can be maintained	• Long construction cycle requiring detours and inconvenience to local residents/business • Increased traffic congestion due to detours, construction traffic • Rain or snow can significantly postpone completion • Large quantity of materials must be imported • Old materials must be properly disposed • Highest cost alternative • May require additional effort to correct subgrade problems • Significant carbon footprint
Recycling surface, base, and subgrade with cement (full-depth reclamation)	• Provides new pavement structure • Fast construction cycle • Only moderate traffic disruption • Minimal change in elevation, thus eliminating problems with curb and gutter, overhead clearances • Minimal material transported in or out • Conserves resources by recycling existing materials • Local traffic returns quickly • Rain does not affect construction schedule significantly • Provides moisture-and frost -resistant base • Least cost alternative • Requires thinner surface course than traditional construction methods	• May require additional effort to correct subgrade problems • Some shrinkage cracks may reflect through bituminous surface

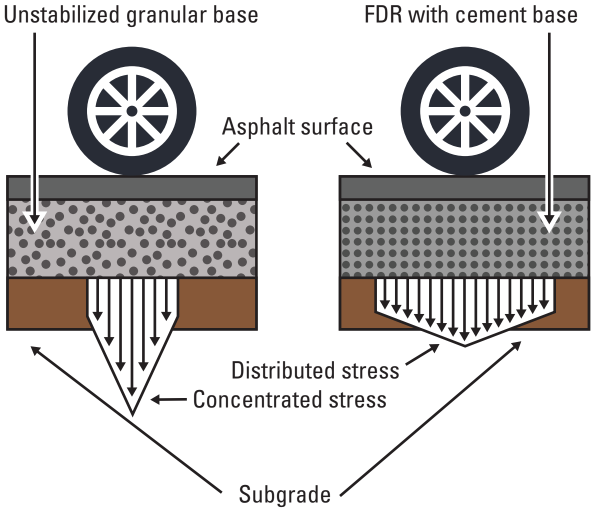


Figure 1.2. Unstabilized asphalt base results in more concentrated stress on the subgrade than FDR with cement

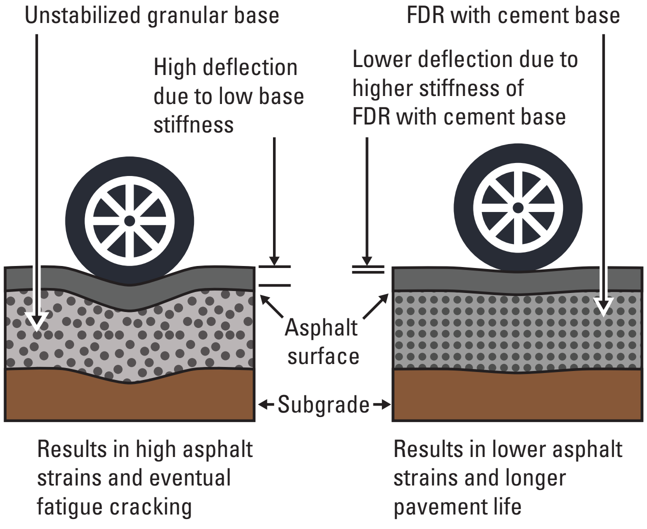


Figure 1.3. FDR with cement base reduces fatigue cracking compared to an unstabilized base

Full-depth reclamation with cement can be performed in a manner that improves roadway geometry. After the existing asphalt is pulverized and mixed with the subsurface layers, the new mixture can be reshaped to the desired cross section. Minor profile and superelevation modifications can be made at this stage, along with roadway widening.

Construction of FDR with cement has less impact on the community than remove-and-replace construction methods. Typically, completed portions of the FDR base can be opened almost immediately to local car traffic as long as the curing material is not affected. This is a major benefit in urban areas where maintaining residential and commercial driveway access is critical during construction. In addition to improved staging, reclaiming in-place materials reduces the overall construction schedule, helping to minimize inconvenience to motorists.

Public officials also recognize the reduced impacts provided by FDR. Since FDR recycles existing materials, there is less truck traffic to haul away existing materials and import new materials to the construction site. Not only does this improve safety and reduce energy consumption but it also has less impact on adjacent streets that may otherwise be damaged due to heavy equipment during construction.

Sustainable construction practices are critical to reducing the carbon footprint of construction activities. Full-depth reclamation with cement will reduce the carbon footprint of roadway rehabilitation projects by reducing the amount of material that will need to be hauled to and from the site and minimizing, if not eliminating entirely, new material that will need to be quarried to incorporate into a new roadway base.

Another benefit of FDR is that an existing roadway can be widened with a uniform base compared with other widening methods that do not involve reclamation. Full-depth reclamation can be used to widen roadways while at the same time blending the underlying poorer quality subgrades with the existing pavement and cement to produce a new uniform base layer. Agencies have been pleased with the success of this method because they are able to expand their existing roadways at a fraction of the cost of alternative road construction methods.

Why Add a Stabilizing Agent?

Asphalt roadways have been used extensively throughout the United States since the late 1800s. When the existing asphalt on these roadways reaches a poor condition, agencies must make a decision about the best way to rehabilitate the roadway. One option is to simply reclaim the existing asphalt pavement through cold-in-place milling and then to use this recycled asphalt pavement (RAP) for a new base material. Another option is to thoroughly mix the existing material in place but without a stabilizing agent.

The use of RAP can be an economical solution for the disposal of existing asphalt pavements. The Federal Highway Administration (FHWA) estimates that as much as 45 million tons of RAP may be produced each year in the United States. However, when either RAP alone or in-place mixed material without a stabilizing agent is used as a base material for an asphalt pavement, the unstabilized layer results in higher stresses and strains compared to a cement-stabilized layer (Figure 1.2). If an asphalt surface is to be constructed at a cost-effective thickness, it requires a uniform and reasonably strong base to carry traffic loads. When RAP is used as a standalone base material, the unconfined compressive strength is negligible, and the base is susceptible to creep deformation (Cosentino et. al.). The Federal Highway Administration estimates the average California Bearing Ratio (CBR) values for a mechanically stabilized FDR mix consisting of 75 percent RAP to be in the range of 5 to 12 percent (Bang et al. 2011). The stabilized base reduces the point loading to the subgrade and spreads the wheel loads more uniformly.

Therefore, RAP needs to be stabilized to achieve the specified strength requirements typically needed in a base for an asphalt surface. Full-depth reclamation with cement combines the existing pavement with the underlying base, binding all the material together to achieve the required stiffness and strength. Typically an FDR base has an unconfined compressive strength in the range of 200 to 500 psi.

Not only does this strengthened base provide more support for the surface course, it is also less susceptible to moisture intrusion. Moisture infiltrates an unstabilized FDR base more easily due to its gradation, causing softening of the base which in turn reduces its strength and stiffness. A cement-stabilized base has a reduced permeability that helps keep moisture out (Figure 1.4). Some states do not allow RAP as a base for concrete pavements for this reason. The high moisture content causes early-age concrete warping and can also result in the formation of secondary ettringite in air voids, causing freeze-thaw damage to the concrete in cold weather states. The end result of adding cement to the FDR mix is a more durable base compared with standalone compacted RAP layers.

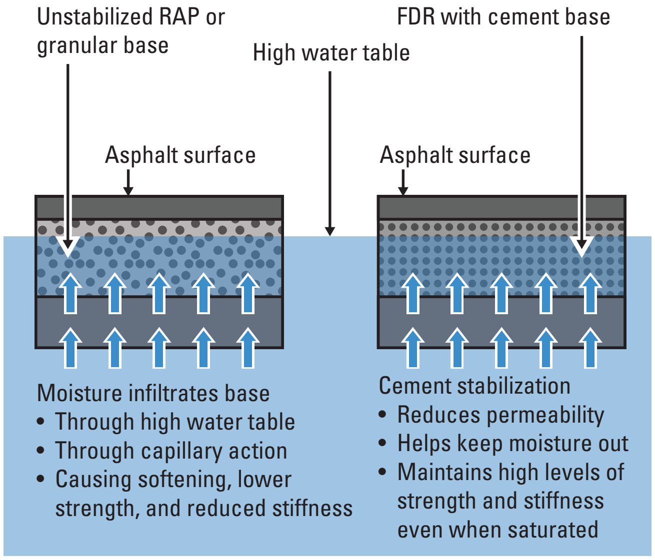


Figure 1.4. FDR with cement reduces the permeability of the base layer compared to a base of RAP or other unstabilized granular material

The University of California Pavement Research Center conducted a study that compared the performance of four different FDR strategies using a heavy vehicle simulator (HVS) to analyze distresses (Jones et al. 2015). The four types of FDR that were analyzed included no stabilization, stabilization with foamed asphalt and portland cement, stabilization with portland cement only, and stabilization with engineered asphalt emulsion. The study concluded that test sections stabilized with cement performed extremely well compared to the other FDR methods. A rut depth of 0.5 in. was recorded on the FDR with no stabilizer section after approximately 490,000 equivalent single axle loads (ESALs) had been applied. This compared to a rut depth of 0.16 in. after 17.7 million ESALs had been applied on the foamed asphalt with portland cement section, and a rut depth of only 0.12 in. after more than 43.3 million ESALs on the portland cement only section.

Types of FDR Stabilization

Three different types of stabilization methods are associated with FDR:

- Mechanical stabilization (addition of aggregate)
- Chemical stabilization (addition of cement)
- Bituminous stabilization (addition of asphalt binder)

Mechanical stabilization is defined by the Asphalt Recycling and Reclaiming Association (ARRA) as pulverization, mixing, and densification of reclaimed materials with the addition of granular materials, if necessary, to produce the required degree of structural support. Mechanical stabilization relies on particle interlock between the pulverized mixture of existing asphalt and subsurface layers. The pulverized mixture is compacted after mixing to the specified density.

Chemical stabilization can be achieved by mixing the pulverized asphalt pavement and subsurface materials with a chemical stabilizing material. Materials that are commonly used with chemical stabilization include:

- Portland cement
- Lime
- Class C or F fly ash
- Cement kiln dust (CKD)
- Lime kiln dust (LKD)
- Calcium chloride
- Magnesium chloride

Bituminous stabilization can be achieved by mixing the pulverized asphalt pavement and subsurface materials with an emulsified asphalt or foamed (expanded) asphalt. Bituminous stabilization can be combined with other stabilizers such as portland cement to achieve optimal FDR performance.

Of the three categories of stabilization, this manual focuses on chemical stabilization with portland cement, unless specifically stated otherwise. The FDR with cement process is an established engineered alternative for agencies seeking a cost-effective solution for roadway improvements. The Portland Cement Association (PCA) estimates agencies that use the FDR process save between 30 to 60 percent in costs over alternative reconstruction methods such as complete removal and replacement of existing pavement. In addition to the economic benefits, FDR with cement can be performed in a shorter time frame, saving weeks of labor and road closures.

Cement-stabilized FDR mixtures typically have higher initial strength values and long-term strengths compared to reclaimed mixtures stabilized with lime or bituminous agents. As mentioned in the previous section, they also have moisture-resistant properties that increase the long-term performance of the base.

Cement stabilization works with a wide range of existing materials and can accommodate higher plasticity soils. Other stabilization methods are not as versatile, since they are more limited in the types of existing materials they can effectively treat (Table 1.2, adapted from ARRA 2015).

Table 1.2. Versatility of Cement Compared to Other Stabilizing Agents[1] Used with FDR

Material type - including RAP	Well graded gravel	Poorly graded gravel	Silty gravel	Clayey gravel	Well graded sand	Poorly graded sand	Silty sand	Clayey sand	Silt, silt with sand	Lean clay	Organic silt/ Organic lean clay	Elastic silt	Fat clay, fat clay with sand
USCS[2]	**GW**	**GP**	**GM**	**GC**	**SW**	**SP**	**SM**	**SC**	**ML**	**CL**	**OL**	**MH**	**CH**
AASHTO[3]	**A-1-a**	**A-1-a**	**A-1-b**	**A-1-b A-2-6**	**A-1-b**	**A-3 or A-1-b**	**A-2-4- or A-2-5**	**A-2-6 or A-2-7**	**A-4 or A-5**	**A-6**	**A-4**	**A-5 or A-7-5**	**A-7-6**
Emulsified asphalt SE > 30 or PI < 6 and $P_{200} < 20\%$	X	X	X	X	X	X	X						
Foamed asphalt PI < 10 and P_{200} 5 to 20%	X		X	X	X		X						
Cement, CKD, or self-cementing class C fly ash PI < 20 $SO_4 <$ 3000 ppm	X	X	X	X	X	X	X	X	X	X			
Lime/LKD PI > 20 and $P_{200} > 25\%$ $SO_4 <$ 3000 ppm								X		X		X	X

SE - Sand Equivalent (AASHTO T 176 or ASTM D2419); PI - Plasticity Index (AASHTO T 90 or ASTM D4318); P_{200} - Percent passing no. 200 sieve

[1] Additives may also be used in combination with a stabilizing agent to optimize performance of the FDR section

[2] USCS: Unified Soil Classification System, ASTM D2487

[3] AASHTO: American Association of State Highway and Transportation Officials, AASHTO M 145

When is FDR Applicable?

FDR can be a cost effective rehabilitation strategy for a number of scenarios including the following:

- Flexural distresses in wheel lanes
- Asphalt distress due to low base failure (pavement condition index below 55 [poor condition])
- Excessive rutting or alligator cracking in the asphalt surface
- Excessive patching (20 percent or more)
- Need to widen the roadway
- Need to increase structural design of the roadway
- Need to correct the asphalt pavement cross slope in conjunction with other needed distresses to be corrected.

Full-depth reclamation is an effective method of roadway rehabilitation and can be a cost-effective strategy for pavements that require patching in excess of 15 to 20 percent of the existing pavement area (Figure 1.5). Full-depth reclamation is also useful for pavements that have deflections or advanced pavement distress such as severe linear or block cracking, alligator cracking (Figure 1.6), shoving, or rutting.

For pavements that have reduced ride quality with significant bumps and dips, FDR can be used to improve these deficiencies. The existing pavement and underlying materials will be pulverized and reshaped to a level base layer prior to the surface course being placed.

Full-depth reclamation also allows the existing pavement cross section to be reshaped. The FDR mixture can be used to improve roadway geometrics, superelevation adjustments, or drainage issues. Full-depth reclamation also allows agencies to widen their existing roadways to provide a consistent base with fewer environmental impacts and reduced cost compared with alternative remove-and-replace construction methods. These improvements are typically not cost effective with overlay projects, where the new surface course is limited to a defined thickness.

Are There Limitations to Using FDR?

Although there are significant advantages to incorporating FDR into a roadway rehabilitation project, certain aspects of the roadway project must be considered. If there are areas with drainage problems such as saturated subgrade or inadequate drainage systems to divert water away from the pavement structure, FDR alone will not rectify this issue. The project should include measures

Figure 1.5. Asphalt pavement with patching

Figure 1.6. Asphalt pavement with extensive alligator cracking

to mitigate drainage issues prior to the FDR process to ensure adequate drainage. Full-depth reclamation can be utilized on the project once drainage issues have been addressed.

Geotextile fabric between pavement layers has not caused challenges for the roadway reclaimer. Experience has shown that grid type mats and geotextile fabrics (woven or unwoven) can be broken up easily and do not hinder the FDR process. If grid type mats or geotextile fabrics are present, however, a thorough review of the existing pavement should be performed to ensure FDR can be accomplished.

Full-depth reclamation should also consider the potential for shallow subsurface utilities beneath the roadway similar to Figure 1.7. Modern pulverizing equipment can exceed 18 inches in depth and, as with all pavement reconstruction methods, the elevation of existing utilities should be checked and documented before selecting FDR as the rehabilitation method.

Full-depth reclamation is not the solution for all pavement distresses. Agencies should consider the condition of existing pavement and the reason for the distress. For pavements with adequate subgrades and bases and existing asphalt pavement in fair or better condition (minor surface cracking), the need for FDR is justified when increased structural capacity is needed to meet future loading conditions.

Like all reconstruction methods, the FDR with cement process requires an engineering pavement evaluation as a part of project selection, as well as implementation of established quality control practices during construction.

How is FDR Constructed?

Full-depth reclamation is similar to other concrete pavement formation in that it relies on mechanical consolidation of materials and chemical hydration processes for its strength. Understanding how FDR works requires a basic knowledge of the FDR construction process.

The first step in the FDR process is using a roadway reclaimer to pulverize the existing asphalt pavement. As mentioned earlier, the depth of pulverization includes the asphalt pavement and a portion of the underlying materials including the base, subbase, and/or subgrade. Not only does pulverizing and blending the underlying materials with the existing asphalt layer provide a uniform mixture, but cutting into the granular base and subgrade also keeps the cutting teeth of the reclaimer cooler. This increases the efficiency of the crew and reduces equipment maintenance costs.

Figure 1.7. Utilities like this manhole may need to be lowered beneath the proposed FDR depth before construction

A schematic of how a roadway reclaimer works is shown in Figure 1.8. The cutting or milling drum on the roadway reclaimer rotates in an "up-cut" direction, opposite to the direction of the reclaimer's tire rotation. The up-cut rotation of the cutting head improves pulverization and assists in reducing the size of the reclaimed asphalt materials. Modern reclaimers have the ability to add water or other fluid stabilizing agents during the reclaiming process.

After the existing asphalt and underlying material have been pulverized and blended together, the mixture is graded to the desired typical section. If there is existing curb and gutter that the new surface must match, some of the existing pulverized mixture may need to be removed to allow sufficient elevation difference for the new surface course. Milling some of the asphalt surface prior to pulverization may also be used to lower the grade.

Once the grading and shaping of the pulverized material is complete, cement is added to the mixture. Cement can be applied either as dry powder (Figure 1.9) or in slurry form (Figure 1.10). The cement application rate is usually specified in terms of weight per area (lb/yd^2). It should be noted that cement can be added to the asphalt surface prior to pulverization, thereby eliminating the need for an additional pass of the reclaimer. This option should be evaluated on an individual project basis to ensure proper pulverization of the existing pavement is achieved.

The pulverized material and cement are mixed by another pass of the roadway reclaimer (Figure 1.11). Water is typically added to the mixture through on-board applicators in the mixing chamber of the roadway reclaimer to achieve the appropriate moisture content for compaction and hydration.

After the cement and water have been thoroughly mixed with the pulverized base material, the mixture is ready for compaction. Compaction can be accomplished with a variety of equipment including padfoot/sheepsfoot rollers, smooth-wheeled vibrating rollers (Figure 1.12), and pneumatic tire rollers.

Finally, the completed FDR base is moist cured or sealed with a bituminous curing seal.

Sustainability of FDR

Sustainable solutions are becoming an important factor for agencies when it comes to selecting roadway rehabilitation strategies. Full-depth reclamation with cement reuses the original construction materials and makes economic sense. Aggregate supplies have been seriously

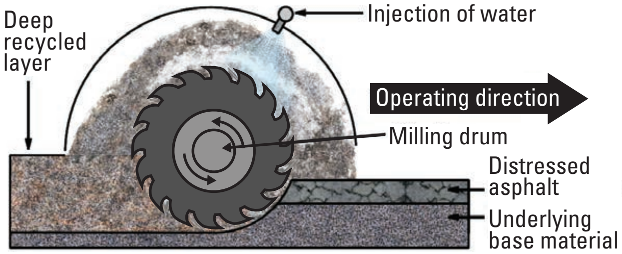


Figure 1.8. Schematic of a roadway reclaimer during FDR process

Figure 1.9. Application of dry cement powder to pulverized mix

Figure 1.10. Application of cement slurry to pulverized mix

Figure 1.11. Full-depth reclamation train with water truck (left) and reclaimer

Figure 1.12. Final compaction of FDR base with a tamping roller (right) and a smooth-wheeled vibrating roller

Figure 1.13. Full-depth reclamation recycles existing materials, for a more sustainable construction method

impacted by a century of growth and urbanization in America. Depending on location, aggregate requirements for new construction projects may require that aggregate be trucked in from a great distance to meet quality specifications.

As valuable resources become more scarce, reconstruction of America's aging infrastructure aggravates the problem. In addition to aggregate extraction, traditional remove-and-replace roadway construction methods require that the existing asphalt and base materials be hauled off site. Not only is the hauling cost expensive, but stockpile space is taken up by materials that could be recycled in place. Additionally, disposal of existing asphalt materials and mining of new aggregate is becoming more expensive due to increasing environmental regulations.

By reusing the existing asphalt pavement, aggregate, and soils, FDR limits the amount of new material that must be quarried and transported to the site. This reduces air pollution, fugitive dust, traffic congestion, and damage of nearby roadways due to hauling materials to and from the site (Figure 1.13).

Full-depth reclamation with cement is a self-sustaining process for roadway reconstruction. The original investment in virgin road materials can be reused by pulverizing and reclaiming with cement stabilization. Full-depth reclamation saves money and reduces the carbon footprint of roadway construction projects by reducing mining, hauling, and disposal of basic construction materials.

Figure 1.14 (adapted from PCA 2010) compares the energy and materials savings of FDR compared to the traditional construction of a new base. The information in this chart is based on 1 mile of a 24-ft wide, 2-lane roadway with a 6-in. base.

Common FDR Projects

The FDR process has been used on a wide variety of projects ranging from airports to residential streets to primary systems and more.

Primary State and Rural Highways

State highways carry traffic at high speeds and need to withstand the heavy loads associated with truck traffic. As agencies grapple with the aging roadway network that was built decades ago, they are also faced with limited budgets for roadway rehabilitation. Distressed asphalt pavements on highways can be recycled using FDR with cement stabilization.

For example, the Idaho Transportation Department (ITD) used FDR with cement on US 20, a freeway with an annual average daily traffic (AADT) of 5,000 and average annual snowfall of approximately 100 in. (Figure 1.15). The ITD used an FDR with 2 percent cement content and a thickness of 6.5 in. A 3.7-in. thick hot-mix asphalt (HMA) surface course was placed over the FDR base. After 13 years of service, even with heavy traffic and extreme weather conditions, visual inspection shows the roadway in very good condition. In addition, the back calculation of falling weight deflectometer (FWD) data revealed the average resilient modulus of the FDR base was 55,515 psi after 13 years of use.

As with all FDR projects, the mix design is critical to ensure the successful long-term performance of the pavement. Full-depth reclamation provides a stronger base than unstabilized granular base layers, which helps reduce stress on the pavement surface. The increased

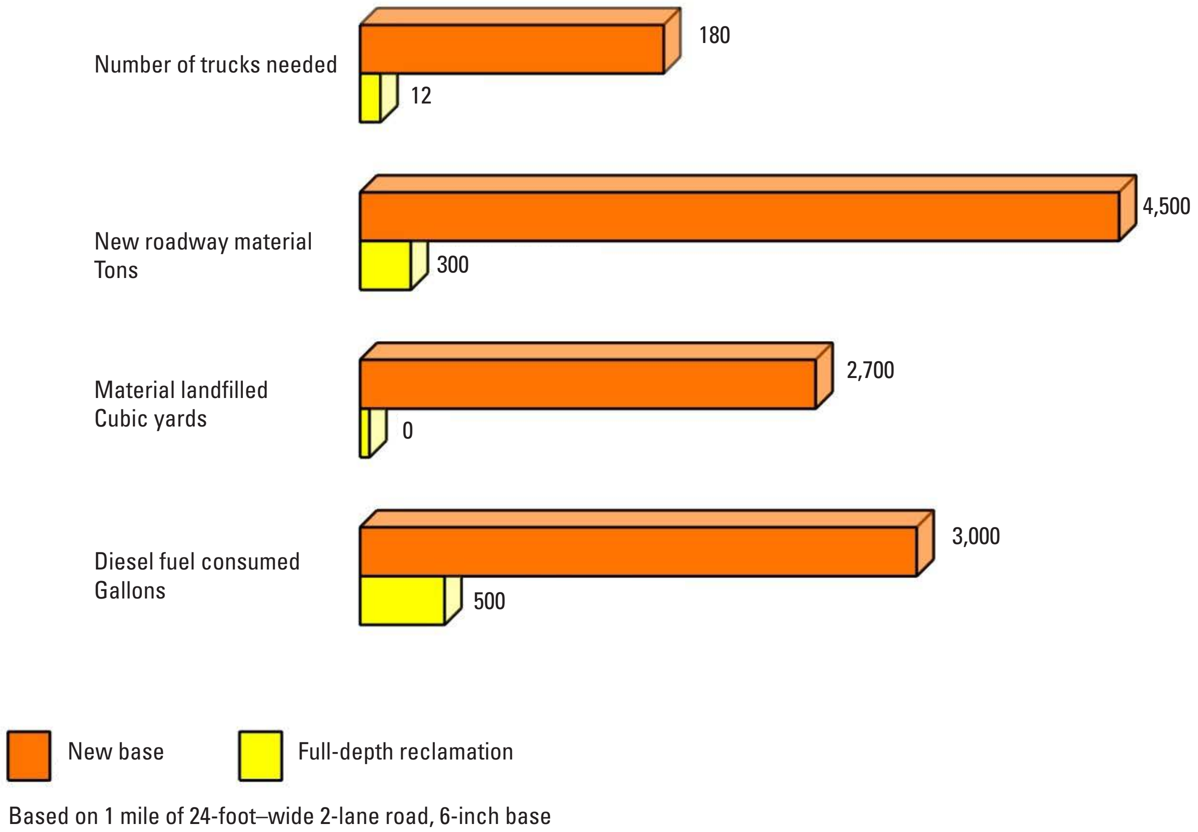


Figure 1.14. Comparison of energy and material use between FDR and construction of a new base

Figure 1.15. US 20 in Idaho after FDR construction

strength of the base layer may allow agencies to reduce the thickness of the surface course. Mixture and structural design are discussed further in Chapters 4 and 5.

Arterials

Similar to primary state highways, urban arterials are designed to carry the heaviest traffic loads in the urban roadway network. To achieve these design parameters, the pavement must be strong and able to withstand heavy loads. Construction schedules are critical, and closures are typically not practical for these high-volume roadways.

Cities have discovered that rehabilitation of existing pavements with extensive surface distresses can be accomplished using FDR with cement. The city of Westminster, California, has successfully used FDR on arterial roadways for almost 25 years. The city uses a 12-in. thick FDR with cement base combined with a 3-in. thick HMA surface course. The city typically specifies a minimum compaction of 95 percent using the modified Proctor test. Westminster has been successful with this method, and officials estimate they have saved 30 to 60 percent on costs when compared to other projects of similar scope (Syed 2007).

Local Streets

Public works directors have recognized the benefits of FDR including early opening to local traffic and shorter construction durations. Full-depth reclamation can be opened to light traffic almost immediately if a detour route is unavailable. Through experience, the Idaho Transportation Department (ITD) has determined the surface course should be applied within 48 hours of the completion of the reclaimed base.

The reduced construction duration and early opening timeframe reduces the inconvenience to adjacent property owners. Figure 1.16 shows a compacted FDR layer on a residential street prior to the surface course application. The project shown in this photo allowed traffic on the completed FDR layer prior to surface course application.

Figure 1.16. This compacted FDR base was opened to light residential traffic before application of surface course

Parking Lots

Many parking lot pavements throughout the United States are surfaced with asphalt. As these pavements fail, business owners are faced with resuscitating them in a cost-effective manner. Full-depth reclamation with cement has proven to be a successful rehabilitation method.

Not only is the investment in the original asphalt pavement preserved, construction traffic entering and leaving the site is reduced due to the use of in-situ materials. The shortened construction schedule also minimizes the impacts on businesses whose customers use the parking lot. It is recommended a surface course be applied to the FDR layer in parking lots to avoid rutting where vehicles are parked for extended periods of time.

Airports

When airport pavements have reached the end of their service lives, reconstruction needs to be completed as quickly as possible to minimize closure time. The officials at the Friedman Airport in Hailey, Idaho, recognized the benefits of FDR when deciding on a rehabilitation method for the airport's only runway. Since the economy in this area relies heavily on tourism, the length of time the runway was closed directly affected the local economy by impacting tourism and conference traffic.

Airport officials wanted to limit the runway closure to 30 days. Analysis had indicated that complete removal and reconstruction of the existing pavement would require roughly 45 to 50 days of runway downtime. Full-depth reclamation with cement was proposed as an alternative. It was estimated the FDR approach would shorten the schedule by 18 days and reduce the thickness of the surface pavement due to the increased base strength. The FDR process was also estimated to eliminate 4,000 truck trips through the community since the existing materials would be recycled on-site. One of the largest benefits of FDR was that the overall cost of construction would be reduced by more than $1,000,000.

