



# TRANSPORTATION RESEARCH SYNTHESIS

Minnesota Department of Transportation  
Office of Transportation System Management  
Research Services and Library  
651-366-3780  
[www.mndot.gov/research](http://www.mndot.gov/research)

TRS 1310  
Published FEBRUARY 2014

## Investigation of Performance Requirements of Full Depth Reclamation Stabilization

### Introduction

Recycling procedures have become increasingly important for the protection of the world's environment. The Environmental Protection Agency of the United States reports that United States citizens recycled approximately 87 million tons of the 250 million tons of trash produced in 2011, equivalent to a 34.7 percent recycling rate [1]. In contrast to conventional recycling is the commercial recycling of pavement and aggregate materials used in the construction of roadways. It is estimated that over 100 million tons of pavement are recycled each year in the USA [2]. One such pavement recycling process is referred to as stabilized full depth reclamation (SFDR)<sup>1</sup>. SFDR recycling is achieved through the pulverization of a distressed roadway's asphalt surface and a predetermined portion of its underlying subgrade to create a rehabilitated and stabilized base course, which is overlain with an asphalt layer. Using SFDR practices, a road construction project in Fairburn, Georgia recycled 3320 tons of aggregate during the repair of a 1.1-mile stretch of roadway [3]. Through its use of SFDR, the Georgia DOT was able to prevent both the use of virgin aggregate and the transport of aggregate. It is evident that SFDR recycling is a large contributor to the protection of the world's environment.

The Minnesota Department of Transportation (MnDOT) recognizes the value of SFDR practices and wishes to promote further use of SFDR in its state. Before widespread application of SFDR is attainable, it is imperative that the performance requirements for SFDR be determined. Since there is an absence of such a specification in Minnesota, the structural capacity of SFDR may not be fully attained. The objective of this research project is to determine optimal properties that SFDR material should attain to be used as a base layer for hot-mix asphalt (HMA) roadways. Optimum SFDR material properties are achieved when rutting and low temperature cracking is minimized. The stabilizing materials used to achieve these parameters are to be determined by the agency that is investigating a specific SFDR project.

---

<sup>1</sup> Most papers use the terms FDR (full-depth reclamation) and SFDR (stabilized full-depth reclamation) interchangeably. The difference between FDR and SFDR is that the latter is stabilized with an agent and the former is not.

## When and Where to use SFDR

SFDR is a globally recognized pavement rehabilitation process and therefore has many different names such as: chemically stabilized roadbed, cement-treated base course, and cement-stabilized reclaimed base [4]. Although SFDR is known by different names, this paper will continue to refer to this specific recycling process as SFDR. According to the Asphalt Recycling and Reclaiming Association, there are five methods of roadway recycling: cold planning, hot recycling, hot-in-place recycling (HIR), cold-in-place recycling (CIR) and stabilized full depth reclamation (SFDR) [5]. These five methods of roadway recycling have been developed to rehabilitate asphalt pavements that have been subject to thermal cracking, extreme traffic loads, poor construction and mechanical failure.

Since SFDR is not the only method of recycling roadways, it must be determined which recycling method is the best option for each specific roadway failure case. The most important factor to consider when determining which recycling method to use is the current state of a roadway; SFDR is recommended for pavements with a base or subgrade problem [6]. If SFDR is chosen as the proper pavement rehabilitation process, the type of pavement that was previously laid and the type of underlying subgrade should be determined initially.

SFDR is used to correct structural deficiencies in pavement [7]; these deficiencies include deep rutting, load-associated cracks, thermal cracks, reflection cracks, and maintenance patches such as spray, skin, potholes, and deep hot mix [8]. SFDR can correct inconsistencies in the subgrade base as well as the asphalt layers [4]. In contrast to structural deficiencies are functional deficiencies such as pavement surface texture. Since cold recycling methods are used to correct for most functional deficiencies, SFDR would be a poor choice as a type of pavement recycling process for this type of deficiency [7]. To determine if a pavement is failing due to structural deficiencies, it is suggested to use the following types of pavement field testing before proceeding with SFDR processes: cores, depth checks, and falling weight deflectometer tests [7]. Table 1 summarizes the different types of road failures that SFDR is recommended for along with which milling depths are appropriate for different roadway rehabilitation processes. It should be emphasized that not all road failure cases may be resolved with SFDR.

