Quality Base Material Produced Using Full Depth Reclamation on Existing Asphalt Pavement Structure

FHWA Contract No. DTFH61-06-R-00031

Task 1 Completion Report: Literature Review

(Oct. 1, 2006 – May 31, 2007)

Submitted to

Federal Highway Administration

By

Nicole Nielsen, Benjamin Hauser, Terje Preber, Peter Sebaaly, Dan Johnston, Dave Huft, Sangchul Bang

South Dakota School of Mines and Technology
South Dakota Department of Transportation

May 31, 2007
# Table of Contents

EXECUTIVE SUMMARY ................................................................................................................................. 5  
1.0 INTRODUCTION ............................................................................................................................. 6  
  1.1 Hot In-Place Recycling .............................................................................................................. 7  
  1.2 Cold In-Place Recycling ........................................................................................................... 9  
  1.3 Full Depth Reclamation ............................................................................................................ 11  
2.0 HISTORY ........................................................................................................................................ 16  
3.0 ECONOMICS ..................................................................................................................................... 20  
4.0 CONSTRUCTION EQUIPMENT ..................................................................................................... 22  
5.0 SPECIFICATIONS/PROCESS ..................................................................................................... 24  
6.0 FIELD TESTING .......................................................................................................................... 26  
  6.1 Falling Weight Deflectometer .................................................................................................... 26  
  6.2 Seismic Pavement Analysis ...................................................................................................... 26  
  6.3 Ground Penetrating Radar .................................................................................................... 27  
  6.4 Pavement Analysis Vehicles .................................................................................................. 28  
  6.5 Visual Distress Surveys .......................................................................................................... 28  
7.0 REVIEW OF FIELD TESTING METHODS ................................................................................... 29  
  7.1 Falling Weight Deflectometer .................................................................................................... 29  
  7.2 Ground Penetrating Radar .................................................................................................... 31  
8.0 REVIEW OF LABORATORY TESTING PROCEDURES ............................................................... 32  
  8.1 Sieve Analysis .......................................................................................................................... 33  
  8.2 Atterberg Limits ..................................................................................................................... 33  
  8.3 Moisture-Density Relationship ............................................................................................. 33  
  8.4 Bulk Specific Gravity .............................................................................................................. 33  
  8.5 Resistance to Permanent Deformation .................................................................................. 34  
   8.5.1 Repeated Load Triaxial Test .............................................................................................. 34  
   8.5.2 Wheel Loading Devices .................................................................................................... 34  
  8.6 Resistance to Moisture Damage ............................................................................................ 35  
   8.6.1 Tube Suction Test .............................................................................................................. 35  
   8.6.2 Freezing and Thawing of Soil Cement Mixtures ............................................................... 36  
   8.6.3 Effect of Moisture on Asphalt Concrete Paving Mixtures ............................................. 36  
  8.7 Unconfined and Confined Compression Test ........................................................................... 37  
  8.8 Resilient Modulus ................................................................................................................... 37  
   8.8.1 Resilient Modulus of Unstabilized FDR Bases ................................................................. 37  
   8.8.2 Resilient Modulus of Bituminous Stabilized FDR Bases ................................................ 38  
  8.9 Modulus of Rupture ............................................................................................................... 39  
  8.10 Dynamic Modulus .............................................................................................................. 39  
9.0 TESTS USED IN PREVIOUS STUDIES ON FDR BASES ............................................................ 39  
  9.1 Compaction ............................................................................................................................. 39  
  9.2 Bulk Specific Gravity .............................................................................................................. 40  
  9.3 Moisture susceptibility ............................................................................................................ 41  
  9.4 Rut Resistance ...................................................................................................................... 42  
  9.5 Resilient Modulus ............................................................................................................... 43  
10.0 ADDITIVES ..................................................................................................................................... 44
EXECUTIVE SUMMARY

Full depth reclamation (FDR) is one of the three major types of asphalt recycling techniques. FDR is considered when the pavement is highly deteriorated or has deep cracking due to design deficiencies or an inadequate base. Other indications that a road could use FDR are frequent transverse and lateral cracking, reflective cracking, severe rutting and frost heaves.

Studies have shown that asphalt recycling can cost up to 50% less than conventional methods, therefore, it is a cost effective and environmentally friendly method of asphalt pavement recycling. FDR consists of pulverizing the entire asphalt pavement section along with a predetermined amount of underlying base, sub-base, or subgrade material to produce a new base course through compaction and addition of additives, which is then overlaid with a new riding surface course. This process can be done by pulverization and mixing in-place with a reclaimer/stabilizer machine or by pulverization in-place then hauling the recycled material to a central plant for mixing.

This report includes the results of an in-depth literature review as part of a comprehensive FHWA research program on FDR, which includes the compilation of current practice on FDR, mix design, establishment of laboratory testing methods, field validation test, and field performance monitoring.

Included in this report are summaries of literature reviews on: the history, economics, construction equipment, and specifications associated with FDR; field testing methods; laboratory testing procedures; and additives. Field testing includes: visual distress surveys, ground penetrating radar, falling weight deflectometer, and seismic pavement analysis. Laboratory testing includes: gradations, Atterberg limits, moisture content, bulk specific gravity, resilient modulus, and dynamic modulus. Three types of material stabilization additives include: mechanical, chemical and bituminous.
1.0 INTRODUCTION

Over the past couple of decades the growing demand for safe, efficient, and cost effective roads has led to an increase in the need to rehabilitate existing roadways. The last 25 years has also seen a dramatic growth in asphalt recycling and reclaiming as an environmentally preferred way of rehabilitating the existing pavements (1). According to the Asphalt Recycling and Reclaiming Association (ARRA), asphalt recycling and reclaiming meets all of our societal goals of providing safe, efficient roadways, while at the same time drastically reducing both the environmental impact and energy (oil) consumption compared to conventional pavement reconstruction.

The three different methods used for in-place asphalt recycling include: hot in-place recycling (HIR), cold in-place recycling (CIR) and full-depth reclamation (FDR). Additional methods of asphalt recycling include: hot recycling (HR) and cold central plant recycling (CCPR). When choosing the right method for a project, the type of distress the road is currently exhibiting should be the main consideration. The difference between CIR and FDR is that CIR mills and screens the top 2-4 inches (50-100 mm) of the existing asphalt layer and places it as a layer for a new base course, while FDR mills and screens the entire asphalt layer and portions of the underlying pavement structure to produce a new base course. HIR is best used when the asphalt is experiencing raveling, flushing, slipperiness, corrugations, shallow rutting or longitudinal (wheel path or joint) cracking (17). Assessment of the existing pavement conditions, mode of failure, causes of distress and testing of pavement material, base, sub-base, and subgrade should be completed before choosing a method of rehabilitation.
CIR and FDR are both suitable for load and non-load associated cracking but since FDR addresses structural and base problems, it should be used when the road has a weak base or subgrade because the subgrade can also be treated. The subgrade, however, is not always treated. FDR is also better than CIR for treating depressions or high spots on the road, especially if the depressions are caused by soft, wet subgrade conditions, or the high spots are caused by frost heave or swelling of an expansive subgrade soil.

Some signs that a road could benefit from FDR include: frequent transverse and longitudinal cracking, reflective cracking, heavy pothole patching, severe rutting, frost heaves, soil strains on the surface, parabolic shape and insufficient base strength to support current loads. FDR eliminates all distress areas in the flexible pavement (12). Other pavement rehabilitation strategies include a thick structural overlay and removal and replacement of the existing base and asphalt surface. Although both provide a new pavement structure they can be very expensive and excessive virgin aggregates are necessary. Because of the uniqueness of each technique, very few roads qualify for more than one recycling technique.

1.1 Hot In-Place Recycling

HIR is a recycling technique where one to two inches (25 to 50 mm) of the hot mixed asphalt (HMA) surface is heated, scarified, remixed and relayed to correct minor deficiencies in a pavement. HIR should be used when a simple HMA overlay is not enough to correct the problem. HIR should not be used for pavements with base problems or deep cracks (usually no deeper that two inches (50mm)). HIR restores and
enhances the HMA properties which provides for improved flexibility, durability, and ride quality (16).

There is currently no nationally accepted mix design method for HIR (19). The goal of a HIR mix design is to restore the properties of the existing asphalt pavement to those of a virgin HMA. This method attempts to account for the changes which might have occurred in the existing HMA over time. Rejuvenating agents or other pavement materials are added and blended with the milled material if needed. Many times the addition of surface course such as, an asphalt overlay or a chip seal is more economical and beneficial than adding material to the existing mix. The recycled material is then spread to the desired grade and compacted to the required density. A full investigation of the existing HMA layer (specifically binder and aggregate properties) should be done before beginning the mix design process for HIR. HIR activities should be accompanied by an improvement or reconstruction of the drainage system.

The equipment utilized in HIR is highly mobile and not dependent on localized operating processes; therefore it is not necessary to work within a close proximity of an asphalt plant; unless the process includes overlaying the HIR pavement with a HMA layer. The HIR paving train is compact and moves along quickly and therefore allows for traffic to continue while repaving. The use of modern indirect radiant or infrared heating units reduces the aging of the asphalt binder in the recycled HMA layer (29). Bringing the temperatures up gradually using multiple pre-heaters operating at lower temperatures will also help to produce a high quality mix that has a good bond between the hot recycled layer and the remained in-place HMA layer. HIR normally costs 10 to 20% less than a mill-and-fill at the same depth because there are fewer trucking costs.
and less virgin aggregate is required. This process also takes about 50% less time than a mill-and-fill. HIR pavements last between 7 and 15 years depending upon the process and the overlay thickness.

