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16. ABSTRACT

The California Department of Transportation (Caltrans) has been using full-depth reclamation (FDR) as a rehabilitation strategy since 2001. Most projects to date have used a combination of foamed asphalt and portland cement as the stabilizing agent. Recently, the increasing cost of asphalt binder coupled with the relatively complex mix-design procedure for foamed asphalt has generated interest in the use of portland cement alone as an alternative stabilizing agent, where appropriate. However, shrinkage cracking associated with the hydration and curing of the cement-stabilized layers remains a concern, especially with regard to crack reflection through asphalt concrete surfacings and the related problems caused by water ingress.

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Pavement Recycling: Literature Review on Shrinkage Crack Mitigation in Cement-Stabilized Pavement Layers

Authors:
S. Louw and D. Jones

Partnered Pavement Research Center (PPRC) Project Number 4.52a (DRISI Task 2708):
Microcracking of Cement-Stabilized Pavement Layers

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation and System Information

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

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Caltrans Technical Lead: D. Maskey			
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Abstract:
The California Department of Transportation (Caltrans) has been using full-depth reclamation (FDR) as a rehabilitation strategy since 2001. Most projects to date have used a combination of foamed asphalt and portland cement as the stabilizing agent. Recently, the increasing cost of asphalt binder coupled with the relatively complex mix-design procedure for foamed asphalt has generated interest in the use of portland cement alone as an alternative stabilizing agent, where appropriate. However, shrinkage cracking associated with the hydration and curing of the cement-stabilized layers remains a concern, especially with regard to crack reflection through asphalt concrete surfacings and the related problems caused by water ingress.

Considerable research has been undertaken on crack mitigation, and a range of measures related to improved mix designs and construction practices have been implemented by road agencies. One of the most promising measures, used in conjunction with appropriate mix designs, is that of microcracking the cement-treated layer between 24 and 72 hours after construction. In theory, this action creates a fine network of cracks in the layer that limit or prevent the wider and more severe block cracks typical of cement-treated layers. Limited research to assess microcracking as a crack mitigation measure has been completed on a number of projects in Texas, Utah, and New Hampshire. Recommendations from these studies have been implemented by the Texas Department of Transportation and other state departments of transportation. Longer-term monitoring on a range of projects in Texas and other states has revealed that microcracking has not always been successful in preventing cracking, with some projects showing reflected transverse and block cracks in a relatively short time period, attributed to a number of factors including but not limited to cement spreading, method of curing, and interval between base construction and placement of surfacing.

Discussions with researchers in Texas indicated that additional research is necessary to better understand the microcracking mechanism, and to identify the key factors influencing performance, including but not limited to aggregate properties, cement content, the time period before microcracking starts, layer moisture contents, roller weights and vibration settings, the number of roller passes, the field test methods and criteria to assess the degree of microcracking, and the effects of early opening to traffic. Early research into the use of "hybrid" stabilizers (cement with small amounts of asphalt emulsion, foamed asphalt, or synthetic polymer emulsions) indicates that these, in conjunction with appropriate mix designs, may further limit the severity of shrinkage cracks on projects that include cement-treated layers.

Keywords:
Full-depth reclamation; cement stabilization, crack mitigation, microcracking

Proposals for implementation:
None

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Signatures:

S. Louw	J.T. Harvey	D. Spinner	J.T. Harvey	D. Maskey	T.J. Holland
1st Author	**Technical Review**	**Editor**	**Principal Investigator**	**Caltrans Technical Lead**	**Caltrans Contract Manager**

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PROJECT OBJECTIVES

This study is a continuation of PPRC Project 4.36 ("Guidelines for Full-Depth Reclamation of Pavements") and addresses the project titled "Microcracking of Cement-Stabilized Layers." The objective of this project is to develop guidelines for mitigation measures to limit/prevent shrinkage cracking in cement-stabilized layers. This will be achieved in two phases through the following tasks:

- Phase 1: Literature review, laboratory testing, and modeling.
  - 1.1 A literature review on research related to crack mitigation in cement-treated materials
  - 1.2 Preliminary laboratory testing to understand crack mitigation mechanisms and identify criteria for modeling the effects of crack mitigation on long-term pavement performance
  - 1.3 Modeling of the effects of crack mitigation on long-term pavement performance
  - 1.4 A summary report with recommendations for Phase 2 testing if appropriate
- Phase 2: Accelerated pavement testing and field testing (depending on the results of Phase 1 and under the direction of the Caltrans project steering committee)
  - 2.1 Monitoring of field projects where crack mitigation measures have been used on cement-treated layers
  - 2.2 Design and construction of a test track to compare different crack mitigation techniques
  - 2.3 Accelerated pavement testing to compare performance of the different crack mitigation techniques
  - 2.4 Laboratory testing of specimens sampled from the test track and from field projects to compare laboratory test results with accelerated pavement test results and to identify suitable criteria for refining mechanistic-empirical design procedures and performance models for pavements with cement-treated layers

2.5 Preparation of a project research report and guidelines for crack mitigation in cement-treated layers

The technical memorandum covers Task 1.1.

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CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003)

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1. INTRODUCTION

1.1 Background

The California Department of Transportation (Caltrans) has been using full-depth reclamation (FDR) as a rehabilitation strategy since 2001. Most projects to date have used a combination of foamed asphalt and portland cement as the stabilizing agent. However, the increasing cost of asphalt binder coupled with the relatively complex mix-design procedure for foamed asphalt has generated interest in the use of portland cement alone as an alternative stabilizing agent, where appropriate.

Cement-treated (or stabilized) materials are mixtures of soil, aggregate, and/or reclaimed asphalt pavement materials, together with measured amounts of portland cement and water, that are shaped and compacted to form sub-base or base layers in pavement structures. In situ subgrade soils can also be treated to improve the properties of the pavement foundation. Cement-treated bases (CTBs) have been widely used as pavement bases for highways, roads, streets, parking areas, airports, and materials-handling and storage areas. Because CTBs typically have better bearing capacity and durability than bases constructed with unstabilized materials they allow for thinner and usually more cost-effective pavement structures. They have been widely used in the past in California, nationally, and internationally, and considerable research has been undertaken and experience gained on their design, construction, and long-term performance. This Technical Memorandum does not document this research.

A well-documented concern about cement-treated bases is the shrinkage cracking associated with the hydration and curing of the stabilized layers. Observations of this cracking date back to ancient Roman times, when horsehair was added to concrete roadways and the structural members in buildings in an attempt to reduce the risk of cracking while the concrete set *(1)*. As hydration and curing progress, the drying shrinkage of concrete and cement-treated materials is known to contribute the most to shrinkage cracking *(2,3)*. In pavements, shrinkage cracks from underlying cement-treated bases can reflect through the asphalt concrete surfacing, allowing water to infiltrate into the base. This water leads to a loss in stiffness in the base layer and results in a faster rate of deterioration compared to pavements that are not cracked.

Although no costs for shrinkage crack repair are readily available for California highways, the Texas Department of Transportation estimated savings of between $3.3 million and $8.6 million in annual net present value maintenance costs if shrinkage cracking could be prevented on projects where CTB layers are placed *(4)*.