**Table 1: Guidelines for selecting the most applicable rehabilitation process [9]**

	HIR			CIR	SFDR
	Surface Recycling	Remixing	Repaving		
<b>Milling Depths</b>					
25 mm (1 in.)	X	-	-	-	-
25 to 50 mm (1 to 2 in.)	X	X	X	X	-
25 to 75 mm (1 to 3 in.)	-	X	X	X	-
50 to 100 mm (2 to 4 in.)	-	-	-	X	X
100 to 150 mm (4 to 6 in.)	-	-	-	-	X
>150 mm (>6 in.)	-	-	-	-	X
<b>Distresses</b>					
Alligator Cracking	P	F	G	G	G
Bleeding, Flashing	F	F	F	F	G
Block Cracking	F	F	G	G	G
Bumps	F	F	F	F	G
Edge Cracking	P	F	F	F	G
Friction Improvement	P	F	G	G	G
Longitudinal Cracks (non-wheel path)	F	F	G	G	G
Oxidation	G	G	G	G	G
Patches	F	G	F	G	G
Polishing	P	G	G	G	G
Potholes	F	G	G	G	G
Raveling	G	G	G	G	G
Rutting	F	G	F	G	G
Reflective Cracking	F	F	G	G	G
Shrinkage Cracking	-	-	-	-	-
Shoulder Dropoff	P	P	P	P	P
Shoving	F	G	F	G	G
Slippage	F	F	G	G	G
Transverse Cracks	F	F	F	G	G
Moisture Damage	P	F	G	G	G
Ride Quality (distress related)	F	F	F	F	G
Minor Profile Corrections	F	F	F	F	G
<p>G – good process for addressing distress                      F – fair process for addressing distress                      P – not likely to fully address distress                      This table is included as a reference for general guidelines and should not be used exclusively to select a recycling process.</p>					

Public roadways are the most common places where SFDR is performed. Since total rehabilitation of a roadway cannot be done without some form of traffic control, SFDR is more often used for long stretches of rural roads [10, 11]. The SFDR process is moving towards other fields of application however; private and regional airports as well as parking lots are being rehabilitated through the use of SFDR [12]. Since SFDR is simultaneously being developed as a technology and applied to roadway systems, there is much potential for future success of SFDR in pavement rehabilitation applications.

### SFDR Process

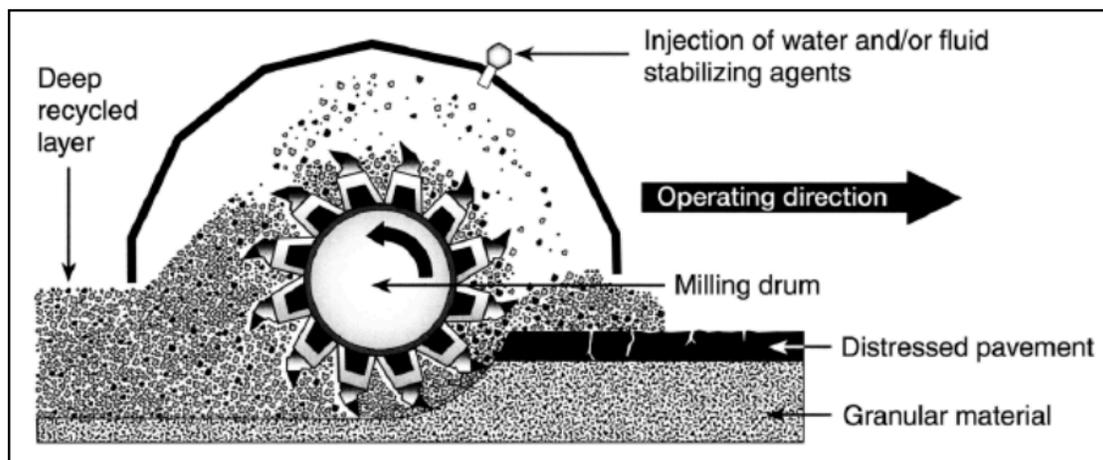
When a Department of Transportation and contractor have agreed that SFDR is the best option for road rehabilitation, there is a general process that is followed to complete the SFDR process. This process may be described in six steps [13]:

1. Mix design selection
2. Pulverization
3. Introduction and blending of additives
4. Shaping of the mixed material
5. Compaction
6. Application of a surface or a wearing course

A more detailed example of an SFDR road rehabilitation process may be similar to the following example taken from a report by the Georgia Department of Transportation (GDOT) on a SFDR project in its state [14]:

1. The pavement structure was pulverized with a reclaimer to begin the SFDR process. The reclaimer made only one initial pass over the pavement surface.
2. Water was then added to the SFDR and blended well.
3. After application of the water, Portland cement was added at a ratio of 6% by weight of the pulverized dry material.
4. The reclaimer made two more passes to blend the SFDR with the cement. The final blend was a homogeneous stabilized SFDR base.
5. Compaction of the SFDR base was achieved by passing a vibratory smooth drum roller over the stabilized base. Two passes were made initially.
6. Additional water was added to the stabilized base as necessary.
7. Further compaction was achieved with four passes of a pneumatic roller.
8. A minimum compaction of 98% of the maximum dry density was achieved.
9. A motor grader then passed over the SFDR base to grade the SFDR and achieve the proper slope of the road.
10. The stabilized and compacted base was then sealed with a bituminous prime coat of 0.7 L/m<sup>2</sup>. The coat was allowed to seal for seven days.
11. Paving operations followed the completion of the stabilized base.

Although the reclamation depth was not specified in the GDOT example, typical depths may be anywhere from 50 - 300 mm (2 - 12 in) [15]. The reclamation depth used is based upon the proportion of pavement to subgrade material. This proportion may change based on the specification of the state in which SFDR is performed, but typical ratios include 50% Recycled Asphalt Pavement (RAP) to 50% base material by weight and 75% RAP to 25% base material by weight [16]. The inner chamber of a pavement reclaimer machine is shown in Figure 1.



