

Long-Term Performance of Failed Flexible Pavements Stabilized with Cement

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ABSTRACT

In recent years, there has been a shift in resources away from the construction of new roadway networks to the maintenance and rehabilitation of the secondary, low-volume roadways. The focus today is how to achieve a strong and durable pavement that is not only cost-effective but also utilizes less virgin materials and is environmentally sustainable. The repair of failed flexible pavements – which make up the majority of most systems – is often an expensive process, especially if the pavement has base or subgrade problems, and a simple overlay will not result in a long-term solution. This is often the case with low-volume roads, where minimum pavement structures are expected to carry heavy traffic and subsequently experience serious pavement deterioration.

A procedure is available, called full-depth reclamation (FDR) with cement, which allows old deteriorated asphalt pavements to be recycled and stabilized with cement, creating a new base that will provide an excellent foundation for long-term pavement performance. The concept of recycling existing pavement materials is especially attractive in locations where quality aggregates may not be readily available. Instead of using new aggregate sources, the aggregates from the old pavement can be recycled, and with the addition of cement, the materials will form a much stronger base to improve the pavement foundation.

Recent studies have shown that agencies have successfully used the FDR with cement process for well over 25 years, with little or no evidence of structural failure in these FDR sections. In fact, the distress identified on the pavement surface was restricted to the hot-mix asphalt overlays and was not a result of failures in these stabilized base layers. Additionally, agencies that use this process have reported cost savings between 30% and 60% over conventional reconstruction methods. Cost savings and environmental benefits result from use of existing pavement materials, reduced hauling associated with removing old materials and placing new materials, and from the longer expected life of a pavement with a cement-stabilized base.

This paper will include the engineering and construction steps involved in designing and building an FDR project, with examples of successful projects constructed over the last 25 years in a variety of challenging environments.

INTRODUCTION

Axle loads on streets and highways have increased significantly over the years, while funds for road maintenance have shrunk. Most public agencies have existing road networks comprised primarily of flexible pavements. Progressive public officials looking to save time, materials and money needed to provide a safe and efficient road network are making it their top priority to salvage these existing flexible pavements at the end of their service lives. Long-term rehabilitation solutions to failed asphalt pavements include a thick structural overlay or complete removal and replacement of the existing

base and asphalt surface. Both methods can be extremely expensive and wasteful of virgin aggregates.

A third choice exists where these failed asphalt pavements that no longer provide economical long-term performance can be rehabilitated by pulverizing and stabilizing the pavement structure. A process called full-depth reclamation (FDR) with portland cement can provide the benefits of reconstruction without the substantial costs and environmental concerns. This procedure pulverizes the existing asphalt and blends it with underlying base, subbase, and/or subgrade materials, which are mixed with cement and compacted to provide a new stabilized base.

This sound engineering and cost-effective technique is popular with state, provincial, county, and city highway agencies attempting to correct their deteriorating pavements and increase the pavements' structural capacity. The FDR with cement technique has been used successfully on pavement projects for more than 25 years resulting in bases that are more uniform, stronger, and provide better long-term performance than the original pavement. Table 1 shows a comparison of flexible pavement rehabilitation strategies.

While the cost advantages of recycling materials from the original pavement are obvious, there are also environmental advantages that are important to the FDR process:

- Conservation of aggregates that must be quarried and transported to the site
- Conservation of land areas that would be used to dispose of the asphalt and base materials from the failed pavement
- Reduced air pollution, traffic congestion, and damage of nearby roadways resulting from hauling new materials to the site, and disposal of old materials

Since pavements must be maintained over many years, it is important to understand the long-term performance of various pavement construction and rehabilitation procedures. Since the FDR process is roughly 25 years old, the Portland Cement Association (PCA) felt that enough field experience existed to adequately evaluate the long-term performance of FDR with cement. A technical report was completed for PCA that summarized actual field performance of more than 75 projects in eight states scattered across the United States that used the FDR with cement process [1]. Results from this extensive investigation into the design, construction, testing, and long-term performance of failed flexible pavements rehabilitated through FDR using portland cement are included in this Paper.