The benefits of FDR were recognized by the airport authority, and construction of 73,440 yd^2 of FDR was successfully completed within the required 30-day schedule. The airport officials now recommend this method to other airports that want to minimize runway closure times (Figure 1.17).

Life Expectancy of FDR

In general, the life expectancy of FDR with cement bases is typically 7 to 10 years when a thin surface course such as chip seal or seal coat is applied, or 15 to 20 years when an asphalt surface course is applied. It should be noted that typically the limiting factor for service life of pavements constructed on FDR bases is the surface course material and not the FDR base. For more information on the long-term performance of FDR, see Chapter 8.

Figure 1.17. FDR construction of airport runway

Chapter 2

Properties and Materials

Full-depth reclamation with cement is an engineered base material, and its successful performance depends on an appropriate mix design and proper construction. Full-depth reclamation bases contain a pulverized asphalt pavement mixed together with all or part of the existing underlying base and subgrade material. The FDR mixture also contains cement and water to provide strength and durability to the pulverized mixture (Figure 2.1). (Chapter 5 provides the mix proportioning steps to achieve the desired properties.)

Tests used to determine the engineering properties of FDR bases include the following:

- Unconfined compressive strength tested according to ASTM D1633 (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders)
- Moisture-density test using ASTM D558 (Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures), which determines the maximum dry density and optimum moisture content to achieve maximum density
- Proper techniques for making and curing soil cement samples according to ASTM D1632 (Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory)
- In-place density tested during construction according to ASTM D6938 (Standard Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)
- Moisture content determined according to ASTM D4959 (Standard Test Method for Determination of Water Content of Soil by Direct Heating) or ASTM D4643 (Standard Test Method for Determination of Water Content of Soil and Rock by Microwave Oven Heating)
- Freeze-thaw durability tested in accordance with ASTM D560 / AASHTO T 136 (Standard Test Methods for Freezing and Thawing of Compacted Soil-Cement Mixtures)

Note: Other test methods used to evaluate durability include the following:

- The vacuum saturation strength testing procedure found in ASTM C593 (Standard Specification for Fly Ash and Other Pozzolans for Use with Lime for Soil Stabilization); a good correlation appears to exist between the vacuum saturation test and the freeze-thaw durability test (Wilson et al. 2012)
- The tube suction test (TST), which provides a good indicator of durability of cement-stabilized bases (Scullion et al. 2005, George 2001)

Properties and related tests are discussed further in the next sections.

Density

Density is one of the most important properties for a successful FDR project. Figure 2.2 shows an example moisture density curve for a very strong cement-treated base. As this figure illustrates, maximum strength is achieved at approximately the point of maximum density and optimum moisture. If compacted at a lower density, the result will possibly be lower strength and durability.

Strength

The strength properties of FDR with cement bases depend on the amount of cement, the type and characteristics of existing materials (e.g., reclaimed asphalt

Figure 2.1. Core of FDR with cement base and HMA surface course

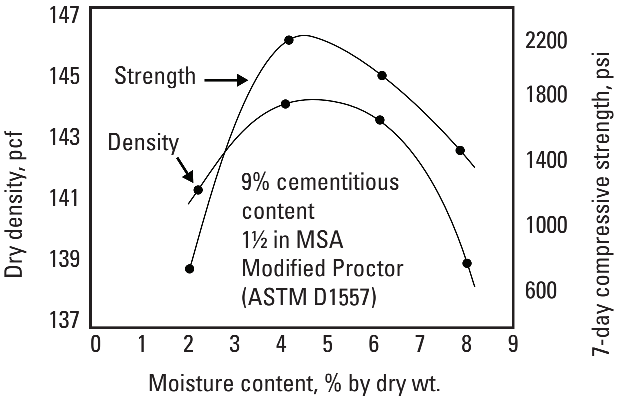


Figure 2.2. Relationship between density and compressive strength

pavement, underlying aggregate, underlying soils), the density of the mixture, and curing efficiency. The strength is strongly influenced by the degree of compaction of this pulverized mixture. Full-depth reclamation with cement bases have a higher compressive and flexural strength than unbound granular base layers due to the addition of cement that bonds the particles together. Figure 2.3 illustrates how FDR with cement bases provide better load-carrying ability than granular bases of similar thickness.

Unconfined Compressive Strength

The unconfined compressive strength (UCS) of FDR with cement bases is typically higher than that of other stabilized base methods such as asphalt emulsions, lime, or fly ash. According to ARRA (2015), typical specified seven-day unconfined compressive strengths range from a minimum of 200 to 300 psi to a maximum of 450 to 800 psi, depending on the application. The PCA recommends a seven-day target UCS of 300 to 400 psi (Luhr et al. 2014). The unconfined compressive strength of FDR with cement bases is determined using ASTM D1633, as shown in Figure 2.4.

Cement-stabilized FDR bases gain strength over time due to continued cement hydration. In a study by the Portland Cement Association (Syed 2007), 23 core samples were obtained on previously constructed FDR with cement bases. These cores were subjected to unconfined compressive strength testing. The results showed that after years of service the average UCS of the core samples was over 900 psi. Typically, these FDR with cement sections were originally designed for a seven-day UCS of 400 to 600 psi.

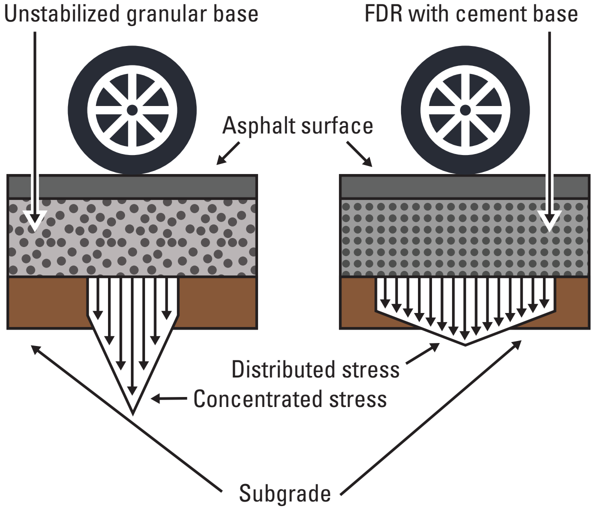


Figure 2.3. Compared to an unstabilized granular base, an FDR with cement base spreads out and reduces the point load to the underlying subgrade

Flexural Strength

Similar to compressive strength, the flexural strength of the FDR with cement mixture depends on the amount of cement, type and gradation of mixed materials, density of the mixture, and curing efficiency. In properly constructed FDR with cement bases, the soil, aggregates, and RAP are densely packed, minimizing deflections and the development of fatigue cracking. The water and cement in the pulverized mixture provide strength by bonding the materials together.

Limited information is available on the flexural strength of FDR with cement bases because of the difficulty of obtaining specimens from actual FDR projects. There is also an absence of a standardized test method for fabricating beams in the field and laboratory. However, the recommended test protocol for flexural strength is ASTM D1635 (Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading) (AASHTO 2008).

The benefit of increased flexural stiffness of FDR with cement bases compared with traditional unstabilized bases is illustrated in Figure 2.5. The improved stiffness reduces strains on the pavement surface and thus prolongs the useful life of the pavement. The University of California Pavement Research Center conducted a study in 2015 to compare the performance of unstabilized FDR layers to layers stabilized with different agents. By using heavy vehicle simulator (HVS) testing, the study concluded that the unstabilized FDR pavement section failed at 5 million ESALs, whereas the cement-stabilized FDR section of the same thickness did not fail even after being subjected to more than 43 million ESALs (Jones et al. 2015).

Figure 2.4. Unconfined compressive strength test being performed on an FDR with cement specimen

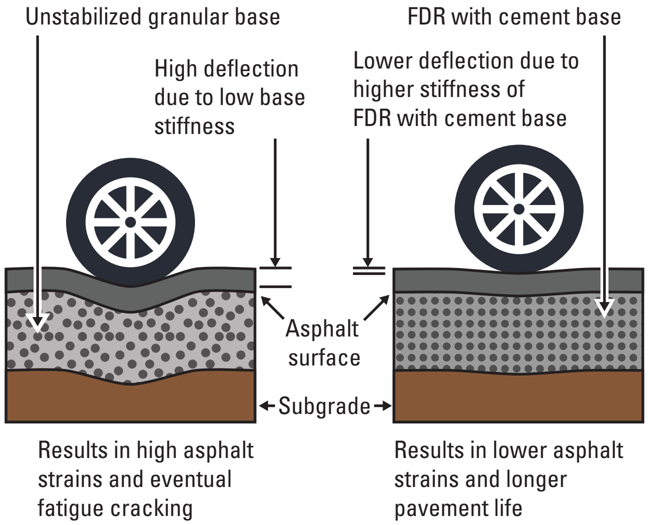


Figure 2.5. Compared to an unstabilized granular base, an FDR with cement base results in lower strains on the asphalt surface layer

Modulus of Elasticity

The modulus of elasticity expresses the ratio between the applied stress and strain, as shown below:

$$E=\sigma/\varepsilon \qquad \text{(Eqn. 2.1)}$$

Where:

E = modulus of elasticity (psi)
σ = stress (psi)
ε =strain (in./in.)

The modulus of elasticity represents the material's tendency to undergo reversible elastic deformation in response to a slowly applied load.

There are limited tests on FDR with cement mixtures relating to the modulus of elasticity. However, the AASHTO *Mechanistic-Empirical Pavement Design Guide* recommends a modulus of elasticity (E) value of 500,000 psi for soil cement for pavement design purposes (AASHTO 2008).

Research by Lim, Seungwook, and Zollinger (2003) established the following equation for converting compressive strength to elastic modulus for cement-treated aggregate base (CTAB) materials:

$$E(t) = 4.38 * w^{1.5} * f_c\ (t)^{0.75} \qquad \text{(Eqn. 2.2)}$$

Where:

$E(t)$ = modulus of elasticity in psi at time t
w = mixture density in pcf
$f_c\ (t)$ = compressive strength in psi at time t

Test results indicated that the relationship between the compressive strength and elastic modulus of CTAB materials could be expressed in a single equation regardless of aggregate type and mixture proportions.

Resilient Modulus

The resilient modulus (M_r) of an FDR layer is a measure of the stiffness of the FDR layer. For slowly applied loads, the modulus of elasticity is stress/strain; for rapidly applied loads, the M_r is stress/strain. The term "resilient modulus" comes from the amount of deformation that is recoverable or "resilient."

The M_r is an important factor when designing flexible pavements. To determine a pavement thickness, the M_r is a direct input for the AASHTO *Mechanistic-Empirical Pavement Design Guide* (2008) and is a measure of how the proposed pavement and underlying base (FDR) will react to rapidly applied loads, such as traffic loads.

The M_r of an FDR mix will depend on the cement content and density of the mix. To obtain the appropriate degree of compaction, it is important to understand the target field density of the FDR mixture. A low density mixture will have a lower M_r than a high density mixture. Because of the cementitious properties of a cement-stabilized FDR base, its resilient modulus is much greater than a base of unstabilized granular material.

The moisture content of the FDR mix will also be a critical component in obtaining appropriate M_r values. The FDR mix should be at the optimum moisture content as defined in the specified mix design. As specimen moisture content increases and degree of saturation approaches 100 percent, the M_r will decrease (Buchanan 2007).

According to research work by Scullion, et al. (2008), M_r can be derived from compressive strength using the following equation for cement-treated bases.

$$\text{resilient modulus (ksi)} = 36.5 * \sqrt{UCS} \qquad \text{(Eqn. 2.3)}$$

Where:

UCS = unconfined compressive strength (psi) at 7 days

Table 2.1 shows sample M_r values for unconfined compressive strengths typical in FDR construction.

Modulus of Subgrade Reaction

The modulus of subgrade reaction, also referred to as the k-value, is a necessary input for rigid pavement design calculations, including rigid pavements placed on an FDR layer. The k-value refers to the stiffness value of a base. Most of the research currently available on FDR bases is related to the M_r and not the modulus of subgrade reaction. The M_r is a necessary value used for the design of flexible pavements.

Traditional correlations of the M_r and k-value for soils used the following equation:

$$k = M_r/19.4 \tag{Eqn. 2.4}$$

Where:

k = modulus of subgrade reaction
M_r = resilient modulus

The above equation should *not* be used for FDR because it will yield an artificially high k-value. For example, the M_r values for FDR bases are typically 200,000 psi or higher. Using the above equation with an M_r value of 200,000 psi would result in a k-value of over 10,000. This is not a realistic value for rigid pavement design inputs. The k-values for FDR bases in the range of 300 to 700 psi/in. are typically used for rigid pavement design calculations.

Permeability

The permeability of FDR with cement bases largely depends on the voids in the compacted FDR mix and the degree of cementitious bonding. Therefore, the permeability is controlled by the mix proportion and the degree of compaction during construction. Full-depth reclamation with cement layers have a permeability that is similar to compacted clay. Low permeability of the mix will improve resistance to freeze-thaw damage and provide improved load support compared to a saturated unstabilized granular base. The PCA publication *Soil-Cement Guide for Water Resources Applications* indicates that the permeability of soil-cement can be as low as 10^{-8} cm/sec (Richards and Hadley 2006).

Permeability is increased at shrinkage cracks, when they occur. Micro-cracking (also referred to as pre-cracking) procedures have improved pavement performance by distributing the shrinkage through narrower but more closely-spaced cracks. These cracks have shown self-healing ability when moisture is present (Adaska and Luhr 2004). (Pre-cracking is discussed in more detail in Chapter 6.)

Table 2-1. Sample Resilient Modulus Values for Various UCSs

UCS (psi)	Resilient modulus (ksi)
200	516
250	577
300	632
350	683
400	730
450	774
500	816

The benefits of reduced permeability of FDR with cement bases are illustrated in Figure 2.6. The reduced permeability provides a higher level of strength compared to unstabilized bases, even when the water table is high.

New testing procedures are being developed that can identify the moisture sensitivity of FDR base materials. The tube suction test has shown promise and can be used to measure the movement of water in a sample of FDR with cement base. This test can assist designers in determining the appropriate amount of cement to use for stabilization to make sure the specimen can "choke off" the movement of water.

Freeze/Thaw Durability

Many agencies in northern climates face challenges when it comes to the durability of roadway bases during freeze-thaw (F-T) cycles (Figure 2.7, from Syed 2007). For

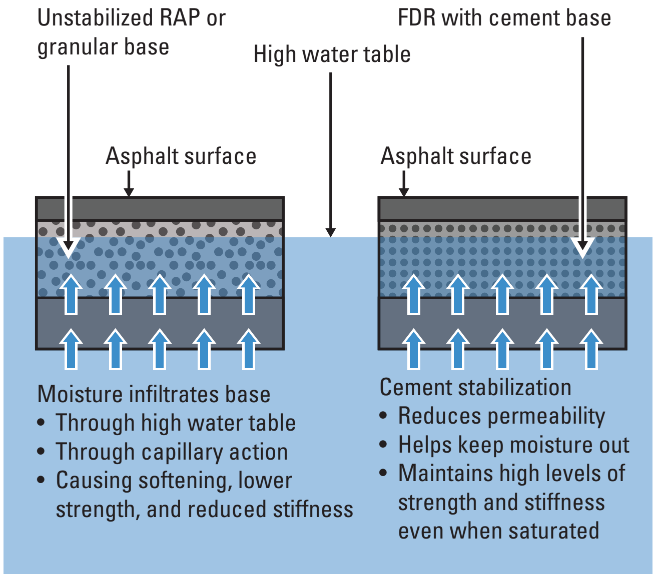


Figure 2.6. FDR with cement is less susceptible to moisture intrusion when compared with a compacted RAP base

Figure 2.7. Effects of extreme climatic conditions such as snow and freezing temperatures can be reduced with FDR bases

successful long-term pavement performance, the amount of moisture contained within the pavement system needs to be limited. If significant moisture is contained within the system, the action of freezing and thawing increases permeability and reduces the M_r of both granular and fine-grained soil. Similar issues can exist in stabilized materials unless there is sufficient durability to resist moisture infiltration and volume change due to freezing and thawing.

In unstabilized granular base material, various factors cause instability of the base material over time. This breakdown can be attributed to environmental conditions, traffic loading, and water movement within pavement layers that cause physical and chemical weathering. According to Syed (2007) the fine-grained soils (silts and particular clays) tend to hold moisture and can expand up to nine percent in volume during freezing weather. During thawing events, the melting ice adds moisture to the unbound particles, causing the affected material to lose shear strength (Syed 2007). This volumetric change and loss of strength can cause roadways to heave, leaving a potentially dangerous situation for motorists.

The mixture for an FDR layer must be designed to limit moisture intrusion in climates where F-T events are likely to occur. There are several important considerations for frost-resistant FDR with cement mixtures:

- Compacting FDR base materials to the highest possible density provides the greatest potential for high strength and low permeability, which are two key factors in achieving durable, frost-resistant FDR bases.
- Curing plays a critical role in providing F-T resistant FDR with cement bases, especially before the surface course is applied. Throughout the construction phase, from mixing to finishing operations, sufficient care should be taken to ensure that excessive evaporation of moisture from the FDR mix does not occur. If precautions are not taken to minimize moisture loss from the surface of the FDR mix, the evaporating (drying) may weaken the FDR surface, thereby reducing its ability to resist F-T damage. Upon completion of FDR compaction, the surface should be kept continuously damp (Figure 2.8) to prevent moisture loss until a curing compound or surface course can be applied. An alternative method to prevent excessive moisture loss is the application of a bituminous sealant upon completion of compaction. Bituminous sealant helps protect the moisture and promote more complete curing.

Field performance studies have indicated that FDR with cement bases have performed well in harsh climatic conditions. Syed (2007) reviewed actual field performance of FDR with cement projects in eight states throughout the country. Of the 79 projects, more than 50 sections were in areas with moderate to severe winter weather. The research indicated the FDR with cement process provided positive benefits for agencies that had previously experienced heaving in the winter or loss of shear strength during spring thawing events with their existing pavements.

The F-T resistance of FDR with cement mixtures can be tested in accordance with ASTM D560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) or AASHTO T 136 (Standard Method of Test for Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures). Other methods, including the vacuum saturation (Figure 2.9) (Wilson et al. 2012)

Figure 2.8. Water application on a compacted FDR base during the curing period

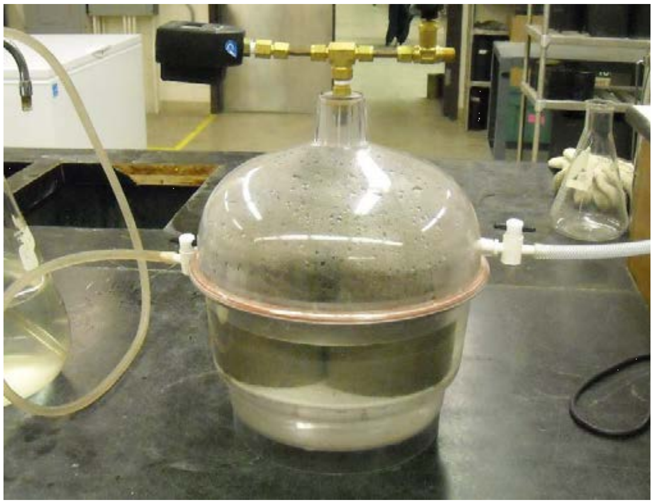


Figure 2.9. Specimens subjected to vacuum saturation testing

and tube suction tests listed earlier, can also be used to evaluate the F-T durability of FDR with cement bases. (Freeze-thaw durability testing is discussed in more detail in Chapter 5.)

Poorly Reacting Soils

Full-depth reclamation with cement bases are comprised mostly of pulverized asphalt. However, consideration must also be given to the base and subgrade materials that are incorporated in such bases. As mentioned in Chapter 1, including Table 1.2, FDR with cement works with a range of soil materials, from non-plastic sands and silts to higher plasticity clay soils. Optimum results are achieved using a well graded mixture containing less than 20 percent passing the no. 200 sieve. More information on materials and gradation is provided in Chapter 5.

Although most base and subgrade materials have relatively little chemical impact on the performance of cement-treated soils, soils with certain characteristics can cause disruption in the cement hydration process. Soil characteristics such as sulfate content, organic content, and pH are all important factors to consider.

The pH of the soil beneath the existing asphalt that will be incorporated into the mix must be analyzed to ensure the pH is at a satisfactory level for proper cement bonding. When the pH of an FDR mixture is lower than 4, the cement may not react properly and therefore will not bond the particles of the FDR layer together. The Georgia Department of Transportation therefore recommends a minimum pH of 4.0 for soils that will be incorporated into an FDR layer.

Sulfates within the proposed FDR mix can also create pavement concerns. The cause of many of these concerns can be attributed to sulfate-induced heave. Sulfate-induced heave can be caused by an expansive mineral called ettringite that is formed from a calcium-based stabilizer (lime or cement) reacting with clay and sulfate minerals (usually gypsum) in the soil (Harris et al. 2006) and in the presence of water will expand several times its normal condition. Typically if the FDR mixture has a soluble sulfate content of less than 3,000 ppm, sulfate-induced heave is not a problem. More information on treating sulfate soils can be found in the Texas Department of Transportation's *Guidelines for Treatment of Sulfate-Rich Soils and Bases in Pavement Structures* (TX DOT 2005).

The organic content of the soil is also a characteristic that should be analyzed for successful FDR projects. Experience has shown that organic soil can be incorporated into the FDR mix. However, studies (Robbins and Mueller 1960) have indicated that organic content greater than two percent in the FDR mix may require higher cement content to account for the organics.

Atterberg limits tests should be performed on the soil to determine the plasticity of soil that exists on site. Highly plastic soils may require special treatment in typical soil-cement mixtures. However, this is not a great concern if the amount of soil in the FDR mixture is a low percentage of the total mix.

Chapter 3

Project Evaluation

Selecting FDR with cement as a rehabilitation strategy requires an understanding of the existing pavement, underlying materials, project surroundings, and project criteria. This chapter covers the evaluation process for an asphalt or unimproved (gravel/sand) roadway to determine if it is a candidate for FDR. The evaluation should consider not only structural issues of the existing asphalt but also cross section limitations and geometric corrections. The information gathered during the evaluation process can be used to help determine the FDR mix design and project specifications.

Determining When FDR is Appropriate

Although FDR with cement can treat a variety of project conditions, each project should be carefully evaluated before selecting a rehabilitation strategy. In many cases, FDR is an effective rehabilitation strategy for roadways that exhibit any of the following traits:

- Problems with subbase/subgrade
- Damaged pavement that is beyond resurfacing
- Full-depth patching is required beyond 15 to 20 percent of surface
- Inadequate for future traffic, or other criteria
- Corrections to roadway geometry needed

Problems with Subbase/Subgrade

Typically, a roadway is determined to need rehabilitation when surface distresses such as cracking and rutting become apparent. Not all roadways exhibit surface distress when there are problems with the underlying subbase or subgrade. Subgrade and subbase problems can affect the rideability of the roadway and require FDR to correct the issue.

Any drainage issues in the underlying soils must be addressed prior to FDR operations for successful long-term performance. Full-depth reclamation does not cure all drainage issues in pavement structures. However, FDR with cement will address drainage issues such as pumping in the subbase and subgrade layers. Pumping is the result of water that accumulates in the layers beneath a pavement. When a vehicle is on the pavement, the downward pressure of the pavement section pressurizes the water, causing the water to move beneath the pavement. Over time, this continuous movement of water can erode and weaken the subbase and subgrade layers, causing premature pavement failure. With FDR, the addition of cement to the pulverized mixture reduces the permeability of the reclaimed layer, preventing moisture from penetrating the FDR base.

Damaged Pavement – Beyond Resurfacing

Asphalt pavements eventually deteriorate due to factors such as environment, traffic loading, utility or maintenance activities, and original construction quality. Deterioration will eventually require the pavement to be replaced. When existing asphalt pavements are structurally damaged or shifting to the point at which resurfacing is not practical, FDR with cement can recycle the existing pavement and base material to create a homogeneous base for a new surface layer. The most common asphalt pavement distresses include the following:

- Fatigue (alligator) cracking
- Block cracking
- Potholes
- Rutting
- Shoving
- Loss of base or subgrade support

Full-Depth Patching Required (>15–20% Surface)

Patching is a common practice for agencies that are tasked with keeping roadways serviceable. When complete reconstruction is not in the budget, cracks and damaged pavement are repaired with full-depth patches (Figure 3.1). Although patching is often necessary, it can be an expensive operation. The PCA has determined (Luhr et al. 2014) that when the area of a pavement requiring full-depth patching exceeds 15 to 20 percent, simple economics make it less expensive to use FDR with cement rather than patching. Not only is FDR a more economical choice than extensive full-depth patching, FDR with cement provides a stronger and more uniform roadway compared with a road that is heavily patched.

Figure 3.1. Excessive patching on asphalt roadway

Pavement Inadequate for Future Traffic

As agencies struggle to keep up with the ever increasing traffic loads on the nation's roads, officials are looking for ways to improve the existing infrastructure in an economical and sustainable manner. In addition to restoring a roadway that is damaged, rehabilitation projects that include FDR can be used to upgrade existing roadways for future traffic projections.

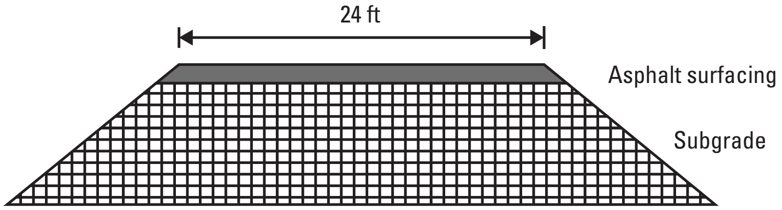
With domestic energy exploration throughout the United States and increased commercial truck traffic, many roadways are under-designed for current and future traffic. When this situation occurs, roads are often overlaid with additional pavement to increase the thickness of the existing pavement and to add structural value. The additional thickness of the pavement requires the shoulders to be built up and extended to match the new pavement elevation. After several iterations of overlay and shoulder widening, a roadway cross section has to be expanded, requiring expensive foreslope adjustments, guardrail modifications, and additional right of way, especially in urban areas.

Full-depth reclamation provides an alternative to the overlay process. Instead of building a pavement up, FDR can strengthen a roadway by "building down," as shown in Figure 3.2 (adapted from Luhr et al. 2014). By pulverizing the existing asphalt pavement and underlying materials to rebuild and strengthen the base, FDR rehabilitates the roadway without changing the original pavement elevation or right of way.

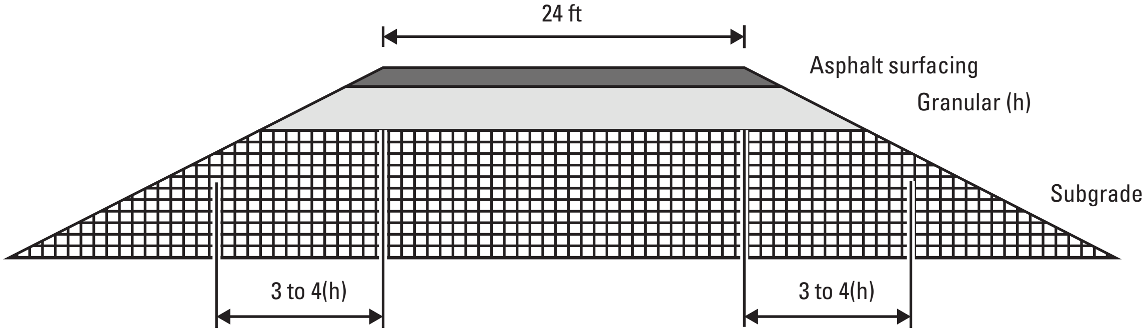
In the past, FDR was generally limited to lower traffic volume roadways because road reclaimers could not pulverize the thicker pavements of high-capacity roads. The FDR process has improved with the availability of larger and more powerful equipment. The more robust equipment allows FDR to be performed on thicker pavements typically found on high-volume roadways and penetrates deeper into the base and subbase below.