1.2 Cold In-Place Recycling

The CIR process consists of milling the existing HMA layer to a specified depth (typically 2 to 6 inches or 50-150 mm) and crushing and screening the reclaimed asphalt pavement (RAP) to meet the contract specifications. Additives are blended in and the final mixture is spread and compacted over the same roadway. It is then overlaid with an HMA or a chip seal. The CIR processing units come in three classes. The Multi-Unit Train cuts to a precise depth. The Two-Unit Train has a variable width cutting head. The Single-Unit Train is an all-in-one system. CIR should be used when the deficiencies are not throughout the entire HMA layer but are still deep enough that they cannot be corrected by HIR or a mill-and-fill. If the pavement has base deficiencies, structural problems or drainage issues CIR should not be used.

Selecting the appropriate pavement section is an important aspect to consider for successful CIR mixtures. Expected traffic volume should also be considered. CIR is typically used for lower volume roads but has been used on interstates in New Mexico, Colorado and Kansas. When CIR is performed on interstates it is usually closed to the traffic until it is overlaid. Fatigue cracking, transverse thermal cracking, reflective cracking and raveling are the types of distress that can be easily corrected by CIR.

CIR provides a base that has good rutting resistance and is cost effective. The resistance to rutting and great amount of flexibility makes it a popular method in warm regions. When the RAP has high asphalt content and/or soft asphalt, rutting becomes
more significant. Although CIR is more flexible than HIR, the higher air voids make it more susceptible to moisture damage. Because of this, the pavement must be sealed with an adequate wearing course. CIR is also good for rural roads because few if any truckloads of material need to be moved. CIR is quick and occupies only one lane of traffic so most roads can be kept open throughout the entire process. CIR costs anywhere between 15 and 50% less than conventional methods and produces roads that last 15 years or more (29).

CIR is a common method that has been used by 24 states (19). In a study between the US DOT, the FHWA and the University of Rhode Island, mix design specifications for CIR of bituminous pavements were analyzed (19). Mix design methods included the Oregon Method, the California Method, the Nevada method, the Chevron Method and more (4, 19). The Oregon Method estimates the initial emulsion content to be added to a recycled mixture. The California method determines the optimum binder content by using the Hveem stabilometer (19). The Nevada method uses the Hveem design with the resilient modulus and the moisture sensitivity tests (4). Asphalt content, aggregate gradation and asphalt viscosity tests are run on the RAP samples. The Chevron Method also determines the optimum binder content. The University of Rhode Island study first evaluated existing mix-design methods, which included determining the asphalt content and RAP gradation. Emulsion content and curing temperature were varied for the experimental design. The study also used the Superpave system modeling/computer analysis to predict performance. The study concluded that the optimum emulsion content determined from five geographically varied locations is between 1.1 and 2.6%. The optimum water content was between 1.8
and 2.9%. The mix design was similar to that for HMA with modifications for the nature of cold mixes. The Modified Marshall Mix Design was not recommended for CIR mix-designs.

### 1.3 Full Depth Reclamation

FDR is a recycling technique for asphalt pavement in which the entire HMA layer and a predetermined amount of the underlying base, sub-base, or subgrade material are recycled to produce a new base course, which can be overlaid with a new HMA layer (27). Other surface treatments such as; single and double chip seals, slurry seals or micro-surfacing can be used during low traffic conditions. The process starts with uniformly crushing, pulverizing and mixing the existing HMA with a predetermined portion of the underlying roadway materials and any other required materials, such as virgin aggregate. The depth of pulverization is usually 6 to 10 inches (150 to 250 mm) with a maximum depth of 16 inches (400 mm) (13). More than one pass of the equipment may be necessary to achieve the proper gradation. The pulverized material is then combined with mechanical, chemical, or bituminous stabilizers to form a high quality stabilized base. With a strengthened base the depth of the asphalt layer may be reduced.

The FDR process can be done using two approaches. In the first approach the existing pavement and base can be salvaged and hauled to a plant for crushing, screening, and mixing. This is a form of central plant recycling and is not common for most FDR applications. In the second approach, the material is crushed, screened, and mixed in-place by a recycling machine. This practice is much more common. Figure 1 shows a schematic of the in-place recycling process. The reclamation can either be
done in a Single Pass or a Multiple Passes process. The Single Pass process is typically used when additives are not used and if the required material gradation is already obtained. The Multiple Passes process is used when the road is widened or there is a change in grade. It should also be used when the depth is greater than six inches (150 mm) or additives are being used.

The advantages of in-place recycling include: reduced material hauling, no plant setup, lower costs, and it can be used with weak subgrade soils where residual base materials provide support for construction operations. The advantages of plant recycling include: better mix of aggregates and additives and more control over the process and product.

The FDR process can be generalized by a six-step process:

1. Perform a site evaluation which includes determining types, levels and sources of pavement damage.

2. Sample the existing roadway to determine the available materials to be recycled. Determine the degree and type of stabilization required.
3. Decide if in-place recycling is appropriate. Pulverized materials from the site should be mixed so that it has a similar consistency of that expected in the field. Laboratory tests such as maximum dry density, plasticity index, sand equivalence, gradation by washing and optimum moisture content should be performed on the mixture to determine if in-place recycling will be suitable.

4. Conduct in-place recycling and verify initial product for specification compliance and suitability.

5. Grade and compact new FDR base material.

6. Construct the new overlay on top of the recycled base. This surface could be hot-mix asphalt, chip seal or concrete.

The main advantage of FDR is the reduction in cost because the use of in-situ materials reduces the amount of materials that must be hauled to or away from the site. Also, with the rising costs of aggregate, virgin material usage is reduced. FDR is also an excellent method for dust and erosion control on existing aggregate roadways reducing complaints from the public and environmental effects on water. Due to a minimal change in elevation, problems with curb, gutter and overhead clearances are eliminated. The construction cycle is fast and there is usually no need for detours.

When rehabilitating a pavement, the road is often built up due to an increase in pavement thickness and requires an extension of the shoulders. This also requires more right-of-way which can be costly. The use of FDR alone does not build the road up like this because the thickness of the recycled asphalt and base is removed and then included within the new base. For sections having a thicker HMA surfacing, widening of the embankment may be required unless some of the existing pavement is removed to maintain the original elevation after surfacing.

Figure 3 shows the difference between a roadway with an additional overlay and a roadway with FDR alone. According to the ARRA (2), "The process (FDR) has been
proven on a wide range of flexible pavement structures to produce quality results at substantially lower costs and considerably shorter construction periods than conventional reconstruction practices."

Unlike CIR, FDR reconstructs the base layer with different types of recycling methods. FDR is therefore most suitable for treating problems related to the base. During construction, the pulverized material can easily be used to change the elevation of the roadway to obtain the desired cross-section and grade. FDR is also the best rehabilitation alternative for deep rutting and load and non-load associated cracking (17). FDR does not result in the typical reflective cracking associated with asphalt overlays while improving the pavement base condition. The FDR procedure allows for pavement and shoulder restoration and replacement, structural resurfacing and shoulder widening. Highly deteriorated roads requiring structural improvements due to
pavement failure, design deficiencies, inadequate sub-base materials or surface rutting and cracking are best rehabilitated using FDR.

There are currently no standard design/mix specifications for FDR (2). Although several agencies have used a number of different mix designs, few of these mix design methods have been reported in the literature. Water is normally added to bring the mixture up to the desired moisture content and the mixture is typically compacted to a density of at least 96% of the standard Proctor density (ASTM International (ASTM) D 558) or 97% of the modified Proctor density (ASTM D 1557) (13). The plasticity index, sieve analysis, dry unit weight, optimum moisture content and specific gravity tests should be conducted on all types of FDR bases. The mix design process will be discussed more in the additives section. Laboratory testing may include resilient modulus and bulk specific gravity tests.

After FDR has been chosen for the recycling method, it is necessary to determine if the presumed base material that can be generated will have enough strength or if it will need to be stabilized. When the material is stabilized, a bonding agent is mixed with the RAP and base aggregate to create a cohesive material. Types of material stabilization include chemical and bituminous. Chemical stabilization changes the chemical properties of the base to increase the strength. Chemical stabilizers include portland cement, calcium chloride, hydrated lime and coal fly ash. The kiln dust of cement (CKD) and lime (LKD) has also been used in some applications. Calcium chloride absorbs moisture, which helps in compaction and maintaining cohesion.
Calcium chloride is the least expensive of the stabilizers and works best in well-graded non-plastic soils (17). Other chemical stabilizers such as portland cement, lime and coal fly ash convey cohesive strength to the base through the hydraulic nature of the stabilizer and its ability to develop substantial compressive strength. These stabilizers are also susceptible to cracking if the strength developed is too great. Bituminous stabilization adds asphalt to the newly formed base. Bituminous stabilizers include foamed asphalt and slow or medium set asphalt emulsions. An emulsion-stabilized base is flexible, fatigue resistant and not prone to cracking. It is however, more expensive than chemical stabilizers or foamed asphalt. The stabilization methods are discussed in detail in Section 10 of this report.

The RAP can also be mixed with other materials to provide mechanical stabilization without a bonding agent while still increasing its strength. The increase in strength can come from the addition of virgin aggregate, crushed glass, and geosynthetic fibers. These materials assure the lowest initial cost but may not be the most cost effective because the increase in strength may not be sufficient or long lasting. Section 2 will cover mechanical stabilization methods in greater details.