**Figure 1: Inner chamber of a pavement reclaimer machine [5]**

### Stabilization Materials

MnDOT initially suggested the use of cement and emulsion as stabilizing additives for SFDR base used for Minnesota roadways [17]. Although cement and emulsion had been suggested as the two additives to be used for this research project, it was later determined that the stabilization materials should be determined by the agency conducting the SFDR project. The choice of a specific additive is based upon the type of existing pavement as well as the type of existing aggregate base of a roadway, and is not restricted solely to cement and emulsion. A list of common stabilizing additives include [6, 18 & 19]:

- Asphalt emulsion
- Expanded/foamed asphalt
- Calcium chloride
- Portland cement
- Fly ash
- Lime

Both dry cement and cement slurry have been used to stabilize SFDR [20]. Dry cement is more conventional, but leads to fugitive cement dust when spreading. Cement slurry has recently been used to solve the problem of fugitive cement dust. Although the slurry did prevent dust

issues, SFDR stabilized with cement slurry has slightly lower strength values than SFDR stabilized using dry cement [20].

A study conducted by the Virginia Department of Transportation (VDOT) compiled a chart, shown in Figure 2, of different types of stabilizing and base materials. This chart may be used in the selection of a stabilizing material when the base material type is known.

Material Type	Well-graded Gravel	Poorly graded Gravel	Silty Gravel	Clayey Gravel	Well-graded Sand	Poorly graded Sand	Silty Sand	Clayey Sand	Silt, Silt with Sand	Lean Clay	Organic Silt/ Organic Lean Clay	Elastic Silt	Fat Clay, Fat Clay with Sand
USCS	GW	GP	GM	GC	SW	SP	SM	SC	ML	CL	OL	MH	CH
AASHTO	A-1-a	A-1-a	A-1-b	A-1-b or A-2-6	A-1-b	A-3 or A-1-b	A-2-4 or A-2-5	A-2-6 or A-2-7	A-4 or A-5	A-6	A-4	A-5 or A-7-5	A-7-6
Emulsion FDR, Best if SE > 30 and P <sub>200</sub> < 20													
Foamed asphalt, P <sub>200</sub> 5% to 20% and follow maximum density gradation													
Portland cement, PI < 10													
Lime, P <sub>10</sub> > 10 and P <sub>200</sub> < 25 or PI 10-30 and P <sub>200</sub> > 25, SO <sub>4</sub> in clay < 3,000 ppm													

Shaded cells indicate recommended conditions.  
 USCS = unified soil classification system; AASHTO = American Association of State and Highway Transportation Officials; FDR = full-depth reclamation; SE = sand equivalent; P<sub>200</sub> = percent passing No. 200 sieve; PI = plasticity index; ppm = parts per million.  
 Source: The recommendations in this table are from Thomas, T. (2010). Mix Designs for FDR, CIR, and HIR. Paper presented at the Northeast and Mid-Atlantic States In-Place Recycling Conference, Harrisburg, PA, August 24-26.

**Figure 2: Stabilizing material selection based upon base material type [21]**

### SFDR Advantages

Costs of road rehabilitation materials have risen at a rate of approximately 70% over a two-year span [7]. This poses a significant challenge for DOT’s who wish to rehabilitate roadways. This economic challenge has been overcome in the past few years by the use of SFDR. As well as providing a cheaper alternative for rehabilitation of roadways, SFDR offers many other advantages [8, 22, 23, 24 & 25]:

- Reduction in total cost
- Reduction in frost susceptibility
- Improvement of pavement structure without changing basic roadway geometry
- Improvement of ride quality
- Restoration of old pavement to desired profile
- Restoration of crown and slope
- Elimination of existing wheel ruts
- Elimination of potholes, irregularities and rough areas

- Elimination of alligator, transverse, longitudinal and reflection cracks
- Elimination of air quality problems from dust, fumes and smoke
- Elimination of initial pavement disposal
- Reconstruction of shoulders
- Accommodation of pavement widening projects
- Conservation of materials and energy
- Minimization of traffic interruptions
- Preservation of natural resources

### SFDR Practicing Regions

There are multiple states and countries that practice SFDR. Since there exists a plethora of practicing regions, only a few of the most prominent SFDR practicing states will be reviewed in this report. The following list should by no means be considered a comprehensive list of all regions practicing SFDR. A list of regions with innovative SFDR techniques and regions with a significant amount of data on performance of SFDR were considered:

1. Georgia
2. Nevada
3. Virginia
4. Minnesota

A discussion of each region's SFDR practices will be provided in the following sections. Parameters of the region that are similar to Minnesota parameters will be highlighted. The discussions will include reasons why SFDR was chosen as a rehabilitation process, the different stabilizing materials used, any construction highlights that may aid in understanding the SFDR process, and any problems detected by the use of SFDR.

### Georgia – Cement Stabilizer

The Georgia Department of Transportation (GDOT) is in the process of developing cement-stabilized reclaimed base (CSRB). CSRB is an SFDR base that is produced by using Portland cement as a stabilizer for a sand-clay existing base. Once the base has been stabilized, hot-mix asphalt is laid on top of the base to complete the roadway [4]. GDOT is the first transportation agency to develop a specification for the use of CSRB. This specification is summarized in Table 2. Since CSRB uses cement as a stabilizer, the final base course has reduced permeability and is able to keep moisture out. This reduction in permeability means that the base maintains a high level of strength and stiffness even when it has become saturated [4]. CSRB also allows for thinner pavement sections because of its high strength as a base.