With a proper mix design, FDR can be used to strengthen all types of roadways, from urban residential streets to primary interstates.

Existing thin paved structure



Conventional built-up granular structure



Full-depth reclamation structure

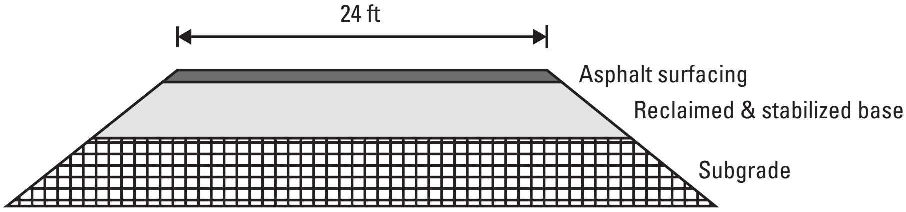


Figure 3.2. Using FDR to "build the pavement downward"

Full-depth reclamation with cement not only reuses the original "investment" and materials in the pavement, it increases the strength of the roadway to carry heavier and more frequent vehicle loads. Decision makers should consider FDR with cement as a viable rehabilitation method when existing roadways need to be upgraded.

Corrections to Crown/Profile (Roadway Geometry)

Full-depth reclamation with cement can improve roadways that require geometric modifications such as realignments, superelevation adjustments, profile adjustments, and widening. These geometric corrections can be accommodated by pulverizing the existing asphalt pavement and underlying base materials, reshaping the pulverized mix to the desired alignment and cross section, and adding cement to form an improved homogeneous base. Full-depth reclamation with cement can also incorporate existing granular shoulders when the roadway is to be widened or realigned.

Although FDR alone can correct minor horizontal and vertical profile deficiencies, if the existing roadway requires extensive modification, additional operations may be required to ensure uniform treatment depth. In situations where major profile adjustments are required, cold planing can be used to correct profile deficiencies in asphalt pavements of sufficient thickness before performing FDR. Alternatively, excess material can be removed after the pulverization process has been completed.

If the existing pavement is thin, aggregate or RAP from an off-site source can be added to the roadway before performing the FDR process (Figure 3.3, from PCA 2005). The additional material must be uniformly blended with the pulverized asphalt pavement and underlying materials during the reclaiming process to provide a strengthened base at the desired profile elevation.

Figure 3.3. Aggregate being added to a roadway for minor alignment adjustments

Note: Any additions, reductions, or amendments to the existing pavement section should be accounted for in the representative field samples acquired for the mix design. This includes the addition of off-site aggregate, RAP, etc., used to modify gradation.

Another alternative for roadways that require extensive profile adjustments is to use FDR to adjust as much of the vertical profile as possible. After the FDR with cement process has been completed, the remaining profile adjustments are addressed by using additional thickness of paving material to achieve the designed profile.

For projects that require alignment adjustments or roadway widening, agencies should consider FDR with cement. Not only does FDR provide a stronger base for the new roadway, it will save the agency money by recycling the in-situ materials and reducing the number of truckloads of material hauled to and from the project site.

In urban areas where curb and gutter elevations are to remain unchanged, the FDR layer must be constructed to account for the thickness of the proposed surface course. One method to accomplish this is to pulverize the entire existing asphalt pavement and underlying materials at a predetermined depth between the curbs. The pulverized mixture can then be bladed off and shaped to the desired cross section and elevations, and any excess material can be removed from the roadway. When the grading and shaping operations are completed, cement is added to the pulverized mix for stabilization and then the surface course is installed to match the existing curb and gutter. One benefit of this method is that a more uniform FDR mixture is achieved when pulverized asphalt is included than when some of the existing pavement is removed prior to pulverization.

Another method for matching existing curb and gutter elevations is to mill off the existing asphalt pavement prior to pulverization to account for the thickness of the proposed surface course. If this method is used, the mix design must account for the loss of thickness of asphalt pavement that is to be milled off. If too much asphalt is milled off, the pulverized mix may result in a material that is similar to cement-treated base (CTB) instead of FDR with cement. The resulting mixture may not achieve the same strength as a mixture of similar depth containing more pulverized asphalt.

Desktop Study

After determining that FDR with cement may be a viable rehabilitation option for a roadway section, the first step in the formal project evaluation process (Figure 3.4, adapted from the California Department of Transportation 2013) is a desktop study. A desktop study includes collecting all relevant information pertaining to the existing roadway. Information to review during the desktop study includes record drawings, photo surveys, and pavement management systems.

Record Drawings – Existing Pavement Structure

During the desktop study, previous project history contained in the record drawings should be reviewed. According to ARRA (2015), information that should be obtained from the record drawings includes the following:

- Thickness of the existing asphalt pavement and underlying granular materials
- Size of aggregates used in the asphalt pavement and underlying granular materials
- Subgrade or subbase gradation and plasticity
- Presence of cobbles/boulders
- Presence of any paving fabrics or other geosynthetics in the asphalt pavement
- Presence of specialty mixtures, such as open-graded drainage layers, open-graded friction courses, and stone matrix asphalt
- Patching locations and ages along with any surface treatments
- Patching material (e.g., hot, warm, or cold mix asphalt, concrete, injection spray patching)
- Crack sealing (product types and ages)
- Age of roadway along with the type of asphalt binder used in the pavement

In addition to the items listed above, any quality assurance information that can be obtained from the original asphalt pavement and underlying base construction should be noted, such as the following:

- Asphalt binder content
- Aggregate gradation
- Soil plasticity
- Field compaction density

The consistency of the existing pavement section is an important factor in determining the appropriate FDR mix design. Since the materials throughout the reclaimed pavement section are inter-mixed, it is important to remember that the composition of the mixed materials can vary with depth and throughout the length of a roadway project. This is especially true when the roadway has been constructed in stages. Each stage may have used different base materials and layer thicknesses. Varying materials and thicknesses will influence the mix design of the proposed FDR project.

A thorough review of previous construction documents and record drawings will help the mix designer get a better understanding of the in-situ materials. Record drawings will also help the designer identify any obstacles to the FDR process that otherwise might not be discovered until construction, potentially creating a costly contract modification.

Photo Surveys

Photo surveys are an efficient method of obtaining information on existing pavement conditions, localized problem areas, and the overall project surroundings. Aerial imagery and street view images from various websites can also be beneficial. Aerial imagery can assist in identifying potential drainage issues that should be corrected prior to the FDR process.

Pavement Management Report/System

Some agencies have a pavement management system in place that helps them make decisions regarding pavement rehabilitation. Pavement management systems often assign a pavement condition index (PCI) rating to a pavement.

The PCI method was developed by the U.S. Army Corps of Engineers and is intended for use on roads and parking lot pavements. According to ASTM D6433 (Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys), the PCI provides a measure of the present condition of the pavement based on the distress observed on the surface of the pavement, which also indicates the structural integrity and surface operational condition (localized roughness and safety). It provides an objective and rational basis for determining maintenance and repair needs and priorities. Pavement condition index values range from zero for pavements that have failed to 100 for pavements in perfect condition. Pavements that are potential candidates for FDR typically fall within a PCI range of 0 to 55. Pavements with higher PCI ratings may also be considered economically

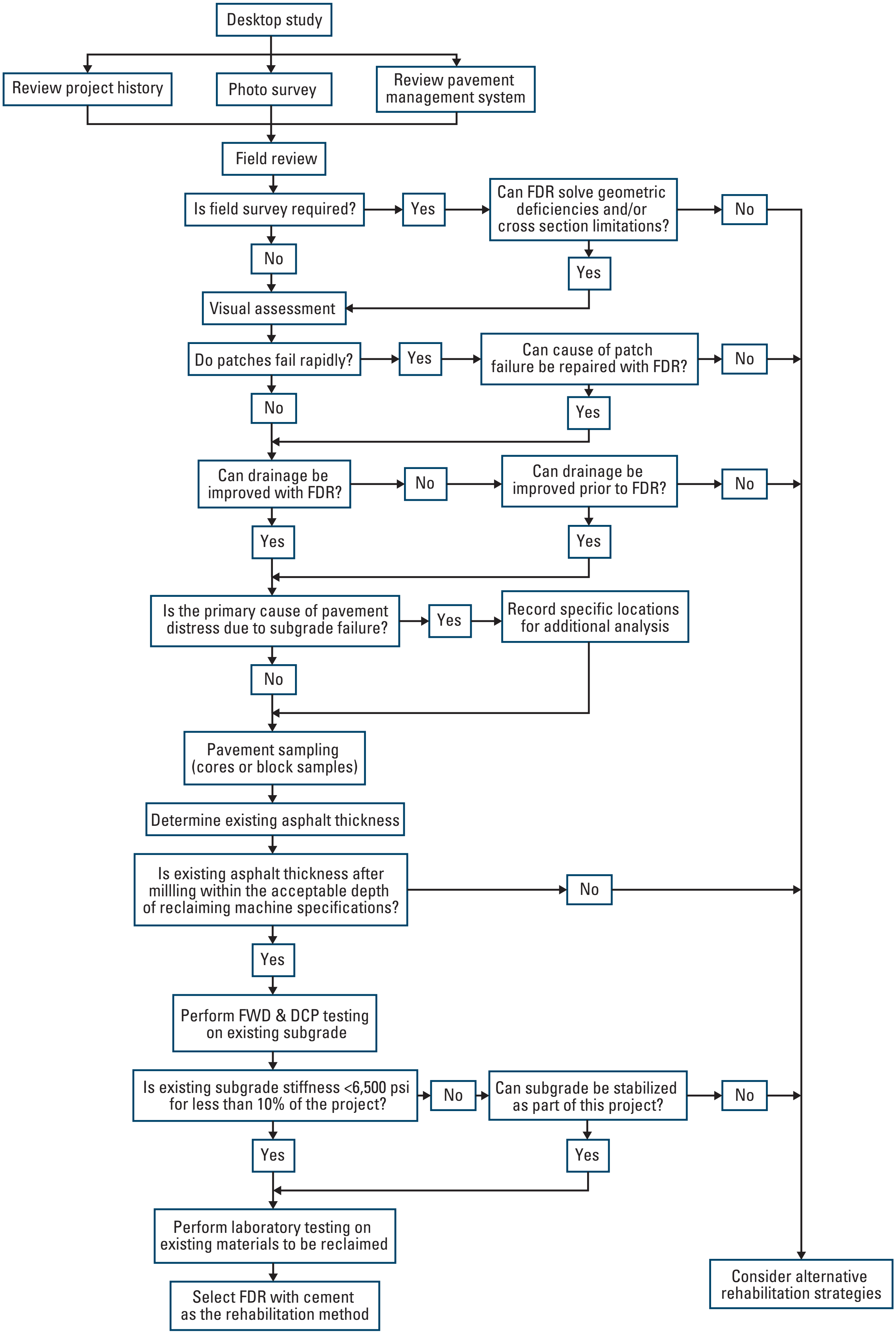


Figure 3.4. Decision tree for selecting FDR with cement as rehabilitation method

viable candidates for FDR with cement as a maintenance and repair method, depending on other site conditions and other pavement use.

If the roadway being analyzed has an updated pavement management survey, this information can be reviewed during the desktop study to provide a measure of the condition of the existing pavement. The pavement management system can also reveal any maintenance activities that have been completed on the roadway.

Field Review

The desktop study and review of pavement management systems should be completed prior to making a site visit to perform the field review. As discussed earlier, the desktop study can help identify issues that may be important to analyze in the field.

The field review should be completed as early as possible in the scoping or design phase and should be completed during a time of year when moisture is most common. Items that should be analyzed during the field review include the following:

- Drainage issues
- Depth checks of existing utilities
- Project surroundings
- Pavement conditions throughout the corridor
- Overall geometrics
- Traffic volume
- Traffic control alternatives during construction

The field review should involve a visual assessment of the roadway and material sampling of the existing asphalt pavement and underlying materials. The field review should also determine the causes of pavement failure so that these problems can be corrected during construction. During the field review, existing subsurface utilities should be analyzed and coordinated with the appropriate utility providers to proactively avoid utility conflicts during construction.

Drainage

Drainage of the roadway and adjacent areas should be reviewed during the field review stage. If the roadway is lower than the natural ground level there is the potential for drainage issues if no subdrain or other drainage systems are present. A review of culverts and storm sewer systems should also be conducted to ensure water does not pond near the proposed FDR base. Although FDR with cement is less permeable than granular or soil bases, it is not a rehabilitation method that can correct major drainage deficiencies. Any drainage corrections to the roadway should be addressed before the FDR with cement process.

Depth Checks of Existing Utilities

Existing utilities throughout the corridor should be analyzed during the field review stage to identify potential utility conflicts prior to construction. Utility companies that have facilities beneath the proposed FDR layer should be contacted to begin the utility coordination process.

Once the approximate locations of the existing utilities are identified, the depth of the utilities should be determined via potholing or other methods. If the existing utilities are within the proposed FDR depth, they should be lowered, abandoned, or moved prior to the reclaiming process (Figure 3.5).

Utility covers such as manholes, intakes, and valves should also be documented during the visual assessment. These obstructions should be lowered to at least 4 in. below the proposed FDR treatment depth, and each structure or valve should be accurately recorded. After lowering, the obstructions should be covered with a steel plate and the excavation should be backfilled with a suitable material (ARRA 2015). Once these obstructions have been backfilled, the FDR process can commence along the entire length of the project. After the FDR with cement process has been completed and the surface course has been applied, the manholes and valves will be located and raised to match the elevation of the finished surface course.

Figure 3.5. Existing utilities should be lowered before the pulverization process

Visual Assessment

The visual assessment of the proposed roadway should identify the type, quantity, and severity of pavement distress. This pavement assessment is often summarized in a value such as the PCI discussed earlier. Common asphalt pavement distresses include fatigue (alligator) cracking, block cracking, potholes, rutting, shoving, and loss of base or subgrade support. Following is additional information regarding each of these distresses.

Fatigue (Alligator) Cracking

Fatigue cracking, also referred to as alligator cracking, is a series of interconnected cracks caused by fatigue failure of the asphalt surface under repeated traffic loading. In thin pavements, cracking initiates at the bottom of the asphalt layer where the tensile stress is the highest, then propagates to the surface as one or more longitudinal cracks. However, top-down cracking can occur when high tensile stresses in the surface develop through asphalt binder aging. Fatigue is the failure of a material due to repetition of loads. The larger the load, and the thinner the asphalt, and the wetter the subbase/subgrade, the fewer number of loading cycles is needed to cause failure.

Asphalt pavement sections that are weakened during the spring thaw are more susceptible to fatigue failure at that time than they are during the rest of the year.

Low to medium severity (Figure 3.6) – An area of interconnected cracks forming a complete system; cracks may be slightly spalled; no pumping or loose pieces are evident.

High severity (Figure 3.7) – Pockets of vertical surface depressions, along with small severely spalled interconnected cracks forming a complete pattern; pieces may move when subject to traffic; when pumping is evident, the roadway profile has dropped or is irregular.

Summary of possible causes:

- Excessive loading (repetitions)
- Weak surface, base, or subgrade
- Thin surface or base
- Poor drainage
- Dried-out asphalt binder from oxidation (aging)
- Any combination of the above

Figure 3.6. Low- to medium-severity alligator cracking

Figure 3.7. High-severity alligator cracking

Block Cracking

Block cracking is a series of interconnected cracks that divide the pavement into rectangular pieces. They are typically caused by an inability of asphalt binder to expand and contract with temperature cycles because the asphalt has hardened due to binder aging or poor choice of binder in the mix design. The type of block cracking discussed here is associated with unstabilized base material.

Localized pavement surface areas with vertical drops should not be confused with block cracking. Such areas are more likely to be alligator cracks caused by poor subgrade support and fatigue fracture.

Low to medium severity (Figure 3.8) – Cracks ≤ ¾-in. wide with raveled edge

High severity (Figure 3.9) – Cracks > ¾-in. wide or adjacent to severe random cracking and/or with vertical distortion

Summary of possible causes:

- Asphalt binder aging (oxidation)
- Poor choice of asphalt binder in the mix design
- Combination of aging, poor binder and heavy loading

It should be noted that block cracking of asphalt pavement can also be caused by a cement-treated base (CTB) that is too stiff. This type of block cracking can be attributed to a higher than necessary cement content within the stabilized base. A technique called microcracking can be used to help alleviate the severity of block cracking in the treated base. Microcracking will be discussed further in Chapter 6. Block cracking of a cement-treated base can be seen in Figure 3.10.

Figure 3.8. Low- to medium-severity block cracking

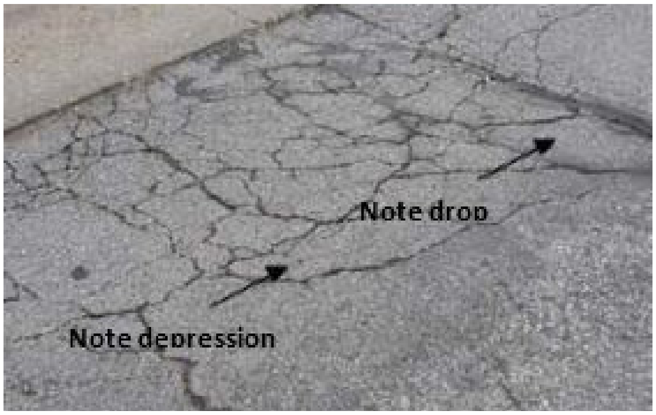


Figure 3.9. High-severity block cracking

Figure 3.10. Block cracking on a compacted CTB layer

Potholes

Potholes are small, bowl-shaped depressions in the pavement surface that penetrate all the way through the asphalt down to the subbase course. Generally, potholes are the end result of severe fatigue alligator cracking. The interconnected cracks create small chunks of pavement that can be dislodged as vehicles drive over them (popouts), eventually forming potholes. Potholes are most likely to occur with thin asphalt surfaces (1-in. to 2-in. thick) and seldom occur with 4-in. thick or deeper asphalt.

Low to medium severity (Figure 3.11) – Less than 1-in. deep for asphalt greater than 4-in. thick and covering a small and isolated area

High severity (Figure 3.12) – More than 1-in. deep and/or covering a large area

Summary of possible causes:

A possible progression of alligator fatigue cracking:

- As alligator cracking becomes severe, the interconnected cracks create small chunks of pavement, which can be dislodged as vehicles drive over them.
- The remaining hole after the pavement chunk is dislodged is called a pothole.

Figure 3.11. Low- to medium-severity pothole

Figure 3.12. High-severity pothole

Rutting

Rutting is a surface depression in a wheel path. Permanent deformation in any of a pavement's layers or subgrade is usually caused by consolidation or lateral movement of the materials due to traffic loading. Specific causes of rutting can be insufficient compaction of asphalt layers during construction, subgrade rutting, and improper mix design or compaction.

Low to medium severity (Figure 3.13) – Rutting depth ≤ 1½ in. and little or no fatigue cracking

High severity (Figure 3.14) – Rutting depth > 1½ in. with fatigue cracking

Summary of possible causes:

- Insufficient compaction of asphalt layers during construction (If the asphalt is not compacted enough initially, it may continue to densify under traffic loads.)
- Subgrade rutting (e.g., as a result of inadequate pavement structure)
- Improper mix design or manufacture (e.g., excessively high asphalt content, excessive mineral filler, insufficient amount of angular aggregate particles, or aggregate segregation)

Figure 3.13. Low- to medium-severity rutting

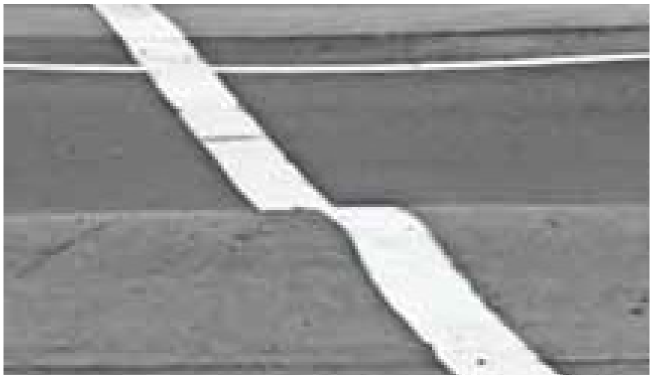


Figure 3.14. High-severity rutting

Shoving

Shoving (slippage) is a form of plastic movement typified by ripples (corrugation) or an abrupt wave (shoving) across the pavement surface. The distortion is perpendicular to the traffic direction. It usually occurs at locations where traffic starts and stops (corrugation) or where the asphalt abuts a rigid object (shoving).

Low to medium severity (Figure 3.15) – Small, localized areas

High severity (Figure 3.16) – Large areas indicative of asphalt failure

Summary of possible causes:

- Generally caused by braking or accelerating vehicles or by a poor tack coat between asphalt lifts, and is usually associated with vertical displacement.
- May be caused by an unstable (i.e., low stiffness) asphalt layer due to mix contamination, poor mix design, or lack of aeration of the liquid emulsion.

Figure 3.15. Low- to medium-severity shoving

Figure 3.16. High-severity shoving

Additional Information

Pavements also suffer from a loss of base or foundation support if distresses such as block cracking or potholes are visible. These distresses can occur due to various factors such as moisture degradation, traffic overloads, or subgrade failure.

The types of failures mentioned in this section are common on the secondary roadway system throughout the United States. Secondary roads are often underdesigned when it is difficult to estimate future traffic growth. Traditional maintenance treatments such as a thin asphalt overlay will only be temporary solutions; these distresses will typically resurface within a few years. Full-depth reclamation with cement is an economical rehabilitation method that permanently addresses these issues.

The visual assessment should also include a determination of whether pavement distresses are confined to the pavement surface and if they are caused by other issues such as structural inadequacy or poor drainage. Analyze the following items during the pre-FDR visual assessment to determine the cause of pavement distress:

- Type, severity, and extent of alligator cracking or pumping (extensive fatigue cracking and pumping of fines through the cracks usually indicate subgrade problems)
- Extent of maintenance and patching areas (the visual assessment should analyze the condition of patches relative to the service life of the maintained areas; e.g., are the patches or adjacent areas failing prematurely?)
- 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 (e.g., road shape, side drains, ditches, culverts)
- Land use immediately adjacent to the roadway (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 impacts on adjacent roadway

Sampling of Pavement System

To properly design an FDR mixture, a thorough understanding of the existing asphalt pavement and underlying soil and aggregate is necessary. To understand the types and characteristics of the materials that will be incorporated into the FDR mix, sampling of the existing roadway should be performed. Based on the review of record drawings, the project should be divided into areas of similar materials and a field sampling plan developed to ensure sampling provides a representative sample of the roadway.

The samples should be examined throughout their full depth to determine the physical properties of the proposed FDR mix. The samples should be measured, inspected, and tested for mix design purposes. In addition to the material sampling, testing of the subgrade is desirable to ensure there will be a solid foundation beneath the proposed FDR layer. Refer to Chapter 5 for more information on field sampling.

Final Determination

The selection of FDR with cement as a rehabilitation method should be carefully considered by an agency. Before making a final decision, officials should perform an economic assessment and research the environmental and scheduling considerations.

Economic Assessment

The final determination of whether FDR with cement is a viable rehabilitation method for a particular project should include an economic assessment. The economic analysis will not only consider initial costs but will also include all costs/expenses and benefits related to the roadway over the determined analysis period. The following costs and benefits should be included in the economic assessment:

- Initial construction costs
- Future maintenance/rehabilitation costs
- Salvage value (residual value and serviceable life)
- Engineering and administrative costs
- User costs where applicable (e.g., travel time, vehicle operation, crashes, discomfort, delay costs, and extra operating costs) during maintenance/rehabilitation activities

The economic assessment should identify an expected service life of the FDR with cement rehabilitation. The service life is the length of time between the initial construction of the FDR with cement base and the need for additional maintenance or reconstruction. The ARRA (2015) has indicated that FDR projects with an asphalt surface course typically have expected service lives of up to 20 years. The PCA's study of the long-term performance of FDR projects (Syed 2007) showed there was no evidence of structural failure in the FDR with cement layer itself. Typically, the service life of an FDR base is limited to the service life of the surface course and not of the FDR layer.

The expected service life of an FDR with cement roadway should be determined by each agency. The following factors will impact long-term performance (ARRA 2015):

- Local conditions
- Climate
- Traffic
- Existing materials to be reclaimed
- Adequacy of the structural design
- Quality of construction

Reduced Community Impacts

During the project evaluation stage it is important to remember that construction of FDR with cement projects has less impact on the community than traditional remove-and-replace construction methods. Typically, completed portions of the FDR base can be opened almost immediately to local car traffic as long as the curing material is not affected. This is an important benefit, especially in urban areas where residents and local businesses need access to their properties.

Public officials also recognize the reduced impacts provided by FDR with cement projects. Since FDR recycles existing materials, there is less truck traffic hauling away existing materials and importing new materials to the construction site. Not only does this improve safety and reduce energy consumption, but it has less impact on adjacent streets that may otherwise be damaged by heavy equipment during construction.

Scheduling

Scheduling of the FDR with cement process will depend on factors such as FDR depth, project surroundings, gradation, and potential alignment adjustments. Due to these factors, each project will need to be analyzed on an individual basis to develop an accurate construction schedule. Daily production rates of FDR with cement vary on average from 4,750 yd^2 to 9,500 yd^2. The contractor's experience with such projects will also play a role in the overall construction schedule.

Chapter 4

Structural Design

Pavement design using FDR for the base layer is relatively straightforward using standard design assumptions. The FDR mix design and construction practices must meet or exceed design assumptions, whether for a flexible or rigid pavement. The benefits and limitations of a bonded portland cement concrete (or simply bonded concrete) overlay on an FDR layer may be considered under specific circumstances. Note that the design methods discussed in this chapter are not meant to be all inclusive. Where proven local design procedures are available, they may also be used.

Background

Full-depth reclamation design considers FDR as a base for either a flexible or rigid pavement surface. Historically, the majority of FDR projects are designed with an HMA surface course, referred to as a flexible pavement in this chapter. The stiffness of the FDR with cement base layer contributes significantly to the structural capacity of the pavement and allows the asphalt thickness to be substantially reduced compared with an unbound aggregate base or unstabilized FDR layer. An equally viable alternative is to construct a concrete or rigid pavement using the FDR layer as a base.

The FDR base must be designed to support and address stresses, strains, and deflections required to meet environmental conditions and traffic loads distributed from the surface. Figure 4.1 (from Syed 2007) illustrates that FDR bases using portland cement can be designed to cost effectively carry heavy truck traffic.

When an FDR layer is to serve as a base for an asphalt surface, it is generally defined in terms of the resilient modulus (M_r) of the base. The FDR base contributes significantly to the structural capacity of the asphalt pavement, which allows the asphalt thickness to be reduced.

When an FDR layer is to serve as a base for a concrete surface, it is defined in terms of the composite modulus of subgrade reaction (k value). Because the concrete surface is a rigid structure and, compared to an asphalt surface, reduces loading to the base, the FDR base has distinctly less effect on the concrete surface thickness than it has on an asphalt surface thickness. The exception is when the FDR layer is considered part of the pavement thickness itself, as when the surface is a bonded concrete overlay.

The properties of the FDR layer are highly dependent on the properties of the existing asphalt pavement layer, the amount of cement added, and the thoroughness of mixing, compaction, and curing. From a design standpoint, the FDR layer can be considered as cement-treated base (CTB) in terms of its strength and deformation properties.

Figure 4.1. Well designed and constructed FDR project in South Carolina

The thickness and properties of the FDR layer are required for the design of both rigid and flexible pavement sections. The thickness of the FDR layer is generally assumed to be equivalent to the existing asphalt layer(s) and a portion of the existing base or subbase layers and may be adjusted somewhat due to changes in current and future loading conditions or grade control parameters. The FDR layer thickness usually ranges from 8 to 12 in. but may be reduced to as little as 6 in. for low-volume roads.

The thickness of the FDR layer is based on the load-carrying requirements of the rehabilitated roadway; the subgrade soil type, stability, and engineering properties; the environmental conditions; the presence of buried utilities; and the existing pavement thickness. The thickness of the FDR layer, in conjunction with its strength, has a significant impact on the required thickness of the surface layer.

