

# Base Stabilization Guidance and Additive Selection for Pavement Design and Rehabilitation

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## PURPOSE OF THIS DOCUMENT

This guidebook focuses on the stabilization of Aggregate Base Materials for new construction and Stabilized Full Depth Reclamation (SFDR) and to assist with the selection of suitable nonproprietary stabilization additives for individual specific project(s). Stabilization additives addressed in this guidebook are readily available and nonproprietary. A range of products are available including bituminous and pozzolanic chemical stabilizers such as cement or fly-ash, all of which permanently stabilize base materials for roadway construction, but it is not always clear which product is the right one to use.

Improvements continue to be made in base stabilization practice that include design specifications and methodology, experience with the selection of stabilizing additives, and equipment for distribution and uniform blending of additives. For the rehabilitation of existing pavements, base stabilization has delivered performance as good as or better than reconstruction at a reduced cost. Proprietary products that may provide stabilization benefits are not the focus of this report, but questions to consider are addressed.

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## INTRODUCTION

Base stabilization in this document refers to techniques that amend base aggregate material, through the incorporation of a stabilizing additive, to produce a homogeneous base layer with enhanced characteristics for strength, stability, and durability. Improvements to strength and stability translate into improved performance of the supported pavement structures. It is essential that the stabilizing additive provide permanent and durable improvement in the strength and stability.

Base stabilization can improve the pavement structure in many ways including [1]:

- **Shear strength** – the ability to resist shear stresses and permanent deformation, rutting and shoving, due to traffic loading.
- **Modulus (stiffness)** – the ability to maintain physical volume and respond elastically to traffic loading and minimize permanent deformation.
- **Durability** – the ability to maintain material and engineering properties and resist the absorption of water when exposed to environmental conditions such as moisture and temperature change.
- **Resistance to fatigue** – the ability to extend pavement service life by addition of a crack resistant base layer that transfers maximum horizontal tensile strains from the bottom of the hot mix asphalt (HMA) layer deeper into the pavement structure.
- **Grade change restrictions** – the ability to minimize the thickness of the HMA overlay by strengthening the underlying base layer.

Base stabilization is a valuable tool roadway engineers can employ when designing new pavement structures as well as rehabilitating their existing pavements. Stabilized Full Depth Reclamation (SFDR) is a method used to produce a stabilized aggregate base layer from an existing pavement structure.

## BASE STABILIZATION

Base Stabilization refers to permanent improvements made to a base aggregate layer resulting in a bound structural pavement layer with measurable enhancements to elastic and strength characteristics. Increased structural capacity derived from stabilizing a base layer can result in an overall more economical equivalent pavement structure with a surfacing layer that is thinner but not excessively thin. A laboratory mix design is required to optimize the type and quantity of additive to be incorporated that allows the mixture to meet performance requirements for strength, elasticity and durability. Performance testing varies based upon stabilization technique and additive utilized. Field confirmation testing is recommended to assure material as placed meets laboratory mix design characteristics translating to improved pavement performance and expectations.

This guidebook identifies four key elements to the stabilization process and separates stabilization into two categories based upon additive type used: Chemical Stabilization and Bituminous Stabilization.

### Key Elements to Stabilization

1. **Aggregate Base Product:** Aggregate material type and gradation influence stabilization recommendations for additive type and amount to be incorporated. A reclaiming machine is typically used to blend additive with an aggregate product. Reclaiming can pulverize an existing asphalt pavement to a predetermined depth then incorporate and blend stabilizing material; a method referred to as Stabilized Full Depth Reclamation (SFDR). New aggregates can also be added to the in-place reclaimed material to obtain a desired gradation for the final product.
2. **Additive:** Stabilizer material that is blended with the aggregate product. Asphalt stabilizing material is typically a liquid asphalt blended into the aggregate. Chemical stabilizing products are typically dry and mechanically spread over the aggregate product then blended.
3. **Compaction:** Compaction usually starts with vibratory pad foot roller and continues with a pneumatic roller and finishes with vibratory or static smooth drum rollers.
4. **Application of an overlay:** The new stabilized base layer is covered with either a bituminous or concrete surface. In some low volume applications a thin surface treatment, such as chip seal, otta seal, or microsurfacing, may be used as a final surfacing.

## BASE MODIFICATION

Base Modification refers to the incorporation of additives to base materials that provide short term improvements intended to facilitate construction as a compaction aid. In general long-term permanent improvements are not relied upon nor considered in the design thickness of the overlying surfacing; the base layer is thought to remain essentially unbound. Modifiers, additives that may be the same as used for stabilization and include proprietary products, in general do not have design procedures or laboratory and field verification testing to identify contributions to the pavement structure and confirm long term sustained performance.

## IN PLACE PAVEMENT RECYCLING METHODS

A wide range of pavement distresses can be addressed by in place pavement recycling which include [2]:

- All forms of cracking; fatigue, edge, slippage, block, longitudinal, and reflective

- Reduced ride quality due to swells, bumps, sags, patches, and depressions

- Permanent deformations including, rutting, corrugations, and shoving

- Loss of bond between pavement layers

- Moisture damage (stripping)

- Loss of surface integrity due to raveling, potholes, and bleeding

- Inadequate structural capacity

- Addressing subgrade instability by increasing structural capacity of the base and surfacing layers

Recycling deteriorated pavements in place routinely utilize methods that include “Full Depth Reclamation” and “Cold in Place Recycling”. These methods do not stabilize base materials and will not be covered in depth in this guidebook but are defined below in an effort to illustrate the differences between the methods. “Stabilized Full Depth Reclamation”, as a primary method used for base stabilization, is discussed in detail on the following pages. Additional Methods available that do not stabilize base materials include “Full Depth Reclamation” and “Cold in Place Recycling”, which are also defined below in order to illustrate the differences between the methods, but will not be covered in depth in this he guidebook.