A variety of crack mitigation approaches have been investigated in recent years, including but not necessarily limited to these:

- Optimizing pavement designs with specific focus on cement content and design strengths. Caltrans specifies a relatively low design strength envelope for full-depth reclamation projects (unconfined compressive strength of between 300 and 600 psi [≈ 2 and 4 MPa] after an accelerated 7-day cure).
- Improved construction procedures with specific focus on curing and the use of microcracking treated layers to alter shrinkage crack development

Limited research has been undertaken on the influence of using of small quantities of asphalt emulsion or foamed asphalt in combination with the cement to alter the hydration process and resulting shrinkage.

Microcracking is a technique originally developed in Austria to limit the amount of shrinkage cracking on cement-stabilized layers. The process entails driving a vibrating steel drum roller over the layer between 50 and 70 hours after construction of the layer. In theory, this action creates a fine network of cracks in the layer that limits or prevents the wider and more severe block cracks typical of cement-treated layers. Limited testing has been completed on a number of projects in Texas, Utah, and New Hampshire. Recommendations from these studies have been implemented by Caltrans and other state departments of transportation. Longer-term monitoring on a range of projects in Texas and other states has revealed that microcracking has not always been successful in preventing cracking, with some projects showing reflected transverse and block cracks in a relatively short time period. Discussions with the Texas researchers indicated that additional research is necessary to better understand the microcracking mechanism, and to identify the key factors that influence performance, including but not limited to aggregate properties, cement content, the time period before microcracking starts, layer moisture contents, curing procedures, roller weights and vibration settings, the number of roller passes, and the field test methods and criteria to assess the degree of microcracking.

1.2 Related Studies

During the period covered by the 2011–2014 PPRC contract (for Project 4.36), a test track was constructed to assess four different FDR strategies (with no stabilization [FDR-NS], using foamed asphalt with cement [FDR-FA-C], using engineered asphalt emulsion [FDR-EE], and using portland cement [FDR-PC]). An additional microcracking experiment was included in the test track design, but problems with the control of the cement application on the day of construction prevented any testing on this lane and limited any further research at the time. A 0.2 ft. (60 mm) asphalt concrete surfacing was placed on all the reclaimed layers. Accelerated pavement testing in the dry condition was carried out on the four lanes. Limited laboratory testing on cores sampled from the test track was also undertaken. The FDR-PC section designated for accelerated pavement testing was not microcracked and some shrinkage cracking was observed on the base approximately 15 days after construction and through the asphalt concrete surfacing approximately six months after construction. No reflection cracking was observed in the asphalt on the test section after more than one million load repetitions; however, deflection tests indicated considerable loss of stiffness in the structure during the testing period (i.e., from ±20 GPa to ±13 GPa), which was attributed to shrinkage cracking in the base and to breakdown of the cemented bonds during trafficking. Extended accelerated pavement testing may have led to the cracks reflecting through the asphalt concrete surface.

1.3 Problem Statement

Microcracking is a promising technique for limiting or preventing shrinkage cracking in cement-stabilized layers that could reflect through the asphalt concrete surfacing. However, insufficient research has been conducted to fully understand the mechanism, to develop procedures for microcracking (i.e., time interval between construction and microcracking, vibration settings, the number of microcracking cycles, etc.), and to identify suitable criteria for mechanistic-empirical design procedures and performance models of pavement structures that incorporate a microcracked cement-stabilized layer (which could theoretically have a different mechanistic behavioral life cycle than structures with cement-stabilized layers that have not been microcracked). Caltrans specifications currently require microcracking on full-depth reclaimed cement-stabilized layers, but the instructions state only that:

> "During the period from 48 to 72 hours after compaction, microcrack the surface by applying 3 passes of the vibratory steel drum rollers used during final compaction at high amplitude, regardless of whether asphaltic emulsion has been applied."

No additional information is provided and no tests are required to determine whether microcracking was effective in reducing initial stiffness. The results of using this specification have not been evaluated.

The following problem statements have been determined with regard to microcracking and require additional research or refinement/calibration for California conditions:

- No comprehensive guidelines exist to guide design engineers, contractors, and project specification writers on how to decide on the optimal microcracking procedure for a specific layer design and how to determine whether the desired result has been achieved.
- The research completed in Texas was limited to a small number of projects with a limited range of materials and cement contents. Subsequent observations have found that cement content can have a significant influence on the effectiveness of microcracking. Additional research is required to determine key factors influencing the effectiveness of microcracking. These may include but are not limited to the following:
  + Adjusting the time interval between the end of construction and the start of microcracking
  + Selecting a specific weight of roller

  + Selecting specific vibration settings
  + Selecting multiple microcracking actions
  + Setting required specific changes in measured stiffness after microcracking
- There is no established procedure for accurately measuring the effectiveness of microcracking actions. Currently, a percentage change in stiffness measured with a falling weight deflectometer, light weight deflectometer, or soil stiffness gauge is recommended. Implementable guidelines based on actual field performance need to be prepared for this activity. Consideration needs to be given to whether the load applied during falling weight deflectometer testing causes additional microcracking in the drop zone, thereby influencing conclusions regarding the level of stiffness change that has been achieved.
- There is no procedure for simulating microcracking in the laboratory as part of a mix design/pavement design process. Such a procedure needs to be developed.
- There is no documented research linking microcracking with layer curing, opening to traffic, and to the period between construction and paving.
- There is no documented research investigating the use of other additives, such as small quantities of asphalt emulsion, foamed asphalt, or synthetic polymer emulsion to enhance crack mitigation when using microcracking.
- There is limited documented research on using alternative strategies to reduce shrinkage cracking, including the use of fibers or retarders to slow the rate of hydration.

1.4 Project Objective/Goal

This study is a continuation of PPRC Project 4.36 ("Guidelines for Full-Depth Reclamation of Pavements") and addresses the project titled "Microcracking of Cement-Stabilized Layers." The objective of this project is to develop guidelines for mitigation measures to limit/prevent shrinkage cracking in cement-stabilized layers. It is envisaged that this will be achieved in two phases through the following tasks:

- Phase 1: Literature review, laboratory testing, and modeling.
  - 1.1 A literature review on research related to crack mitigation in cement-treated materials.
  - 1.2 Preliminary laboratory testing to understand crack mitigation mechanisms and identify criteria for modeling the effects of crack mitigation on long-term pavement performance.
  - 1.3 Modeling of the effects of crack mitigation on long-term pavement performance.
  - 1.4 A summary report with recommendations for Phase 2 testing if appropriate.
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  - 2.1 Monitoring of field projects where crack mitigation measures have been used on cement-treated layers.
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  - 2.3 Accelerated pavement testing to compare performance of the different crack mitigation techniques.

2.4 Laboratory testing of specimens sampled from the test track and from field projects to compare laboratory test results with accelerated pavement test results and to identify suitable criteria for refining mechanistic-empirical design procedures and performance models for pavements with cement-treated layers.

2.5 Preparation of a project research report and guidelines for crack mitigation in cement-treated layers.

This technical memorandum covers Task 1.1.