The key material property of the FDR layer for design is the unconfined compressive strength, which typically ranges from 250 to 400 psi (seven-day). This value is correlated to the appropriate strength parameter for rigid pavement design (which is the k value) or for flexible pavement design (which is the M_r). The designer selects an appropriate strength for the FDR layer and, through the mix design process, the strength is adjusted to meet this requirement. Although FDR bases can be designed to higher strengths, the higher strengths may result in undesirable reflective cracking in the surface layer. It is important to remember that the design of the FDR layer should meet minimum strength and durability requirements and not have excessive strengths.

The target value for the unconfined compressive strength (UCS) used in the design of the FDR layer is determined in the laboratory and is primarily a function of the cement content and the type and gradation of the mixed materials. In actual application, the strength also depends on the efficiency of the blending process, the level of compaction, water content, and curing. The UCS can be verified by molding cylinders in the field or coring the as-built FDR layer and performing laboratory tests as a quality assurance/quality control measure.

The structural design methods that are suitable for FDR analysis range from empirical methods such as the *AASHTO Guide for the Design of Pavement Structures* (4th Edition) (commonly referred to as the 1993 AASHTO Design Guide) (AASHTO 1993) to mechanistic design methods such as the AASHTO Mechanistic-Empirical Pavement Design procedure (AASHTOware Pavement ME Design, or simply Pavement ME); the American Concrete Pavement Association (ACPA) StreetPave procedure (ACPA [no date]); and the Bonded Concrete on Asphalt–Mechanistic-Empirical procedure (BCOA-ME) (Vandenbossche 2016).

Design Considerations

The structural design of both rigid and flexible pavements has a number of user-defined inputs that can be classified as either site-related or design-related. Site inputs for FDR projects include traffic, environment, and existing pavement characteristics. Design inputs for FDR projects include existing subgrade characteristics, layer thicknesses and subbase/base material properties, and the type, thickness, and engineering properties of the desired pavement surface type (asphalt, concrete, chip seal). Note that for both site and design variables, a detailed evaluation of the existing pavement and realistic future inputs are required.

Three design methods are considered in this document based on historical use and ease of application. The 1993 AASHTO Design Guide and the StreetPave procedure are used for both flexible and unbonded rigid pavement designs, while the BCOA-ME is used for the bonded concrete design. Note that the concrete section can be designed as either a new pavement (unbonded overlay) or as bonded overlay, as discussed in the rigid pavement design section.

Site-Related Input Values

As previously mentioned, the site inputs for FDR projects include traffic, environment, and existing pavement characteristics.

Traffic Characterization

Traffic characterization is one of the most critical inputs in any pavement design. Reasonably accurate traffic counts, in terms of the number of vehicles (particularly trucks), vehicle weights, number of axles and so on, are necessary for all projects. This baseline value is increased by incorporating a traffic growth factor for the specified design period. Note that the structural design is based on the number and weights of heavy trucks and is relatively unaffected by car and light truck traffic.

The 1993 AASHTO Design Guide uses the concept of 18,000-lb equivalent single axle loads (ESALs) to characterize all traffic types. This input relates the relative damage done to the pavement by any axle configuration and vehicle weight.

Traffic counts should focus only on the number of trucks larger than two-axle, four-tired vehicles (FHWA Class 4 and above). Note that the distribution of axle weights will vary by the type of roadway; i.e., the axle weights for trucks travelling on minor arterials will exceed those on collector streets and so on. Accurate traffic counts and estimates of future traffic are critical for developing an adequate design.

Support Conditions

The soil conditions on which the FDR base is to be constructed should be thoroughly evaluated in terms of uniformity, strength, and deformation characteristics. The soil characteristics may be assessed by consulting the original pavement design assumptions, correlations to soil type, material sampling, and laboratory testing or by the use of non-destructive testing methods such as the falling weight deflectometer (FWD) or dynamic cone penetrometer (DCP). The time and expenditure devoted to soil characterization are based on the scale and importance of the project. Residential streets typically rely on soil-type correlations, but major arterials typically include sampling and laboratory testing, DCP testing, or FWD evaluations (where unstable subgrade is suspected).

Flexible pavement design is based on the M_r value of the subgrade soil. The thickness and layer properties of the pavement surface (asphalt), FDR layer, and the existing base and subbase are designed to limit the amount of stresses, strains, and deflections in the subgrade as determined by the M_r value. Weak subgrade soils and heavier traffic volumes require an overall thicker pavement structure than strong, deformation-resistant subgrades.

Rigid pavement design is based on the k value. The actual k value is determined directly by full-scale plate load tests. Due to time and expense, however, plate load tests are rarely performed, and the values used in design are based on correlations to other material parameters. Due to the manner in which rigid pavements distribute load (slab action), the composite k is a combination of the subgrade soil, FDR layer, and the existing base and subbase layers.

Unlike flexible pavements where a stronger FDR layer has a significant impact on the required thickness of the asphalt surface layer, the concrete slab thickness is only minimally affected by the strength of the FDR layer. With a rigid pavement, the primary purpose of the FDR base is to minimize erosion potential and enhance uniformity of the support.

Existing Pavement Structure

A comprehensive evaluation of the existing pavement structure is required to determine the layer thicknesses and material properties of the existing asphalt surface, base, and subbase. For highly trafficked roadways, this can be done in conjunction with the subgrade soil investigation and likely involves a limited amount of coring and laboratory materials analysis. For less critical projects, simply determining the layer thicknesses and conducting a visual assessment of the materials may suffice. The overall condition of the asphalt, aggregate gradation, and aggregate type is required in the mix design process to determine the amount of cement to be added. Checking with local and state specifications for sampling and mix design procedures is recommended.

Design-Related Input Values

Design-related variables include those inputs that are selected by the pavement designer to meet the requirements of a specific project. Decisions regarding these variables have a significant impact on pavement performance, constructability, long-term maintenance and rehabilitation requirements, initial and long-term costs, and numerous other related issues.

Design life

The design life represents the estimated time, in years, to reach a specified level of pavement distress. The design life is an important parameter, since the accumulated damage in the pavement is a function of the initial traffic volume and the specified growth rate per year. Note that the design life does not equate to failure of the pavement; it relates only to a specified level of distress. Typical design life estimates range from approximately 20 to 40 years depending on the type of roadway, traffic, and environment.

Reliability

The design reliability is a measure of how well the pavement will perform over the design life or, in other words, the factor of safety against premature failure. Reliability has a significant effect on the design thickness, particularly at very high levels (greater than 95 percent). The specified reliability should consider the traffic volume and speed, availability of alternate routes, user costs related to roadway maintenance and rehabilitation, and so on. Relatively higher levels of reliability are used for urban roadways but always depend on the roadway classification. The reliability levels used in practice range from 50 percent for low-traffic streets to 95 percent for high-volume roadways.

FDR-Related Properties

The properties of the FDR layer are project specific and depend on a number of factors including thickness of the existing asphalt layer, FDR mix design, thoroughness of mixing, compaction, and curing. It is critical that the construction practices ensure that the design assumptions are reached in terms of both strength and compacted layer thickness.

The 1993 AASHTO Design Guide equates the structural benefit of each layer comprising the pavement system (surface, base, and subbase) to a structural layer coefficient based on the M_r of the material. A higher modulus material has a proportionately higher layer coefficient. For example, an asphalt surface layer generally has a layer coefficient of approximately 0.44, while an unbound crushed stone granular base is approximately 0.11. In other words, the asphalt layer contributes approximately four times the structural benefit of an unbound aggregate layer. Although there have not been formal research studies on structural layer coefficient for FDR at certain cement contents, the widely accepted value for FDR with cement is approximately 0.20 to 0.27. See ______ (2011), in which these values ranged from 0.26 to 0.33.

For rigid pavements, the 1993 AASHTO Design Guide relies on the composite k value as previously described. The relative contribution of the FDR layer in this case will be based on the existing subgrade soil properties as well as the FDR layer properties. Generally speaking, for a given subgrade soil strength, a higher-strength base course material will result in a higher composite k value. For example, assuming that the subgrade soil has a k value of 100, a 6-in. unbound granular base will result in a composite k value of approximately 130 pci (pounds per square inch per inch of plate penetration), whereas a moderately strong 6-in. cement-treated base would result in a composite k value of approximately 240 pci or greater depending on the compressive strength. This difference in the k value has only a minor effect on the design thickness of concrete but can have a significant effect on pavement performance.

Additional Design-Related Inputs

Initial serviceability is based on the pavement condition at the time of construction and is heavily weighted towards smoothness (i.e., ride quality). The terminal serviceability is the point at which the pavement reaches a predetermined level of deterioration that requires a significant amount of rehabilitation. This value is used in the design process as the end point of pavement life.

The standard deviation in the 1993 AASHTO Design Guide is a measure of how well the data used in the development of the design equation match observed performance. These values are assumed to be 0.45 for flexible pavements and 0.35 for rigid pavements.

Pavement Design

For any given project, numerous pavement designs can meet the specified performance criteria. Selection of realistic and appropriate input values establishes a baseline from which to generate the designs. Designing the most economical pavement section requires sound engineering judgment and a thorough understanding of the interrelationship between design variables.

It is possible to optimize the design by considering the economic impact of the design-related inputs. For instance, the thickness and strength of the FDR layer will have a direct bearing on the thickness of the asphalt layer in a flexible pavement and, to a much lesser extent, the slab thickness in a rigid pavement. Optimization is used to select the most economically feasible alternative for a fixed level of pavement performance.

Flexible Pavement Design

The most appropriate flexible pavement design method when using an FDR base is the 1993 AASHTO Design Guide. The following input values were assumed for generating the structural numbers shown in Figures 4.2 and 4.3:

Initial serviceability: Assumed at 4.2 for this analysis

Terminal serviceability: Assumed at 2.0 for low-traffic roads and 2.5 for moderate to high-traffic roads

Reliability: Assumed at 80 percent for low-volume roads, 90 percent for high-volume roads

Standard deviation: 0.45

Subgrade M_r: Assumed a 3,000 to 9,000 psi, but this is a site-specific variable. (This value is based on specific soil properties including mineralogy, particle shape, gradation, moisture state, and degree of compaction and is oftentimes referenced to soil classification. The National Cooperative Highway

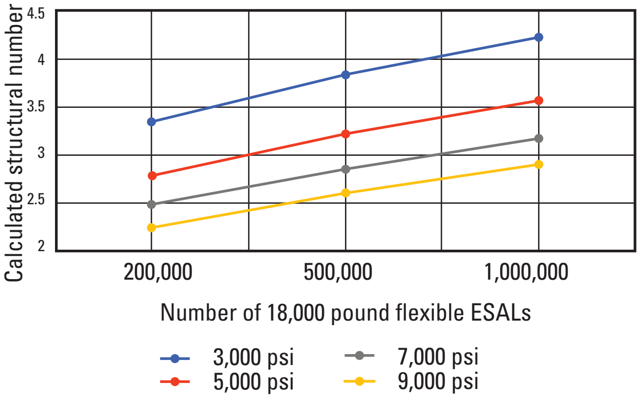


Figure 4.2. Calculated structural number for low-volume roads based on subgrade M_r

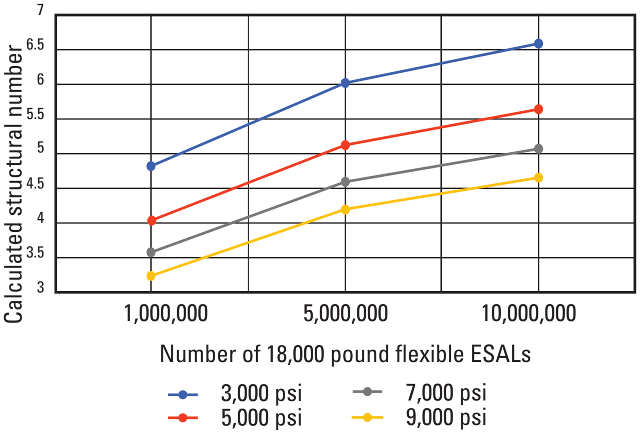


Figure 4.3. Calculated structural number for moderate volume roads based on subgrade M_r

Research Program (NCHRP) Study 01-28A (Witczak 1998) concluded that this is a non-linear relationship, unlike previous methods of estimation. Under the NCHRP 128 Guidelines, a California Bearing Ratio (CBR) of 2 corresponds to a M_r of 3,140 psi, and a CBR of 9 corresponds to a resilient modulus of 8,735 psi. Note that this value changes throughout the year in response primarily to moisture variations. An average value should be used in estimating this number for design.)

Traffic (flexible ESALs): Assumed at 200,000 to 1,000,000 for low-volume roads and 1,000,000 to 10,000,000 for moderate volume roads. (This is a site-specific variable and is an estimate of the number of 18,000 single axle loads on the road during its design life. Note that pavements are designed almost solely on the number of trucks expected over the design life, with ESALs commonly used to express this type of loading.)

Figures 4.2 and 4.3 show the structural number (SN) required for the level of traffic in terms of flexible 18,000 pound ESALs and subgrade support as determined by the M_r. These figures were generated using the latest version of the WinPAS software (ACPA 2012) based on the 1993 AASHTO Design Guide.

The 1993 AASHTO Pavement Design Guide procedure calculates a structural number (SN) based on the level of traffic (flexible ESALs) and subgrade support. This value represents the overall pavement structure required to carry the imposed traffic loads. The SN is then used to determine the required structural layers in terms of the thickness and material properties of the surface, base, and subbase layers. Note that the thickness and strength of the FDR layer is used in determining the required thickness of the AC surface.

The SN is indicative of the overall pavement structure required to carry a specific volume of traffic, as shown in the following equation:

$$SN = a_1t_1 + a_2t_2 + a_nt_n \qquad \text{(Eqn. 4.1)}$$

Where:

a_1, a_2, a_n represent the structural layer coefficient corresponding to layer 1, layer 2 and so on through layer n

t_1, t_2, t_n represent the thickness of layer 1, layer 2 and so on through layer n

The structural layer coefficient for each material is based on the M_r as referenced in the 1993 AASHTO Design Guide. The M_r of the FDR layer will vary according to the properties of the existing asphalt, cement content, and construction practices.

The M_r of a typical portland cement–treated FDR layer ranges from approximately 100,000 to 1,000,000 psi and depends primarily on the compressive strength, existing pavement materials, and construction practices. The range of unconfined compressive strengths corresponding to these values is generally in the range of 250 to 600 psi or higher at seven days. The majority of FDR layers are typically designed at less than 400 psi unconfined compressive strength for economy and to minimize the risk of reflective cracking in the as-designed new pavement surface layer.

The relationship between the M_r, unconfined compressive strength, and structural layer coefficients of cement-treated FDR layers has been evaluated in a number of studies. However, there is currently no definitive relationship that establishes these correlations, although trends in existing data suggest that a reasonable value for layer coefficients ranges from approximately 0.20 to 0.27. Figure 4.4 shows the relationship established by Scullion et al. (2012) for soil-cement bases relating the M_r and the unconfined compressive strength of a soil-cement layer. Resilient modulus in ksi = 36.6 times the square root of UCS. These values are thought to be the best approximation currently available relating these variables.

For a moderately strong FDR layer with an M_r of 730,000 psi and an unconfined compressive strength (UCS) of approximately 400 psi, a corresponding layer coefficient of approximately 0.26 is suggested. This corresponds to the value used by the South Carolina Department of Highways and Public Transportation (2008) for a cement-treated recycled base material. It is also in line with the 0.22 used by the Indiana Department of Transportation (Nantung et al. 2010) for an asphalt-bound FDR layer. Note that for a low strength FDR layer with a M_r of 516,000 psi and a UCS of approximately 200 psi, a layer coefficient of approximately 0.20 is suggested. Care should be exercised when selecting a structural coefficient within the boundaries shown, as these values are somewhat subjective based on the FDR mix design and material properties.

Figure 4.5 (Christopher et al. 2006) represents various means to characterize the layers underlying the FDR layer. In other words, these values are required to estimate the structural layer coefficients of the existing base and/or subbase that are not altered during the FDR process.

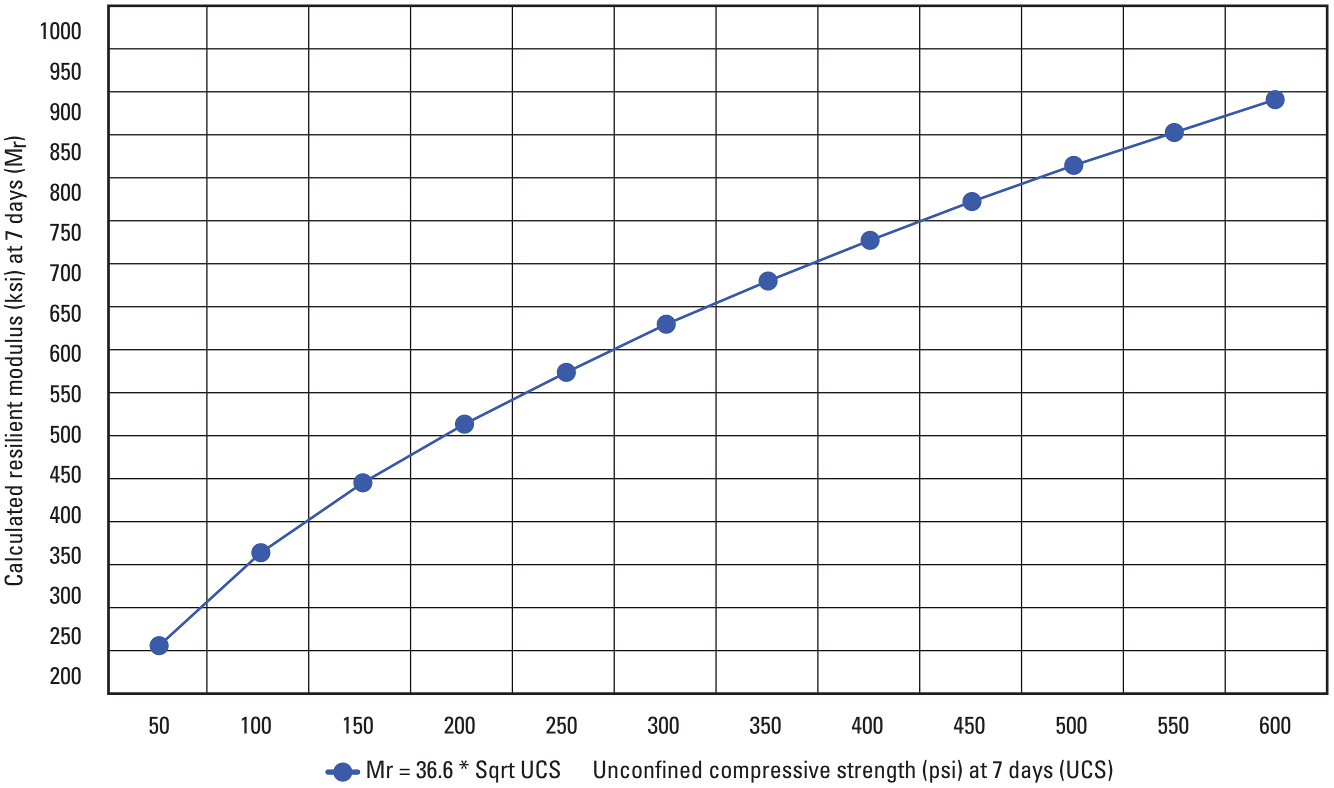
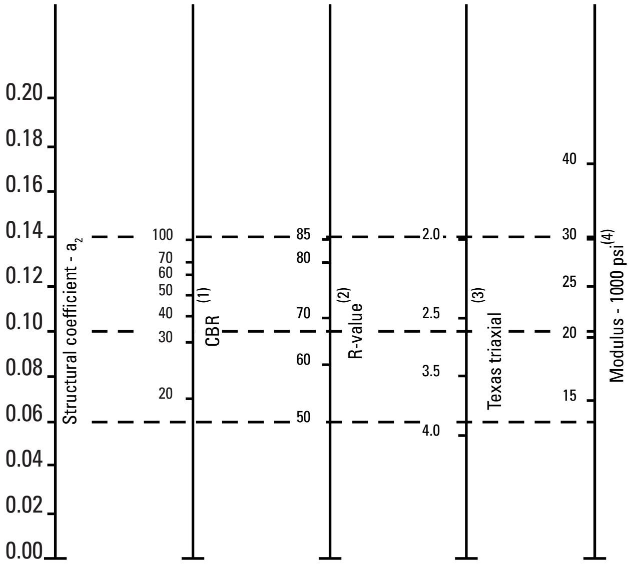


Figure 4.4. Relationship between unconfined compressive strength and M_r of FDR



(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico, and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project *(3)*.

Figure 4.5. Structural layer coefficients based on M_r values for unbound granular bases (under the FDR layer)

Following is an example of calculations for flexible pavement design:

Full-depth reclamation has been determined the most feasible option for an existing asphalt road with moderate traffic. Soil tests have confirmed that the M_r of the subgrade soil is approximately 3,000 psi. Projected traffic for the next 15 years has been estimated at 3,000,000 flexible 18,000-lb ESALs. During the pavement evaluation process, it was determined that the existing asphalt surface is 4 in. thick over 6 in. of unbound granular base material with an M_r of 25,000 psi and 6 in. of granular subbase with an M_r of 21,000 psi. Three design variables must be considered: the thickness of the new asphalt surface and the thickness and strength of the FDR layer.

Based on Figure 4.3, a structural number of 5.6 will be required. Note that interpolation is permitted for the data ranges shown. Based on an evaluation of the materials comprising the existing pavement, the base has a structural layer coefficient of approximately 0.12 and the subbase approximately 0.10 based on Figure 4.5. Assuming that a moderately strong FDR layer will be used with a resilient modulus of 730,000 psi, the corresponding layer coefficient is assumed to be 0.26. It has been determined that due to the existing pavement condition the FDR layer will be 8 in. thick, incorporating both the existing asphalt surface and part of the existing base material. The new asphalt surface layer is generally assigned a layer coefficient of 0.44, and the structural number equation is then used to calculate the required thickness of the asphalt surface (t_1):

$$5.6= 0.44\ (t_1) + 0.26\ (8) + 0.12\ (2) + 0.10\ (6) \qquad \text{(Eqn. 4.2)}$$

Note that the remaining base thickness of 2 in. and the subbase must be considered, since they contribute to the structure of the pavement after the FDR is constructed.

Therefore, the required thickness of the new asphalt surface (t_1) is approximately 6.1 in. Design optimization can be performed by varying the modulus and thickness of the FDR layer and balancing the cost of the FDR layer versus the required asphalt thickness and cost.

Rigid Pavement Design

Rigid pavement design methods applicable to FDR design include the 1993 AASHTO Design Guide and ACPA's StreetPave software. The differences between these methods is substantial, the former generally regarded as over-designing the required thickness of the concrete slab. Note that the thickness and strength of the FDR layer is used in determining the overall support conditions (composite k value) and therefore the required slab thickness. As stated previously, unlike asphalt pavements, the strength of the support conditions is not as critical to performance as the uniformity of support.

1993 AASHTO Design Guide

The following input values were assumed for generating the required slab thicknesses shown in Figures 4.6 and 4.7.

Initial serviceability: Assumed at 4.2 for this analysis and representing a well- constructed concrete pavement

Terminal serviceability: Assumed at 2.0 for low-traffic roads and 2.5 for moderate to high-traffic roads

Reliability: Assumed at 80 percent for low-volume roads and 90 percent for high-volume roads

Standard deviation: 0.35

Composite k value: The composite k value is comprised of the subgrade, subbase, base, and the FDR layer and can be determined using the ACPA k-value calculator that can be accessed using the following link: http://apps.acpa.org/applibrary/KValue/.

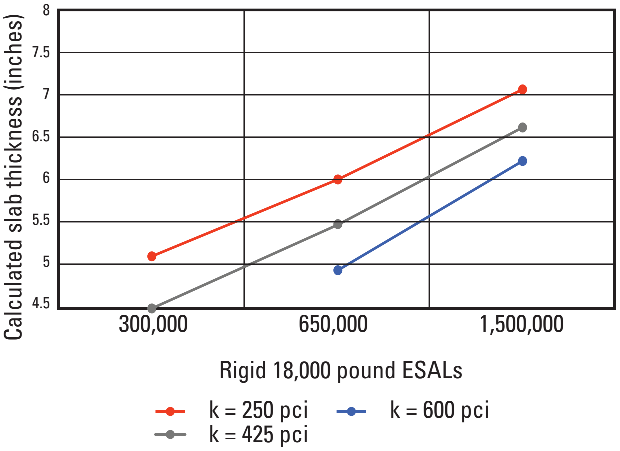


Figure 4.6. Calculated slab thickness for low-volume roads, concrete flexural strength = 650 psi

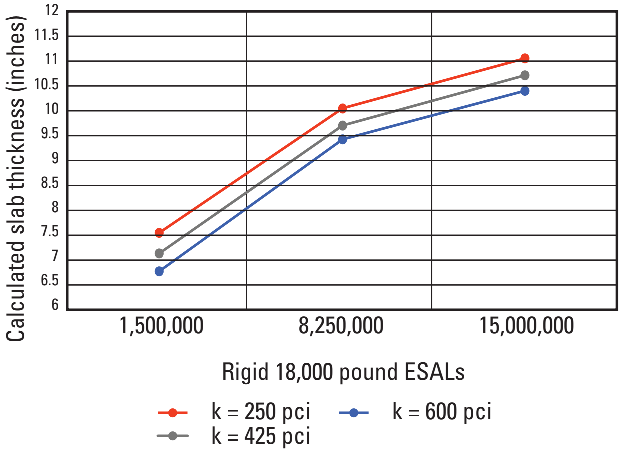


Figure 4.7. Calculated slab thickness for moderate volume roads, concrete flexural strength = 650 psi

In lieu of using the ACPA k-value calculator, Figures 4.8 through 4.11 may be used to estimate the composite k-value. To use these graphs, the subgrade M_r must be estimated or determined through testing. The graphs are based on a subgrade M_r value of 3,000, 5,000, 7,000, or 9,000 psi, respectively. After selection of the appropriate graph, the M_r of the FDR layer is assumed to be 100,000, 500,000, or 1,000,000 psi, and the FDR thickness from 8 through 12 in. After selection of the appropriate input values, the composite k-value is estimated. Note that interpolation is allowed in both the subgrade M_r and FDR layer M_r. The contribution of the remaining base and/or subbase materials after construction of the FDR layer is not considered but does not contribute significantly to the composite k value.

Note that interpolation is allowed in the previous four figures.

Traffic (rigid ESALs): According to the documentation found in the 1993 AASHTO Design Guide, rigid ESALs are approximately 1.5 as great as the corresponding flexible ESALs for the same level of traffic. Therefore, rigid ESALs are assumed at 300,000 to 1,500,000 for low-volume roads and 1,500,000 to 15,000,000 for moderate volume roads. Note that this is a site-specific variable and has an accompanying change in the specified level of reliability.

Concrete strength characteristics: The flexural strength is project specific but assumed to be 650 psi for this analysis along with a correlated modulus of elasticity. Note that the required pavement thickness may be reduced somewhat by the use of a higher concrete flexural strength.

Drainage coefficient: Assumed at 1.0 and is a measure of the overall drainability of the pavement structure. Note that a value of 1.0 means that it is neutral and does not affect the calculated design thicknesses.

Load transfer coefficient: Assumed at 3.6 in all cases and selected corresponding to the level of traffic and aggregate interlock load transfer.

Following is a sample thickness calculation using the 1993 AASHTO Design Guide:

Full-depth reclamation has been determined the most feasible option for an existing asphalt road with moderate traffic. A comprehensive pavement evaluation has confirmed that the existing structure consists of clay subgrade soil (M_r = 3,000 psi), a 6-in. unbound subbase layer (M_r = 21,000 psi), a 6-in. unbound granular base (M_r = 25,000 psi), and a 4-in. asphalt surface. Projected traffic for the next 15 years has been estimated at 4,500,000 rigid 18,000-lb ESALs.

Due to the initial pavement evaluation results, it has been determined that the FDR layer will be 8-in. thick with a corresponding M_r of 730,000 psi. Note that this value will rely on the mix design process to determine the required percentage of cement to be added. Therefore, the corresponding composite k value is 390 pci, according to Figure 4.8.