## Full Depth Reclamation (FDR)

Full Depth Reclamation (FDR) is a rehabilitation method in which the full thickness of the asphalt pavement is pulverized and blended with a predetermined portion of underlying materials (base and/or subbase) to provide an upgraded, homogeneous material [2]. Additional granular materials (e.g. new aggregate) or recycled materials (e.g. reclaimed asphalt pavement (RAP), add rock or crushed concrete) can be added to improve load carrying capacity of the FDR layer. No stabilization additive is used in FDR operation and the FDR layer remains unbound. The use of a laboratory mix design and addition of a stabilizing additive redefines an FDR as an SFDR.

## Stabilized Full Depth Reclamation (SFDR)

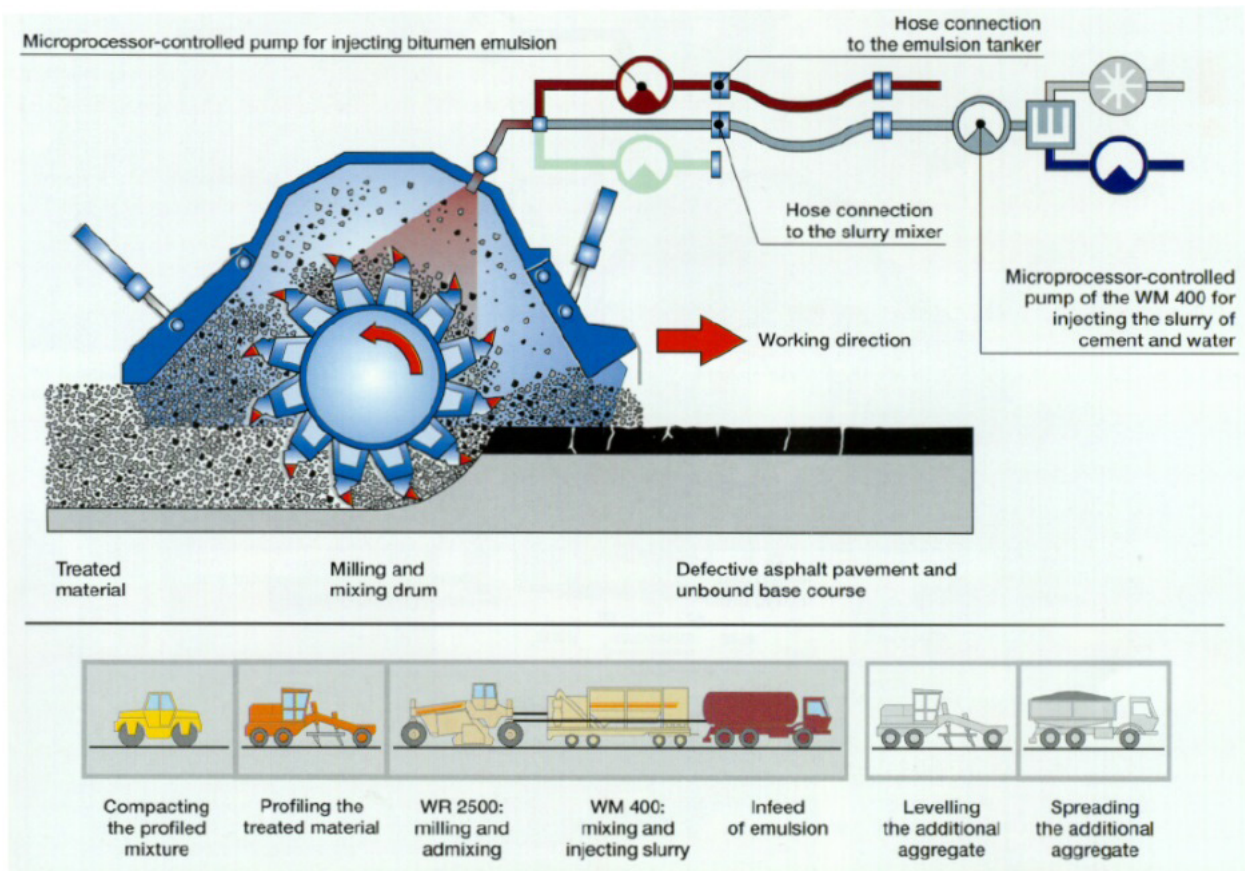
SFDR is the method of performing a Full Depth Reclamation through pulverization of a bound surfacing layer and blending a stabilization additive into the pulverized/reclaimed material to produce a homogeneous base material. Underlying aggregates or add rock distributed over the surface may be incorporated during the reclaiming and blending processes and as identified through the mix design procedure. SFDR recycles the existing pavement structure in a manner that provides a permanent and measurable long term structural improvement to a base layer and reuses the existing subgrade thereby reducing project cost by eliminating the need for subgrade excavations and material replacement. SFDR, as an in place pavement recycling method, eliminates pavement distresses as mentioned above.

Figure 1 on the next page, shows a schematic of the SFDR process for a single machine, shows the process where a single machine is capable of breaking, pulverizing and injecting a stabilizing additive in one or two passes.

## Cold In-place Recycling (CIR)

Cold In-place Recycling (CIR) is a method of removing and reusing a portion of an in-place hot mix asphalt (HMA) layer to produce a restored pavement layer. The CIR method usually involves milling the top few inches (usually 3 to 5 inches) of the existing HMA surface, mixing the pulverized RAP with a bituminous stabilization additive (engineered emulsion, commodity emulsion or foamed asphalt), and placing it back down with a paver. The CIR method uses 100% of RAP generated. CIR stabilization does not involve the underlying layers (base/subbase) and provides performance characteristics that are different from full depth reclamation methods.

FIGURE 1: SCHEMATIC OF THE SFDR PROCESS FOR A SINGLE MACHINE [3]



Source: BARM

## STABILIZATION ADDITIVES

This guidebook divides base stabilization additives into two broad categories: chemical stabilization and bituminous stabilization.