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2. LITERATURE REVIEW

2.1 Flexible Pavement Distresses Related to Base Failure

Cement-treated base (CTB) failures typically cause one or a combination of distresses on the surface of flexible pavements, including transverse cracking, longitudinal cracking, block cracking, fatigue cracking and/or rutting. The cause of these distresses can be load related, non-load related (e.g., environmental effects such as temperature, moisture, and/or freeze-thaw), or a combination of the two. This UCPRC study only discusses cracks associated with cement-treated base behavior, although the authors acknowledge that distresses in asphalt concrete surfacings can also be caused by factors other than base failure.

2.1.1 Transverse and Longitudinal Cracking

Transverse cracks in asphalt pavements over CTB (Figure 2.1) may be caused by the shrinkage associated with hydration and drying in the CTB after construction *(3,5,6)*. Shrinkage cracking in CTBs begins soon after completion of compaction as hydration reactions begin and the layer dries back. The rate of reflection of these cracks through the asphalt concrete layer is typically dependent on the thickness of that asphalt layer and the cement content of the base (higher cement contents typically result in wider cracks with higher associated stress fields).

Figure 2.1: Transverse crack.

Zube et al. *(7)* reported that cracking is prominent in CTB with high unconfined compressive strengths (UCS). This is caused by the higher cement content requiring more water for hydration, which leads to higher drying shrinkage and in turn causes more cracking than in pavements with lower cement contents *(3,7)*. The restraints from friction between the base and the subbase or subgrade, and between the base and the asphalt surface layer cause tensile stresses in the material around the crack to exceed the tensile strength of that material, resulting in transverse cracks that reflect through to the surface *(2)*. The rate of crack reflection is again dependent on the cement content in the treated layer and to the asphalt layer thickness. The rate of reflection can also be influenced by the integrity of the bond between the base and the surface, with poor bonding leading to a faster rate of cracking in the asphalt layer *(2)*.

A survey conducted by Wen *(8)* as part of a National Cooperative Highway Research Program (NCHRP) study revealed that transverse cracking and block cracking were considered to be the most severe distresses associated with CTB.

Longitudinal cracking in flexible pavements with CTB (Figure 2.2) have also been recorded *(9,10)*. This distress, usually in the wheelpaths, is caused by the high shear/tension stress at the surface of the asphalt caused by high wheel loads and/or tire pressures *(8)*. Longitudinal cracking outside the wheelpath is more commonly caused by expansive soils and construction effects *(5)*.

Figure 2.2: Longitudinal crack.

2.1.2 Block Cracking

Block cracking (Figure 2.3) in asphalt concrete surfaces can also be attributed to shrinkage cracks in the CTB that have reflected through the asphalt over time. They are caused by cement hydration and to thermal expansion and contraction in the cement treated base, leading to a series of longitudinal and transverse cracks that eventually join to form a series of blocks in the base that eventually reflect through the asphalt concrete surfacing (Figure 2.4) *(11)*. Although block cracks will occur in both trafficked and untrafficked areas of the pavement, their formation is not necessarily dependent on traffic loading.

Figure 2.3: Block cracking. **Figure 2.4: Block crack progression.**

2.1.3 Fatigue Cracking

Fatigue cracking in asphalt surface layers over CTB (Figure 2.5) can result from the formation of weak areas at the top of the treated layer, caused by carbonation of the cement, laminations, or overcompaction, which in turn can lead to fatigue and compression failures. These weak areas can lead to delamination in the CTB or debonding between the top of the CTB and the bottom of the asphalt layer creating conditions of minimum friction between the different layers *(12)*. The laminations and loss of friction are susceptible to erosion and loss of fines by pumping (Figure 2.6). The strain levels at the bottom of the asphalt surface layer increase as the surface of the base weakens, leading to the fatigue failure.

Figure 2.5: Fatigue cracking. **Figure 2.6: Pumping through fatigue cracking.**

2.1.4 Rutting

Rutting in well-constructed CTB layers is rare given the relatively high strengths and stiffnesses. However, on pavements with severe cracking that allows water to infiltrate into the base, rutting often occurs as a result of deformation of the softer base materials under traffic loading (Figure 2.7).

Figure 2.7: Rutting caused by water ingress through cracks into the base.

2.2 Shrinkage Crack Mitigation

Shrinkage cracks in CTB layers can be mitigated through a number of different approaches. Most research has focused on design, in terms of optimizing cement content and layer thicknesses, and on construction, in terms of better mixing, curing, and quality control. Limited research has been undertaken on precracking or microcracking the layer to alter its cracking behavior and thereby reduce the severity of the shrinkage cracks, or on other mitigation measures such as adding asphalt emulsion, foamed asphalt, or synthetic polymer emulsions to the mixing water to alter the hydration reaction of the cement.

2.2.1 Design and Construction Considerations

The Portland Cement Association (PCA) *(13)* has advocated for the use of seven-day unconfined compressive strength values that are lower than those traditionally sought in the past. A range of strengths between a minimum of 300 psi (2.1 MPa) and a maximum of 400 psi (2.8 MPa) are now recommended. These strengths are considerably lower than the previously recommended strength range of 600 psi to 750 psi (4.2 MPa to 5.2 MPa). The Texas Department of Transportation (TxDOT) has reduced cement contents even further in some districts, moving away from previously specified minimum seven-day strengths of 500 psi (3.5 MPa) to seven-day strength ranges of between 200 psi and 300 psi (1.4 MPa to 2.1 MPa) in an attempt to better mitigate shrinkage crack problems that they are experiencing *(11)*. This reduction was based on UCS tests done on cores sampled from treated roads, which revealed that seven-day laboratory-determined strengths of 500 psi typically translated to strengths in excess of 1,500 psi (3.4 MPa) in the road. The high cement contents required to achieve these strengths results in a layer susceptible to very high shrinkage and to cracking associated with the brittle nature of the compacted material.

The 2010 (and provisional 2015) Caltrans Standard Specifications for cement-treated bases (Section 27) specify a minimum seven-day UCS of 750 psi (5.2 MPa). The minimum specified seven-day UCS for full-depth reclamation with cement (Section 30.4) will depend on the project requirements, but will typically be set to a minimum 7-day strength (with modified curing as specified in Section 30.4) of 300 psi (2.1 MPa) and a maximum of 600 psi (4.1 MPa). Caltrans does not have a durability requirement for cement-treated layers.

The PCA is also recommending that thicker layers up to 12 in. (300 mm) be constructed at these lower strengths to create a quality base with a balanced design that can support design loads and be sufficiently durable and impermeable in order to resist volume changes, the effects of freeze-thaw cycles, and the effects of moisture changes. Thinner layers (i.e., 6 in. to 8 in. [150 mm to 200 mm]) tend to be more brittle and susceptible to more severe shrinkage cracking. Recent developments in pulverizing equipment have made it possible to achieve consistent in-place mixing to these recommended depths. Other construction considerations to limit the severity of shrinkage cracking include using these *(3)*:

- The lowest possible moisture content needed to compact the layer that will still achieve the target strength and density
- Appropriate techniques to slow the rate of curing of the layer. Techniques include maintaining constant moisture content in the layer with regular water spraying (avoiding wetting and drying cycles), using a curing membrane, and/or applying the surfacing layer as soon as the target moisture content has been achieved.
- Stress relief layers to decrease the potential for shrinkage cracks to reflect through the surface layer. Interlayers include a bituminous surface treatment, geofabrics or geogrids, or a granular layer between the asphalt concrete surface and the cement-treated base.