SCOPE OF WORK

A list of state and local transportation agencies that were known to have actively used a FDR program was prepared by the investigator in conjunction with PCA. These state,

county, city, and private agencies are shown on the Project Location Map in Figure 1. Because the focus of the work was on the long-term performance of FDR with cement pavements, all of the projects studied were at least three years old. The average project age was 9 years, and the oldest was 26 years. The age distribution of these projects is shown in Figure 2.

Agency personnel involved with the FDR process were contacted and interviewed about the methodology used to select candidate projects, and about the design and construction of their FDR projects. Performance-related data such as pavement inventory, functional and structural information, traffic data, material composition, amount of cement added, and construction details were collected. Data on pavement subgrades, when available, were collected with the assistance of the highway agencies and/or experienced FDR contractors.

The extensive performance evaluation process consisted of interviewing the agency/owner of the facility, performing visual pavement surveys, taking cores at select pavement locations, and performing strength measurements on the cores. This provided a qualitative assessment of the long-term strength and stiffness of the reclaimed pavements. Overall, the results showed that the FDR with cement process has had significant success and is very popular with public transportation agency officials, who are trying to maintain an acceptable ride quality of their roads in the face of shrinking budgets.

PAVEMENT VISUAL SURVEYS

Pavements rehabilitated using the FDR with cement process underwent a visual inspection, which focused on finding evidence of pavement distress at the selected project sites – particularly distresses that may have been due to the condition of the base (such as block cracking, roughness, and deep potholes). The pavement distresses were systematically recorded to identify their type, extent, and severity. From this data, a numerical composite distress index, termed the Pavement Condition Index (PCI), was calculated. The PCI values range from zero for a failed pavement to 100 for a pavement in perfect condition. Table 2 summarizes the breakdown of PCI values and corresponding pavement surface conditions.

Table 3 summarizes the results of the pavement condition surveys in the study. It shows that almost all of the roads rehabilitated using the FDR with cement process are performing well, with a few exceptions. The overall average PCI for the agencies ranged from 88% to 97%, or excellent.

Most of the distresses noted during visual inspection of the pavement sections were in the asphalt layer. Any distresses caused by the base (such as minor reflective cracking) did not affect the roughness or overall road performance. No cases were observed where severe road distress was caused by the reclaimed cement-stabilized base.

LONG-TERM STRENGTH AND DURABILITY

The stabilized base must be strong enough to provide adequate pavement support for the current and future traffic loading conditions. In addition, the stabilized base needs to remain hard and durable and be able to resist the volume changes or hydraulic pressures caused by freezing-and-thawing and moisture changes that could gradually break down the cementitious bonds.

Representative core samples of the reclaimed base from some of the pavement sections were visually examined and photographed. Upon confirmation of their in-situ condition, the cores were subjected to laboratory strength measurements to determine the in-situ strength of the reclaimed base after many years of performance. Core samples were obtained from 33 locations, of which 23 were considered adequate for unconfined compressive strength (UCS) measurements as prescribed in ASTM International (ASTM) C42, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. The remaining samples were damaged during the coring process. The average UCS was 6.3 MPa. Typically, these FDR with cement sections were designed for a 7-day UCS of 2.8 to 4.1 MPa.

In addition to strength, the durability of the road base subjected to wetting-drying and freezing-thawing cycles is a critical parameter for any roadway's satisfactory performance. Durability issues are especially challenging in wet, northern climates where deeply penetrating freeze-thaw patterns can cause the unstabilized pavement base to lose strength and stiffness. Of the 79 projects that were part of the study, more than 50 sections were in areas with moderate to severe winter weather conditions. Overall, the FDR with cement process has been a very positive experience for agencies in northern areas that have severe weather. The agencies have successfully provided public roads that do not heave in the winters or lose shear strength during spring thaws, and have enhanced road safety. For many agencies, the FDR with cement process has enabled them to build "all weather" roads [2].