### Chemical Stabilization

With chemical stabilization, strength gain is achieved by creating a matrix that binds the aggregate particles together. Chemical stabilizers react chemically with the material being stabilized (e.g., lime reacts with clay) or react on their own to form cementing compounds (e.g., cement). Chemical additives should be incorporated in a range that produces increased strength and stability without creating a rigid brittle blend



that can induce cracking of the overlying pavement surface. An insufficient amount of stabilizing agent will not provide adequate binding within the matrix and too much stabilizing agent can increase the rigidity of the base layer with the potential to induce cracking. Primary chemical stabilization additives are as follows:

- **Cement:** Portland or hydrated

- **Lime:** hydrated or quick lime

- **Fly-ash:** by-product of coal combustion and can be in the form of self-cementing Class C or Class F (when used in combination with other additives)

- **Cement Kiln Dust (CKD):** by-product of cement production

- **Lime Kiln Dust (LKD):** by-product of lime production

Cement, Cement Kiln Dust (CKD), and fly-ash typically are limited to aggregate materials where the plasticity index is less than 20. Lime and/or Lime Kiln Dust (LKD) are more often recommended for aggregate materials with a plasticity index of about 20 or greater. The calcium oxide (CaO) component of the lime products reacts with clay particles to reduce plasticity.



Cement stabilization in McLeod County

## Bituminous Stabilization

With bituminous stabilization, strength gain is achieved by coating aggregate particles and development of adhesive bonding. Bituminous is a viscoelastic material that also waterproofs aggregates by coating them. Bituminous does not react chemically and its strength properties are dependent on temperature and rate of loading. Additive should be incorporated in a range that waterproofs the aggregate with enough asphalt to increase strength without the matrix becoming unstable. Bituminous stabilization is usually done in one of the following forms:

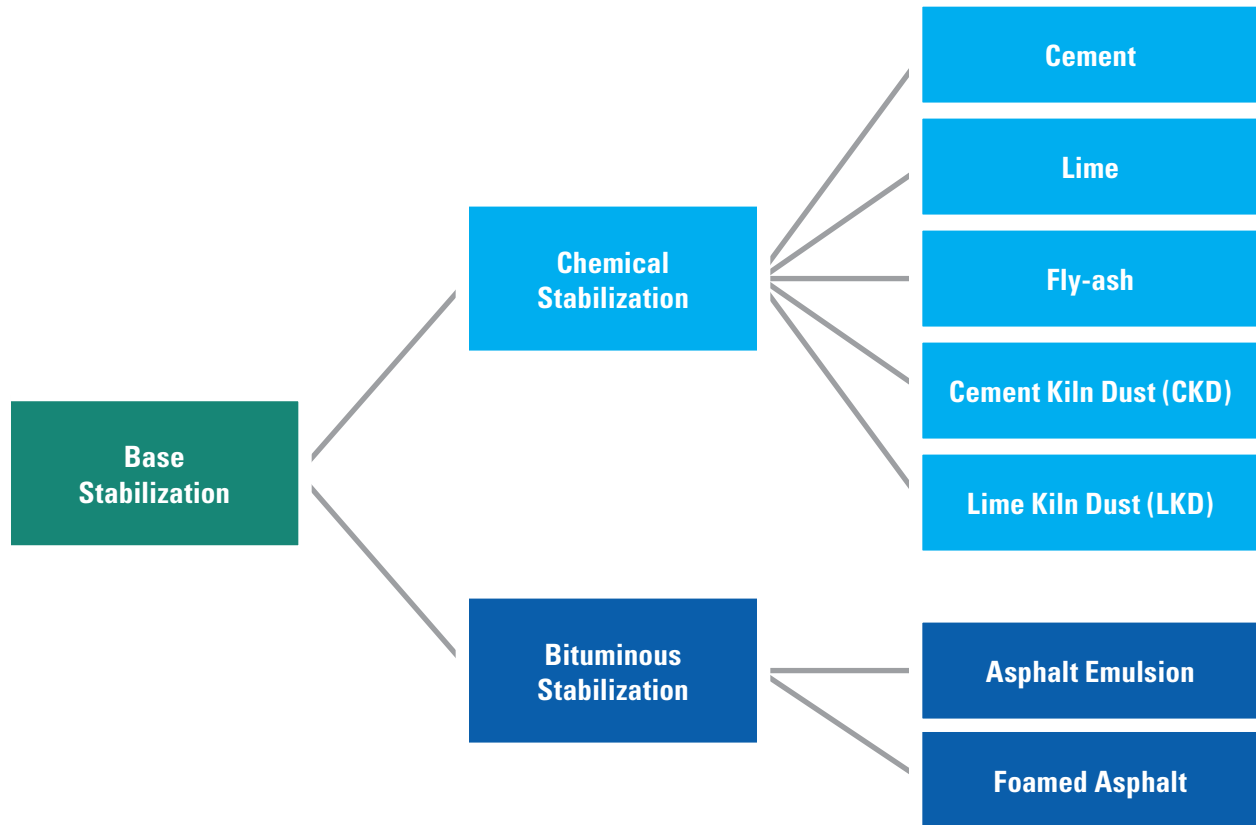
- Asphalt emulsion is a mixture of asphalt binder, water, and an emulsifier. When an emulsion “breaks” the asphalt binder separates from the water and sticks to the aggregate materials. Asphalt emulsion does not require heat during the stabilization process and therefore is not expected to age the asphalt.
- Foamed asphalt is a mixture of compressed air and a small amount of cold water injected into hot asphalt binder (140°C to 170°C). Foamed asphalt adheres to fine particles creating an asphalt bound filler that acts as mortar binding the coarse aggregates together. With foamed asphalt between about 5 to 20 percent of the material passing the 200 sieve is needed. Insufficient fines can result in “stringers” or asphalt-rich agglomerations of fines that act as a lubricant resulting in a reduction in strength and stability of the mixture [2]



Bituminous Stabilization in Cottonwood County

The following Figure 2 shows the base stabilization categories and the stabilization additives under each category.

FIGURE 2. BASE STABILIZATION CATEGORIES AND STABILIZATION ADDITIVES.





