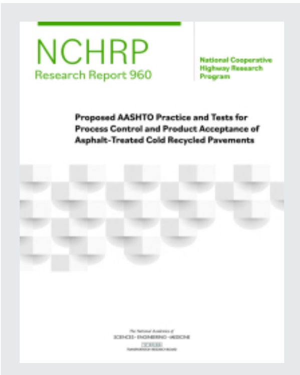

Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements (2021)

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 960

Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements

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2021

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Field of Materials and Construction—Bituminous Materials

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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

NCHRP Research Report 960: Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements will improve our ability to make time-critical decisions on opening asphalt-treated, cold recycled pavements to traffic and surfacing. Thus, the report will be of immediate interest to engineers in state and local transportation agencies and industry with responsibility for the construction and quality assurance of cold recycled pavements.

Pavement recycling offers significant economic and environmental benefits through reductions in material and energy consumption, cost of construction, and user delays. However, there are currently no universally agreed upon rapid process control and product acceptance test methods to ensure that the constructed materials comply with commonly specified parameters and are ready for traffic and surfacing. Asphalt-treated, cold recycled materials used in cold in-place recycling (CIR), cold central-plant recycling (CCPR), and full-depth reclamation (FDR) have traditionally been accepted based on moisture content and density in the field and performance tests in the laboratory. These tests do not lend themselves to rapidly assessing the as-constructed quality and performance of cold recycled materials, nor do they help determine the proper time for application of traffic and surfacing without causing damage. Therefore, a standard practice for process control and product acceptance of cold recycling operations was needed to promote consistency among agencies. Appropriate time-critical field tests performed during construction are also needed to rapidly determine the quality of the as-constructed cold recycled pavement and evaluate its readiness for traffic and surfacing.

Under NCHRP Project 09-62, “Rapid Tests and Specifications for Construction of Asphalt-Treated Cold Recycled Pavements,” the Virginia Transportation Research Council was tasked with developing rapid, time-critical tests for asphalt-treated CIR, FDR, and CCPR materials that provide criteria for determining when the pavement can be opened to traffic and surfaced as well as a standard practice for using these tests for process control and product acceptance.

The research was conducted in three phases. Phase I included a comprehensive literature review, a stakeholder survey, and a review of agency specifications. A few tests routinely used in the field were identified that could assess desired time-critical properties. Phase II was a series of laboratory experiments that evaluated several existing and newly developed tests for their ability to determine in the field when a pavement was ready to accept traffic or surfacing. Phase III assessed the most promising tests from Phase II in a field setting where the properties of cold recycled materials from 16 construction projects were measured in situ to determine the pavements’ readiness for traffic or surfacing. Finally, the most promising rapid test methods from the field experiment were incorporated in a proposed AASHTO standard practice that guides their use for making time-critical decisions regarding opening cold recycled pavements to traffic and surfacing.

The key outcome of this research is the proposed AASHTO Standard Practice: Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements and its associated test methods. This practice is presented as Appendix B. Two new test methods developed in the project are presented in Appendices C and D.

CONTENTS

Appendix D Proposed AASHTO Standard Method of Test for Evaluating the Raveling Resistance of Asphalt-Treated Recycled Pavement Applications Using a Short-Pin Fixture

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements

Pavement recycling is a technology that can restore the service life of pavement structures and stretch available funding for pavement rehabilitation (Asphalt Recycling and Reclaiming Association 2015). In general, pavement recycling techniques remix the existing pavement material (either in situ or through a mobile plant) and reuse it in the final pavement in the form of a stabilized layer. Some of the most commonly cited benefits of using pavement recycling techniques to rehabilitate and repair asphalt concrete pavements include reductions in costs, emissions, use of virgin materials, fuel consumption, construction time, and disruption to traffic.

Limitations to further widespread implementation of pavement recycling processes have been reported in previous national research efforts. Among these limitations are a lack of rapid quality tests that can be used to assess the time to opening to traffic and time to surfacing a newly constructed recycled layer. This research study, which was conducted in three phases, investigated and suggest a series of tests that could be used for this purpose.

Phase I included a review of the current literature related to tests that could assess the engineering properties of cold recycled materials stabilized with either emulsified or foamed asphalt, with or without a cementitious active filler. In addition, tests that were commonly used for other materials were considered. Also included as part of Phase I were an online stakeholder survey and a nationwide review of agency specifications. The stakeholder survey and specification review reinforced the concept that few tests were conducted routinely in the field that could assess desired properties beyond the currently used assessments of moisture content and density.

Phase II included the assessment of identified tests in a laboratory setting on materials sampled from actual recycling projects in the United States and Canada. Sampled materials were collected and remixed in the laboratory, according to their mixture design, to produce test slabs. Early exploratory testing included development of the procedure to mix, fabricate, and then conduct testing on the test slabs at early curing times. Tests were arranged and conducted on multiple replicates to assess test variability, and multiple tests were conducted on the same slab where practicable. In addition, several exploratory tests were attempted that proved unsuitable for use with recycled materials for various reasons. The identified tests were assessed based on their potential to quantify expected changes in mixture properties with respect to curing time and presence of cement as an active filler, their variability, and their correlation to other tests. Test slabs were fabricated and tested over a series of curing times that ranged from 1 hour to 72 hours after fabrication. All curing was allowed to occur in a typical laboratory environment (that is, curing was not accelerated by heat or other methods). During Phase II, a ruggedness evaluation was completed that identified certain test fixture dimensions as being significant factors. From Phase II, selected tests were recommended for field study.

Phase III included the assessment of selected tests in a field setting where the properties of materials from actual construction projects were assessed in situ. The properties of 16 recycled pavement sections were assessed where each section exhibited either a unique combination of recycling processes, a stabilizing/recycling agent, the presence of an active filler, or another property expected to influence the test result. Testing was conducted on the field projects immediately after compaction and at specified intervals up to 48 hours after compaction. The field study showed that the results of the selected tests followed trends similar to those observed in the laboratory. As part of Phase III, an interlaboratory study (ILS) was performed at a unique field-based research project. The ILS was performed in conjunction with research by others where multiple recycling processes, stabilizing/recycling agents, and active filler contents were employed. This unique opportunity allowed an ILS to be conducted on field-produced and placed recycled materials at early ages that would not have been possible in a laboratory setting. The ILS was conducted to develop precision statements for the suggested tests. Based on the results of the testing in Phase III, the ILS, and a correlation analysis of the selected tests, a recommendation was made to use the shear and raveling properties of recycled materials in an effort to quantify the time to surfacing and time to opening to traffic, respectively. Specifically, the number of blows and torque values from a long-pin shear test and a short-pin raveling test were recommended. By use of a statistical approach, suggested threshold values for each test were developed. Draft guide specifications and preliminary draft standard practice documents were developed to assist agencies with using these new tests.

CHAPTER 1

Background

Pavement recycling is a technology that can restore the service life of pavement structures and stretch available funding for pavement rehabilitation (Asphalt Recycling and Reclaiming Association [ARRA] 2015). In general, pavement recycling techniques remix the existing pavement material (either in situ or through a mobile plant) and reuse it in the final pavement in the form of a stabilized layer. Some of the most commonly cited benefits of using pavement recycling techniques to rehabilitate and repair asphalt concrete pavements include reductions in costs, emissions, use of virgin materials, fuel consumption, construction time, and disruption to traffic (Nataatmadja 2001, Thenoux et al. 2007, Robinette and Epps 2010, Stroup-Gardiner 2011, Pakes et al. 2018). Pavement recycling methods include the following processes: cold planing (CP), hot in-place recycling (HIR), cold recycling (CR), and full-depth reclamation (FDR). CR includes the techniques cold in-place recycling (CIR) and cold central-plant recycling (CCPR) (ARRA 2015). This NCHRP study focused on FDR, CIR, and CCPR using asphalt stabilizing/recycling agents with and without a cementitious active filler.

Pavement recycling techniques, including FDR, CIR, and CCPR, are viable and economically and environmentally advantageous rehabilitation strategies for many asphalt pavements. The benefits of pavement recycling are derived primarily from reusing the in-situ pavement materials or existing pavement millings (RAP) and from using stabilizing/recycling agents to bind the RAP particles at ambient temperatures rather than heating the materials to high temperatures. Robinette and Epps (2010) reported both the life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) of multiple in-place recycling methods, quantifying cost savings and positive environmental impacts.

FDR can be used to correct severe structural deficiencies and defects that are deep within an existing pavement structure or to prepare a stabilized foundation on a new roadway using imported material (termed "imported FDR"). The depth of pulverization achieved with the reclaimer depends on the thickness of the bound layers of the existing pavement and is typically up to 12 in. (ARRA 2015). For existing pavements, FDR is performed on the bound layers and a predetermined portion of the underlying unbound materials. FDR may consist of simply pulverizing and remixing the roadway foundation (termed "mechanical stabilization"), but it most often incorporates one or several stabilizing agents. Chemical stabilization describes FDR performed using cementitious products such as cement, lime, fly ash, and cement and lime kiln dust. Bituminous stabilization describes FDR using asphalt-based stabilizer, namely asphalt emulsion or foamed asphalt (ARRA 2015). Bituminous stabilization is most commonly performed using an asphalt-based stabilizer plus an active filler such as lime or cement (Wirtgen 2010). An asphalt mixture overlay or surface treatment (e.g., chip seal) is usually applied after the FDR layer has been allowed to cure. FDR has been used successfully by numerous highway agencies in several states (Mallick et al. 2002, Bemanian et al. 2006, Lewis et al. 2006, Guthrie et al. 2007, Jones et al. 2008, Hilbrich and Scullion 2008, Diefenderfer and Apeagyei 2011, Johanneck and Dai 2013, Diefenderfer et al. 2015, Howard and Cox 2016) and countries (Saleh 2004, Berthelot et al. 2007, Loizos 2007, Lane and Kazmierowski 2012). A photograph of a reclaimer performing FDR on imported material is shown in Figure 1.1.

CIR rehabilitates the upper portions of the bound layers of an asphalt pavement, typically extending to depths of 4 to 6 in. (ARRA 2015). CIR has been shown to be an effective treatment process by many agencies, although its earliest use in the United States was primarily in the central and western portions of the nation. One reason for this is that CIR was originally developed as a process in which several large pieces of equipment were joined together to form a long CIR train. These trains could consist of tanker trucks, milling machines, sizing and grading machines, crushers, pavers, and rollers. Because of the substantial length of these trains,

Figure 1.1. FDR process used on I-64 in Virginia, 2017.

Photo by Wirtgen.

Figure 1.3. CIR using a rear-discharge cold recycler.

they were most effectively used on long stretches of open highway. However, it is becoming increasingly common to see shorter CIR trains where the equipment may consist of only a water and bitumen tanker, cold recycler, paver (needed only if a paving screed is not included as part of the cold recycler), and rollers, as shown in Figure 1.2. Other recent advancements include a rear-discharge cold recycler that discharges the recycled material into the hopper of an asphalt paver, as shown in Figure 1.3.

Typical recycling agents for CIR include asphalt emulsion and foamed asphalt. In many cases, an active filler such as cement, lime, fly ash, and lime kiln dust is used in combination with asphalt recycling agents to improve dispersion of the foamed asphalt, improve resistance to moisture damage, help achieve early strength, and expedite opening to traffic (ARRA 2015). On higher volume routes, a single or multi-course asphalt mixture overlay is typically applied, but other treatments (such as chip seals) may be used on lower volume facilities (Bemanian et al. 2006, Maurer et al. 2007). CIR has been successfully used for many projects in the United States, Canada, and other countries (Crovetti 2000, Thomas et al. 2000, Forsberg et al. 2002, Sebaaly et al. 2004, Morian et al. 2004, Lane and Kazmierowski 2005, Bemanian et al. 2006, Emery 2006, Loizos and Papavasiliou 2006, Cross and Jakatimath 2007, Jahren et al. 2007, Loizos et al. 2007, Loria et al. 2008, Thompson et al. 2009, Schwartz and Khosravifar 2013, Sanjeevan et al. 2014, Diefenderfer et al. 2015).

CCPR is a process through which RAP, generated by taking millings from the existing project, other projects, or existing stockpiles, is recycled and used to construct a roadway. The RAP is brought to a centrally located plant (an example is shown in Figure 1.4) that is used to mix recycling additive(s), similar to those used with CIR, consistently with the RAP. The plants are portable in that they can be temporarily set up on or near a project or kept at a fixed location.

Recent studies have also shown mechanical properties of CCPR and CIR to be similar (Apeagyei and Diefenderfer 2013, Diefenderfer et al. 2016a, Schwartz et al. 2017). CCPR also offers the opportunity to process the RAP through a mobile crusher on site before adding it to the CCPR plant

Figure 1.2. CIR using a single-unit cold recycling train on I-81 in Virginia, 2011.

Figure 1.4. CCPR plant; the recycled product is discharged from elevator at right of image.

Figure 1.5. Paving CCPR on I-64 in Virginia, 2017.

for improved gradation control compared to CIR, although this has not been shown conclusively to benefit the final product. The primary benefits of using the CCPR process are twofold. First, material can be removed from the roadway and then returned as a recycled layer after the underlying foundation is either stabilized (using FDR) or replaced if needed. Second, existing stockpiles of RAP can be treated and used in the construction of new pavements or in the rehabilitation of different existing pavements. Although the CCPR process has not been used as widely as CIR, it has been successfully implemented recently on high-traffic sections of roadway (Diefenderfer et al. 2016b, Ma et al. 2017, Timm et al. 2018). Figure 1.5 is a photograph of CCPR paving.

1.1 Problem Statement

Despite the significant benefits, several impediments have hampered the widespread use of pavement recycling techniques by agencies. Important among these is the lack of technical standards for rapid process control and product acceptance during construction. From the contractor perspective, a lack of valid and rapid process control procedures makes it difficult to deliver and document consistent placement that meets the design requirements. Current tests include the seldom-used proof rolling and the more popular nuclear density gauge (NDG) density and moisture measurements, neither of which has been shown individually to correlate well with performance. From an agency perspective, it is difficult to make a time-critical assessment of material quality when there are no rapid product acceptance procedures. Rapid product acceptance procedures are critical to help an agency decide when the recycled layer is ready to be opened to traffic or when it is ready to be surfaced. The procedures are also vital for predicting whether the current engineering properties of the recycled material meet the design intent in the fully field-cured state.

1.2 Objectives

The objectives of this study were to develop (1) time-critical tests for asphalt-treated CIR, FDR, and CCPR materials; and (2) guide specifications for using these tests for process control and product acceptance that provide agencies with a basis for determining when the pavement can be opened to traffic or when it can be surfaced.

1.3 Current Recycled Material Quality Tests

Currently, agencies use several proxy tests to assess the quality of a recycled pavement during construction. These proxy tests are most often related to level of compaction and moisture content. Density measurement is one of the most common tests used by agency and contractor personnel to assess the quality of the recycled material during construction. Density measurements have been shown to be somewhat correlated with stiffness properties of recycled materials (Schwartz et al. 2017), and the experience of the recycling community has suggested that poor compaction density leads to poor material quality (ARRA 2015, Asphalt Academy 2009). However, density measurements do not fully indicate whether the recycled material is of sufficient quality or stability for trafficking or surfacing. Further, density measurements do not account for the curing process that is known to occur with asphalt-stabilized recycled materials. Previous studies have shown that asphalt-stabilized recycled materials gain stiffness and strength with time (Lane and Kazmierowski 2005, Loizos et al. 2007, Diefenderfer and Apeagyei 2011, Diefenderfer et al. 2016b) while density remains constant.

Aside from density testing, quality tests that are often performed by the contractor may include using a proof-rolling process or compacting molded specimens in the field as part of a process control or quality assurance program. Proof rolling can effectively identify deficient structural issues; however, there are few standard methods to apply the test, and thus results are rarely transferable from one project to another. Molded specimens fabricated in the field are exposed to accelerated curing procedures in the laboratory to simulate the long-term curing process that occurs in the field prior to testing for strength properties. Again, there are no AASHTO or ASTM standards for this curing process, only loosely agreed-upon temperatures depending on the recycling/stabilizing agent, none of which had been proven to simulate field conditions. In addition, the curing simulation may be a multiday process and thus does not provide time-critical information.

Although moisture content measurements are sometimes used at early ages as an indicator of the curing process, the measurement methods employed have inherent issues.

Current procedures usually include using an NDG (or similar device), where the measured moisture content is affected by the presence of hydrogen in the asphalt binder and recycled pavement, or destructively testing a sample of the recycled material for moisture loss using forced-draft oven or microwave oven drying. Although the microwave oven drying process is faster, it is difficult to remove all of the moisture, and some binder may be lost; thus, some error is inherent in the measurement. The forced-draft oven method may remove nearly all free moisture, but it is completed at elevated temperatures and typically requires a day or more to provide results. However, the main limitations of these approaches include that the moisture content of a material does not always correlate well with its structural properties or when a recycled layer can be opened to traffic or surfaced.

When an agency does attempt to quantify the appropriate time to open a recycled layer to traffic or surfacing, most highway agencies currently follow one of two approaches. The first approach is to wait a predetermined time for the material to gain enough stability to carry traffic via a material curing process. Wait times from agency specifications range from a few days to 2 weeks. This process is highly inefficient in that under certain conditions, the material may have reached the ability to carry traffic without deterioration much sooner than allowed by the specification. This increases agency costs by delaying the project and increases costs to the traveling public through increased travel time and reduced utility of the roadway. The second approach includes performing a moisture content test and allowing surfacing or traffic once a predetermined moisture content is reached, usually around 50% of the optimum value obtained during the mix design process. Although this criterion is perceived to be more scientific by virtue of a quantifiable measurement, it too can be problematic since the moisture content is only loosely correlated with material structural properties. Studies have suggested that as a recycled material loses moisture, the particle bonds are enhanced and strength properties are increased (Fu et al. 2010a, Fu et al. 2010b). However, if the material were to become rewetted, the properties of the recycled material would not automatically revert to those it had in the uncured condition; its properties would depend on the degree of bond quality that was established prior to the rewetting.

Even given the aforementioned deficiencies, the test methods currently used to determine when a recycled pavement can be opened to traffic or surfaced have been used extensively in the past, and many pavement recycling process practitioners are comfortable with their use based on experience. However, these methods sometimes fail to discriminate successfully between sufficient and deficient material quality, can often result in significant delays to project completion, and may lead to inappropriate "emergency" corrective actions such as adding more active filler. The development of appropriate rapid quality tests will significantly improve the ability of agencies to accept well-performing materials while minimizing the risks of accepting deficient materials. In addition, the pavement recycling industry will have the process control tools to demonstrate material quality rapidly.

1.4 Scope of Report

This report summarizes the work completed under NCHRP Project 9-62 to identify and develop time-critical quality tests and guide specifications for using these tests with asphalt-treated CIR, FDR, and CCPR. The report is divided into five chapters, including this background Chapter 1. Chapter 2 discusses the research approach, and Chapter 3 presents the findings and applications based on responses to the online stakeholder survey, specification review, laboratory testing, and field testing. Chapter 4 presents the conclusions and offers suggestions for continued research. Chapter 5 discusses ideas for training and implementation. The references used in the preparation of this report follow Chapter 5. Detailed responses from the stakeholder survey, field testing data sheets, preliminary draft standard practice documents, and preliminary draft revisions to existing test methods are included in the appendices.

CHAPTER 2

Research Approach

Chapter 2 provides an overview of the work completed during this study. The objectives of the study were addressed through three phases. In Phase I, current and emerging test methods for quality assessment and process control of cold recycled materials where emulsified asphalt or foamed asphalt serves as the stabilizing/recycling agent were identified. The three primary sources of information used were a literature review, a review of agency specifications, and an online stakeholder survey. Phase II, a laboratory-based experiment, was conducted with test slabs of recycled materials fabricated in the laboratory using materials sampled from recycling projects in the United States and Canada. Phase III, a field-based experiment, was conducted where the most representative tests identified in Phase II were used to assess the early-age properties of recycled materials on nine field projects in the United States.

2.1 Phase I—Current and Emerging Quality Tests

From the literature review, agency specifications review, and stakeholder survey, the research team identified relevant material properties that were key to addressing the study objectives and candidate tests that could assess the relevant material properties of interest. Through these steps, the following key properties were identified: product uniformity, moisture, compaction, thickness, curing, strength/stiffness, and raveling resistance. Assessing one or more of these properties could then be used to determine if a recycled material was ready to be opened to traffic or ready to be surfaced. The work focused on identifying those tests that could assess these properties, were relatively inexpensive, were easy to operate in the field, and were able to capture the anticipated material property trends associated with changes in stabilizing/recycling agent types, the presence of active fillers, and field curing.

The review of agency specifications for asphalt-stabilized FDR, CIR, and CCPR and the stakeholder survey were conducted to identify and summarize current practices. The agency specifications review was completed with the goal of identifying current traffic opening and surfacing requirements and other material quality tests. The survey of academic, industry, and agency stakeholders was conducted to identify any additional tests not discovered during the literature review (such as those that might come from unpublished studies or from ongoing research) and to help the research team identify the curing time(s) from which the stakeholders would seek to use the results of any proposed tests.

2.1.1 Specification Review

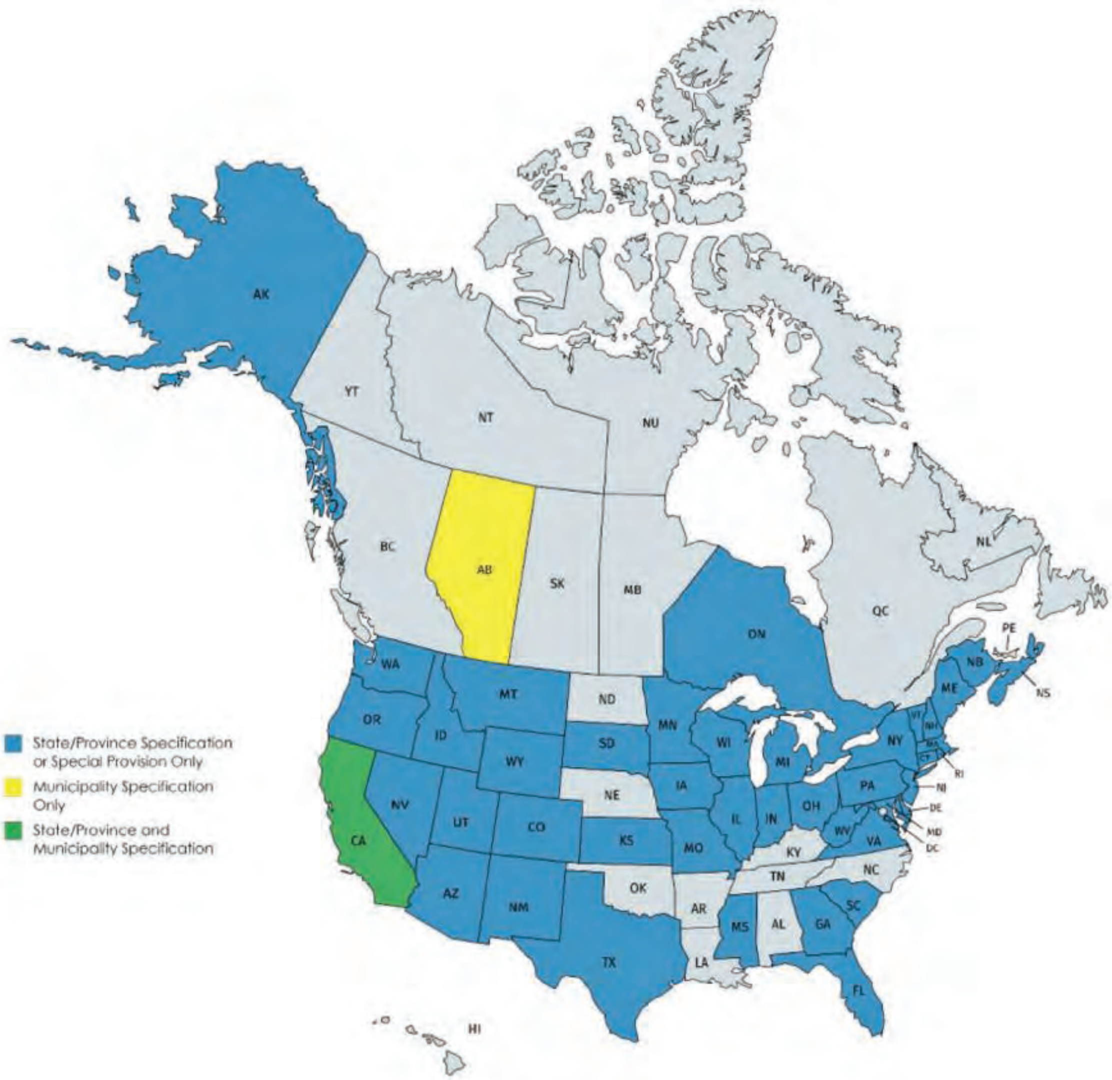
The standard specifications and special provisions for asphalt-based CIR, CCPR, or FDR from U.S. states and Canadian provinces were collected and reviewed. Of the 50 U.S. states, 41 states, in addition to FHWA's Federal Lands Highway Division, had at least one of the relevant specifications. Of the 10 Canadian provinces/territories, three included asphalt-based CIR, CCPR, or FDR in their standard specifications. In addition, the specifications from three municipalities in the United States were collected and reviewed.

In total, 83 specifications were reviewed. Of these, approximately 54% (45 specifications) governed CIR, 17% (14 specifications) governed CCPR, and 29% (24 specifications) governed FDR. Figure 2.1 is a map of the United States and Canada that identifies the locations of all state/province/municipal CIR, CCPR, and FDR specifications that were reviewed.

2.1.2 Stakeholder Survey

An online stakeholder survey was conducted from October through December 2017. The objectives of this survey were to identify:

- Tests that were being assessed but had not yet been incorporated in current agency standard specifications or special provisions,



Alberta (AB) is the only municipality in the "Municipality Specification Only" category, and California is the only state in the "State/Province and Municipality Specification" category. Color figure can be viewed in the online version of this report.

Figure 2.1. Location of all state, province, and municipality CIR, CCPR, and FDR specifications reviewed in this study.

- Procedures used by practitioners for process control that are not standardized or published,
- Potential hurdles that exist with implementation of current methods of product acceptance and specifications,
- Rankings of the most important test method characteristics by practitioners (e.g., time taken to perform the test, equipment required),
- Potential field projects that could be used in Phase III of the study for evaluating the testing procedures developed in Phase II, and
- Recommended improvements to existing tests from practitioners.

The stakeholder survey questions are presented in Appendix A. The online survey link was distributed to the AASHTO Committee on Materials and Pavements, selected TRB committees in the pavements and asphalt materials sections, and in presentations at regional and national pavement recycling conferences. A total of 84 survey responses were received.

2.2 Phase II—Laboratory Testing

Using the information collected during the literature review and stakeholder survey, the research team developed a laboratory experiment conducted in Phase II of this study. The experiment was conducted on test slabs of recycled materials fabricated in the laboratory. The slabs were fabricated from loose recycled materials sampled during construction of projects from across the United States and Canada, as shown in Figure 2.2. For this work, loose materials were defined as the processed RAP and any other material required to produce an FDR, CIR, or CCPR layer but not including any stabilizing/recycling agent or active filler. Industry and agency partners assisted the research team with identifying relevant projects, obtaining the mix designs, and shipping approximately 500 lb to 600 lb of loose materials from each project. Along with the loose materials, the research team received the designated asphalt emulsion or binder to replicate the mix design in the laboratory. The research team followed the developed mix design, mixed the provided materials, and compacted slab specimens in the laboratory. These slabs were tested with the tests identified in Phase I to determine the tests' ability to discern differences in material behavior related to curing time, type of stabilizing/recycling agent, and presence of active filler.

2.2.1 Objectives

The objectives of the laboratory testing included assessing tests that could be conducted easily, quickly, and inexpensively in a field setting and could quantify material property differences resulting from changes in curing time, type of stabilizing/recycling agent, and presence of active filler. Preferably, tests would provide an immediate result.

2.2.2 Experimental Design

To accomplish the objectives of the laboratory experiment, the research team chose to conduct the laboratory experiment using a partial factorial design. A partial factorial design was selected because of the high number of potential combinations given the possible factors (including recycling

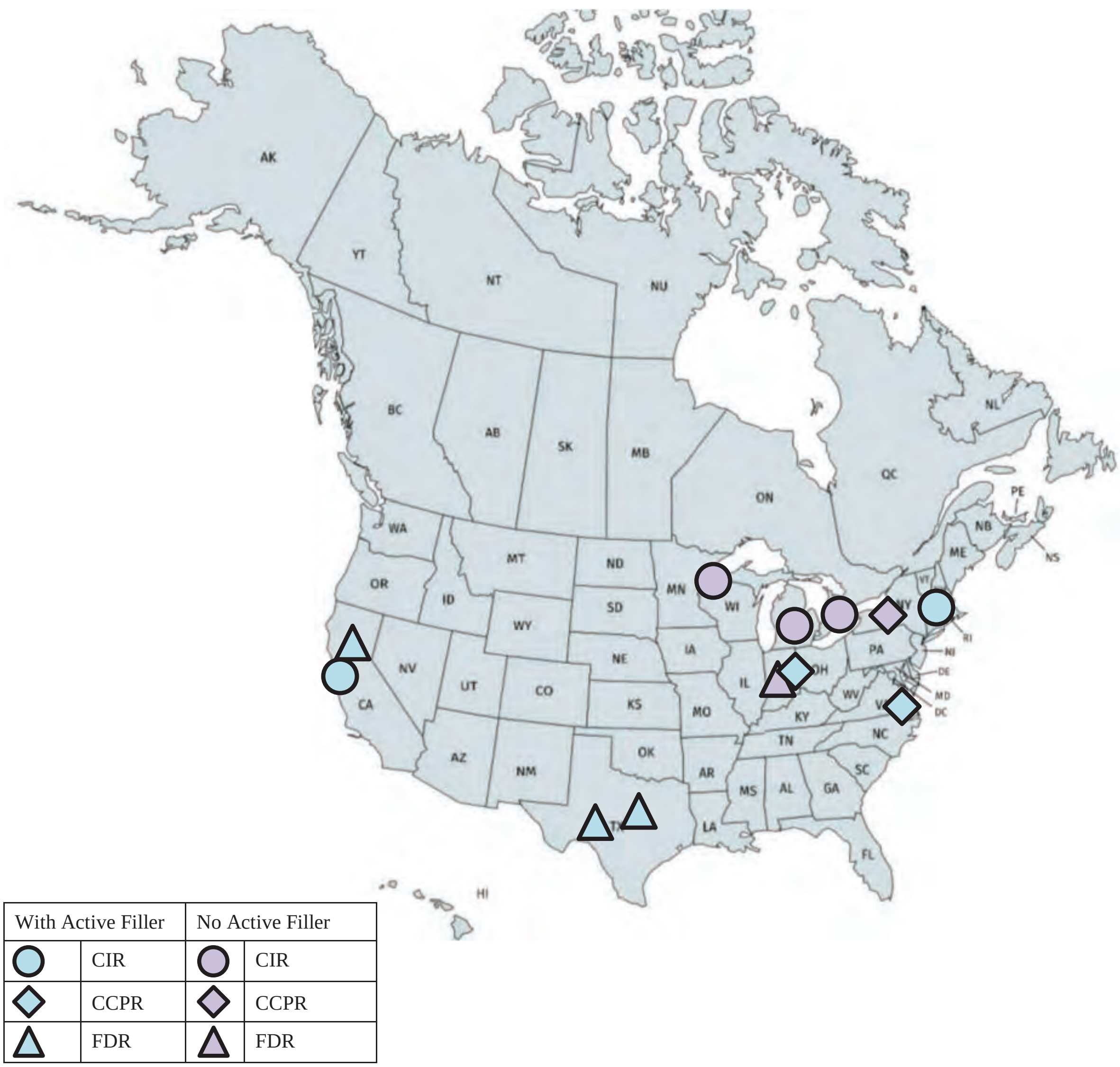


Figure 2.2. Project locations for Phase II materials sampling.

processes; stabilizing/recycling agent types; presence of active fillers; RAP, asphalt binder, and aggregate sources; and curing time), multiple levels of each factor, and number of tests.

The experiment was designed using factors and levels that were expected to yield the greatest range of results for the testing conducted. For example, for a test that measures stiffness of a recycled material, rather than each possible combination of recycling process, stabilizing/recycling agents, chemical additives/active fillers, geographic location, and RAP type being tested, an experimental design could be developed that studied the combinations expected to produce the least and the greatest stiffness. From this, the effectiveness of each test (or more tests) could be studied in a way that was more efficient while still technically valid.

Multiple sets of test slabs were fabricated to conduct all the tests. This was necessary given (1) the limited size of the test specimens, (2) the desire to conduct testing on undisturbed sections of the test specimens, and (3) the need to provide replication. Each test specimen was fabricated in accordance with the mix design, and the quantity of each ingredient was recorded. Subsequent test specimens from the same project were fabricated using the same ingredient quantities.

2.2.3 Source Projects and Materials Sampling

With the help of industry and agency partners, the research team was provided with a mix design (which included an optimum density, a stabilizing/recycling agent content, and an active filler content [if used]) and materials from 14 recycling projects located across the United States and Canada. From each project, the supporting contractor or agency provided the research team with 10 to 12 5-gal buckets of the loose material (composed of RAP and sometimes unbound materials from underlying layers) and 4 to 6 gal of emulsified asphalt for those projects where emulsified asphalt was used. For those projects where foamed asphalt was used, a performance grade (PG) 64-22 binder already available in the laboratory was included. To help develop a more complete matrix of material types, 24 and 48 5-gal buckets of loose material were sampled from two ongoing research studies in California and Virginia, respectively. These extra materials were used to produce additional mixtures using both emulsified and foamed asphalt (each with and without an active filler) from the same source.

Table 2.1 describes the projects from which the loose materials were obtained. The stabilizing/recycling agent dosage ranged from 1.2% to 4.5%, with 2.5% being the most common agent content. In addition, the active filler content ranged from 0% to 1.5%, with 0% and 1% being the most common.

2.2.4 Slab Specimen Fabrication

Compacted slab specimens (500 mm × 400 mm × 110 mm) were manufactured from field-produced materials. The slabs were prepared with the loose materials sampled from each field project upon which the various laboratory tests were conducted. Following the mix design from (or developed for) each project, the loose materials were mixed with stabilizing/recycling agents and active fillers (where used) in a Wirtgen WLM30 laboratory-scale twin-shaft pug mill. This equipment has the capacity to mix a batch of approximately 30 kg (66 lb). For those mixtures using emulsified

Table 2.1. Phase II source projects summary.

Mix ID	Stabilizing/ Recycling Agent	Active Filler	Process	State	Project Description	Agent Content, %	Active Filler Content, %	Target Density, lb/ft^3
1	Emulsified asphalt	Cement	CCPR	IN	SR 101	2.5	1.0	128.0
2				VA	I-64 Segment II	2.5	1.0	128.0
3			FDR	TX	I-10	4.5	1.1	135.0
4				CA	UCPRC Test Track	2.5	1.0	128.0
5		No cement	CCPR	NY	Courtland	3.0	0.0	134.0
6				VA	I-64 Segment II	2.5	0.0	128.0
7			CIR	ON	Huron County, Road 87	1.2	0.0	121.5
8			FDR	IN	Shelby County, SR 252	2.5	0.0	118.0
9				CA	UCPRC Test Track	2.5	0.0	128.0
10	Foamed asphalt	Cement	CCPR	VA	I-64 Segment II	2.5	1.0	128.0
11			CIR	CA	Hayward, Soto Road	2.0	1.0	124.8
12				MA	Southwick	2.5	1.0	129.5
13			FDR	TX	FM 1245, Groesbeck	2.4	1.5	124.8
14				CA	UCPRC Test Track	2.5	1.0	128.0
15		No cement	CCPR	VA	I-64 Segment II	2.5	0.0	128.0
16			CIR	MI	Jackson County, Rosehill Road	2.2	0.0	130.0
17				WI	Douglas County, STH 35	2.0	0.0	121.5
18			FDR	CA	UCPRC Test Track	2.5	0.0	128.0

asphalt, the emulsion (kept at a temperature of 40°C) was added directly during the mixing process. For those mixtures using foamed asphalt, a Wirtgen WLB10S laboratory foaming unit produced the foamed asphalt at a temperature of 163°C. Once the emulsified or foamed asphalt, mixing water, and active filler (if used) were combined, the mixed materials were transferred to a slab compactor to fabricate the slab specimens.

The following example calculations demonstrate how the quantities for mixing a batch of material were determined. Two examples are shown, one for foamed asphalt materials and the other for emulsified asphalt materials. For each example, 1.0% cement was included, the RAP had an "in-the-bucket" moisture content of 2.4%, and the optimum moisture content was 4.0%. For the foamed asphalt example, a binder content of 2.0% was assumed. For the emulsified asphalt example, a binder content of 2.5% (⅔ residual binder, ⅓ water) was assumed. The actual mix design from each project was used when the test specimens were made.

Foamed asphalt materials:

1. Weigh RAP (assume a batch weight of 25 kg) and account for existing moisture of 2.4% = 25,000 g + 2.4% = 25,600 g.
2. Add 1.0% cement based on mass of dry RAP = 25,000 × 1.0% = 250 g × 1.0% = 253 g.
3. Add water to reach an optimum moisture content of 4.0% = 25,600 × (4.0% − 2.4%) + 253 × 4.0% = 420 g.
4. Add 2.0% foamed asphalt based on mass of dry RAP = 25,000 × 2.0% = 500 g.

Emulsified asphalt materials:

1. Weigh RAP (assume a batch weight of 25 kg) and account for existing moisture of 2.4% = 25,000 g + 2.4% = 25,600 g.
2. Add 1.0% cement based on mass of dry RAP = 25,000 × 1.0% = 250 g × 1.0% = 253 g.
3. Calculate 2.5% emulsion mass based on mass of dry RAP = 25,000 × 2.5% = 625 g.
4. Calculate water to reach an optimum moisture content of 4.0% and subtract the water proportion (assumed as ⅓) of emulsion = 25,600 × (4.0% − 2.4%) + 253 × 4.0% = 420 g − 625 × (⅓) = 166 g.
5. Add 166 g of water.
6. Add 625 g of emulsion.

For foamed asphalt materials, the research team used the same PG 64-22 binder so that the foaming temperature and amount of foaming water would be the same. For emulsified asphalt materials, the research team used the emulsion supplied by the agency/contractor. The day prior to mixing, approximately 1,000 g of loose material was taken from a sealed 5-gal bucket and placed in a forced-draft oven set at 40°C until a constant mass was reached, and then the moisture content was calculated.

Each test slab had dimensions of 500 mm in length × 400 mm in width and a thickness of approximately 110 mm. To fabricate each slab, two batches of mixed materials were required. The batches were produced as follows:

1. Calculate the mass of parent material required for desired slab size and mix design density.
2. Using two mostly full 5-gal buckets of loose material, add one-half of each bucket to an 18-gal tub, and mix by hand. Transfer the contents of one 5-gal bucket into the other and empty the mixed contents of the 18-gal tub into the empty 5-gal bucket. Add the contents of the second 5-gal bucket to the 18-gal tub and mix by hand. Empty the 18-gal tub into the second 5-gal bucket.
3. Add and mix the contents of each 5-gal bucket in the pug mill for 1 minute. After mixing, empty the contents into a 50-gal tub.
4. Based on the desired slab density, calculate the amount of mixed material required. Place approximately equal portions of mixed material from the 50-gal tub into two 5-gal buckets.
5. Add enough loose material to the 5-gal buckets to account for the measured moisture content (determined as described previously).
6. Add the contents of one 5-gal bucket into the pug mill.
7. Add water if needed (calculated as described previously) and mix for 1 minute.
8. Add cement if needed (calculated as described previously) and mix for 1 minute.
9. If emulsion is used, add emulsion directly to the pug mill and mix for 1 minute. If foamed asphalt is used, spray the foam into the pug mill and mix for 1 minute.
10. Transfer contents to an empty 50-gal tub.
11. Repeat steps 6 through 10 for the second 5-gal bucket.

The slab specimens were prepared using an IPC Global/Controls Group Advanced Asphalt Slab Roller Compactor. The slab compactor used a roller head segment (having a radius of 535 mm) and applied the compaction load to the material by the specimen mold carriage moving back and forth under the roller head with the load applied in a pendulum-like action. The slab compactor was used since it could operate in a displacement control function so that the desired thickness of the test specimen could be set, and thus the approximate bulk density was controlled by adjusting the mass of material added.

After mixing in the pug mill, the mixed materials were transferred to the slab mold. The mixed material was added by hand, filling the corners first and then the lower edges to reduce the chances of having lower density in these areas.

The mixed material was rodded using a concrete molding rod until the material surface was below the maximum that could be accommodated by the slab compactor. For certain mixtures having higher densities, the height of the loose material exceeded the maximum that could be accommodated by the slab compactor (approximately 155 mm prior to compaction), and thus all slabs (regardless of initial height) were rodded. Following rodding, a sheet of heavy-duty aluminum foil was used to cover the rodded material to prevent it from sticking to the compactor roller head segment. No other lubricants or bond breakers were used. The slab compactor was set to compact using a displacement rate of 1 mm per pass until the machine had compacted the slab to the desired height of 110 mm.

Prior to the testing, the research team needed to determine the best way to produce the slabs and then handle them without causing damage. It was originally planned to demold the slabs after compaction but prior to testing. After the first few slabs were fabricated, it was observed that the slabs tended to crack during handling when removed from the mold, as shown in Figure 2.3. To counter this, a metal base plate was placed in the slab mold before the mixed material was added. The idea was that the metal base plate would support the slab while the slab was removed from the mold. The plate did assist with reducing handling damage, but it was soon discovered that any testing away from the center of the slab (especially at early ages) caused the slab to crumble because of a lack of confinement.

The research team next tried confining the slab by removing the slab from the mold and using metal plates along the edges of the slab. The metal plates were held together with a tie-down strap and wood blocks to hold the plates tight to the slab, as shown in Figure 2.4. It was discovered that the confinement pressure was variable and difficult to replicate. In addition, exploratory testing with a lightweight deflectometer (LWD) showed a large difference in stiffness properties depending on the amount of pressure applied by the tie-down strap. For these reasons, all testing was conducted within the fabrication mold.

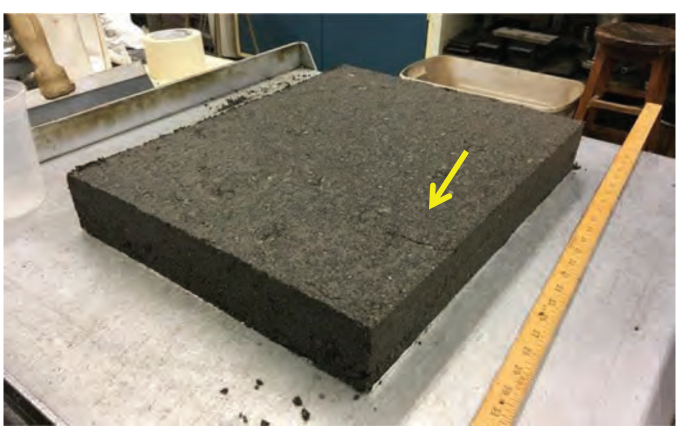


Figure 2.3. CCPR slab with arrow showing crack that formed during the demolding process.

Figure 2.4. LWD testing of slab confined using metal plates and confined with tie-down strap and wood blocks.

2.2.5 Slab Specimen Testing

A series of existing and newly developed tests capable of assessing the early-age condition of recycled materials were identified in Phase I. These tests, listed in Table 2.2, were grouped into the following material property categories: density, stiffness, penetration resistance, deformation

Table 2.2. List of properties and tests for Phase II testing.