DESIGN

Agency officials realize the importance of design, and do their best in spite of shoestring budgets to perform a proper engineering investigation prior to design and construction of the FDR with cement process. Most of the agencies adopt, to varying degrees, the PCA recommendations in the *Guide to Full-Depth Reclamation (FDR) with Cement* [3]. Some agencies rely on past experience when deciding on the thickness of the reclaimed base and the amount of cement to be added to the mix.

In many cases, little will be known about the materials in the existing pavement and the thickness of the existing layers. The best way to determine these will be to sample the roadway. How frequently the samples should be taken depends on how variable the existing pavement is. The candidate project section is typically sampled at intervals of 0.8 kilometers. Some engineers add aggregate material if added thickness or modification of materials is required from a pavement design perspective. The

thickness of the cement reclaimed base typically ranges from 150 mm to 300 mm (depths exceeding 300 mm are difficult to compact in one lift and are not recommended) and is a function of:

- existing in-situ pavement material
- thickness required for pavement design
- traffic loading
- past experience (in some cases)

FDR pavement thicknesses can be designed using the American Association of State Highway and Transportation Officials (AASHTO) procedure for pavement design or by using thickness design procedures that follow a more mechanistic-empirical process [4].

The ability of a pavement base to carry loads depends on the strength of the base material and the depth of the base layer. A thin, but strong base can theoretically carry the same load as a thick, but weaker base. However, the thin, strong base should be avoided because it can become brittle and fracture, resulting in reflection cracks in the pavement surface. When selecting thicknesses for reclaimed pavements, a thicker base with less strength should be preferred. Today's more powerful in-place pulverizing equipment has made the job of obtaining thicker mixed-in-place layers much easier and more reliable compared with equipment used years ago.

Designing the proper amount of water and cement for the stabilized base is not only important to obtain a good final product it also provides important information for quality control during construction. Publications exist that provide information on testing procedures for determining the appropriate cement content, water content and compaction requirements for cement-stabilized materials [5]. Research has shown that cement-stabilized materials have better strength and performance when they are well compacted, so determining compaction density is fundamental to the design procedure.

The amount of water and cement required in the mix will depend upon the project specified strength and gradation of the final blend obtained from pulverizing the asphalt during construction and mixing it with the base material. Typical specifications for pulverizing call for 100% passing the 75 mm sieve, a minimum of 95% passing the 50 mm sieve, and a minimum of 55% passing the 4.75 mm sieve. If the blend contains more fine-grained soil, then more cement and water will be required because of the larger surface area of the finer particles.

In most cases, the samples are compacted with varying cement contents using the standard Proctor test outlined in Standard Test Method for Moisture-Density Relations of Soil-Cement Mixtures (ASTM D558). Using the optimum moisture content from the initial moisture-density test, a series of FDR specimens are prepared at different cement contents to determine a 7-day UCS. A target UCS between 2.1 MPa and 2.8 MPa has

been shown to be satisfactory for most FDR applications and is determined by the Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633). Based on an agency's experience, the 7-day UCS design strength varies significantly between 1.0 MPa and 4.1 MPa.

Some agencies in environments subjected to extremes in wet and dry conditions will also perform the Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures (ASTM D559). Additionally, many agencies in the cold climates check the proposed mixture for frost susceptibility by performing a full or partial freeze-thaw test as recommended in Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures (ASTM D560).

CONSTRUCTION

The construction process for FDR is straightforward. Typical equipment requirements include a pulverizer/mixer (also referred to as a reclaimer), motor grader, cement spreader, water truck, and a roller. The process begins with the reclaimer pulverizing the existing asphalt pavement (Figure 3). Once the existing roadway has been pulverized and blended together, the material is graded to the desired elevation and shape. When working between curb and gutter, there may be a need to remove some of the pulverized material and haul it away in order to leave room for the pavement surface layer.