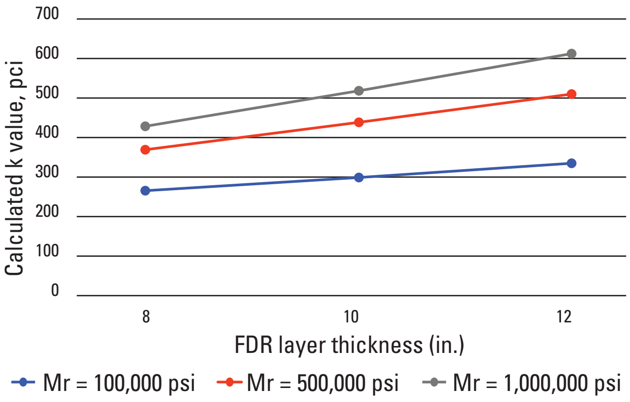


Figure 4.8. Composite k values, subgrade M_r = 3,000 psi

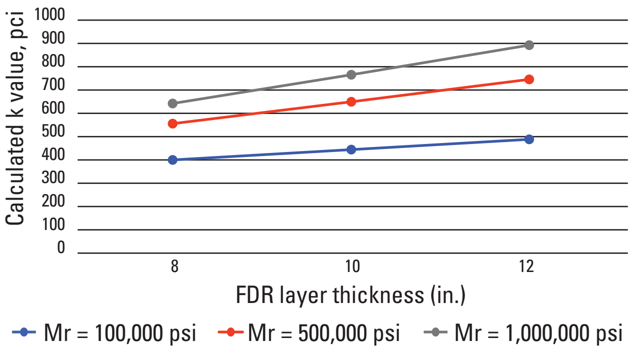


Figure 4.9. Composite k values, subgrade M_r = 5,000 psi

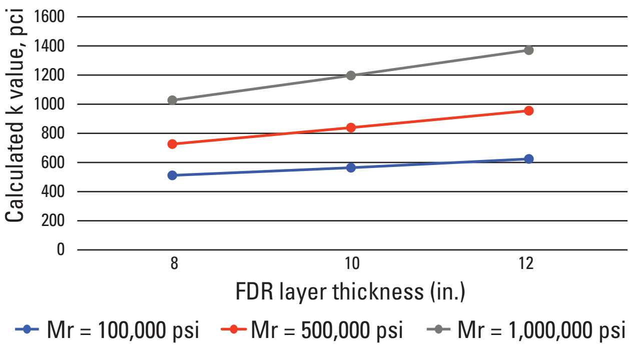


Figure 4.10. Composite k values, subgrade M_r = 7,000 psi

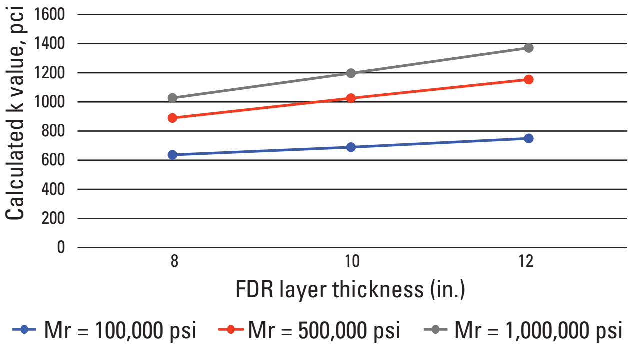


Figure 4.11. Composite k values, subgrade M_r = 9,000 psi

The required pavement thickness is then determined by consulting Figure 4.7, which shows that 8.5 in. of slab thickness is required. Design optimization must consider the concrete strength and the FDR modulus and thickness.

StreetPave Design Procedure

The StreetPave procedure uses many of the same input values as previously discussed but uses a mechanistic/empirical approach to calculate the design thickness. This mechanistic/empirical design approach is based on calculating the stresses and strains within the pavement as a result of applied loads and then relating those to empirical data that estimate cracking and erosion (faulting). This design method has a number of advantages over the strictly empirical approach of the 1993 AASHTO Design Guide.

The primary difference in input values is the method of traffic characterization. StreetPave uses traffic load spectra to determine the effect of each type and number of applied loads. Fortunately, for purposes of comparison, the program also calculates the number of 18,000-lb rigid ESALs, as previously discussed.

Figures 4.12 and 4.13 were generated using identical input values as Figure 4.6 for low-traffic roads and as Figure 4.7 for moderate traffic roads, where applicable. However, since the traffic characterization differs between 1993 AASHTO Design Guide and StreetPave, these values were adjusted to arrive at the appropriate ESAL values for comparison.

Note that the values shown in Figures 4.12 and 4.13 are for pavements without dowels. For thicknesses greater than or equal to 8 in., dowels are recommended, effectively reducing the required slab thickness below the values indicated.

Based on the inputs used in the preceding example for the 1993 AASHTO Design Guide, the required pavement thickness using StreetPave is approximately 7.5 inches (Figure 4.13).

Alternate Pavement Design Assuming Bonding Between the Slab and FDR Layer

The 1993 AASHTO Design Guide and StreetPave design procedures for new pavements discussed above assume no bonding between the concrete slab and the FDR layer. In these examples, the FDR layer simply acts as a strong base layer underlying the new concrete pavement. If a bonded condition is assumed between the FDR layer and the concrete slab, however, the design essentially becomes a bonded concrete overlay, and the required slab thickness is reduced. The required thickness is reduced because, with a bonded concrete overlay, the concrete surface course and the FDR layer behave together as one monolithic structure.

With a bonded concrete overlay, a long-term bond between the FDR base and the concrete slab is required. Therefore, care should be used in adopting the following procedure to determine slab thickness. There are only a few cases in the United States in which a bonded concrete overlay of an FDR layer has been successfully designed and constructed. The most notable and well documented bonded concrete overlay of an FDR layer was successfully completed in 2003 in Sheridan, Wyoming, and remains in good condition as of the most recent survey in 2016 (Figure 4.14).

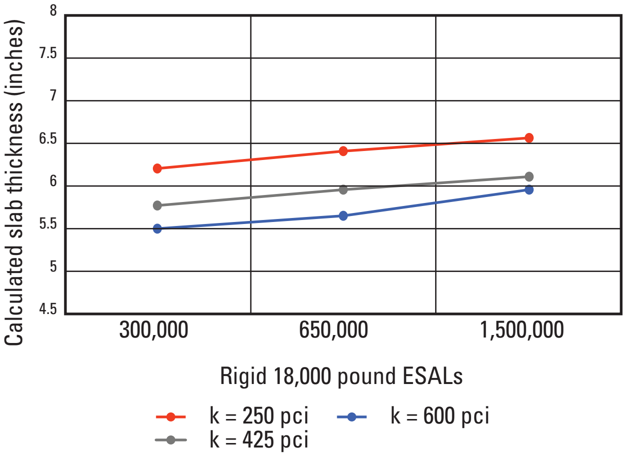


Figure 4.12. Calculated slab thickness for low-volume roads, concrete flexural strength = 650 psi

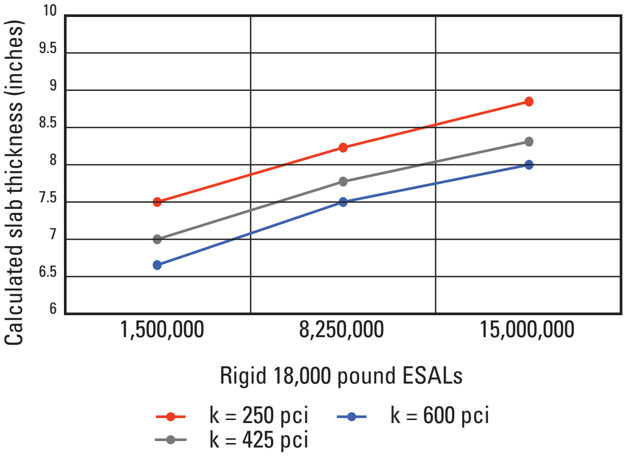


Figure 4.13. Calculated slab thickness for moderate volume roads, concrete flexural strength = 650 psi

Figure 4.14. Bonded concrete overlay of FDR layer

If the new pavement is designed as a bonded concrete overlay system, failure to achieve an adequate bond between the concrete and FDR layers will result in premature pavement failure. Before a bonded concrete overlay of an FDR layer is considered, a thorough knowledge of the process and potential shortfalls needs to be well understood.

The key to achieving a long-term bond is to ensure that the FDR surface is relatively dense and free from loose aggregate particles, dust, or other contamination. Figure 4.15 shows a properly constructed and prepared FDR surface suitable for placement of a bonded concrete overlay. Refer to Chapter 6 for additional details on the construction process.

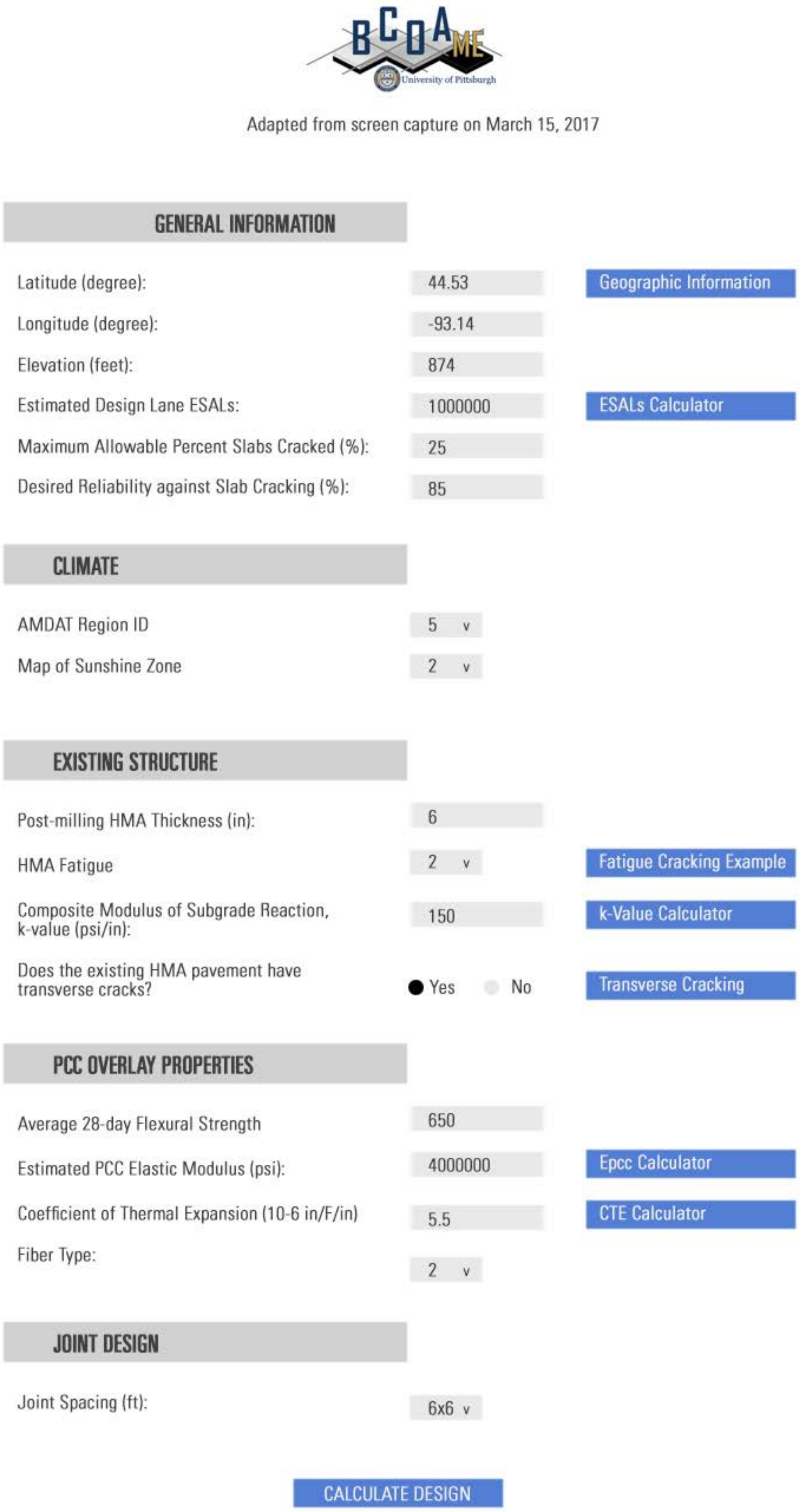
Figure 4.15. Properly prepared FDR surface for a bonded concrete overlay

The approach used in calculating the required slab thickness, assuming that bonding is achieved during and after construction, is basically the same approach used for thin bonded overlays of an asphalt pavement. There are no current design methodologies that are directly applicable to this type of pavement structure, although the BCOA-ME method provides a good approximation.

To illustrate the effects of an assumed bond, BCOA-ME (Vandenbossche 2016) was used to calculate the required thickness of a concrete slab using the same level of traffic, support conditions, concrete properties, and FDR properties as the previous rigid pavement design example using the 1993 AASHTO Design Guide. The joint spacing was assumed at 6 ft by 6 ft, and the location as Champaign, Illinois. (Location is a parameter in M-E design due to environmental effects on performance.)

The reproduction of a sample screen capture on the following page (Figure 4.16, from Vandenbossche 2016) shows the input values assumed in the analysis as well as the calculated design thickness. Note that the thickness of the FDR layer was assumed to be equivalent to the residual asphalt thickness after milling required in the design procedure. Since no provision exists in the program to input the M_r of the existing asphalt layer, the FDR layer is assumed to have approximately the same characteristics in terms of M_r (730,000 psi in this case).

Based on these assumptions, the required slab thickness is 4.5 in. Because the FDR layer stiffness (M_r) approximates that of an asphalt layer, the possibility of reflective cracking exists. The effects of reflective cracking may be minimized by using synthetic fibers in the concrete overlay and following proper jointing practices. Note that the addition of low-modulus synthetic fibers may not necessarily reduce the required overlay thickness, as shown in the BCOA analysis. However, the fibers are still advantageous in increasing load transfer at reflective cracks and adding a measure of fracture toughness.



Adapted from screen capture on March 15, 2017

GENERAL INFORMATION

Latitude (degree): 44.53
Longitude (degree): -93.14
Elevation (feet): 874
Estimated Design Lane ESALs: 1000000
Maximum Allowable Percent Slabs Cracked (%): 25
Desired Reliability against Slab Cracking (%): 85

CLIMATE

AMDAT Region ID: 5
Map of Sunshine Zone: 2

EXISTING STRUCTURE

Post-milling HMA Thickness (in): 6
HMA Fatigue: 2
Composite Modulus of Subgrade Reaction, k-value (psi/in): 150
Does the existing HMA pavement have transverse cracks? ● Yes ○ No

PCC OVERLAY PROPERTIES

Average 28-day Flexural Strength: 650
Estimated PCC Elastic Modulus (psi): 4000000
Coefficient of Thermal Expansion (10-6 in/F/in): 5.5
Fiber Type: 2

JOINT DESIGN

Joint Spacing (ft): 6x6

Figure 4.16. Sample BCOA input values and calculated design thickness

Joint Spacing

Transverse joints are either contraction or construction joints placed in concrete pavements to control random cracks. Joint spacing is an important performance parameter and should be carefully considered in pavement design to minimize curling and warping stresses in the slab as well as stresses due to restrained thermal movement and drying shrinkage.

As shown in Table 4.1, maximum joint spacing is based on slab thickness calculations as recommended by StreetPave software (ACPA [no date]). Pavement performance may be enhanced by reducing the joint spacing. However, the required calculations are outside the scope of this document.

Table 4.1. Maximum Recommended Transverse Joint Spacing

Slab thickness (in.)	Maximum recommended joint spacing (ft)
5.5	11
6.0	12
6.5	13
7.0	14
7.5	15
8.0	15
8.5	15
9.0	15
9.5	15
10.0	15

Chapter 5

Field Sampling and Mix Design

The correct proportioning of materials is important to the production and quality of FDR mixes. The mix design process should be a scientific and systematic approach that balances the existing and desired engineering properties, constructability, durability, and economics. Figure 5.1 illustrates the general steps in determining the mix design for the FDR layer. Note that the mix design guidelines in this chapter are not intended to be used as specifications for an agency or a specific project. Rather, these guidelines can assist in developing a framework for an agency or project-specific need. Contact the Portland Cement Association with specific questions or for additional information.

The FDR mix design process includes sampling the existing roadway to determine the thickness of the existing asphalt and aggregate base and subbase and classifying the types of materials that will be incorporated into the FDR layer. The sampled material is tested in a laboratory where an appropriate cement content, optimum moisture content, and maximum density are determined to achieve the desired strength and durability for long-term performance.

One element that can affect the overall FDR mix design is the amount of the subbase and/or subgrade that will be incorporated in the FDR layer. This could include underlying soils mixed with the asphalt pavement during the reclamation process. It is important to understand how the physical and chemical properties of these soils can impact the mix design. Chemical properties such as sulfate content, pH, and organic content can affect hydration. Physical properties including gradation and plasticity index have a direct influence on the cement content. This chapter discusses the importance of testing for these properties and their impact on the mix design.

Local experience, engineering judgment, and consideration of the needed design reliability should dictate the level of mix design rigor. Local knowledge about the current pavement's performance can be a guide to determining the thoroughness of material testing required during the mix design process. If the design team has knowledge and/or experience with FDR projects and is familiar with the soils in the project area, some of the steps discussed in this chapter may not be necessary. However, if the design team does not have prior knowledge and/or experience with FDR projects or is unfamiliar with the soils in the project area, it is recommended that all the steps for proper FDR mix design outlined in this chapter be followed.

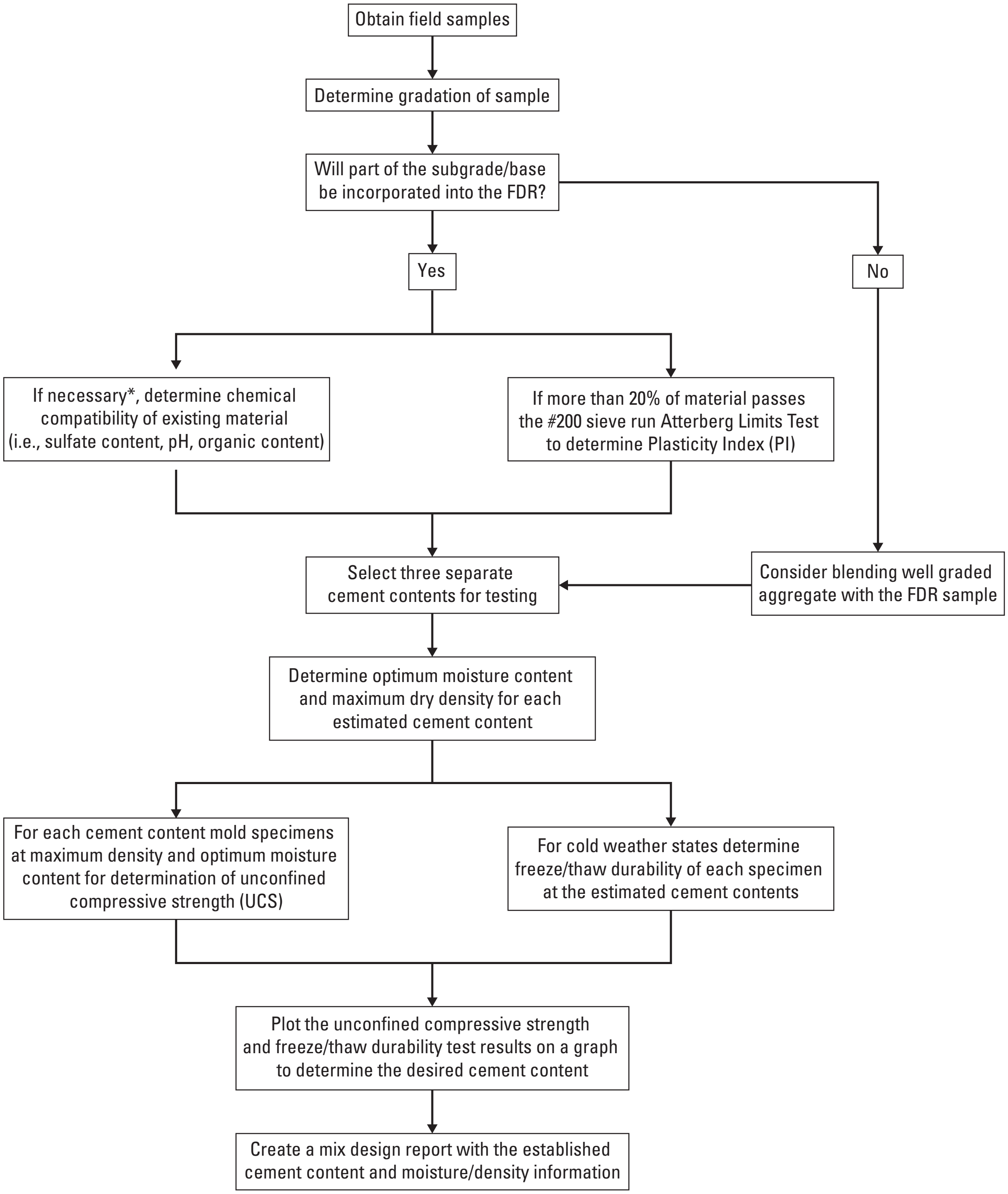
The mix design should account for variances in material types and thicknesses throughout the length of the roadway to be reclaimed. It is recommended that the mix design be changed when the material types and thicknesses significantly change. Thorough sampling of the existing roadway will assist in determining if multiple mix designs are required over the length of the project. Adequate sampling of the roadway is important to ensure a successful mix design.

Obtain Field Samples

The first step in a successful FDR project is a complete and thorough understanding of the materials that make up the existing roadway to be reclaimed. Samples of the existing roadway must be obtained to fully understand the composition of the failed pavement section that will be incorporated into the FDR layer. The samples should not only identify the thickness of the existing asphalt but should also include the underlying subbase and subgrade materials within the proposed depth of reclamation.

During field sampling operations, the sampling team should make visual observations of the existing roadway to determine if areas of major distress, such as excessive patching or severely rutted areas, warrant additional material samples, particularly if the subgrade/subbase is considered to be wet or unstable. If the project evaluation determines that material types and/or thicknesses change throughout the roadway, samples should be taken at each varying material location. All material samples should be kept separate with their locations recorded in a coring log. If sample gradation and material type vary significantly along the project length, several mix designs may be required. To prevent this, engineering judgment should be used to determine the representative case. It is up to the engineer to understand the worst case condition and make a decision on how to handle the situation.

It is recommended that samples be obtained at varying offsets along the roadway alignment. Samples can be taken at the pavement edge, between wheel paths, and near the centerline to get a thorough representation of the roadway. If paved shoulders are to be reclaimed, samples should be taken from the shoulders as well. It is recommended that approximately 350 pounds of material be obtained for each mix design. Each layer of each sample should be analyzed to determine the thickness of all roadway materials at that location.



*Local conditions or past experience will help determine whether testing for chemical compatibility is necessary.

Figure 5.1. General steps for determining mix design for FDR layer

If the surface of the existing roadway is to be milled prior to FDR, the anticipated milled amount of asphalt should not be included in the final sample used in the mix design. For example, if the project calls for milling and removing 1.5 in. of existing asphalt, then the top 1.5 in. of asphalt should not be included in the mix design sample. It is very important to determine the mix design using actual field conditions that are expected during construction, including an accurate amount of asphalt that is to be reclaimed. If additional material such as corrective aggregate (natural aggregate, RAP, or recycled concrete aggregate (RCA)) will be added during FDR operations, the same amount of corrective aggregate should be added to the material samples for mix design purposes.

After sampling has been completed, it is recommended that the sample holes be filled with a cold mix patch or mortar. The cold mix or mortar should be adequately consolidated so that it is flush with the adjacent pavement surface and provides a smooth ride for the traveling public.

A variety of methods can be used to obtain material samples. Examples of these methods include core or auger sampling, block samples, or a combination of these methods.

Core or Auger Sampling

Core sampling is a simple and cost-effective sampling method for FDR projects (Figure 5.2). Each core should be measured to the nearest ¼-in. Cores are typically cut with a 6-in. diameter bit, and the holes can be filled with cold mix patch or mortar.

Auger sampling (Figure 5.3) utilizes a specialized drill bit or a small mill head attached to a skid steer that replicates the pulverization that will be done by the reclaiming equipment during construction. Auger sampling can be accomplished using a spade bit or a finger bit attached to an auger on a skid steer. An auger with a finger bit is commonly used, as it can churn out the material in a gradation that will be similar to a pulverized material. The benefit of using an auger with a finger bit is that it does not create a large core hole in the existing roadway and, due to a smaller patch size, allows traffic on the road sooner. Auger sampling is typically the preferred sampling method for FDR.

The core or auger samples should be obtained to a depth of 6 in. below the anticipated bottom of the FDR layer at each sample location, as the FDR thickness may be adjusted based on the material gradation. The aggregate subbase and subgrade soil to be included in the FDR layer should be stored in a sealed container to allow for accurate moisture content measurement. The 6-in. of material below the proposed FDR layer should be stored in a separate sealed container with the appropriate measurements and sampling location recorded. This material will be used for soil classification purposes. Using a device such as a bent spoon or hand auger is recommended to prevent asphalt or soil from contaminating the base material sample. It is also important to keep the sample edges as vertical as possible to obtain an accurate ratio of the different materials.

Figure 5.2. Core sampling

Figure 5.3. Auger sampling

Block Samples

Block sampling is completed by saw-cutting and excavating a block of the existing pavement and the underlying subbase and subgrade materials. This method of sampling provides a larger and more representative sample of the existing pavement system. The downside of block sampling is that it is more labor intensive and has a significant impact on traffic. It also results in fewer samples being taken from the roadway, so variability in pavement and base thickness or materials are not determined with this sampling method. The blocks are large and heavy, and equipment is usually required to lift and transport the samples to the laboratory. The size of the temporary patches at the sampling locations can result in maintenance and safety issues until the rehabilitation process begins.

Block samples should also be obtained to a depth of 6-in. below the anticipated bottom of the FDR layer at each sample location, as the FDR layer thickness may be adjusted based on the material gradation. This material will be stored separately, with the sampling location recorded for soil classification purposes.

Frequency of Sampling

The frequency of sampling is important. Sufficient samples should be obtained to provide a truly representative sample of the entire pavement to be reclaimed. This includes, but is not limited to, samples within and between wheel paths, at pavement edges, and near lane lines. When possible, the existing roadway should be sampled with a staggered approach as detailed in Figure 5.4 (ARRA 2015 [draft]). On higher volume roads, this may require extensive traffic control.

In accordance with Figure 5.4, the ARRA's recommended rates of sampling for each value (L [offset distance in the adjacent lane] and D [prescribed sampling rate]) are listed as follows:

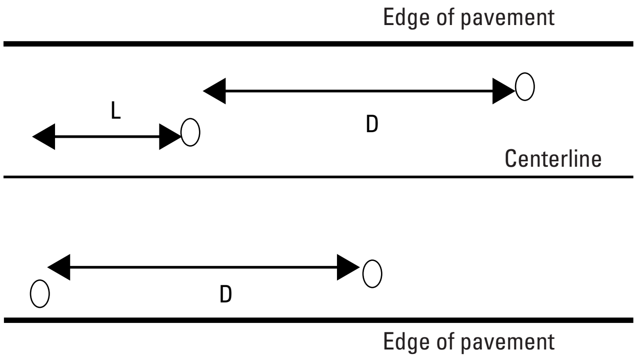


Figure 5.4. Staggered sampling diagram (Note: Typically L=D/2)

Highways and airports

- D – 1.0 mi maximum
- L – 0.5 mi maximum
- At least 15 percent of sampling shall be in the shoulder if the shoulder is getting recycled
- At least 25 percent of sampling shall be on or within 3 ft of centerline.

Arterial and industrial streets

- D – 2,000 ft maximum
- L – 1,000 ft maximum
- At least 25 percent of sampling shall be in the shoulder if it is getting recycled or within 3 ft of gutter
- At least 25 percent of sampling shall be on or within 3 ft of centerline

Residential streets

- Streets less than 250 ft long, two cores (to determine consistency) when grouped with other streets to obtain the quantity of material required for mix design
- Streets 250 to 500 ft long, two samples when grouped with other streets to obtain the quantity of material required for mix design; one within 3 ft of gutter, the other within 3 ft of centerline
- Streets over 500 ft long, three samples when grouped with other streets to obtain the quantity of material required for mix design; one within 3 ft of gutter, one within 3 ft of centerline, the third between the two

The sampling rates listed above are recommended rates. Each project should be analyzed on an individual basis to determine if the frequency of sampling should be increased or decreased. As mentioned earlier, samples should be obtained at locations where thickness and/or material types change within the proposed project limits. A separate mix design may be necessary for different segments of a roadway if materials vary.