2.0 HISTORY

The full depth recycling process dates back to the early 1900’s (14). Full depth recycling began with scraping off the asphalt and mixing it in-place with ordinary graders. Then self-propelled mixers were utilized to blend the mixture to provide a more uniform mix. The asphalt was first broken up with a sheep's-foot roller and then remixed with additional asphalt. This mixture was then laid and compacted. It wasn’t until later that portland cement was added to the mixture of pulverized material and
base course to increase the strength. At this time a new lift of hot or cold mix asphalt or conventional concrete could be placed on top.

Milling machines to grind a thin hot mix pavement were not developed until the early 1970’s (14). By the late 1970’s, equipment manufactured by Bomag was able to pulverize HMA concrete up to 4 inches (100 mm) in thickness. Milling machines were developed that could pulverize to depths even greater but generate large pieces of the HMA because of the slow rotor speed. In the early 1980’s Bomag and Bros developed machines called reclaimers that had conical shaped carbide teeth which enabled them to pulverize materials up to 12 inches (300 mm) deep. These machines had higher rotor speeds and could create a well graded material that was similar to aggregate bases. Since the 80’s the reclaimer has continued to be enhanced and can pulverize mixtures up to 20 inches (500 mm).

In February of 2007, the South Dakota Department of Transportation (SDDOT) sent out a survey to 50 states and local government agencies with the intent of determining the extent of the use and knowledge of FDR. A total of 118 agencies responded. Of the 118 responses, 83 agencies continue the use of FDR. Of the 31 respondents that have never used FDR, the reasons included; lack of familiarity, lack of contractor experience, lack of specifications and lack of appropriate sites. Of the four agencies that discontinued the use of FDR, the main reason was because of lack of appropriate sites. Only two agencies reported discontinued use due to unacceptable performance or difficulty in achieving compaction. Figure 4 shows the history of FDR use with the earliest being 1970. The current highway condition and the existing subgrade and base conditions were reported as the main selection criteria. Figure 5 is
a graph of agencies specifications. A total of 71% of agencies reported using bituminous additives, 65% reported using mechanical stabilization and 34% reported using chemical additives. Also, 61% of respondents claimed that the FDR performed about the same as conventionally constructed pavements. Reflective cracking, block cracking and stripping were reported as having occurred the least. Load related cracking, transverse cracking and rutting were reported as occurring rarely or occasionally. None of these pavement deficiencies had over 8% of agencies reporting as having occurred frequently. Figure 6 shows a summary of the types of distresses that have been encountered on FDR projects. The majority of agencies reported that they planned on using FDR for low and high volume highways and 77% of 84 agencies plan on using FDR at approximately the same rate as they are currently using it.

Figure 4. The history of FDR usage by the various agencies.
Figure 5. FDR specifications indicated as being used by the various agencies.

Figure 6. Number of states reporting various problems related to FDR usage.
3.0 ECONOMICS

FDR maximizes the use of existing materials and, because of this; it is a very cost effective technique. In 2006, bituminous materials were 70% higher in cost than two years previous (4), therefore, it is becoming more crucial to construct longer lasting roads at minimum costs. FDR is very economical since the process can be done rapidly in-place as the unrecycled residual base materials provide a stable construction platform for the process. Figure 7 displays some of the parameters for the cost savings basis. FDR is utilized in many areas where there is a limited budget for road maintenance (5). Recycling costs are normally 25 to 50% less than the removal and replacement of the old pavement (13). When an area exceeds 15 to 20% full depth patching, it is more economical to perform FDR rather than continuing patching. Costs and environmental issues are minimized because of fewer truck hauls, material disposal is greatly reduced and structural improvements in the base can be made with little effort. In some localities, old asphalt concrete can no longer be disposed of in landfills due to stricter environmental laws making the disposal process exorbitantly expensive.
According to the article “Full-Depth Reclamation: Recycling Roads Saves Money and Natural Resources” (13), for a one mile (1.6 km) stretch of road that is 24 feet (7.3 m) wide and six inches (150 mm) deep, the number of truckloads needed is reduced from 180 to 12, the new roadway material is reduced from 4,500 to 300 tons (4090 to 292 metric tons), and the diesel fuel consumed is reduced from 3,000 to 500 gallons (4090 to 1925 liters).

The Nevada DOT has reportedly saved over $600M over the past 20 years with the use of CIR and FDR (4). The cost-effectiveness of the use of CIR and FDR has allowed for a significant reduction in project backlog (approximately 60%) without an increase in expenditures. A life cycle cost analysis done by the Nevada DOT shows that the use of FDR and overlay at $382,000 per centerline mile ($237,000 per centerline kilometer) is a far more cost-effective technique than complete reconstruction.
at $715,000 per centerline mile ($444,000 per centerline kilometer). The difference in cost using FDR rather than complete reconstruction is $333,000 per centerline mile ($207,000 per centerline kilometer).

4.0 CONSTRUCTION EQUIPMENT

FDR can be done with various types of equipment. FDR equipment can be categorized by two types: recycle and general. FDR projects require some form of recycling equipment ranging from in-place recycling equipment to plants for mixing base and HMA materials. Several equipment companies manufacture recycling machines with the types varying from portable/detachable units for front-end loaders to large reclaimers which can mill, screen and mix additives in 8+ft (2.5+ m) wide sections to 16 inch (400 mm) depths. Figures 8, 9 and 10 illustrate various types of in-place recycle equipment. Figure 11 shows the milling operation for a two-stage FDR operation.

Figure 8. CAT model RM-500 road reclaimer (Photo courtesy of CATERPILLAR®).

Figure 9. Wirtgen WR 2500s road reclaimer (Photo courtesy of Wirtgen Ameriac Inc.).
When using the rotor, the depth can be varied, making it able to use any portion of the existing base or sub-base. The condition and cross section of the existing pavement are major stipulations in determining what depth to use. The reclaiming machine turns the pulverized material into a homogenous well-graded material. Although the machine doesn’t crush the aggregate, the material normally has a maximum particle size of 2 inches (50 mm) (12).

After the RAP has been placed and stabilized, general construction equipment typically found on highway projects, such as graders and compactors are used for FDR projects as well. According to an article published by Edward J. Kearney and John E. Huffman (17), the equipment typically used on a FDR project includes:

1. A self-propelled reclaiming machine equipped with a liquid additive system,

2. A spreader for the application of dry additives,

3. Motor graders for mixing, aeration, and shaping,

4. Tanker trucks for hauling water, emulsified or cutback asphalts,
5. Water trucks for adjusting subgrade and reclaimed material moisture content and damp curing,

6. Regular or bottom dump trucks for hauling aggregate or asphalt millings,

7. Pneumatic trucks for hauling or spreading cement, lime or fly ash,

8. An asphalt distributor for application of prime coat, curing seal, or fog seal,

9. Rollers.

5.0 SPECIFICATIONS/PROCESS

The Iowa Department of Transportation is one of the few states that have detailed specifications for FDR. The Department uses an asphalt emulsion residual application rate of 3.0% by dry mass (10). This is used to determine the estimated plan quantity of the asphalt stabilizing agent. Specifications for stabilizing agent include; portland cement must meet ASTM Type 1, fly ash may come from any available source, hydrated lime must meet the requirements of Article 4193, and limestone fines shall come from limestone crushing operations. The mix design establishes the depth of milling, the actual asphalt content, the amount of residual asphalt to incorporate into the milled material and the optimum laboratory compaction moisture. The gradation specification requires that the top size of the gradation material shall not be greater than 25% of the depth of the compacted recycled material. The states DOT specifications also include a field density of at least 94% of the laboratory density based upon the dry weight of compacted material. There was no testing procedure indicated for testing laboratory density. The surface density is determined using a nuclear probe.

The equipment must include a self-propelled machine capable of reclaiming the existing pavement to the specifications of the contract documents. The machine must
also have automatic depth control and maintain a constant cutting depth and width. The equipment must be fitted with a test nozzle to provide a field sample of the foamed asphalt when necessary.

The Maine Department of Transportation specifications require that the pulverized and recycled material shall be processed to 100% passing a 2 inch (50 mm) sieve. The recycled material must be free of winter sand, granular fill, construction debris, and any other material not consistent with bituminous material. The entire depth of the existing pavement along with 1 inch (25 mm) of underlying gravel shall be pulverized into a homogenous mass. Density must be determined by the Department using nuclear density gauges. A section at the beginning of the project will be used as a control section. The control section must have water added to the pulverized material until testing indicates that it has reached optimum moisture content and it can then be compacted until the nuclear density readings show an increase in dry density of less than 1 pound per cubic foot (0.16 kN/m³) for the last four vibratory roller passes. This density will be used as the target density and the remaining FDR material will be compacted to a minimum density of 98% of the target density.

The pulverizer must be self-propelled and equipped with standard automatic depth controls to maintain a constant cutting depth and width. The pulverizer must also be equipped with a gauge to show the depth of the material being processed. Placement of the recycled material will be done with an approved highway grader. The recycled material shall be rolled with a vibratory pad/tamping foot roller with a minimum 4.6 feet (1.4 m) diameter single drum.
Additional specifications for other states using the FDR process will be discussed in greater detail in Task 2, Specifications and Construction Experiences.

6.0 FIELD TESTING

Field testing includes destructive and nondestructive types. Destructive methods that have been used include coring and excavating examination trenches.

6.1 Falling Weight Deflectometer

The most common nondestructive test for FDR projects is Falling Weight Deflectometer (FWD) testing. FWD is a testing method in which a load is applied to the pavement surface through circular loading plate and the resulting deformations are measured at fixed distances from the loading. Data collected from the deflection sensors map out the deflection basin. FWD results are used to determine the stiffness of the various pavement layers if the layers thickness are known. The structural number of the existing pavement can be calculated from FWD results as well. Figure 12 shows the SDDOT FWD testing vehicle.