Type I/II portland cement is usually spread in a controlled manner by spreader trucks that are designed for this operation. Placing the cement in an uncontrolled manner by blowing under pressure should be avoided. Cement is most commonly applied dry (Figure 4), but can also be applied in a slurry form (Figure 5). Most specifications call for the application of cement in terms of weight per area (e.g., kilograms of cement per square meter).

Mixing is performed by the reclaimer/mixer, either by injecting the proper amount of moisture into the mixing chamber (Figure 6), or by placing water on the ground with a water truck in a separate operation. In either case, obtaining the correct amount of moisture is very important in achieving the target compaction. After the materials are well mixed, it is time for compaction and final grading (Figure 7). Smooth-wheeled vibrating rollers or tamping rollers can be used to provide initial compaction, with smooth-wheeled or pneumatic-tire rollers used to complete the operation.

Traditionally, the compaction requirements are 95% to 98% of the laboratory-measured density with the standard Proctor (ASTM D558) energy. Some of the more progressive agencies are now requiring the use of the modified Proctor energy or similar in the laboratory evaluation as described in Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³)), (ASTM D1557). Consequently, these agencies have field density requirements of 95% to 98% of modified Proctor energy.

Proper curing is very important to the quality of the final product. If the base is allowed to dry, it will develop cracks, and the continued gain in strength over time will be compromised. While typical specifications require seven days moist curing, the PCA study found that curing could vary from one-half day to seven days. For logistical reasons, most if not all the agencies would like to use a shorter curing time. Many agencies do not have alternate detour routes, making it difficult to close the road over an extended period. Some agencies prefer to use moist curing over a period of three to seven days, where others prefer the use of a bituminous coating or a curing compound that can allow the road to be opened to traffic within one-half to one day.

The completed FDR base can have any type of pavement surfacing (e.g., chip seal surface treatment, hot mixed asphalt (HMA), or concrete). The surfacing can be applied as soon as the base is stable (does not rut or shove) under construction traffic. The time required for this can range from 4 to 48 hours. Traffic can be placed on the base in the same time frame, as long as repeated applications of heavy trucks are not involved. In many cases with low-volume roads, traffic is allowed to run on the compacted base until the project is ready for surfacing. For conditions where heavy truck traffic is involved, up to seven days may be required to make sure the base has gained sufficient strength for a high volume of heavy trucks. Field quality control procedures are similar to those used for standard soil-cement base construction [6].

INNOVATIVE TECHNIQUES

The major issue with the FDR with cement process is in balancing strength and performance. Figure 8 illustrates how increasing the amount of stabilizer may eventually lead to a decrease in performance (because of excessive cracking). The higher cement content yields higher strength, but it increases the stiffness of the reclaimed base, which can become brittle and increase the possibility that cracks in the base may lead to cracks in the asphalt surface. Bases with high cement content will also shrink more, which could also cause reflective cracks. If the engineering design warrants higher strength because of durability issues, then agencies deal with shrinkage cracking challenges by sealing them as they appear.

Agencies realize that durability is the key issue in the design of the FDR with cement mixtures and therefore perform laboratory evaluations to ensure that the FDR with cement mix that they use on their projects is durable. Others try to tweak the UCS test results to get the desired performance. The PCA study showed that the minimum cement content should be based on the mixture passing the durability tests (ASTM D559 or ASTM D560).

Hundreds of thousands of kilometers of roads with cement stabilized bases have been constructed in all climates with excellent performance. There are a number of preventative measures that can be taken to minimize the chance that wide cracks will occur in a cement-stabilized material [7]. Shrinkage cracking is also related to the amount of clayey subgrade soils in the reclaimed layer. Some agencies do not blend subgrade soils in the reclaimed layer. However, because of budget constraints or other

design factors, agencies may decide to blend the subgrade soil with the reclaimed materials. They also may use the reclaimed layer to widen their roads from 4.9 meters to 6.1 meters.