**Table 2: Georgia Standard Specification 814.02 – Classification Requirements for SFDR Process Using Cement Stabilization [26]**

<b><u>Soil Property</u></b>	<b><u>GDOT Specification</u></b>
Clay Content (%)	5-25
Volume Change (% max.)	18
Liquid Limit (max.)	25
Plasticity Index (max.)	10
% Passing 0.075-mm Sieve	0-30

GDOT has rehabilitated many roadways by the use of SFDR for the following reasons: normal vehicular traffic causing load-fatigue cracking of the pavement surface, water penetrating the granular base, underlying clay retaining water and deforming the base, and heavy timber trucking and overweight farm equipment causing deterioration [4]. GDOT would have conventionally recommended a complete removal of the existing asphalt pavement for the roadways with the aforementioned issues. However, SFDR offered a less expensive alternative, therefore GDOT pursued SFDR as a pavement rehabilitation process [4].

The use of SFDR by GDOT allowed for a total cost reduction of 42% in comparison to complete reconstruction of pavement structures using conventional rehabilitation methods [4]. GDOT determined that the optimal mixing ratio needed for stabilization was 6% cement by weight of the dry existing base course [4]. This addition of cement achieved the desired level of unconfined compressive strength of 3,100 kPa [4]. GDOT also determined that the optimal moisture content of the SFDR was 11.6% [4]. Review of the pavement structures after one year of project completion revealed that a few problems were caused by the use of SFDR. Minimal cracking occurred due to excessive amounts of cement being used to stabilize the base. Also, minimal rutting had occurred from the base not being fully stabilized [4].

#### Georgia – Lime Stabilizer

Reconstruction of a Georgia roadway occurred in April of 2006 [26]. It was determined that the roadway was to be repaired by the use of SFDR. Base and pavement cracking were caused by instability in the underlying subgrade material that consisted mostly of clay-silt soils [26]. The use of lime as a soil stabilizer is a well-known construction technique and was used in this project to stabilize the underlying base course.

Soil stabilization occurs when lime is added to a reactive soil. This addition of lime generates long-term strength through a chemical reaction that produces calcium silicate hydrates and calcium aluminate hydrates. These hydrates provide strength to the pavement structure [27]. This reaction may occur for longer than a decade as long as sufficient amounts of lime are present ( $\text{pH} > 10$ ) [27]. The Thompson procedure states that most fine-grained soils, such as the clay-silt in the SFDR, may be stabilized with 3-10% lime on a dry soil weight basis [28]. The optimal mixing ratio determined was 6% lime by volume [26]. GDOT also determined that the optimal moisture content for the SFDR base was 13% by weight [26].

During construction of the roadway, the lime was well mixed to achieve the benefits of the lime stabilizer. Some of these benefits included: high and long lasting strength gains, increase in resilient modulus values, improvements in shear strength, plasticity reduction, reduction in moisture-holding capacity, and improved stability [26]. Soil and falling weight deflectometer testing were performed by GDOT before and after the SFDR process and the results indicated substantial improvement in the structure of the pavement and the subgrade base [26]. No problems as a result of the SFDR process were reported for Georgia's use of lime.

## Nevada

The Nevada Department of Transportation (NDOT) uses both cold-in-place recycling (CIR) and SFDR pavement rehabilitation methods as a way to reduce the cost of roadway rehabilitation projects. The department has saved over \$600 million over the past 20 years by its use of SFDR and CIR [7]. NDOT estimates that it saves \$330,000 per centerline mile when it uses SFDR or CIR recycling techniques rather than complete pavement reconstruction [7]. 96% of all roadways in Nevada are considered to be a "good" ride quality which is the highest percentage of "good" ride quality roads in the nation [7]. Nevada experiences reflective cracking of its pavement, and NDOT has established SFDR as the conventional method to fix pavement structures with this type of cracking.

NDOT has developed some special techniques for its implementation of SFDR. After pulverization of the pavement, the material must have a 95% to 100% passing by mass rate for a 2-in. sieve [7]. NDOT uses cement as a stabilizer at a rate of 2% cement by weight of the reclaimed material. In some regions of Nevada, the climate is more severe, and so the cement content was reduced to 1.5%; this reduction in cement proportion prevented long-term transverse cracking [7]. The pulverized material is compacted to no less than 95% relative maximum density and then is coated with seal coat to allow for hydration of the cement [7]. After the base course has cured, a 3 ½ - 5 ½ inch plant-mix bituminous surface is laid over the processed base [7].