![Figure 12. SDDOT FWD testing vehicle.](image)

6.2 Seismic Pavement Analysis

The Seismic Pavement Analyzer (SPA) is a device used for nondestructive evaluation of pavements. SPA’s are used to determine the thickness of the pavement
layers. The principle of SPA consists of applying a load to the pavement surface and recording the waves produced with geophones to determine the layer thickness of the pavements. The geophones record the seismic waves produced and the time for the waves to reach the geophones spaced at intervals from the load application. Calculations of the distance from the load center and the time of wave arrival indicate the layer thickness.

6.3 Ground Penetrating Radar

The Ground Penetrating Radar (GPR) is similar to SPA in that it results in layer thickness. GPR utilizes electromagnetic waves which are radiated into the pavement and reflected back to the receiving antenna. Different layers reflect the electromagnetic waves differently. The reflections are recorded and analyzed to determine the layer thickness. In addition to layer thickness GPR can also detect irregularities within the pavement. Irregularities could be voids, foreign objects, or areas with moisture damage.

![Image of ground penetrating radar data.](image)
6.4 Pavement Analysis Vehicles

Pavement analysis vehicles collect data from cameras and lasers mounted to them. As the vehicle travels down a section of roadway it records information on the amount and types of pavement distress. Fatigue and rut data are all collected with the vehicle. Profiles of the roadway can also be collected. Figure 14 shows the SDDOT road and pavement data collection vehicle.

![Image of SDDOT road and pavement data collection vehicle]

**Figure 14.** SDDOT road and pavement data collection vehicle.

6.5 Visual Distress Surveys

In order to determine how a pavement performs with time, visual distress surveys may be performed. Some states have written their own distress survey manual; however, the extent and severity levels of distresses are mostly based on those given in the Strategic Highway Research Program’s (SHRP) Distress Identification Manual for the Long-Term Pavement Performance Project, 1993 Edition (32). For flexible pavements, the distress categories include transverse cracking, fatigue cracking,
patching and patch deterioration, block cracking, rut depth, and roughness. Transverse cracking are cracks that are running perpendicular to the pavement centerline. The extent and severity is divided into three categories of low, medium and high, depending on crack width and depression. Likewise, fatigue cracking is categorized from low when only a single crack runs parallel to the wheel path(s) to high when a clear alligator skin pattern with spalling has developed. Patch and patch deterioration ranges from low when the patches show no distress to high when the patches break up and cause roughness. Block cracking may range from just longitudinal cracks between the wheel paths to interconnected transverse and longitudinal cracks forming blocks less than 3 feet (0.91 meter) in length or width. Rutting and roughness are divided into four categories such as low, moderate, high and extreme. Rut depths of less than 1/8 inch (3 mm) is classified as low distress while rut depths greater than 1/2 inch (13 mm) is considered extreme. Roughness ranges from less than 170 inch/mile (2683 mm/km) for low distress to greater than 225 inch/mile (3551 mm/km) for extreme.

7.0 REVIEW OF FIELD TESTING METHODS

Extensive research has been done using field testing. Field testing methods include; falling weight deflectometer and ground penetrating radar.

7.1 Falling Weight Deflectometer

In an investigation into a failed foamed asphalt pavement project in Texas, the FWD was used to test for any structural deficiencies in failed sections (6). The pavement was tested in over 100 locations with an overall spacing of 200 feet (60 m) except in locations where damage levels were significant. FWD data were analyzed
and it was determined that pavement and subgrade layer moduli were not substantially different between the failed and non-failed sections.

The FWD was used in a Georgia study on the use of cement stabilized FDR base to compare the moduli of the pavements before and after the stabilization (20). The FDR sections showed less average deflections than before stabilization. The FDR sections also showed lower deflection than a section that was overlaid only.

FWD testing was also used extensively in research projects to determine a rational and practical design guide for FDR (27). In one research, test sections were constructed using different base stabilization techniques. The FWD was used to evaluate sections both before and after stabilization. Data collected on the different types of stabilized bases suggested that cement plus water treated base had no significant difference but when compared to emulsion stabilized bases, they showed lower deflections. The structural numbers of the stabilized bases were also compared to those before stabilization took place. In all cases the structural number increased after stabilization.

Mallick, et al. described the use and methodology of nondestructive testing using mostly seismic property and portable seismic property analyzers (SPA and PSPA) (24). The authors suggest that, by combining known properties of FWD, seismic, and resilient modulus of asphalt and subgrade, the properties of foamed asphalt stabilized FDR can be back calculated.

The use of FWD data to determine the resilient modulus of pavement layers has been used extensively in the past. However, the structural composition of the FDR pavements has led to complications in the process. Mallick, et al. used the FWD to
evaluate the properties of the foamed asphalt sections (24). Three FWD tests were completed on each pavement section. At each of the FWD sites, two PSPA tests were conducted and cores were obtained for laboratory testing. Both HMA and portions of the stabilized base cores were taken and tested for resilient modulus by the ASTM D 4123 method in the laboratory. It was determined that the base moduli could be estimated if the modulus of the HMA layer is known and composite modulus of the HMA plus stabilized base is measured.

In a study to evaluate the field performance of Class C fly ash as an additive to FDR base courses FWD was used to determine the layer modulus (35). A total of 23 FWD tests were performed on various sections at 4-days and 1-year after construction. Results suggested that the layer modulus increased 49% during the first year after construction.

A project was undertaken in the City of Edmonton during August and September 2001, using FDR with foamed asphalt stabilization (11). FWD testing was performed prior to construction and after the project completion. The results suggested a deflection decrease in the range of 44 – 65% due to the FDR process. In all cases, the results indicated a significant increase in the structural capacity of the pavement due to the FDR process.

**7.2 Ground Penetrating Radar**

A study attempting to determine layer moduli of foamed asphalt base and compare it with that of plant mixed recycled asphalt pavement used the GPR to determine if unknown layers were present prior to reclamation (26). In addition to
identification of unknown layers, the GPR was also used to check the uniformity of the layers.

8.0 REVIEW OF LABORATORY TESTING PROCEDURES

Laboratory testing of FDR bases can be divided into two groups: one group to support the American Association of State Highway and Transportation Officials (AASHTO) empirical pavement design and another group to support the AASHTO Mechanistic-Empirical (M-E) pavement design. Tests done for pavement design are further dependent upon the type of material being tested. As discussed earlier, FDR bases are divided into three groups: unstabilized, chemical stabilized and bituminous stabilized. The various laboratory tests are grouped based on their usage with the various types of FDR bases.

- Tests used for all types of FDR bases:
  - Sieve analysis
  - Atterberg limits
  - Moisture density relationship
  - Bulk specific gravity
  - Resistance to permanent deformation
  - Resistance to moisture damage

- Tests used with the unstabilized FDR bases only:
  - Confined compressive strength
  - Resilient modulus (Mr)

- Tests used with the chemical stabilized FDR bases only:
  - Unconfined compressive strength ($q_u$)
  - Modulus of rupture (MR)

- Tests used with the bituminous stabilized FDR bases only:
  - Dynamic modulus ($E^*$)

The following presents a brief description of each test:
8.1 Sieve Analysis

The sieve analysis determines the gradation of the roadway materials. If the base has been previously stabilized, the crushing process to be used affects the gradation. It is particularly important to know the existing material gradation because the mix design and depth of the reclamation partially depend on this information. The sieve analysis is done in accordance with ASTM C 136.

8.2 Atterberg Limits

The Atterberg limits refer to a set of tests in which the plasticity index is determined. The tests that make up the Atterberg limits include: liquid limit, plastic limit, and shrinkage limit. The Atterberg limits are done to ASTM D-4318 specifications and are used for the AASHTO empirical design.

8.3 Moisture-Density Relationship

The optimum moisture content to produce the greatest density from compaction can be determined from ASTM D-1557 or D-558 standard test methods for laboratory compaction characteristics of soil using the modified effort. In addition to the modified compaction effort, the Superpave gyratory compactor can also be used to compact laboratory samples of bituminous stabilized FDR bases.

8.4 Bulk Specific Gravity

Bulk specific gravity is the ratio of the weight in air per unit volume at a given temperature to the weight in air of an equal volume of distilled water. The purpose for the bulk specific gravity is to determine the amount of compaction. The specific gravity is also needed for the AASHTO empirical pavement design.
8.5 Resistance to Permanent Deformation

The resistance of FDR bases to permanent deformation can be measured by either the repeated load triaxial test or the wheel loading devices.

8.5.1 Repeated Load Triaxial Test

The resistance to permanent deformation under repeated loading can be measured using the repeated load triaxial test. The test is performed on specimens 4 inches (100 mm) in diameter and 6 inches (150 mm) high. The specimen is placed in a triaxial chamber and tested under a confining stress. A haversine load deviator stress is applied lasting 0.1 seconds, followed by a rest cycle of 0.5 second. Axial deformation is measured over the middle 4 inches (100 mm) of the specimen, as the LVDTs are attached one inch (25 mm) from the top and one inch (25 mm) from the bottom of the specimen. The test is performed under different temperatures representing the temperature differentials that can be expected in the field.

