Full-Depth Reclamation using Portland Cement: A Study of Long-Term Performance

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Abstract

Full-Depth Reclamation (FDR) with cement is a procedure where failed asphalt pavements are pulverized and reclaimed, using cement to stabilize the recycled materials and create a new pavement base. This cement-stabilized base is then surfaced to provide an new, long-lasting pavement structure.

This report summarizes the long-term performance of pavement construction projects where the FDR with cement process has been used. The actual field performance of more than 75 projects in eight states were evaluated. The average project age was 9 years, and the oldest was 26 years.

Overall the performance of the FDR with cement projects has been excellent. There was no evidence of premature structural failure in any of the sections. In addition, the economics of the process has helped the agencies reconstruct 50% to 100% more projects than the conventional remove and replace methods.

Keywords

Full-depth reclamation, FDR, pavement, cement-treated base, CTB, cement stabilization, long-term performance, soil-cement, pavement recycling

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WARNING: Contact with wet (unhardened) concrete, mortar, cement, or cement mixtures can cause SKIN IRRITATION, SEVERE CHEMICAL BURNS (THIRD DEGREE), or SERIOUS EYE DAMAGE. Frequent exposure may be associated with irritant and/or allergic contact dermatitis. Wear waterproof gloves, a long-sleeved shirt, full-length trousers, and proper eye protection when working with these materials. If you have to stand in wet concrete, use waterproof boots that are high enough to keep concrete from flowing into them. Wash wet concrete, mortar, cement, or cement mixtures from your skin immediately. Flush eyes with clean water immediately after contact. Indirect contact through clothing can be as serious as direct contact, so promptly rinse out wet concrete, mortar, cement, or cement mixtures from clothing. Seek immediate medical attention if you have persistent or severe discomfort.

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1 – Introduction

The Idaho Transportation Department's Mission Statement summarizes the many expectations of the modern transportation system:

"We are expected to provide a world-class transportation system that moves freight and passengers efficiently and safely, while protecting the environment, complying with the Americans with Disabilities Act, guarding against earthquakes and terrorism, supporting economic development and livable communities, involving all parts of the community, creating jobs, improving intermodal connections and accommodating bicyclists and pedestrians — all with limited resources."

This grandiose objective is very difficult to achieve under the current operating conditions of state and local agencies. 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.

Worn-out asphalt pavements that no longer provide economical long-term performance can be rehabilitated by pulverizing and stabilizing the pavement structure with portland cement, using a process called Full-Depth Reclamation (FDR) with cement. The stabilized pavement layer becomes the base or subbase for the rebuilt pavement structure. This cost-effective technique is popular with state, 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 on pavement projects for more than 20 years. Other common acronyms used to describe the process of FDR with cement are:

- Full-Depth Recycling (FDR)
- Cement Recycled Asphalt Base Stabilization (CRABS)
- Cement-Treated Existing Roadway Materials (C-TERM)
- In-place Full Depth Cold Flexible Pavement Reclamation
- Base Stabilization
- Cement Stabilized Reclaimed Base (CRSB)

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) feels that enough field experience exists to adequately evaluate the long-term performance of FDR with cement, and to summarize the findings in a technical report. The primary questions studied were:

- What is the long-term performance of roads rehabilitated using FDR with cement?
- What is the design protocol for field and laboratory investigation for FDR with cement pavements?
- What problems do agencies encounter by implementing this technique?
- What are the guidelines for successful implementation?

This report summarizes actual field performance of more than 75 projects in eight states that used the FDR with cement process.

2 – State and Local Agencies

A list of state and local transportation agencies that were known to have actively used a FDR program was prepared in conjunction with PCA. The states are shown in the Project Location Map in Appendix B.

The projects studied were at least three years old. The average project age was 9 years, and the oldest was 26 years. The project age distribution is shown in Figure 1 below.

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. Experienced FDR contractors, including E. J. Breneman, LP., M & M Road Recycle, Inc. and Mark-Lang, Inc. also assisted with performance-related information. Data on pavement subgrades, when available, were collected with the assistance of the highway agencies and/or the contractors.

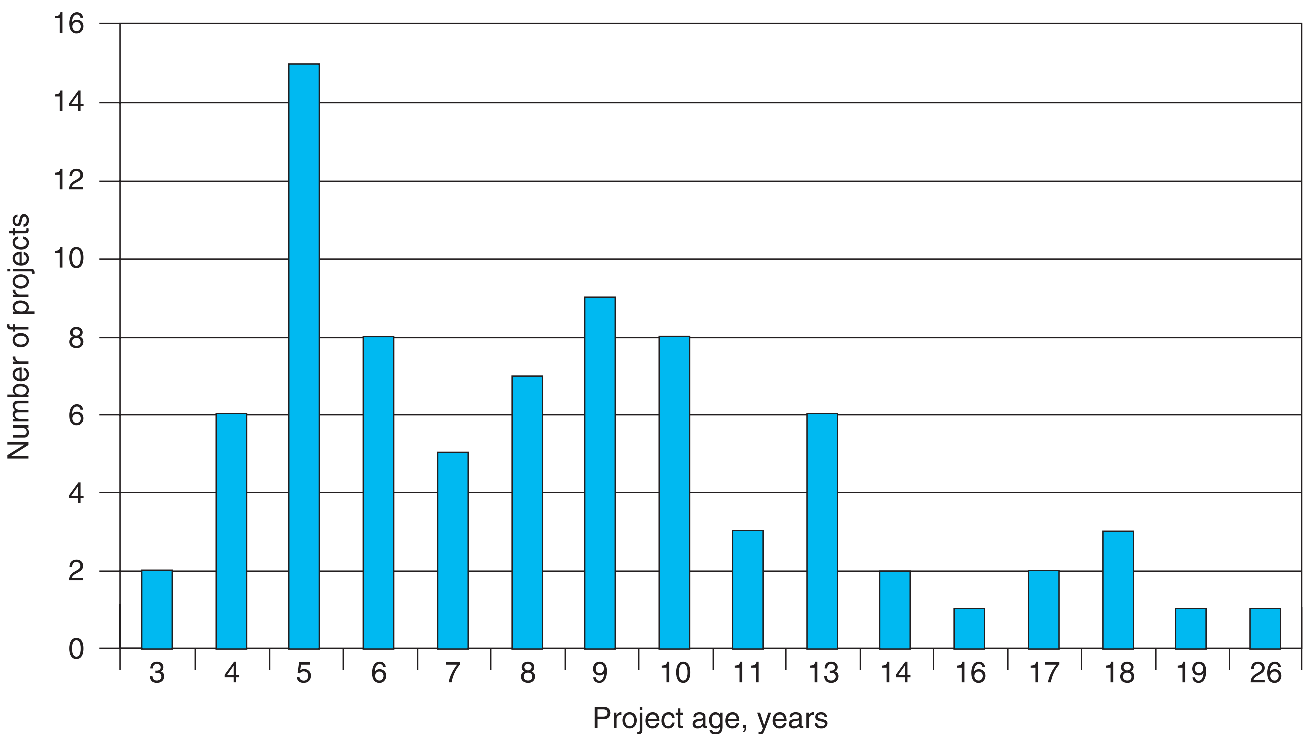


Figure 1. Histogram showing age of projects in study.

3 – Performance Evaluation

The 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. The detailed pavement evaluation results, along with the individual successes and occasional problems with the FDR technique, are presented in Appendix A.

Figure 2. Example road surveyed in Spokane County, WA.

3.1 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 1 summarizes the breakdown of PCI values and corresponding pavement surface conditions.

Table 1. PCI Value and Pavement 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 2 summarizes the results of the pavement condition surveys in this 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. All the roads, with the exception of Spirit Lake Cut Off in Bonner County, Idaho, had PCI values greater than 70, translating to very good surface conditions. As discussed in the detailed report on Bonner County roads in Appendix A, this particular road had significant potholes and some rutting problems, but the distress does not appear to be caused by the cement-stabilized base.

Table 2. 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**

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.

3.2 Long-Term Strength

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. The remaining samples were damaged during the coring process.

Figure 3. Coring FDR with Cement Roadways.

The UCS test results for the 23 project locations are summarized in Figure 4.

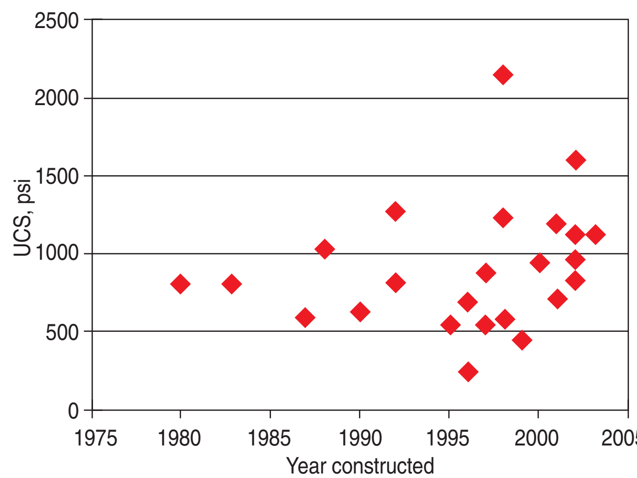


Figure 4. Unconfined compressive strength measurements.

The UCS ranges from a minimum of 260 psi for a project section after ten years in service to a maximum of 2,110 psi after eight years of service. The average UCS is 914 psi. Typically, these FDR with cement sections were designed for a 7-day UCS of 400 to 600 psi.

Most of the cores were tested for strength with the UCS test prescribed in ASTM C 42. In addition to UCS determination, four core samples were tested to determine the seismic modulus using the free–free resonant column method developed at the University of Texas at El Paso. Appendix E provides details of this method. The primary reason for performing the seismic modulus was to obtain the resilient modulus for the reclaimed pavement, which is the required input for the new AASHTO Mechanistic-Empirical pavement design guide.

Figure 5 shows the test results from the four core samples that were subjected to UCS and seismic modulus measurements. Based on this figure, a UCS of 465 psi corresponded to a resilient modulus value of 442 ksi, while the sample with a UCS of 1,239 psi had a resilient modulus of 1,519 ksi.

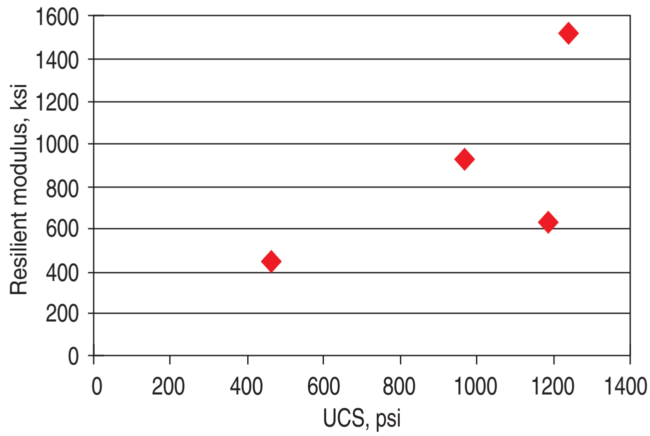


Figure 5. Resilient modulus and UCS measurements.

Figure 6. Example location of road in Idaho under winter conditions.

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

3.3 Durability

Durability of the road base subjected to wetting/drying and freezing/thawing cycles is a critical parameter for any roadway's satisfactory performance. The 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 this study, more than 50 sections were in areas with moderate to severe winter weather conditions. Traffic loads, environmental conditions and water movement within pavement layers cause physical and chemical weathering, which leads to breakdown of coarser materials into finer particles. The fine-grained soils (silts and clays) tend to hold moisture, which expands up to 9% in volume during freezing weather. When it thaws, the melting ice adds additional moisture which causes the material to lose shear strength. This volume change and loss of strength cause heaving roadways, posing a serious safety risk to drivers.

County engineers, including Jim Whitbread of Stevens County, Wash. (just south of the Canadian border) and District 6 State Engineer Tom Cole of the Idaho Transportation Department (ITD) say road heaving due to winter freeze and rutting due to spring thaw are among their biggest challenges. Mr. Whitbread reported that Stevens County roadways could heave 12 inches or more in winter. During spring thaw, the roads would become weak and significant distress/failures would appear. Mr. Cole of ITD faced similar problems, as Idaho roads experience more than 100 inches of snowfall during most winters. The FDR with cement process has been very successful for Mr. Whitbread, Mr. Cole, and others. The heaving has been eliminated and the engineers are pleased to report that their roads are operable in cold-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. According to Howard Hamby, pavement manager for the Spokane County, Wash. Public Works Department, the FDR with cement process has enabled the county to build "all weather" roads.

In areas with significant rainfall, durability problems due to wetting and drying are common. South Carolina Route 97 in York County had constant costly and frustrating maintenance problems, according to engineers in District 4 of the South Carolina Department of Transportation (SCDOT). Significant rainfall (48 inches per year), along with inadequate pavement structure, weak subgrades, and poor drainage, caused many problems. The road was reconstructed using the FDR with cement process in 1995.

The SCDOT District Engineer, Frank (Stan) Bland, Jr., P.E., says he is "very pleased" with the road's performance, adding that a perennial maintenance problem has stayed in good to excellent condition for more than ten years after reconstruction with the FDR with cement process.

Figure 7. FDR with Cement road in South Carolina.

3.4 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 (1). 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. The candidate project section is typically sampled at half-mile intervals. 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 6 to 12 inches and is a function of:

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

Most agencies try to limit the amount of Recycled Asphalt Product (RAP) to about 50%. The annual daily traffic on candidate project sections varies from a few hundred vehicles up to 25,000. The truck percentage in the traffic varies from a typical 5% to as high as 16%.

In most cases, the samples are compacted with varying cement contents using the standard Proctor test (ASTM D 558). The minimum cement content is based on achieving a 7-day target UCS of between 300 to 400 psi. Based on an agency's experience, the 7-day UCS design strength varies significantly between 150 psi to 600 psi. Some agencies in the cold climates check the proposed mixture for frost susceptibility by performing a full or partial freeze-thaw test recommended in ASTM D 560. Other agencies, such as the Texas Department of Transportation (TxDOT) and some city agencies in California recommend pre-cracking of the FDR with cement reclaimed base if the 7-day UCS is higher than 350 psi. In some cases, if the underlying subgrade soils exhibit significant swelling and shrinkage, geogrids are placed on top of the subgrade.

3.5 Construction

Typically, equipment called a "reclaimer" pulverizes old, distressed flexible pavements. If thicker sections are required, some agencies add aggregate or soil base material and blend them with the pulverized pavement. Water and portland cement are then added to the pulverized pavement to form a stabilized mixture, which is compacted and becomes the base or subbase layer of the pavement structure.

The pulverization process requires that the maximum size of the crushed pavement be no more than 2.5 to 3.0 inches. Type I/II portland cement is used mostly in dry form; however, some agencies place cement in the form of a slurry. Agencies continue to search for procedures to minimize any dust that might be caused by the construction process.

Figure 8. FDR with cement construction, Spokane County, WA.