2.2.2 Microcracking

The process of microcracking cement-treated layers involves applying several passes of a steel drum vibratory roller, at maximum vibration frequency and amplitude settings, over the CTB within a set time window after construction of the treated layer. The theory of microcracking is that the action creates a fine network of cracks in the treated layer that will relieve initial stresses during early hydration of the cement, and thereby limit or prevent the wider and more severe block cracks typical of cement-treated layers. The use of microcracking was first reported in Austria in the mid-1990s *(14,15)*.

Despite fairly wide use of microcracking, including in California, there appears to be very little documented research on the process, when and how to do it, and how it affects the short- medium-, and long-term behavior and performance of the treated layer. Caltrans specifications (Section 30) simply specify microcracking on full-depth reclaimed cement-treated layers as follows (there is no microcracking requirement in Section 27 [Cement Treated Bases]):

> "During the period from 48 to 72 hours after compaction, microcrack the surface by applying 3 single passes with a 12-ton vibratory steel drum roller at maximum amplitude travelling from 2 to 3 mph, regardless of whether asphaltic emulsion has been applied."

Litzka and Hasleher *(14)* summarized the findings of their research in Austria as loading the cement-treated layer with up to five passes of a vibratory roller, 24 to 72 hours after final compaction, thus creating a microcracked structure in the stabilized layer. They concluded that microcracking prevents the development of larger stress cracks, which in turns prevents reflective cracking through the asphalt overlay. Further work in Austria by Brandl *(15)* concluded that the use of microcracking was effective after 24 hours, but that additional microcracking is required if the compressive strength exceeds 725 psi (5.7 MPa) after two days of curing. A target stiffness reduction of 40 percent of the stiffness measured before microcracking was suggested.

Apart from the early work in Austria, the Texas Department of Transportation appears to have undertaken the most work on the topic, but the researchers acknowledge that the interim recommendations published to date are based on a limited experimental design and limited testing, and that the findings are not necessarily conclusive based on these limitations *(16)*. Research in Texas was conducted between the years 2000 and 2005, during which five projects with a total of 36 test sections were evaluated *(4,9,11,17,18)*. The interim recommendations proposed that microcracking should be performed between 24 and 48 hours after final compaction of the treated layer. The process recommended three or four single passes of a steel wheel roller, with maximum vibration frequency and amplitude settings *(17)*. No research comparing the effect of roller weight or vibration frequency and amplitude settings appears to have been published.

<u>Summary of Texas Projects: City of College Station (Edelweiss)</u>

The Edelweiss project consisted of four test sections (one control and three microcracked) constructed in the summer of 2000 *(11)*. The pavement structures were comprised of 6 in. (150 mm) of lime-stabilized subgrade, 6 in. (150 mm) of CTB, and a 2 in. (50 mm) HMA surfacing. The base design was based on a seven-day unconfined compressive strength of 500 psi (3.5 MPa), which required a cement content of seven percent by mass of the dry aggregate.

Microcracking was performed after 24 hours on two of the sections and after 48 hours on the third using a 12 ton steel drum roller set at maximum vibration amplitude and moving at 2 mph (3.2 km/h, i.e., walking pace). A web of surface cracks was observed in some areas of the layer after microcracking. The effect of the microcracking on base stiffness was measured with a Humboldt stiffness gauge and a falling weight deflectometer (FWD) before starting microcracking, after two roller passes, and after four roller passes. A second round of FWD measurements was taken approximately six months after construction. The results are summarized in Table 2.1.

Table 2.1: College Station Project: Stiffness Measurements

Time	Number of Roller Passes	FWD		Stiffness Gauge	
		Stiffness (GPa)	Stiffness Change (% of original)	Stiffness (MN/m)[1]	Stiffness Change (% of original)
Construction	0	8.1	0	55.4	0
	2	2.1	75% reduction	38.0	31% reduction
	4	1.2	85% reduction	29.5	47% reduction
+ 48 hours[2]	N/A	Not measured		41.2	26% reduction
+ 6 months[3]	N/A	12	48% increase	Not measured	
[1] MN/m = meganewtons per meter	[2] 48 hours after microcracking		[3] Approximately 6 months after microcracking		

The FWD measurements show that the first two roller passes caused a significant (75 percent) reduction in stiffness, while the third and fourth roller passes resulted in only a small (additional 10 percent) reduction. The stiffness gauge results differed from those of the FWD and did not follow the same trend in stiffness reduction after two and four roller passes. It is not clear whether the impact of the falling weight caused an additional reduction in stiffness in the drop zone. Both the FWD and the stiffness gauge results show that the drop in stiffness was temporary and that it had recovered to that of the control section, which was not microcracked, during the six-month interval between evaluations. Transverse cracks were noted on all sections after six months. Crack lengths were between 2.4 ft and 5.6 ft per 100 ft (0.5 m and 1.2 m per 100 m) of pavement on the three microcracked sections, and 27.3 ft per 100 ft (5.8 m per 100 m) of pavement on the control section. The TxDOT researchers concluded that microcracking did not adversely affect the load bearing capacity of the bases, and appeared to significantly reduce shrinkage cracking in the first six months after construction. Further monitoring was recommended to assess longer-term performance over a number of seasonal wetting and drying cycles.

<u>Summary of Texas Projects: Bryan District (Road SH47)</u> *(17)*

Road SH47 was rehabilitated in 2002 using a full-depth reclamation process. The road was pulverized to a depth of 14 in. (350 mm) after which three percent cement was mixed in and then compacted. The laboratory mix design indicated a seven-day UCS of 384 psi (2.6 MPa). The road was divided into 12 sections, based on the day of construction. The CTB was microcracked with a 25-ton roller 24 hours (eight sections of the project), 48 hours (three sections), and 72 hours (one section) after compaction. Three full passes were applied. A 4 in. asphalt concrete overlay was placed on the CTB as a surfacing 72 hours after microcracking of the last section. The effect of microcracking on stiffness was monitored with an FWD on five of the sections (three of the 24-hour sections and two of the 48-hour sections). Average stiffness reduction after microcracking was 60 percent of the stiffness measured before microcracking, with no significant differences noted for the different microcracking intervals. FWD measurements were repeated after 12 months and stiffnesses were approximately double the stiffness measured prior to microcracking. No cracking was observed at this time. A statistical analysis indicated that the time interval between compaction and microcracking (i.e., between 24 and 48 hours) did not influence the stiffnesses measured after 12 months.

A visual evaluation in 2004 (i.e., 24 months after construction) revealed two transverse cracks on one of the sections. No cracks were observed on the remainder of the project. A follow up evaluation in 2005 found that additional cracking had occurred on the original section with cracks and that new cracks had formed on four additional sections, all which had been microcracked after 24 hours. Crack lengths on each section varied between 16 ft and 1,404 ft (5 m and 428 m). Some of the cracks were attributed to construction problems (e.g., longitudinal joints) and not to shrinkage in the cement-treated layer. The change in stiffness before and after microcracking was not measured on the section with the most cracks, and consequently it was not possible to determine whether the additional cracking on this section could have been attributed to inadequate microcracking. The researchers concluded that measurements of stiffness reduction with an FWD, light weight deflectometer, or stiffness gauge should be a specified project requirement to ensure that adequate and consistent stiffness reduction is achieved during microcracking.