Property	Suggested Test or Device
Density	Mass of dry material divided by slab volume
Stiffness	Soil stiffness gauge
	Lightweight deflectometer
Penetration resistance	Dynamic cone penetrometer
Deformation resistance	Marshall hammer
Shear resistance	Long-pin shear test*
Raveling resistance	Short-pin raveling test*
Moisture	Electromagnetic moisture probe

*Conceptual test proposed by the research team.

resistance, shear resistance, raveling resistance, and moisture. The density was assessed by dividing the mass of dry material by the slab volume. The stiffness of the recycled materials was assessed by using a commercially available LWD and soil stiffness gauge (SSG). The penetration and deformation resistance were assessed using a commercially available dynamic cone penetrometer (DCP) and a Marshall hammer (MH) assembly having a 4-in.-diameter foot, respectively. Shear and raveling resistance were assessed using custom-fabricated fixtures developed during the project. Moisture was assessed using an electromagnetic moisture probe. Tests were conducted on single or replicate slabs; the number of replicates varied depending on the test conducted.

All tests were conducted within the slab specimen compaction mold. This was necessary since recycled materials tend to be susceptible to damage during handling, especially at early ages and when unconfined. It was recognized that there were likely some unaccounted edge effects that could influence the magnitude of the test results. However, the purpose of the Phase II laboratory testing was to assess the response of the various test methods with respect to changes in material properties in the laboratory. It was expected that trends in the measured responses in the laboratory and during field testing would be similar.

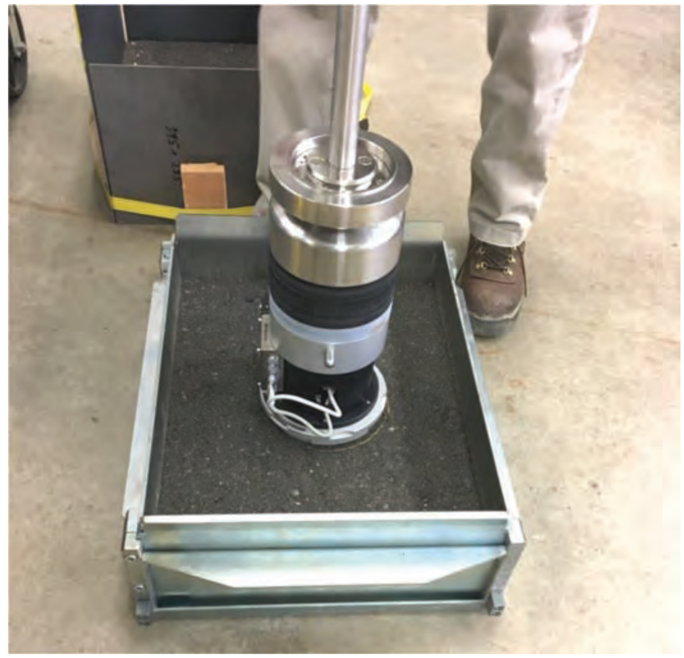


Figure 2.5. LWD test conducted at the center of a test slab.

2.2.5.1 Stiffness Tests

Stiffness testing was completed using commercially available LWD and SSG devices. Both devices were used to calculate the stiffness of the test slabs at 2 and 72 hours after slab fabrication. The time that the slabs were fabricated was used to denote the start of the curing time. For LWD testing, a known load pulse was applied to induce a deflection on a test slab surface, as shown in Figure 2.5. The vertical movement of the surface was measured directly under the LWD with a 6-in.-diameter load plate and a fixed center deflection sensor. The deflection measurements were then used to determine the surface deflection modulus (stiffness) of the test slabs using Equation 1:

$$E_0 = \frac{f * \sigma_0 * a * (1 - \nu^2)}{d} \quad (1)$$

where E_0 is a surface deflection modulus; f is a factor for stress distribution, taken as 2 for the measurements in this study; σ_0 is a stress under the LWD plate; ν is Poisson's ratio (assumed to be 0.35); a is the radius of the plate; and d is the center deflection under the LWD.

The test variability was reduced when a total of 10 drops were used for each test, with the average of the last three drops being reported. The drop height required to complete the test at early ages without plastically deforming the material was investigated, and it was found that drop heights ranging from 4 in. to 12 in. produced similar test results (using a 10-kg mass). All testing with the LWD was completed using a drop height of 12 in. This height/mass combination applied a force of approximately 800 lbf and a pressure of approximately 35 psi.

The SSG uses an electromechanical vibration to impart a small dynamic load as low-frequency sound waves on the surface of a test slab. The resulting surface deflection as a function of frequency is measured. The test surface vibration is applied between 100 Hz and 196 Hz at 4-Hz increments, producing 25 steady-state frequencies. The magnitude of the applied force is about 9 N, and the induced deflections are less than about 0.00005 in. The stiffness of the test slab is determined for each of the 25 frequencies, and the average value from these measurements is reported as the stiffness. Three replicates of the SSG test were performed at the center of a test slab by rotating the device approximately 120° between tests, and the average stiffness value of the three replicates was reported.

2.2.5.2 Moisture Content Tests

Moisture content testing was conducted using a recently developed commercial electromagnetic moisture device. The device was manufactured to be used in conjunction with a low-level NDG. Since the device could not be driven into the

Figure 2.6. Moisture testing.

test slab itself, the probe end was inserted into a hole created by driving a metal rod (like that used for nuclear density testing in the direct transmission mode) into the test slab or by using the hole that remained after dynamic cone penetrometer testing. Figure 2.6 shows the device and data collection unit. Not shown in Figure 2.6 is the probe sensor, which is inserted into the test slab and is the same size as the probe rod of an NDG.

2.2.5.3 Penetration Resistance Tests

The penetration resistance of the recycled material was measured using an MH assembly and a commercially available DCP (conforming to the requirements of ASTM D6951). DCP testing was conducted by placing the DCP on top of the recycled slab and then dropping the 8-kg mass 575 mm and recording the penetration after each drop. Testing was conducted at 2 and 72 hours after compaction using the same slabs used during stiffness testing, and again at 1 and 24 hours after compaction for the same test slabs used during raveling testing (discussed in the following sections). DCP testing was conducted by placing the tip of a fixed cone on the recycled slab. The penetrated depth was recorded with each blow, starting at a penetration of zero.

An MH assembly with a 4-in.-diameter foot and a 17.6-lb sliding weight falling 22.6 in. was used, as shown in Figure 2.7. The test procedure included dropping the weight on a location 20 times with recording of the penetration depth every five drops. The penetration depth was measured using a digital caliper with an external depth blade. The penetration depth was measured at three locations along a line (at approximately a 1-in. spacing) across the full diameter of the penetrated area, as shown in Figure 2.7. MH testing was conducted at 2 and 72 hours after compaction on the same test slabs used during stiffness testing.

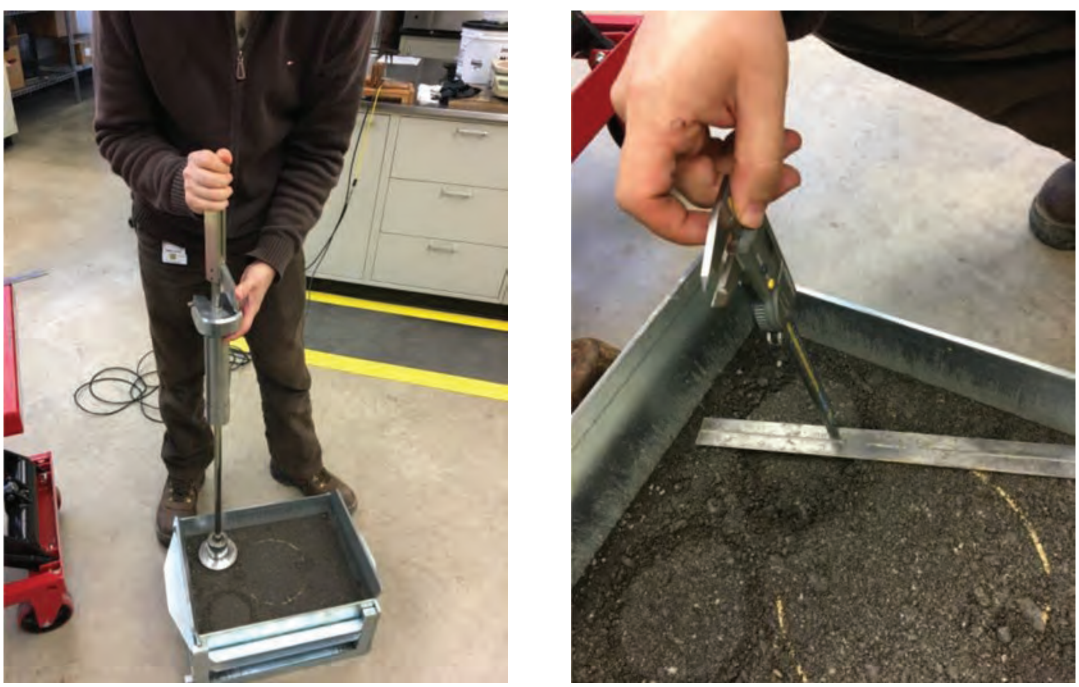


Figure 2.7. Marshall hammer testing of a recycled slab* (left) *and penetrated area measurement* (right)*.

2.2.5.4 Shear and Raveling Tests

Shear resistance was assessed using a developed fixture that could be driven using the upper assembly of a standard DCP. The developed prototype shear fixture, shown in Figure 2.8, consisted of a steel base plate approximately 5 in. square with four outer pins (each 13⁄32-in. in diameter, extending 3.0 in. from the base plate) located along four points of a circle approximately 3.5 in. from a ½-in.-diameter, center pin that extended 3.0 in. from the base plate. The test performed with this fixture was termed a "long-pin shear test." The term "long-pin" is used to differentiate this fixture from a similar-looking fixture with shorter pins used to assess raveling resistance.

To conduct the test, the shear test fixture was driven into the test slab until the plate seated on the surface, using the upper assembly of a DCP that fits over the center shaft on top of the fixture base plate, as shown in Figure 2.9. The center shaft had a diameter of 1.0 in. with a hexagonal head milled into it so that a ¾-in. socket could be attached to the center to accommodate a handheld torque wrench. After the fixture was driven in and the number of blows until the base plate touched the slab surface was recorded, the operator used a torque wrench to apply a rotational force, as shown in Figure 2.10. The maximum torque reading was recorded. The length of pins was intentionally chosen to match the approximate minimum thickness of a recycled layer (approximately 3 in.). Pins were included in the fixture design, rather than solid vanes, to reduce damage to the recycled layer caused by testing.

The raveling resistance of the recycled materials was assessed using a modified version of the shear test fixture. The raveling fixture is similar to the shear test fixture, but the outer pins used for the raveling test extend 1.0 in. from the base plate, as shown in Figure 2.11. The test performed with this fixture is termed a "short-pin raveling test." The length of pins was chosen to be similar to the likely maximum particle size of most recycled materials (approximately 1 in.). The test procedure was essentially the same as the long-pin shear test in that the upper assembly of a DCP was used to drive the raveling test fixture into the test slab, as shown in Figure 2.12. To maintain a constant normal force that kept the short pins from riding up onto the slab surface, two 10-lb plates were added on top of the raveling test fixture to apply a normal force. The operator used a torque wrench to apply

Figure 2.9. Upper assembly from a DCP used to drive the long-pin shear test fixture.

Figure 2.8. Prototype long-pin shear test fixture.

Figure 2.10. Measuring torque with long-pin shear test fixture.

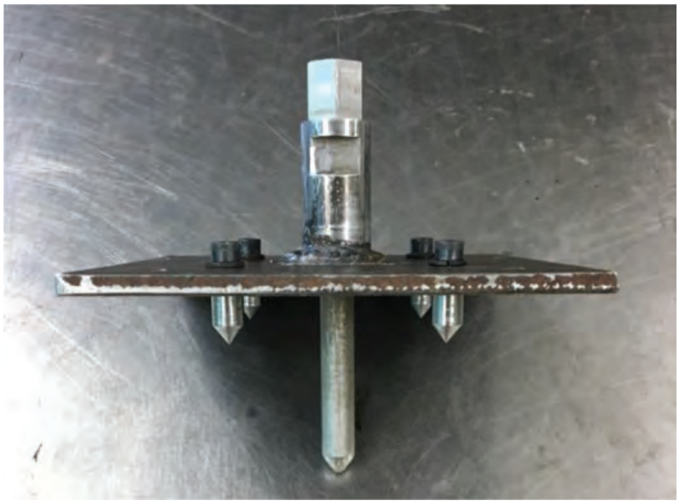


Figure 2.11. Prototype short-pin raveling test fixture.

a rotational force, as shown in Figure 2.13, and the maximum torque reading was recorded.

Since the raveling fixture pins were of different lengths, two separate blow counts were recorded for the short-pin raveling test, as described in the following. The number of blows required to drive the fixture to the tip of the shorter outer pins was counted and denoted N_1. The cumulative number of blows required to drive the entire fixture to the level of the base plate was recorded and denoted N_2. The number of blows to these various positions was recorded in case one measurement proved to be a more significant predictor of performance than another.

Figure 2.12. Applying blows using DCP upper assembly with short-pin raveling test fixture.

Figure 2.13. Applying torque to measure raveling resistance.

2.2.5.5 Other Tests Considered

Several other tests were considered for the laboratory experiment but ultimately were not chosen by the research team. These tests included penetration resistance tests using a rapid compaction control device, a stiffness test using a Clegg hammer, stiffness assessment using an ultrasonic pulse velocity and portable seismic pavement analyzer, a raveling/abrasion test using the Wet Track Abrasion Test and cohesion testing (ASTM D3910), and a cohesion test with a field-portable pneumatic cohesion tester (based on the ASTM D3910 cohesion test). Ultimately, these tests were not selected because of issues such as limited device availability, incompatibility with early-age properties of the recycled material, and difficulties with demonstrating expected performance trends with changes in material properties. These tests, which were not part of the laboratory experiment, are not discussed further in this report.

2.2.5.6 Test Arrangement

Three sets of test slabs from each project were fabricated to accommodate all the tests. For each project, single slabs or replicates were fabricated depending on the amount of loose material available. The first set of slabs was fabricated to facilitate moisture, stiffness, and penetration resistance testing. The second set was used for stiffness (by LWD only) and shear resistance testing. The third set of slabs was used for stiffness (by LWD only), DCP, and raveling testing. The three sets of tests were conducted to maximize the amount of information that could be collected while reducing the potential for one test to influence another.

Moisture, stiffness, and penetration resistance testing was conducted on the first set of slabs. The tests were arranged on the slab so that one slab could be used to support multiple tests at two curing times (2 and 72 hours after slab fabrication), as shown in Figure 2.14. At the 2-hour test, LWD and then the SSG tests were conducted at the center of the slab. Next, the MH was used for penetration resistance testing at two corner locations on one side of the slab (e.g., upper left and lower left, as shown in Figure 2.14). The tests were conducted such that the MH foot was approximately 2 in. from any edge of the slab. Following this, the DCP was used at approximately the midpoint between the two MH tests and approximately 4 in. from the edge of the slab. Moisture content measurements with the moisture gauge were taken in the hole left after the DCP test. At the 72-hour test, the LWD and SSG tests were again conducted at the center of the slab. The MH, DCP, and moisture tests were then conducted at the end of the slab opposite to the end used in the 2-hour test. Moisture contents at the 2-hour test were compared to the moisture content during mixing, and the moisture content at the 72-hour test was compared to the moisture content of a sample taken from the slab after all tests were completed and then dried in an oven.

Stiffness and shear resistance tests were conducted on the second set of slabs. These tests were arranged differently since the shear test is destructive. Two or three replicate slabs were prepared from each source project. Tests were conducted on each slab at 1, 3, 6, and 24 hours after compaction. The LWD test was conducted first, followed by the shear test at the same location. At each curing time, a different corner of the slab was tested. Figure 2.15 is a schematic of the test locations.

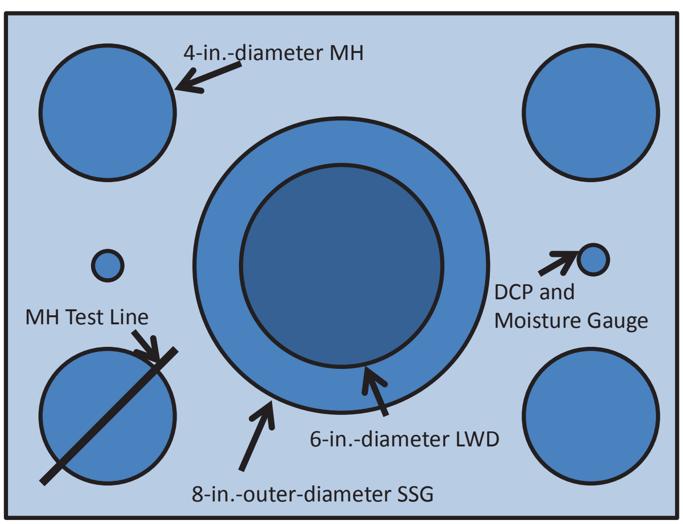


Figure 2.14. Test locations for laboratory-fabricated slabs for stiffness and penetration resistance tests (400 mm × 500 mm), shown to scale.

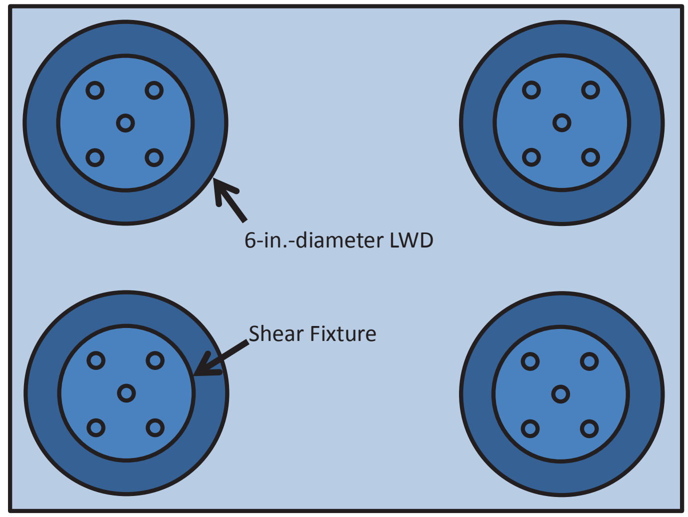


Figure 2.15. Test locations for laboratory-fabricated slabs for shear tests (400 mm × 500 mm), shown to scale.

Stiffness, DCP, and raveling tests were conducted on the third set of slabs in a similar way to those performed on the shear test slabs. One or two replicate slabs were prepared from each source project. Tests were conducted on each slab at 1, 3, 6, and 24 hours after compaction. The LWD test was conducted first, followed by the raveling test at the same location. At each curing time, a single measurement using the LWD and raveling fixture were conducted in a different corner of the slab. The DCP test was conducted adjacent to the longest dimension of the slab at 1 and 24 hours only. Figure 2.16 is a schematic of the test locations.

2.3 Phase III—Field Testing

Testing to assess the short-term properties of recycled materials on nine field projects in the United States was conducted at the locations shown in Figure 2.17. The field projects included CIR, CCPR, and FDR using either emulsified or foamed asphalt as the stabilizing/recycling agent with and without cement as an active filler. The projects were completed by multiple contractors using different source materials and were located in different climatic regions.

2.3.1 Objectives

Phase III field testing was conducted to assess the most applicable tests from Phase II and to determine the appropriate

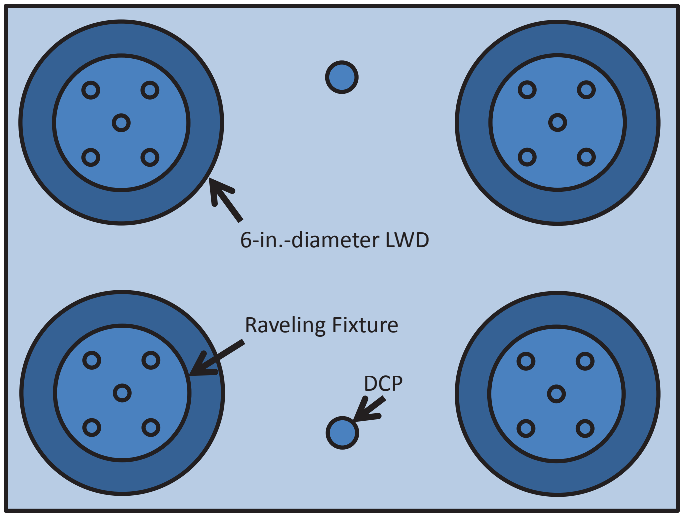


Figure 2.16. Test locations for laboratory-fabricated slabs for raveling tests (400 mm × 500 mm), shown to scale.

limits of the tests for identifying time to opening or surfacing. The research team tested multiple locations within the same project when changes in material properties were observed.

In addition to the test assessment, a field-based preliminary interlaboratory study (ILS) was performed at one project location to obtain an indication of the precision of the test methods. It was impractical to ship (and receive undamaged) test slabs produced in the laboratory to other research team members while maintaining curing conditions. So the ILS was conducted in the field, as has been done with previous studies on the DCP and for fresh properties of Portland cement concrete. Lessons learned, draft methods of test, and precision statements were developed from this Phase III testing.

2.3.2 Field Project Summary

Table 2.3 shows a summary of the Phase III field projects. All testing was done during the 2019 construction season. The additive and filler contents shown in Table 2.3 were obtained from the material mix designs that were completed by the contractor or agency. Either a contractor or an agency representative used an NDG to measure the field density within or near the test location; the measured field densities are shown in Table 2.3.

2.3.3 Test Block Layout

At each field project, the research team met with agency and contractor representatives to discuss the goals of testing and the specific locations available that day. All testing was conducted by members of the research team, but considerable logistical support was provided by the local agency and contractor representatives. All tests were performed within test blocks that were approximately 4 ft (in the direction of traffic) by 2 ft (perpendicular to the direction of traffic), as shown in Figure 2.18. Within each test block, one field density test and three replicates of stiffness (LWD and SSG), DCP, shear (torque and number of blows), and raveling (torque and number of blows) were conducted. Based on the results of laboratory testing, MH testing was not conducted at the field projects. For several of the early projects, moisture tests were also conducted in the same hole following the DCP tests. Where possible, replicate test blocks were used to gain knowledge of test variability at multiple locations. An NDG was not available for every testing block, so selected test blocks were located near previously performed field density tests. All tests within each test block were completed within approximately 30 minutes.

2.3.4 Testing Details

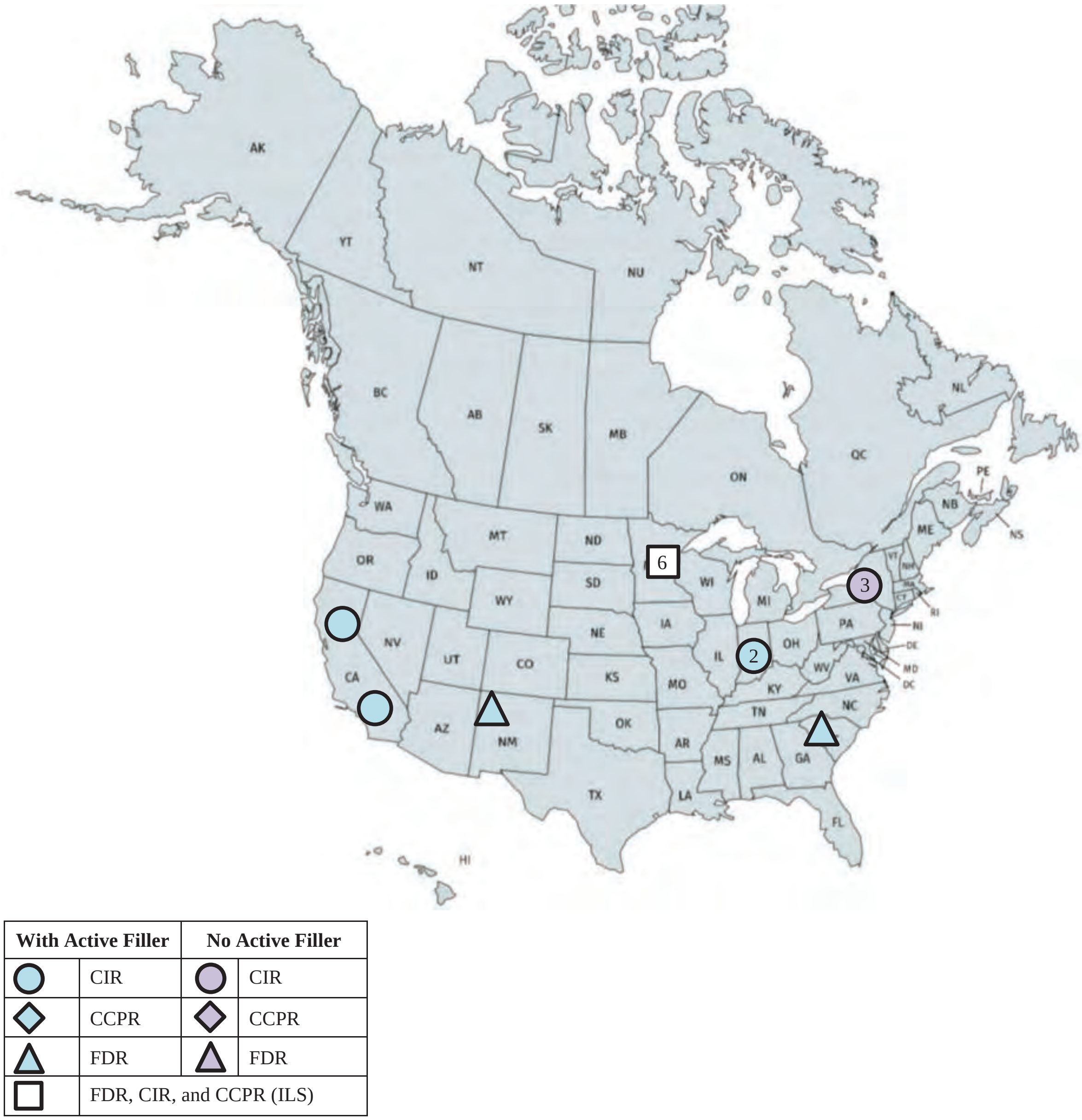
The research team conducted at least one test block at selected curing times ranging from 0.5 hour to 48 hours after the contractor completed the compaction process at the selected test location within the project. Table 2.4 shows the curing times and number of replicate test blocks for each field project.

Table 2.5 shows the distribution of testing by process and material type. From Table 2.5, the total number of sections exceeds the number of sites visited since multiple sections were tested at some projects. A total of eight unique process and material combinations were assessed from testing 14 sections and 51 test blocks.

2.4 Repeatability and Reproducibility of Field Raveling and Shear Tests

A preliminary evaluation of repeatability and reproducibility of the raveling and shear tests developed in this research was conducted by means of a ruggedness evaluation and an ILS in accordance with ASTM C802. In accordance with ASTM E1169 and ASTM C1067, the ruggedness evaluation was needed prior to the ILS since the raveling and shear tests were newly developed. Once completed, a precision statement was prepared for each test.

A ruggedness evaluation is a controlled experiment where factors or test conditions are varied to evaluate their effect on the test response. Examples of factors that were initially considered include test temperature, lift thickness, load/torque applied, and test equipment apparatus physical characteristic dimensions or rates. For each factor, variations or levels were determined at the expected extreme values for each level, and the respective test was conducted. If the impact of level variation due to operating conditions and tolerances proved



Numbers in shapes indicate number of projects/processes tested if more than one.

Figure 2.17. Project locations for Phase III.

Table 2.3. Phase III project summary.

State	Project	Nearest Town	Process	Agent	Agent Content, %	Active Filler	Active Filler Content, %	Field Density, lb/ft^3
NY	Route 30	Andes	CIR	Emulsion	2.5	None	0.0	129.1
	Route 28	Meredith		Emulsion	3.0			141.0
	Route 23A	Prattsville		Foam	2.8			131.9
MN	70th Street	Albertville	CCPR	Foam	2.3	Cement	1.0	133.8
				Emulsion	3.5	None	0.0	131.3
			CIR	Foam	2.3	Cement	1.0	130.6
				Emulsion	2.8	None	0.0	129.0
			FDR-HD	Emulsion	3.0	Cement	1.0	133.0
			FDR-LD	Emulsion	3.0	Cement	1.0	117.3
SC	SC 123	Clemson	FDR	Foam	2.3	Cement	1.0	119.4
IN	SR 1	Ft. Wayne	CIR-GS	Emulsion	2.5	None	0.0	122.5
			CIR-PS	Emulsion	2.5	None	0.0	122.5
CA	SR 178	Ridgecrest	CIR	Emulsion	3.4	Cement	0.5	121.6
NM	U.S. 491	Tohatchi	FDR	Foam	2.0	Cement	1.0	134.0
CA	SR 22	Woodland	CIR	Foam	2.2	Cement	1.0	127.9

Notes: FDR-HD = full-depth reclamation, high density; FDR-LD = full-depth reclamation, low density; CIR-GS = cold in-place recycling, good support; CIR-PS = cold in-place recycling, poor support.

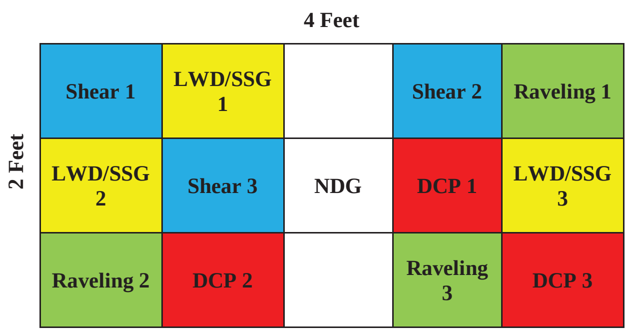


Figure 2.18. Phase III test block layout.

Table 2.4. Phase III project testing details.

State	Project	Process	Curing Time	No. of Replicate Test Blocks
NY	Route 30	CIR E-N	1 hour	2
			24 hours	2
	Route 28	CIR E-N	1 hour	1
			48 hours	1
	Route 23A	CIR F-N	1 hour	1
			18 hours	1
MN	70th Street	CCPR F-C	1 hour	3
		CCPR E-N	1 hour	3
		CIR F-C	1 hour	3
		CIR E-N	1 hour	3
		FDR E-C HD	3 hours	3
		FDR E-C LD	3 hours	3
SC	SC 123	FDR F-C	1 hour	2
			4 hours	1
IN	SR 1	CIR E-N GS	1 hour	1
			3 hours	1
			6 hours	1
			24 hours	1
IN	SR 1	CIR E-N PS	1 hour	2
			3 hours	1
			6 hours	1
			24 hours	1
CA	SR 178	CIR E-C	1 hours	1
			1.5 hours	1
			3 hours	1
NM	U.S. 491	FDR F-C	0.5 hours	2
			2 hours	1
			3 hours	1
			4 hours	1
			24 hours	2
CA	SR 22	CIR F-C	2 hours	1
			6 hours	1
			24 hours	1

Notes: CIR E-N = cold in-place recycling, emulsion, no cement; CIR F-N = cold in-place recycling, foam, no cement; CCPR F-C = cold central-plant recycling, foam plus cement; CCPR E-N = cold central-plant recycling, emulsion, no cement; FDR E-C = full-depth reclamation, emulsion plus cement; FDR E-C HD = full-depth reclamation, emulsion plus cement, high density; FDR E-C LD = full-depth reclamation, emulsion plus cement, low density; CIR E-N GS = cold in-place recycling, emulsion, no cement, good support; CIR E-N PS = cold in-place recycling, emulsion, no cement, poor support.

Table 2.5. Phase III total number of sections and test blocks by process.

Process	Agent and Filler	No. of Sections	No. of Test Blocks
CCPR	F-C	1	3
	F-N	–	–
	E-C	–	–
	E-N	1	3
CIR	F-C	2	6
	F-N	1	2
	E-C	1	3
	E-N	4	18
FDR	F-C	2	10
	F-N	–	–
	E-C	2	6
	E-N	–	–
Total number of sections			14
Total number of test blocks			51
Total number of unique process/material combinations			8

Notes: F-C = foam plus cement; F-N = foam, no cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

to be too great, the test method needed to be refined further or the tolerance reduced prior to performing an ILS.

Following the ruggedness evaluation, an ILS was conducted to generate precision statements for the newly developed test methods in accordance with ASTM C802. For this study, multiple laboratories were represented by three institutions in the research team. Multiple materials were assessed at the field-testing site at the MnROAD test track in August 2019 (as shown in Figure 2.17).

The ILS is termed "preliminary" because it was not possible to fulfill all of the requirements of ASTM C802, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials, which include a valid written test method, a ruggedness test prior to the ILS, and a minimum of 10 participating laboratories. Proposed test methods were written for each test, ruggedness tests were conducted for each test, and at least six materials were used per test method. However, only three laboratories participated because the tests were new and commercially available equipment was not available. Also, the ILS was conducted in the field rather than in a laboratory. This was done because of the difficulty associated with preparing, shipping, and testing undamaged slabs.

2.4.1 Ruggedness Evaluation

A ruggedness evaluation was performed using a single material for both the shear and raveling test methods in accordance with ASTM C1067-2, Standard Practice for Conducting a Ruggedness Evaluation or Screening Program for Test Methods for Construction Materials. The laboratory testing conducted as part of Phase II and engineering judgment by the research team were used to identify potentially influential factors. Optimally, a ruggedness evaluation would

Table 2.6. Raveling test factors and levels for ruggedness evaluation.

Level	Factor				
	Outer Pin Length, in.	Pin Tip Angle, °	Applied Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.
Level 1 (+1)	0.85	70	90	Sharp	1/2
Level 2 (−1)	0.65	50	60	Dull (0.1 in.)	13/32

Table 2.7. Shear test factors and levels for ruggedness evaluation.

Level	Factor				
	Length, in.	Tip Angle, °	Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.
Level 1 (+1)	3.1	85	90	Sharp	1/2
Level 2 (−1)	2.9	65	60	Dull (0.1 in.)	13/32

assess each influential factor both independently and interdependently using full factorial designs. However, this was not possible given the time and material resources required. Thus, a partial factorial experiment was designed in accordance with ASTM C1067. This standard provides clear direction for the design of a ruggedness evaluation for construction materials using the Plackett-Burman design.

2.4.1.1 Ruggedness Evaluation Factors and Levels

Eight specimens were prepared and tested using a single material for each evaluated test. Per a Plackett-Burman design, up to seven factors could be considered, with each factor having two levels. In the ruggedness evaluation experimental design, a partial factorial was developed by varying the combinations of factor upper and lower levels among the eight specimens.

Tables 2.6 and 2.7 show the factors and levels for the raveling and shear tests, respectively. The factor and level combinations were randomly assigned to different slabs as part of an experimental design. The factors investigated included length of the outer pins, pin tip angle, angular rate applied to the torque wrench, tip dullness, and outer pin diameter. The tip dullness was adjusted by first performing the tests with a sharp tip and then grinding off approximately 0.1 in. of the tip to a more flattened tip. Tables 2.6 and 2.7 indicate two levels, denoted with plus (+) and minus (−) signs. A plus (+) sign for a given factor indicates that the measurement was made with that factor at the high level, and a minus (−) sign indicates the factor was at a low level. The factors and values for each level were determined based on the results of concurrent laboratory testing in Phase II, limited field testing, and the engineering judgment of the research team. Tables 2.8 and 2.9 show the associated experimental

Table 2.8. Raveling test experimental design for ruggedness evaluation.

Specimen	Factor				
	Length, in.	Tip Angle, °	Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.
Specimen 1	+1	+1	+1	–1	–1
Specimen 2	–1	+1	+1	+1	+1
Specimen 3	–1	–1	+1	+1	–1
Specimen 4	+1	–1	–1	+1	+1
Specimen 5	–1	+1	–1	–1	+1
Specimen 6	+1	–1	+1	–1	+1
Specimen 7	+1	+1	–1	+1	–1
Specimen 8	–1	–1	–1	–1	–1

Table 2.9. Shear test experimental design for ruggedness evaluation.

Specimen	Factor				
	Length, in.	Tip Angle, °	Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.
Specimen 1	+1	+1	+1	–1	–1
Specimen 2	–1	+1	+1	+1	+1
Specimen 3	–1	–1	+1	+1	–1
Specimen 4	+1	–1	–1	+1	+1
Specimen 5	–1	+1	–1	–1	+1
Specimen 6	+1	–1	+1	–1	+1
Specimen 7	+1	+1	–1	+1	–1
Specimen 8	–1	–1	–1	–1	−1

designs for the raveling and shear test methods, respectively. The ruggedness study was conducted in accordance with ASTM E1169, Standard Practice for Conducting Ruggedness Tests.

2.4.1.2 Slab Preparation for Ruggedness Test

Slabs prepared using RAP from Lockwood, Nevada, and PASS-R emulsified asphalt were used to conduct the ruggedness evaluation. Oven-dried RAP was mixed with 3% water and 4% emulsion (2.4% residual bitumen) until uniformly coated. The optimum moisture content and emulsion content were selected by comparing strength test results for specimens prepared in a gyratory compactor. For the shear tests, a Vibroplate compactor was used to compact the mixture to a target density of 130 lb/ft^3 in a mold having dimensions of 24 in. × 59 in. × 3.5 in. Test slabs for raveling tests were fabricated in the same manner, but the molds had dimensions of 24 in. × 30 in. × 3.5 in. For the shear test, the length of the mold was increased from 30 in. to 59 in. so that all the experiments could be performed on the same slab with minimum disturbance from previous tests. The molds were anchored to the concrete floor, as shown in Figure 2.19. All the shear and raveling tests were conducted after 4 hours of curing at ambient conditions. The slabs were cast outside and exposed directly to the sun.

Figure 2.19. Compacted slab for ruggedness evaluation.

2.4.2 Interlaboratory Study

The research team conducted an ILS to develop preliminary precision statements for the shear and raveling tests developed in this study. The term "preliminary" is used since only three laboratories participated in the ILS. The ILS was conducted in accordance with ASTM C802 and ASTM C670, Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials. During the ILS, DCP tests were conducted in addition to the shear and raveling tests, allowing precision statements to be prepared for this test.

ASTM C802 outlines the following general requirements for an ILS:

1. A valid and well-written test method;
2. Established tolerances for various conditions in each test method (e.g., from a ruggedness study);
3. Clearly defined and an available apparatus for performing the test;
4. Personnel in participating laboratories with adequate experience;
5. Preliminary knowledge of how changes in materials and conditions affect the test results;
6. Procedures and facilities for obtaining, preparing, and distributing test specimens;
7. Randomized selection of test specimens for distribution to laboratories;
8. Application of the test method on materials with a range of properties representative of the characteristics for which the method will be used;
9. Adequate number of participating laboratories, with at least 10 recommended; and
10. At least three materials or materials with three different average values of the measured test characteristic.

For this study, the research team was unable to satisfy requirements 6, 7, and 9. Requirements 6 and 7 could not be satisfied because the research team could not distribute samples to participating laboratories without damaging the samples because of the nature of the material and the effects of transportation and aging. However, within ASTM C802, a provision exists that operators can convene at one location if material cannot be distributed. The research team incorporated this provision by performing all testing near the MnROAD test track as part of another ongoing study on a portion of 70th Street in Albertville/Oswego, Minnesota. At this location, multiple recycling processes and stabilizing/recycling agents were used on the roadway to better understand their performance as a pavement rehabilitation technique. An example of the preconstruction condition is shown in Figure 2.20.

Figure 2.20. Preconstruction view of 70th Street, Albertville/Otsego, Minnesota.

The research team for this study was able to conduct the ILS during this unique opportunity. Requirement 9 was left unsatisfied since the number of member institutions on the research team was less than the required number and the developed tests were not yet commercially available. A photograph of the research team members conducting the ILS is shown in Figure 2.21.

Figure 2.21. Members of research team conducting ILS.

2.4.2.1 Experimental Design

The ILS was conducted on six unique pavement test sections. The test sections included CIR, CCPR, and FDR using emulsified or foamed asphalt, and some contained cement as an active filler. Table 2.10 illustrates the planned test sections; each test section was 500 ft long. Note that the larger MnROAD experiment included mill and fill and thinlay sections that were not tested by the research team. The initial plan was to conduct testing on both the eastbound and westbound lanes for cells 1 through 6. Because of weather restrictions and construction challenges, this was not feasible. Table 2.11 shows the recycling work that was completed and the five sections that were used during the ILS. The beginning of one section (FDR E-C) was found to have lower density than the remainder of the section using the nuclear density

Table 2.10. Proposed ILS test sections.

Direction	Test Section							
	1	2	3	4	5	6	7	8
Westbound	FDR F-C	FDR E-C	CIR F-C	CIR E-N	CCPR E-N	CCPR F-C	Mill & fill thinlay	Thinlay
Eastbound	FDR F-C	FDR E-C	CIR F-C	CIR E-N	CCPR E-N	CCPR F-C	Mill & fill thinlay	Thinlay

Notes: CIR E-N = cold in-place recycling, emulsion, no cement; CIR F-C = cold in-place recycling, foam plus cement. CCPR F-C = cold central-plant recycling, foam plus cement; CCPR E-N = cold central-plant recycling, emulsion, no cement; FDR F-C = full-depth reclamation, foam plus cement; FDR E-C = full-depth reclamation, emulsion plus cement.

Table 2.11. Actual ILS test sections.

Direction	Test Section							
	1	2	3	4	5	6	7	8
Westbound	–	–	–	–	–	–	CCPR F-C	–
Eastbound	FDR E-C	–	CIR F-C	CIR E-N	CCPR E-N	–	CCPR F-C	–

Notes: CIR E-N = cold in-place recycling, emulsion, no cement; CIR F-C = cold in-place recycling, foam plus cement; CCPR F-C = cold central-plant recycling, foam plus cement; CCPR E-N = cold central-plant recycling, emulsion, no cement; FDR E-C = full-depth reclamation, emulsion plus cement.

gauge. The research team completed testing in this area and considered it a sixth material type.

The research team established three adjacent test blocks in a random location along the length of the test section and in the center of the lane. Each of the three laboratories was randomly assigned to one of the test blocks. The location of each test within the test block was arranged in a way similar to that shown in Figure 2.18. Three replicate LWD, SSG, DCP, shear, and raveling tests were performed in each test block as soon as the test section was available following compaction. After all testing was complete, the roadway was reopened to traffic. From the collected data, the single-operator and multi-laboratory precision values were calculated.

CHAPTER 3

Findings and Applications

This chapter presents the results from the three phases of this research study. The results of the literature review are presented as they relate to the identification of existing and developing quality tests. The results of the laboratory and field testing are summarized and analyzed with respect to the ability of each test to detect changes in material behavior related to changes in stabilizing/recycling agent content and type, presence of an active filler, and curing time. The results of the ruggedness study and ILS are also presented.

3.1 Current and Emerging Quality Tests

The research team sought to identify current and emerging quality assessment and process control tests for cold recycled materials where emulsified asphalt or foamed asphalt serves as the stabilizing/recycling agent. This work was completed by reviewing the available literature, conducting a review of agency specifications, and conducting an online stakeholder survey.

3.1.1 Literature Review

The literature survey showed that the quality of recycled materials is most often assessed in the field during or just after construction by measuring the density and moisture content of the recycled layer. Other tests that are commonly performed on materials collected as either loose samples or plant-produced, laboratory-compacted specimens include the gradation of the recycled mixture, the determination of the stabilizing/recycling agent content, and various strength tests such as indirect tensile strength (ITS) and Marshall stability (Chen and Jahren 2007, Asphalt Academy 2009, Wirtgen 2010, Diefenderfer et al. 2015). Properties of the compacted recycled layer, such as stiffness, penetration, and shear resistance, and field versions of current laboratory-based tests have also been reported (VanFrank 2015).

The density of the recycled layer is most often measured using a nuclear density gauge. The density achieved during construction is usually compared to either a laboratory-based reference density (determined during mix design) or the density achieved for a test section completed prior to full-scale construction. Other options include comparing the field density to a field-measured standard such as a modified Proctor test, but this is less commonly employed. Density measurements have been shown to be somewhat correlated with stiffness properties of recycled materials (Schwartz et al. 2017), and the experience of the recycling community has suggested that poor density generally leads to poor material quality (Nataatmadja 2001, ARRA 2015). However, recent research has reported that density and permanent deformation resistance in the laboratory may not be well correlated (Bowers et al. 2018).