NDOT has completed almost 900 miles of SFDR since 1985 [7]. Since it has such a long history of practicing SFDR, it is able to record great data on the longevity of this process. Multiple 10-year performance reports indicate that most NDOT SFDR projects performed well. Minor cracking was encountered and failed pavements had typically occurred for reasons other than the use of SFDR [7]. 10-15 year reports begin to show the fatigue of the pavement. Most pavement structures performed well, but several projects exhibit transverse or fatigue cracking [7]. It was determined that the transverse cracking occurred because of the relative stiffness of the SFDR base [7]. Selective core tests were performed and it was shown that the cracking had been reflected through the SFDR layer. Non-wheel path longitudinal cracking was also observed to be a result of inadequate compaction of the SFDR during construction [7]. Therefore, good construction techniques are imperative to the success of an SFDR project. After 15 years of use, nearly all SFDR projects experienced reflective cracking and some have been rehabilitated again.

## Virginia

The Virginia Department of Transportation (VDOT) constructed three trial SFDR sections in the summer of 2008 [21]. These trial sections each used a different agent to stabilize the FDR. The stabilizing agent used in the first and second sections of roadway was Portland cement, the second section used a combination of asphalt emulsion and foamed asphalt binder to stabilize the FDR.

The VDOT study concluded that SFDR should be used in the future as a roadway rehabilitation option for its cost savings potential. VDOT estimates that it could potentially save \$1.42 million per year if it used SFDR on roads that qualify for rehabilitation [21]. VDOT also concluded that the structural capacity of pavement rehabilitated by the use of SFDR is dependent on both the chosen stabilizing agent, as well as time [21]. Estimation of the structural capacity of a newly rehabilitated road structure could not be accurately completed immediately after a project is completed. VDOT noticed change in the structural capacity of the pavement for at most two years after project completion, however, core sample testing typically showed no difference in structural capacity of 5 month samples and 33 month samples [21]. Laboratory tests showed that there was no statistically significant difference between the resilient modulus values of FDR stabilized with foamed asphalt and FDR stabilized with emulsion [21].

## Minnesota

Minnesota currently practices SFDR and has been for many years. Since there is history of SFDR in Minnesota, it will be explored in this section. This data will be most valuable to this research project. Different articles were reviewed and their results are shared in the following paragraphs.

MnDOT currently allows the use of RAP as Class 7 aggregate base. A team of researchers, Attia, Abdelrahman, and Alam, conducted research on the effect of freeze-thaw and severe moisture conditions on the structural capacity of pavement base layers [29]. They studied many different types of pavement base including: one sample of 100% RAP, one sample of virgin aggregate, and three samples of SFDR. The research team performed laboratory testing on the materials and measured properties such as the resilient modulus (MR) and shear strength after conditioning the samples. The samples were compacted using a Supverpave gyratory compactor. Resistance to abrasion and degradation of the samples was tested using the Micro-Deval test. Structural capacity was determined by testing the MR of the samples following the National Cooperative Highway Research Program (NCHRP) 1-28A protocol. The triaxial shear test was used to determine shear strength of the samples.

Attia, Abdelrahman, and Alam concluded that the MR for all RAP material was higher than that of the virgin aggregate, specifically Class 5 [29]. The MR of the material was also found to be dependent on the confining pressure. The research team further concluded that there was no significant loss of MR due to freeze-thaw conditioning for the tested samples [29]. This effect was only significant at low confining pressures. As the pressure increased, this correlation

ceased to exist. The research team concluded that RAP should be perceived as a viable option for use as a pavement base layer.

Kim and Labuz from MnDOT and UMN have published a report on the performance characteristics of base material produced from RAP and aggregate [30]. Their research objective was to determine the strength and deformation characteristics of the base material they were studying. Since the base material they were studying are similar to the base materials studied for this research project, their mechanical test methods are valuable.

Kim and Labuz concluded that at least two times greater permanent deformation occurred in specimens with RAP than the 100% aggregate material; as RAP increases, more permanent deformation occurs [30]. They also concluded that permanent strain and energy loss reached a constant value as the number of cycles increased in a triaxial test for shear strength [30]. They reported that the order of permanent strain and energy loss for the first five cycles was the same as the order for the entire cycling. This indicates that more permanent strain and energy loss occurs when the proportion of RAP is increased [30].

Kim and Labuz considered Young's modulus and found that for the first five cycles of a triaxial shear strength test, the aggregate specimen was the stiffest, but the 25% aggregate – 75% RAP specimen was the stiffest after 5000 cycles [30]. Kim and Labuz concluded that when considering stiffness and strength of the base course material, 50% aggregate and 50% RAP mixtures perform similar to 100% aggregate base that has been properly compacted [30].

MnDOT has completed many SFDR construction projects on different trunk highways (TH) and country roads (CR) throughout the state of Minnesota. These projects and their respective mix designs are displayed in Table 3. All of these mix designs were determined by American Engineering Testing (AET) according to the Road Science specification *Guidelines for Asphalt Emulsion Full Depth Reclamation (FDR) and Granular Base Stabilization (GBS)* [31].

**Table 3: MnDOT SFDR Projects**

<b>Road</b>	<b>Mix Design</b>
CR 30	4 to 5 % Emulsion
TH 55	4 to 5 % Emulsion
TH 65	1.5 % Cement and 3 to 3.5 % Emulsion
TH 70	1.5 % Cement and 4 to 5 % Emulsion

### Current Issues

It is apparent that SFDR processes have multiple advantages such as the ones listed previously in this report. The list of advantages may be extensive, but the SFDR process still has issues. Some of these issues were seen in Georgia and Nevada's implementation of SFDR in its roadways. NDOT has found after 20 years of SFDR practice, that the greatest lifetime of a SFDR

rehabilitated pavement structure is 15 years. After 15 years, or less if poor construction techniques were used, different forms of fatigue begin to appear.