Traditionally, the compaction requirements are 95% to 98% of the laboratory-measured density with the standard Proctor (ASTM D 558) energy. Some of the more progressive agencies are now requiring the use of modified Proctor (ASTM D 1557) energy or similar in the laboratory evaluation. Consequently, these agencies have field density requirements of 95% to 98% of modified Proctor energy.

The curing practices adopted by different agencies upon completion of the construction process vary between one and seven days. Many agencies open the finished reclaimed base layer almost immediately to local traffic because of a lack of detour routes. 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.

District 6 of ITD had problems created by the curing seal, because the blotter material placed over the curing seal required a significant amount of water for dust abatement. The blotter material was a graded product that became expensive to produce, similar to chips for seal coats. On some projects, traffic traveled over the reclaimed base surface for two or more weeks before the hot-mix asphalt (HMA) surfacing layer was placed. In this length of time, the base surface began to rut and deteriorate. ITD decided to eliminate the curing seal and required HMA to be placed within 48 hours of completion of the reclaimed base. ITD believes they obtain a smoother final project at a lower cost.

3.6 Innovative Techniques

The major issue with the FDR with cement process is in balancing strength and performance. Figure 10 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.

Some agencies, such as TxDOT, use a process called "micro-cracking" 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 micro-cracks in the base to absorb the shrinkage, rather than single shrinkage cracks that are wider. The tiny cracks are too small to reflect up through the asphalt surface.

Figure 9. Reflection cracks on FDR with cement road, Stevens County, WA.

Shrinkage cracking is also related to the amount of clayey subgrade soils in the reclaimed layer. Some agencies like ITD 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 16 feet to 20 feet.

Many agencies are trying to address durability issues during the design phase. Agencies such as the Montgomery County Department of Public Works in New York and other agencies in northern climates subject duplicate samples to UCS measurements as per ASTM D 1633. One sample will employ standard curing techniques, and the other will employ a 4-hour soak or 24- to 72-hour freeze. The soaked or frozen sample is required to retain between 75% and 85% of the strength obtained from the sample cured with the standard technique.

TxDOT addresses the moisture sensitivity issue by requiring the samples to pass the Tube Suction Test (7). Standard test specimens are placed in a ¼-inch deionized water bath whose surface is monitored for ten days by measuring the dielectric constant with a probe. Samples that do not exceed the surface dielectric constant of 10 over the ten-day period correlate with samples that are likely to pass the wet-dry (ASTM D 559) and freeze-thaw (ASTM D 560) tests.

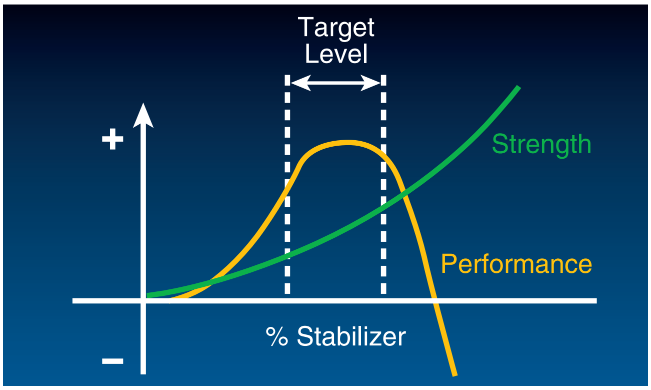


Figure 10. Amount of cement becomes a balance between strengh and performance.

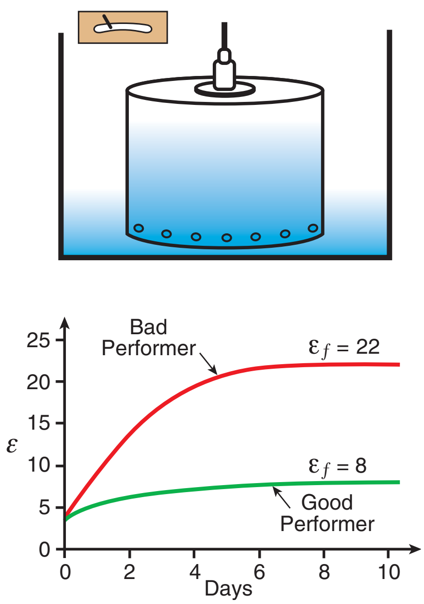


Figure 11. Depiction of Tube Suction Test set-up and results.

3.7 Ground Penetrating Radar

TxDOT sometimes uses Ground Penetrating Radar (GPR) to locate areas of variability in pavement thickness on projects that are candidates for FDR. These areas are sampled during field investigations. GPR is also used in FDR projects for performance evaluation and to locate areas of moisture susceptibility. The dielectric constants measured with GPR are related to the surface dielectric measurements performed in the Tube Suction Test (2, 3).

4 – Conclusions

FDR is a popular technique used by state, county and city highway agencies to rehabilitate large portions of their deteriorating highway networks. The purpose of this study was to investigate the long-term performance of these reclaimed pavements under a variety of loading, climatic and subgrade conditions across the United States.

4.1 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% to 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.

Figure 12. Before and after photos of FDR with cement roadway in Westminster, CA.

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 this study intend to continue the use of the FDR with cement technique and fine-tune the process for the future. With up to 26 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.

4.2 Strength vs. Durability

Little et. al. studied the severe northern Ohio climate with a depth of frost penetration into the uncovered soil of approximately nine feet — similar to the conditions encountered in Geauga County, Ohio; Montgomery County, New York; Bonner County, Idaho; and Stevens and Spokane Counties, Washington. They report that the insulation effect of approximately six inches of HMA reduces the number of freeze-thaw cycles in a year to around seven in the cement-treated subgrade. However, the low permeability of the cement-stabilized base will prevent the formation of ice lenses. The authors performed freeze-thaw tests (ASTM D 560) on several samples comprised of low plasticity clay and moderate plasticity silts treated with 4% to 10% cement, and found that on average the loss of strength is around seven psi per cycle irrespective of compressive strength (8).

PCA researchers found that only about 20% of the samples with a UCS of 300 psi would pass ASTM D 560, whereas about 70% of the samples would pass with a UCS of 500 psi. They observed a correlation between UCS and percentage of samples passing the ASTM D 560. In the past, many agencies chose higher strength to raise the probability of passing the ASTM D 560. However, freezing and thawing damage is primarily a function of pore structure and saturation level, so the relation to strength may be coincidental. Other factors that yield higher strength, such as higher cement contents and higher density, also decrease pore size and reduce permeability. This makes the sample more difficult to saturate. While strength may improve durability, strength alone is no guarantee of durability (9, 10).

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. This study showed that the minimum cement content should be based on the mixture passing the durability test (ASTM D 559 and D 560 or the Tube Suction Test (7)). If the cement content induces shrinkage cracking, then it should be addressed with a crack-sealing program, or the formation of cracks can be reduced through the use of micro-cracking. A number of agencies that have been performing crack sealing on stiff bases for years report they are happy with the results.

The roads that were inspected in this study are located in some very severe climatic regions. This performance evaluation clearly indicates that FDR with cement is a proven technique to extend the life of old flexible pavements in a cost-effective manner.

4.3 Compaction

Most of the initial research and design development took place many years ago with ASTM D 558, a test procedure that uses standard Proctor energy. The field compaction requirement is based on the contractor trying to achieve 95% to 98% of the laboratory density in the field. Very often, the field technicians report that, "more than 100% density is achieved."

There is merit in exploring whether modified Proctor effort should be used to make samples in the laboratory and to establish moisture-density relations. Some agencies have already started specifying modified Proctor for acceptance of FDR with cement reclaimed base layers. This step requires further evaluation.

4.4 Curing

While typical specifications require seven days moist curing, this 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. An agency like TxDOT opens the road to local traffic almost immediately upon completion of construction. The early application of loads was one of the factors (Syed and Scullion, 1998) attributed to the good cracking performance of reclaimed pavements in Texas. This reconstruction process (Bryan District) was done under traffic, which meant that at the end of each day, the completed section was sealed with a two-course surface treatment and then opened to traffic.

Based on this study, many agencies are opening their FDR with cement bases to traffic early. The merit of early opening to traffic should be explored further.

4.5 Environmental Considerations

Finally, one of the major benefits of the FDR with cement process is environmental. The sources of good-quality aggregate and asphalt are limited. Past processes of recycling plant mix are good only if we begin with consistent good-quality plant mix, something that most of our highways, once they reach an age of 30-plus years, no longer have. The environment has stripped the asphalt binder away from the aggregate, traffic has rutted and raveled the surface, and maintenance has been performed with different asphalts and gradations of aggregate. Because of these factors, obtaining a good quality recycled material is almost impossible.

The disposal of old plant mix is an environmental problem. The material must be used within the new product, stock-piled for future use, or hauled to an approved landfill — all costly options. The FDR with cement process uses all material in place, or creates a product that can be used easily in other areas to create additional benefits.

Moreover, some agencies, such as the City of Westminster in California, get state government credit for recycling when they use the FDR with cement process.

5 – Summary

This 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% to100% 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 Test prescribed in ASTM D 559 and ASTM D 560. Other agencies have developed newer test methods like the Tube Suction Test (7) while the rest rely on indirect UCS correlations and/or experience to determine durability of the proposed FDR with cement mix.

The construction process can vary somewhat with regard to compaction and curing. Compaction requirements sometimes differ from standard Proctor to modified Proctor methods. Curing time for the completed FDR with cement layer varies from opening immediately to local traffic to curing for up to seven days. The prime reason for choosing a shorter curing time is the lack of detour routes. The experience of Bryan District of TxDOT indicated that early opening to traffic was similar to microcracking of the FDR with cement section.

Core samples of FDR pavement sections ranging in age from three years to 26 years showed UCS ranged from 260 psi to more than 2,000 psi. The resilient modulus values ranged from 442,000 psi to 1,239,000 psi.

Some agencies, such as ITD District 6, 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 #200) of the subgrade soils influences the shrinkage and durability characteristics of the reclaimed mix. Higher fines content can lead to excessive shrinkage cracking and requires more cement.

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. This investigation has provided evidence that the FDR with cement pavement sections with sealed shrinkage cracks are performing satisfactorily.

Appendix A

DETAILED PROJECT REPORTS

This Appendix contains detailed reports on 79 full-depth reclamation (FDR) with cement pavement projects. Although more than 150 FDR projects in the United States were inspected as part of this study, this Appendix includes only those that have been in service for more than three years. The projects summarized in this Appendix include those from six city agencies, three private developers, eight county agencies, and four districts within state departments of transportation. Some of these projects have been in service since 1980.

Each project listed in the Appendix was inspected in the field to evaluate the long-term pavement performance after FDR with cement construction. While information was gathered about the project history, the amount of information contained in each report varies according to the age of the roadway and the availability of data from the contractors, design engineers/consultants, and owners. Some of the individuals involved in the original FDR work were no longer available to provide information on projects.

For each project listed, the year of construction, thickness of base layer, current Average Daily Traffic (ADT), and Pavement Condition Index (PCI) is reported if available. The PCI is a subjective numerical rating of pavement condition, ranging from 0 (for a pavement in the worst possible condition) to 100 (for the best possible condition). For some selected projects, cores were taken from the pavement structure to visually inspect the condition of the reclaimed base, and to test the Unconfined Compressive Strength (UCS) of the cement-treated base. Table 1 summarizes the different types of projects and number of core samples taken in this study.

Table 1. Number of Projects and Core Samples

Agency Type	Locations	Core Samples	No. of Projects
City	Cities of Buena Park, Westminster, Fullerton and Los Alamitos, California	4	9
	City of Stephenville, Texas	—	6
	Village of Endicott, New York	3	4
Private Developers	Anne Arundel, Prince George's and Harford County, Maryland	—	3
County	Bonner County, Idaho	—	4
	Washington County, Maryland	—	4
	Montgomery County, New York	6	6
	Geauga County, Ohio	—	4
	Clark, Pierce, Spokane and Stevens County, Washington	14	22
State DOT	Idaho Transportation Department — District 6	—	6
	Texas Department of Transportation — Bryan and Fort Worth Districts	—	4
	South Carolina Department of Transportation	6	7

The detailed project reports have been subdivided into four broad classifications:

CITY AGENCIES – These are residential (subdivision), collector, and arterial roads maintained by city agencies.

Multiple Projects in Westminster and Buena Park; Orange County, California

Acacia Avenue in Fullerton and Bloomfield Street in Los Alamitos; Orange County, California

Multiple Projects in Stephenville; Erath County, Texas

Multiple Projects in the Village of Endicott; Broome County, New York

PRIVATE DEVELOPERS – The projects in this category include facilities such as tennis courts, parking and circulation access roadways, and residential (subdivision) streets constructed and maintained by private agencies/developers.

Sherwood Forest Tennis Courts in Crownsville; Anne Arundel County, Maryland

Parking areas at East Gate Shopping Center in Glendale; Prince George's County, Maryland

Residential Streets at Water Vale Farm in Bel Air; Harford County, Maryland

COUNTY AGENCIES – Included in this group are roadways constructed and maintained by County forces.

Multiple Projects in Bonner County, Idaho

Multiple Projects in Washington County, Maryland

Multiple Projects in Montgomery County, New York

Multiple Projects in Geauga County, Ohio

Multiple Projects in Clark, Pierce, Spokane and Stevens Counties; Washington

STATE DOTs – These include the local roads, collector roads and freeways constructed and maintained by State DOTs.