The moisture content of the recycled layer is most often measured using a nuclear density gauge or collecting a sample from the field for analysis in the laboratory by oven drying. The advantage to the former is that the nuclear density gauge is already used at the project for density measurements. There are a host of non-nuclear methods available that are reported less in the literature. These methods include electromagnetic methods (time-domain reflectometry/dielectric, frequency domain reflectometry/capacitance, amplitude domain reflectometry/impedance, phase transmission, and time-domain transmission) and tensiometric methods (matric suction). These alternatives can be helpful in that moisture measurements using the nuclear density gauge are affected by the hydrogen present in the asphalt binder. Moisture content measurements using the nuclear density gauge are often corrected by using an offset calculated from oven-based drying in the laboratory.

Deficient moisture content may inhibit the ability to achieve the compaction necessary for good performance. Excessive moisture not only may reduce the ability to achieve compaction but may also significantly delay the placing of any subsequent layer. Measurements of the recycled material's moisture content are often cited in specifications for determining the appropriate time to open a recycled layer to traffic or surfacing; however, it is unclear as to what maximum moisture content is permissible that will still achieve satisfactory performance of the constructed layer. Previous studies have suggested that as a recycled material loses moisture, the particle bonds are enhanced and strength properties increase (Mohammad et al. 2003, Bemanian et al. 2006, Lee and Im 2008, Lee et al. 2009, Kim et al. 2011, Tebaldi et al. 2014). Therefore, it is a concern of agency practitioners that a recycled layer not be surfaced or released to traffic too early so that permanent deformation of the recycled layer does not occur. However, the moisture content is truly only a proxy, as the desired parameter is the sufficiency of the recycled layer to carry loading without damage.

Agency specifications often require that a defined moisture content be achieved prior to surfacing or release to traffic. These requirements vary from a 2% reduction in the as-placed moisture content to a moisture content of half the optimum to as low as an in-situ measured value of 1% to 2% (Kim et al. 2011, Texas Department of Transportation [DOT] 2018, Woods et al. 2012). Rather than measuring the moisture content, certain agency specifications may require the contractor to wait a predetermined time prior to surfacing or release to traffic. These wait times may range from a few hours to more than 2 weeks (Woods et al. 2012). A problem with such wait time provisions is that they do not address ambient conditions that can significantly affect curing.

In addition to nuclear gauge measurements of the recycled material's moisture content, the oven drying method may be the most direct method. However, the results of the test are not available for up to 24 hours, making it more of a quality assurance than a quality control procedure. Some contractors and agencies may use an on-site propane burner, microwave drying, or calcium carbide gas pressure meter (Speedy) method for drying samples to obtain results in less time. Even with these additional methods, the paving process will be some distance away by the time the moisture content measurements are available, and the opportunity to provide a corrective action may be lost.

Lee and Im (2008), Lee et al. (2009), and Kim et al. (2011) explored the relationships between curing time and the results of various strength tests. After showing that recycled material strength generally increased with reductions in moisture content, they evaluated methods for assessing the moisture content to assess field curing. A handheld capacitance sensor and a portable time-domain reflectometry unit were used to assess the moisture content, along with an SSG and LWD to assess the stiffness and measure the modulus of the recycled layers, respectively.

Measuring the stiffness of the recycled material or the load carrying capacity of a pavement structure with recycled material layers is most often done using a falling weight deflectometer (FWD) (Diefenderfer and Apeagyei 2011). Deflection testing with an FWD is most often performed several days to weeks after construction as the stress applied can cause plastic deformation in a recently completed recycled layer (Schwartz and Khosravifar 2013). In addition to deflection testing with an FWD, the literature reports several other devices that could be used to assess the stiffness of the recycled material. These devices include the SSG, the LWD, the portable seismic pavement (or property) analyzer (PSPA), and Clegg hammer (Wilson and Guthrie 2011). In addition, penetration resistance may be assessed using a DCP (Sebesta et al. 2009).

The LWD is quickly becoming a popular device for field-based deflection testing of unbound layers primarily because of its portability and because its output is a fundamental engineering property (stiffness). An LWD operates on a principle similar to that of an FWD but at a much lower stress level. The LWD consists of a falling weight traveling on a guide rod with both attached to the center of a load plate. A deflection sensor within the load plate measures the deflection of the pavement layer caused by the falling weight, and from this the elastic modulus is calculated. Schwartz and Khosravifar (2013) and Meocci et al. (2017) used the LWD to study the placement of CCPR materials. They reported that the LWD was useful for this purpose and had the advantage of providing a direct engineering property (i.e., material stiffness).

Schwartz and Khosravifar (2013) used the LWD to evaluate the field stiffness gain of a CCPR material placed in Maryland. They found that the LWD was able to quantify the stiffness gain of the CCPR material, but they encountered operational issues with the LWD used in the study. By means of finite element analysis, the authors found that the zone of influence from the LWD was about twice the diameter of the loading plate. This is an important concept for all measurement devices but was seldom reported in the literature that was reviewed. Betti et al. (2017) also used the LWD to assess the stiffness of recycled layers soon after construction and followed up with the FWD to assess the stiffness at later curing stages.

Schwartz and Khosravifar (2013) discussed an aspect of deflection testing that is often overlooked: the zone of influence of the measurement. The zone of influence is the area within the pavement structure that responds to the stress applied during the test. The authors point out that the zone of influence from LWD testing may extend well beyond the depth of the recycled layer, especially for thinner applications. Another consideration is the ability of the deflection device to differentiate between the recycled layer and any adjacent asphalt mixture layer. It may be difficult to isolate completely the stiffness properties of the recycled layer in a multilayered pavement structure, as described by Diefenderfer et al. (2012, 2016b).

The SSG was developed as a low-cost and portable tool to assess the stiffness of compacted soils. The SSG operates by applying a vibrating force to the soil surface through a seating foot. The force and displacement–time history are measured and used to calculate the stiffness of the soil. Scullion (2002) used the SSG to study the stiffness change in soil–cement bases that were pre-cracked in an effort to reduce reflection cracking. Alshibli et al. (2005) and White et al. (2013) used the SSG as one of the tools to monitor the change in modulus with time and other properties for various compacted layers.

Schwartz and Khosravifar (2013) used the SSG to assess the stiffness of a CCPR layer placed in Maryland. By the fourth day after construction, they found the stiffness of the CCPR layer to be greater than the upper limit that can be measured by the SSG. Although reaching a measurement limit could be a concern for long-term monitoring of a recycled section, the time frame fits within the time window expected by the present research team for tests used in this study. Woods et al. (2012) show that an SSG could be used to assess the stiffness of a recycled layer such that the contractor could use the measurement to determine when an overlay should be placed. However, their study did not suggest stiffness values or changes in stiffness values that would identify optimal timing of the overlay.

The collection of cored samples from a project is perhaps the best way to ensure that the strength properties of only the recycled layer are assessed. Although core sampling permits direct testing of the materials in their as-placed and field-cured condition, there are several significant drawbacks. Core sampling is not a reliable method for obtaining test materials at early ages of the recycled layer. It is likely to be difficult to retrieve the cored sample until the recycled layer has cured sufficiently to withstand the coring process, approximately 4 weeks to 6 weeks after construction (Asphalt Academy 2009). With respect to testing once a core sample is retrieved, the most suitable test conditions are yet to be established. Recent research has shown that confinement has a significant influence on the stiffness and permanent deformation resistance properties of recycled materials (Diefenderfer and Link 2014, Schwartz et al. 2017), and this can be difficult to replicate for certain test geometries (especially indirect tensile). The ability to collect a sample of adequate size is also a concern and has given rise to several studies looking at alternative specimen sizes (Li and Gibson 2013, Bowers et al. 2015, Schwartz et al. 2017).

Another method for assessing the strength of the recycled layer is proof rolling. This procedure is most often used as a process control tool but is occasionally specified for acceptance. Its use as part of a process control or quality assurance program could be expanded if the test was standardized. Proof rolling can effectively identify deficient material issues and inconsistencies; however, there is no standard method to apply the test, and thus results are not currently transferable from one project to the next. A review of the literature found that work has been performed in Ohio, Pennsylvania, Texas, and Wisconsin and by the Federal Aviation Administration to standardize the process (Texas DOT 2001, City of Columbus 2012, Ohio DOT 2013, Federal Aviation Administration 2014, Pennsylvania DOT 2016). Crovetti and Schabelski (2002) discuss the development of an instrumented tandem-axle dump truck (instrumented to measure the resulting deformation), which, when loaded, can be used to automate a proof roll test. These references document proof rolling using either a heavy roller or a loaded truck with a gross vehicle weight ranging from 30 tons to 36 tons. Unacceptable permanent deformation values were noted as ranging from 0.5 in. to 1.5 in.

Ground penetrating radar (GPR) is a well-known but not frequently used device that can be used to assess the thickness of pavement layers (Maser and Scullion 1992, Maser et al. 2006, Holzschuher et al. 2007). For recycled pavement projects, GPR is used to assess the pavement thickness either prior to recycling operations to assist with the design of the pavement structure or after recycling in forensic applications (Loizos and Plati 2007, Mallick et al. 2007). Measuring the thickness of the layers postconstruction is especially beneficial during the analysis of FWD test results where changes in thickness can influence the calculated pavement structural capacity, as discussed in more detail in Diefenderfer and Apeagyei (2011).

In addition to thickness measurements, GPR has been used more recently to assess the density uniformity of asphalt mixtures by correlating the measured dielectric constant to the air-void content from collected cores (Al-Qadi et al. 2010, Leng et al. 2012). To date, this work has been performed on hot-mixed asphalt mixtures and not on cold recycled mixtures, but the principles of operation would be similar. Although not assessing the air-void content per se, GPR could be used as a tool to evaluate the uniformity of the layer by observing the changes in correlated air-void content. Recent advances in this area have been commercialized as a rolling density meter, which includes multiple GPR antennas either mounted on a pushcart or attached to a vehicle. Figure 3.1 shows examples of a GPR system equipped for pavement thickness testing and pavement density testing.

The DCP has also shown promise in the evaluation of unbound, fine-grained soils (Chen et al. 2001, Jersey and Edwards 2009, Kazmee et al. 2017) and recycled materials (Alghamdi 2016, Sargand et al. 2016). The DCP consists of a weight attached to a metal rod that ends with a penetration cone. The weight is dropped from a given height onto an

*Figure 3.1. GPR system for pavement thickness testing (*left*) and pavement density testing (*right*).*

anvil that pushes the cone into the test material. A connected scale measures the distance of penetration per drop, and this penetration has been correlated with strength parameters such as the California bearing ratio (Alghamdi 2016). Although there are many publications citing the use of DCP in unbound materials, its use for bound recycled materials is less common. Tingle and Jersey (1999) and Siddiki et al. (2008) provide guidance on using the DCP for acceptance of compacted material.

The PSPA has been used to measure fundamental properties of pavement layers by using wave propagation techniques. This is accomplished with a high-frequency wave propagation source and receiver accelerometers. The PSPA measures the seismic modulus of the surface pavement layer. Williams and Nazarian (2007) state that a primary benefit of measuring the moduli of pavement layers using the PSPA is the portability of the device; the main drawback is that the stress state imposed on the tested material is quite different (and significantly less) than that applied by a wheel load. Williams and Nazarian (2007) discuss the relationship between seismic modulus (at low strain levels) and resilient modulus (at higher strain levels) and report the relationship at low strain levels. From this, the prospects of using the PSPA for recycled materials (assuming a granular-like behavior) is promising, although it depends on the commercial availability of the device. A procedure for using the PSPA on FDR layers is presented by Mallick et al. (2007).

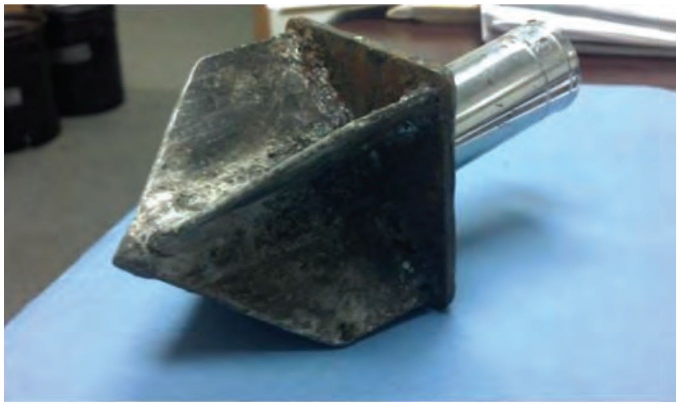
A test to assess the resistance to raveling has been used for some time in a laboratory setting. The specification, ASTM D7196, describes the procedure to assess the raveling resistance of CIR materials using a laboratory stand mixer applying a load to a rubber hose. The rubber hose abrades the surface of the CIR specimen, and mass loss is measured. This test is designed for a laboratory setting, but an alternative might be developed to make it field ready. These alternatives could be as simple as using the turning movement caused by the steering axle of a loaded truck to an oscillating/rotating load applied in a way that is like the laboratory test. Piratheepan et al. (2012) discussed a laboratory testing program to investigate the effect of curing on the raveling resistance of CIR mixtures in accordance with ASTM D7196. They stated that most agency specifications allow a maximum of 2% mass loss.

Other tests that were identified but that appear to need further development include a modified version of the laboratory abrasion test detailed in ASTM C944 using a studded wheel (Dong et al. 2010), a modified version of a cohesion test detailed in ASTM D3910 (Dong et al. 2010), a wire brush test detailed in ASTM D559, and a modified version of the emulsion-surface–treated sweep test detailed in ASTM D7000 (Johannes et al. 2011).

3.1.1.1 Recent Developments in Field Quality Testing of Recycled Materials

A series of research reports published by the Utah DOT details research investigating novel methods for assessing the quality of CIR mixtures (VanFrank et al. 2014, VanFrank 2015). Included among these methods are a shear vane test to assess stability properties, an MH-based field test to assess deformation resistance, and the use of the DCP to study penetration resistance. These reports are discussed herein in a separate section rather than by test type as they are the most comprehensive studies found in the literature with direct application to this study. Based on these studies, the Utah DOT states in its *Guidelines for Evaluation, Mix Design, and Field Acceptance of Cold Recycling of Asphalt Pavements Using Solventless Emulsion* that cold recycled materials shall be assessed for release to traffic by using the results of the shear vane and Marshall field tests (Utah DOT 2007).

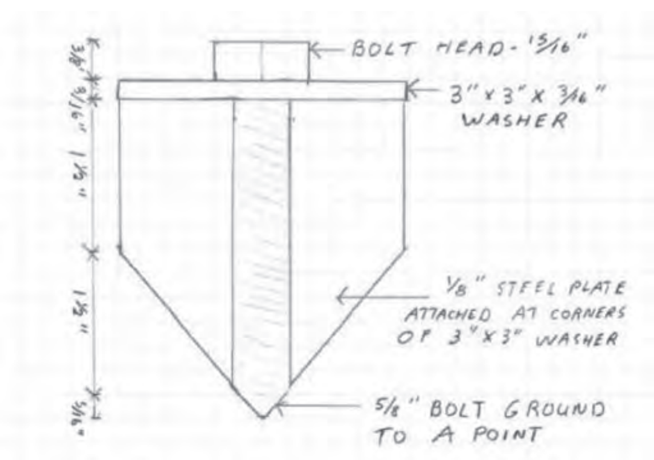
Figures 3.2 and 3.3 show a photograph and a schematic of the modified shear vane used by the Utah DOT, respec-



Source: Utah DOT 2017.

Figure 3.2. Utah DOT shear vane used for cold recycled materials.

tively. This modified shear vane is much more robust than similar products used for unbound materials and is made from a 3-in.-square steel washer having a 3⁄16 in. thickness, a 5⁄8-in.-diameter bolt that has the end fashioned to a point, and 1⁄8-in.-thick steel plate flanges welded to the bolt and the steel washer. The shear vane is hammered into a CIR layer using a 5-lb hammer until the top washer is flush with the surface. A torque wrench is attached to the bolt head using a standard socket, and torque is applied such that the end of the torque wrench travels 90° in 10 seconds. The greatest torque read on the dial of the torque wrench prior to the material breaking loose is recorded as the shear value (in foot-pounds) along with the pavement temperature at a depth of 2 in. VanFrank (2015) stated that the recycled layer was ready for traffic when a shear value of 30 ft-lb was obtained during field testing.



Source: Utah DOT 2017.

Figure 3.3. Schematic of Utah DOT shear vane used for cold recycled materials.

The Utah DOT (2017) also discussed the use of an MH to assess the time to release to traffic and the completion of compaction efforts. The test was conducted using an MH (as specified in AASHTO R 68) in the field, and 50 blows were applied to the surface of the recycled layer. The depth of penetration was measured with respect to the level of the undisturbed surface. The Utah DOT (2017) stated that the layer is not ready for final rolling and opening to traffic if the depression is greater than 10 mm, the height of the lateral deformation is greater than 5 mm, or if bleed water appears. It is not clear if the test should be used only as a release to traffic assessment or as an indication that the layer is ready for final compaction in addition to a release to traffic.

VanFrank (2015) also noted that the DCP was used as a third assessment tool for recycled materials. From field studies it was found that when the DCP penetration was less than 10 mm per blow, the recycled layer was ready for release to traffic. It is not yet clear why the agency did not include DCP testing in the instruction manual. However, VanFrank (2015) stated that during field testing, it was found that both the shear vane and DCP criteria could be met while the recycled material was still in a plastic state—that is, still susceptible to flow instability. The author attributed the inability of the shear vane to identify this as because of the localized nature of the testing and the high degree of particle displacement around the shear vane edges. The author found that including the MH field test allowed assessment of the bulk particle movement from a larger stress influence. VanFrank (2015) also noted that multiple tests were needed to achieve the desired result of identifying a time for release to traffic.

3.1.2 Stakeholder Survey

The following details the results of the responses to the online stakeholder survey. The survey link was distributed to agencies via the AASHTO Committee on Materials and Pavements and to attendees of regional and national pavement recycling conferences. There were 81 responses to the survey.

3.1.2.1 Demographics

The demographics of the survey respondents are shown in Figures 3.4 through 3.6. Figure 3.4 shows that although 23% of the respondents had less than 2 years of experience with pavement recycling techniques, 47% had more than 10 years of experience. Figure 3.5 shows that 74% of the survey respondents identified their organization as a state or local agency, 15% as a member of industry (including contractors, suppliers, and testing firms), and 10% as academic. Figure 3.6 shows the geographic location of the survey respondents; 44% of the respondents reported their location as either northeast or northcentral United States.

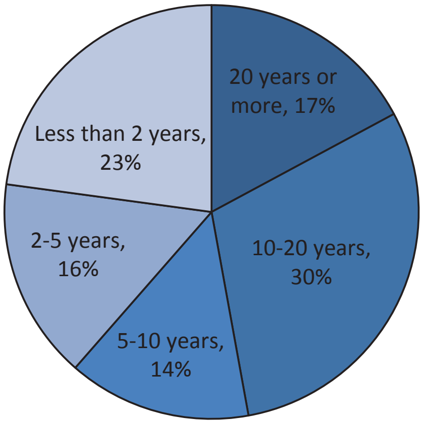


Figure 3.4. Stakeholder survey respondent experience with recycling techniques.

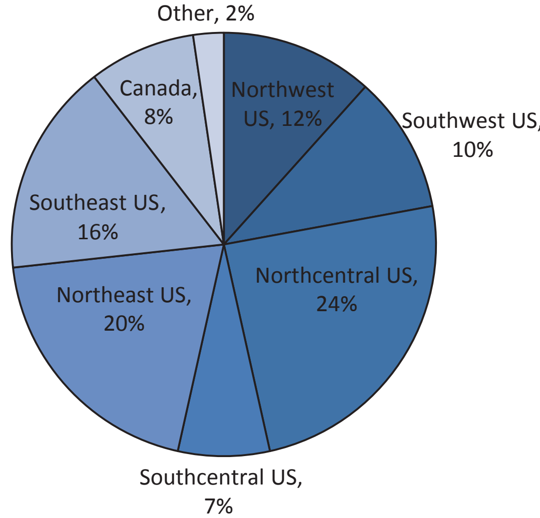


Figure 3.6. Stakeholder survey respondent geographic work location.

3.1.2.2 Stabilizing/Recycling Agent and Active Filler Use

Figure 3.7 presents the information gained about the use of particular stabilizing/recycling agents and shows that emulsified asphalt was used by the survey respondents more often than foamed asphalt. Figures 3.8 through 3.10 show that cement was the most prevalent active filler used by the survey respondents regardless of whether the stabilizing/recycling agent was emulsified or foamed asphalt.

3.1.2.3 Turnaround Time

Figure 3.11 shows the responses from the respondents when asked about the maximum acceptable turnaround time for a test that determines when a cold recycled pavement may be opened to traffic or surfaced. Figure 3.11 shows that most respondents identified that the maximum allowable turnaround time for a test to determine opening to traffic was less than 4 hours (65%). Most of the respondents identified that the maximum allowable turnaround time for a test to determine the time to surfacing was within 1 day (74%). Based on this finding, the research team focused on testing that could be completed within the first 24 hours following construction of a recycled layer.

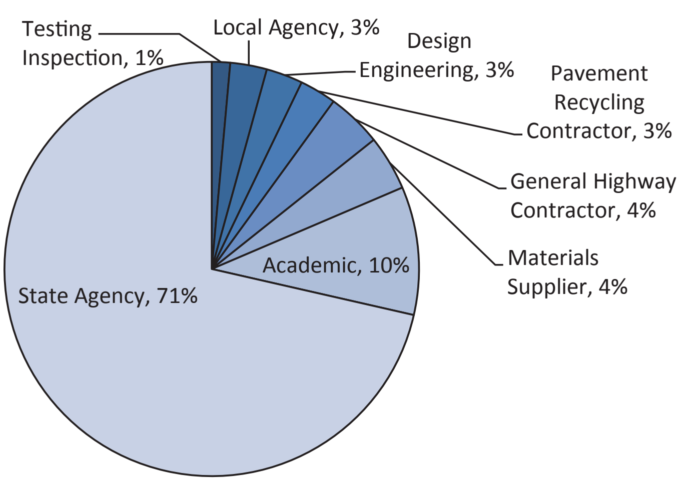


Figure 3.5. Stakeholder survey identified organization.

3.1.2.4 Challenges in Implementing Specifications

In replying to the question about challenges encountered with implementing public-agency specifications for CR, a lack of experience was noted as an area of concern by 43% of the respondents. (Of agency respondents, 54% indicated that agency experience was a concern, and 55% of industry respondents agreed; 27% of industry respondents cited industry experience as a concern, and 56% of agency respondents agreed.) Challenges regarding tests and specifications were identified by 39% of the respondents. Additional challenges identified are shown in Figure 3.12.

3.1.2.5 Recommended Tests and Suggested Changes to Existing Tests

The survey asked the recipients to indicate any recommended tests for process control or acceptance, time to trafficking/surfacing, and long-term performance. From the responses, several suggestions were identified that influenced the tests selected for the laboratory testing. These suggestions included density and moisture assessments, deflection testing, penetration resistance, proof rolling, and field shear testing.

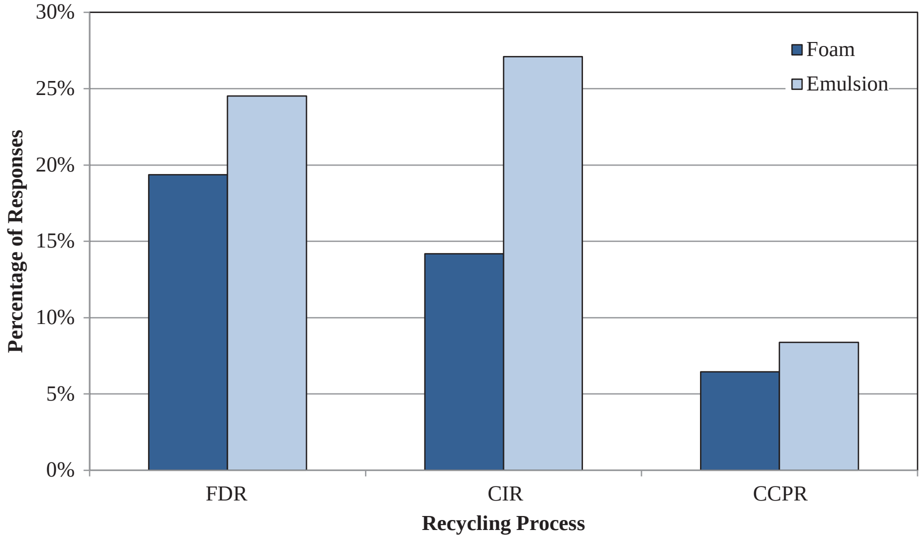


Figure 3.7. Stabilizing/recycling agent by recycling process.

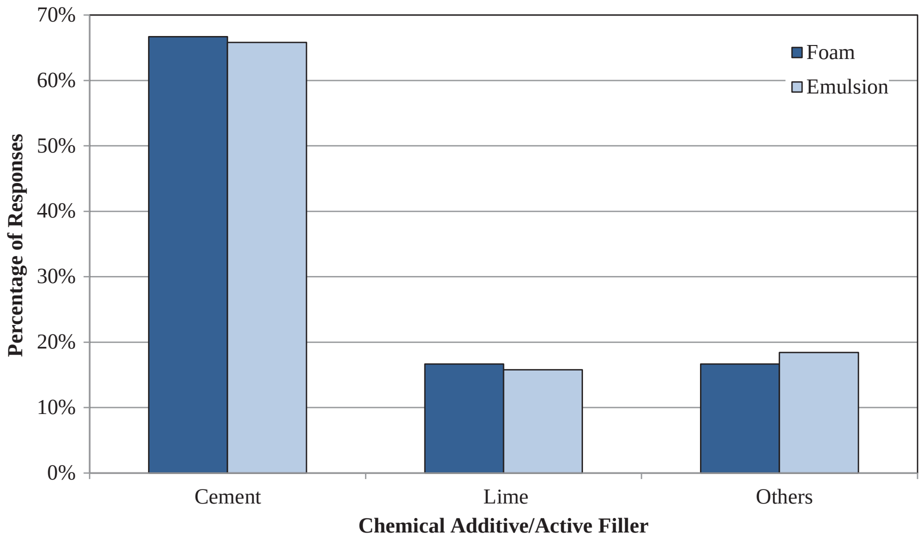


Figure 3.8. Active fillers used with FDR.

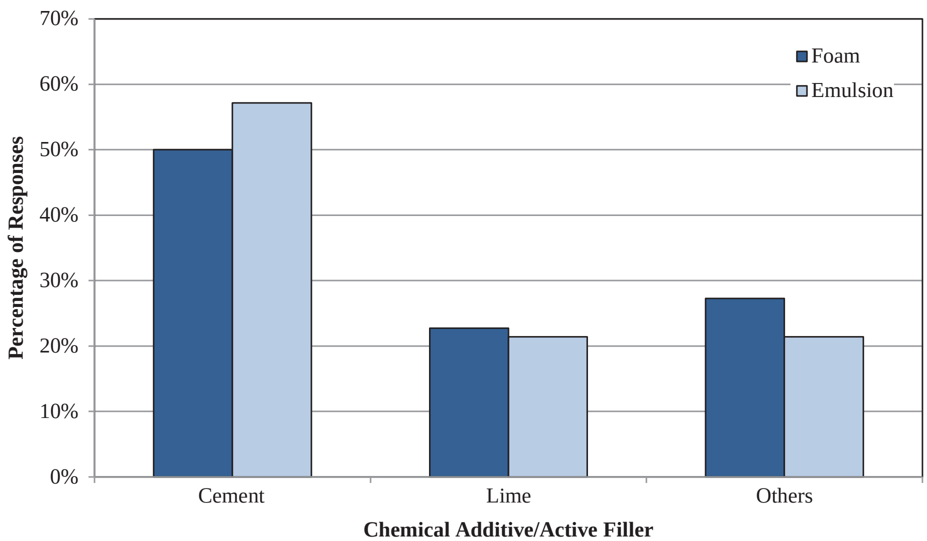


Figure 3.9. Active fillers used with CIR.

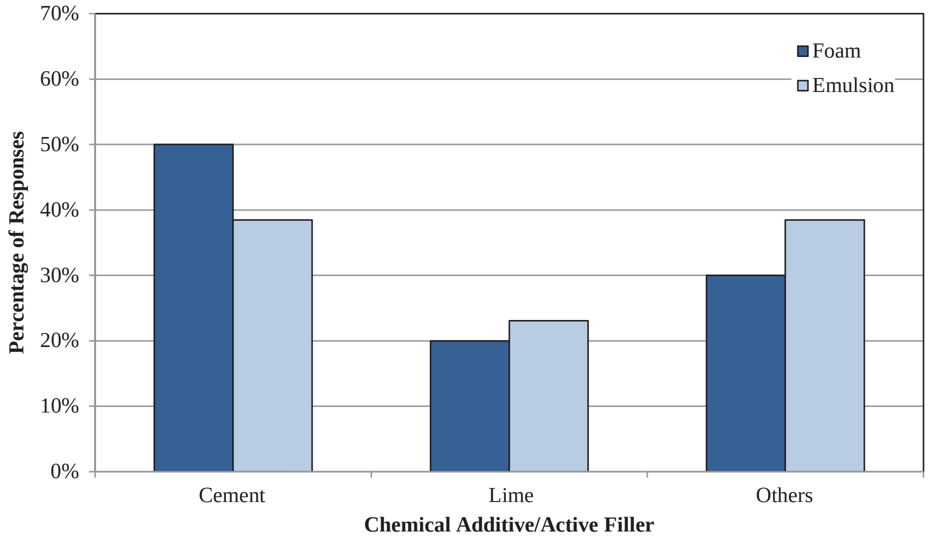


Figure 3.10. Active fillers used with CCPR.

3.1.2.6 Evaluation Factors

The survey recipients were asked to rate the importance of several broadly characterized evaluation factors to help the research team determine the priority of tests proposed for laboratory testing. The respondents rated the importance of the following evaluation factors across three time frames (initial, short term, and longer term):

- The time until results are available for the contractor and agency staff to make decisions;
- Test location (on the road or in a laboratory);
- Condition of the material (loose/molded or in situ);
- Equipment availability, cost, and portability;
- Application of test results to mix design, construction quality, and validation of the design intent;
- Level of skill required by the test operator;
- Stated accuracy, precision, and bias (APB) of the test; and
- Applicability of results across CIR, CCPR, and FDR materials.

The survey recipients were asked to rate the importance of each evaluation factor as being very important, somewhat important, or not important. The three ratings were assigned a numerical value, and the average rating for each evaluation factor was calculated. The ranked order from the

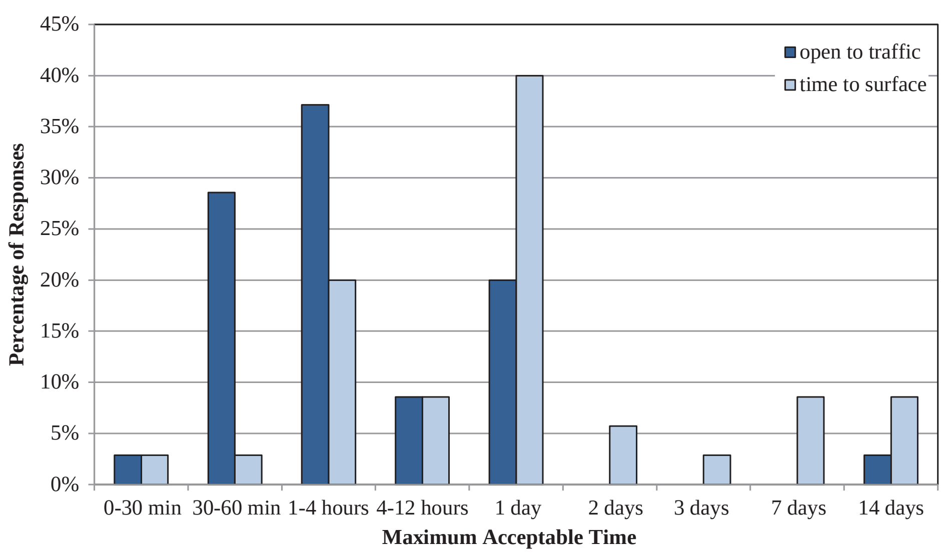


Figure 3.11. Maximum acceptable turnaround time for a test that determines when a cold recycled pavement may be opened to traffic or surfaced.

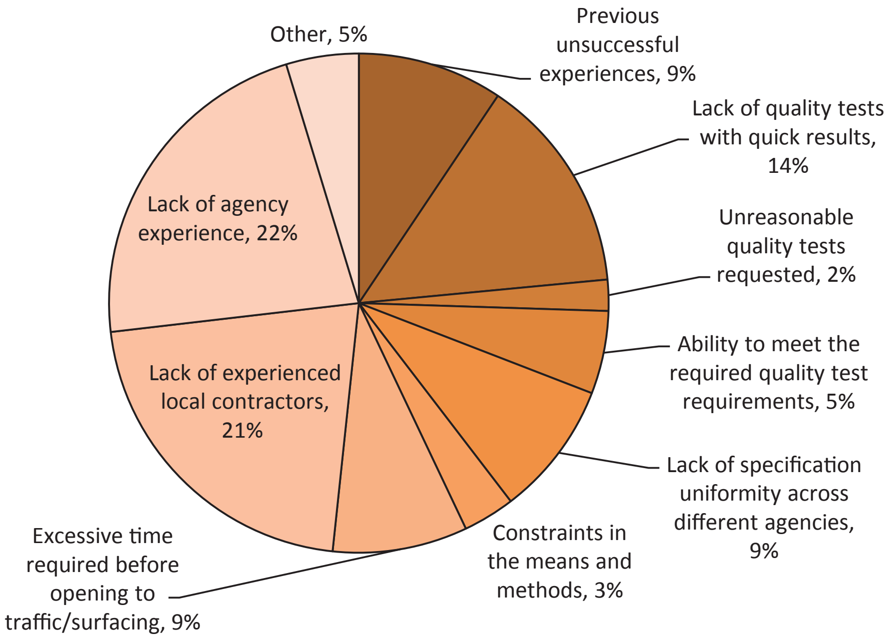


Figure 3.12. Challenges encountered with implementing agency specifications for pavement recycling.

survey responses was used in the evaluation of candidate tests. Table 3.1 shows the ranking of each evaluation factor by time frame, where a value of 1 indicates the highest-rated factor and a value of 8 indicates the lowest-rated factor. Given the objectives of this study and the results of the stakeholder survey, the results based on the initial and short-term time frames are most relevant.

3.1.2.7 Preferred Location for Time to Trafficking/Surfacing Test

The survey recipients were also asked to identify their preferred location for time to trafficking/surfacing test. Options available were field, laboratory, and no preference. Logically, the field location was the option with the highest percentage of responses at 73%. The laboratory location and no preference of location were selected by 7% and 20% of the respondents, respectively. This finding helped to direct the study toward particular tests for Phase II.

3.1.2.8 Tests Most Often Used for Suggested Properties

Survey recipients were asked to identify those tests that were most often used for determining the deformation resistance, raveling resistance, density, stiffness, and curing initiation; the responses are shown in Figures 3.13a through 3.13e, respectively. Figure 3.13 shows that most respondents did

Table 3.1. Survey ranking of evaluation factors by time frame.

Evaluation Factor	Ranking		
	Initial	Short Term	Longer Term
The time before results are available for the contractor and agency staff to make decisions with	2	1	3
Test location (on the road or in a laboratory)	5	2	8
Condition of the material (loose/molded or in situ)	6	3	7
Equipment availability, cost, and portability	3	4	3
Application of test results to mix design, construction quality, and validation of the design intent	1	5	1
Level of skill required by the test operator	7	6	3
Stated APB of the test	3	7	2
Applicability of results across CIR, CCPR, and FDR materials	8	8	6

Note: A lesser number indicates a higher-rated factor.

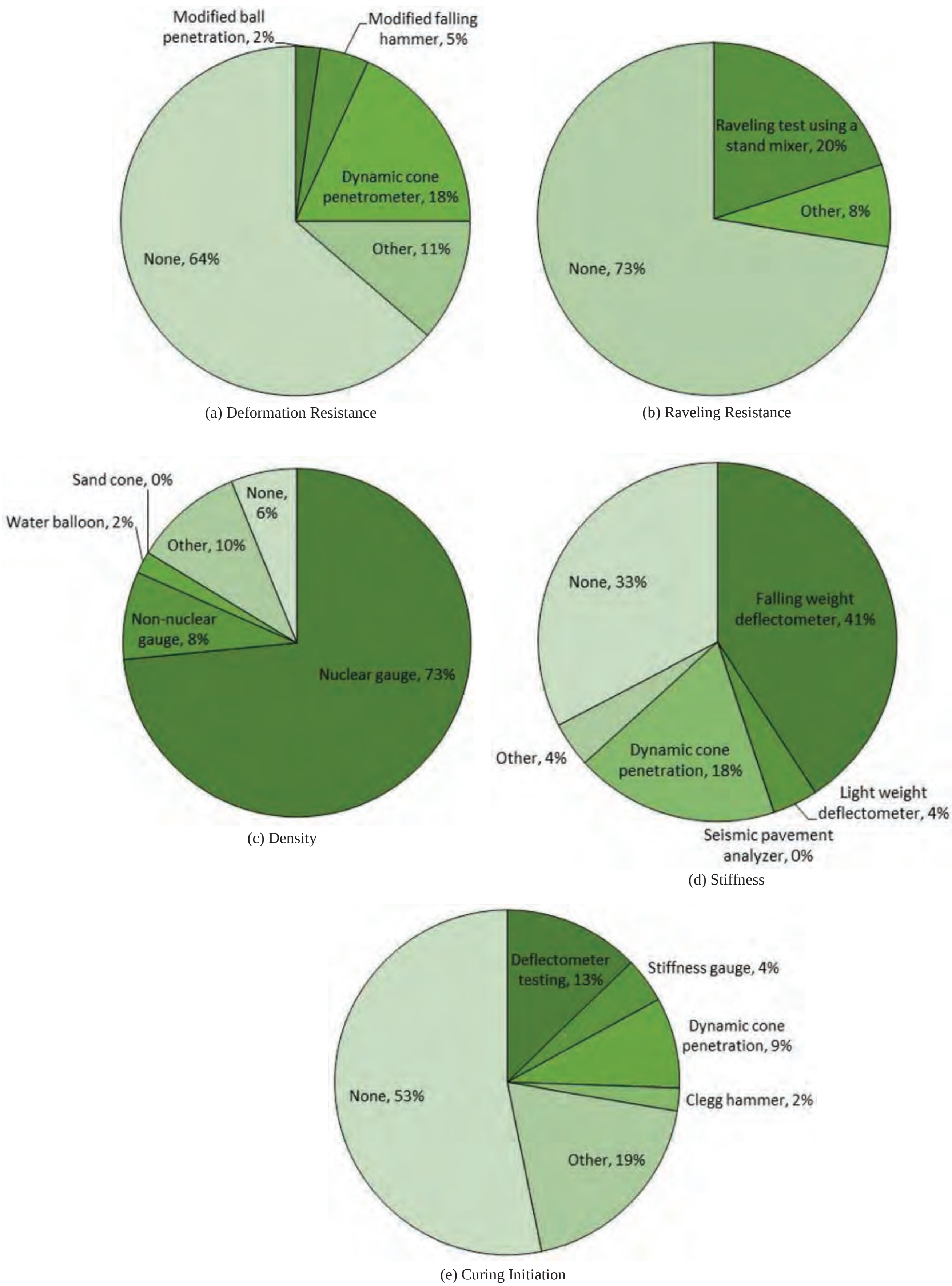


Figure 3.13. Tests most often used to determine (a) deformation resistance, (b) raveling resistance, (c) density, (d) stiffness, (e) curing initiation.

not have a particular test for determining the deformation resistance, raveling resistance, stiffness, or curing initiation. Density was most often assessed by the nuclear density gauge.

For those properties where no particular test was mentioned by most of the respondents, one or two particular tests were mentioned more than others. DCP was most often selected for deformation resistance, and the raveling test using a stand mixer was most often selected for raveling resistance. FWD was most often selected for stiffness. When identifying a test for curing initiation, the respondents most often selected "none"; "other" was selected the next most often. For each property assessed, the respondents may have chosen "other" to indicate a test that was not on the list provided by the research team. The survey recipients were asked to identify the "other" test methods, and the results are shown in Table 3.2.

3.1.3 Specification Review

A total of 83 Canadian/U.S. provincial/state and local agency specifications were reviewed, as indicated in Figure 3.14. These specifications included only those for asphalt-based stabilizing/recycling agents. Figure 3.14 also shows the geographical distribution of specifications by recycling process; 24 FDR, 45 CIR, and 14 CCPR specifications were reviewed. The reviewed specifications generally contained the following major sections: description of the process, materials, equipment, methods, quality measures, weather, curing, and measurement and payment. The degree of detail in each specification varied widely, from a short construction section and measurement and payment to more detail including all sections listed previously and sections on a preconstruction meeting, a preconstruction quality control plan, a detailed description of equipment requirements, and acceptance testing. This is similar to findings by Stroup-Gardiner (2011) and Salomon and Newcomb (2000). The following discussion focuses on summarizing the post-construction quality characteristics and measures found in the reviewed specifications. The methods used to assess material quality after construction varied widely by agency but most often included a measure of density, moisture content, curing time, strength value, and gradation.

Figure 3.15 shows the measures most often required for quality of the constructed layer. Density was the most popular measure (included in 94% of the specifications reviewed), followed by gradation, moisture content, and curing time. (Gradation will not be discussed further in this section since it is a laboratory-measured property, and the results of the stakeholder survey indicated a clear preference for field-based tests.) Figures 3.16 through 3.18 show the distribution of construction quality characteristics for FDR, CIR, and CCPR respectively. As reflected in the cumulative analysis shown in Figure 3.15, density is the most commonly prescribed quality characteristic for all three recycling processes. Given the relatively lower percentages for performance tests (e.g., DCP, stability, test/proof rolling), few specifications apply performance testing to field acceptance of the recycled layer at this time.

Specifications requiring moisture content readings as an indicator of curing or trafficking/surfacing readiness often required the moisture content to be in a range of from 1% to 3.5% or to be a percentage of the optimum moisture content established during mix design. Of all reviewed specifications (29 specifications), 35% called for a moisture reading of 2% or less before a recycled layer could be surfaced. Of the specifications referencing the optimum moisture content from design, 15.7% (13 specifications) required a moisture reading of less than 50% of the optimum moisture content, and some specifications, which were placed under the "other" category, required a moisture reading to be within some range of the optimum moisture content. Table 3.3 shows the required moisture content and the percent of specifications that required a specific moisture content as a percent of all specifications that required moisture readings. For specifications where an either/or scenario about moisture content was stated (e.g., either percent of total moisture content or 50% of target optimum moisture content), both cases were counted; thus, the percent occurrences in Table 3.3 add to more than 100%.

Based on the proportion of agency recycling specifications that included it as a characteristic, estimating that a newly placed recycled layer is cured is a concern. However, most definitions of "curing" relate to a moisture content measurement rather than to curing itself being a true measure of the

Table 3.2. Tests recommended in stakeholder survey.