Summary of Texas Projects: San Antonio District (Road SH16) *(17)*

Road SH16 was rehabilitated in 2003 using a full-depth reclamation process. The existing road was pulverized to a depth of 8 in. (200 mm), treated with three percent cement, and compacted to form a subbase. A new 5 in.-thick base was imported and treated with two percent cement. The road was divided into four sections, based on the day of construction. Section 1 was not microcracked and served as a control, Section 2 was microcracked with a 12-ton roller 24 hours after compaction, and Section 3 and Section 4 were microcracked with three and two and passes respectively with the same roller 48 hours after compaction. Maximum vibration amplitude was used on all sections. The effect of microcracking on stiffness was monitored with an FWD. Stiffness reductions of 42, 73, and 46 percent were recorded on Sections 2, 3 and 4, respectively (Table 2.2).

Table 2.2: San Antonio District Project: Stiffness Measurements

Section	MC[1] Process (hours/passes)	Stiffness (ksi [GPa])			% Change of Original	
		Initial	After MC[1]	+ 3 months	After MC	+ 3 months
1	0/0	100 (0.7)	N/A	340 (2.3)	N/A	240% increase
2	24/3	120 (0.8)	70 (0.5)	410 (2.8)	42% reduction	242% increase
3	48/3	390 (2.7)	105 (0.7)	435 (3.0)	73% reduction	12% increase
4	48/2	250 (1.7)	135 (0.9)	255 (1.8)	46% reduction	2% increase

[1] MC = Microcracking

A surface treatment (chip seal) was applied as an initial wearing course, followed by 2 in. of hot mix asphalt. The sections were retested with an FWD after three months (Table 2.2 and Figure 2.8). The reason for the limited stiffness increase on Section 4 could not be explained. No cracks were observed. A second visual assessment of the project was conducted after 13 months. All of the sections had cracks, with crack length on Section 2 slightly less than that on the other sections (77ft [23.5 m] compared to 90, 94, and 95 ft [27.4, 28.7, and 30.0 m] on Sections 1, 3 and 4, respectively).

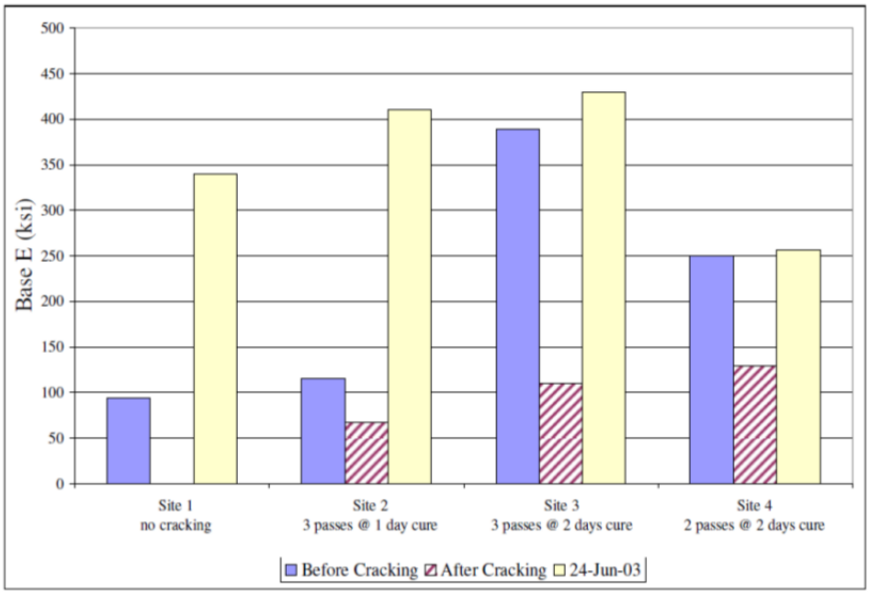

Figure 2.8: San Antonio District Project: average modulus results *(17)*.

Summary of Texas Projects: Texas A&M Riverside Campus *(17)*

This project was constructed at the Texas A&M Riverside campus in September 2003 to facilitate monitoring of microcracked pavements under controlled conditions. Two roads (Avenue C and Avenue D) were selected for the project. The existing material was pulverized and compacted to form a 6 in.-thick (150 mm) subbase. New aggregate base was placed on the subbase, stabilized with cement and then compacted. Avenue C was constructed with a cement content of eight percent and Avenue D with four percent. The roads were not surfaced for the duration of the study to allow researchers to monitor the cracking behavior. Each road was divided into six sections with a different crack mitigation treatment, as follows:

- No moist curing, no microcracking (control)
- Moist cure on Day 0, no microcracking, prime coat curing membrane on Day 1
- Moist cure on Days 0 through 3, microcrack on Day 1
- Moist cure on Days 0 through 3, microcrack on Day 2
- Moist cure on Days 0 through 3, microcrack on Day 3
- Moist cure on Days 0 through 3, no microcracking

Stiffness on the sections was measured with an FWD after microcracking and again after 10 and 21 months. Crack lengths were measured after 21 months. The results are summarized in Table 2.3 and Table 2.4 and in Figure 2.9 and Figure 2.10.

Table 2.3: Texas A&M Riverside Project: Stiffness Measurements

Cement Content (%)	Treatment	Stiffness Before Microcracking ksi, (GPa)	Stiffness After Microcracking ksi, (GPa)	Stiffness After 10 Months ksi, (GPa)	Stiffness After 21 Months ksi, (GPa)
4	Dry cure, no MC[1]	911 (6.3)	N/A	1,030 (7.2)	681 (4.8)
	Prime Coat Day 1	1,006 (6.9)	N/A	1,200 (8.4)	1,035 (7.2)
	MC Day 1	525 (3.6)	253 (1.7)	1,960 (13.7)	1,175 (8.2)
	MC Day 2	900 (6.2)	262 (1.8)	2,170 (15.2)	1,161 (8.1)
	MC Day 3	860 (5.9)	348 (2.4)	2,495 (17.5)	1,089 (7.6)
	Moist cure, no MC	924 (6.4)	N/A	2,000 (14.0)	1,582 (11.1)
8	Dry cure, no MC	802 (5.5)	N/A	2,300 (16.1)	1,746 (12.2)
	Prime Coat Day 1	1,692 (11.7)	N/A	1,200 (8.4)	1,178 (8.3)
	MC Day 1	1,650 (11.4)	507 (3.5)	4,050 (28.4)	2,401 (16.8)
	MC Day 2	1,450 (5.9)	485 (3.3)	2,500 (17.5)	2,093 (14.7)
	MC Day 3	2,120 (14.7)	890 (6.1)	2,800 (19.6)	1,651 (11.6)
	Moist cure, no MC	2,824 (19.5)	N/A	1,400 (9.8)	1,597 (11.2)