Multiple Projects in District 6 of the Idaho Transportation Department (ITD)

Multiple Projects in District 4 of the South Carolina Department of Transportation (SCDOT)

Multiple Projects in the Bryan and Fort Worth Districts of the Texas Department of Transportation (TxDOT)

PROJECT SUMMARY TABLE

Project I.D.	Location	Use	Year	Thickness	Surface
CITY AGENCIES					
Multiple projects	Buena Park, CA	Residential and collector roads	1997-2001	9-12 ins.	HMA overlay
Multiple projects	Westminster, CA	Residential, collector and arterial roads	1990-2001	9-12 ins.	HMA overlay
Acacia Avenue	Fullerton, CA	Collector road	1989	9-12 ins.	HMA overlay
Bloomfield Street	Los Alamitos, CA	Collector road	1989	9-12 ins.	HMA overlay
Multiple projects	Stephenville, TX	Residential, collector and arterial roads	1993-2004	6-8 ins.	HMA overlay
Multiple projects	Village of Endicott, NY	Local roads	1980-1988	6-8 ins.	HMA overlay
PRIVATE DEVELOPERS					
Sherwood Forest	Anne Arundel County, MD	Tennis courts	2002	12 ins.	HMA overlay
E. Gate Shp. Ctr.	Prince Geoerge's County, MD	Parking	2002	12 ins.	HMA overlay
Water Vale Farm	Harford County, MD	Residential streets	2002	8 ins.	HMA overlay
COUNTY AGENCIES					
Multiple projects	Bonner County, ID	Collector roads	1997-2001	10 ins.	HMA overlay
Multiple projects	Washington County, MD	Local, collector and arterial roads	2001-2005	8-10 ins.	HMA overlay
Multiple projects	Montgomery County, NY	Local and collector roads	2000-2004	8-10 ins.	HMA overlay
Multiple projects	Geauga County, OH	Local roads	1996-2002	8-12 ins.	PPC/HMA
Multiple projects	Clark County, WA	Local and collector roads	1999-2001	6 ins.	BST/HMA overlay
Multiple projects	Pierce County, WA	Local, collector and arterial roads	1987-1998	6 ins.	BST/HMA overlay
Multiple projects	Spokane County, WA	Local and collector roads	1999-2002	8-10 ins.	BST/HMA overlay
Multiple projects	Stevens County, WA	Local and collector roads	1996-2003	6-12 ins.	BST/HMA overlay
STATE DOTs					
Multiple projects	District 6, ID	Freeways	1993-2003	6-9 ins.	HMA overlay
Multiple projects	District 4, SC	Local and collector roads	1996-2002	6-12 ins.	HMA overlay
Multiple projects	Bryan District, TX	Collector roads	1996	10 ins.	BST
Multiple projects	Fort Worth District, TX	Collector roads	1997	9-10 ins.	HMA overlay

A.1 CITY AGENCIES

A.1.1 City of Buena Park

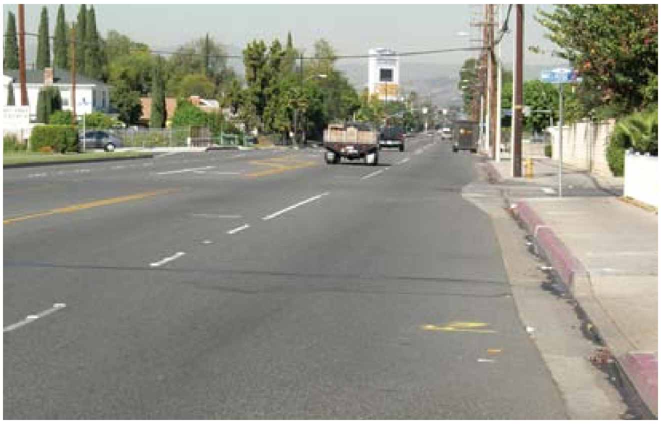


Figure 1. Western Avenue, Buena Park; Orange County, California.

Owner:	City of Buena Park, California
Type of Use:	Collector Road
Year Built:	1997
Limits:	Artesia Boulevard to Orangethorpe Avenue
Thickness:	9-12 inches
Cement Content:	6% to10% by weight
ADT:	—
PCI:	89
Annual Rainfall:	15.1 inches
Annual Snowfall:	None
Temperature:	48.3°F / 84.8°F
Subgrade Soils:	Silty fine sand with gravel; silty clayey sand

Prior to reconstruction of this street in 1997, the pavement surface exhibited extensive distress in the form of alligator cracking, rutting, raveling, etc. The traffic on the roadway also had increased significantly. Adding an asphalt overlay to mitigate the problems was not a solution. Therefore, FDR with cement was chosen to improve the stiffness and durability of the road base layer and provide long-term performance.

The existing 3 to 5 inches of the deteriorated HMA and existing base/subgrade soil was pulverized to a depth of 9 to 12 inches. The roadway was reshaped and 2.75 to 4 inches of excess material was hauled away. Cement was spread on the base material at a rate of 6% to10% by dry weight of roadway material and then dry-mixed into the base/subgrade soil to a depth of approximately 9 to 12 inches. Water was then added to the mix to achieve a uniform blend of materials and moisture. Upon final grading, the reclaimed base was rolled to desired compaction (typically 95% of standard Proctor, ASTM D 698). The finished reclaimed base was allowed to cure for seven days. During this period, local/residential traffic comprised of light vehicles was permitted to use the road. After curing was complete, a thin layer (1.25 to 2.0 inches) of asphalt was placed on the reclaimed base. A geotextile fabric was placed over the asphalt to retard thermo-shrinking, followed by the placement of the final 1.5 to 2.0 inches thick asphalt layer.

Figure 2. Truck Route, Western Avenue; Buena Park, California.

While a significant amount of truck traffic was observed on this road, the ADT or the equivalent single axle load (ESAL) information was not available. A Honda car dealership is close to the street. The street had a few utility patches, most of which had plan dimensions of 4 feet by 2 feet. One patch had plan dimensions of 25 feet by 30 feet. While some transverse cracking was apparent, there is no evidence that any of these cracks could be related to the underlying reclaimed base.

Figure 3. El Dorado Drive, Buena Park; Orange County, California.

Two other subdivision streets were also inspected. The results are summarized below:

Road:	El Rosal Circle
Limits:	West of Western Avenue to end
Year:	2001
Structure:	9 ins.
ADT:	—
PCI:	96
Road:	El Dorado Drive
Limits:	West of Western Avenue to end
Year:	2001
Structure:	9 ins.
ADT:	—
PCI:	98

City officials like the FDR process because it is very cost-effective (30% to 90% less than conventional reconstruction) and can be accomplished in half the time without extensive detours or street closures. Above all, the process provides a superior end product that is environmentally friendly, since it uses the in-situ material that taxpayers have already purchased once.

A.1.2 City of Westminster

Figure 4. Edwards Street, Westminster; Orange County, California.

Owner:	City of Westminster, California
Type of Use:	Collector Road
Year Built:	1990
Limits:	Westminster Ave to Garden Grove
Thickness:	9-12 inches
Cement Content:	6% to 10% by weight
ADT:	—
PCI:	96
Annual Rainfall:	15.1 inches
Annual Snowfall:	None
Temperature:	48.3°F / 84.8°F
Subgrade Soils:	Silty fine sand with gravel; silty clayey sand

This street, which passes through a school district, was overlaid with a slurry seal in 2004. City Engineer, Dr. Marwan N. Youssef, P.E., was pleased with the performance of the FDR technique on this and other city streets where FDR was used. This street was among the initial group of roadways that in 1990 were rehabilitated by the Orange County Engineering Department using FDR with cement. Some longitudinal and transverse cracks were noted. Overall, the roadway looked to be in good shape.

The City of Westminster had similar issues of extensive pavement surface distresses in the form of alligator cracking, rutting, raveling, etc., prior to reconstruction of this street with the FDR process in 1990. The increased traffic volume on the roadway combined with the poor pavement condition in 1990 precluded addition of an asphalt overlay to mitigate the problems. Traditional roadway reconstruction processes included ripping off the asphalt surface and about six inches of the existing base, which would be excavated and transported to a dumpsite, increasing roadway traffic because of the large number of trucks on the streets. Then, additional heavy trucks would bring in new base material from an aggregate pit, that would be laid down in preparation for the paved finished surface. Therefore, FDR with cement was considered as a quick and cost-effective alternative that would improve the stiffness and durability of the road base layer, sustain the increased traffic, and provide better long-term performance.

The construction process was identical to the methodology adopted by the City of Buena Park. Since the street was open to local traffic almost immediately, the flow of traffic in the vicinity of the FDR process was maintained. Of the four lanes on both sides of the street, only two were closed at any given time on either side. The Contractor performed the reclamation work with the FDR technique on the two outside lanes and then moved to the inside, allowing traffic to continually flow, which is another advantage of this process. Most road rehabilitation projects close down roads completely.

A few other streets were also inspected. They were Newland Street (reconstructed in 1992), 18th Street (reconstructed in 1997) and Hazard Avenue (reconstructed in 2001).

Figure 5. 18th Street, Westminster; Orange County, California.

Summary of the additional pavement inspections are as follows:

Road:	Newland Street
Limits:	Hazard Avenue to Westminster Avenue
Year:	1992
Structure:	9-12 ins.
ADT:	—
PCI:	100
Road:	18th Street
Limits:	Monroe Street to Beach Blvd.
Year:	1997
Structure:	9 ins.
ADT:	—
PCI:	89
Road:	Hazard Avenue
Limits:	Beach Blvd. to Hoover Street
Year:	2001
Structure:	9-12 ins.
ADT:	—
PCI:	91

Pavement distresses in the asphalt pavement surface were due to fatigue and to poor workmanship by utility companies in trying to close the cuts that they made in the street to facilitate their work.

Typically, the city uses a nine-inch thick FDR base with three inches of HMA surface for its local and residential streets. For heavy traffic collectors and arterials, the city uses a 12-inch thick FDR with cement base with a three-inch thick HMA surface layer. Compaction requirements are 95% of the maximum density obtained with the standard Proctor Test (ASTM D 698). The FDR with cement base is moist-cured for seven days and local traffic is allowed to pass on the reclaimed base during the curing period. If weak subgrade areas are encountered during construction, the city prefers to increase the percentage of cement, and most of the time the subgrade shows improvement. However, if the subgrade is still weak, the city prefers to undercut the weak areas from 12 to 18 inches deep, treat the material with cement and place it back. They have reported success with this method.

For the surface HMA layer, the city places a geotextile fabric at the mid- to lower-third point in the asphalt layer to overcome any shrinkage cracking. Some of the problems that have been reported during the FDR process are caused when the subgrades contain an excessive amount of clay. Other problems are related to cuts made by utility companies after the FDR process is complete. Overall, the City of Westminster has enjoyed great success with the FDR process and officials are confident that this process has helped them save between 30% and 60% on costs, compared to other projects of the same size and magnitude. The streets are performing well and city officials are happy to get the biggest bang for their buck.

Core samples of the reclaimed base were taken from all the streets. The core sample from 18th Street disintegrated. The core samples from the remaining three streets were intact and thus subjected to UCS testing. The results are summarized below:

Road:	Edwards Street
Limits:	Westminster Avenue to Garden Grove
Year:	1990
Thickness:	10.0 ins.
UCS, psi:	639
Road:	Newland Street
Limits:	Hazard Avenue to Westminster Avenue
Year:	1992
Thickness:	9.0 ins.
UCS, psi:	819
Road:	Hazard Avenue
Limits:	Beach Blvd. to Hoover Street
Year:	2001
Thickness:	9.0 ins.
UCS, psi:	724

A.1.3 City of Fullerton

Figure 6. Acacia Avenue, Fullerton; Orange County, California.

Owner:	City of Fullerton, California
Type of Use:	Collector Road
Year Built:	1989
Limits:	Orangethorpe Avenue to Commonwealth Avenue
Thickness:	9-12 inches
Cement Content:	6% to 10% by weight
ADT:	—
PCI:	87
Annual Rainfall:	15.1 inches
Annual Snowfall:	None
Temperature:	48.3°F / 84.8°F
Subgrade Soils:	Silty fine sand with gravel; silty clayey sand.

In 1989 this street was maintained by the Orange County Engineering Department. At that time, more than half of this project called for removal and reconstruction of the roadway at a cost of $2.15 per square yard. Instead, this road was rehabilitated with the FDR with cement process at a cost of $1.38 per square yard, resulting in a savings of more than 35% as well as employing a more environmentally friendly process. The surface layer was 2.5 inches thick HMA. The street has been in service since 1989 and the FDR base is performing well. This street is located in an industrial area and has significant truck traffic. A visual inspection revealed some block cracking at the intersections, and some mild alligator cracking in a small section of the street.

Figure 7. Acacia Avenue Located in an Industrial Zone; Fullerton, California.

The City likes the FDR process because it provides better performance with lower construction costs. The street down time and citizen complaints were reduced considerably compared to what would be expected with removal and reconstruction of the roadway. The shortened construction times also reduced the potential for accidents and congestion.

A.1.4 City of Los Alamitos

Figure 8. Bloomfield Street, Los Alamitos; Orange County, California.

Owner:	City of Los Alamitos, California
Type of Use:	Collector Road
Year Built:	1989
Limits:	Cerritos Avenue to Ball Road
Thickness:	9-12 inches
Cement Content:	6% to 10% by weight
ADT:	—
PCI:	94
Annual Rainfall:	15.1 inches
Annual Snowfall:	None
Temperature:	48.3°F / 84.8°F
Subgrade Soils:	Silty fine sand with gravel; silty clayey sand.

The removal and reconstruction of the roadway for this project section was estimated at $1.97 per square foot in 1989. The Orange County Engineering Department decided to use the FDR with cement process, which cost $0.99 per square foot in 1989, a savings of more than 50%. The surface layer is comprised of a 2.5-inch thick HMA overlay. Barring minor asphalt maintenance, the street has had a successful performance from the FDR base layer. The inspection revealed some minor cracking on the pavement surface. Overall, the roadway looks to be in great shape. The city has an improved base for better asphalt performance, along with reduced chances for potholes.

A.1.5 City of Stephenville

Figure 9. Belknap Street, Stephenville; Erath County, Texas.

Owner:	City of Stephenville, Texas
Type of Use:	Local Road
Year Built:	1993
Limits:	Collins Street to Frey Street
Thickness:	6 inches
Cement ccontent:	5% by weight
ADT:	—
PCI:	89
Annual rrainfall:	29.7 inches
Annual Snowfall:	2.1 inches
Temperature:	30.0°F / 93.6°F
Subgrade Soils:	Clay and sand

The City of Stephenville in Erath County, Texas, adopted FDR with cement in 1992 to rehabilitate city streets that were beyond their design life and were exhibiting pavement distress in the form of base failures and rutting/potholes. Consulting Engineer Sanford LaHue, Jr., of Schrickel, Rollins and Associates of Arlington, Texas, assisted the city in the development of a comprehensive pavement maintenance program. The city performs visual pavement evaluations to determine which streets require rehabilitation. Streets with minor pavement surface cracking receive a standard asphalt overlay, while streets with base failure are candidates for FDR with cement. The first step in adopting the FDR with cement strategy is to sample material from the candidate project sections targeted for rehabilitation, and test them for index properties, such as gradations and Atterberg limits, along with UCS of cylindrical samples made with varying percentages of cement.

Over the years, the city has found that 15 to 35 pounds per square yard (on average, 25 lbs/yd^2 equates to 5% by dry weight of roadway material) of cement is required to produce a uniform and durable six-inch thick mixture of recycled asphalt pavement and the underlying base/soils. Initially, the city used up to 50 pounds per square yard of cement, but the appearance of cracks in the pavement surface led to the decision to cut back on the cement content.

City specifications require contractors to pulverize the existing asphalt surface and base 6 inches deep. Streets with good base and surface materials require less cement than those with marginal or poor quality materials. The FDR with cement layer is pulverized and mixed with cement and water to obtain the right moisture for compaction. The City targets a field density that is equal to or better than 95% of standard Proctor density determined in the laboratory in accordance with ASTM D 698. The reclaimed base layer is shaped and compacted to the final grade elevation and moist-cured for five to six days. Excess material is used to adjust the crown, if required, or is otherwise hauled away. Upon completion of the curing period, a 1.5-inch thick HMA overlay is placed on the reclaimed base layer.

The pavement inspection showed some longitudinal cracking that was slurry sealed, as well as some edge cracking and utility patches. Overall, the pavements are in good condition and the minor cracks that were observed are not related to the reclaimed base layer. Some additional streets were also inspected. The results are summarized below.

Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Dale Avenue Tarleton Street to FM 988 Loop 1993 6 ins. — 93
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Overhill Drive FM 988 Loop to Lydia Street 1993 6 ins. — 89
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Frey Street Graham Street to Rowland Street 1993 6 ins. — 87
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Lillian Street Frey St. to Lingleville Hwy (SH 9 Loop) 1993 6 ins. — 88
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Harbin Road Washington St. to Lingleville Hwy (SH 8 Loop) 1995 8 ins. — 91

Harbin Road, a major high-volume collector road through the city, was originally maintained by TxDOT until 1994, when the state discontinued maintenance. With the assistance of Mr. LaHue, the city decided to reclaim the road with cement to a finished reclaimed base thickness of 8 inches with 32 pounds per square yard of cement. The surface is comprised of a two-inch thick HMA layer. The visual inspection of the street showed some minor longitudinal cracking. Overall, the pavement is in good condition and there was no evidence of problems with the reclaimed base layer. The City has been reclaiming its streets since 1992, and has had positive experiences with the FDR process. The streets have performed well and the city has been able to direct its resources toward other problems.

A.1.6 Village of Endicott

Figure 10. North McKinley Avenue, Village of Endicott, New York.

Owner:	Village of Endicott, New York
Type of Use:	Local Road
Year Built:	1980
Limits:	Jenkins Street to Pine Street
Thickness:	6 inches
Cement Content:	4% to 5% by weight
ADT:	Heavy, especially during peak hours
PCI:	73
Annual Rainfall:	42.3 inches
Annual Snowfall:	91.3 inches
Temperature:	11.2°F / 83.6°F
Subgrade Soils:	Silty clay

The Village of Endicott is in Broome County in southern New York. This area is subject to severe winter weather and several freeze-thaw cycles. The village adopted the FDR with cement process in 1980 to rehabilitate North McKinley Avenue between Jenkins Street and Pine Street. This segment of the street carries heavy traffic during peak hours as it feeds into State Route 26 and eventually into State Route 17. The original pavement section was comprised of 1.5 inches of asphalt pavement over a 3 to 4-inch thick gravel base. The first step in the FDR with cement process was to pulverize the existing asphalt surface and the underlying gravel base, and then blend the subgrade soils with the pulverized mixture. Finally, portland cement (5% by dry weight of roadway materials) and water was added to the mix, which was compacted to produce a 6-inch thick reclaimed layer. A HMA overlay of 1.5 inches thick was placed on top of the reclaimed layer. In the early to mid-1990's, an additional 1.5-inch thick HMA overlay was placed on this street.

A visual inspection of the pavement surface showed significant longitudinal and transverse cracks of low to medium severity, as well as some rutting in the asphalt layer at isolated locations, and some cracks of low to medium severity associated with shoulder drop-offs. These cracks were sealed, and the pavement performed well. Village officials said they were satisfied that the road held up so well for so long, while the residents wondered why the village has not used FDR with cement for the remainder of its streets.

A visual inspection of three other streets reconstructed with the FDR with cement process revealed some low to medium severity longitudinal and transverse cracking, as well as some edge cracking of low to medium severity at isolated locations on the pavement. The PCI for each street is summarized below.

Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	N. Roosevelt Avenue Jenkins Street to Pine Street 1988 6 ins. Moderate 79
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Lower Governeurs Lane Skye Island Drive to dead end 1988 6 ins. Low 83
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Prince Edward Court Governeurs Lane to Cul-de-sac 1988 8 ins. Low 87

The distresses on the section of North Roosevelt Avenue between Jenkins Street and Pine Street were higher, in part because the Village had done extensive sewer repairs along this street, and the pavement replacement work was not of good quality. Overall, the pavement sections are in good condition and there is no visual evidence of any problem with the reclaimed base layer.

Core samples of the reclaimed base were taken from all the streets with the exception of Prince Edward Court. The core sample from North Roosevelt Avenue disintegrated. The core samples from the remaining two streets were intact and subjected to UCS testing. Results are summarized below.

Road: **Limits:** **Year:** **Thickness:** **UCS, psi:**	N. McKinley Avenue Jenkins Street to Pine Street 1980 6 ins. 811
Road: **Limits:** **Year:** **Thickness:** **UCS, psi:**	Lower Governeurs Lane Governeurs Lane to Cul-de-sac 1988 6 ins. 1,030

A.2 PRIVATE DEVELOPERS

A.2.1 Anne Arundel County, Maryland

Figure 11. Sherwood Forest Tennis Courts, Crownsville, Maryland.

Owner:	Sherwood Forest, Crownsville, Maryland
Type of Use:	Tennis Courts
Year Built:	2002
Limits:	—
Thickness:	12 inches
Cement Content:	4% to 5% by weight
ADT:	—
PCI:	98
Annual Rainfall:	44.8 inches
Annual Snowfall:	4.5 inches
Temperature:	23.8°F / 87.7°F
Subgrade Soils:	Silty clay

In 2002, the tennis courts showed extensive distress. The FDR with cement process was used to reclaim the courts that were comprised of a five-inch thick asphalt layer supported on the silty clay subgrade. The asphalt layer and the underlying clay subgrade were pulverized to a depth of 12 inches. After re-shaping, 50 pounds per square yard of cement was mixed to obtain a total depth of 12 inches. The tennis courts were moist-cured for seven days, and appear in good condition with hardly any distress.

A.2.2 Harford County, Maryland

Figure 12. Water Vale Farm, Bel Air; Harford County, Maryland.

Owner:	Water Vale Farm; Bel Air, Maryland
Type of Use:	Residential Streets
Year Built:	2002
Limits:	—
Thickness:	12 inches
Cement Content:	5% to 6% by weight
ADT:	—
PCI:	98
Annual Rainfall:	43.8 inches
Annual Snowfall:	12.8 inches
Temperature:	23.8°F / 87.7°F
Subgrade Soils:	Silty sandy clay

The residential streets had perennial maintenance issues due to weak subgrade soils comprised of silty, sandy clay. The road was reclaimed by the FDR with cement process. The existing roadway, comprised of 8 inches of asphalt and base material, was pulverized and mixed with the underlying subgrade soils along with an additional 52 pounds per square yard of cement, to obtain a completed layer 12 inches deep. The reclaimed base was moist-cured for seven days. A two-inch thick HMA overlay was placed as the surface layer.

A.2.3 Prince George's County, Maryland

Figure 13. East Gate Shopping Center; Glendale, Maryland.

Owner:	East Gate Shopping Center; Glendale, Maryland
Type of Use:	Parking
Year Built:	2002
Limits:	—
Thickness:	12 inches
Cement Content:	7% to 8% by weight
ADT:	—
PCI:	95
Annual Rainfall:	43.8 inches
Annual Snowfall:	12.8 inches
Temperature:	23.5°F / 87.2°F
Subgrade Soils:	Silty clay

Because of extensive distress, the parking lot pavement required reconstruction in 2002. Recycling the pavement with the FDR with cement process was chosen as a cost-effective method. The existing pavement structure, comprised of 4 to 5 inches of HMA and 6 inches of aggregate base, was pulverized and mixed with the underlying clay subgrade, along with 80 pounds per square yard of cement, to obtain a compacted depth of 12 inches for the reclaimed base. The reclaimed base was moist-cured for only three days. A three-inch thick HMA layer was placed as the surface.

A.3 COUNTY AGENCIES

A.3.1 Bonner County, Idaho

Figure 14. Dufort Road; Bonner County, Idaho.

Owner:	Bonner County, Idaho
Type of Use:	Collector Road
Year Built:	1997
Limits:	15 miles in length
Thickness:	10 inches
Cement Content:	3% to 5.5% by weight
ADT:	—
PCI:	78
Annual Rainfall:	33 inches
Annual Snowfall:	120 inches
Temperature:	19.0°F / 80.0°F
Subgrade Soils:	Varies from clays to silts to sands to gravels

Bonner County, Idaho has 700 miles of roadway within its jurisdiction, including about 250 miles of paved roads and 450 miles of gravel roads. The county has actively used FDR for pavement rehabilitation since 1997 and has approximately 80 miles of FDR with cement roads. While traffic data is not available, typical volumes are low, with increases during tourist seasons. The subgrade soils range from clays to silts to sands to gravels. These soils are incorporated into the FDR with cement process. Initially, the county used the FDR process without cement, which led to extensive failures of roadways. Based on that experience, the county began using cement for stabilization. The county constructs approximately 12 miles of FDR with cement every year. On an annual basis, the county receives approximately 120 inches of snow and experiences around three to four freeze/thaw cycles. The county has had mostly successful experiences with the FDR with cement process; however, a few failures have been reported.

Typically, the FDR with cement roads are 24 feet wide and 10 inches deep, with a 2.5-inch HMA surface layer covered with a single stone chip seal treatment. The chip seal is used to help keep water out of the pavement structure. County employees visually inspect the roadways to select candidate projects for FDR with cement, and obtain samples which are subject to a laboratory evaluation that includes index properties like gradation and Atterberg limits. A mix design is performed to obtain the optimum cement content. Initially, the county used 8% cement with a 21-day UCS of 900 psi, but it now uses 3% to 5.5% cement with a 21-day UCS of 700 psi.

The county hires contractors to perform the pulverization, cement spreading and mixing work, and uses its own personnel to perform the grading, shaping, curing, and paving work. Compaction is monitored during construction with a nuclear density gauge. The minimum density requirements are 90% of the density obtained in the laboratory, but most of the projects report field density of 95% or above. STE-1 tack oil is applied at the rate of 0.1 gallons per square yard for curing. The county cuts roadway cores after 21 days to test for UCS verification.

While the county is generally happy with the FDR process, one of the complaints is that after about three years or so, there was some roadway cracking, some of which would become as large as ⅜-inch wide in winter. County employees recognize that cracking is an aesthetic and not a structural issue. Recently, the county has reduced the target 21-day UCS to 700 psi from 900 psi, and over the last five years has used geotextile fabric to reduce reflective cracking.

Dufort Road was reconstructed with the FDR with cement process in 1997. The reclaimed base layer was 10 inches thick with 2.5 inches of HMA and chip seal. A visual inspection revealed some minor block cracking of low severity, as well as good, positive drainage in the roadway section. Geotextile fabric was not used in this pavement section. The roadway gets heavy truck traffic from a sawmill located at one end. The overall pavement condition was good. In addition to Dufort Road, some other pavement sections were also inspected. The results are summarized in the adjacent column:

Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Gooby Road 1.5 miles in length 1997 10 ins. — 78
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Lakeshore Drive 12 miles in length 2001 10 ins. — 93
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Spirit Lake Cut Off 12 miles in length 1998 10 ins. — 43

Figure 15. Spirit Lake Cut Off; Bonner County, ID.

The Spirit Lake Cut Off road section is about 12 miles long and was constructed with the FDR with cement process in 1998. This roadway section is comprised of 10 inches of reclaimed base, a geotextile fabric, and 2.5 inches of HMA and chip seal. The pavement evaluation revealed significant potholes up to three inches deep across the roadway, as well as substantial rutting and minor settling in some areas. Since the PCI is based on functional features, the PCI for this roadway dropped to 43. This issue needs to be investigated further, but a close visual examination indicates that the pavement distresses appear to be within the asphalt layer.

A.3.2 Washington County, Maryland

Figure 16. Poffenburger Road; Washington County, Maryland.

Owner:	Washington County, Maryland
Type of Use:	Local Road
Year Built:	2001
Limits:	Railroad crossing east of MD 65 to the bridge over Antietam Creek
Thickness:	9.5 inches
Cement Content:	3% by weight
ADT:	1,390
PCI:	96
Annual Rainfall:	39.5 inches
Annual Snowfall:	27 inches
Temperature:	20.8°F / 86.1°F
Subgrade Soils:	Silty clays and sands

Washington County in Maryland started using the FDR with cement process in 2001. The existing pavement structure was comprised of a 2- to 7-inch thick deteriorated asphalt layer over 2 to 4 inches of aggregate base on subgrade soils that have fair support conditions. The county receives a significant amount of rain and snowfall. Although the FDR with cement pavement sections are relatively new, county officials are interested in documenting the process so they can make design and construction adjustments as they go along. The County requires a minimum UCS of 200 psi at three days. It uses a structural layer coefficient of 0.20 for the reclaimed base material produced with the FDR with cement process. The pavement design is performed according to the guidelines established in *1993 AASHTO Pavement Structural Design Guide*. The cement content for the earlier projects performed in 2001 was at 3% of the maximum dry unit weight of reclaimed base, although the current practice is to use 5%. In 2001, although the contract was set up for 5% by weight, field personnel erroneously determined cement content based on volume instead of weight. Through a study, personnel determined that 5% by volume was approximately 3% by weight. Field tests were run to verify minimum UCS was being achieved.

Almost all the roads inspected were local roads, located mostly in areas with agricultural and industrial traffic. Observers noted some longitudinal cracking in the median of the roads as a primary distress, along with minor edge cracking. Overall, the roads appear to be in very good shape.

Road:	Reidtown Road
Limits:	Marsh Pike to Byers Road
Year:	2001
Structure:	8 ins.
ADT:	283
PCI:	97
Road:	Salem Church Road
Limits:	MD 58 to Salem Reformed Church
Year:	2001
Structure:	8 ins.
ADT:	379
PCI:	98
Road:	Washington Monument Road
Limits:	US 40A to Zittlestown Road
Year:	2001
Structure:	8.5 ins.
ADT:	585
PCI:	95

For the construction of the FDR with cement, the County engaged independent consultants to obtain samples every 1,000 feet. These samples were used to determine cement content required to obtain a minimum UCS of 200 psi at three days. Typical results for cement content ranged from 3% to 6% by dry weight of material. The 5-day UCS results ranged from 190 to 378 psi. The roadway was proof-rolled prior to placement of the surface asphalt layer. An asphalt emulsion was applied to the road surface to control dust. A sanding coat for roughness was included in project specifications.

Based upon the 2001 testing, the County specifications for cement application were changed in 2003 to require a uniform cement content of 5% by weight. This eliminated the lab testing and corresponding delays required to determine the optimum cement content. The independent laboratory determines the unit weight of road material every 1,000 feet. Because asphalt emulsion was not effective in controlling dust, it was deleted from the current contract. Water trucks, which keep the surface of the reclaimed base moist, are now used for dust control.

To handle design and construction difficulties related to proposed grade changes, personnel remove material prior to FDR and then replace it after the excavation in the case of crests. For sags, additional material is brought in to achieve final grade.

For shoulder drop-offs, the County has used DCR (Dirty Crusher Run), topsoil and CR-6 (Crusher Run Aggregate). However, County officials are not satisfied with the performance and are currently using a combination of DCR followed by topsoil. It is still too early to gauge the effectiveness of the new procedure.

County officials report the big advantage of FDR with cement is the speed of construction, but delays caused by requiring laboratory determination of optimum cement content became an issue. As a result of the field and laboratory testing since 2001, the county has determined that about 5% cement content by weight is optimum for the several differing types of reclaimed material present in county roads. Now the County uses a standard 5% cement by dry weight of material for all its roads. The County believes that the reduced time for construction offsets any cost increase due to possibly having a slightly higher than optimal cement content.