Property	Recommended Test
Deformation resistance	Various lab-based tests including IDT, triaxial, Hamburg Observation of the rolling process (visual observation)
Raveling resistance	ASTM D7196 (mostly used during mix design only)
Density	–
Stiffness	DCP Nuclear density gauge
Curing initiation	CoreLok Moisture content by field drying (AASHTO T 255)

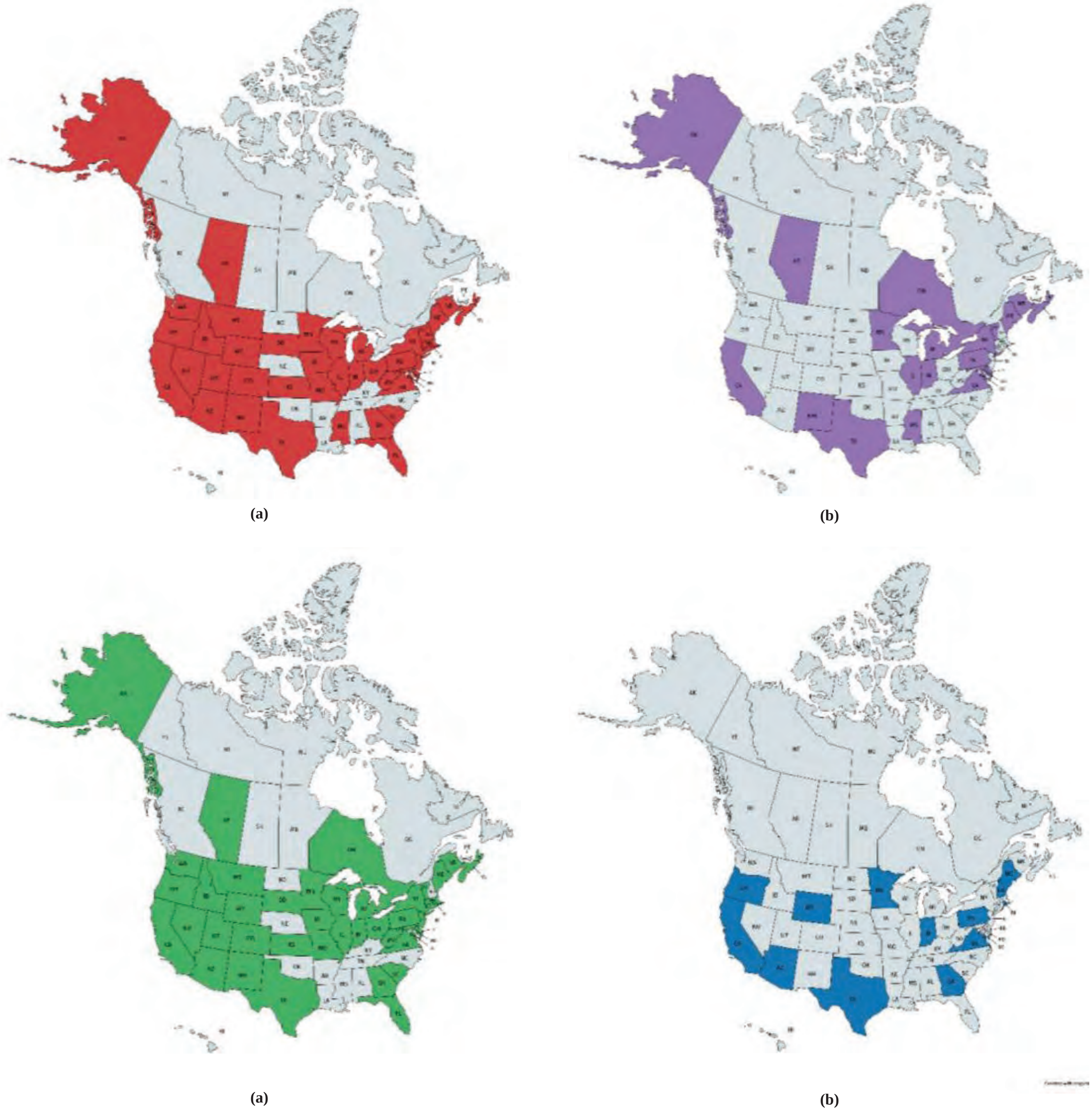


Figure 3.14. Reviewed agency recycling specifications, shown by shaded area: (a) all recycling processes, (b) FDR, (c) CIR, (d) CCPR.

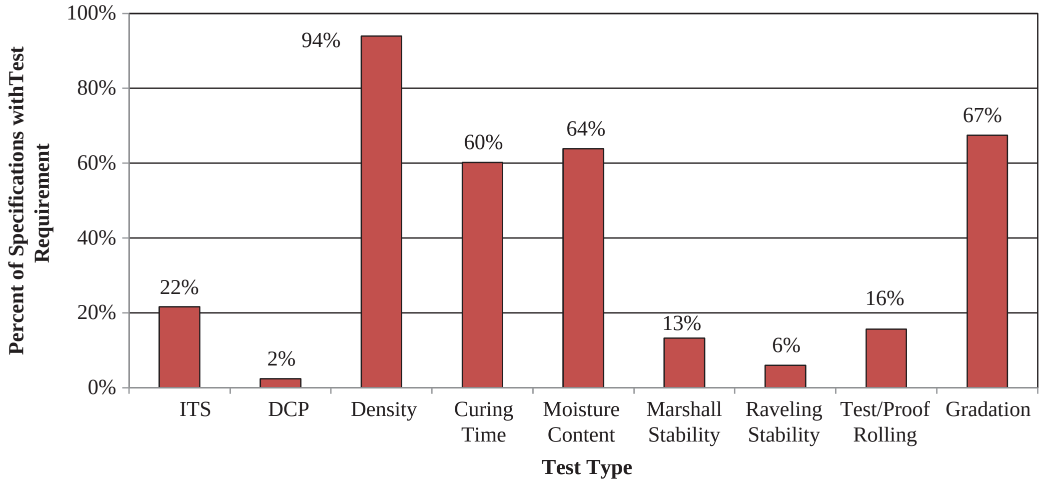


Figure 3.15. Distribution of constructed quality characteristic including all recycling processes.

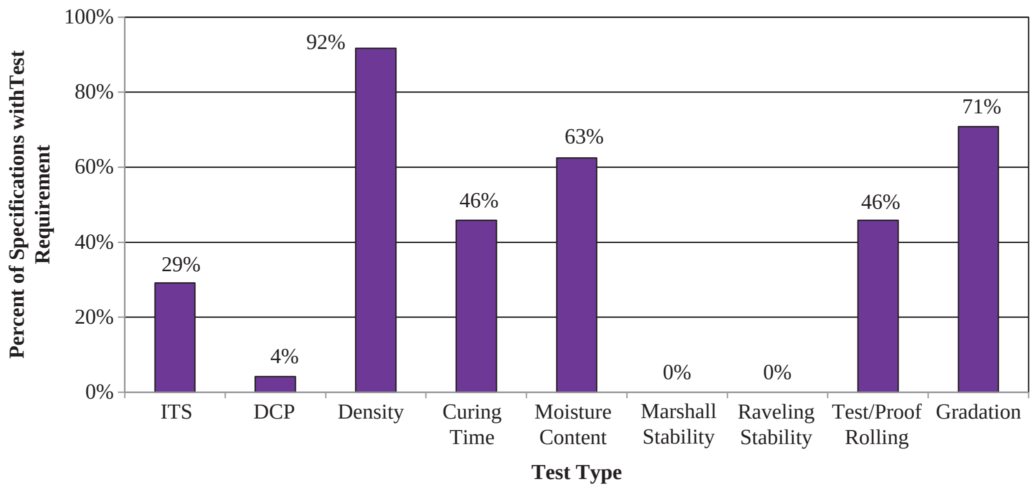


Figure 3.16. Distribution of constructed quality characteristic for FDR.

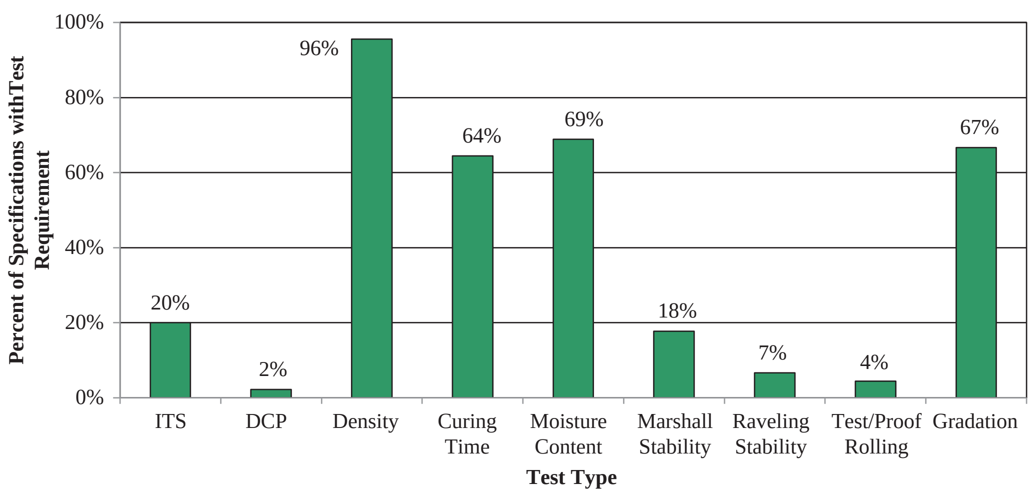


Figure 3.17. Distribution of constructed quality characteristic for CIR.

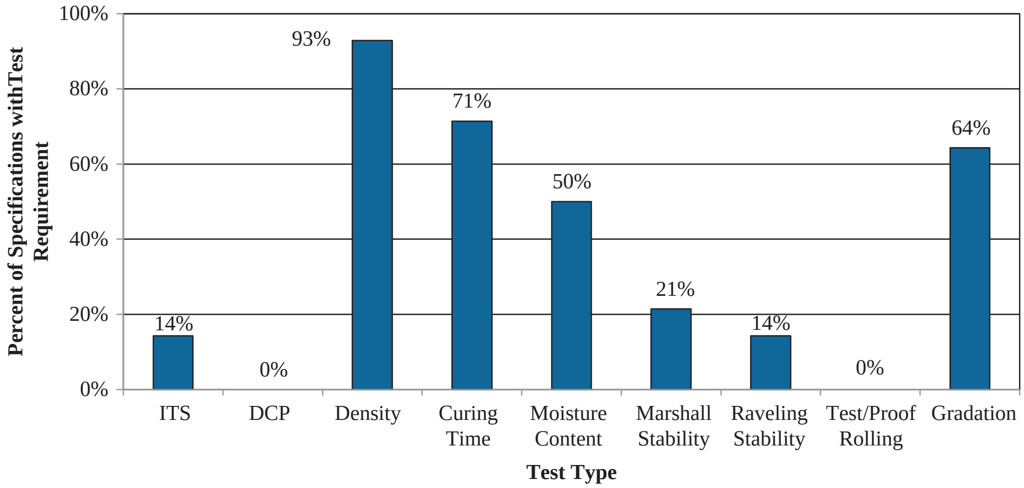


Figure 3.18. Distribution of constructed quality characteristic for CCPR.

ability to withstand loading without damage (by premature rutting or raveling) as a function of moisture content. A specified curing time prior to surfacing was required by 60% (50 specifications) of the reviewed agency specifications, and 64% (53 specifications) required a specific moisture content or moisture reduction. Thirty-six percent (30 specifications) of reviewed agency specifications stated that both a cure time and moisture content requirement must be satisfied prior to surfacing of the recycled layer. Of the specifications that listed a required curing time, it ranged from 1 hour to multiple days, with a maximum of 14 days. Table 3.4 provides various curing time durations and subsequent percent of occurrences for the reviewed specifications. Assuming a curing time of zero for those specifications that did not specify a required curing time, 52% (43 specifications) of the reviewed specifications required a cure time of between 2 to 14 days. In Table 3.4, there are cases where a specification called for curing times that bridged multiple represented curing periods (e.g., a specification called for a minimum of 2 days of curing and a maximum of 7 days). In these cases, the specification would be counted in each of the representative curing time categories (e.g., categories of 2 days, 3 days, and 4 to 7 days for a required 2 to 7 days of curing). This causes the total percentage in the Table 3.4 "Percent of Occurrences" column to be greater than 100%.

Table 3.3. Required moisture content before resurfacing and percent of occurrences.

Moisture Content, %	Percent of Occurrences
≤1	2.4
≤1.5	6.0
≤2	26.5
≤2.5	6.0
≤3	6.0
<3.5	1.2
50% of OMC	15.7
Other	6.0
Not specified	36.1

Note: OMC = optimum moisture content.

3.2 Candidate Tests

After the literature review and the stakeholder survey, the research team worked to develop a list of potential (or candidate) tests. This was started by listing those material properties thought to describe best the condition of a recycled layer at initial, short-term, and longer-term time frames. Next, a list of potential (or candidate) tests that could describe these properties was created. The two lists were grouped based on the tests' ability to assess properties of the recycled layer at three time frames: initial, short term, and longer term. The three time frames were not rigidly defined but instead were thought of as being soon after compaction, within the first 1 to 2 days, and longer than 2 days, respectively. The three time frames are described in more detail as follows:

- *Initial tests:* most often used for process or construction quality control purposes during and immediately after

Table 3.4. Required curing times and percent of occurrences.

Curing Time	Percent of Occurrences
1 hour	1.2
2 hours	3.6
4 hours	1.2
6 hours	1.2
2 days	8.4
3 days	21.7
4–7 days	16.9
>7 days	12.0

compaction of the recycled layer. Examples include in-situ moisture content, active filler content, recycling depth, grading, compaction density, and initial stiffness gain.

- *Short-term tests:* most often used to quantify the progression of curing and can indicate the relative performance of the surface of the recycled layer. Examples include stiffness gain, penetration/deformation resistance, raveling resistance, and moisture content.
- *Longer-term tests:* used to determine if the engineering properties of the recycled layer meet the design intent and to obtain an indication of long-term performance. The results of longer-term tests have been used to develop and refine mechanistic–empirical design procedures for in-place recycled pavements. An example is material stiffness characterization.

The research team initially listed as many relevant candidate tests (and the properties they describe) as possible that could be used to assess not only time to opening or surfacing but also material quality. The research team intentionally did not include any test that used visual observation as the basis of measurement; only tests with quantifiable results were included. This list of material properties and their associated candidate tests for initial, short-term, and longer-term properties is shown and described in Tables 3.5 through 3.7, respectively. Some material properties and tests appear across multiple time frames. The research team identified candidate tests with the knowledge that some tests would be included only for completeness, whereas others would progress on to evaluation in the laboratory testing.

3.3 Selected Tests

The material property/candidate test lists were further refined by evaluating each material property in terms of several evaluation factors, including the following:

- The time before results are available to the contractor or agency;
- Test location (laboratory or in situ);
- Condition of the material (loose, molded, or in situ);
- Equipment availability, cost, and portability;
- Application of test results to mix design, construction quality, and validation of the design intent;
- Skill level required by the test operator;
- Stated APB of the test; and
- Applicability of the test for CIR, CCPR, and FDR materials.

These factors were incorporated into an evaluation matrix that the research team used to objectively evaluate the merit in assessing each material property. The material property was evaluated rather than a particular test because this improved the objectivity of the evaluation and reduced any potential bias toward or against a particular test. The evaluation also used a weighting factor (defined as the ranked priority of the evaluation terms from the stakeholder survey; a lower value indicates a higher priority) and a usage level (determined by the research team based on their experience; a lower value indicates a higher usage level). Summing the product of the weighting factor and the usage level from each evaluation term resulted in a total score for each material property. (A lower score indicates a higher justification to include in Phase II.) The evaluation matrices for initial, short-term, and longer-term parameters are shown in Tables 3.8, 3.9, and 3.10, respectively. The ranked results of the evaluation matrices assessment are shown for each time frame in Table 3.11.

The research team elected to focus on those properties that were most highly ranked (having the lowest score shown in Table 3.11). A cut-off value of 50 was selected, and those properties that had a score under 50 were used to determine the tests that would be evaluated as part of the laboratory testing: density/compaction; stiffness; penetration, deformation, shear resistance/bearing tests; raveling resistance; and in-situ moisture. Specific tests to assess these properties in the laboratory testing included the tests shown in Table 2.2.

3.4 Laboratory Testing

To assess the desired properties shown in Table 2.2, a laboratory experiment was developed using compacted slab specimens manufactured from field-produced materials sampled from actual recycling projects. Replicate test slabs from each field project were fabricated and tested in three sets. Each test slab had dimensions of 500 mm in length × 400 mm in width and a thickness of approximately 110 mm. Using multiple slab sets was necessary given (1) the physical size of the tested area from each test, (2) the desire to conduct testing on undisturbed sections of the slab where possible, and (3) the necessity to account for replication. Table 3.12 shows the tests and curing times assessed for each set of slabs.

The results of each test are presented in the following sections. The data were analyzed with respect to the ability of the test to provide (1) a low variability among repetitive measurements for a given mixture, (2) a low variability among mixture replicates, and (3) a wide range or spread with respect to curing time and presence of cement.

3.4.1 Density/Compaction

The density of each slab was to be assessed using a thin-lift nuclear density gauge. During exploratory testing, the research team compared nuclear density gauge readings with the bulk slab density obtained by dividing the slab mass by

Table 3.5. Assessed properties and candidate tests for initial parameters.

Property Assessed	Candidate Test(s)	Need/Key Measures	Typical/Current Practice	Existing Standard?	Cost to Conduct Test?
In-situ moisture content	Gravimetric moisture content Nuclear gauge–based moisture content Electromagnetic moisture probe GPR	Confirm proper mixing/compaction moisture content	Gravimetric test prior to start of project	ASTM D6780/ASTM D7830/ASTM D6836 AASHTO T 310/ ASTM D6938 ASTM D7830 No, but research papers exist	Low
Active filler content	Tarp or pan test	Confirm correct amount of active filler has been applied	Tarp or pan test	No, but common practice	Low
Recycling depth	Probe Slit trench	Determine that design requirements are met	Probe, slit trench	No, but common practice No, but common practice	Low
Gradation	Sieve analysis	Check that appropriate grading curve is achieved and that there are no oversize particles	Sieve analysis on mixture without recycling/ stabilizing agent	ASTM C136/AASHTO T 27	Low
Curing time	Cohesion tester	Typically used for measuring curing time in slurry mixtures. Can be used to assess the time for opening to traffic	ASTM D3910 with modification; can be done on laboratory-compacted samples or on compacted mat in the field	ASTM D3910; can be easily modified and adopted for laboratory and field applications	Low
Density/ compaction	Using nuclear gauge Sand cone Rubber balloon	Proxy test for assessing material quality; some correlation with stiffness	Nuclear density (ASTM D2950) or similar state-specific specifications	ASTM D2950 ASTM D1556 ASTM D216	Low
Stiffness	Soil stiffness gauge LWD PSPA Clegg hammer Rapid compaction control device	Can be used to determine degree of curing	These stiffness tests have been used primarily on research projects for recycled materials.	ASTM D6758 (withdrawn in 2017) ASTM E2583/ASTM E2835/draft specs from TPF-5(285) and NCHRP Project 10-84 No, but research papers exist ASTM D5874 No, but agency procedures exist	Medium
Penetration, deformation, resistance, bearing tests	Ball penetration Marshall hammer Dynamic cone penetrometer Vane shear tests Proof rolling Rapid compaction control device	Indicator to determine if curing process has initiated and road can be opened to traffic or is ready for paving	Variations of these tests have been used for recycled and other materials.	ASTM C360 modified ASTM D1559/AASHTO T 245 modified ASTM D6951 ASTM D2573/AASHTO T 223/ASTM D4648 Yes, agency specs No, but agency procedures exist	Medium

Table 3.6. Assessed properties and candidate tests for short-term parameters.

Property Assessed	Candidate Test(s)	Need/Key Measures	Typical/Current Practice	Existing Standard?	Cost to Conduct Test?
In-situ moisture content	Gravimetric moisture content Nuclear gauge–based moisture content Electromagnetic moisture probe GPR	Confirm proper mixing/ compaction moisture content	Gravimetric test prior to start of project	ASTM D6780/ASTM D7830/ASTM D6836 AASHTO T 310/ASTM D6938 ASTM D7830 No, but research papers exist	Low
Stiffness	Soil stiffness gauge LWD PSPA Clegg hammer	Can be used to determine degree of curing	These stiffness tests have been used primarily on research projects for recycled materials. Upper limits may be quickly exceeded.	ASTM D6758 (withdrawn in 2017) ASTM E2583/ASTM E2835/draft specs from TPF-5(285) and NCHRP Project 10-84 No, but research papers exist ASTM D5874	Medium
Penetration, deformation, resistance, bearing tests	Ball penetration Marshall hammer Dynamic cone penetrometer Vane shear tests Proof rolling Rapid compaction control device	Indicator to determine if curing process has initiated and road can be opened to traffic or is ready for paving	Variations of these tests have been used for recycled and other materials.	ASTM C360 modified ASTM D1559/AASHTO T 245 modified ASTM D6951 ASTM D2573/AASHTO T 223/ASTM D4648 Yes, agency specs No, but agency procedures exist	Medium
Curing time	Cohesion tester	Typically used for measuring curing time in slurry mixtures. Could be modified for field use?	ASTM D3910 with modification. Modified for field use?	ASTM D3910 with modification; modified for field use?	Low
Raveling resistance	Stand mixer raveling test	Indicator to determine if compacted surface will ravel under traffic	ASTM D7196. Can be done in laboratory on prepared/cored specimen or on the road in field. Based on a Hobart mixer. Can be evaluated after the curing time determined by the cohesion tester.	Yes, ASTM D7196, see also ASTM C779, ASTM D4060, ASTM C1138, ASTM C1803	Low
Material strength	Indirect tensile strength Unconfined compressive strength Triaxial resilient modulus Dynamic modulus	Check that design intents are being achieved	Indirect tensile strength	ASTM D6931/AASHTO T 283 ASTM D2166/ASTM D5102/AASHTO T 208 ASTM D4767/AASHTO T 296/T 297 ASTM D3497 (withdrawn in 2009)/AASHTO T 378	Medium/ high

Table 3.7. Assessed properties and candidate tests for longer-term parameters.

Property Assessed	Candidate Test(s)	Need/Key Measures	Typical/Current Practice	Existing Standard?	Cost to Conduct Test?
Stiffness	FWD Plate load test	Determine expected life by monitoring changes in stiffness over time; relate measured values to intended design assumptions	Dynamic response Static response	ASTM D4694 ASTM D1194/ AASHTO T 221	High

the slab volume. It was discovered that the nuclear density gauge reported unreasonable density values likely because of the testing of a small slab relative to the size of the nuclear density gauge. Following the exploratory testing, the calculated bulk density was used as the density value for each compacted slab. The slab densities are detailed in tables for each test in the following sections.

3.4.2 Moisture

Moisture content measurements using a Troxler Model 6760 Moisture Probe were collected on fabricated test slabs at 2 and 72 hours of curing. Details of the mixture proportions for the tested slabs are provided in Table 3.13. The moisture readings were given as a frequency rather than as direct moisture content, and the moisture content was determined by oven drying of a sample removed from the test slab. Since this process was destructive, moisture content measurements were collected only at 72 hours of curing once all other tests were completed.

Figure 3.19 shows an example of exploratory testing where the moisture probe was used to assess the moisture content of loose RAP material. The RAP was mixed in a bucket mixer with different amounts of water over a moisture content range of approximately 0% to 7.5%. The results shown in Figure 3.19 suggest that the moisture probe could be quite accurate once a calibration process was completed as recommended by the manufacturer. This step is likely most practical for a large project where many moisture readings might be collected. The calibration process for the exploratory testing was completed within approximately half a day. Also, during the exploratory testing, it was determined that the moisture device could not be driven into the test slab. The manufacturer included a pin and hammer like those used for a nuclear density gauge test conducted in direct transmission mode. During the exploratory testing it was found that the hole remaining from DCP testing could also be used to accommodate the moisture device probe so long as the DCP was extracted carefully after testing.

Figure 3.20 shows the mean frequency values obtained from the electromagnetic moisture device for all mixtures at 2 and 72 hours. The moisture device probe was inserted into the hole in the test slab following DCP testing. Three replicate measurements were collected by rotating the moisture device approximately 120° about the hole. Figure 3.20 shows that, for most mixtures, there is a separation between the mean frequency values at the two curing periods. In general, the trend from 2 to 72 hours is in the same direction for all mixtures except Mixture 3. Figure 3.21 shows the variability of the replicate measurements in terms of the coefficient of variation (COV) for all tests at 2 and 72 hours. Figure 3.21 shows a very low COV, with all values less than 6%. Figure 3.22 shows the variability of measurements on replicate slabs, with all values less than a COV of 8%.

Figure 3.23 shows the relationship between the moisture probe frequency and the moisture content obtained by oven drying of a sample. Figure 3.23 shows that the correlation between the two is poor. When the moisture probe was loaned to the research team, the manufacturer stated that the probe needed to be calibrated for each mixture. This calibration was not completed for each mixture and would likely have improved the correlation, as demonstrated in Figure 3.19.

3.4.3 Stiffness

Stiffness testing at 2 and 72 hours of curing was completed for 16 different mixtures that were fabricated from 12 different source projects. The number of mixtures is greater than the number of source projects because the research team created some additional mixture types by modifying the mixture design from certain source projects. This was done to facilitate testing of additional mixture types. Two or three replicate slabs were fabricated from most source projects. In a limited number of cases, a single slab was tested because of the amount of material available. For certain source projects, the replicate slabs had different densities. Rather than discarding the slabs, they were included to evaluate the ability of the test to capture changes in density. As a consequence, the stiffness testing was performed on 30 test slabs from the 16 mixtures. Stiffness testing was conducting using an SSG and an LWD.

Table 3.8. Evaluation matrix for initial properties.

Evaluation Term	Weighting Factor (Ranking from Survey)	Usage Level			Usage Level for Material Property (Assigned by the Project Team)						
		1	2	3	In-situ Moisture	Active Filler Content	Recycling Depth	Gradation	Density/ Compaction	Stiffness	Penetration, Deformation, Shear Resistance/ Bearing Tests
Time to available test results	2	quick	medium	long	3	1	1	2	2	2	1
Location of test	5	field	on-site lab	lab	1	1	1	3	1	1	1
Material condition (loose, molded, or in-place)	6	all	in situ only	loose/molded	2	3	3	3	1	2	1
Equipment required (availability, portability, and cost)	3	3 positive	2 positive	1 positive	1	1	1	1	2	1	1
Application of results (mix design, construction quality, design validation)	1	3 positive	2 positive	1 positive	2	2	3	3	2	1	2
Operator/data skill analysis level required	7	low	medium	high	1	1	1	1	1	2	2
Accuracy, precision, and bias of the test	3	spec plus APB statement	spec but no APB statement	no spec	1	3	3	1	1	1	1
Applicability to different materials (CIR, CCPR, FDR)	8	3 positive	2 positive	1 positive	1	1	1	1	1	1	1
			score = sum of weighting factor rank multiplied by usage level		**46**	**54**	**55**	**61**	**41**	**50**	**43**

Table 3.9. Evaluation matrix for short-term properties.

					Usage Level for Material Property (Assigned by the Project Team)				
Evaluation Term	**Weighting Factor (ranking from survey)**	**Usage Level**			**In-situ Moisture**	**Stiffness**	**Penetration, Deformation, Shear Resistance/ Bearing Tests**	**Raveling Resistance**	**Material "Strength"**
		1	**2**	**3**					
Time to available test results	1	quick	medium	long	3	2	1	1	3
Location of test	2	field	on-site lab	lab	1	1	1	1	2
Material condition (loose, molded, or in-place)	3	all	in situ only	loose/molded	2	2	1	2	3
Equipment required (availability, portability, and cost)	4	3 positive	2 positive	1 positive	1	1	1	1	3
Application of results (mix design, construction quality, design validation)	5	3 positive	2 positive	1 positive	2	1	2	2	1
Operator/data skill analysis level required	6	low	medium	high	1	2	2	1	2
Accuracy, precision, and bias of the test	7	spec plus APB statement	spec but no APB statement	no spec	1	1	1	1	1
Applicability to different materials (CIR, CCPR, FDR)	8	3 positive	2 positive	1 positive	1	1	1	1	1
			score = sum of weighting factor rank multiplied by usage level		**46**	**46**	**47**	**44**	**60**

Table 3.10. Evaluation matrix for longer-term properties.

Evaluation Term	Weighting Factor (Ranking from Survey)	Usage Level			Usage Level for Material Property (Assigned by the Project Team)
		1	2	3	Stiffness
Time to available test results	3	quick	medium	long	2
Location of test	8	field	on-site lab	lab	1
Material condition (loose, molded, or in-place)	7	all	in situ only	loose/molded	2
Equipment required (availability, portability, and cost)	3	3 positive	2 positive	1 positive	2
Application of results (mix design, construction quality, design validation)	1	3 positive	2 positive	1 positive	1
Operator/data skill analysis level required	3	low	medium	high	2
Accuracy, precision, and bias of the test	2	spec plus APB statement	spec but no APB statement	no spec	1
Applicability to different materials (CIR, CCPR, FDR)	6	3 positive	2 positive	1 positive	1
			score = sum of weighting factor rank multiplied by usage level		**49**

Table 3.11. Results of evaluation matrix ranked by score.

Parameter Time Frame	Property	Score
Initial	Density/compaction	41
	Penetration, deformation, shear resistance/bearing tests	43
	In-situ moisture	46
	Stiffness	50
	Active filler content	54
	Recycling depth	55
	Gradation	61
Short term	Raveling resistance	44
	In-situ moisture	46
	Stiffness	46
	Penetration, deformation, shear resistance/bearing tests	47
	Material strength	60
Longer term	Stiffness	49

Table 3.12. Test, curing time, and slab set information.

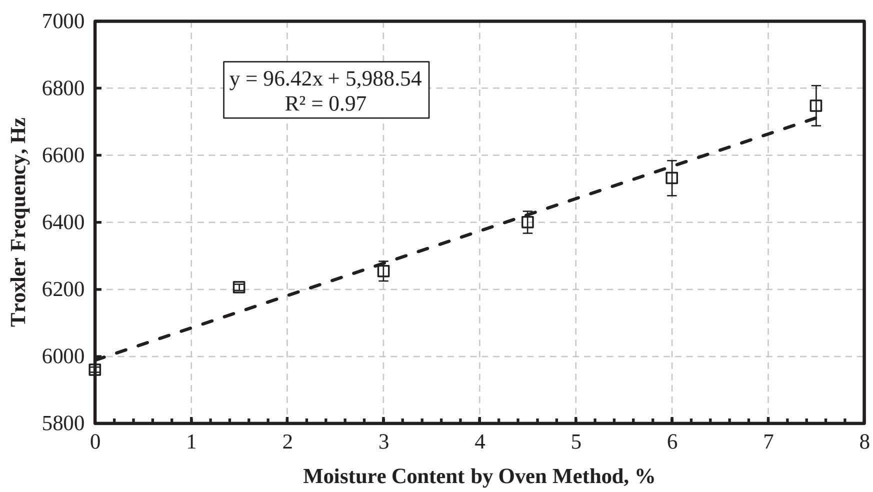
Test	Curing Time (hours)		
	Slab Set 1	Slab Set 2	Slab Set 3
Moisture	2, 72		
Soil stiffness gauge	2, 72		
Lightweight deflectometer	2, 72	1, 3, 6, 24	
Dynamic cone penetrometer	2, 72	1, 3, 6, 24	
Marshall hammer			
Long-pin shear test		1, 3, 6, 24	
Short-pin raveling test			1, 3, 6, 24

3.4.3.1 Soil Stiffness Gauge

Figure 3.24 shows the average stiffness of the mixtures measured using the SSG at 2 and 72 hours of curing. (For clarity, error bars are not shown.) The average value is made up of three tests per replicate, with the number of replicates shown in Table 3.13. As seen in Figure 3.24, the SSG was generally able to capture the effect of curing time. Of 16 mixtures, three mixtures (Mixtures 8, 13, and 14) showed a decrease in stiffness with respect to curing time. In addition, when individual specimens were considered, 10 of 30 specimens had a lower stiffness with respect to

Table 3.13. Specimen and mixture details for moisture content testing.

Mix ID	Stabilizing/Recycling Agent	Active Filler	Process	State	Agent Content, %	Active Filler Content, %	Actual Density, pcf	No. of Replicates
1	Emulsified asphalt	Cement	CCPR	IN	2.5	1.0	119.6	2
2				VA	2.5	1.0	131.5	3
3			FDR	TX	4.5	1.1	122.9	1
4				CA	2.5	1.0	127.8	0
5		No cement	CCPR	NY	3.0	0.0	124.8 130.2	2 (2 densities)
6				VA	2.5	0.0	128	2
7			CIR	ON	1.2	0.0	120.5	2
8			FDR	IN	2.5	0.0	118	2
9				CA	2.5	0.0	127.8	0
10	Foamed asphalt	Cement	CCPR	VA	2.5	1.0	127.6	0
11			CIR	CA	2.0	1.0	120.4	2
12				MA	2.5	1.0	119.4	2
13			FDR	TX	2.4	1.5	125.9	2
14				CA	2.5	1.0	126.6	3
15		No cement	CCPR	VA	2.5	0.0	127.6	0
16			CIR	MI	2.2	0.0	129.8	2
17				WI	2.0	0.0	121.3 118.6	2 (2 densities)
18			FDR	CA	2.5	0.0	127.8	3



Note: Error bars represent plus/minus one standard deviation.

Figure 3.19. Measured moisture content (oven method) versus electromagnetic moisture probe results from loose RAP material.

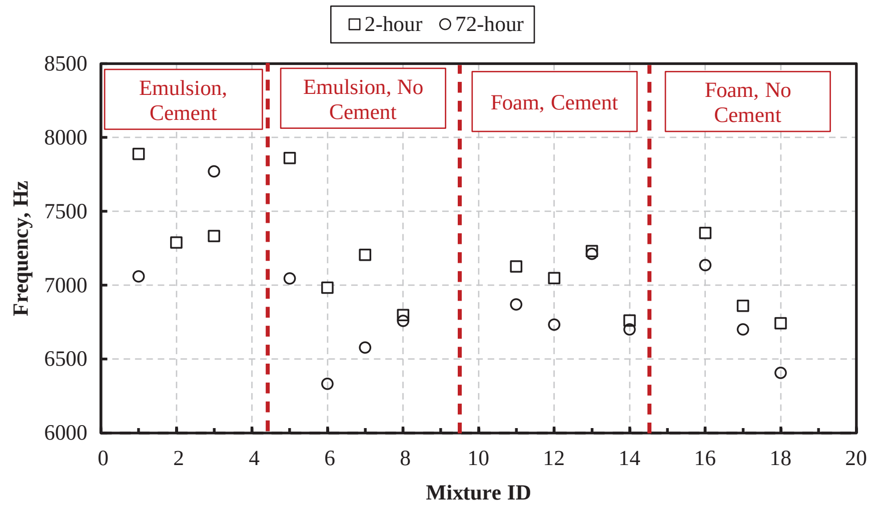


Figure 3.20. Electromagnetic moisture device results for all mixtures.

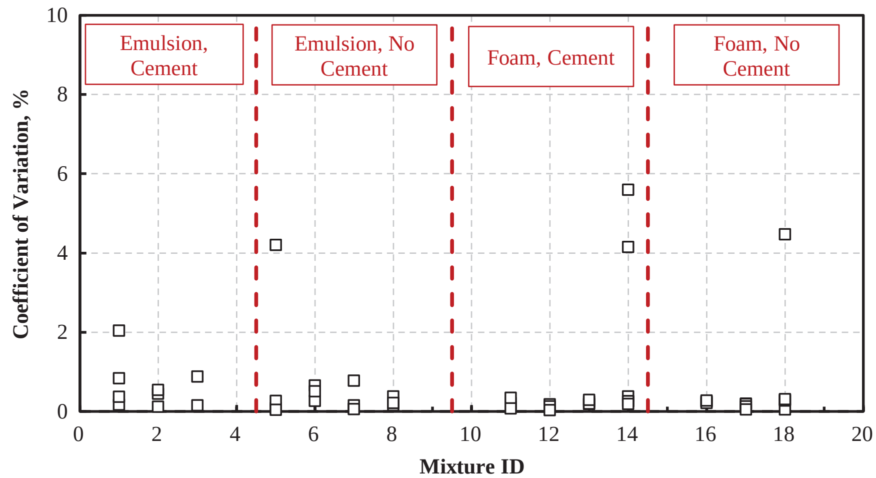


Figure 3.21. Within-test slab variability for electromagnetic moisture device based on replicate measurements.

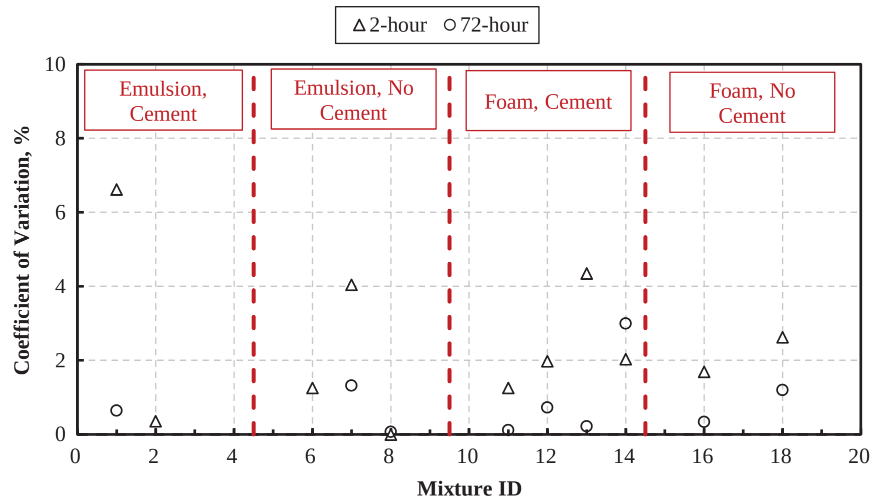


Figure 3.22. Between-test slab variability for electromagnetic moisture device based on replicate specimens.

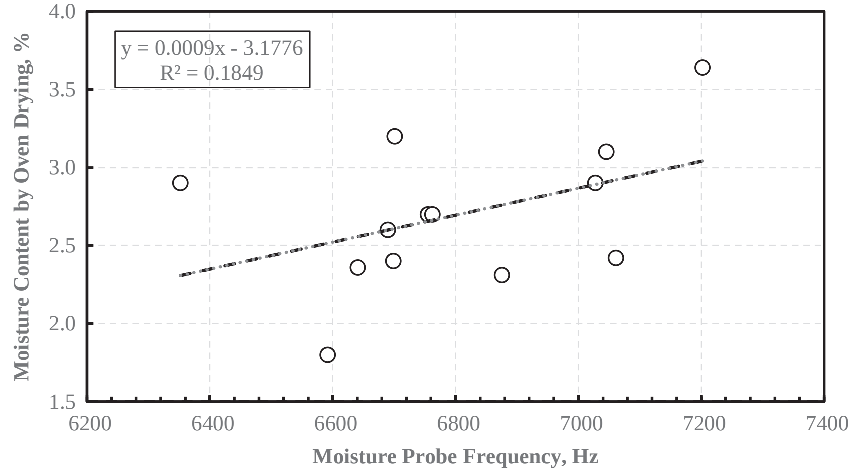


Figure 3.23. Moisture probe frequency versus measured moisture content (by oven drying) on compacted test slabs at 72 hours of curing.

increased curing time. Although such a trend was unexpected, several possible reasons might have contributed to this outcome. These include the variability of the material and the fact that the high-frequency test range (from 100 Hz to 196 Hz), small magnitudes of applied force (about 9 N), and small applied strains (approximately 0.00005 in./in.) are thought to reduce the ability to couple the material with the test device. Also, the zone of influence of the device is expected to be greater than the thickness of the test slabs.

Table 3.14 shows the descriptive statistics of SSG stiffness with respect to curing time. From Table 3.14, the mean SSG stiffness increased with respect to curing time, as expected, showing the ability of the SSG test to capture the effect of curing. The spread of the SSG-measured stiffness was evaluated using the interquartile range (IQR). The IQR was considered, rather than the standard deviation, since the IQR is resistant to effects of outliers. Table 3.14 also shows that the SSG stiffness IQR decreased slightly with respect to curing time. This could be expected since other research (e.g., Schwartz et al. 2017) has shown the similarity in stiffness of different mixture/additive combinations at later ages.

Table 3.15 shows the descriptive statistics of SSG stiffness with respect to recycling agent and presence of cement as an active filler. The mean SSG stiffness increased when cement was included for both emulsified asphalt and foamed asphalt mixtures, as expected. Table 3.15 also shows that the IQR increased with the presence of cement as an active filler. This suggests that the presence of cement as an active filler could

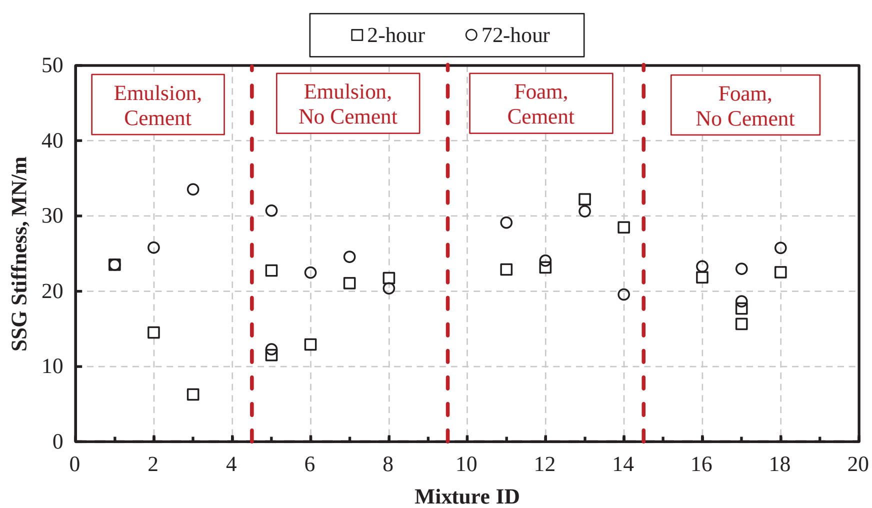


Figure 3.24. Stiffness of the mixtures as measured by soil stiffness gauge.

Table 3.14. Descriptive statistics of SSG stiffness by curing time.

Curing Time	Mean, MN/m	Minimum, MN/m	Quartile 1, MN/m	Quartile 3, MN/m	Maximum, MN/m	Range, MN/m	Interquartile Range, MN/m
2 hours	19.9	6.3	14.8	23.1	32.2	25.9	8.3
72 hours	24.2	12.3	20.9	28.3	33.5	21.2	7.4

Table 3.15. Descriptive statistics of SSG stiffness by recycling agent and active filler type.

Material Combination	Mean, MN/m	Minimum, MN/m	Quartile 1, MN/m	Quartile 3, MN/m	Maximum, MN/m	Range, MN/m	Interquartile Range, MN/m
Emulsion, cement	21.2	6.3	12.5	27.7	33.5	27.3	15.3
Emulsion, no cement	20.0	11.5	12.8	23.2	30.7	19.2	10.4
Foam, cement	26.3	19.6	22.9	30.2	32.2	12.6	7.3
Foam, no cement	21.0	15.7	17.9	23.2	25.7	10.1	5.3

have a larger influence on the SSG-measured stiffness of certain mixtures. Further, when the mean SSG stiffness values were compared, those mixtures that included foamed asphalt (both with and without cement as an active filler) tended to be stiffer than those mixtures that included emulsified asphalt; the difference was greater for those mixtures that included cement.

The within-specimen variability of the SSG stiffness was evaluated in terms of a COV. As shown in Figure 3.25, the COV for replicate measurements was generally less than 10% (for 54 of 60 conditions; 30 test specimens at two different curing times). The average COV was 4% and 6% for the 2- and 72-hour tests, respectively. Replicate measurements at each curing time were possible only for the SSG and LWD tests.

The variability of the SSG stiffness among mixture replicates was also assessed via the COV. Figure 3.26 presents the range of COV among the evaluated mixtures. The missing points in Figure 3.26 are due to not having a replicate specimen for a given mixture. In general, the COV among mixtures was less than 30% (30 of 32 conditions). The high variability seen for Mixture 13 was also observed in other tests considered in this study, as shown in the following sections. The average COV was 14.3% and 18.2% for the 2- and 72-hour testing, respectively. The higher COV at 72 hours was due, in part, to the high variability observed for Mixture 13.

A way to evaluate the discrimination potential of the SSG test with respect to curing time is to assess the curing ratio. The curing ratio is defined here as the ratio of the stiffness at 72 hours to the stiffness at 2 hours. Figure 3.27 shows the curing ratio of the mixtures. The SSG measurements indicated that a total of three mixtures had a lower stiffness with an increase in curing time (i.e., a curing ratio of less than 1). The curing ratio ranged from 0.69 to 5.36, with an average curing ratio of 1.44.