Another technique rapidly gaining wide acceptance by agencies is a process called “microcracking” to reduce reflection cracking. This procedure uses a compaction roller on the surface of the cement-stabilized base one to two days after construction. The effect of the roller is to initiate hundreds of tiny microcracks in the base to absorb the shrinkage, rather than single shrinkage cracks that are wider. Compared to moist curing alone, microcracking improves the performance of FDR bases by reducing the crack width, reducing the total crack length, or both. Through these mechanisms, microcracking reduces the risk of reflective cracking through the surface layer [8].

ECONOMICAL CAPITAL IMPROVEMENT PROJECTS

The FDR with cement process is popular with agencies that seek a cost-effective method to improve their roads. Agencies that use the process save between 30% and 60% over conventional reconstruction methods. Since the FDR with cement process is much quicker, it also saves weeks or months of labor and road closure time. Agencies have been able to blend the underlying poor quality subgrades with the existing pavement and cement to produce a new pavement layer, while at the same time widening the road. The agencies are pleased as they are able to expand their roadways at a fraction of the cost of conventional road construction.

Roads evolve over time as population and demand grows. Consequently, roadway widening over the years introduces non-uniform cross-sections that age or deteriorate at variable rates. The FDR with cement process helps create a uniform section whose long-term performance is more predictable, helping the agency’s pavement management efforts.

Maintenance and rehabilitation activities over the years compromise the crown and cross-slope of the roadway, creating drainage problems. Water ponding within the pavement structure due to inadequate drainage saturates and compromises the subgrade support conditions. The FDR with cement process allows the existing road to be pulverized and bladed to a slope with adequate cross drainage, despite the condition of the original road.

The rehabilitation of urban sections that have curbs and gutters presents a different challenge. How does the engineer increase the strength without increasing the thickness and requiring new curbs and gutters? The FDR with cement process adds strength to the underlying material and allows the removal of some pulverized material, allowing the existing profile to remain without adjustment to cross-slope or curb and gutter elevations.

The FDR with cement process is not a cure for all pavement maintenance and rehabilitation problems, and should not be used in all cases, but its versatility makes it a

rehabilitation option to seriously consider for almost every project. The agencies that participated in the PCA study intend to continue the use of the FDR with cement technique and fine-tune the process for the future. With over 25 years of experience with the FDR with cement process, the agencies are very satisfied with the long-term performance and are constantly improving techniques for the process.

ENVIRONMENTAL CONSIDERATIONS

FDR with cement conserves virgin construction materials and makes smart economic and strategic sense. A century of modern growth and urbanization in North America has depleted once plentiful aggregate supplies. Frequently, aggregates either come from distant quarries at great expense or from local sources offering only marginal quality.

Continuing to exhaust these valuable resources to rebuild existing roads only propagates and accelerates the problem. Additionally, if old asphalt and base materials are not recycled, they must be disposed of or stockpiled, increasing transportation costs and utilizing valuable landfill space (Figure 9). In some locales, old asphalt can no longer be landfilled. Environmental laws are becoming stricter, thus adding to the expense of mining new materials and landfilling old.

FDR with cement makes the reconstruction of old roads a largely self-sustaining process. The original “investment” in virgin road materials becomes a one-time cost, which is reclaimed through cement stabilization and addition of a new, thin surface course [9]. Moreover, some agencies, most notably in California, get state government credit for recycling when they use the FDR with cement process.

SUMMARY OF THE STUDY

The projects evaluated and summarized in the report prepared for PCA on the long-term durability of FDR with cement pavements included those from six city agencies, three private developers, eight county agencies, and four districts within state departments of transportation. Along with the excellent durability noted in these pavements, one of the biggest advantages of FDR with cement is the versatility that it offers in terms of its use in various geographic and environmental conditions and loading applications.

The PCA study investigated the performance of FDR with cement to rebuild distressed asphalt pavements. The project sections studied were between three and 26 years old with an average age of nine years. The FDR with cement process is popular with state and local agencies trying to maintain their highway network in the face of shrinking budgets. The economics of the FDR with cement process has helped the highway agencies reconstruct 50% to 100% more projects than the conventional construction process.