Washington County has not performed any evaluation of the material placed, other than visually observing the finished product and inspecting the depth and cement placed in the base course. In the future, the County plans to perform the following:

- Post FDR UCS testing at the 5% cement content.
- Select falling weight deflectometer (FWD) testing to determine actual in-place strength of new roadways at intervals of five years to gain an accurate picture of service life.
- Increased use of the FDR process.

A.3.3 Montgomery County, New York

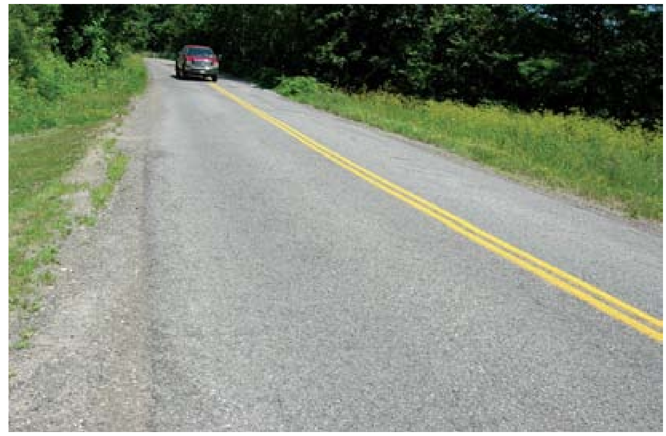


Figure 17. Polin Road, Montgomery County, New York.

Owner:	Montgomery County, New York
Type of Use:	Local Road
Year Built:	2000
Limits:	State Route 30A to Reed Hill Road
Thickness:	8.0 inches
Cement Content:	3% to 5% by weight
ADT:	150
PCI:	89
Annual Rainfall:	36.2 inches
Annual Snowfall:	52.9 inches
Temperature:	11.0°F / 84.0°F
Subgrade Soils:	Sandy clays and silts

Montgomery County, in northeastern New York, has approximately 400 miles of roads in its highway system, including roads with both asphalt and gravel surfaces. Historically, the roads were built to “get the farmer out of the mud.” Now the county is faced with the challenge of maintaining and rehabilitating these roads at the end of their service lives, along with widening the roads to support increased agricultural traffic. Polin Road in Charleston was reconstructed in 2000. Visual pavement inspection revealed some longitudinal cracking near the roadway median, as well as some minor corrugations and localized rutting on the pavement surface. Most of the distress seemed confined to the asphalt pavement surface, and the reclaimed base was in good shape.

Since the county experiences significant freeze-thaw cycles, a prime concern for the road bases was durability. Significant heaving led to premature failure of the county roadways. The County started recycling existing pavements and incorporating the material in the base for road widening (from 12- to 14-feet wide to 18-feet wide) during the late 1980’s. Initially, liquid calcium chloride was used to facilitate compaction. Over the years, county personnel experimented with other products to achieve increased strength and durability in the new road bases. County officials like the performance of the reclaimed cement-treated bases in terms of strength and durability, and starting in 2000, the county has exclusively used the FDR with cement process for roadway rehabilitation.

The existing road was comprised of 2 to 3 inches of HMA and 6 to 8 inches of gravel base, which was pulverized and mixed in place with portland cement and with the underlying subgrade, to produce a 10-inch thick reclaimed layer. A 3.5-inch cold-mix asphalt layer was used as the base layer, and a ¼-inch thick single surface bituminous treatment was placed as the surface pavement layer.

In addition, an inspection of the following roads revealed longitudinal cracking of low to medium severity along the road medians. Some locations also displayed corrugations and rutting of low to medium severity. The pavement distresses were observed in the asphalt layer, while the reclaimed layer seemed to be in good condition. The individual PCIs are summarized below.

Road:	Anderson Road
Limits:	MP 2.00 to Currytown Road
Year:	2000
Structure:	8-10 ins.
ADT:	200
PCI:	78
Road:	Sacandaga Road
Limits:	Stoners Trail Road to Caballero Road
Year:	2000
Structure:	8-10 ins.
ADT:	1,000
PCI:	84
Road:	Brand Road
Limits:	Rural Grove Road to Green Road
Year:	2001
Structure:	8-10 ins.
ADT:	300
PCI:	88
Road:	Burtonville Road
Limits:	Brand Road to NY State Route 30A
Year:	2001
Structure:	8-10 ins.
ADT:	200
PCI:	83
Road:	Blaine Road
Limits:	Mapletown Road to Carlisle Road
Year:	2001
Structure:	8-10 ins.
ADT:	200
PCI:	84

A mixture design process that includes index tests of moistures, gradations, and Atterberg limits, along with UCS of samples with varying cement content, is performed to determine the optimum amount of cement to be added to the reclaimed base. Typically, the County uses portland cement at a rate of between 4% and 6% by dry weight of roadway material for performing the FDR with cement process. The UCS tests are performed afterwards on two sets of samples for different cement contents as follows:

1. after seven-day curing, and
2. after subjecting to freeze/soak cycles.

The cement content that provided 7-day UCS of 200 psi and retained about 75% of its strength in the freeze/soak sample was selected as the design cement content. In the future, the county is looking at using a target 7-day UCS of 150 psi.

Core samples attempted at each of the six roads discussed above broke upon retrieval.

County officials say they are pleased with their experiences with the FDR with cement process, as it has successfully widened the roadways with in-situ materials at a fraction of the cost of conventional construction. The use of cement has improved the strength and durability of the end product, leading to improved long-term road performance. The county constructs the reclaimed base to a width wider than the overlying asphalt course, eliminating the need to pave off of the stabilized base. The compaction process is critical and the county requires a sheep's foot roller on all its projects. Application of dust control is done as soon as possible after final grading. The county believes that this helps hold the moisture in, making it good for the curing process as well as for dust control.

The County likes the fact that the FDR with cement process is not as subject to weather-related issues as most other processes. In its experience, a light rain can actually be beneficial because extra moisture can help with compaction. The County lets traffic on the base very soon after final compaction. Overall, the County views the FDR with cement process as very user friendly because sections can be worked and completed without disrupting adjacent sections.

A.3.4 Geauga County, Ohio

Figure 18. West Park Circle Drive, Geauga County, Ohio.

Owner:	Geauga County, Ohio
Type of Use:	Local Road
Year Built:	1996
Limits:	Washington Street (SR 606) to Park Circle Drive
Thickness:	12 inches
Cement Content:	12% by weight
ADT:	—
PCI:	82
Annual Rainfall:	37.3 inches
Annual Snowfall:	49.5 inches
Temperature:	16.0°F / 81.0°F
Subgrade Soils:	Silts and clays

Geauga County is in northern Ohio and has a wet climate with deeply penetrating freeze thaw activity. In such conditions, pavement layers must be durable and offer consistent performance; otherwise, they will lose strength and stiffness from both harsh climatic conditions and from traffic loads. Geauga County started the FDR with cement process in 1996 to extend the pavement life and eliminate heaving due to deep freeze-thaw cycles. Like other counties, Geauga County uses the FDR with cement process for reconstruction because of the economy and the superior strength and durability offered by the reclaimed base stabilized with cement. During the reconstruction process, the county also widens the roadway. The first couple of projects that the county constructed were in an industrial area where heavy truck traffic combined with clay subgrades created severe performance challenges.

The West Park Circle Drive was reconstructed in 1996 using the FDR with cement process. The existing asphalt pavement had several distresses. The asphalt layer along with the underlying aggregate base course and subgrade was pulverized and blended with 12% portland cement by dry weight of roadway material to produce a compacted reclaimed base layer of 12 inches thick. A 9-inch thick portland cement concrete pavement was placed over the reclaimed base. The visual inspection indicated blow-outs of medium severity at expansion joints, and patches at some joint locations on the concrete pavement surface. Overall the pavement is in good condition.

Other roads were also visually inspected. Park Circle Drive has a portland cement concrete pavement surface, while Nash Road and Sherman Road have asphalt pavement surfaces. The FDR process used 12%, 10% and 6% by weight of portland cement for Park Circle Drive, Nash Road and Sherman Road, respectively. Blow-outs of low to medium severity near the joints and some patches were observed on the concrete pavement of Park Circle Drive. Longitudinal cracking of low severity along the median, as well as edge cracking, and some transverse cracks of low severity, were observed at some locations on the asphalt surfaced roads. The roads are in good condition as summarized below.

Road:	Park Circle Drive
Limits:	SR 606 to West Park Circle Drive
Year:	1996
Structure:	12 ins.
ADT:	—
PCI:	83
Road:	Nash Road
Limits:	Jug Street to Mumford Road
Year:	1998
Structure:	8 ins.
ADT:	600
PCI:	78
Road:	Sherman Road
Limits:	Bass Lake Road to Blue Heron Trail
Year:	2000
Structure:	10 ins.
ADT:	275
PCI:	87

To obtain the optimal cement content for the FDR, the county uses a mixture design process where the moisture-density curves are determined based on AASHTO T 99 (standard Proctor). The minimum cement content required for a 7-day UCS of 200 psi as per ASTM D 1633 is chosen as the design cement content. With regards to field QA/QC, the county requires compaction of 96% or better of the laboratory maximum dry density values (standard Proctor). The county requires curing of reclaimed bases for a period of five to 10 days before placing the 4 to 4.5-inch thick surface HMA layer.

In the last six years, the County has either been using straight portland cement or 50/50 blends of portland cement with lime kiln dust as the stabilizer. While the cost of the blend is slightly less, it requires more quantity than the straight portland cement.

A.3.5 Clark County, Washington

Figure 19. NE 314th Street, Clark County, Washington.

Owner:	Clark County, Washington
Type of Use:	Local Road
Year Built:	1999
Limits:	NE 102nd Avenue to NE 122nd Avenue
Thickness:	6 inches
Cement Content:	6% to 8% by weight
ADT:	—
PCI:	91
Annual Rainfall:	53.4 inches
Annual Snowfall:	4.5 inches
Temperature:	31.8°F / 79.1°F
Subgrade Soils:	Sandy silt, silty clay

Clark County, in southwestern Washington, is one of the leaders in implementing an aggressive pavement management program. It performs pavement evaluations with visual inspections and non-destructive testing with a FWD. This data is used to prioritize the maintenance and rehabilitation needs of its pavement network. Around the mid to late 1990's, the pavement design and analysis programs revealed a need for five inches of HMA overlays to maintain road functionality. Faced with a shortage of funds to maintain its roads, the county began using the FDR with cement process in 1999.

Typically, roadways that are candidates for FDR with cement would be 18 feet wide, comprised of 0.5 to 2 inches of bituminous surface treatment over 4 to 6 inches of aggregate base course. In the initial stages of the FDR with cement program (1999-2001), the county reclaimed the asphalt and aggregate base layer to produce a 6-inch thick reclaimed base layer stabilized with cement. With the excess material, the County widened the reconstructed road to 20 feet. Thus, the middle 18 feet of the roadway section is supported on a FDR base, while the outer 1-foot width on either side of the roadway is not.

NE 314th Street was one of the initial roads that was constructed with the FDR with cement process. Flushing of the asphalt emulsion was observed in some locations, along with some edge cracking due to an inadequate base layer beneath the pavement surface. In addition to NE 314th Street, the following roadways were also evaluated. All the roads receive significant truck traffic from the proximity of quarries, logging industry, agriculture and housing construction work in the area. Overall, the roads are in good condition.

Road:	NE 159th Street
Limits:	NE 92nd Avenue to NE 50th Avenue
Year:	2000
Structure:	6 ins.
ADT:	—
PCI:	93
Road:	NE 112th Avenue
Limits:	NE 299th Street to NE 314th Street
Year:	2000
Structure:	6 ins.
ADT:	—
PCI:	95
Road:	NE JA Moore Road
Limits:	NE 284th Street to end
Year:	2001
Structure:	6 ins.
ADT:	—
PCI:	93
Road:	NE 279th Street
Limits:	NE 82nd Avenue to end
Year:	2001
Structure:	6 ins.
ADT:	—
PCI:	94
Road:	NE Landerholm Road
Limits:	NE 40th Avenue to end
Year:	1999
Structure:	6 ins.
ADT:	—
PCI:	92

The county started off using 6% to 8% cement that translated to a 7-day UCS of 1,200 psi for the reclaimed base layer. The county does not mix the silty subgrade soils into the reclaimed base layer. In recent years, the county has cut down on the cement content in the reclaimed layer to 4% to 6% to achieve a target 7-day UCS of 400 psi. Based on the experience gained with the FDR process, the county is now constructing 8- to 10-inch thick reclaimed base layers rather than the 6-inch thick layer it used from 1999 through 2001.

The compaction requirement for the reclaimed base layer is 95% or better of the modified Proctor (ASTM D 1557). The reclaimed base layer is moist-cured for three to five days and is opened to local traffic immediately after construction. To facilitate the curing process, truck traffic is prohibited for three to five days. County officials like the fact that they have a uniform reclaimed base layer rather than the variability that is created with variable depth asphalt patching. The surface layer on roads with low traffic volumes is a triple shot bituminous surface treatment (¾-inch thick). County officials are interested in techniques that will improve the ride quality of these surfaces. For high volume traffic roads, the pavement surface is comprised of a 2.5 to 3-inch thick HMA layer on top of the reclaimed base layer.

A.3.6 Pierce County, Washington

Figure 20. 224th Street East, Pierce County, Washington.

Owner:	Pierce County, Washington
Type of Use:	Local, Collector and Arterial Roads
Year Built:	1992
Limits:	Orting-Kapowsin Highway East to 146 Avenue East
Thickness:	6 to 8 inches
Cement Content:	5% to 7% by weight
ADT:	2,375
PCI:	93
Annual Rainfall:	48.7 inches
Annual Snowfall:	9.8 inches
Temperature:	31.7°F / 77.0°F
Subgrade Soils:	Silty gravel and silty sand

Pierce County is just south of the Seattle-Tacoma metropolitan area. In the late 1980's, it was faced with reconstruction of 18- to 20-foot wide local access roads that had significant truck traffic serving the logging and other industries. The roadways had significant distresses in the form of rutting, pumping, and alligator cracking. Repeated maintenance efforts that included variable depth asphalt patches were not providing a reasonable solution, leaving reconstruction as the only option. Since the cost of conventional roadway reconstruction was beyond its budget, the county started the FDR with cement process in 1992 and has completed nearly 200 lane miles of projects using the FDR with cement technique.

The county's first step was to obtain samples of the existing project pavement section at 500-foot intervals, and classify the subgrade soils based on gradation and index tests. The optimum cement content is based on guidelines provided by PCA and a target 21-day UCS of 200 to 400 psi. County personnel faced some difficulty while working with poorly graded soils, soils with large amounts of organic material, and soils with cobbles.

In the reconstruction process, the existing 2 to 3 inches of asphalt was pulverized with the underlying 4 to 6 inches of aggregate base material and ½ to ¾ inches of the silty gravel subgrade. The pulverized mix was blended with water and 5% to 7% cement to produce the reclaimed base layer. The excess material was used to widen the street by 1 foot on both the edges. Thus, the outer one-foot pavement sections on both edges are not supported on FDR pavement layers, making them prone to edge cracking.