Georgia did not report many problems with the performance of its lime SFDR pavement structures, but this is likely due to a shorter time of roadway observation. The use of cement as a stabilizer in Georgia did show signs of fatigue. Minimal cracking occurred due to excessive amounts of concrete being used and minimal rutting occurred due to the base not being fully stabilized.

NDOT experienced cracking of the SFDR base course, which was often reflected to the pavement surface. Transverse cracking and fatigue cracking has also been noticed in Nevada's SFDR pavement structures. Even though NDOT has over 20 years of SFDR data, it still encounters cracking problems in its structures. Poor construction techniques may also lead to cracking and fatigue issues, therefore a well-informed contractor is imperative to successful SFDR implementation.

### Laboratory Testing

Understanding the mechanical performance of the SFDR base is critical for determining optimal design parameters. To determine the mechanical properties of the SFDR, it is necessary to test SFDR samples in a laboratory to determine specifications for pavement materials such as modulus and shear strength values. After a review of the literature, it was found that fracture energy tests of SFDR have not yet been performed by other research agencies. Fracture energy tests are very important for determining the low-temperature cracking potential of SFDR, so it is suggested that fracture energy tests be performed in the proposed research. This section describes some of the current tests performed on SFDR laboratory samples.

### Gyratory Compaction

Research samples are typically compacted using a gyratory compactor [7, 26, 29 & 30]. Samples prepared using gyratory compaction methods more closely resemble densities of aggregates measured in the field. Table 4 displays how the gyratory compactor achieved higher densities in comparison to the proctor method.

**Table 4: Compaction of Base Materials [30]**

Soil Identification Letter	Description	Proctor		Gyratory	
		Maximum Dry Density (kg/m <sup>3</sup> )	Optimum Moisture Content (%)	Maximum Dry Density (kg/m <sup>3</sup> )	Optimum Moisture Content (%)
S	In-situ Blend, CR 3	1984	9	2032	7.8
T	100% Aggregate, CR 3	2000	10	2032	8.8
U	75% Aggregate - 25% RAP, CR 3	2000	10	2032	8.7
V	50% Aggregate - 50% RAP, CR 3	1952	9.5	2032	8.0
W	25% Aggregate - 75% RAP, CR 3	1920	8.5	2032	7.2
X	In-situ Blend, TH 23	2000	7	2080	5.4
Y	In-situ Blend, TH 200	2096	6.5	2144	5.7
Z	In-situ Blend, TH 5	1984	8.5	2112	6.6

### Resilient Modulus Testing

Resilient modulus (MR) tests are conducted following the National Cooperative Highway Research Program 1-28A test protocol [30]. In this procedure, cycles of repeated axial stress are applied to a laboratory sample at a given confining pressure within a conventional triaxial cell. From the report of Kim and Labuz, MR was seen to increase with increase of confining pressure [30]. MR also showed little change for changes in deviator stress. Kim and Labuz also report that the MR test results showed an increase in MR with the addition of RAP [30]. Attia, Abdelrahman, and Alam also performed MR testing on their samples and followed the same testing protocol as Kim and Labuz [29].

Kim and Labuz have shown in their report that the MR value is dependent on the stress applied during the loading of the samples. The research team explored many different models to find one that most accurately describes their data [32-36]. The model, which most accurately matches their data, is given by equation (1) [32 & 33]:

$$M_R = k_1 \cdot \left( \frac{\sigma_3}{P_a} \right)^{k_2} \quad (1)$$

where  $k_1, k_2$  = regression coefficients  
 $P_a$  = atmospheric pressure (0.101 MPa)  
 $\sigma_3$  = confining pressure

This equation fit the data well if the regression coefficient  $k_2 = 0.50$ . Kim and Labuz also reported that MR increased as the confining pressure increased. They described this relationship with a square-root dependence in equation (2) [30]:

$$\frac{M_R}{P_a} = k \cdot \left( \frac{\sigma_{mean}}{P_a} \right)^{0.5} \quad (2)$$

where  $\sigma_{mean} = (\sigma_1 + \sigma_2 + \sigma_3)/3 =$  confining pressure

$P_a =$  atmospheric pressure (0.101 MPa)

$k =$  regression coefficient

### Shear Strength Testing

The report by Kim and Labuz also included shear strength testing of the samples. Their samples were tested at confining pressure values of 34.5 kPa and 69 kPa [30]. Determination of the friction angle ( $\phi$ ) and cohesion ( $c$ ) which was used by Kim and Labuz is given in equations (3) and (4) [30]:

$$\sigma_{1f} = 2c\sqrt{K_P} + K_P\sigma_3 \quad (3)$$

$$K_P = \frac{1 + \sin \phi}{1 - \sin \phi} \quad (4)$$

where  $\sigma_3 =$  confining pressure

$\sigma_{1f} =$  confining pressure + deviator stress

Cyclic triaxial testing is often conducted to evaluate samples for their shear strength. For example, Kim and Labuz used a 5000 cycle test to evaluate their samples.