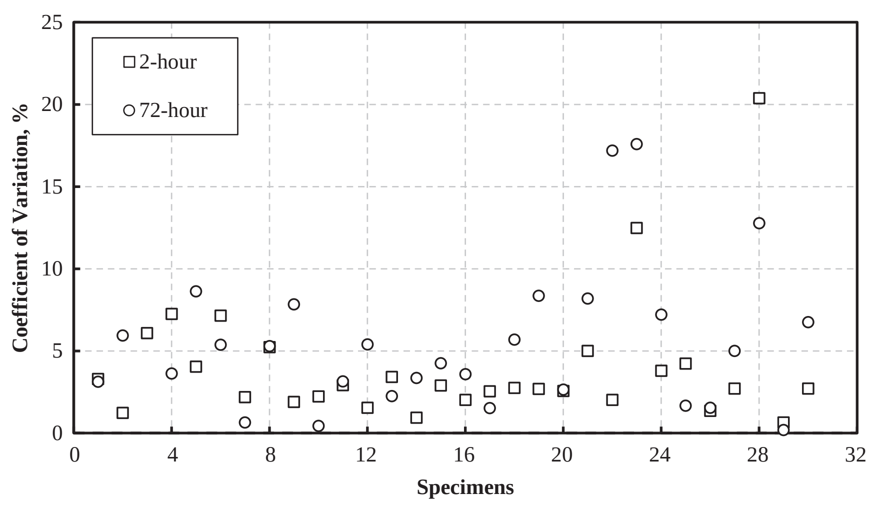


Figure 3.25. Within-specimen soil stiffness gauge variability in terms of a coefficient of variation.

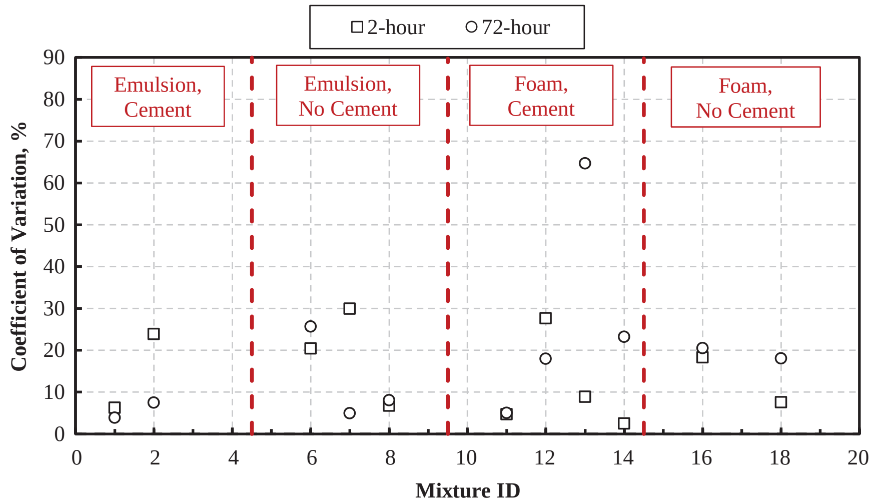


Figure 3.26. Soil stiffness gauge variability among mixture replicates in terms of a coefficient of variation.

The generated data were statistically analyzed to investigate the effect of the recycled mixture parameters considered in this study on SSG stiffness. An analysis of covariance (ANCOVA) at a confidence level of 95% was used to test for significant factors on the SSG stiffness response among various mixture parameters. The mixture parameters used as factors were process type, recycling agent type and rate, active filler (cement) rate, and curing time. The experiment was a nested design as it was not intended to have a factorial design for the levels of the various factors. In other words, although the recycling agent type (emulsion or foam) was not nested as a factor in the process type (CR or FDR), the recycling agent rate and cement rate were nested as a factor in the recycling agent type. The density was input as a covariate during the analysis.

Table 3.16 presents the ANCOVA statistics for the SSG stiffness. It is shown that the SSG stiffness was significantly varied (the p-value was less than 0.05) as a function of curing time and recycling agent content with different recycling agent types. The cement rate could not be estimated and was removed from the analysis by the statistical software (Minitab), potentially because of the interaction effect between the recycling agent rate and cement rate in addition to how the analysis design was set up (i.e., both recycling agent rate and cement rate were nested under recycling agent type). This observation does not suggest that the cement rate was not a significant factor; rather, having recycling agent rate as a statistically significant factor and the interaction effect with cement suggest that cement rate might be a significant factor. Although the data were not checked at a mixture level, it is

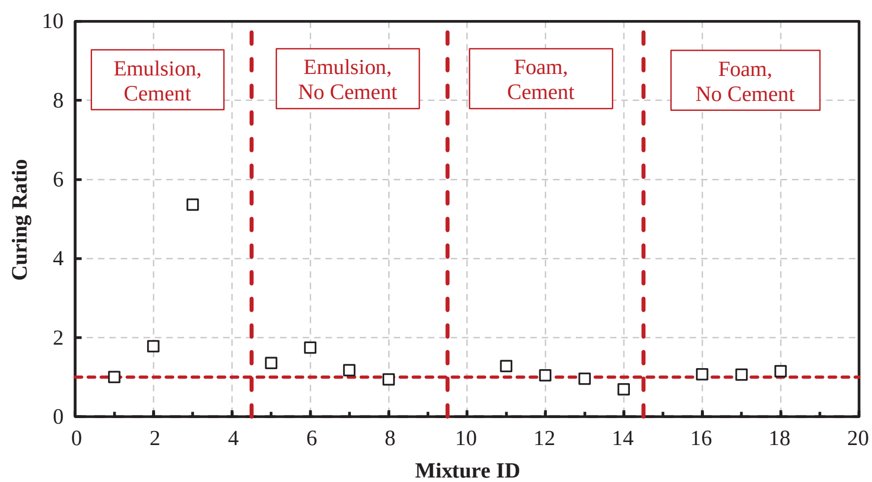


Figure 3.27. Curing ratio of mixtures from soil stiffness gauge.

Table 3.16. Results of ANCOVA for SSG stiffness.

Source	DF	*f*-Value	*p*-Value
Slab density	1	0.1	0.752
Recycling process	1	0.15	0.703
Recycling agent type	1	14.79	**0.000**
Curing time	1	14.05	**0.000**
Recycling agent content	6	3.22	**0.005**

Notes: DF = degrees of freedom; bolding indicates that the *p*-value shows the source to be significant.

anticipated that the curing time is a statistically significant factor only for the mixtures with cement because the variation in the response values with respect to time for the mixtures without cement did not vary significantly from each other.

3.4.3.2 Lightweight Deflectometer

The LWD was used to assess the modulus of each test slab immediately after testing with the SSG. During the LWD test, the first three drops of the falling weight were applied as seating loads, followed by seven additional drops. The average LWD modulus was calculated based on the deflections from the last three drops.

Figure 3.28 shows the average modulus of the mixtures as measured with the LWD at 2 and 72 hours. (For clarity, error bars are not shown.) Overall, the LWD test was able to capture the effect of curing; however, three mixtures (Mixtures 7, 14, and 17) showed a lower modulus with respect to curing time. When individual specimens were examined, five had a lower modulus with respect to increased curing time with the LWD test. As with the SSG testing, results could be affected by the relatively small magnitude of the applied force and deformation levels in addition to testing variability (especially among replicates). Also, the zone of influence of the device is expected to be greater than the thickness of the test slabs.

Table 3.17 shows the descriptive statistics of the LWD modulus with respect to curing time. From Table 3.17, the mean LWD stiffness increased with respect to curing time, as expected, showing the overall ability of the LWD test to capture the effect of curing. The spread of the LWD modulus was evaluated using the IQR. The IQR unexpectedly decreased slightly with respect to curing time.

Table 3.18 shows the descriptive statistics of the LWD modulus with respect to recycling agent and presence of cement as an active filler. The mean LWD modulus increased when cement was included for both emulsified asphalt and foamed asphalt mixtures, as expected. Table 3.18 also shows that the IQR increased when cement was included for emulsified asphalt mixtures but decreased when cement was included for foamed asphalt mixtures. This could suggest that the presence of cement as an active filler has a larger influence on the LWD modulus of mixtures containing emulsified asphalt.

The within-specimen variability of the LWD modulus was also assessed via the COV. As shown in Figure 3.29, the COV for repetitive measurements was less than 10% except for a single data point. The average COV was 2.6% and 2.7% for the 2- and 72-hour testing, respectively. Replicate measurements at each curing time were possible for the SSG and LWD tests. The variability of the LWD modulus among mixture replicates is shown in Figure 3.30. Missing data points in the figure indicate no replicate specimen for a given mixture. As with the variability observed for the SSG stiffness, the COV among the mixtures for the LWD modulus was less than 30% except for Mixture 13 at 72 hours. The high variability

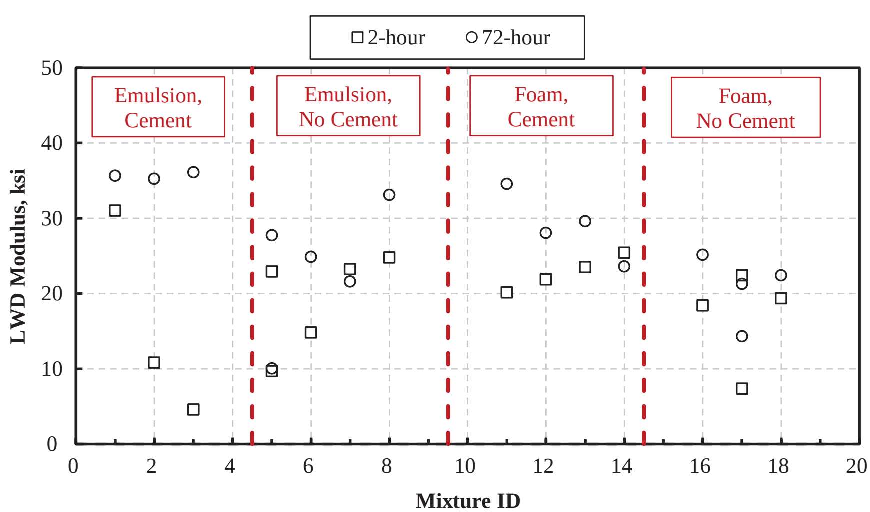


Figure 3.28. Modulus of mixtures as measured by LWD.

Table 3.17. Descriptive statistics of LWD modulus by curing time.

Curing Time	Mean, ksi	Minimum, ksi	Quartile 1, ksi	Quartile 3, ksi	Maximum, ksi	Range, ksi	Interquartile Range, ksi
2 hours	18.8	4.6	11.8	23.4	31.0	26.4	11.6
72 hours	26.5	10.0	21.8	34.2	36.1	26.1	12.4

Table 3.18. Descriptive statistics of LWD modulus by recycling agent and active filler type.

Material Combination	Mean, ksi	Minimum, ksi	Quartile 1, ksi	Quartile 3, ksi	Maximum, ksi	Range, ksi	Interquartile Range, ksi
Emulsion, cement	25.6	4.6	9.3	35.8	36.1	31.5	26.5
Emulsion, no cement	21.3	9.7	13.6	25.6	33.1	23.5	12.0
Foam, cement	25.9	20.2	22.3	29.2	34.6	14.4	6.95
Foam, no cement	18.8	7.4	15.3	22.4	25.2	17.8	7.08

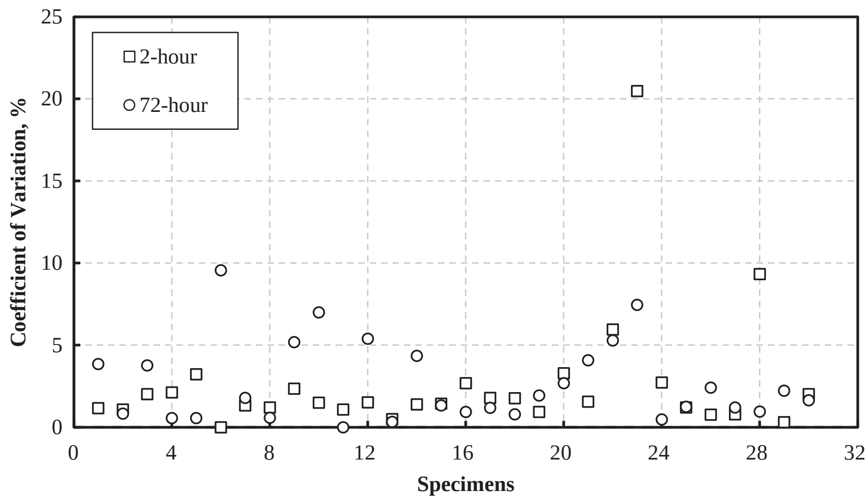


Figure 3.29. Within-specimen LWD variability in terms of a coefficient of variation.

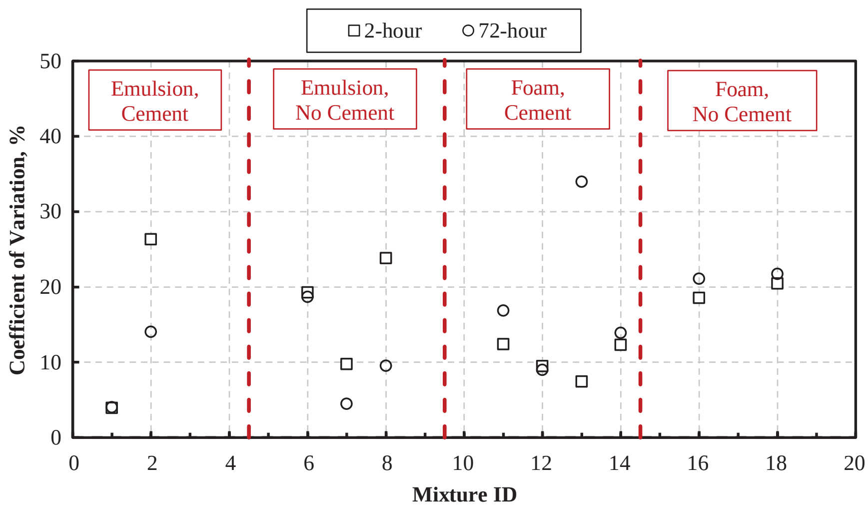


Figure 3.30. LWD variability among mixture replicates in terms of a coefficient of variation.

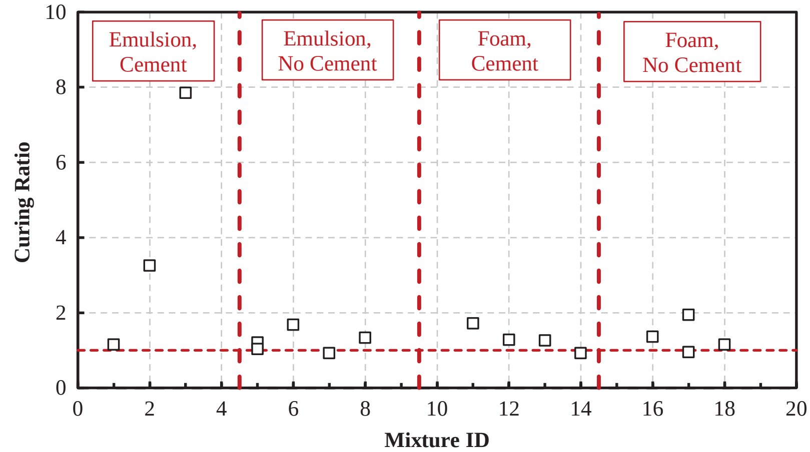


Figure 3.31. Curing ratio of mixtures from LWD.

with Mixture 13 was also observed for the SSG stiffness. The average COV was 14.9% and 15.2% for the 2- and the 72-hour tests, respectively. The curing ratio is shown in Figure 3.31. The curing ratio ranged from 0.9 to 7.8, with an average curing ratio of 1.8.

Table 3.19 presents the ANCOVA results at a confidence level of 95%. The ANCOVA was performed to investigate statistically the effect of the recycled mixture parameters considered in this study on LWD modulus. Table 3.19 shows that the LWD modulus was significantly varied (the *p*-value was less than 0.05) as a function of curing time and recycling agent content with different recycling agent types, the same factors identified in the analysis of the SSG stiffness. The process type was not identified as a significant factor in the analysis of LWD modulus (the same observation as in SSG stiffness analysis). Unlike in the analysis of the SSG test, the density was identified as a significant factor for the mixtures considered in this study. The cement rate could not be estimated and was removed from the analysis by the statistical software (Minitab) for the same reasons cited in the SSG discussion.

3.4.3.3 Comparison Between SSG and LWD Tests

The parameters used to assess the SSG and LWD test results were compiled and are shown in Table 3.20. This was done to rate the test methods to discern their ability to be used to make time-critical decisions regarding opening to traffic and surfacing of recycled materials. Using the column labeled "Desired Trend" as a guide, the range/observation for either the SSG or LWD was highlighted depending on which device better demonstrated the desired trend. As seen in Table 3.20, the LWD test generally identified the desired trend better than the SSG test based on the parameters and range of the mixtures used in this study.

Table 3.19. Results of ANCOVA for LWD modulus.

Source	DF	*f*-Value	*p*-Value
Slab density	1	10.98	**0.001**
Recycling process	1	0.11	0.745
Recycling agent type	1	3.9	0.080
Curing time	1	58.04	**0.000**
Recycling agent content	6	4.97	**0.001**

Notes: DF = degrees of freedom; bold/highlight = the *p*-value shows the source to be significant.

3.4.3.4 Additional LWD Tests

As discussed previously, additional sets of slabs were prepared for other tests, and the LWD testing was repeated on some of these additional slab sets at 1, 3, 6, and 24 hours of curing. The LWD test was performed immediately prior to the shear and raveling tests. Table 3.21 shows the details of the combined testing matrix from the long-pin shear test (LPST) and short-pin raveling test (SPRT) phases that resulted in a total of 18 mixtures for the additional LWD testing. Each mixture set included at least two replicates, and there were additional mixtures prepared at half the design binder content of the original mixtures. This new set of LWD tests at curing times of 1, 3, 6, and 24 hours was analyzed, in a fashion similar to that used for the 2- and 72-hour LWD data, in order to investigate whether the LWD was able to provide consistent results (repeatability) and to capture the changes in material characteristics in a shorter curing duration.

Figure 3.32 presents the LWD modulus at different curing times and for all material combinations considered. Figure 3.32 indicates that curing time had an impact on the LWD modulus measured at a relatively shorter curing duration and more frequent intervals. (As presented previously, this was the case for the measurements collected at 2 and 72 hours.) Overall observations from Figure 3.32 and Table 3.22 include that the mean LWD modulus increased with an increase

Table 3.20. Comparison of SSG and LWD tests.

Parameter	Range/Observation SSG	Range/Observation LWD	Desired Trend
Variability (within specimen) at 2 hours, COV	4%	2.6%	Lower
Variability (within specimen) at 72 hours, COV	6%	2.7%	Lower
Variability (among specimen replicates) at 2 hours, COV	14.3%	14.9%	Lower
Variability (among specimen replicates) at 72 hours, COV	18.2%	15.2%	Lower
Stiffness range at 2 hours	25.9 ksi	26.4 ksi	Higher
Stiffness range at 72 hours	21.2 ksi	26.1 ksi	Higher
Interquartile range at 2 hours	8.3 ksi	11.6 ksi	Higher
Interquartile range at 72 hours	7.4 ksi	12.4 ksi	Higher
Number of mixtures that lost stiffness over time	3	3	Lower
Number of replicate specimens that lost stiffness over time	10	5	Lower
Range of curing ratio (average)	0.69 to 5.36 (average = 1.44)	0.9 to 7.8 (average = 1.8)	Higher
Number of mixtures with statistically significant difference between the 2-hour vs. 72-hour tests	1	3	Higher
Captured the effect of density	Generally	Generally	Always
Captured the effect of active filler presence	Generally	Generally	Always

Note: Highlights in columns denote which device better demonstrated the desired trend.

Table 3.21. Test slab details for LWD stiffness testing at 1, 3, 6, and 24 hours.

Mix ID	Stabilizing/Recycling Agent	Active Filler	Process	State	Agent Content, %	Active Filler Content, %	Actual Density, pcf	No. of Replicates
1	Emulsified asphalt	Cement	CCPR	IN	2.5	1.0	119.1	3 rep full 0 rep half
2				VA	2.5	1.0	127.6	2 reps full 0 rep half
3			FDR	TX	0.5	1.1	131.5	2 rep full 1 rep half
4				CA	2.5	1.0	127.8	3 reps full 1 rep half
5		No cement	CCPR	NY	3.0	0.0	122.0	3 rep full 0 rep half
6				VA	2.5	0.0	127.6	5 reps full 0 rep half
7			CIR	ON	1.2	0.0	121.4	2 rep full 1 rep half
8			FDR	IN	2.5	0.0	119.1	3 rep full 0 rep half
9				CA	2.5	0.0	127.8	4 reps full 0 rep half
10	Foamed asphalt	Cement	CCPR	VA	2.5	1.0	127.6	5 reps full 1 rep half
11			CIR	CA	2.0	1.0	117.4	3 rep full 1 rep half
12				MA	2.5	1.0	121.0	3 rep full 1 rep half
13			FDR	TX	2.4	1.5	125.6	4 reps full 1 rep half
14				CA	2.5	1.0	127.8	3 reps full 1 rep half
15		No cement	CCPR	VA	2.5	0.0	127.6	2 reps full 1 rep half
16			CIR	MI	2.2	0.0	129.8	3 rep full 0 rep half
17				WI	2.0	0.0	121.3	3 rep full 0 rep half
18			FDR	CA	2.5	0.0	127.8	2 reps full 1 rep half

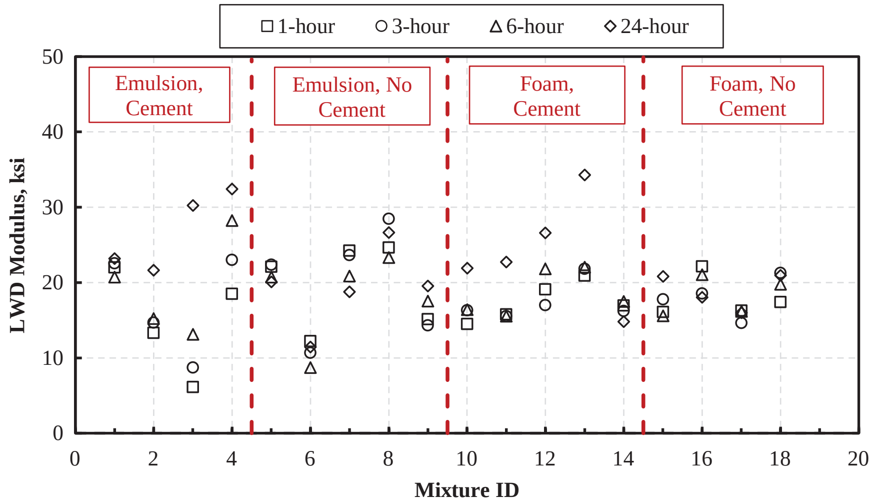


Figure 3.32. Modulus of mixtures as measured by LWD at shorter time intervals.

in curing time when the LWD moduli of all mixtures were combined without consideration of the specific characteristics of the mixtures. Likewise, the spread of the LWD modulus (as quantified by range and IQR), in general, also increased with an increase in curing time. Figure 3.32 also reveals that the impact of curing time on the LWD modulus is more evident with the presence of active filler (cement). Table 3.23 reflects that the spread of the LWD modulus is wider for the mixtures with cement than for the mixtures without cement. It was also noted from the table that the mixtures with cement tended to have a higher LWD modulus, as expected.

Figure 3.32 reveals that there was, generally, a reduction in the measured LWD modulus followed by a slight increase in modulus over the four curing periods for the mixtures without cement, an observation also noted with other tests considered in this study. For those mixtures incorporating cement, in general, a continued increase in the LWD modulus with respect to an increase in curing time was observed, as expected.

Figure 3.33 presents the mixture-to-mixture variability of the LWD modulus measured at shorter curing intervals in terms of the COV. The COV for the LWD measurements, considering all curing times, was less than 30% except for a few observations (4 of 72). It is interesting that for the curing time considered in this part of the study, two of four observations with more than 30% COV were for Mixture 13. With regard to the LWD data for 2- and 72-hour tests in addition to observations from other tests used in this study, Mixture 13 had a consistently higher variability compared to the other mixtures. Nevertheless, the overall average COV for the LWD measurements at shorter curing intervals was 15.9%, which was slightly higher than the average COV of 14.9% and 15.2%

Table 3.22. Descriptive statistics of LWD modulus by curing time.

Curing Time	Mean, ksi	Minimum, ksi	Quartile 1, ksi	Quartile 3, ksi	Maximum, ksi	Range, ksi	Interquartile Range, ksi
1 hour	17.6	6.1	15.0	22.0	24.7	18.5	7.1
3 hours	18.2	8.7	14.7	22.4	28.5	19.8	7.7
6 hours	18.6	8.7	15.6	21.3	28.3	19.5	5.6
24 hours	22.2	11.4	18.6	26.6	34.3	22.8	8

Table 3.23. Descriptive statistics of LWD modulus by recycling agent and active filler type.

Material Combination	Mean, ksi	Minimum, ksi	Quartile 1, ksi	Quartile 3, ksi	Maximum, ksi	Range, ksi	Interquartile Range, ksi
Emulsion, cement	19.6	6.1	13.7	23.2	32.4	26.3	9.5
Emulsion, no cement	19.3	8.7	14.5	23.6	28.5	19.7	9.0
Foam, cement	19.4	14.5	15.9	21.9	34.3	19.8	6.0
Foam, no cement	18.3	14.6	16.1	20.9	22.1	7.5	4.8

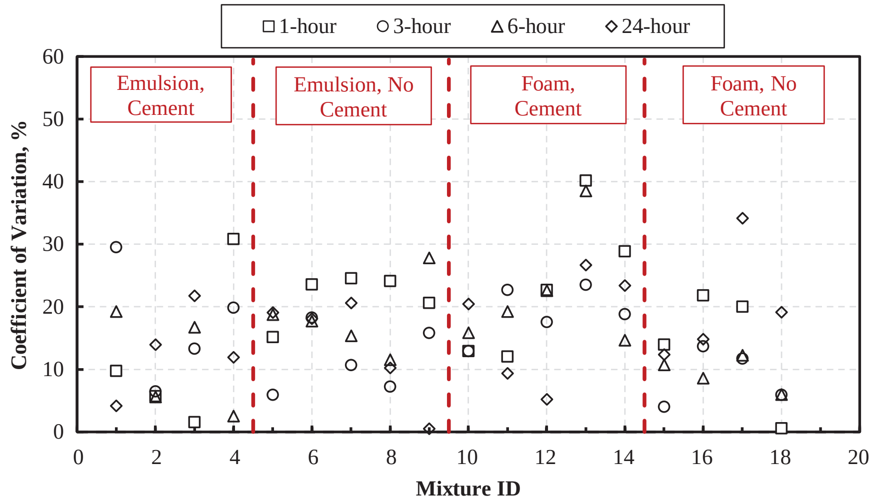


Figure 3.33. Variability of LWD modulus at shorter time intervals.

observed for the 2- and 72-hour LWD tests, respectively. The average COV for repetitive measurements was less than 1.5%, a statistic resulting from testing of 18 mixtures with at least two replicates at four different curing times with each test having three replicate measurements. The average COV for repeat measurements was 2.6% and 2.7% for the 2- and 72-hour LWD tests, respectively. Figure 3.33 shows that the magnitude of the observed variability does not vary as a function of the process type and recycling agent type or the curing time, the same observation as with the 2- and 72-hour LWD tests.

As part of the study, selected mixtures (a total of 10) were purposely prepared with one-half binder content to investigate whether the LWD test could capture such a change in material composition. Figure 3.34 presents the test results for those mixtures at curing times of 1, 3, 6, and 24 hours. Only one replicate was prepared for the half-binder content mixtures. The trend-wise performance behaviors of the half-binder mixtures were like those of the mixtures with the full binder content. In general, the LWD modulus increased with an increase in curing time for the mixtures with cement. There was an immediate reduction in the LWD modulus of the mixtures without cement, followed by an increase in modulus with increasing cure time. Similarly, the mixtures with cement tended to attain a higher LWD modulus. In comparing the magnitude of the LWD modulus of the mixtures at each curing time, it was observed that the mixtures prepared with full binder content had a higher LWD modulus (in 31 of 40 observations) than the mixtures prepared with one-half binder content. These lower magnitudes of the

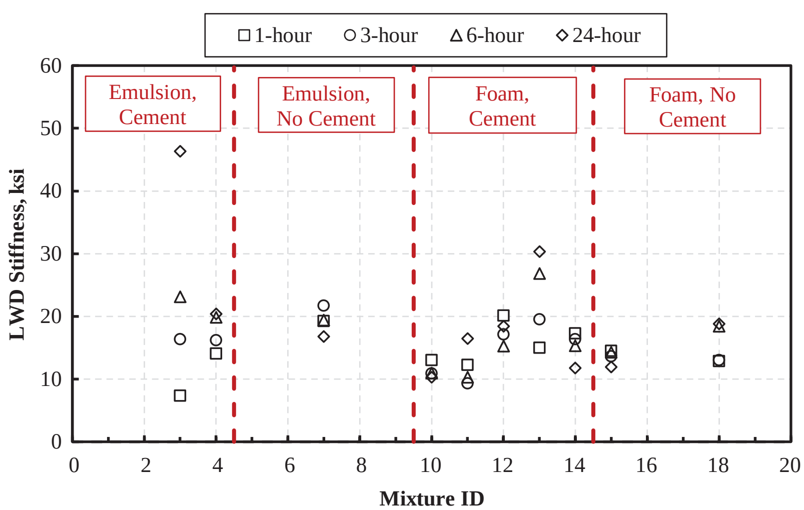


Figure 3.34. LWD modulus of mixtures prepared at a half binder content tested at shorter time intervals.

Table 3.24. Results of ANCOVA for LWD modulus at shorter curing times.

Source	DF	f-Value	p-Value
Slab density	1	54.46	**0.000**
Recycling process	1	25.21	**0.000**
Recycling agent type	1	1.96	0.163
Curing time	1	9	**0.000**
Recycling agent content	6	9.25	**0.000**

Note: DF = degrees of freedom; bold/highlight = *p*-value shows the source to be significant.

LWD modulus were from Mixture 3 at all curing times, Mixture 12 at two curing times, Mixture 13 at a single curing time, and Mixture 14 at two curing times. It is interesting to note that the common factor for the mixtures was that they were prepared with cement, and three of the four mixtures were FDR mixtures. The test results presented herein show that overall the LWD test is sensitive to a change in a recycling agent content rate.

Table 3.24 shows the ANCOVA results at a confidence level of 95% for the mixtures tested with an LWD at shorter curing intervals. This was the same analysis performed for the 2- and 72-hour LWD tests and combined all the mixtures together to investigate statistically the effect of the recycled mixture parameters considered in this study on LWD modulus. It is evident from the table that the LWD modulus varied significantly (the *p*-value was less than 0.05) as a function of curing time, recycling agent type, and process type and density.

The results presented herein for shorter curing times indicated consistency with the results presented for the 2- and 72-hour LWD tests. However, in this analysis, the process type was identified as a statistically significant factor, potentially because of the increased number of mixtures, replicates, and curing time categories used in the analysis, which resulted in more data points and hence improved the power of the statistical analysis. The cement rate could not be estimated and was removed from the analysis by the statistical software (Minitab), as was the case previously described.

3.4.4 Deformation Resistance

Using the same test slabs that were used for stiffness testing, deformation resistance testing was conducted using the upper assembly of an MH for 16 different mixtures fabricated from 12 sources, as shown in Table 3.12. For most of the mixtures, tests were conducted on either two or three replicate slabs. In a limited number of cases, a single slab was tested because of the amount of material available. The MH testing was performed at two different locations (two corners) per slab at 2 hours and at the other two corners at 72 hours after compaction, leading to two average readings per curing duration per fabricated slab. For each test, the penetrated depth was measured every five blows over a 20-blow test sequence.

Figures 3.35 through 3.38 show the average penetrated depth at five, 10, 15, and 20 blows, respectively, for each mixture at 2 and 72 hours of curing. The reported values are the average of the penetrated depth at two locations per slab. These figures show that the test captured the effect of curing in that the average penetrated depth was less at 72 hours than at 2 hours for nearly all mixtures at all recorded blow counts. In addition, the difference in penetrated depth with respect to curing time increased as the number of blows increased. As expected, the penetrated depth increased from five to 10 blows, from 10 to 15 blows, and from 15 to 20 blows for all evaluated mixtures.

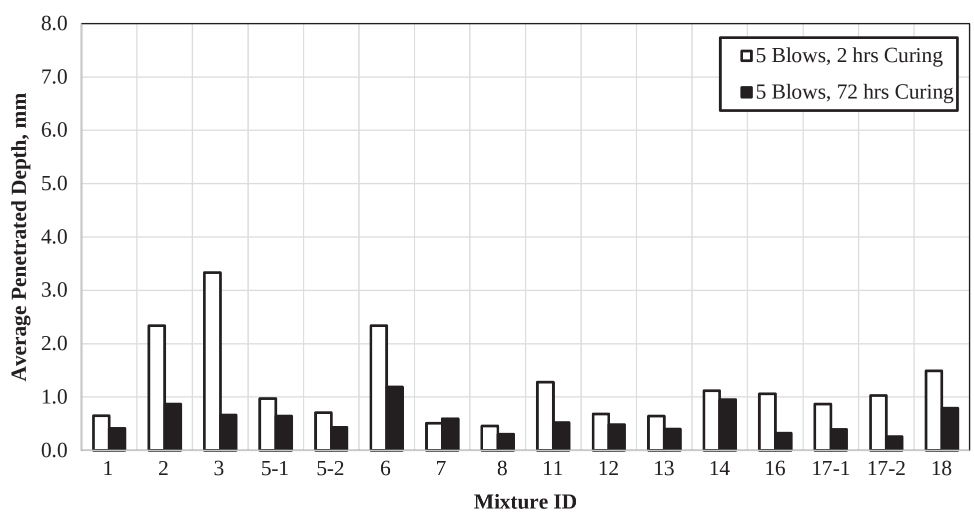


Figure 3.35. Average penetrated depths at 5 MH blows after 2- and 72-hour curing.

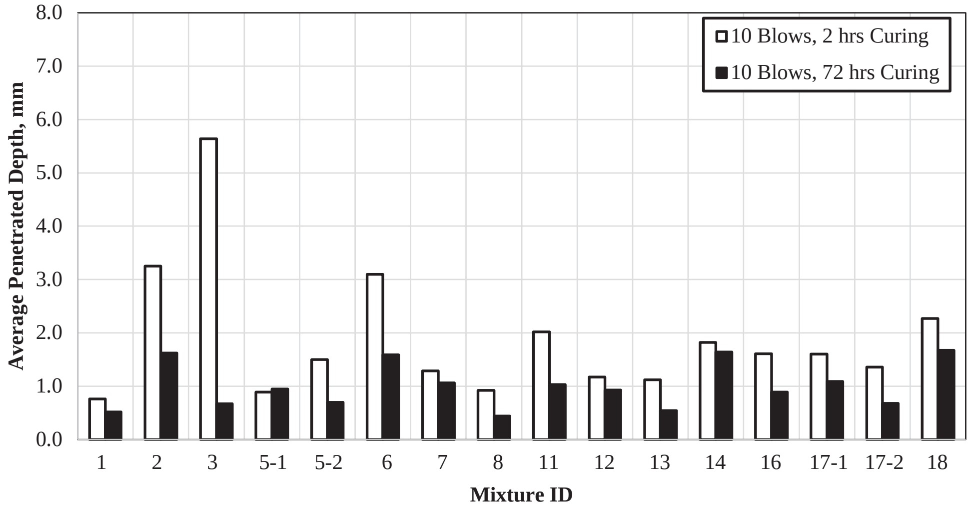


Figure 3.36. Average penetrated depths at 10 MH blows after 2- and 72-hour curing.

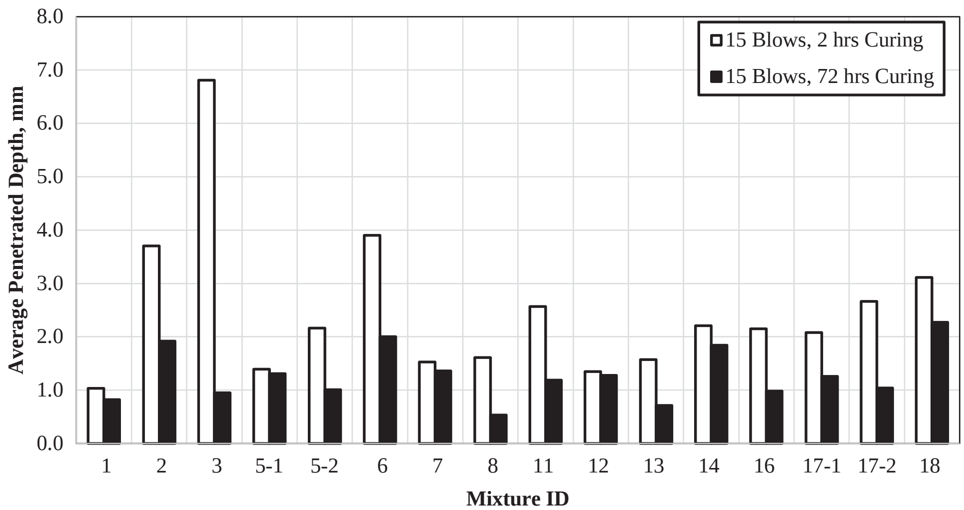


Figure 3.37. Average penetrated depths at 15 MH blows after 2- and 72-hour curing.

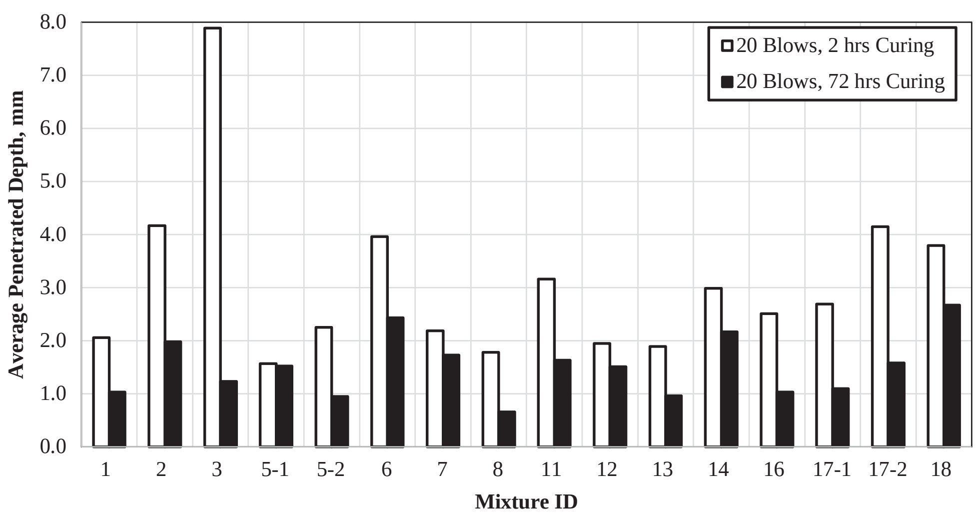


Figure 3.38. Average penetrated depths at 20 MH blows after 2- and 72-hour curing.

Table 3.25. Descriptive statistics of MH testing by number of blows and curing time.

Number of Blows	Curing Time	Penetrated Depth, mm						
		Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
5	2 hours	1.22	0.46	0.66	1.44	3.33	2.87	0.78
	72 hours	0.58	0.26	0.39	0.76	1.19	0.93	0.37
10	2 hours	1.90	0.76	1.13	2.21	5.64	4.88	1.08
	72 hours	1.00	0.44	0.67	1.47	1.67	1.23	0.79
15	2 hours	2.49	1.03	1.54	3.00	6.81	5.78	1.46
	72 hours	1.28	0.53	0.96	1.72	2.27	1.74	0.76
20	2 hours	3.06	1.57	1.98	3.92	7.89	6.32	1.94
	72 hours	1.51	0.66	1.03	1.92	2.67	2.01	0.89

Table 3.25 shows the descriptive statistics of the penetrated depth with respect to number of MH blows (i.e., five, 10, 15, and 20) and curing time (i.e., 2 and 72 hours). The mean penetrated depth increased with respect to the number of blows and decreased with respect to curing time, as expected. Similarly, the IQR increased with respect to the number of blows and decreased with respect to curing time.

The variability of the MH test results at the recorded blow counts was evaluated in terms of a COV computed for those mixtures that had replicates (11 of 16 mixtures). Figures 3.39 and 3.40 show the penetrated depth COV (averaged across multiple slabs) from all evaluated mixtures at 2 and 72 hours after fabrication, respectively, at five, 10, 15, and 20 MH blows. The COV decreased with an increasing number of blows. The research team attributed this to a reduced influence of surface texture as the penetrated depth increased. COV values were lower for nearly all mixtures at 20 blows when compared with a lesser number of blows at both 2 and 72 hours. The average penetrated depth COV at five, 10, 15, and 20 blows was less at 2 hours after fabrication than at 72 hours after fabrication. At 2 hours after fabrication, seven, eight, and seven mixtures had COVs of less than 30% at 10, 15, and 20 blows, respectively.

The generated data were further analyzed to investigate the effect of multiple parameters on the measured MH penetrated depth. An ANCOVA at a confidence level of 95% was used to evaluate the significance of these parameters. Table 3.26 presents the outcomes of the ANCOVA. The agent rate factor was nested within the recycling agent factor. Moreover, the cement content factor was nested within the recycling agent factor. The analysis shows that all factors, except the process type, significantly affected the MH penetrated depth (i.e., p-value < 0.05).

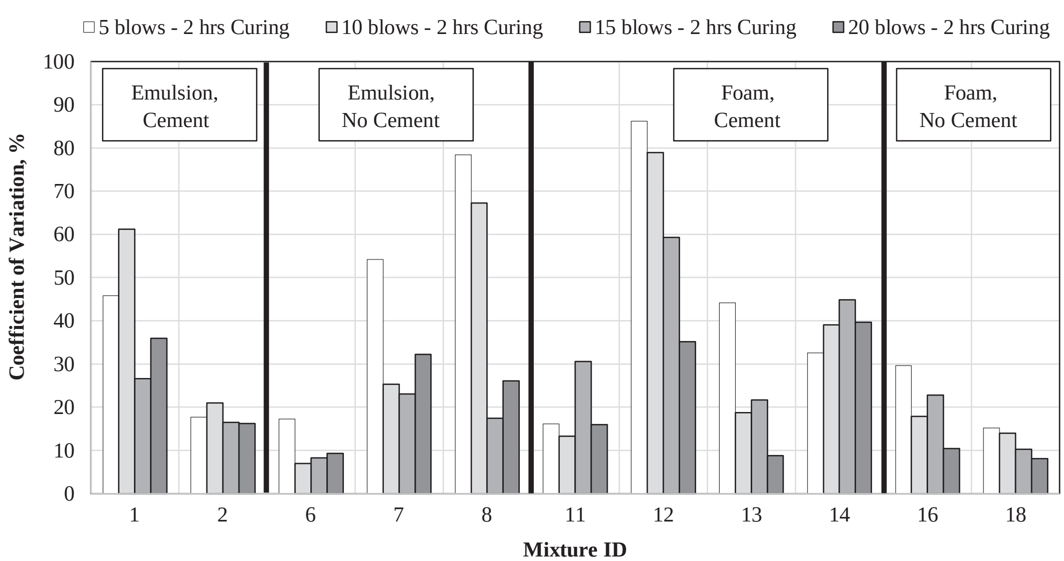


Figure 3.39. Penetrated depth variability after 2-hour curing duration in terms of coefficient of variation.