The compaction requirements for the reclaimed base are 95% and above of the standard Proctor (ASTM D 698) test. The FDR pavement section is opened to local traffic after moist-curing for five to seven days. Vehicles weighing greater than 10 tons are prohibited from using the newly constructed FDR section for a period of nearly three weeks. On low-volume traffic roads, the county's practice is to place a double shot bituminous surface treatment as the surface layer, with a third shot of asphalt emulsion applied the following year. On high-volume traffic roads, the county places a two to three-inch thick HMA overlay atop the reclaimed base layer.

The segment of 224th Street East between Orting-Kapowsin Highway East to 146th Avenue East was reconstructed with the FDR with cement process in 1992. A new asphalt surface was placed in 1998. Some longitudinal and transverse cracking was observed in this project section, along with occasional edge cracking in some areas. Other project sections that were inspected are summarized below.

Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	288 Street E 008 Avenue E to 288 Street S 1998 6-8 ins. 1,200 89
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	288 Street S 008 Avenue S to SR 507 1996 6-8 ins. 1,975 88
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	70th Avenue E MP 7.28 to 224 Street E 1987 6-8 ins. 3,025 95
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	112 Street E MP 1.06 to MP 2.66 1995 6-8 ins. 3,025 87
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	112 Avenue E 144 Street E to 164 Street E 1998 6-8 ins. 10,425 90

Overall, the pavement sections are in good condition and there is no visual evidence of any problem with the reclaimed base layer.

The summary of UCS of core samples extracted from some of the roads is presented in the adjacent column.

Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	288 Street S 008 Ave. S. to SR 507 1996 > 6 ins. 700
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	224 Street E Orting-Kapowsin Hwy E to 146 Ave E 1992 > 6 ins. 1,280
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	70th Ave E MP 7.28 to 224 Stret E 1987 > 6 ins. 600
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	112 Street E MP 1.06 to MP 2.66 1995 > 6 ins. 560
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	122 Ave E 144 Street E to 164 Street E 1998 > 6 ins. 2,110

Based on the test results, it is evident that the FDR with cement layer is durable and has adequate strength over an extended period of time. This is critical to ensuring good long-term performance of the reclaimed pavement layer.

A.3.7 Spokane County, Washington

Figure 21. Charles Road, Spokane County, Washington.

Owner:	Spokane County, Washington.
Type of Use:	Local and Collector Roads
Year Built:	1999
Limits:	Long Lake Road to Dover Road
Thickness:	8 inches
Cement Content:	3% to5% by weight
ADT:	617
PCI:	100
Annual Rainfall:	16.7 inches
Annual Snowfall:	44.5 inches
Temperature:	21.6°F / 82.6°F
Subgrade Soils:	Sandy silt and clayey sand

Spokane County has challenging weather conditions coupled with silty subgrade soils and heavy trucks that service the agriculture and logging industries. The silty subgrade soils are highly susceptible to frost heave, which induces movement within the pavement structure, leading to cracking and loss of roadway service. The problems were severe enough to cause the county to shut the roads for extended periods of time during freezing weather. The cost of reconstructing these roads was prohibitive. In 1999, encouraged by the success of the FDR with cement process in neighboring counties, Spokane County decided to use the FDR with cement process to rehabilitate its dilapidated road network.

Charles Road was reconstructed with the FDR with cement process in 2000. A visual inspection of the roadway indicated that the pavement surface is in excellent condition without any visible distress. The following roads also underwent visual inspection. As indicated by the PCI, all the roads are in excellent condition.

Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Dalton Rd. City of Deer Park to Montgomery Rd. 1999 8 ins. 1,433 100
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Charles Rd. Wood Rd. to Long Lake Rd. 2000 8 ins. 265 100
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Wood Rd. Euclid Rd. to Coulee Hite Rd. 2001 10 ins. 635 99
Road: **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Eloika Lake Rd. Division Rd. to US-2 2002 8 ins. 2,023 100

Figure 22. Trucks for the Logging Industry; Spokane County, Washington.

While the county initially used 4% to 6% cement by dry weight of roadway material to obtain a 7-day UCS of 450 to 800 psi, based on experience, it has reduced the cement content to 3% to 5% for a target 7-day UCS of 270 psi. Compaction requirements are specified as 95% or better in accordance with AASHTO T 134 (ASTM D 558).

The County has a unique partnership with its contractors to construct FDR with cement bases. The contractor brings in the necessary machinery to pulverize the existing 8-inch flexible pavement structure to two-inch minus material, and perform the cement mixing. The cement mixing is performed in tandem with a county water truck, which is attached to a hitch on the front of the contractor's machine and is pushed along the road. The contractor brings another machine to spread the cement on the road. County personnel handle traffic control duties, along with grading, shaping and compaction of the processed material. This relationship enables the county to be more involved with the construction process and have better quality control.

Upon completion of construction of the reclaimed base stabilized with cement, county workers apply a fog seal to seal in the moisture and achieve curing over a seven-day period, during which only local traffic is allowed to pass on the completed reclaimed base layer. Heavy vehicles are prohibited. The surface layer for a low-volume traffic road is typically a ¾-inch thick stone chip layer treated with a triple shot of asphalt emulsion. For roads with higher-volume traffic, a layer of 1- to 3-inch thick crushed stone chips is used as a leveling course prior to placing a 2.5- to 3-inch thick HMA overlay.

Some core samples obtained from the projects that were constructed with the FDR with cement process were subjected to UCS tests. Those results are summarized below.

Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Montgomery Road Sherman Road to Highway 395 2005 10 ins. 370
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Wild Rose Road Austin Road to Monroe Road 2005 8 ins. 470
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Eloika Lake Road Division Road to US-2 2002 8 ins. 1,110
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Eloika Lake Road Division Road to US-2 2002 8 ins. 1,590

While the strength results are very good, it is important to remember that the pavement sections are relatively young. The big advantage of the FDR with cement process is that the addition of cement to the pulverized in-situ pavement materials permanently alters the chemical characteristics of the fines (portion smaller than #200 sieve). These altered fines have a significantly reduced affinity for attracting and holding water molecules. County officials are pleased that they do not have to shut down the roads due to freeze related heave. They believe that the FDR with cement process has helped them build "all-weather roads."

A.3.8 Stevens County, Washington

Figure 23. Williams Lake Road, Stevens County, Washington.

Owner:	Stevens County, Wash.
Type of Use:	Local and Collector Roads
Year Built:	1998
Limits:	State Highway 20 to State Highway 25
Thickness:	8.5 inches
Cement Content:	5% to7% by weight
ADT:	2,350
PCI:	95
Annual Rainfall:	21.9 inches
Annual Snowfall:	33.9 inches
Temperature:	18.6°F / 86.3°F
Subgrade Soils:	Sandy / clayey silt and clayey sand

The pavement evaluation of Williams Lake Road, in the northwest portion of Stevens County in Echo Valley, concluded that the road is in excellent condition. Although minor longitudinal cracks in the median were noticed, there was no evidence of potential problems with the pavement surface layer or the underlying reclaimed cement-stabilized base layer.

Stevens County is in the foothills of the Rocky Mountains, just south of the Canadian border. The area encompasses farmland in the southern half of the county and undeveloped forested land in the northern half. Several lakes are relatively close to the road. The subgrade soils generally consist of glacial drift deposits comprised of stratified and unstratified clay, silt, sand, gravel and boulder materials.

The County experiences extreme year-round weather conditions. The subgrade soils have significant silt-sized particles that are susceptible to heaving in freezing weather. The county engineer, Mr. Whitbread, reported that the heaving could be 12 inches or more. Trucks that would normally travel at 55 miles per hour had to reduce their speeds to 10 miles per hour on the pavement surfaces undergoing heaving. In warmer spring weather, water from melting ice would saturate the subgrades, leading to precipitous loss of stiffness. The pavement surface showed rutting, block cracking, raveling and other significant distresses. The county had closed these roads for weeks to overcome the subgrade freeze/thaw issues. Since the cost of reconstructing the roads with the conventional remove and replace techniques was expensive and time-consuming, the county decided in 1996 to use the FDR with cement process to rejuvenate its road network.

An inspection of the following roads revealed some longitudinal cracks on all of them. Transverse cracks were observed on Garden Spot Road, Artman-Gibson Road and Valley Westside-Oakshot Road. Overall, the pavement surfaces of these roads are in good to excellent condition.

Road:	Valley Westside-Oakshot Rd.
Limits:	Orin-Rice Rd. to Colville City Boundary
Year:	2002
Structure:	6-12 ins.
ADT:	550
PCI:	90
Road:	Artman-Gibson Rd.
Limits:	Old Arden Hwy to State Hwy 20
Year:	2003
Structure:	6-12 ins.
ADT:	557
PCI:	91
Road:	Williams Valley Rd.
Limits:	Swenson Rd. to Olson Rd.
Year:	1996
Structure:	9 ins.
ADT:	662
PCI:	95
Road:	Garden Spot Rd.
Limits:	State Hwy 395 to N. Short Rd.
Year:	1997
Structure:	9-12 ins.
ADT:	1,350
PCI:	89

The initial projects were designed using 5% to 7% cement by dry weight of roadway material mixed with the existing asphalt pavement surface and the underlying aggregate base and subgrade soils. The target 7-day UCS was 450 to 600 psi. Currently, the county uses less cement (4% to 5% by weight) with a target 7-day compressive strength of 400 psi. The county avoids blending subgrade soils with a plasticity index (PI) of over 35 in the reclaimed pavement layer. When subgrade soils with PI's that are too high are found, the County undercuts and removes them, and replaces them with quarry spoils, an approach it finds works well. Compaction requirements are 95% or better of the standard Proctor, with a minimum curing of five days. Although the road is open to local traffic, heavy trucks are not allowed on freshly constructed FDR with cement sections.

Prior to using FDR with cement, county roads experienced heaving of 12 inches or more during freezing weather, making it challenging for vehicles to drive on the road at even a fraction of the posted speed limit. The FDR with cement process has eliminated road heaving and has provided a durable road base. Further, the county roads are no longer closed during the spring thaw season, and remain open in all-weather conditions.

Core samples were taken on some of the roads to study the in-situ strength of the reclaimed bases. The summary in the table below shows the lowest UCS strength of 260 psi was available after ten years of extreme weather conditions. The remainder of the core samples had substantially higher UCS strengths.

Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Williams Lake Rd. State Hwy 20 to State Hwy 25 1998 10 ins. 590
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Valley Westside-Oakshot Rd. Orin-Rice Rd. to Colville City Boundary 2002 4.5 ins. 840
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Artman-Gibson Rd. Old Arden Hwy to State Hwy 20 2003 7 ins. 1,120
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Williams Valley Rd. Swenson Rd. to Olson Rd. 1996 9 ins. 260
Road: **Limits:** **Year:** **Thickness:** **UCS, psi**	Garden Spot Rd. State Hwy 395 to N. Short Rd. 1997 7 ins. 890

A.4 STATE DOTS

Many state departments of transportation now use the FDR with cement process to rehabilitate flexible pavements that cannot be resuscitated with an asphalt overlay. The ITD District 6, the SCDOT District IV, and TxDOT have all been using the FDR with cement technique for a significant length of time.

A.4.1 Idaho Transportation Department – District 6

Figure 24. US-20; Ashton, Idaho.

Owner:	District 6, ITD
Type of Use:	Freeway
Year Built:	1993
Limits:	South Ashton to Dumpground Road
Thickness:	6.5 inches
Cement Content:	2% by weight
ADT:	5,000
PCI:	87
Annual Rainfall:	20.1 inches
Annual Snowfall:	100.3 inches
Temperature:	4.5°F / 86.6°F
Subgrade Soils:	Clay and sand

US-20 is a major route that runs through District 6. The section of US-20 between South Ashton and Green Canyon Road was reconstructed in 1993 with the FDR with cement process. The reclaimed layer is 6.5 inches thick with a 3.7-inch thick HMA layer. While a visual inspection revealed some low-severity longitudinal cracking, the road is in very good condition. The back calculation of FWD data with the MODULUS 5.0 program indicated that the average resilient modulus of the reclaimed base after 13 years in extreme weather conditions was 55,515 psi.

Figure 25. Typical winter conditions experienced in ITD District 6, Idaho.

The PCI of some of the other roads that were visually inspected is summarized below.

Road: **County:** **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	US-20 Madison Dumpground Road to Wood Road 1996 9 ins. 2,810 90
Road: **County:** **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	SH-33 Madison Junction of US-20 to Teton 1997 7 ins. 2,310 91
Road: **County:** **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	US-20 Fremont Wood Road to Gren Canyon Road 1997 8 ins. 3,470 92
Road: **County:** **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	Yellowstone Highway Fremont MP 344.450 – MP 345.850 2003 9 ins. 2,170 92
Road: **County:** **Limits:** **Year:** **Structure:** **ADT:** **PCI:**	I-15B and US-20B Bonneville 19th Street to South Boulevard 1996 6 ins. 25,000 89

The ITD, just like most other state, county, and city highway departments, attempts to meet the burgeoning needs of the public with limited resources. Since most of the roads were constructed or rebuilt during the Interstate Era (30 to 40 years ago), they are past their service lives. However, there are no funds to completely rebuild them. District 6 of the ITD is located in the eastern and central part of Idaho with terrain ranging from high deserts to river valleys to forest-covered mountains. A high volume of out-of-state travelers heading towards Yellowstone or Teton National Parks passes through District 6. The temperatures range from over 100°F in the summer to -40°F in the winter. Rainfall is from 8 to 30 inches per year. All these factors combine to create harsh conditions for roads.

Over the years, engineers from District 6 have tried a myriad of rehabilitation techniques to extend the life of their roads. Many of these techniques performed well, while others posed problems. Part of the problem is that rehabilitation techniques are only effective if they are applied at the appropriate time, which does not necessarily coincide with when funds are available. Consequently, the rehabilitation measures were not lasting the full 12- to 20-year planned design life, exacerbating the maintenance and rehabilitation issues. The FDR with cement process was discovered through contacts within the Strategic Highway Research Program (SHRP). The Nevada DOT had a process called "roadbed modification" which had the potential of providing a long-term solution to the major problems experienced by District 6 of ITD.

The roadbed modification process required scarifying, pulverizing, mixing, and compacting a mixture of existing base and surface material with cement. The process ITD developed is named Cement Recycled Asphalt Base Stabilization (CRABS). The roadway is pulverized to the depth required by the plans. An important distinction is that ITD does not blend subgrades in the reclaimed layer. The depth of the pulverized material allowed to remain in place ranges from 6 to 9 inches.

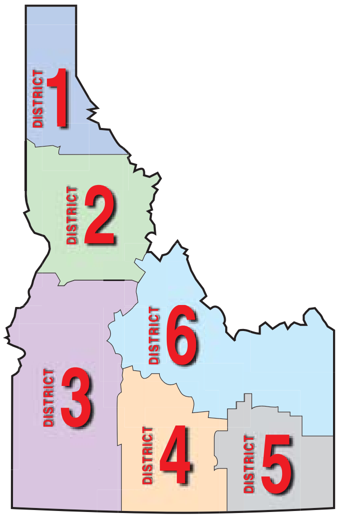


Figure 26. District 6, ITD, Idaho.