8.5.2 Wheel Loading Devices

Rut resistance can be measured empirically by subjecting samples to repeated wheel loading. The Hamburg wheel tracking method uses repeated wheel loads applied under water to determine the amount of rutting that can be expected. The asphalt pavement analyzer (APA) uses the same principles except the sample can be tested under water or dry. Other accelerated testing can also be performed in which loaded wheels are repeatedly ran over test sections built to a large scale. This method differs from the Hamburg and APA methods in that the sections tested are large and testing does not take place under water.
A study done by the Maine Department of Transportation and Worcester-Polytechnic Institute had the objective of developing a mix design for use in FDR (27). Samples were fabricated using the addition of water, asphalt emulsion, cement, asphalt emulsion and cement, and asphalt emulsion and lime at varying percentages. Samples were tested by measuring the amount of rutting in each mix design after repeated wheel passes were ran under water, with 100 psi (690 kPa) of pressure (27). All samples were tested with the Asphalt Pavement Analyzer. Density and resilient modulus versus total fluid content curves were used for selecting the optimum additive content. Indirect tensile strength and accelerated aging tests were also done to guide the development of the mix design.

### 8.6 Resistance to Moisture Damage

The resistance of FDR bases to moisture damage can be measured either by the Tube Suction Test (TST), the Freezing and Thawing of Compacted Soil-Cement Mixtures (ASTM D 560), or the Effect of Moisture on Asphalt Concrete Paving Mixtures (ASTM D 4867).

#### 8.6.1 Tube Suction Test

The TST is a method of determining the moisture susceptibility of granular materials. The TST works by measuring the dielectric constants for each material sample and recording the changes that occur as moisture absorbed into the sample due to capillary action. The dielectric constants for dry particles average in the single digits of $\Delta C$, where $\Delta C$ is the change in capacitance. The dielectric constant for water is 81. As water content increases within the sample, the dielectric constant increases proportionally. The amount of moisture within an FDR base material is important
because stabilized bases tend to fail if subjected to moisture (33). Figure 15 below shows the setup of a TST.

8.6.2 Freezing and Thawing of Soil Cement Mixtures

This test determines the soil cement losses, the water content changes and the volume changes produced by a repeated freezing and thawing of hardened soil-cement specimens. The specimens are compacted in a mold, before cement hydration, to maximum density at optimum water content using the ASTM D 558 procedure.

8.6.3 Effect of Moisture on Asphalt Concrete Paving Mixtures

This test measures the effect of water on tensile strength of the paving mixture. This test method can evaluate the effect of moisture on the specimen with or without additives such as hydrated lime or portland cement. It is also applicable to dense mixtures.
8.7 Unconfined and Confined Compression Test

The unconfined compression test is used to determine the compressive strength of a given stabilized FDR base material. The sample is placed in a compression frame under no confining stress and tested to failure, giving the unconfined compressive strength and static Young's modulus. ASTM tests D 1633, D 5102, and C 593 should be followed when performing unconfined compression tests of cement, lime, and cement-lime-fly ash stabilized bases, respectively. For unstabilized material, it is necessary to test the sample under confining stress. The specimen is placed in a latex membrane and inserted in a triaxial chamber. The sample is then subjected to a confining stress and a deviator stress is applied. The deviator stress is gradually increased until the sample fails. Deformation and load are recorded and the modulus can be calculated at different stress levels. The specimens may be tested dry or saturated. Pore water pressures must be measured throughout the test in the latter case if the strength parameters are to be calculated.

8.8 Resilient Modulus

8.8.1 Resilient Modulus of Unstabilized FDR Bases

Resilient modulus (Mr) is a measure of the recoverable strain associated with repeated loading. The resilient modulus is determined for the base and the subgrade, and is used for the design of the pavement thickness. Determination of Mr is done by applying a haversine waveform with load duration of 0.1 seconds and a rest cycle of 0.9 seconds, such as to apply a load cycle of one second. For base and subgrade material, the specimen is placed in a triaxial chamber and the test is performed at different confining stresses. The higher the Mr, the better performance can be expected during
the life of the material. The Mr can also be used to determine the optimum mix design for a blend of additives and FDR material. Figure 16 shows a typical Mr test in progress. For unstabilized bases, the Mr is done in accordance with AASHTO T307.

8.8.2 Resilient Modulus of Bituminous Stabilized FDR Bases

The repeated-load indirect tension test is commonly used for determining the Mr property of bituminous stabilized FDR mixes (ASTM D 4123). The test is conducted by applying a compressive load with a haversine waveform (loading = 0.1 seconds and rest = 0.9 seconds) on the vertical diametral plane of a cylindrical specimen. The resulting diametral deformations are measured on both sides of the specimen. The magnitude of the applied diametral load and the resulting diametral deformations are used in a relationship to estimate the resilient modulus of the bituminous stabilized FDR mixture. It is very critical to note the temperature at which the Mr property is measured since its magnitude is highly dependent on the testing temperature.

Figure 16. Resilient Modulus test in progress.
8.9 Modulus of Rupture

The Modulus of Rupture (MR) is defined following ASTM D 1635 or AASHTO T97 depending on whether it is conducted on cement stabilized or a combination lime-cement-fly ash bases, respectively. The MR can also be estimated as 0.20 x the unconfined compressive strength.

8.10 Dynamic Modulus

The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) uses the dynamic modulus (E*) master curve to evaluate the structural response of the HMA pavement under various combinations of traffic loads, speed, and environmental conditions. The E* property of bituminous stabilized FDR mixture is evaluated under various combinations of loading frequency and temperature. Using the visco-elastic behavior of the bituminous stabilized mixture (i.e. interchangeability of the effect of loading rate and temperature) the master curve can be used to identify the appropriate E* for any combination of pavement temperature and traffic speed.

9.0 TESTS USED IN PREVIOUS STUDIES ON FDR BASES

This section summarizes previous studies that have used various types of tests to evaluate the properties of FDR bases.

9.1 Compaction

The Superpave gyratory compactor has been used to compact asphalt mixes and recently it was used to compact bituminous stabilized FDR mixes in a study sponsored by the Recycled Materials Resource Center at the University of New Hampshire (27). Its use and some suggestions about the procedure were outlined in a
study of FDR mix designs. When the Superpave gyratory compactor is used for FDR mixes, a slotted mold for water release is suggested. It was also determined that the optimum number of gyrations is 50.

The Superpave gyratory compactor was also used in a study to determine the optimum number of gyrations for CIR (8). Although this research was an investigation of CIR rather than FDR, it is felt that information developed in the study would also be useful to FDR projects. RAP from seven CIR projects was obtained along with asphalt emulsions and mixed in the laboratory. Samples were compacted at curing time intervals of 0, 30, 60 and 120 minutes and the number of gyrations along with the change in density was observed. The study concluded that the mix design samples could be compacted before or after breaking without significant effects. Mixtures compacted before and after the asphalt emulsion breaks required 30 and 35 gyrations, respectively.

9.2 Bulk Specific Gravity

Bulk specific gravity results were compared from three test methods, AASHTO T166, AASHTO T275, and the CoreLok™ method (8). The AASHTO T275 test uses paraffin, which renders the sample unusable for future tests. All samples were tested with AASHTO T166 and select amounts were also tested with the CoreLok™ method for comparison. The CoreLok™ method seals the sample in a bag for the determination. No statistical significance was noted from the comparison of the two methods.

Bulk specific gravity was used in a study to determine the mix design for CIR using foamed asphalt (18). Four different moisture contents in combination with five
asphalt contents were plotted against bulk specific gravity in order to select the optimum content of the foamed asphalt.

9.3 Moisture susceptibility

A study researching recent developments in characterizing durability of stabilized materials suggested that durability problems of such materials are actually due to chemical reversal of the stabilization. The cause of the reversal was postulated to be moisture intrusion into the stabilized material (33). The purpose of this study was to determine the engineering properties of cement stabilized base from the TST. The TST was run on four types of cement stabilized base materials and a correlation was made between higher dielectric constants and poor performance when evaluated by other methods. The authors noted that the TST was easy to perform and took about half the amount of time of the other durability tests.

A study sponsored by the Recycled Materials Resource Center at the University of New Hampshire (27) found that moisture induced damage was a significant factor in the deterioration of base mixes. Hence, any additive that is recommended for use in FDR must be evaluated in terms of its effect on moisture susceptibility of the resultant FDR mix. This study used three methods for determining the FDR material's resistance to moisture susceptibility: tensile strength, tube suction, and a stripping test. The authors concluded that any of the three tests could be used to determine the moisture susceptibility of FDR mixes and agencies should use the method they are most comfortable with.

In a study used to evaluate structural properties of lime stabilized soils and aggregates, the TST was performed on three soils; low, moderate and high plasticity
Testing was continued until all samples reached a maximum dielectric value, which occurred after about 311 hours. For low plasticity soils, no significant change was noted between lime treated and non-treated samples. For moderate and high plasticity soils, a significant reduction was noted in the dielectric properties of the stabilized materials.

9.4 Rut Resistance

Two articles included information about testing FDR bases for rut resistance. Two methods were used to determine the amount of rutting; the Hamburg wheel tracking method and an accelerated method.

In a study designed to determine the best mix design, samples were tested by measuring the amount of rutting after running loaded wheels with 100 psi (690 kPa) over the samples (21). The process was done under water. Density and resilient modulus vs. total fluid content were used for selecting the optimum additive contents.