## STABILIZATION ADDITIVE SELECTION

































The selection of a stabilization additive depends heavily on the properties and uniformity of the aggregate material (gradation, plasticity, etc.), past experience, and economics. Bituminous stabilization is better suited for cleaner aggregate materials, including sands and gravels, that are not infiltrated by marginal silty or clayey material. Chemical stabilization is better suited for aggregate materials that are finer or have been infiltrated by marginal silty and/or clayey materials. Cement, Cement Kiln Dust (CKD), and fly-ash are typically better suited to aggregate materials where the plasticity index is less than 20. In materials where the plasticity index is greater than 20 Lime and/or Lime Kiln Dust (LKD) are more often recommended. The calcium oxide (CaO) component of these chemical stabilization additives reacts with clay particles to reduce plasticity.

Table 1 presents stabilization additive suggestions based on the gradation characteristics of the aggregate material. Under certain conditions incorporating a chemical additive into or with an asphalt stabilizing additive improved outcomes can be achieved. Combining a chemical additive with an asphalt additive is considered when base materials being stabilized have moisture conditions greater than optimum or employed where early or faster strength gain is desired such as during late season construction.

It is strongly recommended that a laboratory mix design be performed to verify an appropriate stabilizing additive and application rate range for the desired improvement. With all stabilizers an insufficient amount of stabilizing agent will not provide adequate improvement. Incorporating too much stabilizing agent is economically counterproductive and for bituminous stabilizing additives can create an unstable matrix or when using a chemical stabilizer can be a catalyst for cracking.

When using virgin or recycled aggregates crushed to a specific gradation range the designing engineer can anticipate and control the stabilizing process and performance. When reclaiming in place bituminous pavement and further blending with underlying materials a greater degree of variability should be expected by the designing engineer. Pavement coring, sampling and testing base and subbase materials for layer thickness and gradation is necessary for a laboratory mix design and optimizing additive usage. Consideration can also be given to the use of ground penetrating radar (GPR) to better define pavement and base layer thickness and improved consistency of the reclaiming process and incorporation of stabilizing additive.

TABLE 1. STABILIZATION ADDITIVE SELECTION GUIDE [2]

Reclaimed Material Type	Well-Graded Gravel	Poorly Graded Gravel	Silty Gravel	Clayey Gravel	Well-Graded Sand	Poorly Graded Sand	Silty Sand	Clayey Sand
USCS <sup>(1)</sup> Classification	GW	GP	GM	GC	SW	SP	SM	SC
AASHTO <sup>(2)</sup> Classification	A-1-a	A-1-a	A-1-b	A-1-b A-2-6	A-1-b	A-3 A-1-b	A-2-4 A-2-5	A-2-6 A-2-7
Asphalt Emulsion SE <sup>(3)</sup> >30 or PI <sup>(4)</sup> <6 P200 <sup>(5)</sup> <20%								
Foamed Asphalt PI<10 5%<P200<20%								
Cement, CKD, and Fly-ash PI<20								
Lime, LKD PI>20 P200<25%								



Not recommended



Recommended



Highly Recommended

(1) Unified Soil Classification System, ASTM D 2487

(2) American AASHTO Association State Highway Transportation Officials, AASHTO M 145

(3) Sand Equivalent (AASHTO T 176 or ASTM D 2419)

(4) Plasticity Index (AASHTO T 90 or ASTM D 4318)

(5) Percent passing No. 200 (0.075 mm) sieve

# STEPS FOR SUCCESSFUL BASE STABILIZATION

The following is a brief overview for pavement recycling illustrating recommended steps to be taken in regard to stabilization of the base material:

## Step 1: Roadway Assessment

For existing roadways to be rehabilitated, it is important to gather all relevant historical data collected and perform a subsurface exploration to follow through with an acceptable pavement design procedure.

### OBTAINING PAVEMENT CORES

- For an existing roadway pavement, cores and shallow soil borings are recommended to obtain pavement and base layer thicknesses and material properties that include gradation and moisture content.
- An acceptable laboratory mixture design procedure is important and the cores and borings provide the material necessary for performing mix design work.
- Surface distresses observed can also provide insight into the condition of underlying materials and should be considered in selecting locations for coring and borings to be completed.

### DETERMINING SUBSURFACE LAYER CHARACTERISTICS AND THICKNESSES

- Additional valuable pavement thickness data can be obtained from Ground Penetrating Radar (GPR), recommended to develop a nearly continuous assessment of pavement and base layer thicknesses.
- Falling Weight Deflectometer (FWD), recommended to identify in place subsurface layer strengths for the design structural thickness.
- Dynamic Cone Penetrometer (DCP) testing through the core holes can provide an assessment of base and subgrade strength. Consideration should be given to the support of construction equipment as part of the recommended depth of reclaiming.

## Step 2: Stabilization Additive Selection and Laboratory Mix Design

Many factors go into additive selection, it is recommended to use Table 1 in this guide in combination with the roadway assessment information and a formal mix design procedure. Regardless of the stabilization additive selected a permanent adhesive or chemical bond is necessary to extend pavement life and a laboratory mix design is recommended for this assessment. Laboratory mix design methods differ. At present, there is no nationally accepted laboratory mix design method for base stabilization design. Mix design procedures should address both the short and long-term strength and resistance to thermal cracking to assure long-term performance of the stabilized layer. Where reclaiming, samples of the asphalt pavement and underlying materials (aggregate base and subbase), are broken down and blended into representative samples of material to be stabilized similar to obtaining graded aggregates for new construction.

- For coarse granular materials, bituminous stabilizers can be expected to provide the best results.
- For finer base materials with a greater plasticity, chemical stabilization can be expected to provide the best results.

## Step 3: Mix/Process Design

For new construction mix designs and construction are performed using controlled materials meeting contract specifications. For recycling material in place it is recommended to conduct mix design testing on the materials to be used. Cores of the bituminous crushed and blended with the correct portion of underlying base and/or subbase material, generally representing the approximate proportions of the target blend through the reclaim process, can be mixed in the laboratory and performance tested.