The gradation of the pulverized material is required to be 100% passing a 3-inch screen and 95% to 100% passing a 2-inch screen. If the material is required to be removed, it may be done by roto-milling before the initial pulverization, or by blading or otherwise removing after the initial pulverization. The initial pulverization is done with a large reclaimer/stabilizer, a large rototiller driven with a 500+ horsepower engine. The carbide teeth head cuts approximately 8 feet to 12 feet wide and up to 16 inches deep.

After the material is pulverized and partially removed if required, the remaining material is bladed and shaped according to the required typical section. The roadway could be opened to traffic at this point. Dry portland cement, Type I or II, is added at a rate of 2% by dry weight of processed material, both as a binder and to increase the strength of the processed material. Care is taken to not allow the cement spread rate to exceed 3% or fall below 2%. A truck capable of metering the material at the specified rate adds the cement, which is spread uniformly by some type of a spreader box able to make a uniform application, similar to a seal coat. The pulverized material is then mixed in place with a pugmill-type mixer, which adds water and does some additional pulverizing. Just enough water is added to reach optimum moisture content, which is maintained until the initial lift of new plant mix is placed. By specification, this is no more than 48 hours. The same equipment that performed the initial pulverization could perform this mixing process.

Final mixed material is bladed, shaped to the typical section, and compacted to density requirements. The rolling pattern is established by using in-place density from an uncorrected nuclear gauge. The required compaction is achieved and final process rolling is defined as when the final roller pass adds no more than 0.5 lb/ft^3 to the previous in-place density. Sufficient additional roller passes are made to determine that a "false break" or leveling-off point is not used for compaction density. The roller pattern is re-established when mixture properties in the processed material change, and at a minimum of every 7,200 square yards of finished surface.

On several of the original projects, a curing seal consisting of MC-250 asphalt was placed over the finished CRABS and covered with a blotter within 24 hours after the water was added. The curing seal was placed to create a film to retain the moisture until the initial lift of plant mix was placed. The initial lift of plant mix could be placed anytime after the curing seal. Current practice calls for moist-curing and placement of a tack coat of CSS-1 emulsified asphalt prior to placement of the HMA layer.

ITD District 6 enginners say the performance of the CRABS process has been extremely satisfactory, and for the last 13 years has provided them with a tool to extend the life of their pavements and improve the condition of their highway network. The engineers of ITD, District 6 are leaders in implementing the FDR with cement process, and are helping other city, county and state agencies to implement the technique.

A.4.2 South Carolina Department of Transportation

Figure 27. SC-97; York County, South Carolina.

Owner:	District 4, SC DOT
Type of Use:	Freeway
Year Built:	1995
Limits:	Chester County Line to Hickory Grove
Thickness:	9–12 inches
Cement Content:	6% by weight
ADT:	375
PCI:	82
Annual Rainfall:	47.9 inches
Annual Snowfall:	3.4 inches
Temperature:	29.3°F / 90.1°F
Subgrade Soils:	Clay and sand

For many years, South Carolina Route 97 in York County was a costly and frustrating maintenance problem for the SCDOT, often requiring a three-man crew for one full day per week.

The agency decided to reconstruct the road in 1995 with the FDR with cement process, after a detailed pavement evaluation that involved deflection measurements with the FWD, sampling of pavement materials, and laboratory testing. The existing pavement section, comprised of 6 inches of soil base and 3.8 inches of asphalt, was pulverized and blended with the underlying subgrade soils and 6% portland cement by dry weight of roadway material to produce a 9-inch thick reclaimed layer. In some localized areas, the reclaimed layer was up to 12 inches thick. A 4-inch thick HMA layer was placed on top of the reclaimed layer.

The visual inspection of the road found some low severity longitudinal and transverse cracks, which have been sealed. The overall pavement condition was good. The SCDOT engineers were pleased that the road that was formerly a perennial maintenance problem has stayed in good to excellent condition for more than ten years.

The following roads rehabilitated with the FDR with cement process were also visually inspected. As the summary in the adjacent column shows, the roads are in good to excellent condition.

Road:	SC 223
County:	Chester
Limits:	SC 901 to SC 9
Year:	2000
Structure:	6 ins.
ADT:	—
PCI:	92
Road:	S-46-162
County:	Chester/York
Limits:	Hall Spencer Rd, SC 901 to SC 21
Year:	1997
Structure:	6.2 ins.
ADT:	1,050
PCI:	91
Road:	S-998
County:	York
Limits:	Robertson Rd, Ogden Rd to E. Rambo Rd
Year:	1997
Structure:	7.7 ins.
ADT:	650
PCI:	92
Road:	S-46-101
County:	York
Limits:	Ogden Rd, SC 190 to Mobley Store Rd
Year:	1998
Structure:	6.4 ins.
ADT:	3,800
PCI:	87
Road:	S-46-102
County:	York
Limits:	Falls Rd, Odgen Rd to SC 322
Year:	1999
Structure:	6.9 ins.
ADT:	3,200
PCI:	86
Road:	SC 322
County:	York
Limits:	McConnells Hwy, SC 324 to Business 21
Year:	2002
Structure:	7.75 ins.
ADT:	5,000
PCI:	92

To obtain the optimum cement content, SCDOT used the minimum at which a mixture would provide a 7-day UCS of 500 psi for the cement-stabilized base. The compaction requirement for the FDR with cement projects is at 98% or better of the standard Proctor test (ASTM D 698). The curing requirements specify three days of moist-curing, followed by the placement of single treatment bituminous surfacing.

Light traffic (passenger vehicles) is allowed on the finished reclaimed layer immediately, while heavy traffic (vehicles withsix tires or more) is kept off the reclaimed layer.

District 4 SCDOT engineers are pleased with the long-term road performance, and feel that FDR with cement produces a stable pavement base layer at a fraction of the cost and time of conventional pavement reconstruction methods. The FDR with cement process is environmentally friendly and allows natural resources to be reused. Compared to untreated material, the uniform reclaimed base layer has improved strength and durability, improves the subgrade's resistance to water penetration, and distributes the traffic loads uniformly.

Core samples from some of the inspected roadways were subjected to UCS testing and seismic modulus determination. The seismic modulus and resilient modulus are parameters that characterize a material's stiffness. These tests were performed in cooperation with other research being conducted for PCA relative to new pavement design procedures, currently being implemented by AASHTO, that incorporate a Mechanistic-Empirical design process. A description of the seismic modulus test is included in Appendix E. The test results are summarized below.

Road:	SC 223
Limits:	SC 901 to SC 9
Year:	2000
Structure:	6 ins.
UCS, psi:	945
Seismic Modulus, ksi:	—
Resilient Modulus, ksi:	—
Road:	S-46-162
Limits:	Hall Spencer Rd, SC 901 to SC 21
Year:	2001
Structure:	6.2 ins.
UCS, psi:	1,185
Seismic Modulus, ksi:	839
Resilient Modulus, ksi:	629
Road:	S-998
Limits:	Robertson Rd, Ogden Rd to E, Rambo Rd
Year:	1997
Structure:	7.7 ins.
UCS, psi:	555
Seismic Modulus, ksi:	—
Resilient Modulus, ksi:	—
Road:	S-46-101
Limits:	Ogden Rd, SC 190 to Mobley Store Rd
Year:	1009
Structure:	6.4 ins.
UCS, psi:	1,239
Seismic Modulus, ksi:	2,025
Resilient Modulus, ksi:	1,519
Road:	S-46-102
Limits:	Falls Rd, Ogden Rd to SC 322
Year:	1999
Structure:	6.9 ins.
UCS, psi:	465
Seismic Modulus, ksi:	589
Resilient Modulus, ksi:	442
Road:	SC 322
Limits:	McConnells Hwy, SC 324 to Business 21
Year:	2002
Structure:	7,75 ins.
UCS, psi:	968
Seismic Modulus, ksi:	1,226
Resilient Modulus, ksi:	920

As is evident, the UCS values range from 465 psi to 1,239 psi, while the computed resilient modulus for the reclaimed base materials range from 442 ksi to 1,519 ksi.

A.4.3 Texas Department of Transportation – Bryan District

Figure 28. FM 3178; Leon County, Texas.

Owner:	Bryan District, Texas Department of Transportation
Type of Use:	Farm-to-Market Road
Year Built:	1996
Limits:	FM 1511 to FM 542
Thickness:	10.0 inches
Cement Content:	4% by weight
ADT:	—
PCI:	85
Annual Rainfall:	43.1 inches
Annual Snowfall:	0.9 inches
Temperature:	34.3°F / 95.0°F
Subgrade Soils:	Silty sandy clay

About 16 of the 24 districts of TxDOT use FDR with cement or other stabilizers to rehabilitate flexible pavements at the end of their service lives. The Bryan and Fort Worth districts have been the leaders in implementing this technique, and some of the earliest sections constructed by these districts in the early 1990's,were included in this study. The Bryan District was the leader in implementing the process to rehabilitate Farm-to-Market (FM) roads at the end of their service lives in the early 1990's. The prime objective was to upgrade the FM road system, which typically consists of 6 to 8 inches of unstabilized aggregate base and a two-course bituminous surface treatment directly over subgrade soils. In the late 1980's, these roads experienced significant pavement failures, making them structurally inadequate to carry increasing agricultural and oil field development traffic.

Leon County had two road sections, FM 3178 and FM 977, that were constructed with the FDR process with cement in 1996. The section of FM 3178 was a five-mile long stretch between FM 1511 and FM 542, while the section of FM 977 was from FM 3 to two miles east. The existing roadways were reconstructed with the FDR with cement process by pulverizing the existing asphalt and base (100% passing a 2.5-inch screen), and blending them with the underlying subgrade soils and 4% portland cement by dry weight of roadway material to produce a ten-inch thick reclaimed layer. A two-course bituminous surface treatment was placed on top of the reclaimed layer.

The visual inspection of FM 3178 indicated some low severity longitudinal and transverse cracks on the pavement surface which had been sealed, as well as low to medium severity edge cracking and corrugations at some locations. Some of the edge cracking could be due to heavy vehicles pulling off the road and cracking the pavement edge because of lack of support underneath the two-course surface treatment. Overall, the pavement is in good condition as indicated by an average PCI of 85.

Figure 29. FM 977; Leon County, Texas.

The section of FM 977 was two miles long between FM 3 and two miles east of the intersection of FM 977 and FM 3. This section was reconstructed in 1996 with 4% portland cement by dry weight of roadway material as the stabilizer. The reclaimed layer was 10 inches thick with a two-course bituminous surface treatment. The visual inspection indicated longitudinal and transverse cracking of low to medium severity. The cracks were sealed and the seal stayed in place without any further deterioration.

Road:	RM 977
Limits:	FM 3 to 2 miles East
Year:	1996
Structure:	10 ins.
PCI:	82

As part of its design procedure, the district samples potential FDR with cement projects at one-mile intervals to a depth of seven feet, logs the pavement structure, and performs subgrade soil characterization in the laboratory. The durability of the reclaimed mix is evaluated with the Tube Suction Test [refer to PCA *Guide to Full-Depth Reclamation (FDR) with Cement*]. The minimum amount of cement required to pass the durability test and a 7-day UCS greater than 300 psi is adopted as the design cement content. If the UCS is greater than 350 psi, alternatives such as microcracking or using a geogrid between the natural subgrade and the reclaimed layer is adopted. Compaction is specified at 95% and above of Tex-120-E (similar to modified Proctor, ASTM D 1557). Curing of the finished reclaimed base is specified for a minimum of three days, and light traffic is allowed immediately upon completion.

In the Bryan District, these sections have had good performance, with the exception of pavement on high PI (>35) subgrade soils.

A.4.4 Texas Department of Transportation – Fort Worth District

Figure 30. FM 51; Parker County, Texas.

Owner:	Fort Worth District, Texas Department of Transportation
Type of Use:	Farm-to-Market Road
Year Built:	1997
Limits:	FM 920 to Trinity River Bridge
Thickness:	9.0 inches
Cement Content:	3% by weight
ADT:	1,914,000 ESAL
PCI:	83
Annual Rainfall:	34.7 inches
Annual Snowfall:	2.0 inches
Temperature:	29.0°F / 95.2°F
Subgrade Soils:	Clayey and silty sand

The Fort Worth District started the FDR with cement process in 1997 when the section of FM 51, from FM 920 to the Trinity River Bridge in Parker County, Texas, was reconstructed. This involved pulverizing the existing pavement structure and blending it with subgrade soils and 3% portland cement by dry weight of roadway material to produce a nine-inch thick reclaimed base layer. A five-inch thick HMA surface layer was placed on top of the reclaimed base layer. The cement content was around 3% (based on achieving 250 psi UCS at 7 days), and the soils are generally sandy. The pavement design used an average subgrade modulus of 15,400 psi and a subgrade depth of 94 inches, based on back calculation of FWD data using the MODULUS 5.0 program. The pavement design was based on a HMA modulus of 500,000 psi and a cement-stabilized reclaimed base modulus of 80,000 psi. TxDOT based the design on a 20-year, 18 kip ESAL forecast of 1,914,000. The TxDOT FPS19 pavement design program indicated that a 2.5-inch overlay will be needed nine years after the road is opened to traffic. So far the pavement structure is performing well, with generally minor longitudinal and transverse cracking.

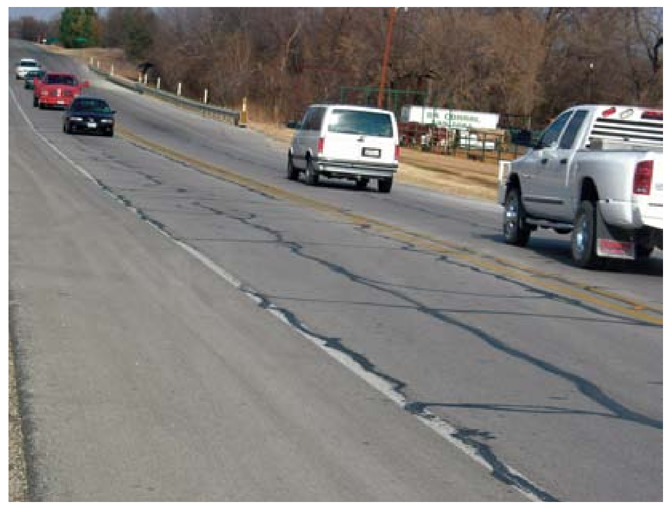


Figure 31. FM 1938; Tarrant County, Texas.