Four test pavements were constructed in pits and tested at the Kansas State University CISL lab in Manhattan Kansas (30). The two pits measured 15 x 20 feet (4.6 x 6.1 m) and 20 x 20 feet (6.1 x 6.1 m). Subgrade material was placed and compacted in each pit. Three foamed asphalt bases and one control base were constructed over the subgrade. The bases were overlaid with a 3 inch (75 mm) Superpave HMA mix. The test pavements were loaded in pairs with a single axle for the first 100,000 passes with 17 kips (75.6 N). An additional 400,000 passes were performed with a double axle and an increased load of 30 kips (133.4 N). At the end of the loading all four pavements experienced rutting in the wheel paths. Transverse and longitudinal profiles indicated that the 9 inch (225 mm) stabilized base had slightly more rutting than the 9 inch (225
mm) control base, which had slightly more deformation than the 12 inch (300 mm) stabilized base. The results from this study indicated that 1 inch (25.4 mm) of foamed asphalt stabilized FDR would equal 1 inch (25.4 mm) of granular base in strength.

9.5 Resilient Modulus

Resilient modulus is one of the most common engineering properties measured on FDR mixes. Most resilient moduli are back calculated from FWD tests. At least eight studies used resilient moduli to evaluate FDR mixes; however, only two performed laboratory testing.

In a study to evaluate the structural properties of lime stabilized soils and aggregates, a rapid triaxial test (RaTT) method was used to determine the resilient modulus (21). AASHTO T 294-94, which loads a sample with 1900-2600 cycles, takes about 45 minutes to run. The research concluded that the RaTT resilient modulus test; 1) provided accurate results, 2) lime stabilization produced greater strength and high resilient moduli and 3) soaking of samples should be done for 48 hours.

A study sponsored by the Recycled Materials Resource Center at the University of New Hampshire used resilient modulus extensively when designing a rational and practical mix design guide (27). Samples constructed in the laboratory using the Superpave gyratory compactor were compacted with different moisture contents and tested for resilient modulus, bulk specific gravity, and tensile strength. Each of these properties plotted vs. fluid content to determine the optimum amount of both water and emulsion. Resilient modulus was also used to determine the optimum number of gyrations. The resilient modulus was also used to calculate the layer coefficients. FDR
mixes from the Nevada DOT were used to verify the mix design using testing for resilient modulus.

10.0 ADDITIVES

Selection of the appropriate type and amount of additive is important to produce sufficient structural strength in the reclaimed base. The three types of commonly used material stabilization include: mechanical, chemical, and bituminous.

10.1 Mechanical Stabilization

Mechanical stabilization has the lowest initial cost but may not be the most cost effective because the increase in strength may not be sufficient or long lasting. Common mechanical stabilization additives include: crushed aggregate, recycled asphalt pavement and crushed concrete. Other additives, which are still in the experimental stage include: foundry sand, crushed glass and fibers. Bottom ash or bottom slag from coal fired power plants may also be available for use as a mechanical additive. Bottom ash is in the experimental stages of being used as an additive to asphalt mixes.

Since there are no bonding materials added, mechanical stabilization is best for areas where age and lack of maintenance are the reason for failure instead of insufficient base strength (2). Mechanical stabilization increases the structural integrity by improving the gradation of the reclaimed material. In order to optimize the appropriate fraction of stabilizing material to be added, samples are collected from the in-situ materials, blended with the new materials and the mechanical properties of the blend are evaluated in the laboratory. Laboratory tests should include the Resilient Modulus (Mr) following AASHTO T307 and the repeated load triaxial test. Lean in-situ
material, which contains high amounts of bitumen, is a good candidate for mechanical stabilization. The excess bitumen coats the added virgin aggregate which decreases the bitumen content and therefore increases the structural stability of the mixture. Road improvements such as widening or increasing the elevation can be easily accomplished with the addition of virgin or recycled material without sacrificing thickness.

Mechanical additives are spread ahead of the pulverization pass or by adding into the blending pass after shaping and pre-pulverization (2). To obtain a high level of uniformity the granular material can be placed with a mechanical spreader or a paver.

A study done at the Brigham Young University used two different base materials along with two different RAP materials to determine the influence of RAP on the mechanical properties of recycled base materials typical of northern Utah (7). It was found that the California Bearing Ratio values decreased as the content of RAP increased. After a 72 hour drying period at 140°F (60°C), there was an increase in stiffness for RAP percentages between 0 and 25% and then a decrease in stiffness between 25 and 100% RAP. The results from the TST implied that the 25 – 50% RAP increased the moisture susceptibility of the recycled material. This study concluded that the impact of RAP content on the mechanical properties of recycled material was substantial enough that engineers should accurately determine the asphalt layer thickness prior to pavement reconstruction and the optimum blending depth should be carefully considered (7).

Braun Intertec Corporation conducted a research study in South Dakota to determine the optimum RAP content of base material for use in bases of new HMA pavements (22). The research evaluated the Process In-Place (PIP) performance both
before and after construction. Ten existing sections of pavement were evaluated (five on each side of the Missouri River) as well as 14 sections constructed for the project. The test sections constructed for this project provided an evaluation of three methods of reclaiming, three blend ratios, and two compactive efforts. Three combinations of blends were tested, these included:

- **75 Percent Blend** – Six inches (150 mm) of the old HMA blended with two inches (50 mm) of underlying aggregate. This would leave four inches (100 mm) of aggregate under the process-in-place.

- **50 Percent Blend** – The first three inches (75 mm) of the old HMA would be milled off. The remaining three inches (75 mm) would be blended with three inches (75 mm) of the underlying aggregate. Two inches (50 mm) of the milled asphalt would also be replaced by two inches (50 mm) of virgin aggregate to result in a total of an eight inch (200 mm) layer.

- **25 Percent Blend** – The first five inches (125 mm) of the old HMA would be milled off. Then one inch (25 mm) of asphalt would be blended with three inches (75 mm) of underlying aggregate. The remaining four inches (100 mm) would be replaced with virgin aggregate to result in an eight inch (200 mm) layer.

It was found that the blend with 75% RAP did not compact as well as the 50% or 25% blends. A condition survey and deflection testing performed two years after construction found very little distress in the sections. Performance monitoring of the various sections indicated that the area with the highest asphalt content generally showed the most rutting. The structural evaluation was done with a Dynatest Model 8000 falling weight deflectometer. Base layer coefficients were determined from the
base moduli determined from back calculation of FWD testing. The sections with the weakest subgrade moduli also showed the most rutting at this time. Laboratory tests confirmed that the material behaved like unbound aggregate except that the reclaimed asphalt consolidates with time. Because of this, the structural capacity is reduced. The construction of the test sections also showed that both the single-stage equipment and the two-stage equipment provided an acceptable product. Recommendations include adding additional compaction requirements to the existing specifications and modifying the control strip method of compaction so that the 97% of the maximum density of the material is required. Performance monitoring has been ongoing.

10.2 Chemical Stabilization

Chemical stabilization includes portland cement, calcium chloride, hydrated lime coal fly ash, and commercial chemicals. When determining the mix design of any chemical stabilizers, the suitability of the reclaimed material should first be determined along with the mechanical properties of the stabilized mix and the proportions of the reclaimed material, additive, and water. The suitability of the reclaimed material is dependant primarily upon the gradation and plasticity index. The amount of reclaimed material, additive, and water is determined by trial and error mixes of varying percentages. The optimum moisture content and maximum dry density are determined for all mixes. The reclaimed material should first be at a moisture content that is similar to in-situ field conditions. After the chemical stabilizer is added, additional moisture can be added to bring the mixture up to varying percentages. Most additives can be added dry or in a slurry form.
10.2.1 Cement

Cement stabilization increases the compressive strength and stiffness of a base material which reduces the amount of deflection due to traffic loads (12). In addition, the uniform support provided by the cement stabilization reduces the amount of stress on the subgrade allowing for a thinner base section (13). Figure 18 shows the amount of stress reduction capabilities of the base when loaded with traffic. Stabilization with cement also forms a base which is moisture resistant so even when the base is saturated it still has higher levels of strength. Cement stabilization is as easy as slurry to apply and is less expensive than emulsion. Improper dry applications can sometimes cause unacceptable dust problems (17). Although cement develops a good early strength and improves resistance to moisture, if the content is high (over 6%), shrinkage cracking can become a problem (17). Portland cement (3 to 6% by dry weight of the material to be stabilized) should be used on materials that are 100% RAP or blends of RAP and underlying granular base or low plasticity soils (2). There should also be enough fines in the mixture to produce an acceptable aggregate matrix for the cement treated base (no less than 45% passing the No. 4 sieve).
The objective for the mix design of cement stabilized FDR is to identify the optimum water and cement content. A variety of cement contents are evaluated and the modified Proctor test is used by most agencies to prepare the compacted samples. According to the ARRA the following tests should be run when utilizing cement: 1) “Moisture-Density Unit Weight Relations of Soil Cement Mixtures” (ASTM D 558-08) to determine the optimum water content, 2) “Compressive Strength of Molded Soil-Cement Cylinders” (ASTM D 1633) to determine the strength of the mixtures. The moisture sensitivity of the mixtures is then determined using either “Wetting or Drying of Compacted Soil-Cement Mixtures” (ASTM D 559), “Freezing and Thawing of Compacted Soil-Cement Mixtures” (ASTM D 560), or the TST, which was described in more detail in the Testing Procedures section. The optimum cement content is then selected from the results of the strength and moisture susceptibility tests.
The evaluated properties of the cement stabilized FDR at the optimum cement content should include: “Compressive Strength of Molded Soil-Cement Cylinders” (q_u) following ASTM D 1633, and Modulus of Rupture (MR) following ASTM D 1635 and the repeated load triaxial test. The Poisson’s Ratio is assumed to be between 0.10 and 0.20. Stabilization with cement should not be performed when the reclaimed material could be frozen prior to full curing (17). Air temperatures in the shade should be no less than 39°F (4°C). The stabilization should be completed at least one month before the first hard freeze.