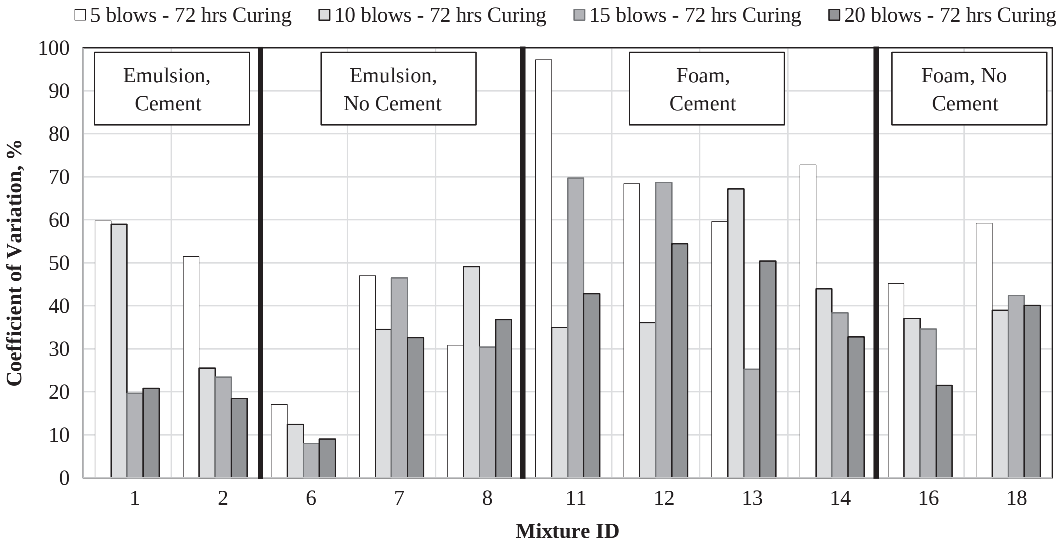


Figure 3.40. Penetrated depth variability after 72-hour curing duration in terms of coefficient of variation.

3.4.5 Penetration Resistance

Using the same test slabs used for testing deformation resistance, penetration resistance testing was conducted using a DCP for the 16 different mixtures fabricated from 12 sources (as shown in Table 3.12). For most of the mixtures, tests were conducted on either two or three replicate slabs. In a limited number of cases, a single slab was tested because of the amount of material available. The DCP test was conducted in accordance with ASTM D6951 with penetration readings collected after each blow.

Figure 3.41 presents the DCP penetration index (DPI) for all evaluated mixtures. The DPI was calculated by dividing the total penetrated depth by the number of blows. The penetration rate was consistent throughout the depth of each slab, indicating material uniformity in the vertical direction. The data provided in Figure 3.41 show that the DPI ranged between 3.2 and 9.0 mm/blow after 2 hours of curing and between 1.2 and 7.3 mm/blow after 72 hours of curing.

Table 3.27 shows the descriptive statistics of the DCP testing with respect to curing time. The mean DPI decreased with respect to curing time, as expected, showing the ability of the DCP test to capture the effect of curing. The spread of the DPI was evaluated using the IQR. Table 3.27 shows that the IQR decreased slightly with respect to curing time. Table 3.28 shows the descriptive statistics of the DPI testing with respect to recycling agent and presence of cement as an active filler. The mean DPI was decreased with respect to the presence of cement for both emulsified and foamed asphalt mixtures. The mean DPI was equal for emulsified and foamed asphalt mixtures containing cement but slightly lower for mixtures using foamed asphalt where no cement was present.

The specimen-to-specimen variability was evaluated for the 11 mixtures having two or more replicates using the COV, as shown in Figure 3.42. The DPI at 2 hours showed a COV that ranged between 0.7% and 48.6%. Only three mixtures (Mixtures 1, 13, and 16) had a COV value greater than 10%. The DPI at 72 hours showed a COV that ranged between 0.9% and 23.6%. Only four mixtures (Mixtures 7, 13, 16, and 18) showed a COV value greater than 10%. Interestingly, Mixtures 13 and 16 showed COV values of greater than 10% after both curing times (i.e., 2 and 72 hours). It is unclear why the variability was much higher for these mixtures. The COV at 72 hours was less than the COV at 2 hours for about half the mixtures.

The curing ratio, defined as the ratio of the DPI at 2 hours divided by the DPI at 72 hours, was used to evaluate the discrimination potential of DCP testing between curing times. Figure 3.43 shows the curing ratio of all evaluated mixtures. The computed ratio ranged between 1.24 and 5.13. No mixtures exhibited a ratio lower than 1.0. An average ratio of 2.07 was calculated for all evaluated mixtures.

Table 3.26. Marshall hammer testing: results of ANCOVA for MH penetration depth.

Parameter	DF	*f*-Value	*p*-Value
Slab density	1	69.58	**0.000**
Recycling process	1	1.06	0.305
Recycling agent type	1	14.47	**0.000**
Curing time	1	129.20	**0.000**
Recycling agent content	6	15.84	**0.000**

Note: DF = degrees of freedom; bold/highlight = the *p*-value shows the source to be significant.

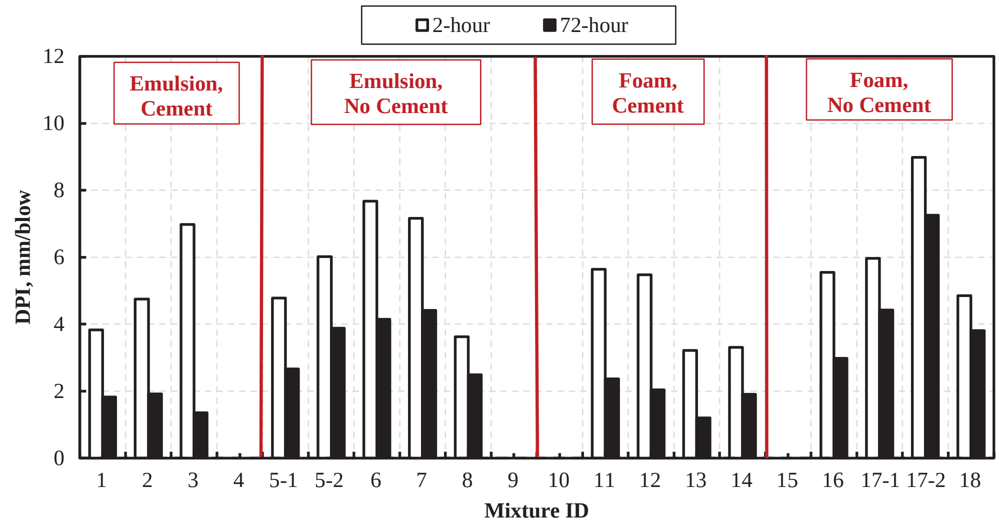


Figure 3.41. DPI for all evaluated mixtures.

Table 3.27. Descriptive statistics of DPI with respect to curing time.

Curing Time	DPI, mm/blow						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
2 hours	4.9	2.1	3.9	5.4	7.9	5.8	1.5
72 hours	2.7	1.0	1.9	3.4	4.8	3.8	1.4

Table 3.28. Descriptive statistics for DPI with respect to recycling agent and active filler type.

Material Combination	DPI, mm/blow						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
Emulsion, cement	3.1	1.7	1.9	4.6	4.8	3.1	2.7
Emulsion, no cement	4.9	2.5	3.7	7.0	7.9	5.4	3.3
Foam, cement	3.1	1.0	2.0	4.2	5.6	4.6	2.2
Foam, no cement	4.3	2.7	3.5	5.1	6.0	3.3	1.6

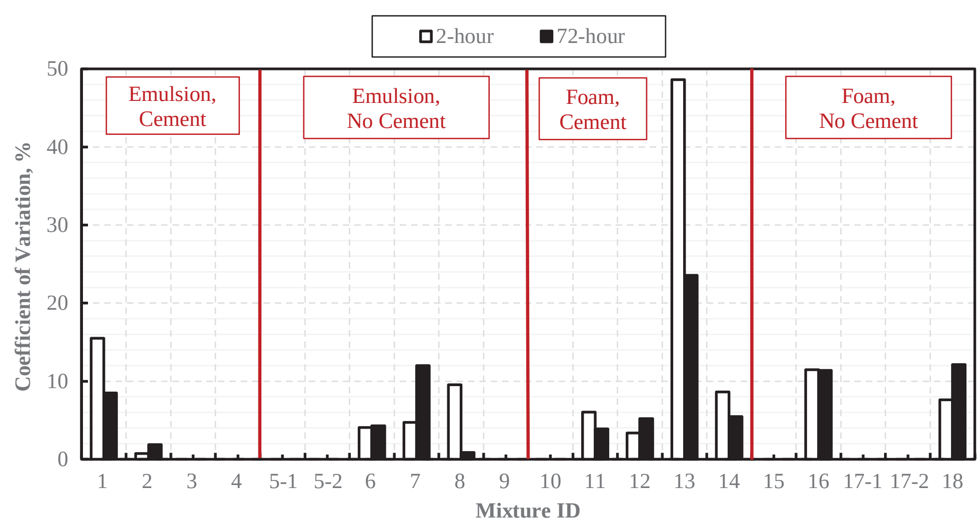


Figure 3.42. Coefficient of variation for DPI for mixtures with replicates.

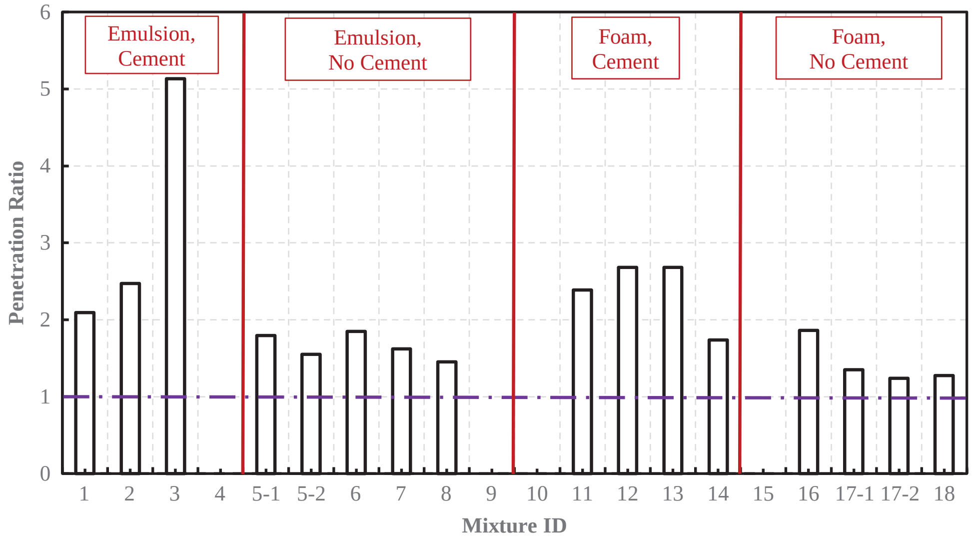


Figure 3.43. Penetration ratio of all evaluated mixtures from DCP testing.

The 11 produced mixtures with two or more slab replicates were further evaluated to investigate the effect of multiple parameters on the DPI. These parameters included recycling agent content, recycling process, recycling agent type, curing time, and density. An ANCOVA at a confidence level of 95% was used to evaluate the significance of these parameters. The cement content factor was nested under the recycling agent factor. Table 3.29 presents the outcomes of the ANCOVA for DPI. The p-values in Table 3.29 show that the DPI was sensitive to all evaluated factors (p-value < 0.05) except the process type and density.

A second round of DCP testing was conducted for selected mixtures using half the emulsified asphalt or foamed asphalt content to determine the influence of reducing the stabilizing/recycling agent on the DPI. Although not shown here, DCP testing was conducted on Mixtures 3, 7, 11, 12, and 13 at 1 hour and 24 hours of curing at both the full and half binder contents. The results of this testing showed that the DPI was not sensitive to the reduction in binder content, suggesting that DCP testing may not be sensitive to parameters that could indicate a higher potential for raveling.

Table 3.29. Results of ANCOVA for DPI.

Parameter	DF	f-Value	p-Value
Slab density	1	2.49	0.122
Recycling process	1	1.66	0.205
Recycling agent type	1	9.10	**0.004**
Curing time	1	58.38	**0.000**
Recycling agent content	4	4.33	**0.005**

Note: DF = degrees of freedom; bold/highlight = p-value shows the source to be significant.

3.4.6 Shear Resistance

An assessment of the shear resistance of the mixtures was made using a fixture developed in this study called a long-pin shear fixture. The LPST included an assessment of the number of blows required to drive the shear fixture into the test slab and then the maximum torque value reached prior to the material being sheared. A total of 18 mixtures were evaluated, as shown in Table 3.30. The collected data included the number of blows required to drive the shear fixture into the test slab and the maximum torque value obtained at 1, 3, 6, and 24 hours after compaction of the test slabs.

Figures 3.44 and 3.45 show the average number of blows required to drive the shear fixture into the test slab and the average torque value at different curing times, respectively. Certain mixture numbers containing no data indicate those mixtures that were not fabricated for testing during this part of the study. Mixture numbers with missing data points indicate that the test was not performed at the designated curing time (e.g., the number of blow counts for Mixtures 4 and 9) or the test could not be performed because the mixture's torque value reached the upper limit of the torque wrench (e.g., Mixtures 3 and 13 at 24 hours curing).

It is evident from Figures 3.44 and 3.45 that the LPST measurements were affected by curing and the presence of cement. A curious trend was also observed for certain mixtures in that the number of blows or torque value was seen to decrease from the 1- to the 3-hour test time and then increase at the 6- and 24-hour test times. The reasons for this are unclear, although this same trend was observed for certain mixtures during the field testing.

Table 3.30. Test slab details for long-pin shear test at 1, 3, 6, and 24 hours.

Mix ID	Stabilizing/Recycling Agent	Active Filler	Process	State	Agent Content, %	Active Filler Content, %	Actual Density, pcf	No. of Replicates
1	Emulsified asphalt	Cement	CCPR	IN	2.5	1.0	119.1	2
2				VA	2.5	1.0	127.6	0
3			FDR	TX	4.5	1.1	131.5	2
4				CA	2.5	1.0	127.8	1
5		No cement	CCPR	NY	3.0	0.0	122.0	2
6				VA	2.5	0.0	127.6	3
7			CIR	ON	1.2	0.0	121.4	2
8			FDR	IN	2.5	0.0	119.1	2
9				CA	2.5	0.0	127.8	2
10	Foamed asphalt	Cement	CCPR	VA	2.5	1.0	127.6	3
11			CIR	CA	2.0	1.0	117.4	2
12				MA	2.5	1.0	121.0	2
13			FDR	TX	2.4	1.5	125.6	2
14				CA	2.5	1.0	127.8	3
15		No cement	CCPR	VA	2.5	0.0	127.6	0
16			CIR	MI	2.2	0.0	129.8	2
17				WI	2.0	0.0	121.3	2
18			FDR	CA	2.5	0.0	127.8	0

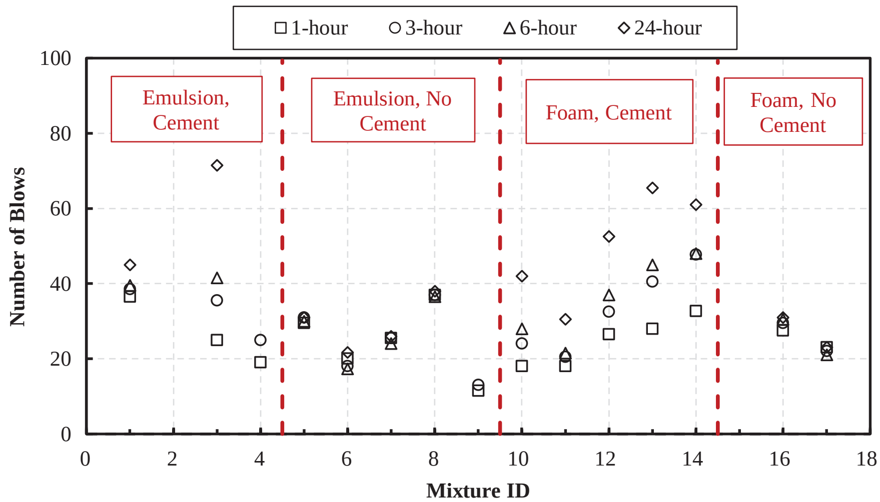


Figure 3.44. Number of blows to drive shear fixture into laboratory produced slabs.

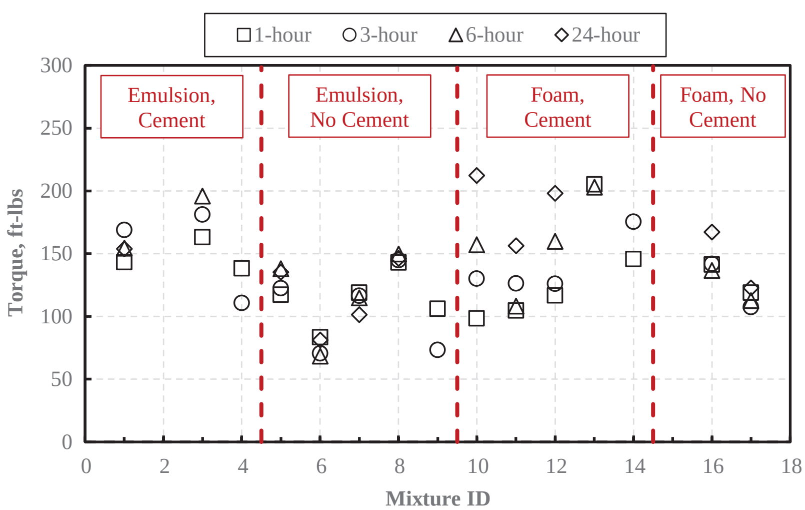


Figure 3.45. Torque values for field long-pin shear test.

Table 3.31. Descriptive statistics of number of blows by curing time.

Curing Time	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
1 hour	25.2	11	19.5	31.8	40	29	12.3
3 hours	29.5	13	21.3	35.6	50	37	14.5
6 hours	32.2	17	22.5	38.5	55	38	16.0
24 hours	41.5	19	26.0	52.5	80	61	26.5

Table 3.32. Descriptive statistics of number of blows by recycling agent and active filler type.

Material Combination	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
Emulsion, cement	40.1	19	33.3	44.0	72	53	10.8
Emulsion, no cement	25.0	11	18.0	31.5	40	29	13.5
Foam, cement	36.3	16	24.5	48.8	80	64	24.3
Foam, no cement	25.9	19	22.3	30.3	37	18	8.0

The descriptive statistics of the LPST testing are shown in Tables 3.31 through 3.34. Tables 3.31 and 3.32 show the descriptive statistics of the number of blows by curing time and recycling agent type, respectively. Tables 3.33 and 3.34 show the descriptive statistics of the torque value by curing time and recycling agent type, respectively. Table 3.31 shows that the mean number of blows and the IQR increased with respect to curing time. Table 3.32 shows that the mean number of blows was greater when cement as an active filler was present for mixtures having both emulsified and foamed asphalt. The IQR was less when cement was included as an active filler for mixtures using emulsified asphalt but greater for mixtures using foamed asphalt. Table 3.33 shows that the mean torque value increased with respect to curing time, as expected. As noted previously, for some mixtures, the torque value at 24 hours could not be recorded since the value exceeded the maximum capacity of the handheld torque wrench. The IQR decreased from 1 to 3 hours but then increased from 3 to 24 hours. Table 3.34 shows that the torque values increased for mixtures using both emulsified and foamed asphalt with cement. The IQR was similar for emulsified mixtures with and without cement but decreased for foamed asphalt mixtures without cement.

The variability of the LPST was assessed in terms of the COV calculated from testing replicate specimens. Figure 3.46 shows the COV for the number of blows, and Figure 3.47 shows the COV for the measured torque values. The COV for the number of blows was generally less than 20% (46 of 54 conditions, considering all curing times), with an average COV of 9.5%. Similarly, the measured torque value COV was generally less than 20% (47 of 49 conditions), with an average COV of 9%. Although some mixtures had a COV of greater than 20%, the data suggested that the variability was not particularly affected by the process type, recycling agent type, or curing time. In general, those mixtures that had lower or higher COVs at the 1-hour test tended to have a relatively similar variability across all curing times.

The generated data were also analyzed statistically to investigate the effect of the recycled mixture parameters considered in this study on the measured torque value and

Table 3.33. Descriptive statistics of torque values by curing time.

Curing Time	Mean, ft-lbs	Minimum, ft-lbs	Quartile 1, ft-lbs	Quartile 3, ft-lbs	Maximum, ft-lbs	Range, ft-lbs	Interquartile Range, ft-lbs
1 hour	127.5	78.0	105.7	150.1	224.3	146.3	44.4
3 hours	128.6	68.7	110.5	149.8	212.7	144.0	39.3
6 hours	138.7	66.8	113.1	166.4	222.2	155.3	53.3
24 hours	147.5	76.8	114.4	179.3	217.3	140.6	64.8

Table 3.34. Descriptive statistics of torque values by recycling agent and active filler type.

Material Combination	Mean, ft-lbs	Minimum, ft-lbs	Quartile 1, ft-lbs	Quartile 3, ft-lbs	Maximum, ft-lbs	Range, ft-lbs	Interquartile Range, ft-lbs
Emulsion, cement	164.3	110.8	137.8	191.9	222.2	111.3	54.1
Emulsion, no cement	111.6	66.8	79.7	133.4	168.0	101.2	53.7
Foam, cement	151.7	94.7	116.1	182.6	224.3	129.7	66.5
Foam, no cement	131.2	99.8	115.4	146.2	179.3	79.5	30.8

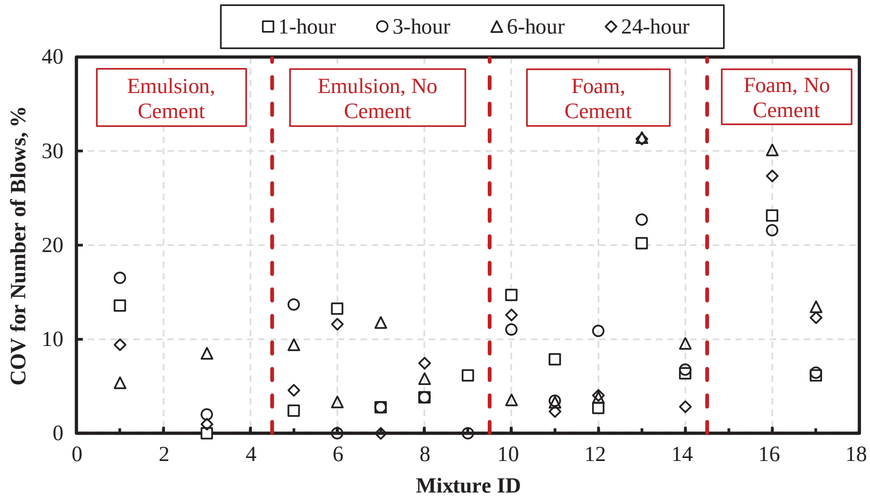


Figure 3.46. Variability of number of blows in terms of coefficient of variation.

the number of blows. An ANCOVA at a confidence level of 95% was used to test for significant factors in the number of blows and the torque among various mixture parameters. The factors used included process type, recycling agent type and rate, active filler (cement) rate, density, and curing time. The experiment was a nested design as it was not intended to have a factorial design for the levels of the various factors. In other words, although the recycling agent type (emulsion or foam) was not nested as a factor in the process type (CIR or FDR), the recycling agent rate and cement rate were nested as a factor in the recycling agent type. Density was used as a covariate factor in the analysis.

Table 3.35 shows the ANCOVA statistics for the number of blows. The number of blows was significantly varied (the p-value was less than 0.05) as a function of curing time, recycling agent rate with different recycling agent types, process, and density. Table 3.36 presents the ANCOVA statistics for the torque value and shows that the torque values were significantly varied (the p-value was less than 0.05) as a function of curing time, recycling agent rate with different recycling agent types, process, and density.

3.4.7 Raveling Resistance

Like the LPST, an assessment of the raveling resistance of the mixtures was made using a fixture developed in this study called a short-pin raveling fixture. The SPRT measured the same penetration and torque parameters as the LPST discussed in the previous section. A total of 18 mixtures were evaluated; mixture details are provided in Table 3.37. These mixtures were manufactured using 12 sources of recycled materials. For some mixtures, two slab replicates

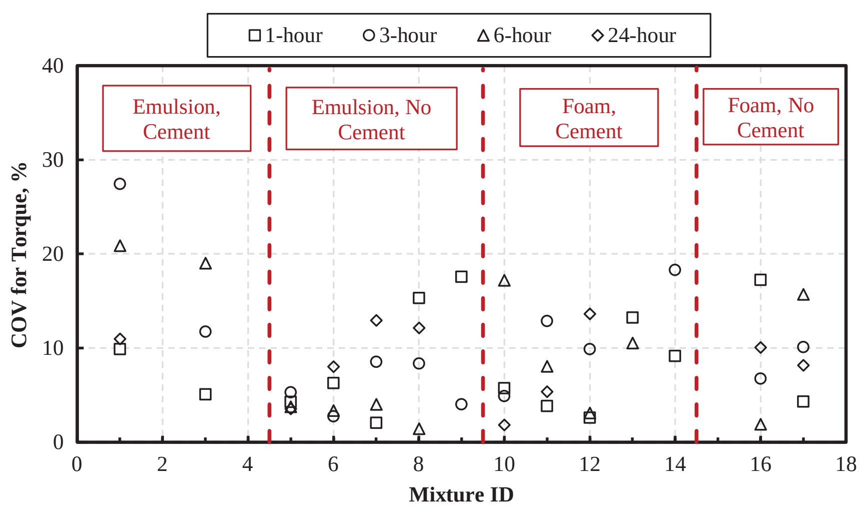


Figure 3.47. Variability of torque value in terms of coefficient of variation.

Table 3.35. Results of ANCOVA for number of blows.

Source	DF	*f*-Value	*p*-Value
Slab density	1	32.89	**0.000**
Recycling process	1	22.17	**0.000**
Recycling agent type	1	2.3	0.132
Curing time	3	20.38	**0.000**
Recycling agent content	6	10.38	**0.000**

Note: DF = degrees of freedom; bold/highlight = *p*-value shows the source to be significant.

Table 3.36. Results of ANCOVA for torque value.

Source	DF	*f*-Value	*p*-Value
Slab density	1	36.75	**0.000**
Recycling process	1	10.56	**0.002**
Recycling agent type	1	17.64	**0.000**
Curing time	3	6.44	**0.001**
Recycling agent content	6	5.57	**0.000**

Note: DF = degrees of freedom; bold/highlight = *p*-value shows the source to be significant.

were produced, whereas one replicate was produced for other mixtures. Table 3.37 also shows that some replicates were produced using the full design stabilizing/recycling agent content, and some were produced at half the design content in an effort to force a more severe raveling situation.

The raveling data are presented with respect to two measurements of the number of blows (N_1 and N_2) required to drive the raveling fixture into the test slab and the measured torque. The value N_1 describes the number of blows required to drive the raveling fixture from the tip of the longer center pin to the tips of the shorter outer pins. The value N_2 describes the number of blows required to drive the raveling fixture from the tip of the long center pin until the base plate was seated against the surface of the test slab. These two separate values were recorded in case they proved useful in the analysis. For each of these measurements, the data are presented at the full design binder content and for certain mixtures at half of the design binder content.

Figures 3.48 and 3.49 show the number of blows (N_1) at the full and half design binder contents, respectively. The

Table 3.37. Specimen and mixture details for short-pin raveling test.

Mix ID	Agent	Filler	Process	State	Agent Content, %	Filler Content, %	Actual Density, pcf	No. of Replicates
1	Emulsified asphalt	Cement	CCPR	IN	2.5	1.0	119.1	1 rep full 0 rep half
2				VA	2.5	1.0	127.6	2 reps full 0 rep half
3			FDR	TX	4.5	1.1	131.5	1 rep full 1 rep half
4				CA	2.5	1.0	127.8	2 reps full 1 rep half
5		No cement	CCPR	NY	3.0	0.0	122.0	1 rep full 0 rep half
6				VA	2.5	0.0	127.6	2 reps full 0 rep half
7			CIR	ON	1.2	0.0	121.4	1 rep full 1 rep half
8			FDR	IN	2.5	0.0	119.1	1 rep full 0 rep half
9				CA	2.5	0.0	127.8	2 reps full 0 rep half
10	Foamed asphalt	Cement	CCPR	VA	2.5	1.0	127.6	2 reps full 1 rep half
11			CIR	CA	2.0	1.0	117.4	1 rep full 1 rep half
12				MA	2.5	1.0	121.0	1 rep full 1 rep half
13			FDR	TX	2.4	1.5	125.6	2 reps full 1 rep half
14				CA	2.5	1.0	127.8	2 reps full 1 rep half
15		No cement	CCPR	VA	2.5	0.0	127.6	2 reps full 1 rep half
16			CIR	MI	2.2	0.0	129.8	1 rep full 0 rep half
17				WI	2.0	0.0	121.3	1 rep full 0 rep half
18			FDR	CA	2.5	0.0	127.8	2 reps full 1 rep half

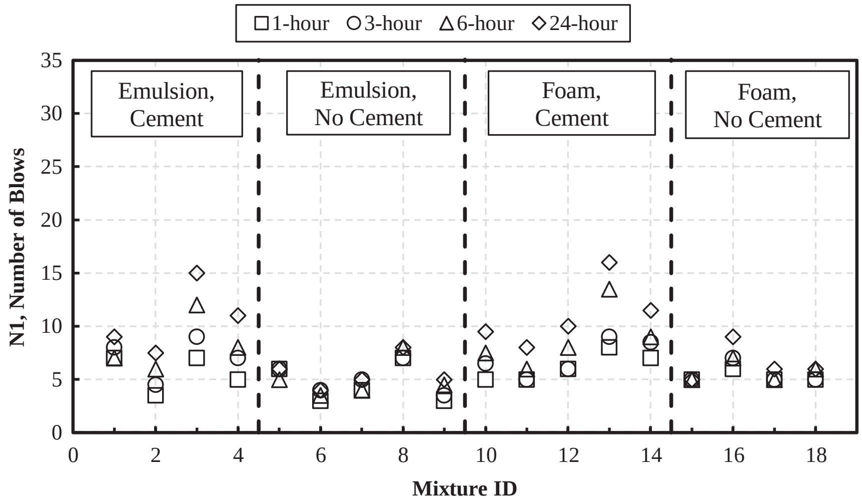


Figure 3.48. Number of blows (N_1) required to drive raveling fixture (full binder content).

figures show that the mixtures with cement tended to have a greater magnitude and spread in the number of blows with respect to the four curing times than those mixtures with no cement. Table 3.38 shows the descriptive statistics for SPRT parameters using all collected data irrespective of curing time, recycling agent type, and cement content. Table 3.39 shows the descriptive statistics for the number of blows (N_1) data with respect to curing time. The mean number of blows increased with respect to curing time. The IQR was similar for all four curing times. Table 3.40 shows the descriptive statistics for the number of blows (N_1) with respect to recycling agent and cement content. The mean number of blows increased when cement was present in both emulsified and foamed asphalt mixtures. The IQR was similar for all material combinations.

Figure 3.50 shows the variability of the number of blows (N_1) in terms of the COV for those mixtures that had replicates. The COV values were all less than about 25% except for Mixture 13. There did not appear to be a clear trend with respect to material combination, in part because of the low number of mixtures that had replicates.

Figures 3.51 and 3.52 show the number of blows (N_2) required to drive the raveling fixture from the tip of the longer center pin until the base plate was seated against the surface of the test slab at the full and half binder contents, respectively. The mixtures with cement tended to have a greater magnitude and spread in the number of blows with respect to the four curing times than those mixtures that did not include cement. As with N_1, N_2 responded as expected to the presence of cement with respect to curing time. As

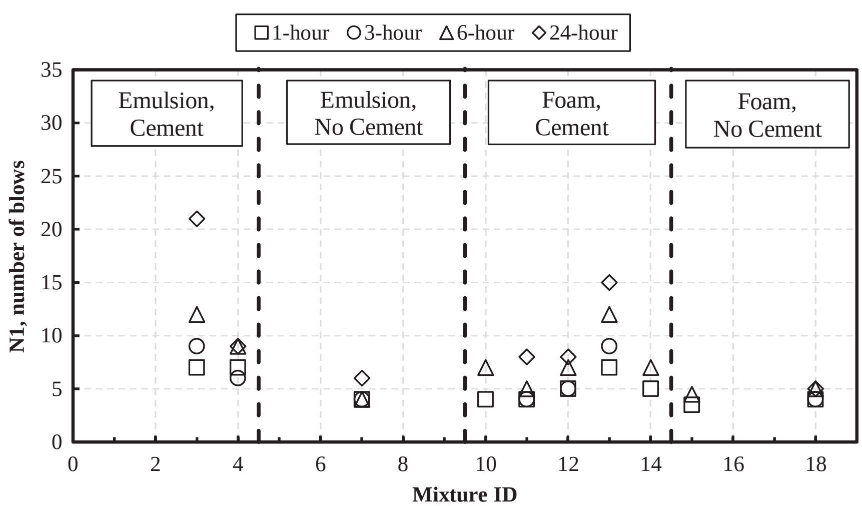


Figure 3.49. Number of blows (N_1) required to drive raveling fixture (half binder content).

Table 3.38. Descriptive statistics of SPRT parameters for full and half binder specimens irrespective of curing time, recycling agent type, and cement content.

Parameter	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
Number of blows, N_1	6.8	3.0	5.0	8.0	21.0	18.0	3.0
Number of blows, N_2	12.1	6.0	9.0	14.0	34.0	28.0	5.0
Torque value	425.7	139.0	281.3	530.1	1,289	1,150	248.9

Table 3.39. Descriptive statistics of number of blows (N_1) for full and half binder specimens with respect to curing time.

Curing Time	N_1, Blows						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
1 hour	5.3	3.0	4.0	7.0	8.0	5.0	3.0
3 hours	6.1	3.5	5.0	7.0	9.0	5.5	2.0
6 hours	7.1	3.5	5.0	8.0	13.5	10.0	3.0
24 hours	8.9	4.0	6.0	10.0	21.0	17.0	4.0

Table 3.40. Descriptive statistics of number of blows (N_1) for full and half binder specimens with respect to recycling agent type and cement content.

Material Combination	N_1, Blows						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
Emulsion, cement	8.6	3.5	7.0	9.0	21.0	17.5	2.0
Emulsion, no cement	5.0	3.0	4.0	6.0	8.0	5.0	2.0
Foam, cement	7.7	4.0	5.0	9.0	16.0	12.0	4.0
Foam, no cement	5.4	3.5	5.0	6.0	9.0	5.5	1.0

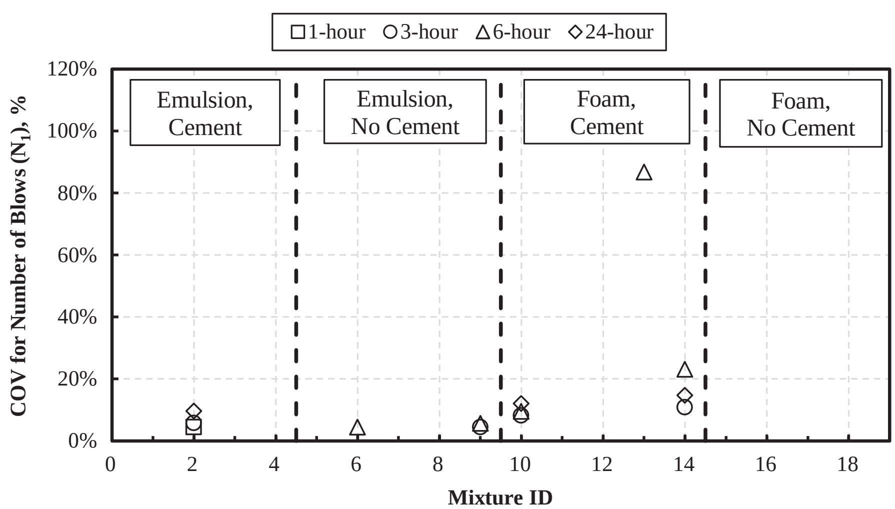


Figure 3.50. Coefficient of variation for number of blows, N_1 (full binder specimens only).

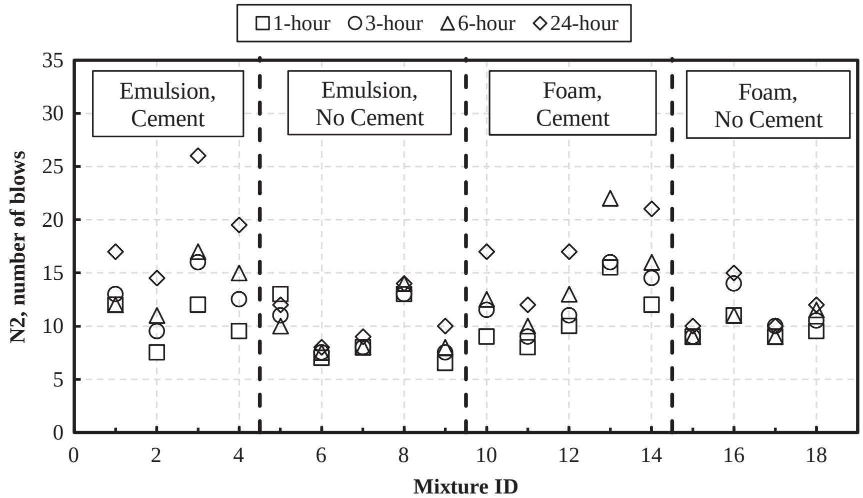


Figure 3.51. Number of blows (N_2) required to drive raveling fixture (full binder content).

with N_1, the range and magnitude of N_2 were similar with respect to the use of emulsified asphalt or foamed asphalt. Comparing Figures 3.51 and 3.52, there did not appear to be a large difference between the number of blows (N_2) between full and half binder contents.

The descriptive statistics for N_2 using all collected data irrespective of curing time, recycling agent type, and cement content are summarized in Table 3.41. The mean number of blows (N_2) increased with respect to curing time, as expected. The IQR was similar for the first three curing times but generally increased with respect to curing time. Table 3.42 shows the descriptive statistics for N_2 with respect to recycling agent and presence of cement. Table 3.42 shows that N_2 increased when cement was present for mixtures using both emulsified and foamed asphalt. A similar trend was found for the IQR. When the results of N_1 and N_2 were compared, N_2 showed a greater range with respect to curing time and material combinations and was thus a better descriptor than N_1.

Figure 3.53 shows the variability of N_2 in terms of the COV for those mixtures that had replicates, with all values less than about 40% except for Mixture 4. There did not appear to be a clear trend based on material type, in part because of the low number of mixtures that had replicates.

Figures 3.54 and 3.55 show the measured torque value using the raveling fixture at the full and half design binder contents, respectively. As with the number of blows, the torque values showed a greater magnitude and spread for those mixtures with cement. In addition, the magnitude and range for mixtures containing emulsified asphalt versus foamed asphalt were similar. As observed for the number of

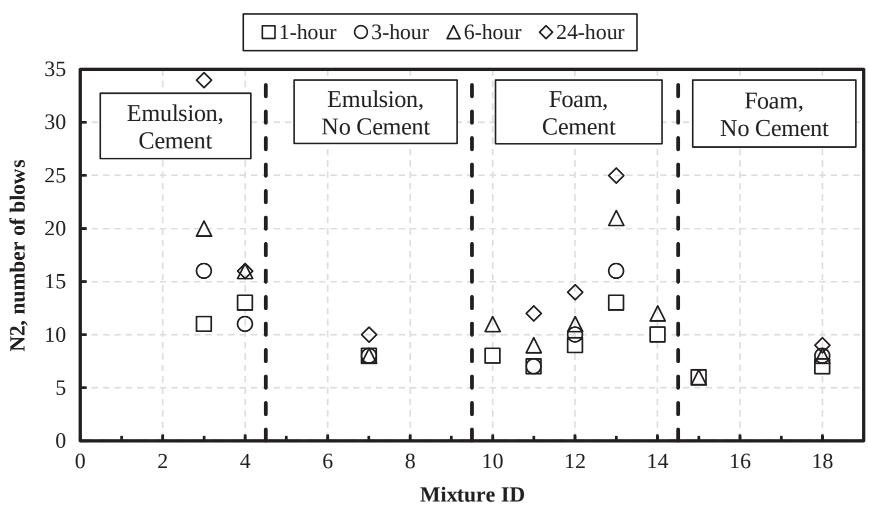


Figure 3.52. Number of blows (N_2) required to drive raveling fixture (half binder content).

Table 3.41. Descriptive statistics of number of blows (N_2) for full and half binder specimens with respect to curing time.

Curing Time	N_2, Blows						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
1 hour	9.8	6.0	8.0	12.0	15.5	9.5	4.0
3 hours	11.2	7.0	9.0	13.0	16.0	9.0	4.0
6 hours	12.1	6.0	9.0	14.3	22.0	16.0	5.3
24 hours	15.7	8.0	10.0	17.0	34.0	26.0	7.0

Table 3.42. Descriptive statistics of number of blows (N_2) for full and half binder specimens with respect to recycling agent type and cement content.

Material Combination	N_2, Blows						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Age	Interquartile Range
Emulsion, cement	15.0	7.5	11.8	16.3	34.0	26.5	4.5
Emulsion, no cement	9.5	6.5	8.0	11.3	14.0	7.5	3.3
Foam, cement	13.4	7.0	10.0	16.0	29.0	22.0	6.0
Foam, no cement	9.7	6.0	9.0	10.9	15.0	9.0	1.9

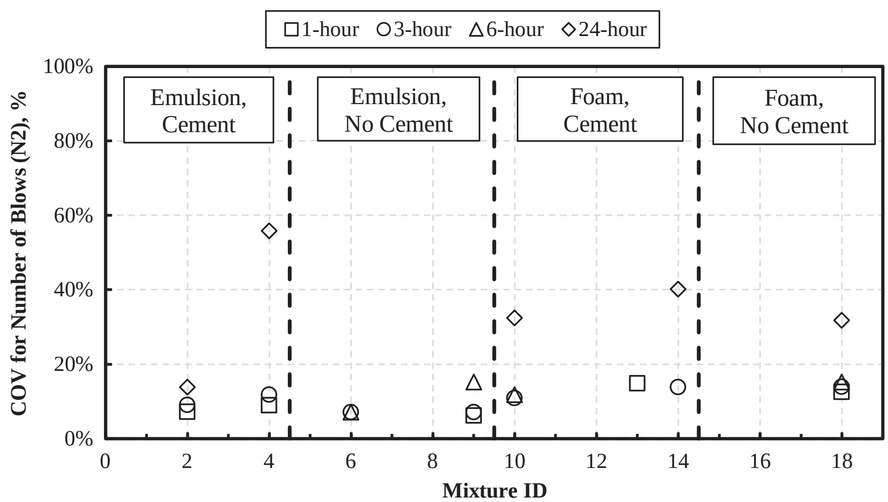


Figure 3.53. Coefficient of variation for number of blows, N_2 (full binder specimens only).

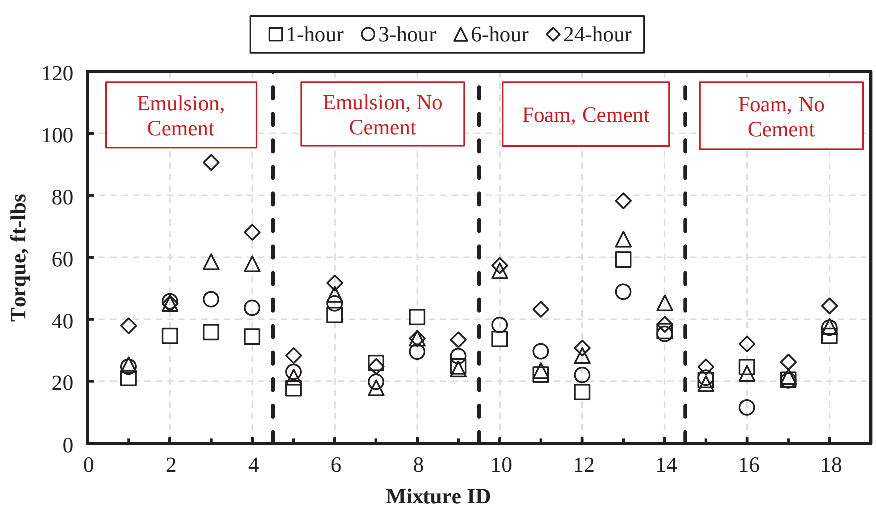


Figure 3.54. Torque value using raveling fixture (full binder content).