- When performing a mix design materials are proportioned according to the methods of construction and what will be left in place when selecting the proper and optimal amount of stabilizing additive. Angularity and uniformity of the aggregate base layer influence are a significant influence to the design and additive selection. Table 1 in this guide provides guidance for additive selection.
- Other information can influence the determination of a suitable recycling method and additive type including drainage, shoulder characteristics, and surface distress levels. Improving drainage or maintaining minimum bridge clearances can dictate the need to raise or maintain the grade of the existing roadway and based upon the economics identify a recycling method.
- Mix design procedures can take several weeks and using samples of the aggregate and stabilizer product is important.

- An overall assessment can provide insight whether CIR, HIR (Hot Inplace Recycling), FDR or SFDR should be selected as the optimal rehabilitation option and target quantity of stabilizer.

- Traffic control requirements during construction can also play a role in method selection. Maintaining traffic is a consideration but it is always the best option to detour the roadway whenever possible. CIR and HIR recycle materials in-place and lay them back down in a full lane width. FDR and SFDR pulverize and for SFDR often introduce additives in a second pass.

- At the time of pavement design consideration should also be given to shoulder widths and drainage improvements. Inadequate shoulders may require material for widening or shoulders may need to be included in the recycle process.

Additional guidance on mix design procedures can be found in Appendix B of this document as well as in the Minnesota Department of Transportation Grading and Base Manual [7] and FHWA Basic Asphalt Recycling Manual (BARM) [2].

## Step 4: Construction

Construction methods should focus on recreating what was designed in the lab. Reclaiming an existing roadway starts by pulverizing the in-place material and blending to depths that provide the same proportions (RAP to Base) that were used in the mix design.

- GPR data can be very beneficial in assuring proper proportioning because it provides guidance for pre-milling or adjusting the depth of the reclaimer when the pavement or base layer thicknesses are not uniform throughout the project.

- Moisture content should also be checked and corrected to as close to optimal identified in the design and for the support of construction equipment.

- Yield and depth checks should be performed to assure the equipment is properly set.

- Other additives that were included in the mix design such as add rock for increased strength should also be pre-pulverized into the roadway to assure conformance with the design.

- Following additive introduction, the compaction process should include a pad-foot roller with adequate passes; until the pad-foot “walks out” or shows light between the drum and compacted base.

- Pad-foot rolling is followed by blading to cut out the pad-foot indentations and construction of the proper cross section and crown.

- Once the cross section and crown are established, steel and pneumatic rollers in combination should be used to obtain optimum density through control strip quality control.

- Water may be added to the surface during the compaction process to assure more uniform cure and improve the results.

- It is recommended for best results to extend the reclaimed section one-foot beyond the new pavement width.
  - When reclaiming an existing roadway, designers should balance material usage with the desired final structure depth, profile, and cross section that can be managed by pre-milling or stockpiling reclaim for shoulder aggregate or other use.

## STABILIZATION TROUBLESHOOTING

Although the vast majority of the base stabilization projects are performing well, performance problems can occur [8]. Table 2 presents some of the common observed problems, their possible causes, and the recommended corrective actions.

TABLE 2. STABILIZATION TROUBLESHOOTING

Problem	Possible Cause	Corrective Action
Longitudinal/shrinkage cracking (in chemical stabilization)	Very stiff stabilized base	Reduce chemical stabilization additive application rate
Inadequate stabilization	Stabilization additive rates are less than the mix design optimum content	Check the application rates during construction/calibrate the equipment
Bonding failure (slippage)	Ineffective tack coat/Dirty or unstable SFDR layer surface	Check the tack coat material and application rate/Make sure SFDR layer surface is clean prior to tack coat application
Inadequate mixing	The reclaimed materials and stabilization additive are not thoroughly mixed	Run an additional pass or slow the speed of the reclaimer

Problem	Possible Cause	Corrective Action
Non-uniform distribution of stabilization additive on outside strips	An outside strip of roadway does not get fully reclaimed/mixed	Mandate a minimum overlap on longitudinal joints
Early load associated distresses	Roadway is opened to heavy traffic during initial curing time	Limit early heavy truck traffic
Surface roughness	Pad-foot depressions left in place	Cut to below pad-foot depressions with grader blade
Stabilized layer surface raveling	Excessive time under traffic prior to overlay	Perform a fogseal surface
Poor ride on the stabilized layer surface	Poor grader operation	Use new laser/GPS technologies
Material does not set up	High moisture content	Dry the material by farming/aeration before additive addition
Unstable overlay	Overlay is placed prior to cure	Allow for adequate cure/check the moisture content and/or check stabilized layer stability.

## LABORATORY MIX DESIGN

Regardless of the stabilization additive used, base stabilization requires a laboratory mix design to be performed. The mix design procedure can take several weeks and requires obtaining samples of the aggregate planned to be used for the base material as well as the stabilizer product. When reclaiming an existing pavement, samples of the asphalt pavement and underlying materials (aggregate base and subbase), are processed into representative samples of blended reclaimed material.

At present, there is no nationally accepted standard laboratory mix design method for base stabilization design. For chemical stabilization the unconfined compressive strength of the cured samples is generally used to assess strength gain in a range that provides increased strength and stability without creating a rigid brittle blend that can induce cracking of the overlying pavement surface. For bituminous stabilization, the mix design procedure should address both the short- and long-term strength and resistance to thermal cracking to assure long-term performance of the stabilized layer.

Some guidance on mix design procedures can be found in Appendix B of this document as well as in the Minnesota Department of Transportation Grading and Base Manual [7] and FHWA Basic Asphalt Recycling Manual (BARM) [2].

# PROPRIETARY PRODUCTS

Proprietary products are available for base stabilization and modification. The product producer usually provides requirements on product application, procedures, equipment, and rates. The producer should also identify any mix design or performance testing to be performed to determine application rates and design parameters. Regardless of the product used it is ultimately the engineer's responsibility to utilize the proper product with the material types present on any project.