More than 60% of the projects were in states with severe cold weather conditions and high potential for winter freeze and spring thaw activity. The cement in the FDR process has improved the resistance of the reclaimed base to freeze-related road heaving and thaw-related loss in strength. The highway agencies no longer need to close their roads because of winter freeze or spring thaw. The ability to have their roads open in extreme weather enhances commuter safety and allows businesses to efficiently move goods.

The design process involves an investigation of the existing asphalt pavement structure, followed by a laboratory evaluation of the engineering property of the material and the amount of cement required to produce a durable FDR with cement section. Durability of the FDR with cement section is critical to ensuring acceptable long-term performance. Some agencies perform some version of the durability tests prescribed in ASTM D559 and ASTM D560, while the majority relies on indirect UCS correlations and/or experience to determine durability of the proposed FDR with cement mix.

Some agencies do not blend subgrade soils in the FDR with cement layer. The performance of the FDR with cement layers minus the subgrade soils is very encouraging, and many agencies are adopting this practice. However, many local agencies are unable to do so because they typically extend the width of their roadways in conjunction with the reclamation process, and don't have adequate pavement structure in place to preclude the use of subgrade soils in their reclaimed layer. The fines content (fraction smaller than sieve size 0.075 mm) of the subgrade soils influences the shrinkage and durability characteristics of the reclaimed mix.

There was no evidence of structural failure in the FDR with cement sections. More often, the distress on the pavement surface was in the HMA-overlay. Reducing the cement content to eliminate shrinkage cracks needs to be balanced with durability requirements. The minimum cement content required for a durable FDR with cement mix should be the only criterion. If that mix exhibits shrinkage cracks, then those cracks need to be sealed, or reduced through microcracking.

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TABLES

Table 1 - Characteristics of Flexible Pavement Rehabilitation Strategies

Solution	Advantages	Disadvantages
Thick Structural Overlay	<ul style="list-style-type: none"> Provides new pavement structure Quick construction Only moderate traffic disruption 	<ul style="list-style-type: none"> Elevation change can present problems for existing curb & gutter and overhead clearances Large quantity of material must be imported Old base/subgrade may still need improvement High cost alternative
Removal and Replacement	<ul style="list-style-type: none"> Provides new pavement structure Failed base and subgrade are eliminated Existing road profile/elevation can be maintained 	<ul style="list-style-type: none"> Long construction cycle requiring detours and inconvenience to local residents/businesses Increased traffic congestion due to detours, construction traffic Rain or snow can significantly postpone completion Large quantity of material must be imported Old materials must be dumped Highest cost alternative
Recycling Surface, Base and Subgrade with Cement (Full-Depth Reclamation)	<ul style="list-style-type: none"> Provides new pavement structure Fast construction cycle No detours Minimal change in elevation, thus eliminating problems with curb/gutter, overhead clearances Minimal material transported in or out Conserves resources by recycling existing materials Local traffic returns quickly Rain does not affect construction schedules significantly Provides moisture- and frost-resistant base Least cost alternative 	<ul style="list-style-type: none"> May require additional effort to correct subgrade problems Some shrinkage cracks may reflect through bituminous surface

Table 2 – Pavement Condition Index Value and Pavement Surface Condition

PCI Value	Pavement Condition
0-10	Failed
10-25	Very Poor
25-40	Poor
40-55	Fair
55-70	Good
70-85	Very Good
85-100	Excellent