An article on cement stabilization in Austria (15) described the experience gained with the recycling-in-place method. It was mentioned that base material with up to 10% content of particle smaller than 0.0008 inch (0.02 mm) was used with few problems. To achieve a higher density a sand content of 30% was recommended. The results of deflection measurements before and after reconstruction showed that an increase in bearing capacity was achieved. An application of a thin bituminous surface treatment was found to be effective because it allowed the stabilized layer to cure and also provided a mechanical wearing course.

10.2.2 Calcium Chloride

Calcium chloride is the least expensive of the stabilizers and works best in well graded non-plastic soils (17). Calcium chloride (1% by weight) should be used if the reclaimed pavement material consists of a blend of RAP and non-plastic base soils with 8 – 12% minus No. 200 sieve (0.075 mm) material (2). Small amounts (3 – 5%) of clay are also beneficial. Calcium chloride absorbs moisture which helps in compaction. Liquid calcium chloride is used in areas where the freeze/thaw cycles are extreme.
Calcium chloride is very environmentally friendly and won’t kill vegetation when being spread. According to the ARRA the following tests should be run when utilizing calcium chloride: liquid limit, plastic limit and plasticity index of soils, ASTM D 4318; moisture density relations of soils and soil-aggregate mixtures, ASTM D 698 or D 1557.

A study conducted in 1989 by Trow Geotechnical Ltd. in Ontario, confirmed that liquid calcium chloride strengthens reclaimed roads by 12% and base durability by 24 to 36% (28). Calcium chloride improves the strength by absorbing moisture, which keeps the reclaimed materials dense and compact. This enhances the load bearing capacity and reduces the effects of frost action by 50 – 60%. FWD testing was used to measure the load-deflection response of the sections. This test showed a 5 – 12% increase in pavement strength. A resilient modulus test was also done to measure pavement flexibility. The recycling process used pulverizing equipment to grind the existing HMA layer and base course into a uniform composition before adding a 35% solution of liquid calcium chloride. A 0.25% per volume solution was added to seal the surface. This study found liquid calcium chloride to be more cost effective than emulsified asphalt, lime, and Class C fly ash.

10.2.3 Lime

Lime is added to improve the load-bearing characteristics and reduce plasticity (21). Hydrated lime or Quicklime (2 – 3% by weight) should be used if the RAP has some amount of silty clay soil typically from subgrade with a plasticity index greater than 10 (2). Small amounts of hydrated lime have been used in combination with asphalt emulsion to produce a mixture with higher early strength and a greater resistance to water damage. Climatic limitations for construction when using lime are the same as
when using cement but should also include a two week minimum of warm to hot weather after completion of the stabilization work (17).

The objective of the mix design of lime stabilized FDR is to identify the optimum water and lime contents. A variety of blends are compacted using ASTM D 1557. The optimum water content of each blend are determined using; “Laboratory Compaction Characteristics of Soil Using Standard Effort” (ASTM D 698). At least three compacted samples should be cured in an airtight, moisture-proof container at 73±4°F (23±2°C) for a specified curing period. At seven days the strength should be evaluated using; “Unconfined Compressive Strength of Compacted Soil-Lime Mixtures” (ASTM D 5102). The moisture sensitivity of these blends can be found using the same test as for cement. The optimum cement content is then selected from the results of the strength and moisture susceptibility tests. The unconfined compressive strength is evaluated following ASTM D 102 procedure. Laboratory tests should also include the repeated load triaxial test to evaluate the rutting resistance of the FDR mix.

10.2.4 Fly Ash

Class C fly ash is a by-product of the combustion of coal and can be utilized by itself for stabilization or in combination with portland cement which could result in better mixture properties at a lower cost than either alone. Class C fly ash (8 – 14% by weight) should be used when there are materials consisting of 100% RAP or blends of RAP and underlying granular base or soil (2). The same tests should be run when using fly ash as when using cement. Climatic limitations for construction when using fly ash should be the same as lime stabilization (17). The self-cementing fly ash is applied over the pulverized material. The material is then mixed again to produce a
homogenous mixture before grading and compacting. During blending, water is injected to achieve the predetermined densities and moisture contents. In some locations the new base must be left un-surfaced and be kept moist-cured for three days. The thickness of the new HMA can sometimes be reduced because the new base is much stronger than the unbound base. When using fly ash the agency must be certain that heavy metals do not leach out into the groundwater.

A paper by James Crovetti describes the construction and performance of a road that was stabilized with fly ash (9). This project took place on Highland Avenue, a rural road in Mequon, Wisconsin. Distress and deflection test results were used to determine performance trends and constructability of the fly ash-stabilized CIR pavement. The fly ash-stabilized test section was constructed by first spreading the Class C fly ash over the top of the pulverized CIR base and then remixing it. Water was also added before grading and compacting. Samples with varying amounts of fly ash and water were compacted with standard Marshall compaction equipment. A travel speed of 2 miles/hour (3.2 km/hour) and a transfer rate of approximately $5.401 \times 10^6$ lb/min (2.45 Mg/min) were determined for an application rate of 3.9 lb/ft$^3$ (186 N/m$^3$). After three years, a visual inspection showed no surface distress. FWD tests were run to back calculate the resilient modulus. The structural integrity was also back calculated from surface deflections using the following variables: structural number, flexural rigidity of pavement, total pavement thickness, area under pavement surface deflection basin. After construction the fly ash test section had the highest structural number. The increase of the structural number would allow for a 28% increase in traffic. The estimated structural coefficient of the fly ash-stabilized material was 0.15. This
represents an increase from the 0.11 for the untreated sections.

Another study that evaluated the field performance of Class C fly ash in FDR was done on County Trunk highway, in Waukesha County, Wisconsin (34). This road had moderate traffic volume, and relatively low fly ash contents were utilized. The existing HMA layer was pulverized in-place and mixed with fly ash and water to function as a base course. Fly ash amounts of 6% and 8% by dry weight were used for evaluation. Nondestructive deflection tests were performed with a FWD. The layer modulus and structural coefficient were back-calculated. One year after construction the modulus of the fly ash-stabilized FDR base course had increased by 49%. The structural coefficient of the fly ash-stabilized base course increased from 0.16 to 0.23 in a one year period.

Particle size analysis showed that the sample contained 68% material larger than a No. 4 (4.75 mm) sieve, 26% between No. 4 (4.75 mm) and No. 200 (0.075 mm), and 6% between sizes No. 200 (0.075 mm) and 0.0002 inch (0.005 mm). A maximum dry density of 192 lb/ft³ (22.3 kN/m³) at an optimum moisture content of 5% was determined. The structural capacity of the FDR layer also increased slightly as it aged due to the pozzolanic reaction. The study concluded that appropriate contents of fly ash can reduce the brittle behavior of base course and still provide enough support for long term performance. The study also noted that a high fly ash application rate could result in the tendency for the pavement to crack.

**10.2.5 Commercial products**

In addition to the stabilizers discussed above, some proprietary commercial additives are also available. Commercial stabilizers can be added into the water when
grading and compacting the base or through the FDR machine itself. The additives work by binding the finer grained material. Unlike other chemically stabilized bases that are solid after curing and cannot be reshaped, this chemical stabilization only needs to be rewetted before it can be reshaped.

10.3 Bituminous Stabilization

Bituminous stabilization includes foamed asphalt, and slow or medium set asphalt emulsions. Bituminous stabilization provides a more flexible base course and is more fatigue resistant (2). Emulsified or foamed asphalt (1 – 3% by weight) should be used when there are materials consisting of 100% RAP or blends of RAP and underlying granular base or non-plastic or low plasticity soils (2). The maximum percent passing the No. 200 (0.075 mm) sieve should be less than 25%, the plasticity index should be less than 6 or have a sand equivalent of 30 or greater. According to the ARRA the following tests should be run when using asphalt emulsion or foamed asphalt; modified Hveem method of emulsified asphalt aggregate cold mixture design, (Appendix E, Asphalt Cold Mix Manual. Manual Series No. 14 (MS-14), Asphalt Institute.); percent air voids in compacted dense and open bituminous paving mixtures, ASTM D 3203; effect of moisture on asphalt concrete paving mixtures, ASTM D 4867; and indirect tension test for resilient modulus of bituminous mixtures, ASTM D 4123. Stabilization with asphalt emulsion or foamed asphalt should not be performed when the reclaimed material could be frozen prior to curing (17). Air temperatures should be no less than 59°F (15°C). Asphalt emulsion or foamed asphalt stabilization should not be performed when there is high humidity (greater than 80%) or foggy conditions. Warm to
hot weather is preferred for all types of bituminous stabilization because of improved 
binder dispersion and curing.

10.3.1 Asphalt Emulsion

An emulsion-stabilized base is flexible, fatigue resistant and not prone to age 
cracking. It is easy to apply but is in general more expensive than cement or foamed 
asphalt and takes time to cure and develop its full strength. In some instances the type 
of emulsion used does not require cement or lime additives due to the emulsifier 
chemical, therefore, it is less expensive than foamed asphalt which does require these 
additives. Emulsion is typically used to put additional binder into the pulverized HMA 
layer. The objective of the Emulsion and Foamed Asphalt mix design is to determine 
the optimum water and emulsion content. When compacting emulsion stabilized 
mixtures with the Superpave Gyratory Compactor a slotted mold is sometimes used so 
that water is able to escape during the compaction process, but if proper water and 
emulsion contents are chosen than a slotted mold is not necessary. Samples should 
cure for at least 24 hours at 104°F (40°C). The optimum water and emulsion content 
can be found using the dry density and resilient modulus or the tensile strength. The 
total water content should include the free water and the water included in the emulsion. 
The moisture sensitivity can be tested using the TST or AASHTO T-283. The E* Master 
Curve for asphalt emulsion and foamed asphalt stabilized bases should be obtained 
following AASHTO TP 62.