### Other Tests

Fracture energy may be determined by either the semi-circular bend (SCB) test or the disc compact tension (DCT) test. The SCB test has been shown to have higher variability in comparison to the DCT, therefore the DCT is recommended over the SCB. However, since it is unsure how the samples will perform under the DCT testing, the SCB test may serve as a substitute for determination of fracture energy. Creep compliance of tested samples may be determined by using the indirect tensile test (IDT). Stiffness of the SFDR samples may be determined by running the dynamic modulus ( $E^*$ ) test.

## Summary

One of the biggest challenges SFDR faces is overcoming the variability of field conditions. Since each road rehabilitation project has different conditions such as existing pavement, existing soil and environmental conditions, determining the correct mixing ratio of additives used in SFDR is often difficult. Difficulty also lies in the mechanics of testing these stabilized bases. Lab result tests may indicate that a certain mixing ratio is projected to perform best in the field. However, field-testing may show that a different mixing ratio performs better. This ambiguity should be resolved by creating a more effective extrapolation of laboratory results to actual SFDR implementation in the field.

Methods for testing SFDR are similar to methods used to test pavement materials. Resilient modulus values indicate the stiffness of the material and therefore determination of this value is imperative to this research study. Other laboratory tests of interest include shear strength testing, fracture energy testing, and creep compliance testing. A review of the literature however, did not find any reports on fracture energy tests performed on Minnesota SFDR. This research project should include fracture energy tests for the SFDR samples. It was also found that gyratory compaction of samples most closely matches the densities of materials in the field.

After a review of the literature, it was determined that the desired physical parameters for SFDR are not well defined. Trial and error methods are typically used when designing a mix for an SFDR project, but there is no general consensus on what makes a good mix design. Through the use of the Mechanistic Empirical Pavement Design Guide (MEPDG) software provided by MnDOT, the optimal physical parameters of SFDR will be determined. Collecting and analyzing cores of existing SFDR roadway bases that are performing well will validate the parameter values given by the MEPDG software. This process will ultimately lead to the determination of the optimal physical properties of SFDR.

## References

- [1] *Municipal solid waste*. (2013). Retrieved 09/22, 2013, from <http://www.epa.gov/epawaste/nonhaz/municipal/index.htm>
- [2] *User guidelines: Reclaimed asphalt pavement, granular base*. (2007). <http://www.tfhr.gov/hnr20/recycle/waste/rap131.htm>
- [3] Kroge, M., McGlumphy, K., & Besseche, T. (2009). Full-depth reclamation with engineered emulsion in fairburn, georgia. *Transportation Research Record*, (2095), 136-143. doi:10.3141/2095-14
- [4] Lewis, D. E., Jared, D. M., Torres, H., & Mathews, M. (2006). Georgia's use of cement-stabilized reclaimed base in full-depth reclamation. pp. 125-133.
- [5] Basic asphalt recycling manual. (2001). *Asphalt Recycling and Reclaiming Association*
- [6] Mallick, R. B., Teto, M. R., Kandhal, P. S., Brown, E. R., Bradbury, R. L., & Kearney, E. J. (2002). Laboratory study of full-depth reclamation mixes. *Transportation Research Record*, (1813), 103-110.
- [7] Bemanian, S., Polish, P., & Maurer, G. (2006). Cold in-place recycling and full-depth reclamation protects by Nevada Department of Transportation: State of the practice. Paper presented at the *Pavement Rehabilitation*, (1949) pp. 54-71.
- [8] Mallick, R. B., Bonner, D. S., Bradbury, R. L., Andrews, J. O., Kandhal, P. S., & Kearney, E. J. (2002). Evaluation of performance of full-depth reclamation mixes. *Transportation Research Record*, (1809), 199-208.
- [9] Recycling and reclamation of asphalt pavement using in-place methods.(2011). *Transportation Research Board - National Cooperative Highway Research Program*, (421)
- [10] Cement-treated, full-depth reclamation method extends pavement life. (2008). *Concrete Products*, 111(2), 15.
- [11] Everything in green. (2011). *Roads & Bridges*, 49(9), 48-51.
- [12] Landers, K. (2001). Rebuilding by reclaiming: The FDR process. *Better Roads Magazine*, 72(7), 6-9.
- [13] Kearney, E. J., & Huffman, J. E. (1999). Full-depth reclamation process. *Transportation Research Record*, (1684), 203-209.
- [14] Lewis, D. (2004). Recycling whole roads! *Presented at Georgia Quality Initiative Workshop*
- [15] Epps, J. A. (1990). NCHRP synthesis of highway practice 160: Cold-recycled bituminous concrete using bituminous materials. *Transportation Research Record, National Research Council*.
- [16] Scullion, T., Sebesta, S., Estakhri, C., Harris, P., Shon, C., Harvey, O., et al. (2012). Full-depth reclamation: New test procedures and recommended updates to specifications. *Federal Highway Administration - Texas Department of Transportation*, (FWHA/TX-11/0-6271-2), 104.
- [17] *Investigation of Optimal Mix Design of Full Depth Reclamation Stabilization with Cement and Emulsion: Project Proposal Form*. (2013). Minnesota

Department  
of Transportation – Minnesota Local Road Research Board.