Table 3 – Summary of Pavement Condition Survey

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

FIGURES

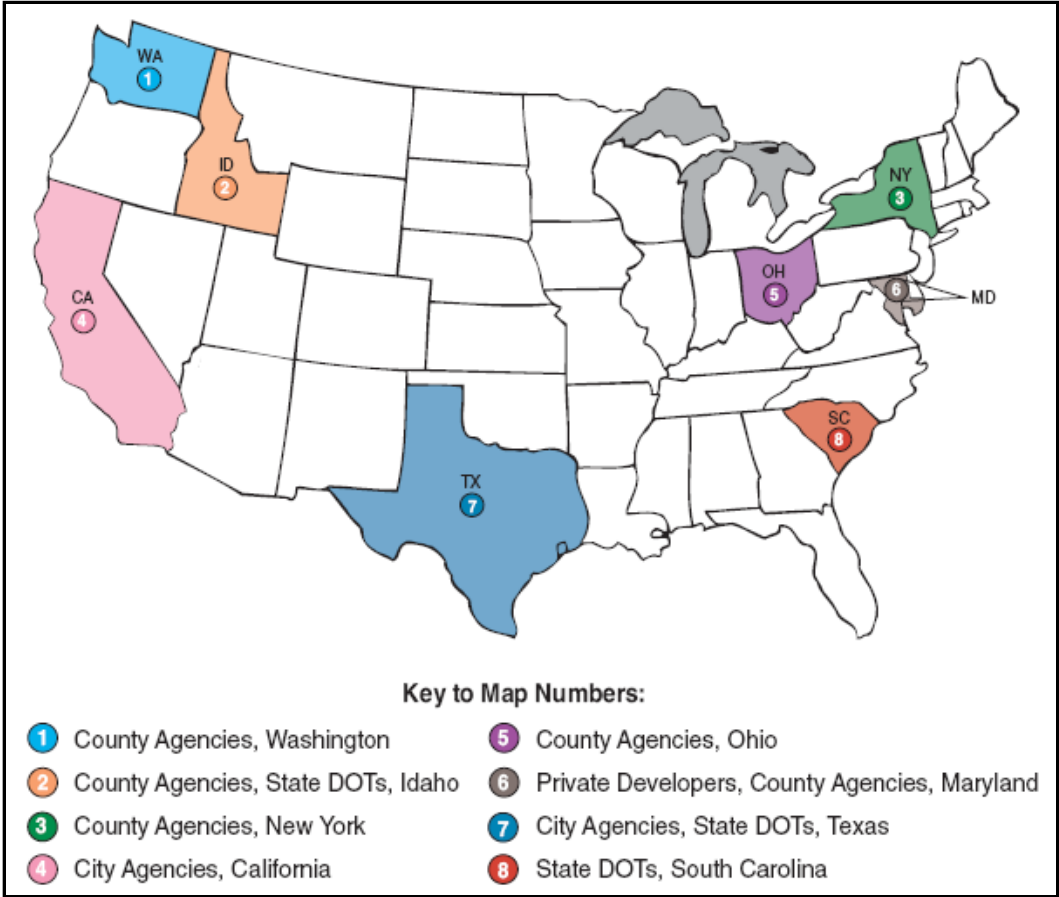


Figure 1 – Project Location Map.

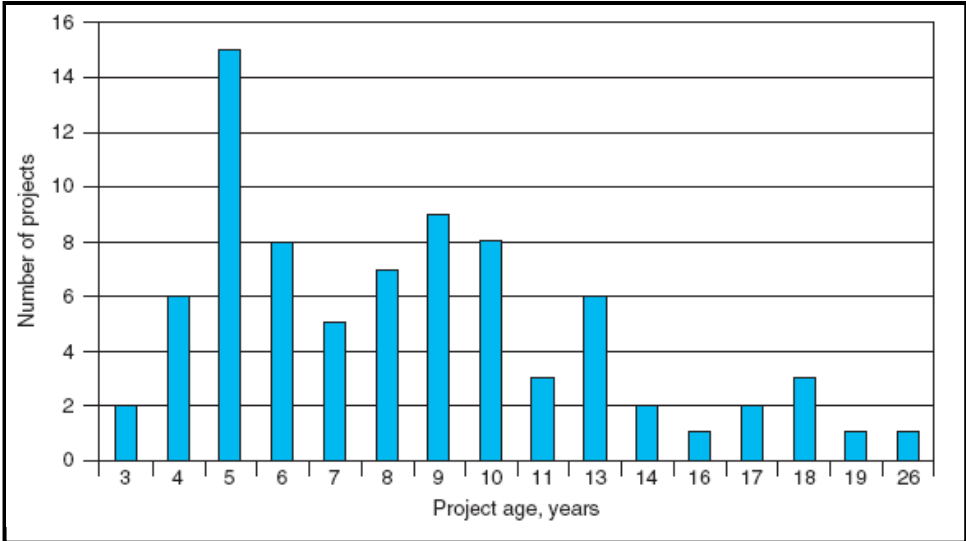


Figure 2 – Histogram showing age of projects in study.