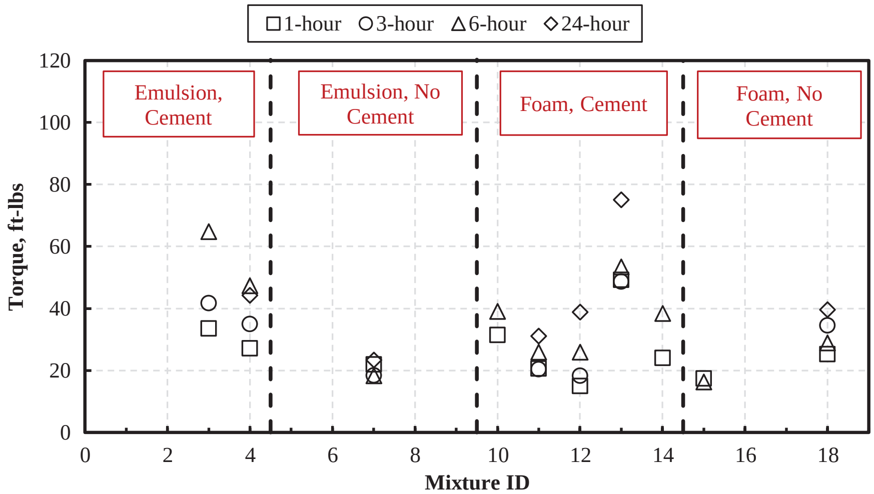


Figure 3.55. Torque value using raveling fixture (half binder content).

blows, Figure 3.55 shows that the torque values were similar at the half binder and at the full binder content.

The descriptive statistics for the measured torque value using all collected data with respect to curing time are shown in Table 3.43. The mean torque value increased with respect to curing time. The IQR also increased with curing time from 1 to 6 hours but decreased from 6 to 24 hours. Table 3.44 shows the descriptive statistics for the measured torque value using all collected data with respect to material combinations. The mean torque value increased with the presence of cement for mixtures using both emulsified and foamed asphalt. A similar increasing trend was observed for the IQR.

Figure 3.56 shows the variability of the torque value in terms of the COV. The COV values were considered low and were all less than about 25%. There did not appear to be a clear trend based on material type, partly because of the low number of mixtures that had replicates.

An ANCOVA at a confidence level of 95% was used to evaluate the significance of various mixture parameters. The agent rate and cement type factors were both nested within the recycling agent type factor. Tables 3.45 through 3.47 present the outcomes of the ANCOVA for N_1, N_2, and raveling torque, respectively. The *p*-values in Table 3.45 show that N_1 was sensitive only to process type factor. Table 3.46 shows that the number of blows (N_2) was sensitive to all evaluated factors. Table 3.47 shows that the measured torque value was sensitive to all factors except the recycling process and the recycling agent type.

Table 3.43. Descriptive statistics of torque value using raveling fixture for full and half binder specimens with respect to curing time.

Curing Time	Raveling Torque, ft-lb						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
1 hour	29.0	15.0	21.0	34.7	59.3	44.3	13.7
3 hours	31.5	11.6	21.2	41.8	48.9	37.3	20.6
6 hours	36.1	16.3	23.3	47.6	65.9	49.5	24.3
24 hours	46.0	23.4	31.1	51.8	107.4	84.0	20.7

Table 3.44. Descriptive statistics of torque value using raveling fixture for full and half binder specimens with respect to recycling agent and active filler type.

Material Combination	Raveling Torque, ft-lb						
	Mean	Minimum	Quartile 1	Quartile 3	Maximum	Range	Interquartile Range
Emulsion, cement	46.6	21.1	34.7	50.1	107.4	86.3	15.4
Emulsion, no cement	29.0	17.8	21.8	33.9	51.8	34.0	12.2
Foam, cement	37.9	15.0	25.5	48.7	78.3	63.3	23.3
Foam, no cement	26.4	11.6	20.4	34.0	44.4	32.8	13.6

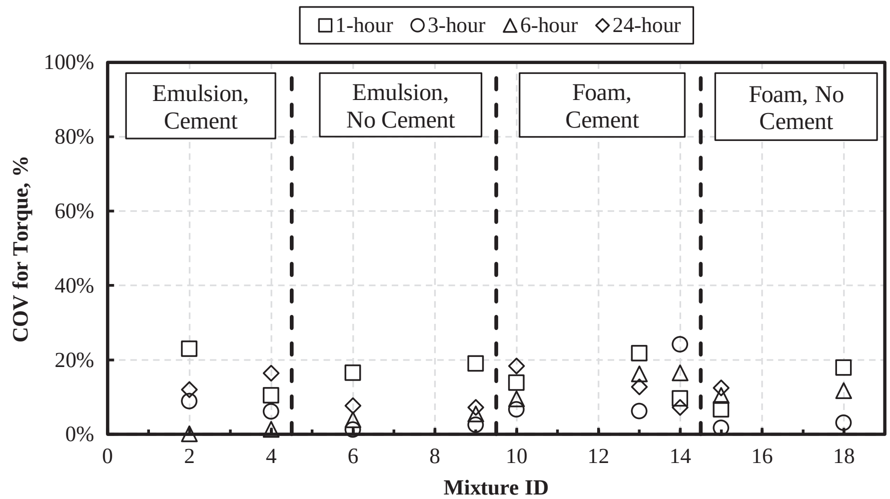


Figure 3.56. Coefficient of variation for torque value (full binder specimens only).

Table 3.45. Short-pin raveling test: results of ANCOVA for number of blows, N_1.

Parameter	DF	*f*-Value	*p*-Value
Slab density	1	24.09	**0.000**
Recycling process	1	6.37	**0.014**
Recycling agent type	1	4.14	**0.046**
Curing time	3	9.61	**0.000**

Note: DF = degrees of freedom; bolding indicates that the *p*-value shows the source to be significant.

Table 3.46. Short-pin raveling test: results of ANCOVA for number of blows, N_2.

Parameter	DF	*f*-Value	*p*-Value
Slab density	1	33.81	**0.000**
Recycling process	1	20.29	**0.000**
Recycling agent type	1	10.37	**0.002**
Curing time	3	12.68	**0.000**

Note: DF = degrees of freedom; bolding indicates that the *p*-value shows the source to be significant.

Table 3.47. Short-pin raveling test: results of ANCOVA for torque.

Parameter	DF	*f*-Value	*p*-Value
Slab density	1	34.08	**0.000**
Recycling process	1	0.69	0.411
Recycling agent type	1	4.26	**0.000**
Curing time	3	5.43	**0.002**

Note: DF = degrees of freedom bolding indicates that the *p*-value shows the source to be significant.

3.4.8 Correlation Analysis

A correlation analysis was performed to investigate the relationship between selected test measurement combinations using the data from the Phase II laboratory study. The analysis was performed by calculating the Pearson correlation coefficient (r) and the associated p-value. The Pearson correlation coefficient describes the linear relationship between two variables and has a range of $-1 < r < +1$, where values closer to −1 or +1 indicate a stronger correlation. A value of −1 or +1 indicates a negative or positive relationship, respectively. The p-value indicates the statistical significance of the relationship; a higher p-value suggests that the correlation may be due to random chance.

Tables 3.48 and 3.49 show the Pearson correlation coefficient and p-value for comparisons of the test slab density, SSG stiffness, LWD modulus, and DPI values at curing periods of 2 and 72 hours, respectively. For those combinations that were shown to have a strong correlation ($|r| > 0.7$, based on categories by Evans [1996]), the p-value was determined to estimate the significance of the relationship (alpha = 0.05). Shaded cells indicate comparisons where both conditions were met. There was a strong correlation between the SSG and LWD at 2 hours of curing. For both comparisons, the p-value indicates that the correlation was statistically significant.

Tables 3.50 through 3.53 show the results of the correlation analysis for those slabs tested at 1, 3, 6, and 24 hours of curing time, respectively. The tables show the Pearson correlation coefficient and p-value for comparisons of the test slab density, LWD modulus, LPST number of blows, LPST torque value, SPRT number of blows (N_1 and N_2), SPRT torque value, and DPI values. Results from MH testing were

Table 3.48. Correlation analysis at 2 Hours of curing, (a) Pearson correlation coefficient, (b) *p*-value.

(a)

	SSG Stiffness, MN/m	LWD Modulus, ksi	DPI, mm/blow
Slab density, lb/ft³	−0.1815	0.4664	0.0461
SSG stiffness, MN/m		**0.7472**	−0.6572
LWD modulus, ksi			−0.5539

(b)

	SSG Stiffness, MN/m	LWD Modulus, ksi	DPI, mm/blow
Slab density, lb/ft³	0.3370	0.0094	0.8089
SSG stiffness, MN/m		**0.0000**	0.0001
LWD modulus, ksi			0.0015

not included because of the high test variability. For those combinations that were shown to have a strong correlation ($|r| > 0.7$), the *p*-value was determined to estimate the significance of the relationship (alpha = 0.05). Shaded cells indicate comparisons where both conditions were met.

The number of blows from the LPST and SPRT have a strong correlation, and the relationship was statistically significant across all four curing times. The LPST torque value and the SPRT number of blows also had a strong correlation with the DPI, with relationships statistically significant at 1 and 24 hours of curing. The SPRT torque value had a strong correlation with the DPI but with the relationship statistically significant only at the 24-hour curing time. Slab density did not have a strong correlation with any of the performance tests. The LPST torque value did not have a strong correlation with the SPRT torque value.

Figures 3.57 through 3.60 demonstrate the relationship between those tests shown in the correlation analysis to have the strongest correlation and a statistically significant relationship. The data are presented with respect to the curing time, and linear trendlines are shown for each. Another trendline type (e.g., polynomial, exponential) might show a higher coefficient of determination, but use of a linear trend is consistent with the relationship shown by the Pearson correlation coefficient.

Figures 3.57 and 3.58 show the relationship between the LPST number of blows and the SPRT number of blows N_1 and N_2, respectively, for curing times of 1, 3, 6, and 24 hours. The trendline slopes were similar for all curing times, and the coefficient of determination generally increased with respect to curing time. Figure 3.59 shows the relationship between the SPRT number of blows N_1 and N_2 for all curing times. The trendline slope values were similar across all curing times, and the coefficient of determination increased with respect to curing time. Figure 3.60 shows the relationship between the LPST torque value and the SPRT number of blows (N_2) for all curing times. The trendline slopes were similar for all curing times, and the coefficient of determination generally increased with respect to curing time.

Figure 3.61 shows the relationship between the LPST torque value and DPI for curing times of 1 and 24 hours. The coefficient of determination increased with respect to curing time, and the slope of the trendline became more negative as curing time increased. Figure 3.62 shows the relationship between the SPRT torque value and DPI for both curing times. As with Figure 3.61, the coefficient of determination increased with respect to curing time, but the slope of the trendline became less negative as curing time increased. Figure 3.63 shows the relationship between the SPRT N_2 and DPI for both curing times. The coefficient of determination increased slightly with respect to curing time, and the slope of the trendline became less negative as curing time increased. A nonlinear trendline would likely better describe the relationships shown in these three figures.

Table 3.49. Correlation analysis at 72 hours of curing, (a) Pearson correlation coefficient, (b) *p*-value.

(a)

	SSG Stiffness, MN/m	LWD Modulus, ksi	DPI, mm/blow
Slab density, lb/ft³	−0.0178	−0.1538	−0.1976
SSG stiffness, MN/m		0.2105	−0.2108
LWD modulus, ksi			−0.5149

(b)

	SSG Stiffness, MN/m	LWD Modulus, ksi	DPI, mm/blow
Slab density, lb/ft³	0.9258	0.4170	0.2952
SSG stiffness, MN/m		0.2641	0.2636
LWD modulus, ksi			0.0036

Table 3.50. Correlation analysis at 1-hour of curing, (a) Pearson correlation coefficient, (b) *p*-value.

(a)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft^3	–0.5056	–0.2964	0.1018	–0.0381	–0.0181	0.3018	–0.5755
LWD modulus, ksi		0.4620	0.0167	0.4550	0.5461	0.3165	*
LPST number of blows			0.5296	**0.7690**	**0.7484**	0.1404	–0.6922
LPST torque value, ft-lb				**0.7659**	**0.8595**	0.5736	**–0.7109**
SPRT number of blows, N_1					**0.9475**	0.3410	**–0.9167**
SPRT number of blows, N_2						0.4750	**–0.8611**
SPRT torque value, ft-lb							–0.6323

* = Combination assessed as part of 2 and 72 hours comparison.

(b)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft^3	0.0032	0.0995	0.5792	0.8227	0.9154	0.0695	0.0197
LWD modulus, ksi		0.0078	0.9276	0.0047	0.0005	0.0563	*
LPST number of blows			0.0136	**0.0000**	**0.0001**	0.5438	0.0183
LPST torque value, ft-lb				**0.0014**	**0.0000**	0.0066	**0.0142**
SPRT number of blows, N_1					**0.0000**	0.1630	**0.0000**
SPRT number of blows, N_2						0.0296	**0.0000**
SPRT torque value, ft-lb							0.0086

* = Combination assessed as part of 2 and 72 hours comparison.

Table 3.51. Correlation analysis at 3 hours of curing, (a) Pearson correlation coefficient, (b) p-value.

(a)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft^3	–0.5269	0.0000	0.0152	0.2209	0.2335	0.4979	DNT
LWD modulus, ksi		0.2978	0.2573	0.5365	0.6171	0.1631	*
LPST number of blows			**0.8734**	**0.8663**	**0.8315**	–0.0319	
LPST torque value, ft-lb				**0.9048**	**0.8644**	–0.1108	
SPRT number of blows, N_1					**0.9565**	0.1154	DNT
SPRT number of blows, N_2						0.0916	
SPRT torque value, ft-lb							

DNT = did not test; * = combination assessed as part of 2 and 72 hours comparison.

(b)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft^3	0.0019	0.0978	0.9340	0.2093	0.1838	0.0027	DNT
LWD modulus, ksi		0.9998	0.0170	0.0011	0.0001	0.3566	*
LPST number of blows			**0.0000**	**0.0000**	**0.0000**	0.8969	
LPST torque value, ft-lb				**0.0001**	**0.0000**	0.6515	
SPRT number of blows, N_1					**0.0000**	0.6381	DNT
SPRT number of blows, N_2						0.7091	
SPRT torque value, ft-lb							

DNT = did not test; * = combination assessed as part of 2 and 72 hours comparison.

Table 3.52. Correlation analysis at 6 hours of curing, (a) Pearson correlation coefficient, (b) p-value.

(a)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft^3	–0.4124	0.1273	0.2375	0.1892	0.1677	0.4711	DNT
LWD modulus, ksi		0.4459	0.3251	**0.7499**	**0.7673**	0.5465	*
LPST number of blows			**0.8050**	**0.7906**	**0.8526**	0.5575	DNT
LPST torque value, ft-lb				**0.8217**	**0.8090**	0.5099	
SPRT number of blows, N_1					**0.9746**	0.6258	
SPRT number of blows, N_2						0.6688	
SPRT torque value, ft-lb							

DNT = did not test; * = combination assessed as part of 2 and 72 hours comparison.

(b)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft^3	0.0190	0.4873	0.1905	0.2620	0.3212	0.0032	DNT
LWD modulus, ksi		0.0105	0.0694	**0.0000**	**0.0000**	0.0005	*
LPST number of blows			**0.0000**	**0.0000**	**0.0000**	0.0086	DNT
LPST torque value, ft-lb				**0.0003**	**0.0000**	0.0182	
SPRT number of blows, N_1					**0.0000**	0.0024	
SPRT number of blows, N_2						0.0009	
SPRT torque value, ft-lb							

DNT = did not test; * = combination assessed as part of 2 and 72 hours comparison.

Table 3.53. Correlation analysis at 24 hours of curing, (a) Pearson correlation coefficient, (b) p-value.

(a)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft³	−0.2052	0.2708	0.1729	0.2712	0.2887	0.4517	−0.5248
LWD modulus, ksi		0.6020	0.4114	**0.8302**	**0.8780**	0.6623	*
LPST number of blows			**0.8479**	**0.9164**	**0.9405**	0.2967	−0.6440
LPST torque value, ft-lb				**0.8555**	**0.9163**	0.3874	**−0.9292**
SPRT number of blows, N_1					**0.9756**	0.4126	**−0.8860**
SPRT number of blows, N_2						0.4371	**−0.8733**
SPRT torque value, ft-lb							**−0.8755**

* = Combination assessed as part of 2 and 72 hours comparison.

(b)

	LWD Modulus, ksi	LPST Number of Blows	LPST Torque Value, ft-lb	SPRT Number of Blows, N_1	SPRT Number of Blows, N_2	SPRT Torque Value, ft-lb	DPI, mm/blow
Slab density, lb/ft³	0.2599	0.1338	0.3440	0.1268	0.1032	0.0083	0.0446
LWD modulus, ksi		0.0003	0.0296	**0.0000**	**0.0000**	0.0000	*
LPST number of blows			**0.0000**	**0.0000**	**0.0000**	0.2475	0.1185
LPST torque value, ft-lb				**0.0016**	**0.0000**	0.1244	**0.0025**
SPRT number of blows, N_1					**0.0000**	0.0998	**0.0000**
SPRT number of blows, N_2						0.0794	**0.0000**
SPRT torque value, ft-lb							**0.0000**

* = Combination assessed as part of 2 and 72 hours comparison.

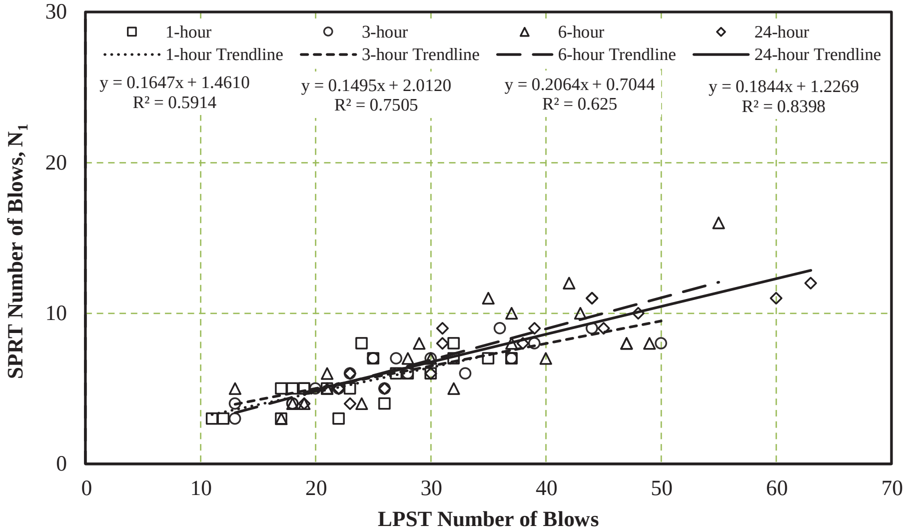


Figure 3.57. Relationship between LPST number of blows and SPRT N_1.

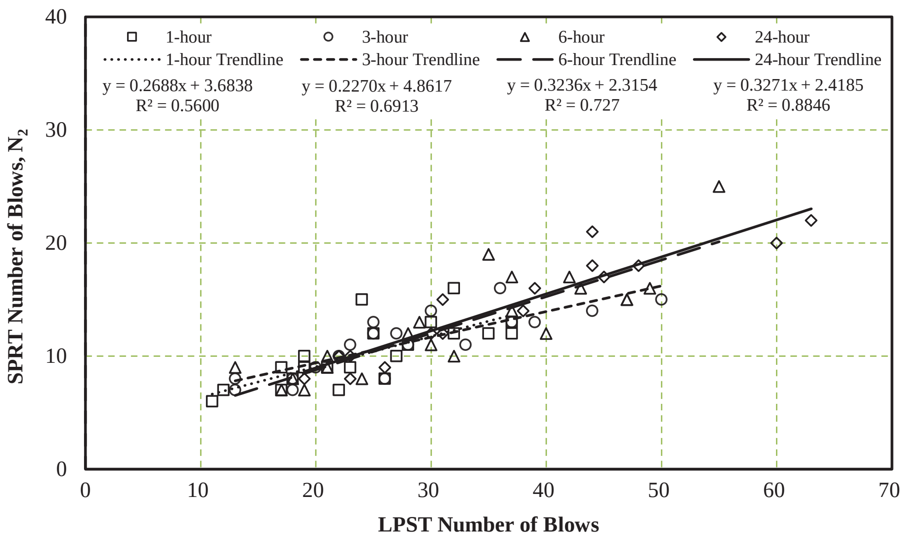


Figure 3.58. Relationship between LPST number of blows and SPRT N_2.

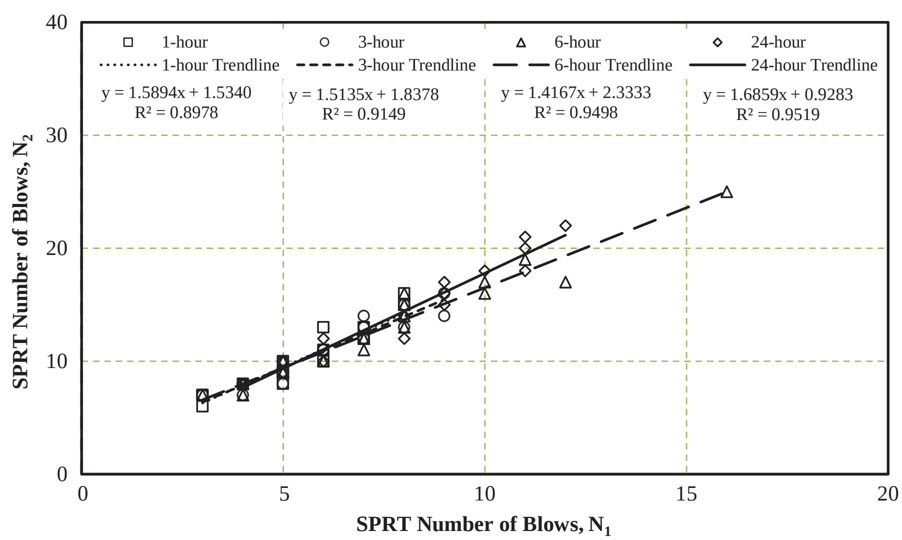


Figure 3.59. Relationship between SPRT N_1 and SPRT N_2.

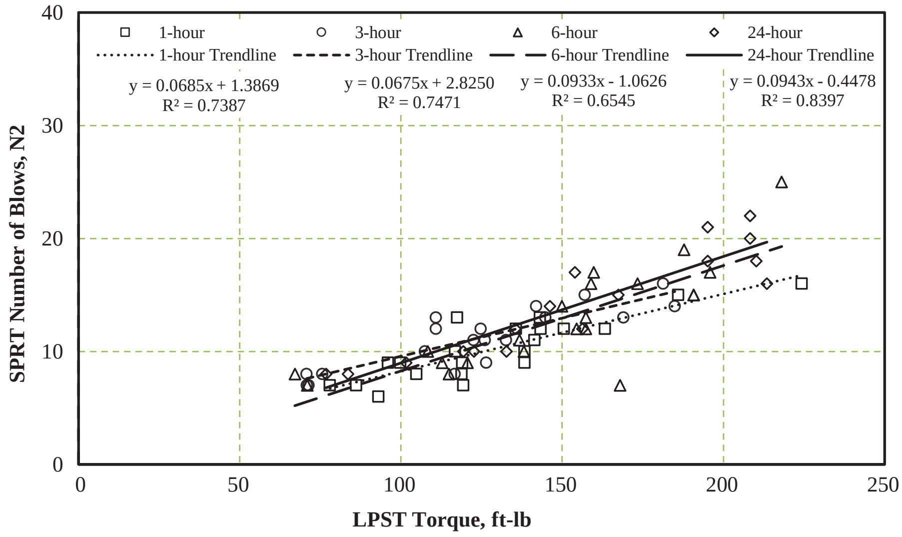


Figure 3.60. Relationship between LPST torque value and SPRT N_2.

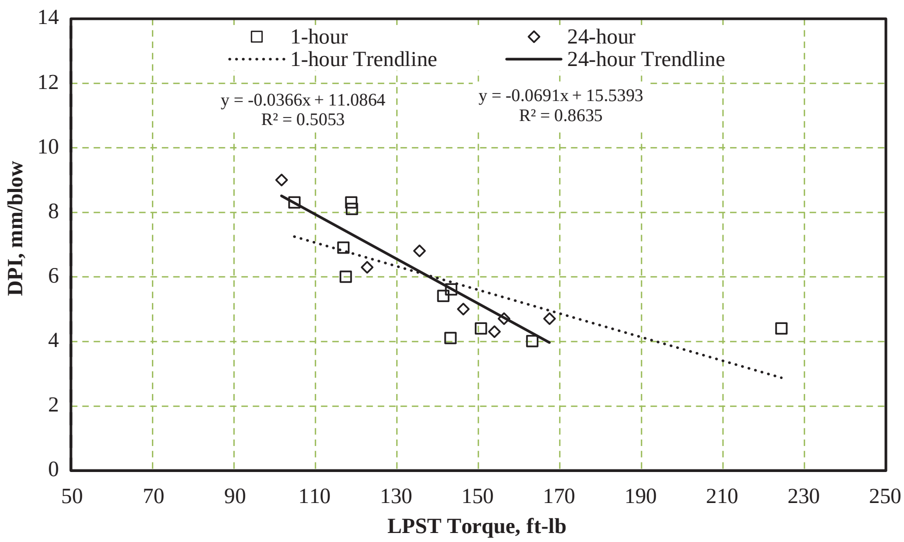


Figure 3.61. Relationship between LPST torque value and DPI.

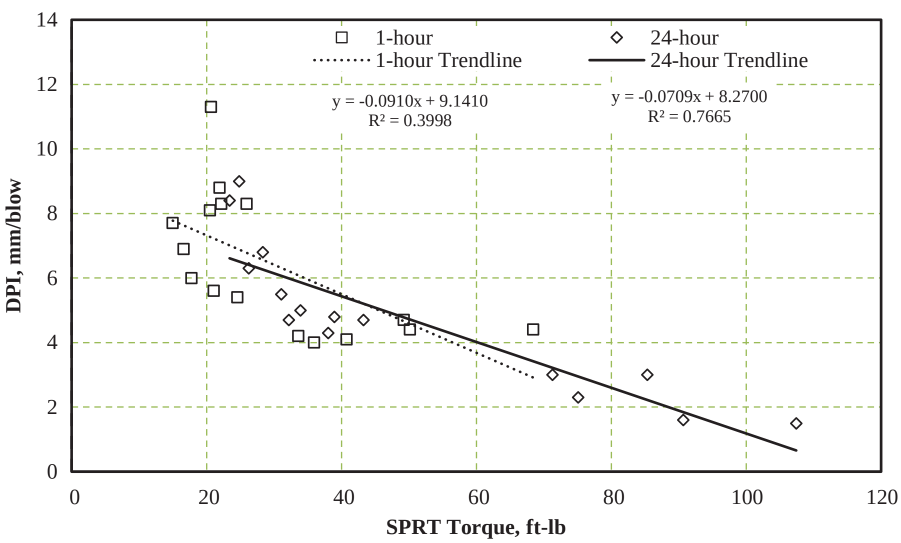


Figure 3.62. Relationship between SPRT torque value and DPI.

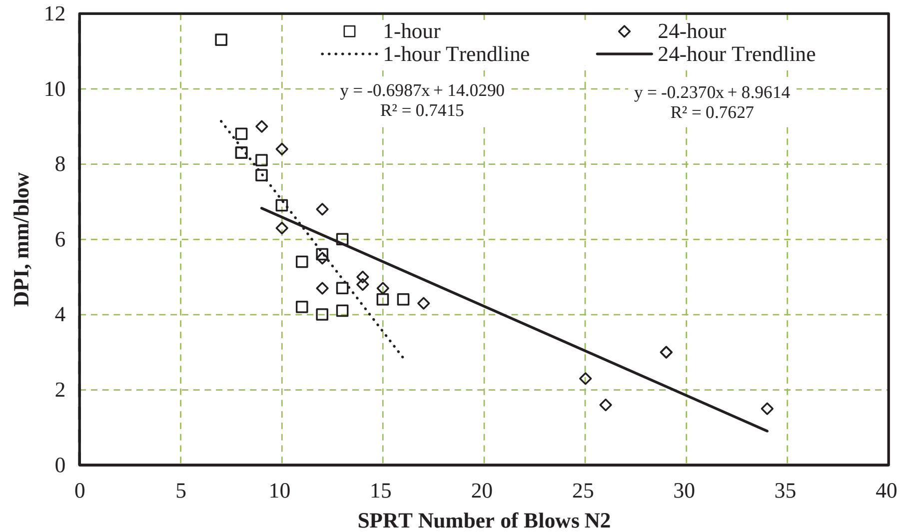


Figure 3.63. Relationship between SPRT N_2 and DPI.

Figures 3.64 and 3.65 show the relationship between the LWD modulus and the SPRT N_1 and N_2, respectively, at curing times of 1, 3, 6, and 24 hours. From both figures, the explanation of the relationship with a linear trend was generally poor at early curing times but improved (i.e., the coefficient of determination increased) as curing time progressed. It is not clear if this is an indication of issues with conducting the test on the slab surface at early curing times or another phenomenon. The slope of the trendline increased with respect to curing time in both figures.

3.4.9 Proposed Tests for Field Testing

Following the laboratory testing, selected tests were suggested for field testing based on the tests' ability to provide responses with low variability and sensitivity with respect to curing time, recycling agent content, and the use of an active filler. Based on the laboratory experiment, these factors were qualitatively evaluated for each test and given a score of good, fair, or poor, as shown in Table 3.54. For variability, the COV was evaluated, and test results were assigned a rating of good, fair, or poor when the between-specimen COV was less than 20%, between 20% and 30%, or greater than 30%, respectively. For range, the ANCOVA results were reviewed, and test results were assigned a rating of good, fair, or poor if the p-value was less than 0.001, 0.001 to 0.05, or greater than 0.05, respectively.

All tests except the MH test were recommended for field testing. The MH test was not recommended for three primary reasons. First, the test had a high variability. Second,

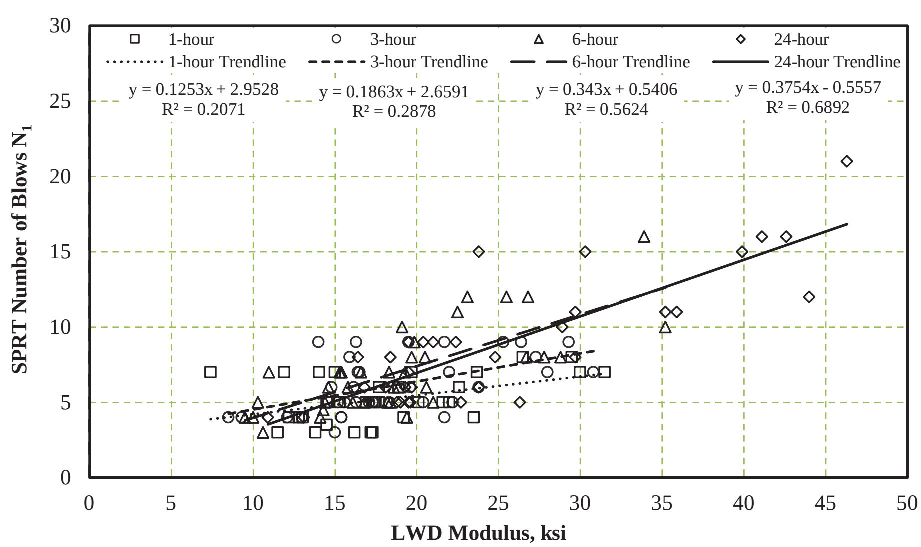


Figure 3.64. Relationship between LWD modulus and SPRT N_1.

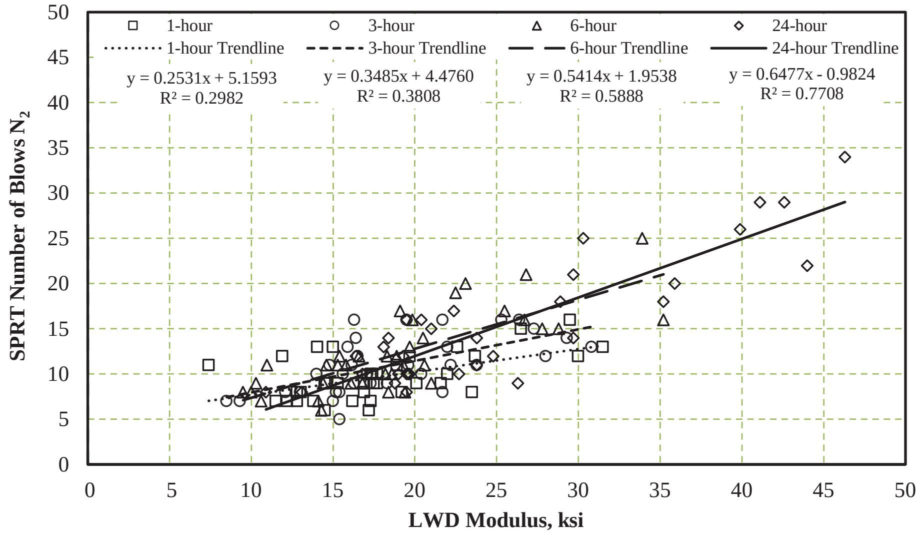


Figure 3.65. Relationship between LWD modulus and SPRT N_2.

the statistical analysis showed that the test was less sensitive to key material factors, including presence of active filler and recycling process. Third, and although not assessed directly, the depth of penetration into the recycled material was also small compared to the particle size, and so changes in surface texture may have had a greater effect on the results of the test. When the number of blows for the SPRT were counted, there was very little statistical difference between choosing the number of blows to drive the fixture from the tip of the center pin to the tip of the outer pins (N_1) versus driving the fixture the full length of the center pin (N_2). However, practically, it is easier to assess when the fixture base plate is flush with the surface of the recycled layer than to determine when the tips of the outer pins are touching. For field testing, counting the number of blows to drive the full length of the center pin (N_2) is recommended.

3.4.10 Ruggedness Evaluation

A ruggedness evaluation was completed to assess the impact of varying the operating conditions and equipment tolerances for both the LPST and SPRT (torque and number of blows for each). For both tests, factors (and levels within these factors) that were expected to influence the test results were varied, and the resulting test value was analyzed with respect to the variation. Tables 3.55 and 3.56 show results

Table 3.54. Assessment of tests for field testing recommendation.

Property	Test	Criterion: Between-Specimen Variability	Range: Curing Time	Range: Recycling Agent Content	Other Test(s) Having Strong Correlation
Stiffness	Soil stiffness gauge	Fair	Good	Fair	LWD, DPI
	Lightweight deflectometer	Fair	Good	Fair	SSG
Deformation resistance	Marshall hammer	Poor	Good	Good	Not assessed
Penetration resistance	Dynamic cone penetrometer	Good	Good	Good	LPST torque, SPRT number of blows and torque
Shear resistance	Long-pin shear test (blows/torque)	Fair/good	Good/fair	Good/good	LPST number of blows and torque, SPRT number of blows and torque, DPI
Raveling resistance	Short-pin raveling test (blows/torque)	Good/good	Good/fair	Good/poor	LPST number of blows and torque, SPRT number of blows, DPI

Table 3.55. Long-pin shear test ruggedness factors and results.

Specimen No.	Factor					Result	
	Pin Length, in.	Tip Angle, °	Torque Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.	Number of Blows	Torque, ft-lb
1	3.1	85	90	Dull	13/32	13	46.4
2	2.9	85	90	Sharp	1/2	14	31.8
3	2.9	65	90	Sharp	13/32	14	47.7
4	3.1	65	60	Sharp	1/2	15	36.6
5	2.9	85	60	Dull	1/2	16	34.4
6	3.1	65	90	Dull	1/2	16	37.1
7	3.1	85	60	Sharp	13/32	12	30.0
8	2.9	65	60	Dull	13/32	12	38.9

of testing along with the factors and levels for the LPST and SPRT, respectively. The factors and values for each level were determined based on the results of concurrent laboratory testing, limited field testing, and the engineering judgment of the research team.

In accordance with ASTM C1067, statistical parameters were calculated to identify which factors significantly influenced the test results. The factor effects were estimated by calculating the difference between average results at the high (+1) and low (−1) levels. The half-normal plots of the effects on number of blows and torque measurements for LPST and SPRT are shown in Figures 3.66 and 3.67, respectively. The data points that are farthest to the right of the reference line are potentially significant factors. Student's *t*-tests at a 5% significance level were performed to the factors that significantly influenced the test results, and the results of the analysis are tabulated in Table 3.57 for both tests.

The outer pin diameter was identified as a significant factor for the LPST number of blows, and the outer pin diameter and torque angular rate were identified as significant for the LPST torque value. The pin length was identified as a significant factor for the SPRT number of blows, and the tip dullness was identified as significant for the SPRT torque value.

3.5 Field Testing

Based on the results of the laboratory testing, field testing was completed at nine different projects during the 2019 construction season. The field projects included CIR, CCPR, and FDR using either emulsified or foamed asphalt as the stabilizing/recycling agent with and without cement as an active filler. The projects were completed by multiple contractors, using different source materials, and were in different climatic regions. Table 3.58 shows the tests that were conducted to assess the desired properties.

The following sections show the results of the data collection at the nine field project sites. Given the objectives of the study, only those data collected during the first 3 hours of curing are shown, although, in some cases, data were collected for up to 24 hours of curing. For each figure, error bars show plus/minus one standard deviation calculated from replicate test blocks. The numerical value at the base of each column indicates the number of test blocks that were tested.

Table 3.56. Short-pin raveling test ruggedness factors and results.

Specimen No.	Factor					Result	
	Pin Length, in.	Tip Angle, °	Torque Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.	Number of Blows	Torque, ft-lb
1	0.85	70	90	Dull	13/32	5	17.2
2	0.65	70	60	Sharp	1/2	4	12.3
3	0.65	50	90	Sharp	13/32	4	17.7
4	0.85	50	60	Sharp	1/2	5	13.8
5	0.65	70	60	Dull	1/2	5	17.2
6	0.85	50	90	Dull	1/2	5	17.9
7	0.85	70	60	Sharp	13/32	5	12.8
8	0.65	50	60	Dull	13/32	4	13.5

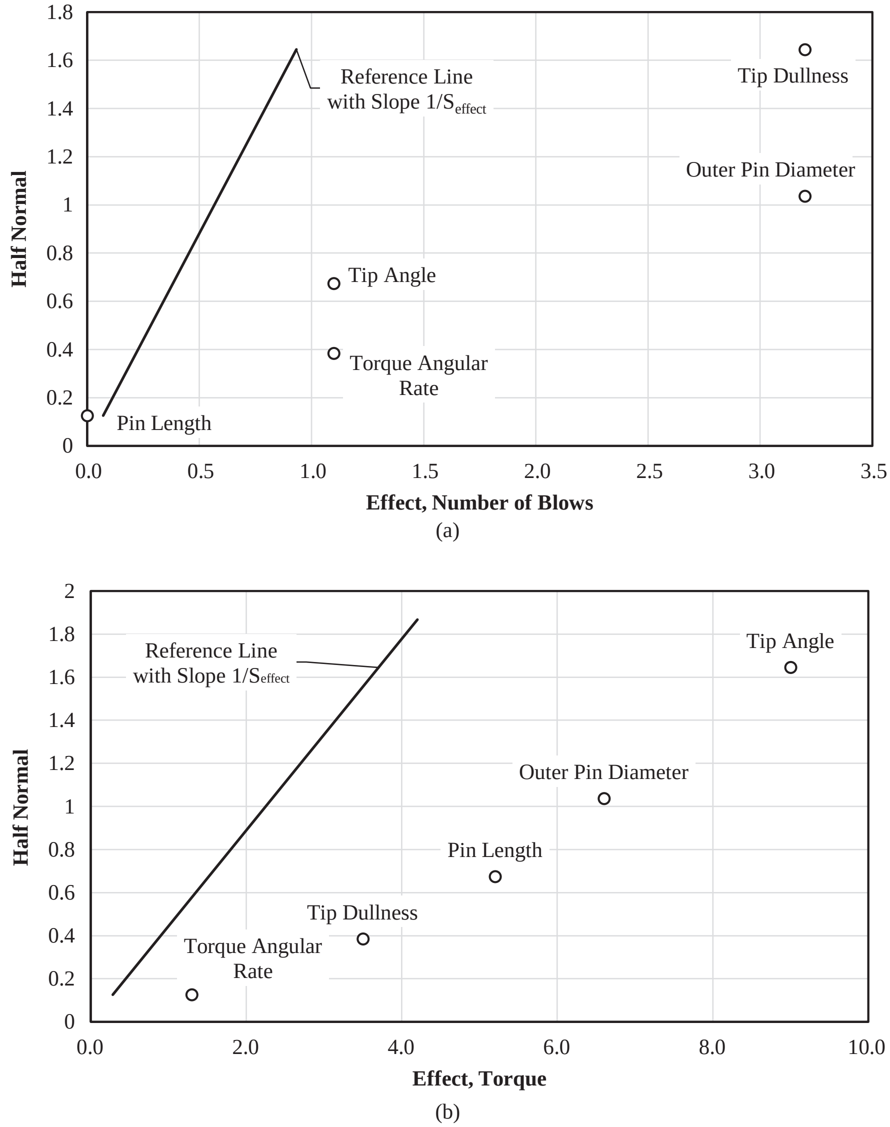
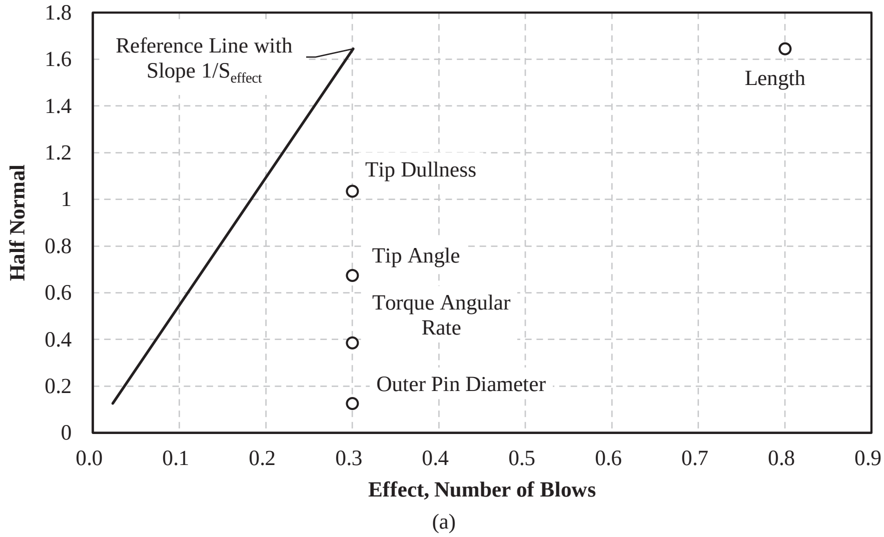


Figure 3.66. Half-normal plot for LPST, (a) number of blows, (b) torque value.



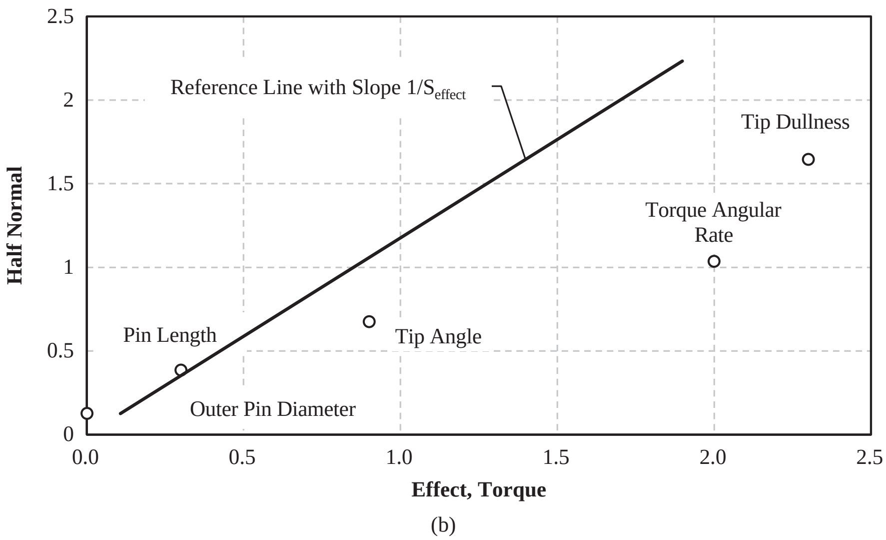


Figure 3.67. Half-normal plot for SPRT, (a) number of blows, (b) torque value.