Subgrade/Subbase Foundation

Testing of the subgrade/subbase is desirable to ensure there will be a solid foundation beneath the proposed FDR layer. If the soil beneath the reclaimed material is soft with a low bearing capacity, adequate compaction of the FDR layer will be difficult to achieve. If records of the original geotechnical investigation and construction are unavailable or if the pavement shows consistent signs of high-severity base or subgrade deformation, then investigation of the subgrade support conditions beneath the proposed FDR layer should be conducted. However, if the existing pavement has performed according to expectations and is in need of reclamation due to some combination of excessively deferred maintenance or growth of traffic volumes beyond the original design, then a detailed investigation may not be warranted.

A dynamic cone penetrometer (DCP) can be used to determine the in-situ strength of the subgrade that will ultimately support the FDR layer. This test should be run in accordance with ASTM D6951 (Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications). The DCP test (Figure 5.5, from Guthrie et al. 2005) can be performed concurrently with the sampling operations; it can be performed at the bottom of the sampling cavity prior to backfilling the sample locations. The DCP test will assist in measuring the strength of the soil that will be directly under the FDR layer, an important factor in ensuring that there is a solid base against which to compact the FDR layer. The DCP results can be correlated to the M_r, which is an indication of strength. A falling weight deflectometer (FWD) can also be used to determine the subgrade support conditions.

Evaluation of the subgrade includes identifying weak areas that will require additional strengthening. The subgrade should be able to withstand construction traffic during the FDR process and should have sufficient strength to limit excessive deflection. Deflecting subgrades will require improvement or stabilization to ensure that adequate compaction of the reclaimed mixture can be achieved.

The soil underneath the FDR layer will have a direct impact on the compaction of the pulverized mix and quality control testing. If the soil under the FDR mix is soft, it will be difficult to achieve the desired level of compaction, especially if rutting is present due to construction equipment. Soft soil beneath the FDR layer will also cause premature failure of the reclaimed base, and rutting may develop under wheel paths over time. Thicker layers of FDR can bridge some weaker underlying soil; however, severe cases of weak underlying soil may require spot removal or chemical stabilization of the undesirable material.

The process used to correct deep subgrade issues requires several steps. The first step is to move the reclaimed material to one side of the roadway. The subgrade is then treated with a small amount of cement (two to four percent by weight) in order to provide a stable foundation for the FDR base. Treating the unstable subgrade with cement (cement-modified soil) helps to reduce plasticity and high volume change characteristics of clay soils due to moisture variations. Silty soils are also subject to moisture changes and are more frost susceptible than sandy or clay soils. Depths of treatment will vary but are typically 6 in. to 18 in. After the subgrade has been improved, the reclaimed material is evenly spread back on the prepared subgrade before adding cement and water to finish the FDR process. This approach addresses more severe subgrade issues and is more costly than typical FDR projects. However, it is often the most cost-effective and time-saving solution. Further discussion of construction techniques are discussed in Chapter 6.

Figure 5.5. Dynamic cone penetrometer test

Determine Gradation of Sample

After the samples have been obtained and delivered to the laboratory, the materials will need to be blended in a manner that will replicate the reclaiming operations during construction. A laboratory milling machine or laboratory crusher can be used to model the anticipated homogenous mix that the reclaimer will produce. The recycled asphalt pavement (RAP) will be combined with the appropriate proportions of underlying subbase and subgrade materials and any added material.

A washed gradation (AASHTO T 11 and T 27 or ASTM C117 and C136) of the combined material should be performed. The PCA's Guide to Full-Depth Reclamation (FDR) with Cement (Luhr et al. 2014) recommends the combined gradation for the FDR mix should meet the requirements in Table 5.1.

A well graded mixture is critical to ensure the FDR layer will be strong and durable with the minimum amount of cement. A poorly graded material (gap graded) that is dominated by two to three sizes or has a high fines content will most likely require a higher cement content.

Full-depth reclamation relies on fine aggregate and nonplastic fines being mixed with the pulverized asphalt and cement to get adequate compaction. The roadway reclaimer will not always break down the existing asphalt pavement into material that is small enough to provide adequate fine aggregate content in the mix. It is for this reason that a minimum of 55 percent passing the no. 4 sieve is required. To obtain enough fine aggregate in the mix to achieve compaction, a portion of the underlying subbase/subgrade normally is incorporated into the FDR.

Full gradation curves that include fine aggregate and fines have been developed by various agencies and equipment manufacturers (Scullion et al. 2012; Wirtgen 2012) for material between the no. 4 and no. 200 sieve. However, experience has shown that a project is limited by the onsite subbase/subgrade material available to be incorporated in the FDR layer. Therefore, limits on the no. 200 sieve provide acceptable control. Twenty percent of material passing the no. 200 sieve is the maximum unless the plasticity index (PI) is ≤ 20. If it is felt the percent fines needs to be reduced without increasing the cement content, additional coarse material (called corrective aggregate) can be added to the mix. If the PI of the material is greater than 20, the material may need to be pretreated with a small amount of cement in order to reduce the plasticity and provide a more friable material for FDR processing. Lime, calcium chloride, and other materials have also been used as effective pretreatment materials. However, bringing in other materials to the project site is not cost effective or time effective, since cement is already on site and can adequately reduce plasticity without a mellowing period as is required for lime.

Table 5.1. Recommended Gradation for FDR Mixture

Sieve size	Minimum percent passing
3 in. (75 mm)	100
2 in. (50 mm)	95
No. 4 (4.75 mm)	55

Atterberg Limits Test

After the sample material has been thoroughly blended to the gradation expected in the field and the sieve analysis has been performed (Figure 5.6), the results should be analyzed to determine how much material passes the no. 200 sieve. If the sieve analysis shows at least 20 percent of the combined mixture passes the no. 200 sieve, performing Atterberg limits testing is recommended to determine how much of the fines is silts or clays. The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the combined gradation provides an indication of the cohesive nature of the soil and the ability of the soil to break down easily during the pulverization process. The PI is determined using AASHTO T 90 or ASTM D4318.

ASTM D4318 states, "The test should only be performed on the portion of a soil that passes the 425-μm (no. 40) sieve. Therefore, the relative contribution of this portion of the soil to the properties of the sample as a whole must be considered when using these tests to evaluate properties of a soil." In general, most FDR projects will not need to test for PI, as the depth of treatment would not incorporate enough fines to be concerned with. However, some FDR projects will extend into the subgrade of the existing roadway and incorporate a considerable amount of fines into the mixture. The PI test will determine whether the fines in the FDR mixture are non-plastic silts or lean or fat clays.

As mentioned earlier, a well graded mixture is important for successful FDR construction. In general, more cement is needed for higher fines content soils such as silts and clays to achieve the same compressive strength compared to more granular materials such as sands, gravels, and RAP. Experience has shown that increasing the cement content for fine-grained soils does not increase the strength of the base as quickly as an increased cement content does for granular soils.

Figure 5.6. Gradation testing on existing materials

If the gradation of the pulverized mixture contains excessive fine material, an alternative to increasing the cement content is to incorporate additional coarse material into the mixture. For example, if the required depth of reclamation includes a substantial amount of fines from the underlying soil, coarse material may need to be added to the gradation to reduce the amount of cement needed to achieve the required strength.

AASHTO Soil Classification

If the design team does not have experience with FDR or is unfamiliar with the soil types in the project area, the pulverized mix can be classified for use in estimating the cement contents for testing. The AASHTO soil classification is based on the sieve analysis, LL, and PI of the material (Table 5.2, based on AASHTO M 145).

Determine Chemical Compatibility of Existing Material

The soil composition of the subbase/subgrade can impact the mix design due to chemical compatibility. In sufficient concentrations as a percentage of the total FDR section, chemical components such as sulfate content, low pH, and organic content can affect how the cement will react with the pulverized materials during construction. It is important to understand the chemical makeup of the FDR mix to ensure a durable and long-lasting pavement base.

If an engineer is experienced with FDR mix design and is familiar with local soil conditions, then determining chemical compatibility in the mix design process can be minimized. However, if the project is in an unfamiliar area or the engineer does not have experience with the FDR mix design process, analyzing the chemical composition of the existing pulverized mixture as a whole is recommended, including the subgrade/subbase that will be included in the FDR mix.

Sulfate Content

Sulfate resistance is cement-treated FDR base's ability to resist attack by, and damage from, sulfates penetrating from outside. Excessive amounts of sulfates in soil or water can, over a period of years, attack and destroy concrete pavements and other structures. Sulfates damage concrete by reacting with hydrated tricalcium aluminate (C3A) compounds in the hardened cement paste and by infiltrating and depositing salts. Due to crystal growth pressure, these expansive reactions can disrupt the cement paste, resulting in cracking and disintegration of the FDR layer.

In areas where sulfate soils may be present, material samples should be visually inspected for the presence of gypsum crystals (Figure 5.7, from Ohio DOT 2011). If gypsum crystals are found in the samples, the sulfate content of the sample should be determined in

Table 5.2. AASHTO Soil Classification Table

General classification	Granular materials (35% or less passing no. 200 sieve)							Silt-clay materials (More than 35% passing no. 200 sieve)			
Group classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve analysis, percent passing:											
No. 10 (2.00 mm). . .	50 max.	....	....	....	....	....	....	....	....	....	....
No. 40 (0.425 mm). .	30 max.	50 max.	51 max.	....	....	....	....	....	....	....	....
No. 200 (0.075 mm).	15 max.	25 max.	10 max.	35 max.	35 max.	35 max.	35 max.	36 min.	36 min.	36 min.	36 min.
Characteristics of fraction passing No. 40 (0.425 mm)											
Liquid limit	....		....	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.
Plasticity index . . .	6 max.		N.P.	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.
Usual types of significant constituent materials	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General ratings as subgrade	Excellent to good							Fair to poor			

accordance with ASTM C1580 (Standard Test Method for Water-Soluble Sulfate in Soil). The sulfate concentration should be calculated as a percentage of the total weight of the material in the FDR section. If the sulfate concentration in the sample exceeds 3,000 ppm (0.3 percent), cement stabilization may not be appropriate due to the possibility of deleterious chemical reactions between the cement and the sulfate (Guthrie [no year]).

Alternatively, if material can be added to reduce the sulfate concentration to within acceptable levels, stabilization can proceed. Type II and Type V cement can be used to mitigate sulfate contents in soil. It is necessary to test the material before use to ensure the sulfate content is adequately mitigated. It should be noted that Type V as well as some of the other sulfate-resistant cements are not always readily available in certain parts of the country. When using cements other than Type I or Type II, it is important that the cement used for construction is the same cement used in the laboratory mixture design phase. Note that sulfate-resistant blended cements in accordance with ASTM C595 and ASTM C1157 can also effectively treat sulfate soils.

pH of Existing Material

The pH of a soil is represented by a scale between 0 and 14 that represents whether the material is an acid or a base, respectively. A pH of 7 is considered neutral, while lower numbers indicate increasing acidity and higher numbers indicate increasing alkalinity.

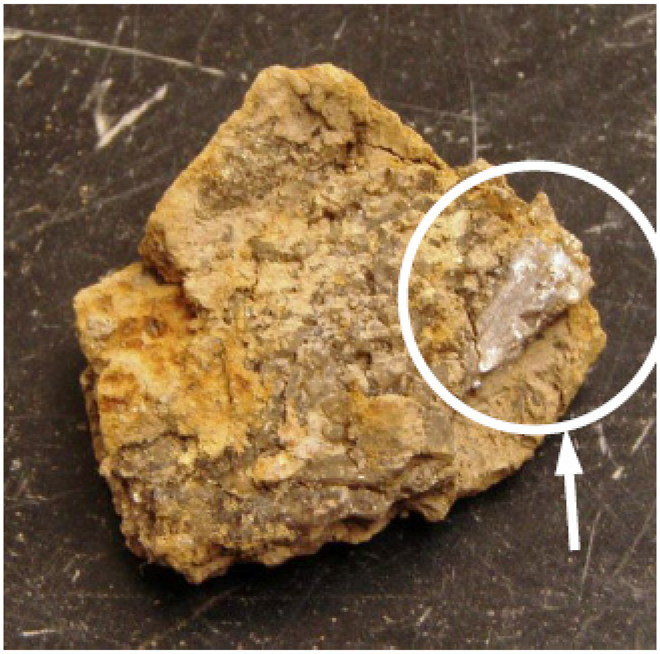


Figure 5.7. Gypsum crystal in clay

As discussed in Chapter 2, the Georgia DOT recommends a minimum pH of 4.0 for soils that will be incorporated into an FDR layer. Low pH material can adversely impact the effect of cement stabilization in FDR mixtures. If the existing soil has a pH of 5.3 or lower (Robbins and Mueller 1960), the soil may not react normally with cement. If the existing soil has a low pH, chemical treatments such as lime or portland cement can be used to neutralize the soil and raise the pH level. The additional cement will help attain strength and durability requirements. The cement content used to neutralize the soil will be in addition to the cement content used for stabilization purposes.

Note that material with a high pH (alkaline) does not typically create strength or durability concerns.

Organic Content

The organic content of the existing material should also be evaluated during the mix design phase. Organic content of 20,000 ppm (two percent) or more (Robbins and Mueller 1960) can prevent the cement stabilized mixture from hardening and may require a higher cement content for stabilization. Although certain types of organic matter, such as undecomposed vegetation, may not influence stabilization adversely, organic compounds of lower molecular weight, such as nucleic acid and dextrose, act as hydration retarders and reduce strength (Army/Air Force 1994). Experience has shown that it is difficult to stabilize certain organic soils with cement because the reduced pH value of these soils causes a precipitation of an alumina-silica gel over the cement particles and inhibits the normal hardening process (Laguros 1962).

If highly organic soils are present within the project limits it is recommended to remove these organic soils prior to FDR. The organic soil that is removed from the project should be replaced with suitable material.

Selecting Cement Contents for Testing

After the chemical compatibility and classification of material has been determined, the appropriate cement content needs to be established. This is determined by testing the mixtures at different cement contents. Typically, three cement contents are used. These cement contents should vary in two to three percent increments in an effort to bracket the design cement content. Recommended cement content percentages are based on the classification of the material. Although the exact cement content of the mixture will not be known at this step of the mix design process, an estimated cement content can be chosen for conducting the test. The cement content can be estimated by using Table 5.3, which is adapted from the Soil-Cement Laboratory Handbook (PCA 1992). The range of values given in this table are somewhat higher than current practice. Therefore, using one to two percent less cement may be more appropriate. These cement contents can be used as preliminary estimates, which should be verified or modified as additional test data become available.

For example, sets of specimens can be molded with three percent, five percent, and seven percent cement contents. Some states recommend that specimens be molded in three percent increments. Checking with the state or local agency is recommended to determine the cement content ranges that should be tested for the proposed project.

The cement that is to be used in the sample testing should come from the same type and source that will supply cement for the FDR construction project. Cement should be stored in a clean and dry environment so that it does not react with moisture before being incorporated into the FDR mixture. All attempts should be made to use the same cement in determining the mixture design as will be used in the field during construction.

Optimum Moisture Content and Maximum Dry Density

After the material has been analyzed in the laboratory and three trial cement contents have been established, the optimum moisture content (OMC) and maximum dry density (MDD) should be calculated. Determining the adequate amount of water and cement for the FDR layer is critical in obtaining the desired moisture and density of the FDR mix. This information is also critical for quality control purposes during construction. Research has shown that cement-stabilized materials have better strength and performance when they are properly compacted. Therefore, determining maximum density and optimum moisture content is an important step in the mix design process.

Table 5.3. Cement Requirements of AASHTO Soil Groups

AASHTO soil group	Usual range in cement requirements		Estimated cement content and that used in moisture-density test, percent by weight	Cement content for wet-dry and freeze-thaw tests, percent by weight
	Percent by vol.	Percent by wt.		
A-1-a	5-7	3-5	5	3-4-5-7
A-1-b	7-9	5-8	6	4-6-8
A-2	7-10	5-9	7	5-7-9
A-3	8-12	7-11	9	7-9-11

Compaction density is determined using test methods AASHTO T 134 or ASTM D558. This test method is a common and inexpensive procedure that can be performed by most construction materials testing laboratories. The test will determine the MDD of the FDR mix and proper moisture content needed to obtain the maximum density.

The test consists of compacting the mixture in a mold at different moisture contents. Following compaction, the wet density and moisture content are determined. The dry density is then calculated and plotted on a graph with the corresponding moisture content. The result is known as the moisture-density curve. The peak of the curve establishes the maximum density and optimum moisture content.

Figure 5.8 (from ASTM D558) is an example moisture-density curve from this test method. If the mix is too dry, not enough moisture is available to lubricate the particles into a denser formation. If the mix is too wet, the excess moisture pushes the particles apart. The moisture content where MDD is selected for mix design and field quality control is called the OMC (Luhr et al. 2014). The MDD and OMC from this test establish the control used in the field for determining if adequate compaction has been achieved. Most specifications require a minimum of 98 percent of the MDD.

After the estimated cement contents have been determined, samples should be prepared to test for the OMC and MDD at the mid-range cement content. In most cases the MDD and OMC will not change appreciably with different cement contents. However, some agencies will require separate moisture-density compaction tests for each of the cement contents (e.g., three percent, five percent, and seven percent). To perform this test,

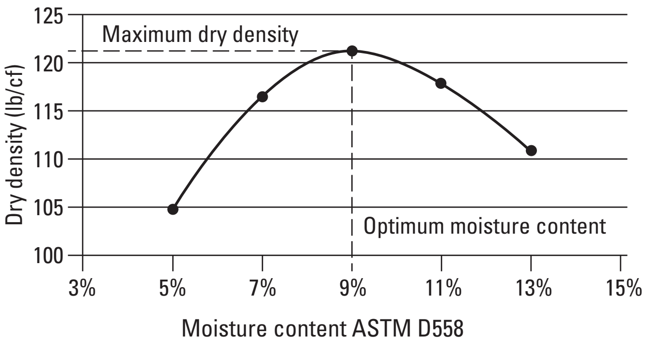


Figure 5.8. Example moisture-density relationship

the required amount of cement should be weighed out. The cement content by weight is based on the oven-dry weight of the soil/aggregate only (cement is not included) and is expressed as the following equation:

$$\text{cement content, } c(\%) = \frac{\text{weight of cement}}{\text{oven - dry weight of soil/aggregate/RAP (excluding cement)}} \times 100 \qquad \text{(Eqn. 5.1)}$$

The amount of water in the mix is called the water content and is defined as the weight of water in the total mixture including cement (expressed as a percentage of the total material).

$$\text{water content, } w(\%) = \frac{\text{weight of water in mixture}}{\text{oven - dry weight of soil/aggregate/RAP cement}} \times 100 \qquad \text{(Eqn. 5.2)}$$

The cement should be added to the unstabilized material and thoroughly mixed before the addition of water. The sample should be molded within two hours of the time the cement and water are introduced to the mixture. Fresh material should be used for each trial mixture. It is recommended that a laboratory or commercial grade mixer be used to replicate actual construction practices. It is important to replicate as closely as possible the anticipated construction process during laboratory testing. If the cement is to be added as slurry during construction, then cement should be added to the samples in slurry form to ensure the laboratory methods will match the conditions encountered during construction.

The tests should be completed without delay to minimize the effects of cement hydration. After the samples have been thoroughly mixed with the anticipated cement content, the OMC and MDD should be calculated in accordance with AASHTO T 134 or ASTM D558. The optimum moisture content will be defined by a best-fit curve from a minimum of four points similar to Figure 5.8.

It is important to note that if the design team does not have previous experience or guidance on what the OMC would be for the treated mixture, it is advisable to run a moisture/density test on the untreated soils before adding cement. The moisture/density test results from the unstabilized mixture will give a range of moisture contents to use as a baseline for further moisture/density testing on the cement-stabilized samples. If moisture/density testing is performed on the untreated mixture, the tests should be performed in accordance with AASHTO T 99 or ASTM D698.

Unconfined Compressive Strength Tests

Based on the optimum moisture content test results of the cement-treated FDR samples that were determined earlier, specimens should be prepared at each estimated cement content (e.g., three percent, five percent, and seven percent) for unconfined compressive strength testing.

Although the optimum moisture content from the trial moisture-density test should be adequate for preparing the unconfined compressive strength specimens, some agencies require that separate moisture-density tests be conducted at each cement content. The Portland Cement Association (Luhr et al. 2014) recommends that a minimum of two specimens be prepared for each cement content. A third specimen can be prepared if needed for retesting or testing at later ages. The unconfined compressive strength (UCS) cylinders should be made in accordance with ASTM D1633, Method A (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders).

Some agencies require the use of modified Proctor testing in accordance with ASTM D1557. Experience has shown that this method may result in a lower optimum moisture content. Due to the characteristics of cement-stabilized soils, sufficient moisture in the mix is important for hydration purposes. If modified Proctor testing is used, it is advisable to allow for a slightly higher moisture content during construction.

After the specimens are mixed and compacted, they should be stored in a moist curing room capable of maintaining a temperature of 73.4 ± 3°F and a relative humidity of not less than 96 percent. The cement-stabilized mixtures should be cured undisturbed for a period of seven days.

After curing the specimens for seven days in the moist curing room, the specimens should be removed and the weight of each recorded. In some areas the specimens may be immersed in a water bath at 77 ± 2°F for four hours immediately before compressive strength testing to allow the sample to absorb water and to identify any expansion characteristics that have not been stabilized.

Once curing of the specimens has been completed, it is time to perform the unconfined compressive strength testing. The UCS values for the cement-stabilized samples should be determined in accordance with ASTM D1633, Method A (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders).

The results of the UCS tests should be plotted on a graph that shows the unconfined compressive strength (psi) on the Y axis and the cement content (%) on the X axis. The desired cement content can be derived from this graph based on the required compressive strength. Figure 5.9 shows an example UCS test with cement contents of three percent, five percent, and seven percent. As you can see from this figure, a target UCS value of 350 psi would result in a cement content of 6 percent. It should be noted that some agencies plot the vacuum saturation test results on the compressive strength test graph to analyze the cement content required to meet durability. The following section describes freeze-thaw and vacuum saturation testing in more detail.

Freeze-Thaw Durability Tests

Full-depth reclamation can be performed in a variety of climates, including northern climates where freeze-thaw patterns can cause unstabilized pavement bases to lose strength and stiffness. The PCA's *Full-Depth Reclamation using Portland Cement: A Study of Long-Term Performance* (Syed 2007) concluded that the cement in the FDR process can improve the resistance of the reclaimed base to freeze-related road heaving and thaw-related loss in strength. In addition to meeting the desired unconfined compressive strength, the mix design should also pass freeze-thaw durability testing to ensure it will be a long-lasting pavement base solution.

Two main tests can be performed to determine how durable an FDR base will be. The first of those tests is ASTM D560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) or AASHTO T 136 (Standard Method of Test for Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures). This test involves curing a prepared specimen for seven days and then subjecting the specimen to 12 cycles of freezing and thawing to imitate severe climates. Each freezing period is 24 hours long in a chamber no warmer than -10°F, and each thawing period is 23 hours long in a chamber at 70°F with 100 percent relative humidity. Within one hour of each thaw cycle, the specimen is brushed on all sides with a wire brush a set number of times with a consistent force (Figure 5.10, from Wilson et al. 2012) (according to ASTM D560 or AASHTO T 136). The durability of the specimen is calculated based on comparing the final mass of the specimen after 12 freeze-thaw cycles and brushing. The measurement is reported as percentage lost. The PCA's Soil-Cement Laboratory Handbook (1992) recommends that the mass-loss of base materials should not exceed 14 percent after 12 cycles of freeze-thaw for soil groups A-1, A-2-4, A-2-5, and A-3.

The second test used to determine the durability of an FDR mix is called the vacuum saturation test. This test follows the general procedures of ASTM C593 (Standard Specification for Fly Ash and Other Pozzolans for Use with Lime for Soil Stabilization) Section 11 Vacuum Saturation Strength Testing Procedure. For this test, samples are prepared and cured for seven days. After curing, the samples are placed in a sealed vacuum chamber, evacuated of air for 30 minutes, and then flooded with water until the samples are fully submerged. The vacuum is then removed and the samples are left to soak at atmospheric pressure for one hour as shown (Figure 5.11, from Wilson et al. 2012).

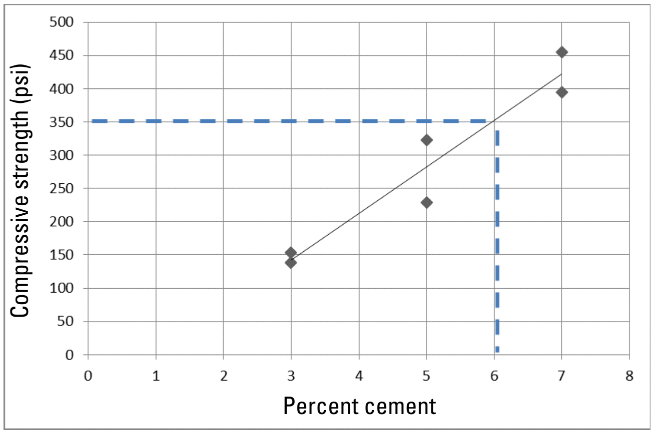


Figure 5.9. Unconfined compressive strength vs. percent cement

Figure 5.10. Brushing during freeze-thaw durability testing

Figure 5.11. Vacuum saturation test

After this step the specimens are tested for UCS and the soaked moisture contents of the specimens are determined. The durability of the sample is typically reported by the resulting UCS value, which can be calculated with Equation 5.3. The baseline UCS value is obtained by conditioning the specimen with a four-hour soak according to the Portland Cement Association (1992) protocols rather than vacuum saturation.

$$UCS_{Retained} = (UCS_{VacSat} / UCS_{Baseline}) \times 100 \quad \text{(Eqn. 5.3)}$$

Where:

$UCS_{Retained}$ = retained UCS after vacuum saturation, %
UCS_{VacSat} = vacuum saturation UCS, psi
$UCS_{Baseline}$ = baseline 7-day UCS, psi

The acceptance criteria specified in ASTM C593 require a minimum compressive strength of 400 psi after vacuum saturation. However, this strength requirement is conservative and results in an excessive strength requirement that increases the cost of FDR and could lead to undesirable cracking. This is especially true if the jurisdictional specifications call for a lower seven-day compressive strength such as 200 psi. In this situation, the ASTM C593 requirement of 400 psi after vacuum saturation testing would override the lower strength requirement of 200 psi and would be overly conservative.

The PCA's Correlation of Vacuum Saturation Testing to Traditional Freeze-Thaw Testing of Cement-Treated Base Materials (Wilson et al. 2012) compares the traditional freeze-thaw durability test (ASTM D560 or AASHTO T 136) with the vacuum saturation test (ASTM C593). The results indicate a good correlation between the two tests and concludes that a minimum 300 psi vacuum saturation test result will ensure that strength and durability requirements are met. Therefore, it appears that the acceptable criteria for the vacuum saturation test could be a minimum compressive strength of 300 psi instead of the 400 psi specified in ASTM C593 to allow a more reasonable approach.

Mix Design Report

After the mix design has been established based on the freeze-thaw durability tests and the unconfined compressive strength, the test results should be reported to the owner agency. The report should contain the following minimum information with the corresponding station limits and/or construction phase (from ARRA 2015 [draft]):

- Gradation of combined mixture (including RAP)
- Liquid limit, PL, and PI of combined material (if applicable)
- Maximum dry density and OMC of the FDR mixture from AASHTO T 134 (ASTM D558)
- Unconfined compressive strength at each trial cement content
- Wet density of compressive strength test specimens before and immediately after moist curing period
- Recommended cement content as a percentage of dry materials
- Material certifications and source information for portland cement

In addition to these items, the graph of unconfined compressive strength versus the percent of cement in the mixture should be provided. The moisture/density curve should also be provided for the recommended cement content. A graph should also be generated that shows the average moisture-conditioned UCS and freeze-thaw durability for each mixture versus the percentage of cement in the mixture.