[1] MC = Microcracking

Table 2.4: Texas A&M Riverside Project: Crack Measurements

Treatment	4% Cement		8% Cement	
	Crack Length			
	(ft)	(m)	(ft)	(m)
Dry cure, no MC[1]	89	27	277	84
Prime Coat Day 1	78	24	328	100
MC Day 1	76	23	92	28
MC Day 2	34	10	105	32
MC Day 3	81	25	88	27
Moist cure, no MC	50	15	70	21

[1] MC = Microcracking

<u>Summary of Texas Projects: IH 45 Frontage Road *(4)*</u>

This project was constructed in Huntsville, Texas, on the IH 45 frontage road. Construction took place in December 2004 and May 2005. The design consisted of 10 in. (250 mm) of lime-treated subgrade, 12 in. (300 mm) of pug mill-mixed cement-treated base, and 5 in. (125 mm) of hot mix asphalt. Seven-day UCS strengths and tube suction dielectric values were assessed for a range of cement contents between two and eight percent. A cement content of four percent was selected, giving a UCS of 1,137 psi (7.8 MPa) and dielectric value of 7.3. Although the strength was significantly higher than the 300 psi (2.1 MPa) typically targeted by TxDOT, the decision to go with the higher cement content was based on the dielectric value *(4)*.

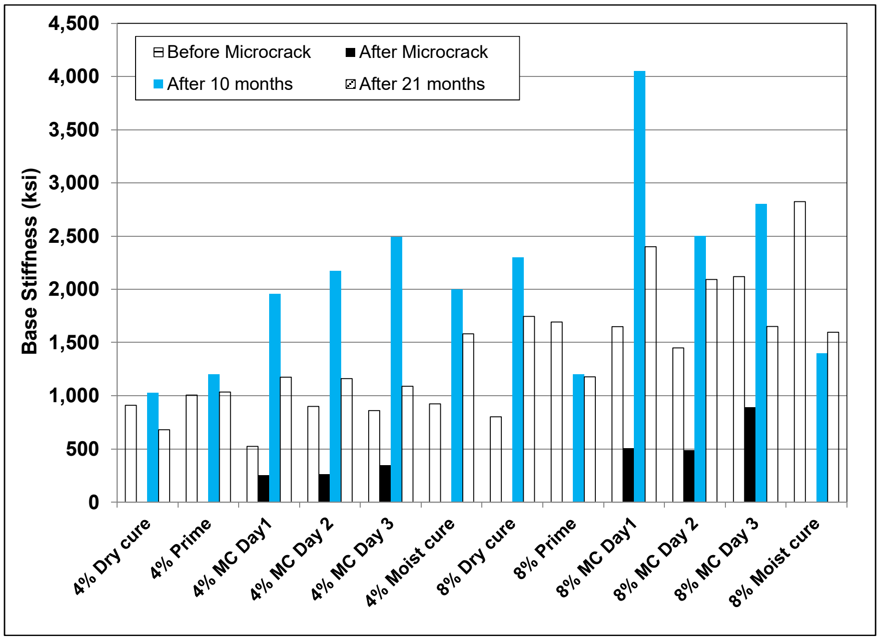

Figure 2.9: Texas A&M Riverside Project: stiffness measurements.

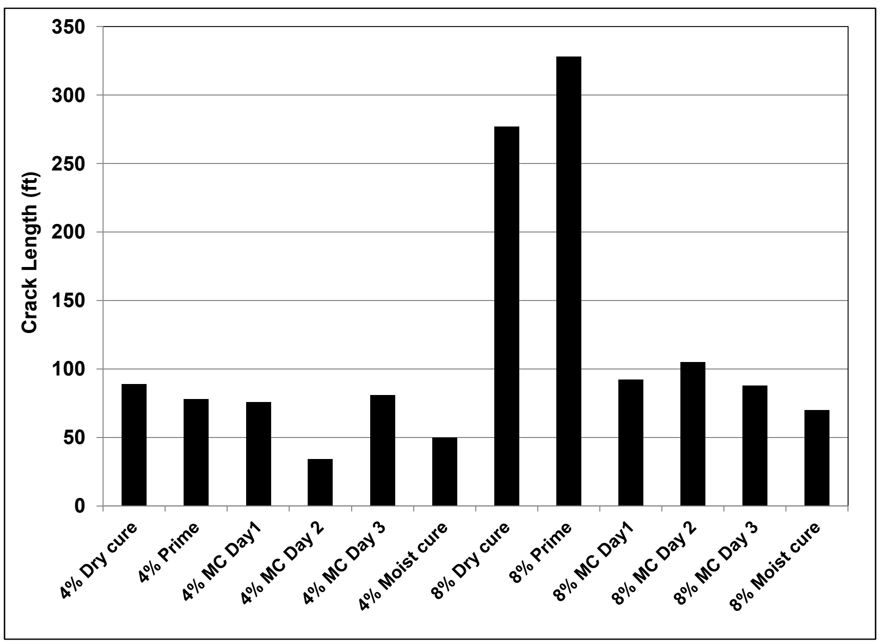

Figure 2.10: Texas A&M Riverside Project: crack length.

All cement-treated sections were microcracked with the exception of a 200 ft (60 m) control section. The sections constructed in December 2004 were microcracked after four days due to the slow strength gain attributed to the cold weather. The sections constructed in May 2005 were microcracked after two days. A light weight deflectometer (LWD) was used to measure any change in stiffness. On the December 2004 sections, average stiffnesses before microcracking ranged between 173 ksi and 358 ksi (1.2 GPa and 2.5 GPa). After microcracking, average stiffnesses ranged between 130 ksi and 245 ksi (0.9 GPa and

1.7 GPa), corresponding to stiffness reductions of 24 to 38 percent. On the May 2005 sections, the average stiffnesses before and after microcracking were 476 ksi (3.3 GPa) and 204 ksi (1.4 GPa), respectively, corresponding to a 57 percent stiffness reduction. A visual evaluation along with FWD measurements was conducted in August 2005. No cracks were observed and there was no difference in the stiffnesses between the microcracked and control sections.

Summary of Texas Projects: Conclusions and Recommendations

Conclusions drawn from the Texas research include the following *(17)*:

- Microcracking, when properly applied, did not result in pavement damage and the base modulus recovered to the same as that measured on the control sections that were not microcracked.
- Problematic cracking occurred on pavements with very high base course cement contents if microcracking was not applied. Problematic cracking implies increased crack width, increased total crack length, or both.
- Microcracking reduced the severity of shrinkage cracks in the base, regardless of cement content, and in some cases also significantly reduced total crack length.
- Appropriate laboratory design combined with microcracking by three passes of a vibratory roller at high amplitude after two to three days of curing provided a marked reduction in shrinkage cracking problems.
- In cooler temperatures when cement curing is slower, microcracking had to be delayed. The study recommended that a minimum modulus value of 200 ksi (1.4 GPa) be attained before the layer is microcracked.
- A target reduction in average base modulus of 60 percent if an FWD is used and 40 to 50 percent if a light weight deflectometer or stiffness gauge is used was recommended.
- Asphalt curing membranes were minimally effective at reducing cracking problems.
- When compared to moist curing with microcracking, moist curing without microcracking resulted in more severe (wider) cracks that quickly reflected through the surfacing.
- The use of higher cement contents in general did not provide a significantly increased base modulus, but did result in more severe cracking problems. Historically, seven-day UCS targets were based upon achieving a high degree of confidence that the material would meet durability criteria—and that it would not be necessary to perform the labor- and time-intensive durability tests. With the recent development of simpler, less time-consuming durability tests (e.g., tube suction), strength requirements should be eased and checked against the new durability requirements. Cement content design should be based on a combination of adequate strength, durability, and moisture resistance.