## Recommended Protocol for Proprietary Products

For a proprietary product to be considered as a base stabilization additive, the product producer should be able to demonstrate that the product can result in a bound layer which is able to satisfy base stabilization performance testing and mix design requirements. One way to achieve this goal is to produce specimens in the lab, using the proprietary product in question and materials from the roadway to be stabilized, and perform testing. Testing may follow the tests presented in Appendix B of this guidebook for chemical and/or bituminous stabilizing materials to show strength and durability characteristics.

## Questions to ask Vendors

- Do you have independent and reproducible long-term performance test data and research results showing effectiveness of your product?

- Do you have lab testing results available to verify your products effectiveness?

- What types of materials can your product effectively stabilize?

- Do you perform a mix design using materials for the project?

- How did do you determine the application rates?

- Can you take a core of the stabilized material and can it be tested in a lab?

- How long does it take to cure before overlaying?

- Do you have examples of your last ten projects using your product? (want an example a long term, short term, successful and unsuccessful; contact information for agencies/references to talk to)

- Are there precautions or concerns to be aware of when using this product?



## RESEARCH ON WHY STABILIZATION WORKS

The Minnesota Road Research Facility demonstrated successful implementation of Stabilized Full Depth Reclamation with construction of three 500 foot test sections in 2007 on MnROAD's I-94 mainline. This effort was realized through a partnership with MnDOT and industry (SEM Materials) to both demonstrate an effective rehabilitation alternative for severely cracked roadways and to help explain the science behind the observed success of this type of construction. Agencies typically repair severely distressed roadways by reconstruction or with HMA overlays. The problem with overlays is the cracking typically reflects back to the surface and the ride deteriorates in a couple years. SFDR allows for the existing surface cracking to be eliminated and the addition of the stabilized layer provides increased structural strength. A high quality thinner HMA surface utilizing the latest mix-designs engineered to minimize both environmental cracking and surface rutting is then constructed.

Three MnROAD test sections were originally built in 1993 and used in this study. After 14 years of service each section was at the end of its service life as shown in "Before Rehabilitation" image. All three test sections were emulsion stabilized and a 3" HMA surface was constructed over the SFDR layer. The design life was expected to be 5 years or a predicted 3 million ESALS. In 2017, after 10 years of service and the application of 6 million ESALS, all three test sections had outperformed their anticipated design life for both cracking and ride as shown in the "After Rehabilitation" image, while providing 10 years of service to the driving public. This is double the structural design life expected. For all agencies, possessing a rehabilitation alternative that can deliver performance that can compare well to new construction at reduced cost, a lower design life cycle cost, is a significant advantage in maintaining and improving any road system.

### I-94 BEFORE REHABILITATION:

14 year old pavement with cracked HMA



### I-94 AFTER REHABILITATION (~10 YEARS LATER):

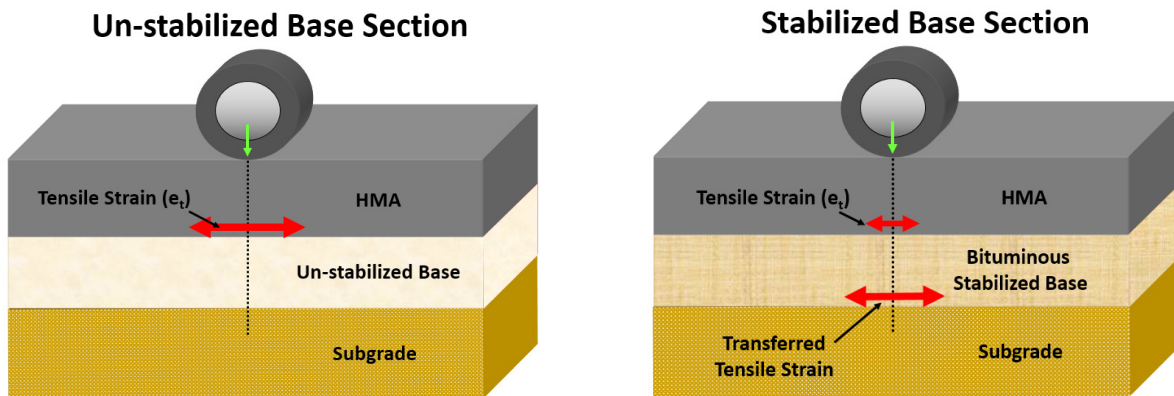
Two times expected ESALS (Traffic) and no reflective cracking



The science behind the performance can be explained through the research done by MnDOT at MnROAD [5]. Test sections were closely monitored for performance (ride and cracking) and instrumentation was installed to measure temperature and strain at critical locations under both the HMA surface layer and stabilized base layers. Similar instrumentation was also installed in a control section with an un-stabilized granular base layer as a comparison. Significant reductions in strain magnitude were measured at the bottom of the HMA mat constructed over stabilized base material as compared to strains measured in the control section with un-stabilized aggregate base material. Additionally, within the stabilized base layer sections strains measured at the bottom of the stabilized base layer were greater than those at the bottom of the HMA layer indicating the stabilized layer successfully transferred strain deeper into the pavement structure.

Tensile strain at the bottom of the HMA was reduced by 50 percent in the section with base stabilization compared to the control section. This reduction and relocation of strain creates a pavement structure with a decreased potential for structural distresses initiating at the bottom of the bound layers. Figure 3 shows the effective tensile strains under the HMA surface for both the un-stabilized and stabilized test sections along with transferring the maximum horizontal strains from the bottom of the HMA layer to the bottom of the base layer in the base stabilized test sections.