The recommended spread rate for the cement should be provided so that a correct amount of cement is applied during construction. This spread rate should be specified in pounds per square yard. If there are varying spread rates throughout a project, station limits or other identifiable markers should be specified to ensure the FDR layer will be consistent along the roadway.

Chapter 6

Construction

To fully reap the benefits of FDR with cement, proper construction practices must be followed. The objective in FDR construction is to obtain a thoroughly mixed, adequately compacted and cured material containing the correct amount of cement.

The first step in any FDR construction project involves pulverizing the existing asphalt pavement and underlying materials using a piece of equipment called a road reclaimer (Figure 6.1). The pulverized mixture is graded to the desired cross section and alignment. Then cement is added to the mixture, and the pulverized material, cement, and water are mixed together to create a uniform, homogeneous blend with the correct moisture content. Finally, this homogeneous blend is compacted, finished, and cured before application of a surface course.

This chapter discusses the typical equipment used in FDR construction and the detailed construction process for a successful FDR project. It also provides information about pre-cracking (micro-cracking), environmental considerations, and opening the FDR layer to traffic.

Equipment

The construction of FDR is accomplished using a variety of equipment. Many contractors performing roadway rehabilitation commonly have this equipment already. Equipment used in FDR construction will vary from contractor to contractor, but the basic equipment is as follows:

- Reclaimer
- Motor grader
- Cement spreader
- Water truck
- Compaction equipment

Reclaimer

A reclaimer (Figure 6.2) is an essential piece of equipment for successful FDR construction. The industry has a variety of reclaimers available today. They typically come with cutting drums in 8- or 10-ft widths. In some models, extensions can be added to increase cutting drum widths. Some reclaimers are as narrow as 6 ft, which improves maneuverability in environments such as urban settings.

For proper treatment depth, the ARRA recommends that reclaimers pulverize a minimum of 12 in. of asphalt pavement and underlying materials in a single pass. Cutting drums on the reclaimer should have both automatic and manual depth control capabilities at each corner and be equipped with replaceable tungsten carbide cutting teeth. The reclaimer's cutting drum should have variable rotating speeds to ensure compatibility with different material types and thicknesses.

The cutting drum of most reclaimers has cutting teeth arranged in a chevron pattern (Figure 6.3) to limit lateral movement of the reclaimed material inside the mixing/pulverization chamber. The bottom edge of the rear door of the mixing/pulverization chamber will strike off the reclaimed material in the desired shape and loose thickness (ARRA 2015).

Figure 6.1. Initial pulverization of residential street

Figure 6.2. Road reclaimer

Figure 6.3. Roadway reclaimer cutting drum

The reclaimer should have automatic forward speed control that responds to on-board load sensing mechanisms. Some reclaimers have four-wheel drive and four-wheel steering to improve versatility.

Notes: Reclaimers are not crushers; they do not reduce material to a smaller size than the original aggregate. In addition, asphalt milling equipment and harrowing discs are not acceptable mixing/pulverizing equipment.

Motor Grader

Motor graders are used to shape the reclaimed mixture after pulverization. The grader can be used to aerate and dry out the mix if it is too wet and to correct geometric deficiencies. In addition, if the reclaimed mixture is too thick for adequate compaction, the blade of the motor grader can be used to windrow the material to one side to allow compaction of the lower section.

Cement Spreader

Before the final mixing pass, cement is added to the mixture. Cement can be added in one of two ways:

Cement can be placed on the grade in dry powder form using a bulk spreader (Figure 6.4). The contractor will need to take care to control fugitive dust, especially during windy conditions. In some cases, the cement spreader can be equipped with a self-contained vacuum system to minimize creation of dust (Figure 6.5). The cement spread rate is typically expressed in terms of lb/yd^2.

The second method of cement application is in slurry form using a slurry spreader device (Figures 6.6 and 6.7) or by injecting slurry under the hood of the reclaimer onto the mixing drum. During application, the contractor should take care to avoid slurry runoff. The consistency of the slurry is also important. The slurry mixer and truck should completely disperse the cement in the water to produce a uniform slurry that remains uniform through agitation or other means (Luhr et al. 2014). The time from first contact of cement with water to application of the slurry on the FDR surface should not exceed 60 minutes, unless some type of retarding admixture is used in the slurry. If a retarding admixture is used, manufacturer specifications or a test section should be provided to the owner to prove that the admixture will not adversely affect the hardened properties of the FDR layer. Mixing should begin immediately after the cement slurry has been applied but should not exceed 30 minutes.

Figure 6.4. Dry powder cement being placed using a bulk spreader

Figure 6.5. Self-contained vacuum system on a bulk cement spreader

Figure 6.6. Cement slurry application

Figure 6.7. Cement slurry application on grade using a concrete ready mixed truck

Water Truck

Water trucks are used throughout construction of the FDR. Most reclaimers have on-board liquid additive systems to accurately add moisture to the reclaimed material. Water trucks can be used to supply the reclaimer with water (Figure 6.8). If the reclaimer does not have an on-board liquid-additive system, water is added to the mixture through a truck sprayer. Water trucks used in the FDR process should have a metering system to ensure the correct amount of moisture is being added to the FDR mix. Water trucks can also be used to add water to the compacted FDR base during the curing process.

Compaction Equipment

Proper compaction of the FDR base is critical to ensure both short-term constructability and long-term performance of the roadway. Compaction can be accomplished using a variety of rollers:

- Tamping-foot roller (Figure 6.9)
- Pneumatic-tired roller (Figure 6.10)
- Smooth-drum vibratory roller (Figure 6.11)

Figure 6.8. Water truck supplying road reclaimer during mixing operations

Figure 6.9. Tamping-foot roller behind reclaimer

The type of compactor used on an FDR layer will depend on such factors as (ARRA 2015) the following:

- Compaction requirements
- Material properties of the FDR mix
- FDR thickness
- Contractor productivity requirements

Detailed Construction Process

The previous section gave an overview of the equipment required to perform FDR. The following sections will go into more detail for each step in the FDR construction process.

Pulverizing

Proper pulverization and mixing of the existing asphalt pavement and underlying materials is critical to the success of FDR. The pulverizing step ensures the reclaimed

Figure 6.10. Finish rolling using pneumatic tire roller

Figure 6.11. Smooth-drum vibratory roller

material is a homogenous mixture of the specified gradation. Pulverizing is accomplished using a roadway reclaimer. The reclaimer's cutting drum rotates in a direction opposite to the direction of the reclaimer's wheels. The teeth of the cutting drum reduce the existing asphalt pavement into smaller pieces and blend the asphalt pieces with the underlying roadway materials. Figure 6.12 illustrates the cutting drum pulverizing a pavement and underlying material.

To begin the pulverizing procedure on pavements without curb and gutter, the contractor typically makes one cross cut with the roadway reclaimer from the roadway shoulder perpendicular to the direction of travel. This cross cut provides a vertical face at the project limits from which to work. The cross cut also reduces cutting tool wear by lowering the drum into the softer shoulder material rather than the pavement layer.

If a cross cut is not possible due to adjacent obstacles, the reclaimer should slowly pulverize the existing asphalt pavement into the underlying base. This method is not ideal because the cutting head may bounce.

After the reclaimer has successfully penetrated the existing asphalt pavement, the reclaimer should be aligned longitudinally along the roadway. To prevent strips of unpulverized pavement between passes, a guide should be provided for the operator in the form of paint markings or string line. Typically, only the first pass of the reclaimer needs to be marked (ARRA 2015).

Due to varying widths of existing roadways and roadway reclaimers, several passes may be required to reclaim the entire pavement width. Each pass of the reclaimer should be overlapped with the previous pass to ensure proper mixing and avoid unpulverized sections. The minimum overlap width should be 6 in. between longitudinal joints and 2 feet between transverse joints (ARRA 2015).

The depth of pulverizing should include a minimum of 1 in. of unbound stone or soil beneath the existing asphalt pavement. The material beneath the pavement will help cool the cutting teeth of the cutting drum during the reclamation process.

Similar to soil that has been excavated, the reclaimed mixture will be uncompacted and higher than the original pavement surface due to an increase in void content (Figure 6.13). The rear tires of the reclaimer will ride on this uncompacted material and may in turn raise the cutting drum. To ensure construction is meeting the specified design, the depth of pulverization should be checked regularly to verify adequate pulverization. With each subsequent pass, the reclaimer will ride on the uncompacted material, and the mixing/pulverizing depth may be affected depending on the additional height of the reclaimed material. Field adjustments to the cutting drum may be necessary to reach the target depth of pulverization.

The depth of the initial pulverization pass is typically 1 to 2 in. less than the final mixing pass to reduce the risk of a thin layer of untreated reclaimed material being left beneath the stabilized layer (ARRA 2015).

After the initial pulverization pass, the contractor should perform light compaction and reshaping to provide a solid working base for equipment in the subsequent construction phases. A smooth working platform will also allow for more accurate control of the final mixing pass of the roadway reclaimer after cement has been added.

As mentioned earlier, reclaimers are not crushers. They do not reduce material to a smaller size than the original aggregate. The gradation of the pulverized material should be checked to verify it meets the specified mix design gradation. This is especially important for

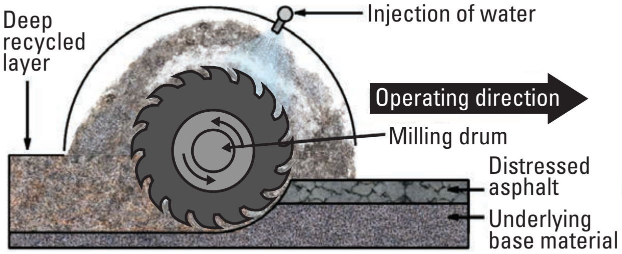


Figure 6.12. Operation of a roadway reclaimer's cutting drum

Figure 6.13. Pulverization of existing asphalt roadway

pavements that have significant alligator cracking before pulverization (ARRA 2015).

Various adjustments to the operation of the reclaimer can affect the gradation of the reclaimed material. One hundred percent of the material should pass the 3-in. sieve; at least 95 percent should pass the 2-in. sieve; and at least 55 percent should pass the no. 4 sieve (Luhr et al. 2014). Some large chunks of existing asphalt pavement may remain after the pulverization pass. It may be uneconomical to make additional passes to further reduce the size of occasional large pieces of pavement. An occasional oversized piece is acceptable (ARRA 20015); however, if several large pieces are left after the initial pulverization, a second pulverization pass is necessary to improve the gradation. Contractors should use a reclaimer with at least 600 horsepower to handle the most difficult conditions. Figure 6.14 shows a typical pulverized mixture.

According to the ARRA (2015), the gradation of the pulverized material is influenced by the following:

- Front and/or rear door opening on the pulverization/mixing chamber
- Breaker bar setting of the pulverization/mixing chamber
- Rotation speed of the cutting drum
- Forward speed of the reclaimer
- Condition of the existing pavement with respect to temperature, depth, cracking, and hardness
- Gradation of the underlying materials

The more the pulverized material comes in contact with the cutting drum, the more the size of the material is reduced. To increase the number of impacts with the cutting drum, the contractor may reduce the reclaimer's speed, increase the cutting drum rotation speed, and/or close the rear door (ARRA 2015).

Figure 6.14. Pulverized FDR mixture

If the existing asphalt layer is thick, a slower cutting drum rotation speed with more torque is typically used. Lower speed and higher torque are also used when the existing granular material is very dense and needs more power to pulverize the materials. The reclaimer can be operated faster in thinner pavement sections or less dense granular materials.

Closing the rear door will cause the material to stay within the mixing chamber for a longer period of time, increasing the material's contact with the cutting drum and reducing the size of the pulverized material. In addition to closing the rear door, adjusting the breaker bar so that it is closer to the cutting drum will also help break down larger chunks of asphalt. Contractors need to strike a balance between closing the rear door and accounting for the additional height of the uncompacted material after the pulverization pass.

Utility Considerations when Pulverizing

All utilities need to be located during the planning stage of the project to minimize the risk of conflicts during construction. Utilities such as manholes that are at the surface of the existing roadway should be temporarily lowered to allow the reclaimer to pulverize through the entire roadway. Manholes can be temporarily lowered by removing the top of the manhole, placing a steel plate over the manhole to prevent material from entering the sewer, and then pulverizing over top of the steel plate. Lighter plastic and wooden cover plates should be avoided to eliminate any possible movement of the plate during mixing operations. After the reclamation process is complete, the plates can be removed and the manholes adjusted to finish grade.

If manhole and utility adjustments are not completed before pulverization, the material can still be pulverized and mixed but the process is more labor intensive. Material directly adjacent to utility lines and structures can be dug up and moved to a location where the reclaimer can pulverize and mix the material. After pulverization and mixing, the material can be moved back to the locations around the utilities and then compacted with smaller compaction equipment.

As the forward speed of the reclaimer is reduced, additional pulverization is achieved resulting in a finer gradation of the reclaimed material. A faster forward speed increases the size of the existing pavement pieces that are dislodged by the cutting teeth and reduces the amount of time the material is retained in the mixing chamber. Performing a test strip with the reclaimer is recommended to determine the appropriate speed of the machine.

The height of the cutting drum in relation to the existing asphalt pavement can also directly affect the gradation of the reclaimed material. A higher cutting drum will cause the cutting teeth of the reclaimer to strike the existing pavement horizontally, which will reduce the tendency to flip or dislodge large chunks of asphalt (ARRA 2015). However, if the cutting drum is too high, the depth of pulverization may not meet the design depth, and a second mixing pass may be necessary.

Grading

During the initial pulverization pass, the reclaimed material will be smoothed and roughly shaped by the bottom edge of the rear door on the mixing/pulverization chamber. The rear door setting of the reclaimer can be adjusted to change how the reclaimed material is placed.

At this point the reclaimed material must be reshaped to meet the designed roadway geometrics. To reshape this material, a motor grader is used to move and place the reclaimed material to the desired cross section and alignment (Figure 6.15). Each project requires varying amounts of grading before cement placement and the final mixing pass. Any alignment, superelevation, or elevation adjustments that are necessary for the project should be completed after the initial pulverization and before the addition of cement. After the FDR layer has been stabilized with cement, the base will become permanent and any reshaping will require costly rework.

Before the addition of cement, the pulverized mixture should be at or near the optimum moisture content as specified in the mix design. This will minimize the need to add any significant amount of water during the cement mixing operation. If the reclaimed material is too wet, it should be graded and disked to dry it prior to the addition of cement.

After the roadway has been graded to the desired cross section, the reclaimed material should be lightly rolled and compacted. This minor compaction will provide a more stable base for the subsequent construction operations and will prevent rutting in the material as equipment drives over it. The initial grading and compaction will also provide a smooth surface to assist in achieving a more uniform thickness during the final mixing pass.

As mentioned earlier, the FDR process will fluff the existing material and increase its volume due to pulverization and the addition of cement. Experience has shown that this material can increase in volume by about 10 percent. If an FDR project is located in a rural area with sufficient right of way, excess material can be bladed to the shoulder and incorporated into the shoulder construction. However, in urban areas where there is existing curb and gutter or other fixed elevations that must be matched, this may not be possible and excess material may need to be hauled off site. Efforts should be made to adjust the grade of the roadway or find other options to incorporate the material into the site to minimize hauling of excess materials.

After grading is complete, excess material should be removed from the site so that it does not get incorporated into the final mixing pass. Excess material should not be used to fill in low areas after stabilization, as the unstabilized material will not adhere to the stabilized base (ARRA 2015).

Additional aggregate may be needed to increase the thickness of the FDR layer or to meet performance requirements of the mix design. If additional aggregate is required, the aggregate should be spread in a uniform thickness over the roadbed. The additional aggregate should be blended with the reclaimed material by performing an additional mixing pass of the reclaimer to produce a homogeneous mixture prior to cement application (ARRA 2015). Any additional aggregate added to the FDR layer should be included in the mix design.

If instability in the pulverized mixture is experienced during grading operations, the grading process should be suspended until the cause of instability is identified

Figure 6.15. Grading of pulverized FDR mix

and addressed. The area of instability should be repaired prior to cement placement, which could involve cement stabilization or removal and replacement of undesirable subgrade material. If excessive moisture in the material is the cause of instability, the reclaimed mixture should be aerated before cement is added.

Cement Placement

Cement placement typically takes place after the initial pulverization and grading have been completed. Cement can be placed in dry powder form or in a cement and water slurry. The application rate for cement is typically specified by weight in lb/yd^2.

Dry Cement Placement

For a uniform application, dry cement powder should be spread after the initial pulverizing pass and prior to the final mixing pass. As discussed earlier, dry cement is spread using a bulk spreader. Avoid placing cement in an uncontrolled manner by blowing it under pressure. Mechanical style spreaders are desired in lieu of pneumatic style spreaders for dry cement placement.

When dry cement is added to the grade, dust control should be a priority to avoid fugitive dust, especially on windy days. Dust control is most critical at the time when cement first makes contact with the ground. Unless very windy conditions are present, dust is not typically an issue once the cement is on the ground. To avoid significant dust during placement, special enclosures can be used on the spreaders as discussed earlier.

Slurry Cement Placement

Cement can also be applied in a slurry form or by injection under the hood of the reclaimer mixing chamber. Slurry should be dispersed uniformly over the entire placement area in a manner that will not allow the slurry to pool or run off. Concrete ready mixed trucks have also been used to apply cement slurry (Figure 6.7). Slurry application will not be affected by environmental conditions such as wind.

Mixing

After the cement has been placed on the pulverized material, final mixing commences. The mixing operation is performed by the roadway reclaimer. Moisture content at time of mixing should be at ± 2 percent of optimum moisture content. If the reclaimed material has a lower moisture content than specified in the mix design, water will be added to the material. Water can be added through on-board applicators of the road reclaimer or in a separate operation. Ideally, water is added through the reclaimer to ensure the correct amount of water is added; the optimum moisture content is critical to achieving the target compaction specified in the construction specifications. The mixing operation will combine the pulverized material, cement, and water into a homogeneous blend (Figures 6.16 and 6.17).

The mixing should be continued until the product is uniform in color, meets gradation requirements set forth in the mix design, and is at the required moisture content throughout. The entire mixing operation should result in a uniform pulverized asphalt, soil/aggregate, cement, and water mixture for the full design depth and width (Luhr et al. 2014). Material around manholes or in other areas inaccessible to the reclaimer must be moved up on the grade where it can be mixed with the cement and water by the reclaimer to ensure uniformity throughout the project.

Special attention should also be given to the mixing of FDR material adjacent to curbs and gutters. To improve


Figure 6.16. Mixing the pulverized material, dry cement, and water


Figure 6.17. Cement slurry mixing operations

mixing, it is recommended that all material be moved away from the gutter for the full-depth of processing using a motor grader or other equipment. After mixing has been performed, the material can be bladed back and compacted (PCA 2001).

Note that cement can be placed directly on the surface of the existing roadway before pulverization to minimize the number of passes of the road reclaimer. This technique combines the pulverizing pass and the mixing pass of the reclaimer into one operation. This method is limited to projects where the existing roadway geometrics and elevations will remain unchanged. This method should also be limited to thin existing pavements such as chip seal roadways to ensure an adequate gradation can be achieved with only one pass of the reclaimer. When this method is employed, perform a test section before commencing the entire project to ensure that adequate gradation, mixing, and moisture content can be achieved.

Compaction and Final Grading

The required minimum strength and successful long-term performance of FDR projects are affected by the degree of compaction achieved during construction. If the reclaimed mix is inadequately compacted, the base will not achieve the necessary strength and durability. In addition, poor compaction will not allow the FDR base to achieve ultimate strength gain, which may result in permanent base failures. The FDR base should be uniformly compacted to a minimum of 98 percent of maximum dry density in accordance with ASTM D558 or AASHTO T 134 based on a moving average of five consecutive tests with no individual test below 96 percent (Luhr et al. 2014).

The type of compactors used on each project will vary depending on the material properties, lift thickness, and contractor productivity targets. Often more than one compactor is used on a project to speed up the construction process. The types of compactors that can be used on a project include tamping-foot, smooth-drum vibratory, and pneumatic-tired rollers. Tamping-foot rollers are effective in compacting the material from the bottom up. The amplitude and frequency of vibration for vibratory rollers will be influenced by the degree of compaction required and the depth of the reclaimed mixture. The reclaimed mixture and compaction requirements will also impact the static weight and tire pressure on pneumatic-tired compactors. Contractors need to make sure that adequate compaction is achieved in accordance with the project specifications.

The contractor should establish a compaction pattern that will achieve the required density without over-compaction. If the subgrade is pumping under the weight of the equipment, compaction operations should be stopped and the FDR layer should be allowed to cure. A test strip may be used to establish a compaction pattern. Care should be taken to avoid possible over-compaction. If the FDR layer is over-compacted, aggregate crushing and loosening of the surface layer may occur, resulting in a non-uniform and weakened base. Over-compaction can also lead to surface raveling due to premature surface drying.

Optimal moisture content is critical to meet the compaction requirements of the mix design. Some of the water in the mixture is lost through both evaporation and cement hydration. Therefore, monitoring the water content throughout the construction process is critical. The FDR process relies on hydration. This process begins as soon as water has been added to the pulverized mixture. A light application of water may be needed during construction to maintain the mixture at optimum moisture, especially if there is a time delay in the compaction and finishing process.

The maximum time between start of mixing and final compaction should not exceed two hours (Luhr et al. 2014). This time limit may vary depending on weather conditions and should be shortened if dry and windy conditions are present. This time limit can be extended under cool, calm, and damp conditions. Intermittent mixing may also be used to extend the time limit. In addition, contractors should be aware of the limitations of their crew, equipment, and site conditions and limit the FDR segment to just enough area to meet moisture and compaction requirements.

As part of the finishing operations, the surface of the FDR material should be shaped to the specified design elevations and cross section as compaction nears completion (Figure 6.18). During the finishing process the

Figure 6.18. Compaction and final grading operations

surface should be kept moist by means of water spray devices that will not erode the surface. Compaction and finishing should be done in such a manner as to produce a dense surface free of compaction planes, cracks, ridges, or loose material. All finishing operations should be completed within four hours from start of mixing.

Curing

It is important that FDR with cement mixtures be properly cured to achieve full strength. The FDR layer should have a strength sufficient to withstand marring or permanent deformation of the surface before traffic is allowed on the compacted FDR.

After the FDR layer has been finished, the surface should be properly cured to allow hydration to take place and strength gain to occur. Curing can be accomplished by using a bituminous or other approved sealing membrane or by moist curing. If a curing membrane is used, it should be applied as soon as possible but not later than 24 hours after completion of finishing operations. The surface should be kept continuously moist prior to the application of curing material (Luhr et al. 2014).

If bituminous curing material is not used, curing of the reclaimed base should be accomplished by moist curing (addition of water to the surface). Regular applications of a light spray of water (Figure 6.19) can help keep the surface moist, but this can be difficult if hot and windy conditions are present. If moist curing is used in lieu of a bituminous curing material, it is critical that the surface of the FDR layer remains moist for a period of seven days unless a surface course is placed within the first seven days. The water spray should be applied in a manner that will not erode the surface of the FDR base.

Figure 6.19. Water truck spraying on compacted FDR layer

Pre-Cracking (Microcracking)

Cement-treated materials will naturally shrink during the curing process due to desiccation and cement hydration (Sebesta 2006). This shrinkage may result in shrinkage cracking of the FDR base. The challenge with shrinkage cracking in FDR bases is to not adversely affect the performance of an asphalt surface pavement. If wide cracks in the base layer are present, concentrated stresses may cause cracks to reflect from the base into the surface course. Normally, this does not affect pavement performance but may influence the appearance of the pavement.

Shrinkage cracking of FDR with cement bases can be controlled through the use of a process called microcracking or pre-cracking. Pre-cracking was originally reported in Austria in 1995, and the method has been successfully tried on several projects in the United States (Adaska and Luhr 2004).

This technique involves several passes of a vibratory roller over the cement-stabilized base 48 to 72 hours after final compaction, after the base has achieved some initial strength. Some states do not perform pre-cracking unless the FDR layer meets or exceeds a minimum unconfined compressive strength such as 250 psi. Typically, pre-cracking is accomplished using a 10- to 12-ton vibratory steel drum roller with the vibrator set at the maximum amplitude. The roller typically travels at a creep speed of approximately 2 mph. The process usually takes three full passes with the vibratory roller over the entire surface, excluding the outside 1 ft. This rolling operation will induce small cracks in the FDR base. Research has shown that pre-cracking can reduce the amount of cracking in a properly designed base by 30 to 70 percent (Sebesta 2006).

Pre-cracking during the early stages of curing does not detrimentally affect the strength of the base. The Texas Transportation Institute at Texas A&M University researched pre-cracking on cement-treated bases. Its research indicated that as long as sufficient cement hydration continues after early pre-cracking, the 28-day strengths of pre-cracked cement-treated bases are not significantly different from strengths obtained by curing without pre-cracking (Sebesta and Scullion 2004).

After performing the pre-cracking operation, curing should be continued. If the FDR with cement base was moist cured prior to pre-cracking, moist curing should be continued for an additional two days. Alternatively, the stabilized base can be moist cured for four hours after pre-cracking and then a sealing membrane should be applied to prevent moisture loss.

If bituminous curing material is used, the FDR surface should be dense, free of all loose and extraneous materials, and sufficiently moist to prevent excessive penetration of the bituminous material. The bituminous material should be uniformly applied to the surface of the completed FDR base. The exact rate and temperature of application for complete coverage, without undue runoff, should be specified by the engineer (Luhr et al. 2014).

Traffic should be kept off the FDR layer until the bituminous curing material has dried sufficiently to prevent material pickup by tires. However, if construction equipment or other traffic needs to use the FDR surface before the bituminous curing material has dried, a sand blotter cover should be applied before allowing traffic on the FDR base (Luhr et al. 2014).

After curing has been completed, a surface course such as chip seal, asphalt overlay, or concrete overlay can be placed on the FDR layer. For additional information on asphalt overlay design and construction, refer to the third edition of the National Center for Asphalt Technology's textbook, *Hot Mix Asphalt Materials, Mixture Design and Construction* (Roberts et al. 2009). PCC overlays are discussed in the following section.

Concrete Overlays

Two types of concrete overlays can be placed over the top of an FDR base: unbonded and bonded. Following is a simple overview. Additional details can be found in the *Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements, 3rd Edition* (Harrington and Fick 2014).

Unbonded PCC Overlay

If the final surface course of an FDR project will be an unbonded concrete overlay, the FDR layer serves as the base and it is recommended to cure the FDR layer with a bituminous prime coat. The bituminous prime coat will aid in preventing moisture loss and will prevent a dust layer from forming that could lead to slippage between the surface course and the FDR layer. It is recommended that the FDR layer cure for two days before application of the unbonded overlay.

In addition to the bituminous prime coat, an interlayer should be installed between the concrete pavement and the FDR layer to act as a bond breaker between the two materials. Pre-cracking of the FDR layer to minimize wide cracks in the base is not necessary. The interlayer can consist of a thin 1-in. asphalt separation layer or a geotextile nonwoven fabric material. Joint spacing for an unbonded overlay ≥ 6 in. thick is 6-ft by 6-ft panels. Joint spacing in the overlay (in feet) should not exceed 1.5 times the thickness of the overlay (in inches).

Bonded PCC Overlay

If the final surface of an FDR project is a bonded concrete overlay, the FDR layer does not serve as a typical base but is considered part of the load-carrying pavement structure. The whole concept of a bonded overlay is that the overlay surface layer and the FDR layer together serve as one monolithic structure. This can only occur if there is a proper and long-term bond between the two layers. Care must be exercised in constructing a bonded concrete overlay over an FDR layer. Very few bonded concrete overlays over an FDR layer have been constructed in the United States.

Bonded concrete overlays over FDR require special considerations because of the increased attention to detail required in all phases of the design and construction that are sometimes overlooked in the execution of a project. The design, specifications, construction, and field supervision require a commitment to proper techniques. For best results, projects should be designed and constructed by personnel experienced in bonded concrete overlays.