10.3.2 Foamed Asphalt

Foamed asphalt is a mixture of air, water and hot asphalt (11). When cold water 
is mixed with hot asphalt the asphalt expands by 10-15 times its original volume. This
increases the asphalt’s viscosity. Foamed asphalt is normally less expensive than asphalt emulsion. Unlike asphalt emulsion, foamed asphalt does not add additional water to the mixture. The strength gain is quick, which allows for immediate traffic loading.

![Diagram of foamed asphalt process.](image)

The Maine DOT has been experimenting with adding stabilizing agents to virgin or recycled base materials to increase stability in FDR practices (26). These additives include cement, emulsion, calcium chloride, and foamed asphalt. It was found that sections which were treated with 3 inches (75 mm) of foamed asphalt had a smoother ride than sections with 1.5 inches (38 mm) or sections which were not treated at all. Smoothness was determined using the International Roughness Index.

A paper by Donovan described three projects undertaken by the City of Edmonton during August and September of 2001, using FDR with foamed bitumen stabilization (11). This was the city’s first experience with foamed bitumen as a
stabilizer. Foamed bitumen stabilization was chosen because the construction time would be decreased, the road would never have to be closed to traffic, the existing pavement structures were suitable for the project, and upon completion of the compaction the driving surface would be sound. The primary distress found in each of the original three sections selected for this research was severe alligator cracking and deformation. Transverse and longitudinal cracking were also found at the first two sites.

The following tests were done to determine the optimum mix characteristics: bulk specific gravity, dry tensile strength, wet tensile strength, and tensile strength ratio. All tests were conducted on mixtures at various bitumen contents. Also tested was the percent by mass of the foamed bitumen to be added to the mix. For two of the projects the foamed bitumen for optimal strength was found to be 2.5% with 1.5% cement as active filler. For the third project the bitumen content was 2% and the cement content was 1.5%. The optimum moisture content was between 5.1-6.1%. The maximum dry density was between 116 to 125 lb/ft³ (18.2 to 19.6 kN/m³).

The process was carried out in a single operation. The moisture susceptibility of the material was determined using ASTM D 560 and ASTM D 559 tests. The tests showed an average weight loss of 3.4% for freeze/thaw and 4.5% for wet/dry testing after 12 cycles. This paper concluded that FDR using foamed bitumen as a stabilizer resulted in a substantial increase in the structural capacity of the roadway.

One notable failure with the use of foamed asphalt was documented in a paper by Chen et al. (6). This paper recorded an investigation into the structural distress of a foamed asphalt stabilized base in Texas. The subgrade in this area was known to be soft and often saturated with water. The foamed asphalt allowed for a capillary rise of
water into the base and weakened the layer. It was concluded from the tests that the lack of strength in the base material from moisture susceptibility was the cause of the failure.

10.4 Combined Stabilizations

Many studies have been done that have verified the efficiency of the use of two or more types of additives combined. The objective of a study by Mallick et al. was to evaluate the benefits of different types of additives, determine a suitable structural number, and determine the suitable compactive effort necessary (24). This study took place on Route 201 near Caratunk, Maine. This route had a medium traffic volume. Tests conducted included; FWD tests, resilient modulus, density of in place material, density of compacted samples, and compaction of loose material in the laboratory. The evaluated additives included; MS-2 emulsion, water, Type II cement, and a combination of MS-2 emulsion and lime. Percentages of lime and cement were based on recommendations from Kearney and Huffman. Cement and emulsion plus lime mixes had high resistance to moisture damage. Emulsion plus lime was best on the basis of wet tensile strength. Cost comparisons showed that recycling with 3.4% emulsion and 2% lime was the most cost effective. Visual inspection showed no significant distresses in any section except for the section with only water.

Anderson Consulting Group in Roseville, California blended calcium chloride, lime, fly ash and water to the recycled asphalt (3). This mix resulted in a road base with high load bearing capacity. This combination was called Geobase and was effective in all soil conditions except those with large rocky material and worked especially well in moist sections. Mix design was site specific and was based upon the percentage of
lime and fly ash needed to get a compressive strength of 200-400 psi (1380 to 2360 kN/m$^2$). Geobase has been applied to a number of projects in California.

11.0 CONCLUSIONS

Three types of in-place recycling are available. These include: Hot In-Place (HIR), Cold In-Place (CIR), and Full Depth Reclamation (FDR). HIR heats the asphalt pavement and allows for compaction and addition of additives. CIR pulverizes the top few inches of the HMA layer and mixes bituminous additive into the RAP which is then placed and compacted. FDR pulverizes the entire asphalt section and a predetermined amount of the underlying base material. The mixture of RAP, base, and additive is then spread and compacted to form a new base material. Several parameters may need to be considered when choosing the proper HMA pavement recycling method but one of the most important is the type and cause of pavement distresses. FDR should be considered as a recycling option if the pavement distresses suggest that the road is not structurally sound. Pavement distresses that can indicate a road is a candidate for FDR include: frequent transverse and longitudinal cracking, reflective cracking, heavy pothole patching, severe rutting, soil strains, frost heaves, warping and insufficient base strength to support current loads.

FDR has been utilized as a recycling method since the early 1900’s but today’s processes are much more advanced. As asphalt binder and aggregate prices increase, FDR becomes more economical and the need for long lasting roads becomes more important. In addition to the economical benefits of FDR, it is also environmentally friendly. As more asphalt is recycled less aggregate needs to be removed from quarries and hauled to locations.
Construction equipment for FDR projects include recycling machinery and common machinery such as: dump trucks, water trucks, graders, and compactors. Recycling can be done either with the use of milling and mixing recycle trains for in-place processing or by milling and hauling the millings to a central plant for mixing. The preferred method for recycling is in place due to lowered costs, time and the reduced likelihood of breaking through to the subgrade. Cold central plant recycling may be chosen if the remaining base and subgrade material is not strong enough to hold the in-place machinery or for other construction requirements such as replacing culverts.

Field and lab testing are performed to determine properties of the HMA layer and base material. Information from testing can be used to design the mix specifications for the reclamation. Typical field testing includes: visual distress surveys, ground penetration radar (GPR), falling weight deflectometer (FWD), and seismic pavement analysis (SPA). Testing typically conducted within the lab includes: gradation of materials, plasticity index, optimum moisture content and compaction, and bulk specific gravity. More advanced testing includes resilient modulus, repeated load triaxial, dynamic modulus, and tests for moisture susceptibility. The mixture of additives, RAP, and aggregates determines which testing is needed.

Additives that can be added in FDR mixes for stabilization are divided into three groups: mechanical, chemical, and bituminous.

Mechanical stabilization contains additives that improve the strength of the material but do not bond the aggregates together. Virgin aggregate, RAP, and crushed concrete have been added as mechanical stabilizers. Other additives that are in the development stages include crushed glass, synthetic fibers and foundry sand.
Mechanical stabilization has the lowest initial cost but may not perform as well as the other stabilization techniques.

Chemical stabilization includes additives that bond the aggregates together. Chemical stabilization increases the hardness of the base material therefore increasing its load carrying capacity. The common chemical additives include: cement, lime, calcium chloride, and fly ash. The suitability of the reclaimed material for chemical stabilization is dependant primarily upon the gradation and plasticity Index. Care must be taken, when selecting the amount of cement to be added, to prevent the possibility of reflection cracking.

Bituminous stabilization includes adding bitumen to the mix of RAP and base to increase the bonding of particles. Bitumen is usually added in the form of asphalt emulsion or foamed asphalt. Asphalt emulsions can be either slow or medium set. Asphalt emulsions are easy to apply but often cost more than foamed asphalt. Foamed asphalt was originally produced by injecting steam into the bitumen; today foamed asphalt is produced by injecting cold water into hot bitumen. The cold water instantaneously changes to steam when in contact with hot bitumen and expands the asphalt to 10-15 times its original volume. One advantage to foamed asphalt and emulsion is that after compaction the surface can be driven on without lengthy curing time periods. Foamed asphalt is being used frequently in Maine and has been used in Texas and Canada as well.

Current FDR techniques have been researched in the above report so that information is readily available for future research. FDR is an environmentally friendly
and economically attractive alternative to reconstruction when added structural strength is needed.

12.0 ACKNOWLEDGEMENTS

The authors are grateful for the technical and financial supports provided by the Federal Highway Administration. The technical program monitor is Jason Harrington, Office of Pavement Technology. The following individuals have served as the Project Technical Panel members and provided valuable comments, suggestions, and review. Their contributions are greatly appreciated.

Randy Battey, Mississippi DOT
Todd Casey, Base Construction Co. (ARRA)
John Epps, Granite Construction, Inc.
Joe Feller, SDDOT
Gary Goff, FHWA ND Division
David Gress, Univ. of New Hampshire
Gregory Halsted, PCA (ARRA)
Brett Hestdal, FHWA SD Division
John Huffman, Terex Roadbuilding (ARRA)
Tim Kowalski, Wirtgen America
David Lee, Univ. of Iowa
Chuck Luedders, FHWA Direct Federal Lands
Ken Skorseth, SDSU
Ken Swedeen, Dakota Asphalt Pavement Association
13.0 REFERENCES