FIGURE 3. HORIZONTAL TENSILE STRAINS IN UN-STABILIZED AND STABILIZED TEST SECTIONS





## REFERENCES

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2. Asphalt Recycling and Reclamation Association – ARRA (2015), *“Basic Asphalt Recycling Manual (BARM)”*, Federal Highway Administration, Publication No. FHWA-HIF-14-001.
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5. Johanneck L. and Dai S. (2013), *“Responses and Performance of Stabilized Full-Depth Reclaimed Pavements at the Minnesota Road Research Facility”*, Transportation Research Record: Journal of Transportation Research Board, pp. 114-125.
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9. Skok E. L. et al. (2003), *"Special Practices for Design and Construction of Subgrades in Poor, Wet, and/or Saturated Soil Conditions"* University of Minnesota and the Minnesota Department of Transportation.
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## APPENDIX A: GLOSSARY OF TERMS

**ASPHALT EMULSION:** emulsion of asphalt and water that contains a small amount of an emulsifying agent; it is a heterogeneous system containing two normally immiscible phases (asphalt and water) in which the water forms the continuous phase of the emulsion, and minute globules of asphalt form the discontinuous phase.

**BITUMINOUS STABILIZATION ADDITIVE:** consists of either asphalt emulsion or foamed asphalt for SFDR and/or CIR.

**CHEMICAL STABILIZATION ADDITIVE:** cement, cement kiln dust, lime kiln dust, self-cementing type C fly ash, and/or blend of these materials used in chemical stabilization.

**ENGINEERED EMULSION:** a class of emulsified asphalt used in SFDR and/or CIR that is designed project by project rather than being a product specified with broad specification values.

**FOAMED ASPHALT:** a mixture of air, water, and hot asphalt binder. Cold water together with compressed air is injected into the hot asphalt binder to produce foamed asphalt.

**PULVERIZATION:** A road rehabilitation method where the action of grinding with a Reclaiming Machine is performed to the full depth of a bound surfacing, typically HMA, then mixed to create a uniform and consistent blend of road base material. A portion of the underlying base material may be incorporated with the reclaimed material and blended to create a uniform and consistent blend of road base material.

**PRE-PULVERIZATION:** The first pass of a Reclaiming Machine performed to the full depth of a bound surfacing, typically HMA, to create a uniform and consistent blend of road base material prior to the incorporation of a stabilizing additive, chemical or asphaltic. A portion of the underlying base material may be incorporated with the reclaimed material and blended to create a uniform and consistent blend of road base material.

**RECLAIMED ASPHALT PAVEMENT (RAP):** asphalt pavement or paving mixture removed from the roadway by either milling or full-depth removal for use in recycled mixes.

**STABILIZATION ADDITIVE:** a material that is added to the base materials to improve the mixture properties through significant, long-term reactions which result in a bound layer.



## APPENDIX B: MIX DESIGN PROCEDURE

The mix design generally includes the following steps:

- Evaluate the condition of the candidate pavement including the types and level of present distresses (preliminary analysis).
- Obtain samples of asphalt pavement and base and underlying materials from the roadway.
- Crush asphalt pavement to generate RAP.
- Combine RAP, base and underlying materials at predetermined ratios (RAP to base ratio is directly related to the planned reclamation depth) and determine:
  - Gradation (AASHTO T 11 and T 27, or ASTM C117 and C136),
  - Moisture content (AASHTO T 255 and T 265, or ASTM D2216),
  - Plasticity index (PI) (AASHTO T 90 or ASTM D4318), and
  - Sand Equivalent (SE) (AASHTO T 176 or ASTM D2419).
- Select suitable stabilization additive (see Table 1 in the main document).
- Determine maximum dry density and optimum moisture content of the blended mixture.

- Mix and compact specimens at desired moisture content with trial percentages of stabilization additive through trial and error and/or experience.
- Cure specimens.
- Test trial mixtures for strength and durability.
- Establish job mix formula (additive application percentages/rates).
- Make adjustments in the field as necessary (water content and/or stabilization additive).

## Chemical Stabilization

For cement, CKD, and self-cementing Class C fly-ash mix designs multiple chemical stabilization additive trial percentages (usually at 2% increments) are evaluated at the optimum moisture content of the mixture. The optimum moisture content can be obtained from AASTHO 134 or ASTM D558, although Standard Proctor (AASHTO T 99 or ASTM D698) or Modified Proctor (AASHTO T 180 or ASTM D1557) are occasionally used. Since optimum moisture contents do not vary significantly with small changes in the additive content, a single test (usually at the middle additive content) is considered adequate. Once the specimens are compacted, they are removed from the molds and cured for typically 7 days, but sometimes for longer periods of time such as 14 or 28 days. Cement and CKD are usually cured at 72 to 77°F (22 to 25°C), while self-cementing class C fly-ash is cured in sealed container at a temperature of 100°F (38°C). Specimens are also subject to capillary soak for 4 hours prior to strength testing.

For lime and LKD the procedure is a little different as the initial trial percentage is typically established in accordance with ASTM D6276 by finding the minimum lime/LKD percentage that produces a pH of 12.4 and then the trial mixture are made at the minimum, 1% above minimum, and 2% above minimum. Also, after mixing and prior to compaction the mixture is allowed to mellow in sealed container usually for 24 hours. After compaction the specimens are wrapped and sealed in air-tight containers at 104°F (40°C) for typically 7 days. Specimens are also subject to capillary soak for 24 to 48 hours prior to strength testing.

Once the specimens are cured and capillary soaked, they will be tested for unconfined compressive strength (AASHTO T 208 or ASTM D 1633) to develop strength-additive percentage relationships. The optimum additive content is selected based on the minimum design strength requirement. The minimum strength requirement is usually specified per project. In lieu of such information, Table B-1 can be consulted for the minimum required 7-day unconfined compressive strength based on the roadway traffic level. Also, as it was discussed before, to avoid a very stiff stabilized base layer and/or formation of premature shrinkage cracking, a maximum compressive strength is usually defined.