Figure 3 – Pulverizing a failed asphalt pavement.



Figure 4 – Placing cement dry.



Figure 5 – Placing cement in slurry form.



Figure 6 – Water being injected during mixing operation.



Figure 7 – Compaction and final grading.

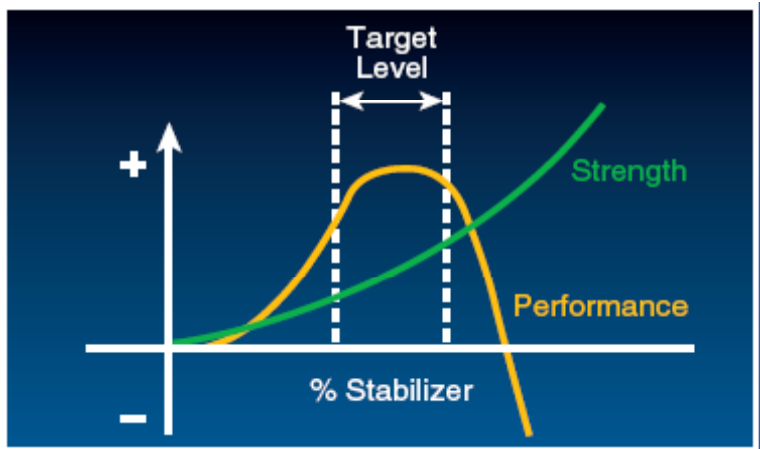


Figure 8 – Amount of cement becomes a balance between strength and performance.

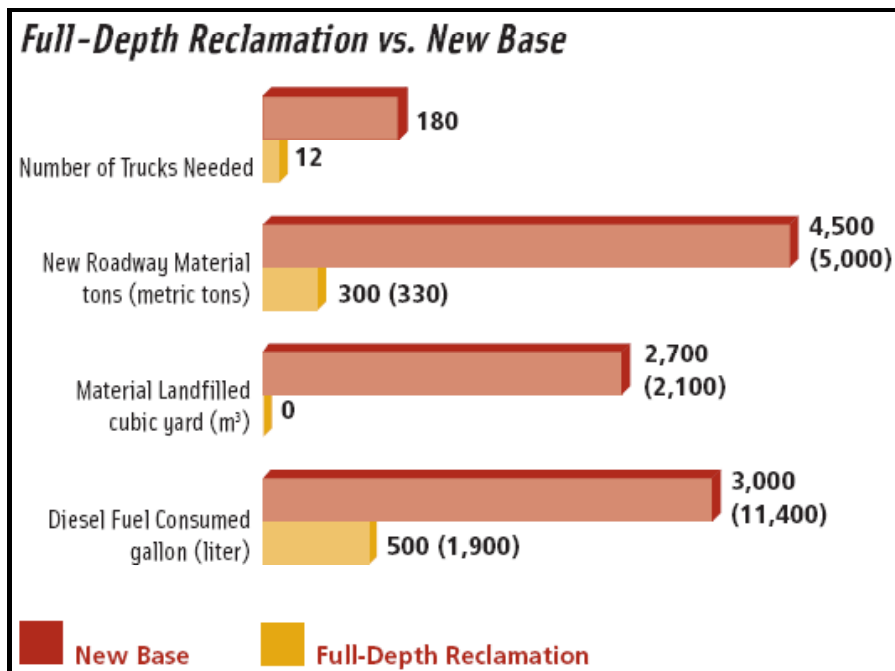


Figure 9 – Energy use and materials for FDR and new base