- [18] Ryan, N. (2010). Y=FDR. *Roads & Bridges*, 48(2), 30-32.
- [19] Reclaiming the streets. (2007). *Roads & Bridges*, 45(10), 46.
- [20] Dixon, P., Guthrie, W., & Eggett, D. (2012). Factors affecting strength of road base stabilized with cement slurry or dry cement in conjunction with full-depth reclamation. *Transportation Research Record*, (2310), 113-120. doi:10.3141/2310-12
- [21] Diefenderfer, B. K., & Apeageyi, A. K. (2011). Analysis of full-depth reclamation trial sections in Virginia. *Virginia Center for Transportation: Innovation and Research*, (11-R23)
- [22] Full-depth report: Washington state uses cement for failed pavements. (2006). *Roads & Bridges*. 76.
- [23] Harris, S. (2007). Reusing roadways. *Roads & Bridges*. 45(5). 60-63.
- [24] Lebanon, Ohio uses FDR to quell reflective cracks. (2012). *Pavement Preservation Journal*. 37.
- [25] Shatnawi, S. (2012). Implementing in-place recycling technologies. *Pavement Preservation Journal*. 33-35.
- [26] Smith, C. R., Lewis, D. E., Turner, J., & Jared, D. M. (2008). Georgia's use of lime in full-depth reclamation. *Transportation Research Record*, (2059), 89-94. doi:10.3141/2059-10
- [27] *Lime and soil stabilization*. (2012). Retrieved 09/23, 2013, from [http://www.lime.org/uses\\_of\\_lime/construction/soil.asp](http://www.lime.org/uses_of_lime/construction/soil.asp)
- [28] Thompson, M. R. (1970). Suggested method of mixture design procedure for lime treated soils. *ASTM, Special Technical Publication 479*.
- [29] Attia, M., Abdelrahman, M., & Alam, T. (2009). Investigation of stripping in Minnesota class 7 (RAP) and full-depth reclamation base materials. *Minnesota Department of Transportation*, (2009-05).
- [30] Kim, W. and Labuz, J.F. (2007). Resilient Modulus and Strength of Base Course with Recycled Bituminous Material, Report No. MN/RC-2007-05, Minnesota Department of Transportation, University of Minnesota. <http://www.lrrb.org/pdf/200705.pdf>.
- [31] Road Science. September 26, 2005. Guidelines for Asphalt Emulsion Full Depth Reclamation (FDR) and Granular Base Stabilization (GBS).
- [32] Dunlap, W.A. (1963). *A Report on a Mathematical Model Describing the Deformation Characteristics of Granular Materials*. Texas Transp. Inst., Tech. Rep. No. 1, Proj. 2-8-62-26, Texas A&M University, College Station, Texas.
- [33] Monismith, C.L., Seed, H.B., Mitry, F.G., and Chan, C.K. (1967). Prediction of Pavement Deflections from Laboratory Tests. *Proc., 2nd Int. Conf. Struct. Des. of Asphalt Pavements*, 109-140.
- [34] Hicks, R.G. (1970). Factors Influencing the Resilient Properties of Granular Materials. Ph.D. thesis, University of California, Berkeley.
- [35] Seed, H.B., Mitry, F.G., Monismith, C.L., and Chan, C.K. (1967). Prediction of Flexible Pavement Deflections from Laboratory Repeated Load Tests. *NCHRP Rep. No. 35*, National Cooperative Highway Research Program.

- [36] Uzan, J. (1985). Characterization of granular material. *Transportation Research Record No. 1022*, 52-59.

## Project Contacts

Richard Kirchner  
Master's of Science Student  
University of Minnesota, Minneapolis  
Department of Civil Engineering  
500 Pillsbury Drive S.E.  
Minneapolis, MN 55455-0116  
kirc0211@umn.edu

Jia-Liang Le, Ph.D., M.Eng., B.Eng  
Assistant Professor  
University of Minnesota, Minneapolis  
Department of Civil Engineering  
500 Pillsbury Drive S.E.  
Minneapolis, MN 55455-0116  
Phone: (612) 625-0752  
jle@umn.edu

Mihai Marasteanu, Ph.D., M.S., Engineer Diploma  
Professor and Director of Undergraduate Studies  
University of Minnesota, Minneapolis  
Department of Civil Engineering  
500 Pillsbury Drive S.E.  
Minneapolis, MN 55455-0116  
Phone: (612) 625-5558  
maras002@umn.edu

Alan J Rindels  
Senior Engineer  
Minnesota Department of Transportation  
Transportation Department  
395 John Ireland Blvd - 330  
Saint Paul, MN 55155-1899  
(651) 366-3779  
alan.rindels@state.mn.us

Shirlee Sherkow  
Research Analysis Specialist  
Minnesota Department of Transportation  
Transportation Department  
395 John Ireland Blvd - 330  
Saint Paul, MN 55155-1899  
(651) 366-3783  
shirlee.sherkow@state.mn.us