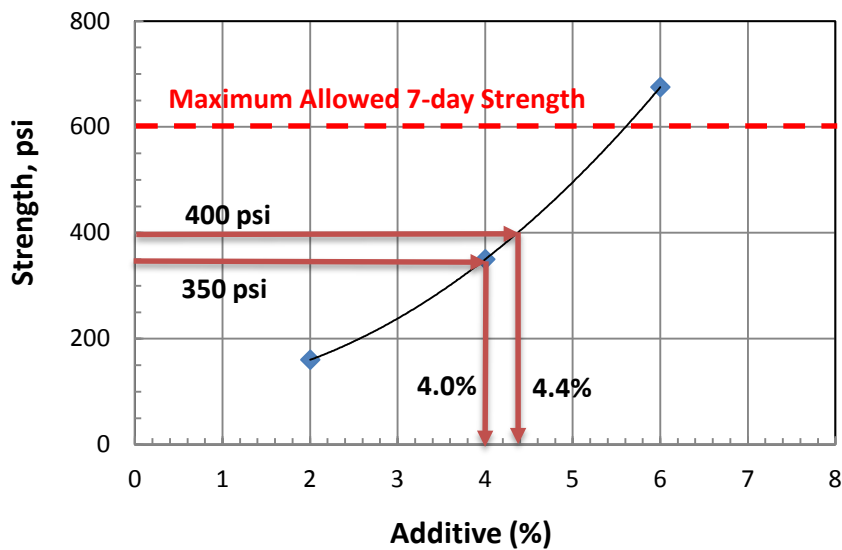
TABLE B-1. SUGGESTED MINIMUM 7-DAY UNCONFINED COMPRESSIVE STRENGTH

Traffic Level	Average Daily Traffic (ADT)	Minimum 7-day Unconfined Compressive Strength*
Low	ADT < 250	200 to 300 psi
Medium	250 < ADT < 1,000	300 to 350 psi
High	ADT > 1,000	350 to 400 psi

\*The maximum 7-day confined compressive strength can be defined as 50% above the minimum suggested values.

Figure B-1 shows strength-additive percentage relationship for a roadway with a high level of traffic as an example. In this case, an additive percentage between 4.0 and 4.4% is recommended to be used to meet the minimum compressive strength requirement.

FIGURE B-1. UNCONFINED COMPRESSIVE STRENGTH VS. ADDITIVE PERCENTAGE FOR 7-DAY CURE

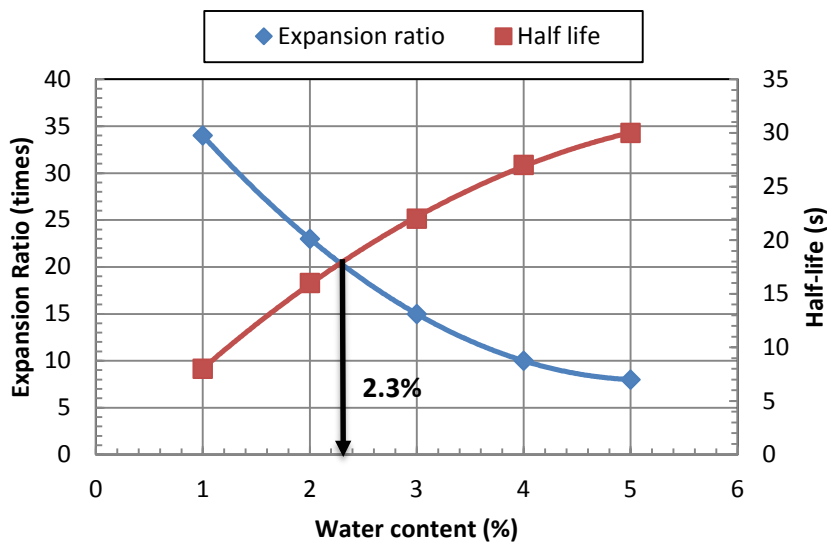


## Bituminous Stabilization

Bituminous stabilization mix design is generally more sophisticated than chemical stabilization mix design as it addresses both the short- and long-term strengths along with resistance to thermal cracking to assure long-term performance of the stabilized layer.

In the case of foamed asphalt stabilization, foaming properties of asphalt binder are optimized by maximizing expansion ratio (times) and half-life (seconds) of the foamed asphalt by determining the percentage of water needed for a given asphalt binder temperature. The optimum percentage of water is usually taken as the intersection of the half-life and expansion ratio curves as shown in Figure B-2. Once the foamed asphalt is produced, specimens are fabricated at typically three different foamed asphalt contents all at 90% of the optimum moisture content of the mixture determined from Modified Proctor test. Following the compaction, the compacted foamed asphalt specimens are cured at 40°C for typically 72 hours.

FIGURE B-2. THE OPTIMUM PERCENTAGE OF WATER IN FOAMED ASPHALT



In asphalt emulsion stabilization, similar to foamed asphalt, specimens are made at a range of binder contents to determine optimum emulsion content. Water contents for asphalt emulsion mixtures are typically 50 to 75% of the optimum moisture content of the mixture determined from Modified Proctor test. Following the compaction, the compacted asphalt emulsion specimens are cured at 60°C typically for 48 hours.

Table B-2 presents a set of lab testing that can be performed as a part of the bituminous stabilization mix design to evaluate the strength and moisture sensitivity properties of the stabilized mixtures. The last column in Table B-2 shows MnDOT requirements for bituminous stabilized mixtures in accordance with 2016 Grading and Base Manual.

TABLE B-2. BITUMINOUS STABILIZATION PERFORMANCE TESTING

Test Property	Standard(s)	Criteria*
Short-Term Strength (g/25 mm of height)	ASTM D1560	175 Minimum
Marshall Stability @ 40°C (lbs.)	AASHTO T 245 ASTM D6927	1,250 Minimum
Retained Marshall Stability (lbs.)	AASHTO T 245 ASTM D6927	Report
Indirect Tensile Strength (ITS) at 25°C (psi)	ASTM D6931	40 Minimum
Conditioned ITS @ 25°C (psi)	AASHTO T 283 ASTM D4867	25 Minimum
Resilient Modulus @ 25°C (ksi)	ASTM D7369	150 Minimum
Thermal Cracking (IDT)	AASHTO T 322	Report

\*In accordance with 2016 Minnesota Department of Transportation Grading and Base Manual [7].



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