For a bonded concrete overlay, it is recommended that moist curing of the FDR layer be used instead of a bituminous curing membrane; oil in the membrane will prevent bonding between the FDR layer and the concrete overlay. The surface of the FDR layer must be tight (no loose surface material or dusting) to allow bonding between the overlay and the FDR layer. To assist in achieving a tight surface, mixing of the materials is important and may require adjustments from normal practices. As discussed in Chapter 5, Determine Gradation of Sample, certain material adjustments may be necessary to obtain a tighter surface. The FDR layer should be moist cured for two days before performing the bonded concrete overlay. It is critical the surface be continuously moist cured, or the tight FDR surface will dry out causing a dusty surface that will not bond to the overlay.

Pre-cracking of the FDR layer is not necessary because the concrete overlay is considerably stronger than the FDR layer and cracks should not reflect into the concrete overlay. Joint spacing (in feet) of the bonded overlay should be limited to 1.5 times the overlay thickness (in inches). See Chapter 4 for thickness design. The designer is encouraged to contact the National Concrete Pavement Technology Center at Iowa State University or the Portland Cement Association for further details.

Environmental Considerations

All construction activities are susceptible to the limitations of weather and environmental conditions. Full-depth reclamation with cement construction is also vulnerable to the environment and should be undertaken when weather conditions are favorable. Environmental factors such as temperature, weather, and wind can play a role in a successful project.

Temperature

The ambient temperature can have an effect on how the existing asphalt pavement is pulverized. In cooler temperatures the asphalt layer is stiff and more brittle, resulting in the pavement being pulverized into smaller pieces. Warmer temperatures cause the asphalt pavement to become more plastic and flexible, and pulverization can cause the asphalt to break off in large chunks. The most efficient ambient temperature for proper sizing of reclaimed material is between 50 and 90°F (ARRA 2015).

Full-depth reclamation should not be conducted when any of the existing materials are frozen or if freezing temperatures are forecast within seven days of FDR completion. An FDR project should not commence when the air temperature is below 40°F (Luhr et al. 2014).

Rain

An FDR base may be adversely impacted if rain occurs during construction. A light rain, especially after finishing operations, should not be detrimental; however, the additional moisture added to the mixture from rainfall during mixing operations may increase the moisture content to an undesirable level. When heavy rains occur, the mixed FDR layer containing cement should be compacted immediately, and further cement spreading should cease until the rain stops. Excessive moisture may adversely affect the ability to achieve the minimum compaction requirement. If the moisture content of the pulverized material is too high, the base should be allowed to dry to within an acceptable moisture content range by intermittently mixing the FDR material.

Wind

When dry cement powder is placed on the pulverized mixture, windy conditions can create dust behind the spreader truck. To control cement dust, contractors can use special enclosures on the spreading mechanism to contain the dust within the enclosure. However, dry cement placement should be avoided in excessively windy conditions, especially in urban environments.

Windy conditions can create not only dust control problems during construction but also significant drying of the cement-treated base that can lead to compaction issues, inadequate strength development, and undesirable shrinkage cracking. Surface moisture can be difficult to control in windy conditions if continuous moist curing methods are employed. Curing membranes applied immediately after finishing operations are an alternative method to avoid excessive drying of the base in windy conditions.

Opening to Traffic

Full-depth reclamation construction can be performed under traffic if the operation is confined to one side of the road (Figure 6.20). Traffic can be controlled with flagging personnel or pilot cars.

The completed FDR base can be opened almost immediately to low-speed local traffic as long as the base is sufficiently stable to withstand marring or permanent deformation from traffic loads. It is recommended that the FDR layer be allowed to cure for two days before the surface course is applied. This allows adequate time for inspection of the FDR layer to determine if any isolated soft spots exist and, if so, to correct them before application of the surface layer.

As soon as a surface course has been applied, the roadway can be opened to all traffic. Early opening to traffic is discussed in more detail in Chapter 7.

Figure 6.20. Full-depth reclamation while maintaining traffic

Chapter 7

Field Inspection and Testing

A well planned and executed quality control program during construction will ensure the project is constructed properly. Sampling and testing of materials, equipment, and processes should be performed to verify that FDR construction is meeting the project specifications.

A certified testing laboratory and other qualified personnel should perform on-site tests and inspections throughout the construction process. If the specifications call for testing services to be provided by the contractor, the proficiency of the testing services should be reviewed and approved by the engineer prior to construction. In addition to reviewing and approving the adequacy of testing services, the owner agency should have unrestricted access to the testing laboratory, split samples, and all test results associated with quality control and quality assurance on the project.

Inspector's Checklists

Field inspection and testing involves the control of five main factors: cement content, moisture content, mixing, compaction, and curing. A list of items that should be reviewed and verified before and during construction is shown below. This checklist was adapted from one in the Full Depth Reclamation Construction Checklist developed by ARRA and the FHWA (2013). Information was also obtained from the PCA's Soil-Cement Inspector's Manual (2001). It should be noted that this list is not all inclusive and specific items and circumstances should be considered on an individual project basis.

Preconstruction Checklist

Before construction, construction and inspection personnel should do the following:

- Review soil survey and laboratory reports, plans, and specifications and check for any discrepancies with job conditions
- Ensure all parties involved in the construction including contractor, site engineer, and testing personnel attend a preconstruction meeting
- Identify and correct any soft and unsuitable areas
- Verify that all underground utilities and drainage structures have been identified
- Ensure that all pre-milling, if required, was performed satisfactorily

Equipment Checklist

Prior to using field equipment on the construction site, it is important for the contractor to demonstrate to the owner/owner's field representative that the equipment to be used for the FDR process meets or exceeds the following criteria:

Reclaimer:

- Reclaimer meets the requirements of project specifications.
- Carbide cutting teeth are all in place and not excessively worn.
- Spray bar and nozzles are working properly and not clogged.
- Correct amount of water is being added to achieve a homogenous mixture and achieve specified percent compaction.
- When using cement-slurry injected directly into the mixing chamber, the on-board slurry system has a positive interlock system linked to the forward speed of the reclaimer so the amount of slurry being added will change according to the operational speed of the reclaimer.

Water trucks:

- Interior of the water tank is not contaminated.
- The flexible hose used to convey water from the water truck to the reclaimer is clean and not contaminated.

Cement spreaders:

- Cement spreaders or other distribution equipment provides a uniform distribution of dry cement while minimizing dust.
- For cement slurry placed on the ground directly in front of the reclaimer, the dispensing equipment is equipped with a metering system to record the amount of slurry being applied.

Motor graders:

- Motor graders have cross slope indicators and are in accordance with those specified in the contract documents.

Compaction rollers:

- Rollers are in accordance with those specified in the contract documents. Large pneumatic-tired, vibratory smooth drum or padfoot rollers may be used for initial and intermediate compaction. Finishing rolling is typically performed with a vibrating smooth drum or static steel roller.
- Number of rollers used is consistent with the rate of material being processed and placed.
- Rollers have the proper operating weight, and the tire pressures on pneumatic-tired rollers are consistent with the tire pressures specified in the contract documents.
- Working water systems are installed on all rollers as required by the contract documents.
- Working scrapers are in place on all rollers as required by the contract documents.

Construction Checklist

It is also critical to inspect the construction process to ensure the FDR layer meets the project specifications. Construction observation personnel should verify the pulverization, grading, cement application, mixing, and compaction operations.

Prior to initial pulverization, the inspector should verify the following:

- All underground utilities and drainage structures have been properly marked and precautions taken by the contractor to protect structures from damage during construction.
- All weak and unstable areas have been corrected.
- The pulverizing limits are marked to guide the operator before pulverization begins.

During initial pulverization of the existing asphalt pavement and underlying materials, the contractor should do the following:

- Verify that the depth of pulverization meets the depth specified in the contract documents.
- Take a depth check anytime the depth changes or if the equipment sits idle.
- Verify the pulverized material meets gradation requirements as specified in the contract documents (Figure 7.1).
- Verify the pulverized material is consistent with samples/cores provided for the mix design.
- Determine the moisture content of the initial pulverized material to determine if an adjustment is needed to reach or maintain optimum moisture.
- Verify pulverization along curbs and around manholes and other structures.

During the cement application process, inspection personnel should do the following:

- Verify the mixer is ready to follow the cement spreader as closely as possible.
- Verify that application rates of stabilizing agent and additive meet the application rates specified in the mix design and remain consistent throughout the treatment area.
- Check application rates are correct by periodically measuring the cement spread.
- Notify the engineer anytime the cement application rate is changed. The cement application rate should be checked and recorded for each segment for which the percentage is changed.

During the mixing stage of construction, inspection personnel should do the following:

- Verify the blending/mixing of water and stabilizing agent is adequate to ensure a homogenous, consistent blend throughout the treatment section.
- Monitor the amount of water introduced to maintain the specified range of optimum moisture content.
- Check that longitudinal joints overlap a minimum of 6 in.
- Check that transverse joints overlap a minimum of 2 ft.
- Verify mixing of all material along curbs and around manholes and other structures.

Figure 7.1. Gradation verification during construction

- Ensure that the time after initial contact of cement with water does not exceed 60 minutes. Mixing operations should begin within 30 minutes of placement of the cement.
- Verify depth of mixing.

During compaction, inspection personnel should do the following:

- Verify an adequate rolling pattern has been established and the compaction roller is immediately following the reclaimer.
- Monitor density/compaction of the material meets specification/contract document requirements.
- If a nuclear gauge is used to determine in-place density, conduct tests in the direct transmission mode to the full depth of the stabilized layer. The moisture content should be taken using microwave oven, direct heating, or established ASTM procedures instead of relying on the nuclear gauge.
- Verify final grade meets specification/contract document requirements.

During grading operations, inspection personnel should do the following:

- Monitor to ensure the motor grader (preferably with automatic grade control) is closely following the compaction rollers.
- Be careful to not overwork the treated mat so as to compromise its structural integrity during the curing process.
- Ensure the material is kept within the roadway width.
- Monitor surface moisture content and apply water as necessary to maintain optimum moisture.
- Check profile.
- Check cross slope.

During finish rolling, inspection personnel should do the following:

- Ensure that finish rolling is done in the static mode and the surface material is not damaged.
- Ensure that the surface is kept moist and not allowed to dry out.
- Verify microcracking (pre-cracking), if required, is performed in accordance with contract documents.

If microcracking (pre-cracking) is specified in the contract documents, inspection personnel should do the following:

- Verify that the delay time between final compaction and start of pre-cracking meets the specified time range.
- Verify that the size, speed, and amplitude of the vibratory roller meets the specification/contract documents.
- Verify that the surface moisture is maintained prior to and after microcracking.

During curing, inspection personnel should do the following:

- Verify the type of curing to be applied and that curing commences soon after final finishing operations.
- If a curing compound is used, verify that the application rate adequately covers the area being stabilized and meets specification requirements.

Prior to initial opening to traffic, inspection personnel should do the following:

- Walk the entire length and width of the FDR surface to ensure the entire area has hardened and no soft spots exist.
- Proof roll the surface to verify material can support light traffic.
- Ensure temporary pavement markings required by the contract documents are in place.
- Ensure initial traffic does not impair material curing.

Quality Control

The successful construction of FDR with cement base relies on the control of depth and uniformity of pulverization, cement content, moisture content, and compaction.

If the subgrade material below the FDR layer is soft and will not adequately support the FDR layer, construction personnel should halt construction until a solution is determined. This situation can often be corrected by blading the pulverized material to one side of the roadway and removing the poor soils under the proposed FDR layer. The excavated area should be filled with suitable fill and compacted before moving the pulverized material back to the roadway and before adding cement. Success has also been achieved in some situations by increasing the depth of pulverization and mixing.

Although full compaction may not be achieved below 12 in., as long as the top foot is compacted and the base can be proof rolled without obvious displacement, satisfactory performance has been attained.

Pulverization

Pulverization of the existing asphalt pavement and underlying material is important in achieving a homogenous mix for cement stabilization. As stated earlier, 55 percent of the pulverized material should pass the no. 4 sieve and 100 percent of the pulverized material should pass the 3-in. sieve. The pulverization of the existing material can be improved by the following:

- Slower forward speed of the mixing machine
- Additional passes, if using a multiple-pass mixing machine
- Replacing worn mixer teeth
- Prewetting and premixing the soil at optimum moisture content before processing begins

The depth of pulverization should be verified by inspection personnel to ensure construction operations are meeting the project specifications. A rod or other measuring device with marks on it can be used to check the depth of the pulverized material. As a rule of thumb, 8 to 9 in. of loose mix will produce a 6-in. compacted thickness (PCA 2001). Frequent depth checks should be performed to ensure uniformity throughout the corridor.

If the pulverized material does not meet the consistency of the material samples used in the mix design, construction and inspection personnel should notify the engineer before adding cement. This situation would likely be observed when the gradation is verified following pulverization. The engineer should determine whether the mix design is still applicable based on the pulverized material on site. Additional testing of the pulverized material may be performed, and a revised cement content may be necessary.

Cement Application

During cement application operations, cement spreaders should be operated at a constant slow rate of speed. A consistent level of cement should be kept in the hopper to obtain a uniform cement spread. String line or other edge markers should be used to obtain the true edge of pavement.

To verify that the spread rate is consistent with the project specifications, inspection personnel can use two methods. The first method is to place a 1-yd^2 canvas (Figure 7.2) or pan on the ground ahead of the cement spreader. After the spreader has passed over the canvas or pan, the inspection staff can pick up the canvas or pan and weigh the cement collected on it.

The second method is to check the distance over which a truckload of cement of known weight is spread. This distance will vary depending on the width of cement spread and the weight of cement on the truck. The inspection staff will have to calculate the travel distance of the truck based on the cement application rate. Inspection personnel can place stakes at the beginning of the test section and at the location where the truck runs out of cement and compare this distance with the calculated value.

Moisture Content

An important factor in a successful FDR mix is moisture content. The FDR mix should be at the optimum moisture content throughout mixing and compaction for the entire treatment depth. It is not recommended to determine the moisture content by nuclear gauge, since the moisture reading with this method can be unreliable.

The moisture content of the mix during construction can be determined either by ASTM D4643 (microwave oven) or ASTM D4959 (direct heating). Figure 7.3 shows the direct heating method. The moisture content of the sample is then calculated using the following equation:

$$\textit{percent moisture} = \frac{\textit{wet weight-dry weight}}{\textit{dry weight}} \times 100 \qquad \text{(Eqn. 7.1)}$$

With a little experience, an inspector can estimate the moisture content of a soil-cement mixture by observation and feel. A mixture near or at optimum moisture

Figure 7.2. Cement application rate verification

content is just moist enough to dampen the hands when it is squeezed in a tight cast. Mixtures above optimum will leave excess water on the hands, while mixtures below optimum will tend to crumble easily. If the mixture is near optimum moisture content, the cast can be broken into two pieces with little or no crumbling.

The hand-squeeze test (Figure 7.4) is not a replacement for the standard moisture-content test, but it does reduce the number of these tests required during construction. The moisture-determination test validates what has been determined by visual inspection and the hand-squeeze test (PCA 2001).

If the moisture content of the pulverized material is low, water should be added to the pulverized mix to reach the target moisture content. Alternatively, if the moisture content is higher than target moisture content, the pulverized material should be aerated.

At the start of compaction, the moisture content of the soil-cement mixture must be at slightly above optimum. A final check of moisture is made at this time. Proper moisture is necessary for proper compaction and for hydration of the cement. Because of evaporation, it is better to have a slight excess of moisture than a deficiency when compaction begins (PCA 2001).

Figure 7.3. Drying an FDR sample by using a stove for moisture content verification

Figure 7.4. Hand-squeeze moisture test

During compaction and finishing operations, the surface of the FDR mixture may become dry, as evidenced by graying of the surface. When this occurs, very light applications of water are made to bring the moisture content back to optimum (PCA 2001).

Uniform Mixing and Depth

A thorough mix of pulverized asphalt pavement, underlying material, cement, and water is necessary for a quality FDR base. The uniformity of the mix can be verified by digging trenches or a series of holes at regular intervals for the full treatment depth and inspecting the color of the exposed material. The area between the mixing lanes should also be checked. The mix is considered satisfactory when there is a uniform color and texture throughout the entire treatment depth. A mixture that has a streaked appearance has not been mixed sufficiently (PCA 2001).

To ensure that cement has been adequately mixed to the full treatment depth, a phenolphthalein solution can be sprayed in the trenches or small holes discussed above. A chemical reaction between the phenolphthalein and cement in the FDR mixture produces a pinkish-red color, indicating the presence of cement (Figure 7.5, from Scullion et al. 2012).

If the pinkish-red color extends to the bottom of the specified FDR depth, adequate mixing has been achieved. However, if the pinkish-red color does not extend to the full depth of the FDR layer, mixing operations should be modified to ensure cement is evenly mixed throughout the FDR depth.

Figure 7.5. Checking depth of cement stabilization with phenolphthalein

Density Tests

In-place density tests should be performed immediately after final rolling at several locations on the first few sections completed. A nuclear gauge can be used to determine the degree of compaction obtained in the field. Nuclear gauges should be used in the direct transmission mode of operation per ASTM D2922 / AASHTO T 238 (Figure 7.6). Many of these nondestructive tests can be run in a short time. It should be noted that nuclear gauges should be properly calibrated, operated, and maintained to ensure results are accurate.

Occasionally it may be necessary to conduct a moisture-density Proctor test in the field. This is done when the in-place field density results differ significantly from the laboratory moisture-density results. Also, whenever there appears to be a change in gradation or other mixture characteristics, the inspector should conduct a moisture-density Proctor test.

The inspector begins by obtaining a representative sample of the mixture from the roadway at the conclusion of the mixing operation. The inspector then compacts the mixture in the mold in accordance with ASTM D558. The mold should be placed on a solid foundation (Figure 7.7).

When completed, the inspector will compare the moisture content and dry density determined from this test with the laboratory developed moisture-density Proctor test used for field control. If the point represented by the field result falls on or close to the point on the moisture-density curve developed in the laboratory, than the laboratory Proctor test results can be considered valid for field control. This is often referred to as a one-point Proctor test; this is an indicator test only and should not be used to establish a new field optimum moisture content and maximum dry density control. If the point represented by the field Proctor test falls significantly outside the laboratory Proctor curve, or if a new optimum moisture content and maximum dry density Proctor curve is requested, then a full series of moisture contents and corresponding dry density points is required in order to establish a new moisture-density Proctor curve.

Figure 7.6. Density of compacted FDR being determined by a nuclear gauge in direct transmission mode

Coring of Completed Work

Upon completion of the FDR layer, core samples can be obtained for verification purposes (Figure 7.8). The cores

Figure 7.7. Proctor test during construction

Figure 7.8. Core from a completed FDR project

can be used to verify FDR layer depth. However, it is not recommended to use compressive strength results from core samples as an acceptance criteria. Unlike concrete, issues with the lower-strength FDR and coring method may cause internal damage to the core, resulting in reduced strength results. Although compressive strength results from cores should not be used as an acceptance criteria, the results can be a good indicator of whether the FDR layer is hardening properly.

Visual inspection of the cores should be made and recorded before compressive strength testing. Record any segregation or voids in the core. Also record the density of the cores prior to testing. Due to the sensitivity of the FDR material at early ages, cores should not be taken until at least seven days after completion of the FDR layer.

Testing Frequency

Quality control during construction should be performed by the contractor or an independent testing laboratory to ensure that operations are meeting the project specifications. The contractor should ensure conformance of all construction operations and materials. All test results should be provided to the engineer. In addition, the contractor should immediately notify the engineer of any failing tests and subsequent remedial action.

Quality assurance should be provided by the engineer or an independent testing laboratory for material tests during construction. The engineer should witness the sampling and splitting of samples and immediately retain the witnessed split samples for quality assurance testing. In addition, the engineer should witness the sampling and testing of all construction tests provided by the contractor.

An example of testing frequencies is shown in Table 7.1. This table may require revised frequencies depending on specific project details such as geographic region, project length, or problems experienced during construction. It is recommended that all quality control tests be performed after startup or any time a change in the mix occurs. In addition, quality assurance verifications by the owner agency can be performed at reduced intervals.

Early Opening to Traffic

The completed FDR with cement layer can be opened to traffic after three days of curing if adequate stiffness is developed in the cement-stabilized FDR layer. The stiffness of the cement-stabilized FDR layer should be estimated over the entire depth of treatment by the dynamic cone penetrometer (DCP) tests performed in accordance with ASTM D6951. The in-situ DCP index measured in the test is correlated to the stiffness of the FDR layer.

The DCP is a simple instrument widely used for quasi-destructive evaluation of subgrades. The DCP consists of a 0.625-in. diameter steel bottom rod with anvil, a hardened point, and a 17.6-lb hammer that is dropped 22.6 in. The hardened point has an inclined angle of 60 degrees and a diameter at the base of 0.79 in. To perform the test, the operator holds the device by the handle in a vertical or plumb position and lifts and releases the hammer from the standard drop height. The recorder measures and records the total penetration for a given number of blows or the penetration per blow. An in-situ DCP index of less than or equal to 10 mm/blow after three days curing of the cement-stabilized FDR layer should be considered acceptable for construction of the subsequent pavement layer.

Curing of the cement-stabilized FDR layer is considered complete upon placement of the subsequent pavement layer. The pavement layer (asphalt, chip seal, or concrete) can be placed any time after finishing, as long as the cement-stabilized FDR layer is sufficiently stable to support the required construction equipment without marring or permanent distortion of the surface.

Table 7.1. Testing Frequencies

	Testing frequency	
Test	**QC start-up frequency**	**QC ongoing frequency**
Depth of pulverization	1 per 500 ft	1 per 1,000 ft
Pulverized material gradation	1 per 0.5 day of production	1 per day of production
Cement application rate	1 per 500 ft	1 per 1,000 ft
Optimum moisture & MDD	1 per 0.5 day of production	1 per day of production
Field moisture content	1 per 500 ft	1 per 2,000 ft
Compacted density	1 per 500 ft	1 per 1,000 ft

Chapter 8

Long-Term Performance

Unless otherwise cited, much of the information in this chapter comes directly from research into the long-term performance of FDR with cement (Syed 2007) and a related research synopsis (Halsted 2007).

Full-depth reclamation with cement projects have a proven track record for providing a sustainable, economical, and durable pavement rehabilitation solution. Studies have shown that agencies that use the process save between 30 and 60 percent over conventional reconstruction methods (Halsted 2007). The FDR with cement process has been used on pavement projects for more than 30 years with great success (Figure 8.1). It has been used successfully at the city, county, and state level to address deteriorating pavements and increase pavements' structural capacity.

Syed (2007) analyzed the field performance of 75 FDR with cement projects in eight states across the country. The age distribution of the projects analyzed is shown in Figure 8.2 (Halsted 2007). Performance-related data such as pavement inventory, functional and structural information, traffic data, material composition, amount of cement added, and construction details were collected.

The evaluation process consisted of interviewing the roadway owner/agency about the methodology used to select candidate projects and about the design and construction of the FDR projects. The process also included performing visual pavement surveys, taking cores at select pavement locations, and performing strength measurements on the cores. This preceded a qualitative assessment of the long-term strength and stiffness of the reclaimed roadways.

Visual Surveys

The visual surveys focused on pavement distresses found at the project sites. In particular, pavement distresses that may have been due to the condition of the base such as block cracking, roughness, and deep potholes were analyzed. The pavement distresses were systematically recorded to identify their type, extent, and severity. The PCI was used to assign a numerical value to the pavement condition based on the observed distresses. Performance condition index values range from zero for a failed pavement to 100 for a pavement in perfect condition.

The average PCI rating for the projects in the study ranged from 88 to 97, which is in the excellent category. The results showed that almost all the roads where FDR was utilized are performing well (Table 8.1, from Halsted 2007).

Most of the distresses identified in the visual surveys were in the asphalt surface course and not in the FDR base. Any distresses caused by the base (such as minor reflective cracking) did not affect the roughness or overall road performance. No cases were identified in which severe pavement distress was caused by the FDR with cement base.

Long-Term Strength

Representative core samples of the reclaimed base from some of the pavement sections were obtained and

Figure 8.1. South Carolina state highway 97 (SC 97) is an FDR with cement project with excellent performance after 20 years of service

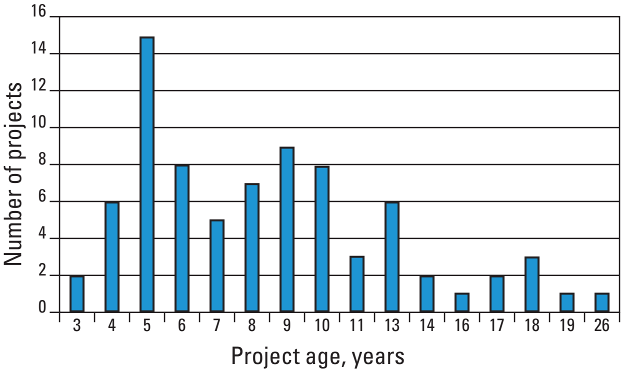


Figure 8.2. Histogram showing age of projects in study

Table 8.1. Summary of PCI Results in PCA Study

Agency	Pavement Condition Index, %			
	Min	Max	Average	Standard deviation
City	73	100	89	6
Private developers	95	98	97	2
County	43	100	89	10
State DOT	82	92	88	4
Overall	43	100	89	8

subjected to laboratory unconfined compressive strength (UCS) measurements to determine the in-place strength of the reclaimed base after many years of performance. The results showed the UCS of these samples ranged from 260 to 2,110 psi, with the average of all samples being 914 psi (Halsted 2007). Typically, these FDR sections were originally designed for a seven-day UCS of between 400 and 600 psi.

The majority of cores were tested for UCS in accordance with ASTM C42, while others were tested to determine their seismic modulus using the free-free resonant column developed at the University of Texas at El Paso. The primary reason for performing the seismic modulus was to obtain the resilient modulus for the reclaimed base, which is a required input for the new American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (2008).

Based on the seismic modulus testing results, the lowest UCS value of 260 psi would roughly correspond to a stiffness of 200,000 psi, which is considered excellent in terms of the reclaimed base's ability to support traffic loads and minimize the stress that is transferred to the subgrade.

Durability

The durability of a roadway base subjected to wetting-drying and/or freezing-thawing cycles is a critical parameter for any roadway's satisfactory performance. Durability issues are especially challenging in wet, northern climates where deeply penetrating freeze-thaw patterns can cause an unstabilized pavement base to lose strength and stiffness. Of the 79 projects that were part of the study, more than 50 were in areas with moderate to severe winter weather conditions.

Volume change and loss of strength caused by traffic loads, environmental conditions, and water movement within pavement layers cause heaving roadways, posing a serious safety risk to drivers. County engineers say road heaving due to winter freeze and rutting due to spring thaw are among their biggest challenges. The FDR process has proven very successful in combating F-T challenges. The heaving has been eliminated, and the engineers are pleased to report that their roads are operable in cold weather conditions.

Overall, the FDR process has been a very positive experience for agencies in northern areas that have severe weather (Figure 8.3). The agencies have successfully provided public roads that do not heave in the winters or lose shear strength during spring thaws, allow businesses to efficiently move goods, and have enhanced road safety. A pavement manager in Washington state indicated that FDR with cement has enabled his county to build "all-weather" roads (Syed 2007).

County and state department of transportation engineers in Idaho explained that road heaving due to winter freeze and rutting due to spring thaw are major challenges. Some roadways in the state experience more than 100 in. of snowfall during the winter months. The FDR with cement projects have been successful for roadways in Idaho. The engineers interviewed in the study indicated heaving has been eliminated and they are pleased that their roads are operable in cold-weather conditions (Syed 2007).

The study analysis also concluded that FDR with cement improved the durability of roadways in areas where significant rainfall is common. A roadway in South Carolina was located in an area where significant rainfall (48 in. per year), combined with inadequate pavement structure, weak subgrades, and poor drainage caused many problems prior to FDR. After the roadway was rehabilitated with FDR, the local engineer indicated the road's performance has improved and the roadway is no longer a perennial maintenance issue; the roadway has stayed in good to excellent condition for more than 20 years.

The PCA's report *Full-Depth Reclamation using Portland Cement: A Study of Long-Term Performance* (Syed 2007) contains analyses of numerous projects throughout the country that have utilized FDR with cement. For additional information regarding the long-term performance of FDR with cement, refer to the PCA's website (www.cement.org/) for case histories of other projects that have used this rehabilitation method.

Figure 8.3. Logging truck on FDR roadway in Spokane County, WA, with nine years of service

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