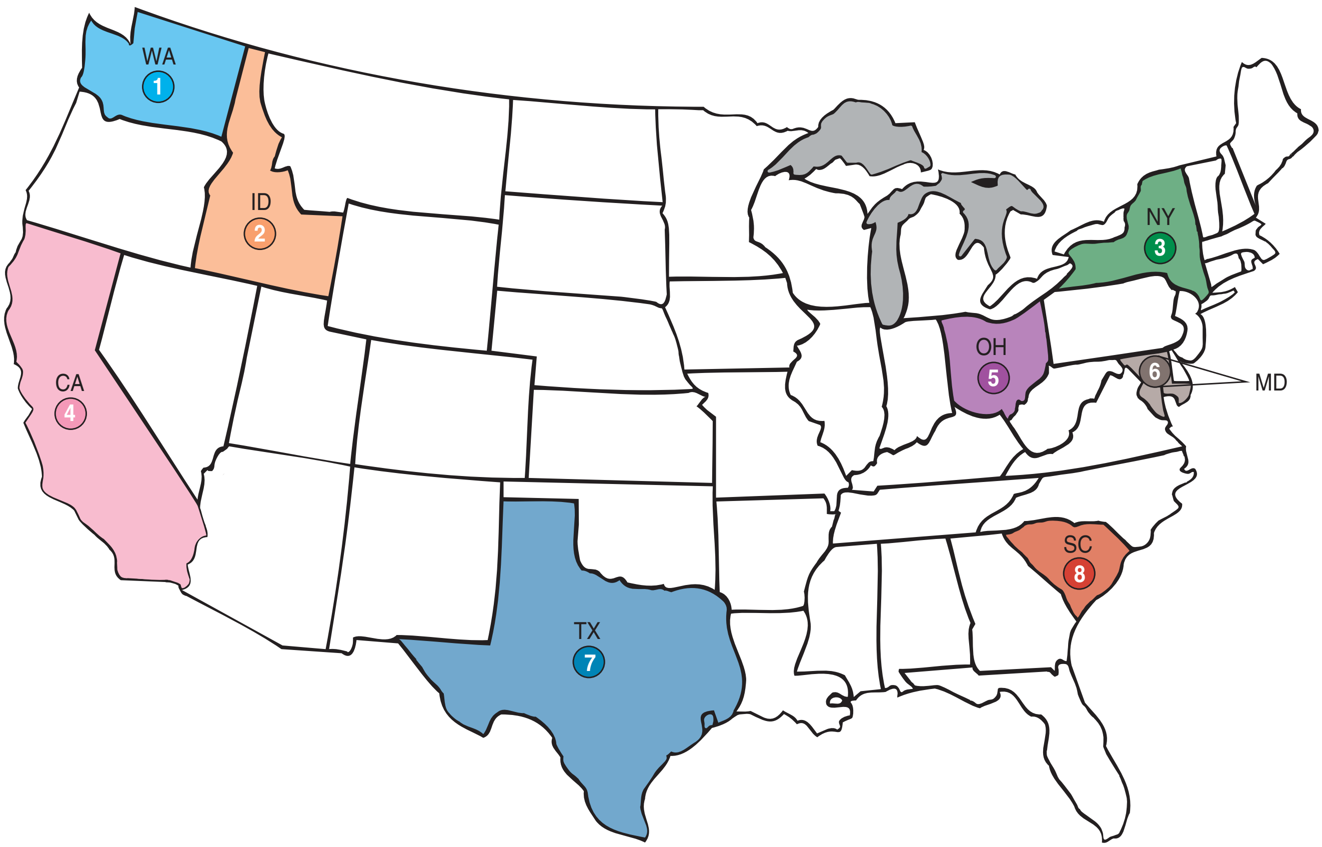
The segment of FM 1938 between Rumfield and Emerald Way in Tarrant County was reconstructed with the FDR with cement process in 1998. This involved pulverizing the existing pavement structure and blending portland cement and underlying subgrade soils to produce a reclaimed base of 10 inches thick. A 4-inch thick HMA overlay was then placed over the reclaimed base. The cement content was 3% (based on achieving a 250 psi UCS at 7 days).

The subgrade soils for this project were comprised of clay and sands. The pavement design used an average subgrade modulus of 21,600 psi and a subgrade depth of 202 inches, based on back calculation of FWD data using the MODULUS 5.0 program. The pavement design assumed a resilient modulus of 500,000 psi for the HMA layer and a resilient modulus of 80,000 psi for the cement-stabilized reclaimed base. TxDOT based the design on a 20 year, 18 kip ESAL forecast of 4,386,000. The TxDOT FPS19 pavement design program indicated that a two-inch thick overlay will be needed 10 years after the road is opened to traffic. The pavement structure is performing well, with generally minor longitudinal and transverse cracking.

Road:	FM 1938
County:	Tarrant
Limits:	Rumfield to Emerald Way
Year:	1998
Structure:	10 ins.
PCI:	87

The pulverization, mix design, compaction, and curing requirements are similar to that adopted by the Bryan District.

Appendix B
Project Location Map



Key to Map Numbers:

1 County Agencies, Washington
2 County Agencies, State DOTs, Idaho
3 County Agencies, New York
4 City Agencies, California
5 County Agencies, Ohio
6 Private Developers, County Agencies, Maryland
7 City Agencies, State DOTs, Texas
8 State DOTs, South Carolina

Appendix C
Review of Existing Literature

The Portland Cement Association (PCA) has published an excellent *"Guide to Full-Depth Reclamation (FDR) with Cement;"* authored by Luhr D. R., Adaska W. S., & Halsted G. E., EB234, ISBN 0-89312-247-5 (1). Additionally, the following documents were reviewed:

1. Texas DOT (TxDOT) research project 3903-S, 1998: *In-place Engineering Properties of Recycled and Stabilized Pavement Layers (2).*
2. TxDOT research project 4182-S, 2003: *Field Performance and Design Recommendations for Full Depth Recycling in Texas (3).*
3. Cement Council of Texas: *Twelve Years and Counting: Recycled Streets Still Going Strong in Stephenville (4).*
4. PCA: *County Highway in Franklin County, Alabama (5).*
5. PCA: *Spokane County Builds All-Weather Roads Using FDR with Cement (6).*

C.1 Synopsis of TxDOT Research Studies

TxDOT districts started using FDR techniques to rehabilitate their roads in the early 1990's. The candidate project sections were roads that required repeated maintenance involving deep cold mix patches just to obtain acceptable ride quality. Many of these road sections exhibited signs of base failures and had lost their crown, creating drainage issues with storm-water runoffs and creating safety problems for drivers. Most of the projects were in rural areas with significant agricultural and oil truck traffic. The primary concern on these roads was to prevent shear failure in the reclaimed base due to individual heavy wheel loads, rather than fatigue cracking caused due to repeated wheel loads. Portland cement was used as the stabilizer. Typically, TxDOT used cement as a stabilizer on the FDR projects where the soil (binder) within the reclaimed base had a plasticity index (PI) of less than 10 (now allowed with PI up to 35). Laboratory testing comprised of index tests, Texas Triaxial tests, 7-day unconfined compressive strengths (UCS) between 150 and 350 psi, and Tube Suction Tests (TST) were used to study the durability of the reclaimed mix. The procedure and interpretation of the TST results are detailed in *"Research & Development Bulletin RD 120 (ISBN 0-89312-236-X), Evaluating the Performance of Soil-Cement and Cement-Modified Soil for Pavements: A Laboratory Investigation, 2005" (7).*

While the construction techniques are similar, the curing process varies. Some districts prohibit vehicular traffic until the curing process reduces the in-situ water content to below 80% of the optimum moisture content, while others require 72 hours of curing prior to opening the section to traffic. The Bryan and Corpus Christi Districts usually open unsurfaced, reclaimed roads to traffic at the end of the day because of a lack of adequate detour routes. Most districts require a minimum 24 hours of curing before allowing vehicular traffic. The Corpus Christi District specifies up to 96 hours of curing, with the caveat that surface treatments should be placed on all finished sections at the end of each workweek. Compaction requirements vary from 95% to 98% of Tex-113-E or ASTM D 698 (standard Proctor). The recent revisions to construction specifications require 95% or better of laboratory-obtained density values as per Tex-120-E (similar to modified Proctor, ASTM D 1557).

Figure 32. FM 51 – from FM 920 to Trinity River Bridge; Parker County, Texas.

The majority of the pavements constructed with the FDR with cement technique are doing well. Typically, districts assume a life expectancy of approximately 10 years from FDR pavements. The districts' have had positive experiences with the FDR with cement technique, which has provided them with good pavement performance by restoring the original structural capacity of the roadway. The process is environmentally friendly, as it reduces waste material in addition to reducing costs for material and hauling. Problems related to longitudinal and transverse cracking are encountered in some pavement sections. Some of these problems are attributed to movement of subgrades with shrink/swell characteristics. Consequently, some districts restrict the use of clay material in the reclaimed base.

The new guidelines recommend FDR as a promising rehabilitation option, if:

- The subgrades are weak and the intent is for the reclaimed base to add to the structure over those weak subgrades.
- Road strengthening is required to handle heavy wheel loads.
- Locally available base material is of low and variable quality.
- The candidate project section is located in a high rainfall area.
- Logistics require early opening to traffic.

The recommendations for desirable material properties of the mixture after 7-days of moist curing are:

- UCS of 300 psi or better.
- Surface dielectric value of less than 10 in the TST.
- Upon completion of the TST, the sample should retain 85% or better of the UCS compared to the sample that was not subjected to TST.
- TxDOT's Flexible Pavement System Design Program (FPS 19) recommends moduli of 200 ksi for reclaimed bases constructed with the FDR method and conforming to the above mixture design properties.

Finally, for new FDR projects, the following is recommended:

- Avoid cutting into the existing subgrades.
- Add new base materials where required.
- Use geogrids and granular base material over the reclaimed base layer where subgrade soils exhibit a PI in excess of 35.
- Should the 7-day UCS be greater than 350 psi, then micro-cracking of the reclaimed base is recommended.

C.2 Synopsis of PCA Publications

The PCA publications are essentially success stories of the FDR process in Stephenville, Texas; Franklin County, Alabama; and Spokane County, Washington, whose agencies constantly face failing roads and shrinking repair and maintenance budgets. Repeated maintenance efforts using full depth patches were unsuccessful in preventing further pavement deterioration, making reconstruction the only rehabilitation option. Since reconstruction with conventional methods was cost prohibitive, the agencies decided to try reconstruction with the FDR with cement technique, whose costs were between 35% and 60% of conventional reconstruction cost. One of the advantages is that over the years, the cost of FDR with cement has not risen as dramatically as the cost of conventional road reconstruction processes. The inconvenience to drivers is also significantly lower in the FDR with cement process compared to conventional road reconstruction methods.

Appendix D
References

1. Luhr D. R.; Adaska W. S.; and Halsted G. E., *"Guide to Full-Depth Reclamation (FDR) with Cement,"* EB234, ISBN 0-89312-247-5, PCA Publications, Skokie, IL, 2005.

2. Syed, I., and Scullion, T., *"In-Place Engineering Properties of Recycled and Stabilized Pavement Layers,"* Report TX-00/3903-S, Texas Transportation Institute, Texas A&M University, College Station, TX, 1998.

3. Scullion, T.; Guthrie, S.; and Sebesta, S., *"Field Performance and Design Recommendations for Full Depth Recycling in Texas,"* FHWA/TX-03/4182-1, Texas Transportation Institute, Texas A&M University, College Station, TX, 2003.

4. PCA, Publication, *"Twelve Years and Counting: Recycled Streets Still Going Strong in Stephenville,"* PCA Publications, Skokie, IL, 2005.

5. PCA, Publication, *"County Highway in Franklin County, Alabama,"* PCA Publications, Skokie, IL, 2005.

6. PCA, Publication, *"Spokane County Builds All-Weather Roads Using FDR with Cement,"* PCA Publications, Skokie, IL, 2005.

7. PCA, Publication, *"Evaluating the Performance of Soil-Cement and Cement-Modified Soil for Pavements: A Laboratory Investigation,"* Research & Development Bulletin RD120 (ISBN 0-89312-236-X), PCA Publications, Skokie, IL, 2005.

8. Esser, G.; Chylik, T.; Pesho, R.; Ganesan, V.; and Little, D. N., *"Assessment of In Situ Quality and Durability of Cement and Lime Stabilized Subgrade Soils in Northern Ohio, USA,"* Presented at Transportation Research Board Meeting, Washington, DC, 2006.

9. PCA, Publication, *"Soil Cement Construction Handbook,"* Engineering Bulletin, PCA Publications, Skokie, IL, 1995.

10. PCA, Publication, *"Soil Cement Laboratory Handbook,"* PCA Publications, Skokie, IL, 1971.

11. Scullion, T., Texas Transportation Institute, Private Communication, 2006.

12. Cole, T., Idaho Transportation Department, Private Communication, 2006.

13. Whitbread, J., Stevens County Department of Public Works, Private Communication, 2006.

14. Hamby, H., Spokane County Department of Public Works, Private Communication, 2006.

Appendix E
Seismic Testing

Details provided by Texas Transportation Institute

Seismic Modulus

The seismic modulus was measured using the free-free resonant column method developed at the University of Texas at El Paso. As shown in Figure E1, a cylindrical specimen is placed on its side on a sheet of insulation foam in the laboratory, and an energy source — a light tap from a hammer equipped with a load cell — is given that measures the energy input and triggers a timing circuit. An accelerometer mounted to the other end of the sample reports the time of P-wave arrival. A computer displays the measured wave response shape, which is used to determine the quality of the test data. The computer screen is shown in Figure E2. It is very easy to get the resonant frequency from the small window on the left side of the screen. The seismic modulus can be calculated from measured P-wave velocities and the known density of the material according to the following Equation 1:

$$E = \rho \cdot V_P^2 \qquad (1)$$

where:

E = seismic modulus (MPa);

ρ = density (kg/m^3);

V_ρ = P-wave velocity (m/s).

The equation for calculating P-wave velocity from the P-wave frequency measured with the seismic resonant column is below:

$$V_\rho = F \cdot 2 \cdot L \qquad (2)$$

where:

F = P-wave frequency (Hz);

L = Length of the specimen (m).

Figure E1. Seismic modulus testing.

The seismic test takes less than three minutes to complete. In Figure E2, the screen shows the typical seismic modulus test result. The initial peak marked with a (+) signifies the frequency of the P-wave as it passes through the sample.

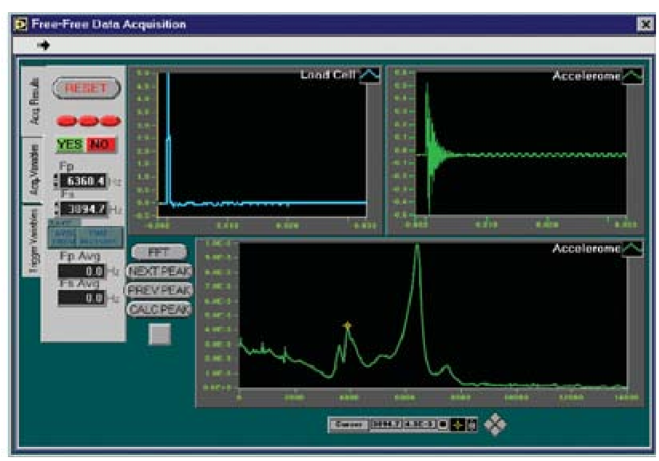


Figure E2. Typical seismic test result screen.

Appendix F
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