Based on the research, TxDOT provided the following recommendations for the design and construction of cement-treated bases:

- Design
  - Seven-day UCS: ≥ 300 psi (2.1 MPa) (according to ASTM D1633, i.e., moist cure)
  - Dielectric value after tube suction test: ≤ 10
- Construction
  - After placement and compaction of the CTB to project specifications, moist cure for two days.

- Microcrack the section using the same (or equivalent) vibratory steel wheel roller that was used for compaction. If microcracking after two days is not feasible, waiting until the base age reaches three days is preferable to microcracking after only one day of curing. Layers should not be microcracked until a minimum modulus of 200 ksi (1.4 GPa) has been attained.
- Continue moist curing to an age of at least 72 hours from the day of placement of the CTB.

2.2.3 Effect of Early Trafficking

Early opening to traffic (i.e., opening to traffic after completion of construction each day) will also result in some degree of microcracking, and it has been observed to reduce the severity of shrinkage cracking in Texas *(15)* and in New England states *(19)*. In the New England experiments, data suggested that early trafficking adversely affected the initial strength gain and base layer stiffness in the cement-treated sections. After two days of curing, trafficked cement-treated sections exhibited FWD modulus values that were 50 percent lower than those measured on the corresponding untrafficked sections.

One concern of early opening to traffic is the potential for raveling of the surface. This can be addressed by regular watering of the compacted layer, by applying dilute asphalt emulsion to the surface during or immediately after compaction of the treated layer, or by applying a surface treatment to the constructed section each day. The latter approach has been used in Texas with reported success *(20,21)*. Work zone traffic speeds should be enforced on the newly opened sections for the remainder of the construction period and pilot cars should be used when possible.

2.2.4 Other Mitigation Measures

In limited studies, Jones *(22)* and Jones and Fu *(23)* observed what appeared to be differences in shrinkage behavior of stabilized materials when cement and asphalt emulsion or cement and foamed asphalt were combined. In these studies, it was hypothesized that drops of asphalt encapsulated the cement particles, thereby retarding or altering the hydration process and consequently limiting shrinkage. Further research on using this approach to mitigate shrinkage cracking on cement-treated layers is recommended.

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3. MEASURING STIFFNESS CHANGE

3.1 Introduction

If microcracking is adopted as a means to reduce the severity of shrinkage cracking on cement-treated layers (new construction or full-depth reclamation), some method of measuring stiffness change during the microcracking process will be required to determine whether the contractor has met his obligations in terms of the project specifications and whether the desired affect has been achieved. Pavement layer stiffnesses can be measured with a variety of different instruments, including the falling weight deflectometer, the light weight deflectometer, or the soil stiffness gauge, each of which is discussed below. The Clegg Hammer stiffness measuring device has also been assessed for monitoring microcracked layers, and although it proved to be effective in measuring strength gain on cement-treated bases *(19,24)*, it was found to be insensitive to stiffness changes associated with microcracking after rolling *(25)*. Therefore, the Clegg Hammer is not discussed in this chapter.

3.2 Falling Weight Deflectometer

The falling weight deflectometer (FWD) is the most commonly used instrument for measuring deflection on pavements (Figure 3.1). Deflection measurements can be backcalculated to determine layer stiffnesses. Concerns have been raised about using an FWD for measuring the effect of microcracking on base stiffness because the heavier falling weight could induce additional microcracking in the region of the drop zone. For this reason, stiffness gauge manufacturers usually recommend that gauge measurements be taken before FWD measurements *(26)*. If percent of stiffness reduction is being used as a control measure for the number of roller passes applied during microcracking, the use of FWD measurements could be misleading because rolling would be stopped when stiffness had dropped to the required percentage of original stiffness in the FWD drop zone, which might not be representative of the stiffness change in the rest of the pavement.

Figure 3.1: Falling weight deflectometer.

3.3 Light Weight Deflectometer

The light weight deflectometer (Figure 3.2) is a portable deflection measuring device originally developed for measuring in situ stiffnesses on subgrades and newly constructed aggregate bases as an alternative quality control procedure to measuring in situ density. It consists of a load plate, a vertically sliding weight, and up to three deflection sensors connected to a handheld device that stores the data collected. Different size loading plates, different mass weights, and different drop heights are available and are selected based on the expected layer stiffness and thickness. An LWD works on the same principles as a traditional FWD but has fewer sensors and a much lower loading capacity. The maximum measureable layer thickness and measurable layer stiffness are typically in the region of 8 to 12 in. (200 to 300 mm) and 435 ksi (3 GPa), respectively.

Figure 3.2: Light weight deflectometer.

3.4 Soil Stiffness Gauge

Soil stiffness gauges (SSG) are offered by a number of different manufacturers and were also originally developed as an alternative to density measurements on compacted, unbound layers. The SSG measures soil stiffness by imparting small deflections to the ground at up to 25 different frequencies, ranging between 100 Hz and 200 Hz. The maximum measureable layer thickness and measurable layer stiffness are similar to those of the light weight deflectometer (i.e., typically in the region of 10 to 12 in. [250 to 300 mm] and 435 ksi [3 GPa], respectively). The devices display the average stiffness, the associated signal-to-noise ratio, which is an indication of the ambient vibrations in the ground, and the standard deviation between the measurements. A Young's modulus can be derived from the user specified Poisson's ratio and the measured stiffness. The stiffness is calculated according to Equation 3.1 *(26)*.

$$S = P/\delta \tag{3.1}$$

Where: S = Stiffness (MN/m)
P = force (MN)
δ = surface displacement (m)

A soil stiffness gauge is portable (Figure 3.3), and typically weighs around 20 lbs (10 kg). It can take measurements with little preparation of the surface. On the hard and rough surfaces typically encountered in the field, a patch of damp sand is used to provide even footing. The device is placed on the sand and twisted to seat the foot (Figure 3.4).

Figure 3.3: Soil stiffness gauge.

Figure 3.4: SSG footprint in sand patch.

3.5 Device Comparison

3.5.1 Soil Stiffness Gauge and Light Weight Deflectometer

A soil stiffness gauge and a light weight deflectometer were used side by side on a number of projects in Utah and Wyoming to compare the instruments for monitoring microcracking on cement-treated bases *(25)*. A statistical comparison between the two datasets (more than 300 measurements with each instrument) indicated an R^2 correlation value of 56.4 based on the relationship shown in Equation 3.2. This correlation is relatively weak, and although no reasons were provided by the researchers, it could potentially be attributed to the increasing variability of the measurements as the stiffness of the cement-treated layer increased towards the maximum limits of the instruments.

$$E_{SSG} = 0.675 \text{ x } E_{LWD} \tag{3.2}$$

Where: E_{SSG} = Stiffness measured with a soil stiffness gauge
E_{LWD} = Stiffness measured with a portable falling weight deflectometer

3.5.2 Soil Stiffness Gauge and Falling Weight Deflectometer

The data collected by Scullion on the City of College Station project in Texas *(11)* was used to compare measurements taken with a soil stiffness gauge to those taken with an FWD. Figure 3.5 shows the relationship between the stiffness measurements from the two devices. The stiffnesses measured with the FWD were substantially higher than those measured with the stiffness gauge. Similar findings were observed on experiments in New England *(19)*. This was attributed to the much higher loading capacity of the FWD and its ability to measure the stiffness of the entire pavement structure compared to the lighter loading capacity of the stiffness gauge, which generally only measures the stiffness to a depth of 8 to 12 in. (200 to 300 mm). A better correlation (R^2 of 83.81) was achieved between these two instruments compared to the correlation between the stiffness gauge and light weight deflectometer. The FWD measured a two-fold reduction in stiffness compared to the stiffness gauge (Figure 3.6).

This large difference in measurements supports concerns about using an FWD for measuring the effect of microcracking on base stiffness in the first month after construction and/or prior to placing an asphalt concrete surfacing since the heavier falling weight could induce additional microcracking in the stabilized base in the region of the drop zone, giving a result that is unrepresentative of the rest of the stabilized pavement layer.

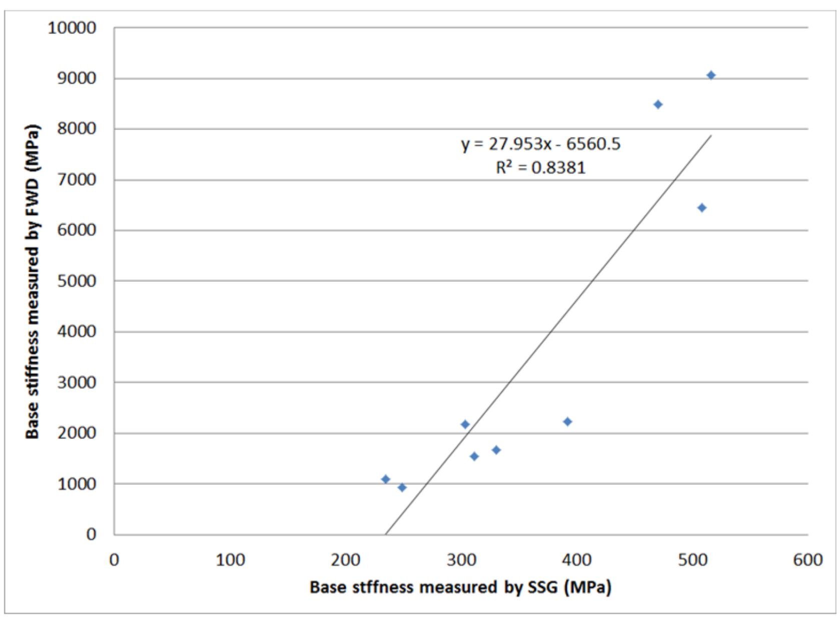

Figure 3.5: Relationship between FWD and SSG measured stiffness *(25)*.

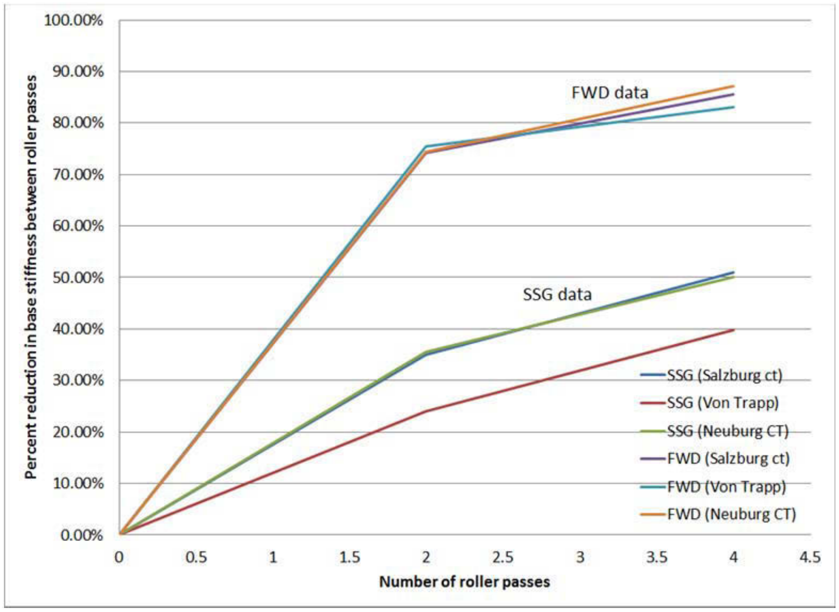

Figure 3.6: Measured stiffness reduction with FWD and SSG during microcracking *(25)*.

3.6 Conclusions

A range of devices are available for measuring the effect of microcracking on the stiffness of cement-treated layers. Each device has limitations that have not been fully quantified in terms of their suitability for use as a microcracking quality control procedure on construction projects.

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4. CONCLUSIONS AND RECOMMENDATIONS

The California Department of Transportation (Caltrans) has been using full-depth reclamation (FDR) as a rehabilitation strategy since 2001. Most projects to date have used a combination of foamed asphalt and portland cement as the stabilizing agent. Recently, the increasing cost of asphalt binder coupled with the relatively complex mix-design procedure for foamed asphalt has generated interest in the use of portland cement alone as an alternative stabilizing agent, where appropriate. However, shrinkage cracking associated with the hydration and curing of the cement-stabilized layers remains a concern, especially with regard to crack reflection through asphalt concrete surfacings and the related problems caused by water ingress.

Considerable research has been undertaken on crack mitigation, and a range of measures related to improved mix designs and construction practices have been implemented by road agencies. One of the most promising measures, used in conjunction with appropriate mix designs, is that of microcracking the cement-treated layer between 24 and 72 hours after construction. In theory, this action creates a fine network of cracks in the layer that limits or prevents the wider and more severe block cracks typical of cement-treated layers. Limited research to assess microcracking as a crack mitigation measure has been completed on a number of projects in Texas, Utah, and New Hampshire. Recommendations from these studies have been implemented by the Texas Department of Transportation and other state departments of transportation. Longer-term monitoring on a range of projects in Texas and other states has revealed that microcracking has not always been successful in preventing cracking, with some projects showing reflected transverse and block cracks in a relatively short time period.

Discussions with researchers in Texas indicated that additional research is necessary to better understand the microcracking mechanism, and to identify the key factors influencing performance, including but not limited to aggregate properties, cement content, the time period before microcracking starts, layer moisture contents, roller weights and vibration settings, the number of roller passes, the field test methods and criteria to assess the degree of microcracking, and the effects of early opening to traffic. Early research into the use of "hybrid" stabilizers (cement with small amounts of asphalt emulsion, foamed asphalt, or synthetic polymer emulsions) indicates that these, in conjunction with appropriate mix designs, may further limit the severity of shrinkage cracks on projects that include cement-treated layers.

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