Table 3.57. Statistical significance of factors for LPST and SPRT.

Test	Property Measure	Factor				
		Pin Length, in.	Tip Angle, °	Torque Angular Rate, °/sec	Tip Dullness	Outer Pin Diameter, in.
Long-pin shear test	No. of blows	NS	NS	NA	NS	S
	Torque, ft-lb	NS	NS	S	NS	S
Short-pin raveling test	No. of blows	S	NS	NA	NS	NS
	Torque, ft-lb	NS	NS	NS	S	NS

NS = not significant; S = significant; NA = not applicable.

Table 3.58. Properties assessed and tests conducted during field testing.

Property	Test
Density	Nuclear gauge density
Stiffness	Soil stiffness gauge
	Lightweight deflectometer
Penetration resistance	Dynamic cone penetrometer
Shear resistance	Long-pin shear test (number of blows and torque value)
Raveling resistance	Short-pin raveling test (number of blows [N_2] and torque value)

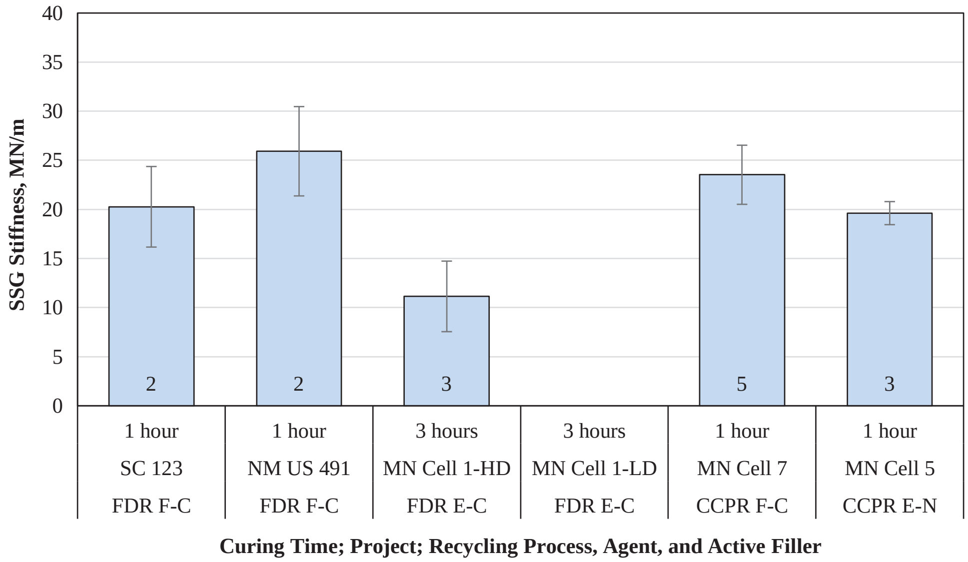


Figure 3.68. Soil stiffness gauge field testing results, FDR and CCPR mixtures.

3.5.1 Stiffness

3.5.1.1a Soil Stiffness Gauge

Figure 3.68 shows the results of field testing using the SSG for FDR and CCPR mixtures, and Figure 3.69 shows them for CIR mixtures. Figure 3.68 shows that the SSG stiffness of two of the three FDR mixtures and both CCPR mixtures was similar. The SSG stiffness of the FDR in Cell 1 from Minnesota was less than that of the other FDR and CCPR mixtures. Given that the SSG measurement zone extends beyond the depth of the recycled layer, this test result is likely influenced by the underlying support condition. When Figure 3.69 is compared with Figure 3.68, the SSG stiffness of the CIR mixtures is similar to that of the FDR and CCPR mixtures.

3.5.1.2 Lightweight Deflectometer

Figure 3.70 shows the LWD modulus field testing results for FDR and CCPR mixtures, and Figure 3.71 shows them for CIR mixtures. Figure 3.70 shows that the FDR and CCPR mixtures had similar LWD modulus values except for the FDR sections from Minnesota. This same trend was observed for the SSG stiffness values. The LWD measurement zone is also known to extend beyond the depth of the recycled layer, and so the underlying foundation is likely influencing this test result.

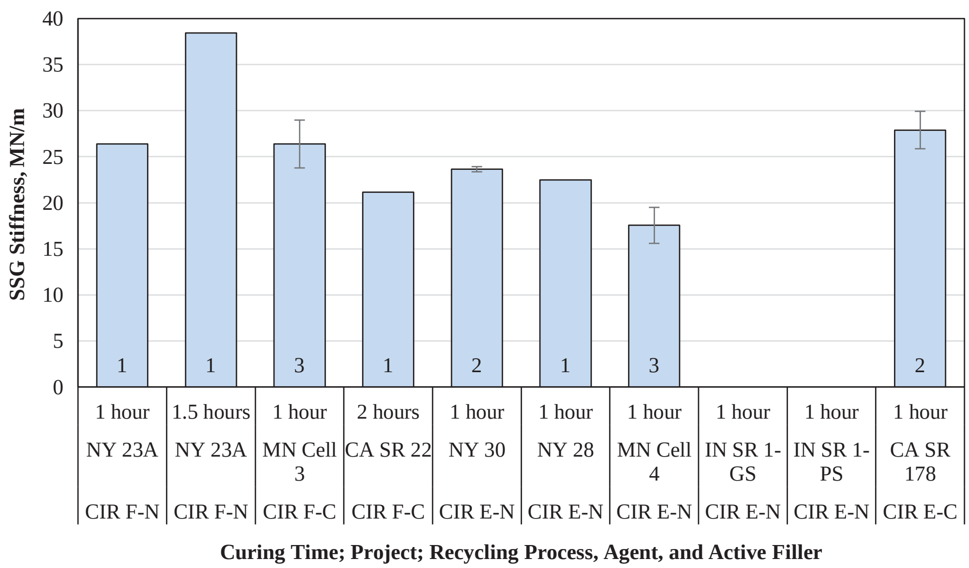
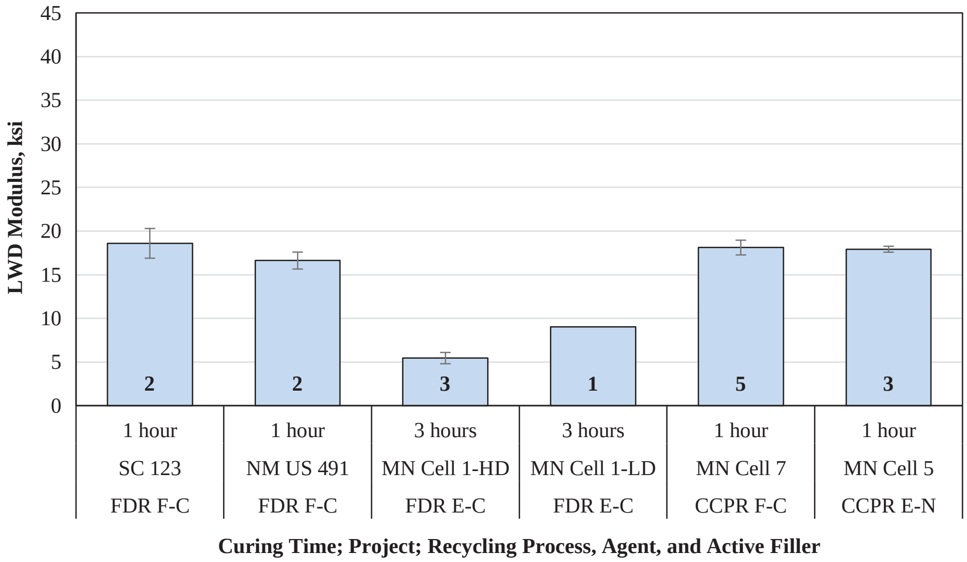


Figure 3.69. Soil stiffness gauge field testing results, CIR mixtures.



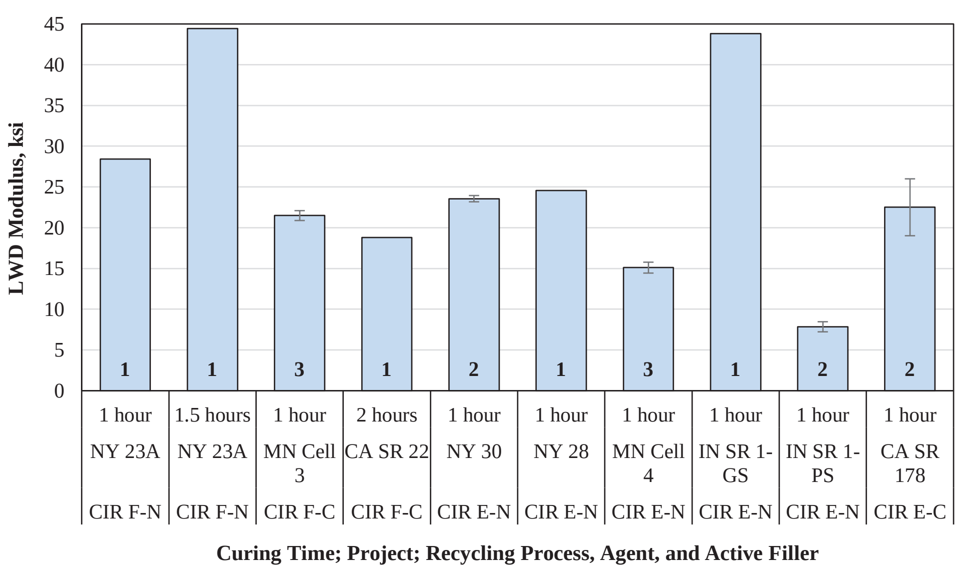
Notes: F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.70. LWD modulus field testing results, FDR and CCPR mixtures.

Figure 3.71 shows that the LWD modulus of the CIR projects was like the FDR and CCPR modulus values. However, two CIR projects showed much higher values, and one showed much lower values, than the other projects. Two of these relatively extreme values occurred from two test sections at the project from Indiana. This project was constructed on a section of roadway that had good foundation material (shown in Figure 3.71 as GS for good support) in the travel lanes but poor quality material (shown in Figure 3.71 as PS for poor support) in the shoulder areas. The research team intentionally tested in these two locations to give a wider range of material properties. Figure 3.71 shows that the support conditions likely influenced the test results. As can be observed in the results for the other tests, those tests that act only on the recycled layer do not show the same difference in properties as identified by the LWD modulus for the GS and PS sections at the Indiana project.

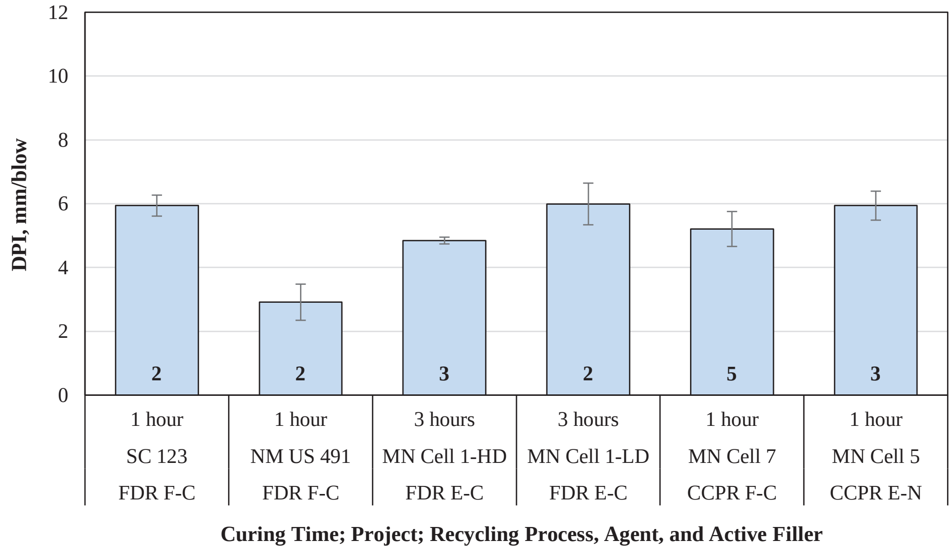
3.5.2 Penetration Resistance

Figure 3.72 shows the results of DCP field testing for FDR and CCPR mixtures, and Figure 3.73 shows them for CIR



Notes: F-N = foam, no cement; F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.71. LWD modulus field testing results, CIR mixtures.

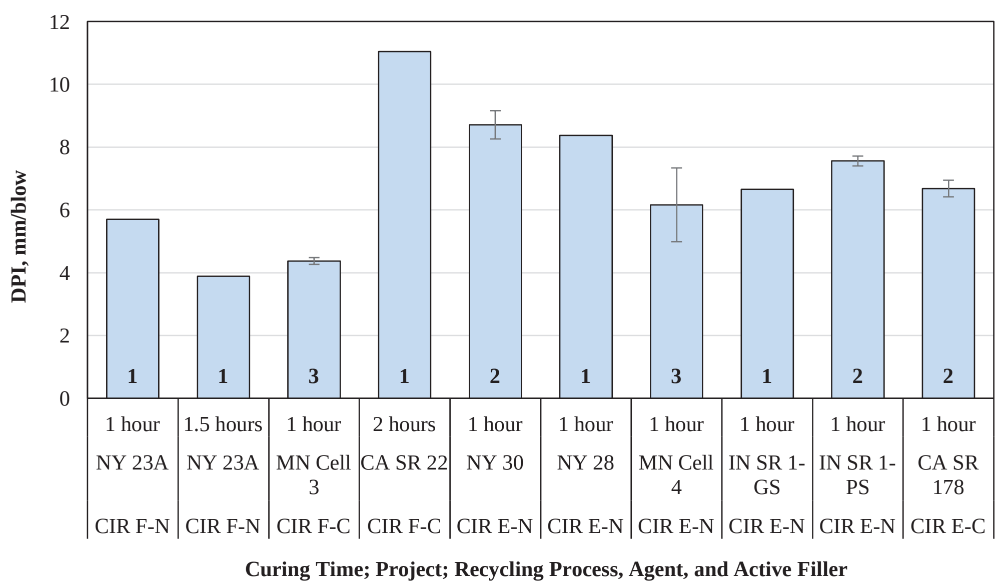


Notes: F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.72. DCP field testing results, FDR and CCPR mixtures.

mixtures. The DCP penetration index values are similar for the FDR and CCPR projects except for the FDR section from New Mexico. Despite the low stiffness and modulus values indicated earlier, the Minnesota FDR sections do not show a significant decrease in the penetration index. The Minnesota FDR section with a lower density (noted as LD in Figure 3.72) had a higher penetration index than the Minnesota FDR section with a higher density (noted as HD in Figure 3.72), as expected. This shows that for similar material, the DCP is sensitive to changes in density under field testing conditions.

Figure 3.73 shows that the DPI also reflects the influence of two other material properties. The NY 23A field project in New York showed that the DPI is sensitive to changes in curing time. (DPI decreased with increasing curing time, as expected.) In addition, the different support conditions from Indiana showed that the poor support section had a higher DPI value than the good support section, as might be expected if the underlying condition had an influence on the recycled material. (As shown in Table 2.3, the densities were the same.)



Notes: F-N = foam, no cement; F-C = foam plus cement; E-N = emulsion, no cement; E-C = emulsion plus cement.

Figure 3.73. DCP field testing results, CIR mixtures.

Figure 3.73 shows that the DCP penetration index values for CIR projects were similar to or slightly higher than those for the FDR and CCPR projects. This is especially true for the SR 22 project from California that had the highest penetration index of all projects. Figure 3.73 also shows the influence of two other material properties. The NY 23A field project from New York showed that the DCP penetration index was sensitive to changes in curing time, where the penetration index decreased with respect to curing time, as expected. In addition, the different support conditions from Indiana showed that the poor support section had a higher penetration index value than the good support section, as might be expected if the underlying condition had an influence on the recycled material. (As shown in Table 2.3, the densities were the same.)

3.5.3 Shear Resistance

3.5.3.1a Number of Blows

Figure 3.74 shows the number of blows from the LPST results for FDR and CCPR mixtures, and Figure 3.75 shows them for CIR mixtures. The figures show a similar range of results when FDR and CCPR are compared with CIR mixtures. In addition, the lower-density section from Minnesota had fewer blows than the corresponding higher-density section, as expected. Figure 3.75 also shows a relatively wider range of test results for the CIR mixtures. Results from the NY 23A project indicated that the LPST number of blows was sensitive to changes in curing time in the field. The two support conditions from the Indiana project showed a similar number of blows. As with the DCP test results, the SR 22 project from California had the fewest blows as compared to the rest of the CIR projects.

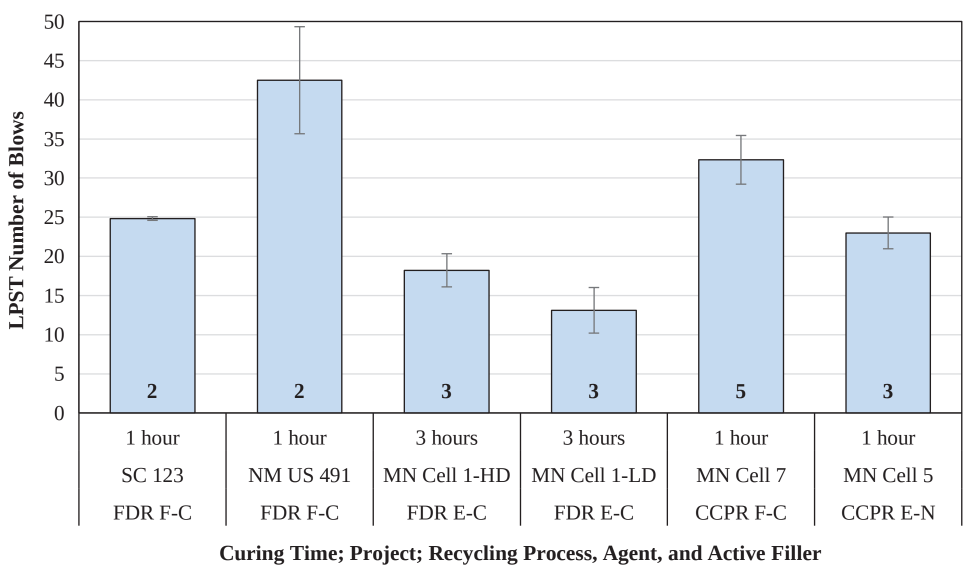
3.5.3.2 Torque Value

Figure 3.76 shows the LPST torque value results for FDR and CCPR mixtures, and Figure 3.77 shows them for CIR mixtures. The figures show a similar range of torque values for all three recycling processes. The lower-density FDR section from the Minnesota project had a lower torque value than the higher-density section, as expected. The two tests from the NY 23A project showed that the LPST torque value was sensitive to changes in curing. A similar LPST torque value was observed for the good and poor support conditions from the Indiana project.

3.5.4 Raveling Resistance

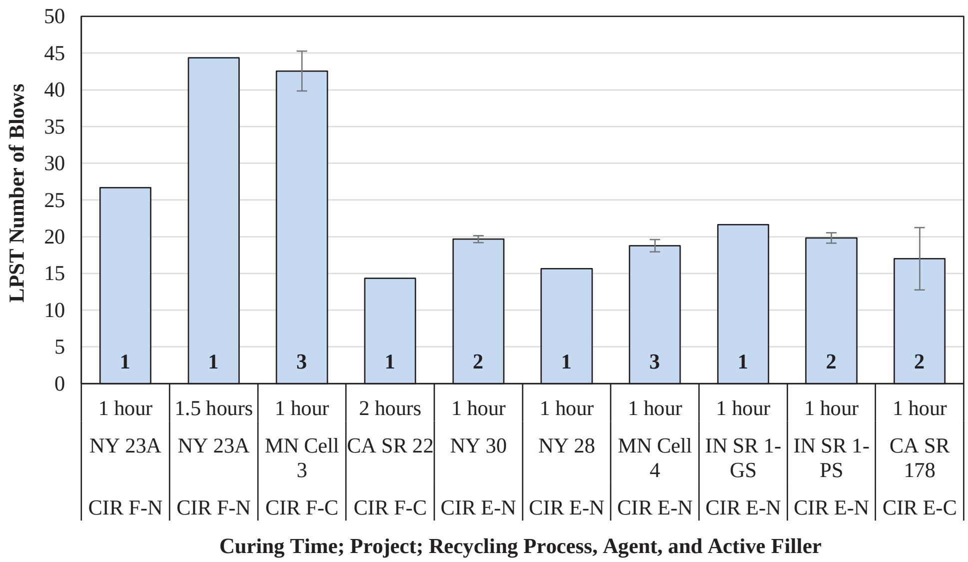
3.5.4.1a Number of Blows

Figure 3.78 shows the SPRT number of blows for FDR and CCPR mixtures, and Figure 3.79 shows them for CIR mixtures. The number of blows shown from the field testing is the same as the number of blows (N_2) shown from the laboratory testing. From Figure 3.78, the SPRT number of blows showed a ranking of projects similar to that of the LPST number of blows. As expected, the lower-density FDR section from the Minnesota project had fewer blows than the higher-density FDR section.



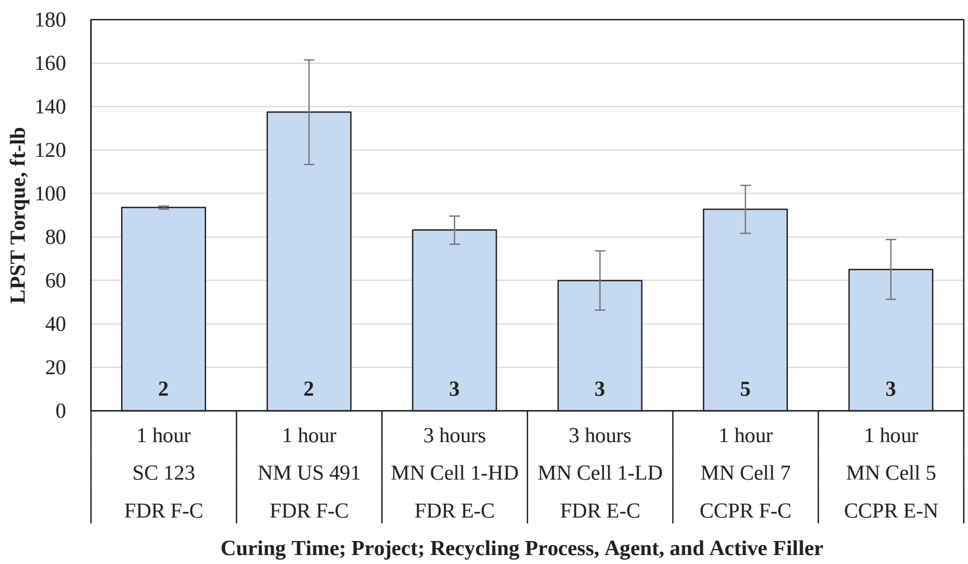
Notes: F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.74. Long-pin shear test number of blows field testing results, FDR and CCPR mixtures.



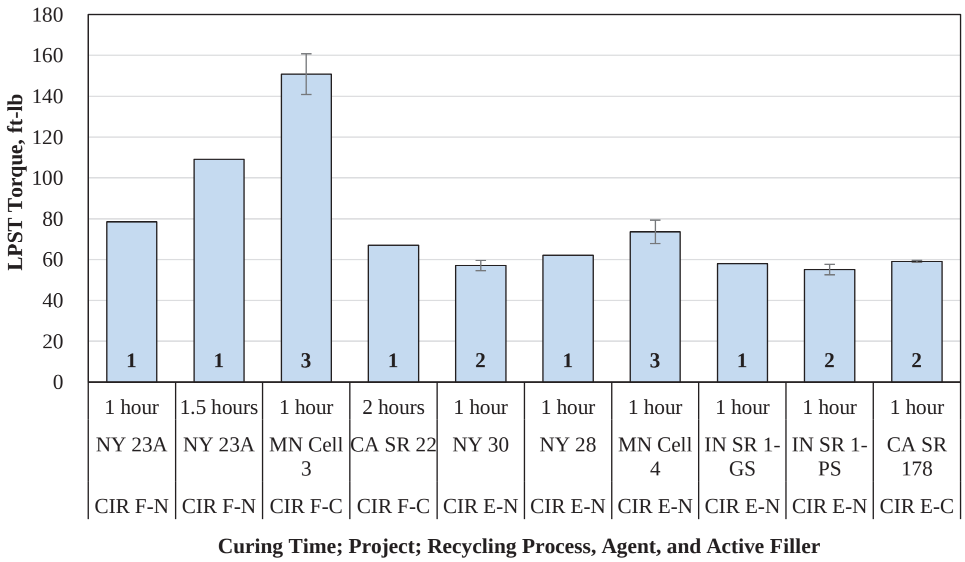
Notes: F-N = foam, no cement; F-C = foam plus cement; E-N = emulsion, no cement; E-C = emulsion plus cement.

Figure 3.75. Long-pin shear test number of blows field testing results, CIR mixtures.



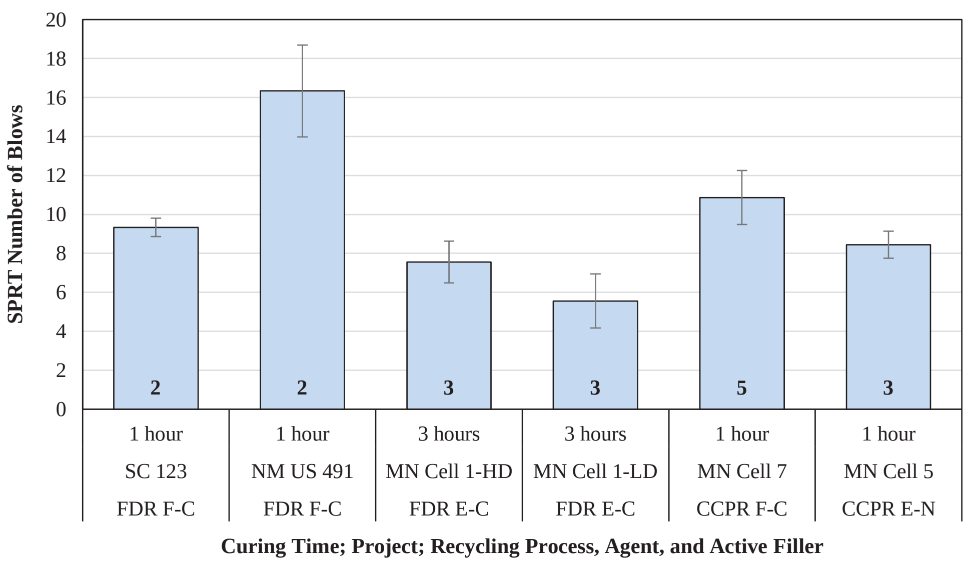
Notes: F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.76. Long-pin shear test torque value field testing results, FDR and CCPR mixtures.



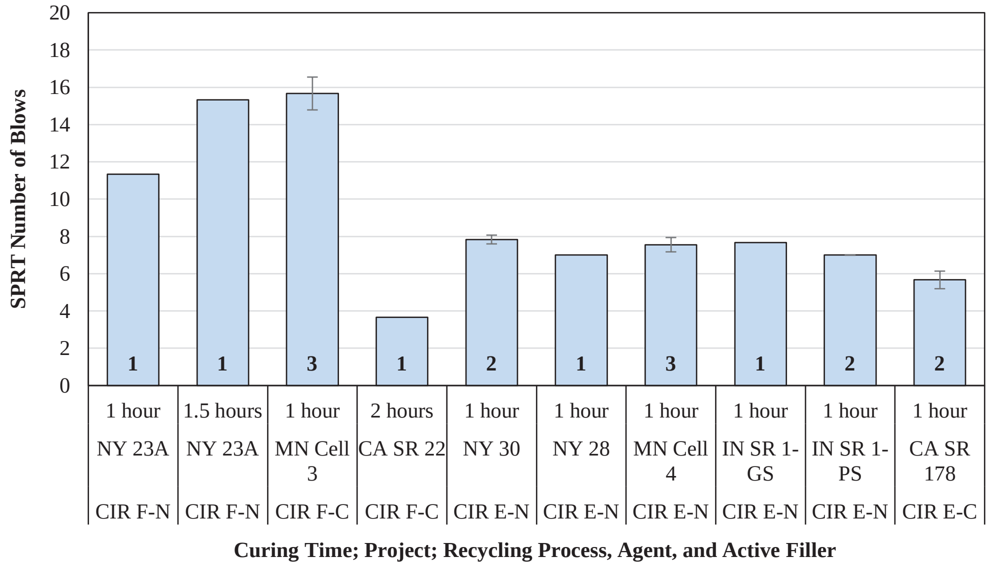
Notes: F-N = foam, no cement; F-C = foam plus cement; E-N = emulsion, no cement; E-C = emulsion plus cement.

Figure 3.77. Long-pin shear test torque value field testing results, CIR mixtures.



Notes: F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.78. Short-pin raveling test number of blows field testing results, FDR and CCPR mixtures.



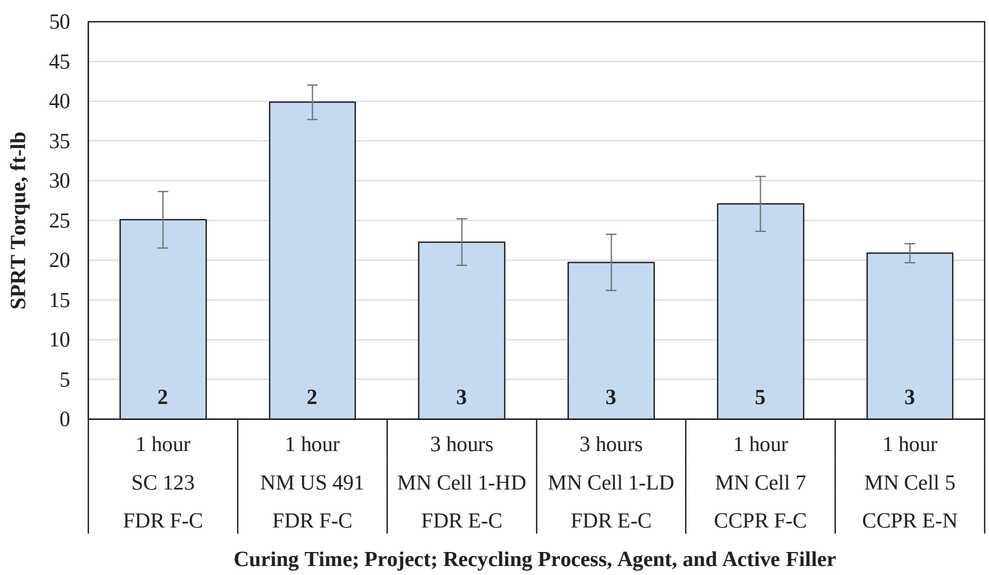
Notes: F-N = foam, no cement; F-C = foam plus cement; E-N = emulsion, no cement; E-C = emulsion plus cement.

Figure 3.79. Short-pin raveling test number of blows field testing results, CIR mixtures.

Figure 3.79 also shows that the projects with the greatest and fewest number of blows from the SPRT fixture were like those identified using the LPST fixture. The number of blows from the SPRT increased with respect to curing time, as seen from the NY 23A project. In addition, there is little difference in the number of blows from the Indiana CIR project for the good and poor support conditions.

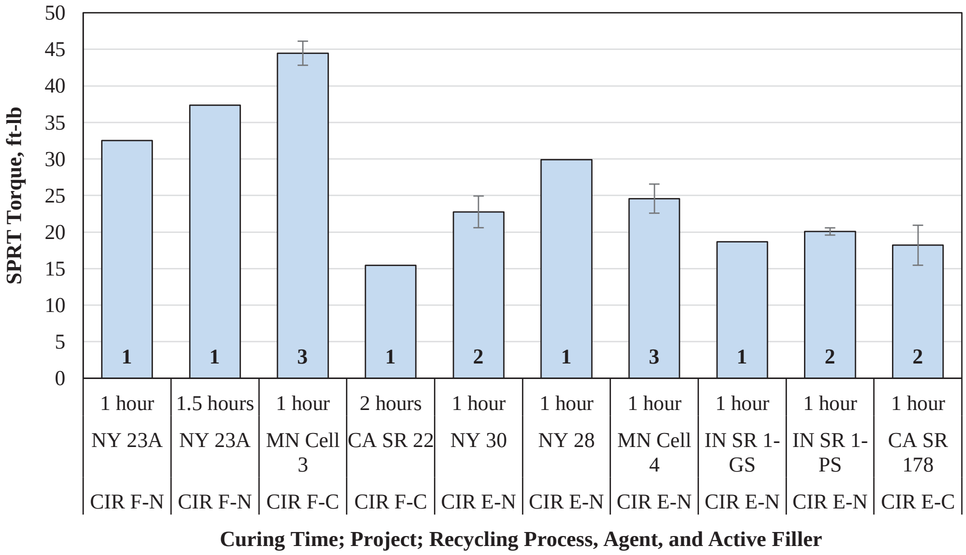
3.5.4.2 Torque Value

Figure 3.80 shows the SPRT torque values for FDR and CCPR mixtures, and Figure 3.81 shows them for CIR mixtures. From Figure 3.80, the SRPT torque values show a relatively wider range of responses and a similar ranking of projects compared to the LPST. Figure 3.80 also shows some



Notes: F-C = foam plus cement; E-C = emulsion plus cement; E-N = emulsion, no cement.

Figure 3.80. Short-pin raveling test torque value field testing results, FDR and CCPR mixtures.



Notes: F-N = foam, no cement; F-C = foam plus cement; E-N = emulsion, no cement; E-C = emulsion plus cement.

Figure 3.81. Short-pin raveling test torque value field testing results, CIR mixtures.

differences between the high- and low-density FDR sections from Minnesota, but the differences are not likely to be statistically significant. Figure 3.81 shows that the SPRT torque values are also like the LPST torque values in terms of the rankings of the three projects with highest torque values. The LPST torque values are similar for seven of the 10 projects shown, but the SPRT torque values have a wider range over these same seven projects. The SPRT torque values also show a difference with respect to curing time for the NY 23A project and a slight difference in the torque values for the high- and low-density FDR sections from Minnesota.

3.5.5 Correlation Analysis

A correlation analysis was performed to investigate the relationship between the tests performed in the Phase III field study. The analysis was performed by calculating the Pearson correlation coefficient (r) and the associated p-value.

Table 3.59 shows the Pearson correlation coefficient and p-value for comparisons of the field-measured density, SSG stiffness, LWD modulus, LPST number of blows, LPST torque value, SPRT number of blows (N_1 and N_2), SPRT torque value, and DPI values. For those combinations that were shown to have a strong correlation ($|r|>0.7$,), the p-value was determined to estimate the significance of the relationship (alpha = 0.05). Shaded cells indicate comparisons where both conditions were met. The analysis showed that the following combinations had a strong, statistically significant correlation:

- SSG stiffness with LWD modulus;
- LPST number of blows with LPST torque value, SPRT torque value, and DPI;
- LPST torque value with SPRT number of blows, SPRT torque value, and DPI; and
- SPRT number of blows with SPRT torque value and DPI.

Figures 3.82 through 3.90 demonstrate the relationship between those tests shown in the correlation analysis to have the strongest correlation and a statistically significant relationship based on the field testing. The data are presented along with a linear trendline to be consistent with the linear relationship shown by the Pearson correlation coefficient. For most comparisons, a linear trendline proved to have the highest coefficient of determination. However, for those comparisons including DPI, a nonlinear trend may prove to describe the relationships better.

A small cluster of data artificially increased the correlation for certain comparisons (especially related to the LPST and SPRT results for NM US 491, NY SR 23A, and MN Cell 3). If the data for these three projects are removed from the analysis, only the SPRT torque values and number of blows were well correlated (i.e., $|r|>0.7$). Including all data shows that the LPST blows and torque, the SPRT blows and torque, and DPI were all well correlated. When the data from the three projects were removed, the correlation between the tests was reduced.

3.5.6 Lessons Learned During Field Testing

Prior to conducting any of the tests in the field, suitable and uniform sites were selected based on visual observation of the recycling process and the completed recycled layer. As an example, cement as an active filler was observed to be applied non-uniformly across the width of the lane on

Table 3.59. Field testing correlation analysis (a) Pearson correlation coefficient, (b) *p*-value.

(a)

	SSG stiffness, MN/m	LWD Modulus, ksi	LPST Number of Blows	LPST Torque, ft-lb	SPRT Number of Blows	SPRT Torque, ft-lb	DPI, mm/blow
Density, lb/ft³	0.0338	0.0831	0.5562	0.4963	0.5639	0.5389	–0.3611
SSG stiffness, MN/m		**0.9106**	0.6237	0.3298	0.5488	0.5134	–0.2496
LWD modulus, ksi			0.3686	0.0759	0.3189	0.2505	–0.0604
LPST number of blows				**0.8839**	–0.4291	**0.8654**	**–0.7363**
LPST torque, ft-lb					**0.8863**	**0.8756**	**–0.7033**
SPRT number of blows						**0.9281**	**–0.7921**
SPRT torque, ft-lb							–0.6648

(b)

	SSG stiffness, MN/m	LWD Modulus, ksi	LPST Number of Blows	LPST Torque, ft-lb	SPRT Number of Blows	SPRT Torque, ft-lb	DPI, mm/blow
Density, lb/ft³	0.9128	0.7596	0.0253	0.0505	0.0229	0.0313	0.1694
SSG stiffness, MN/m		**0.0000**	0.0227	0.2711	0.0521	0.0727	0.4108
LWD modulus, ksi			0.1601	0.7800	0.2287	0.3494	0.8243
LPST number of blows				**0.0000**	0.0972	**0.0000**	**0.0011**
LPST torque, ft-lb					**0.0000**	**0.0000**	**0.0024**
SPRT number of blows						**0.0000**	**0.0003**
SPRT torque, ft-lb							0.0050

one field project. Thus, testing was conducted where the cement was observed to be applied uniformly. Also, if a large amount of loose material, cracks, segregated material, binder agglomerations, or crack sealant was observed, another location was selected. Testing was completed approximately within the center of the lane, and replicate tests were performed at a center-to-center spacing of approximately 1 ft to help ensure that testing was completed on the most uniform material.

During stiffness testing with the SSG, surface preparation was important to obtaining test results having low variability. The surface to be tested was prepared by applying a thin layer of moist sand using a hand trowel such that any irregularities in the surface were filled with sand. The SSG foot was placed lightly on the sand patch, and the gauge was rotated approximately 90° clockwise, back to zero, then 90° counterclockwise, and then back to its original position without any downward force being applied to seat the foot. After each test, the foot was wiped clean with a rag and the sand patch was re-leveled with the hand trowel; more sand was added if needed.

Stiffness testing using the LWD was influenced if the gauge was not solidly seated and if any hand pressure was applied to the LWD handle that resulted in a downward force. The LWD testing was conducted by placing the LWD on the surface and checking for a firm footing. If the LWD rocked back and forth, it was moved slightly until the rocking ceased. While the drops were being applied, the LWD was held still only by loosely circling the operator's hand around the handle just below the top of the handle.

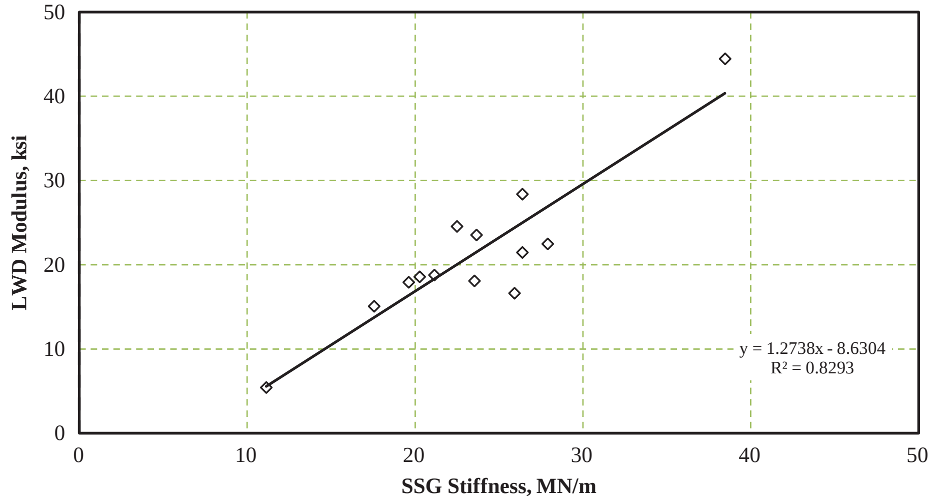


Figure 3.82. Relationship between soil stiffness gauge stiffness and LWD modulus.

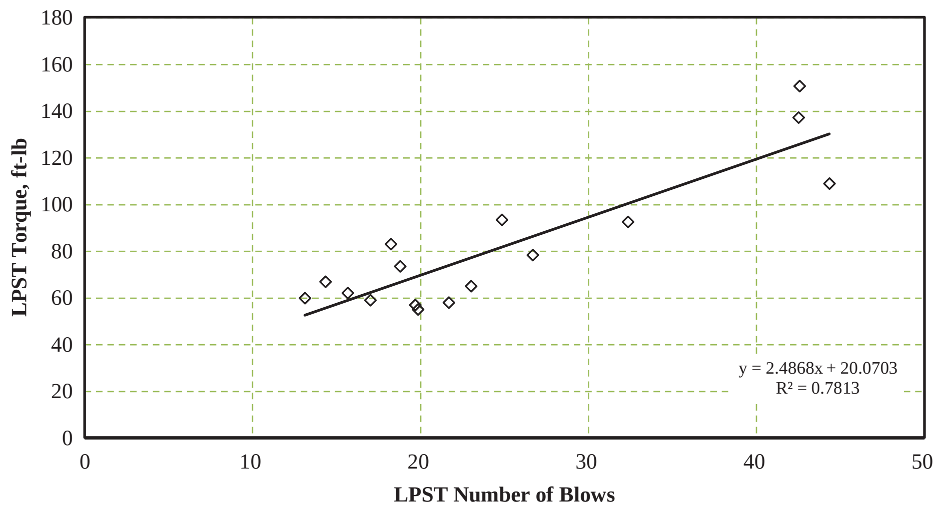


Figure 3.83. Relationship between long-pin shear test number of blows and long-pin shear test torque value.

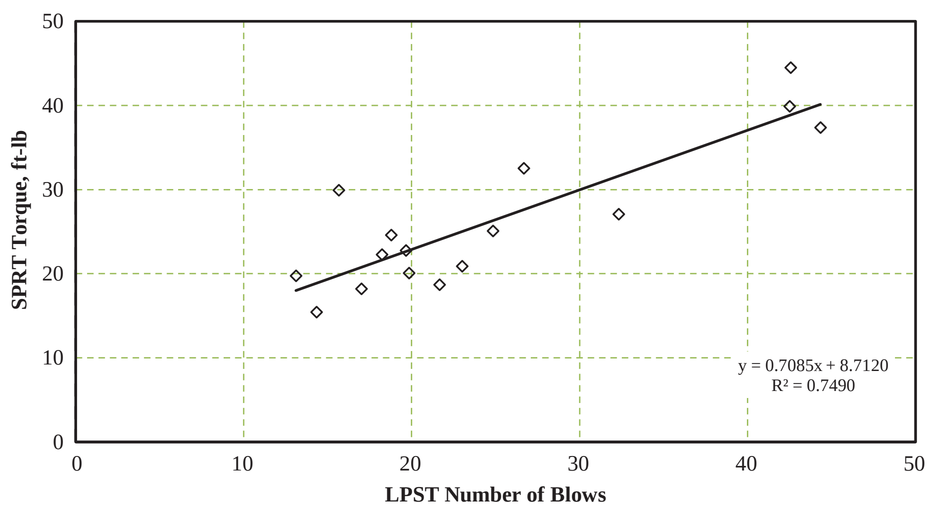


Figure 3.84. Relationship between long-pin shear test number of blows and short-pin raveling test torque value.

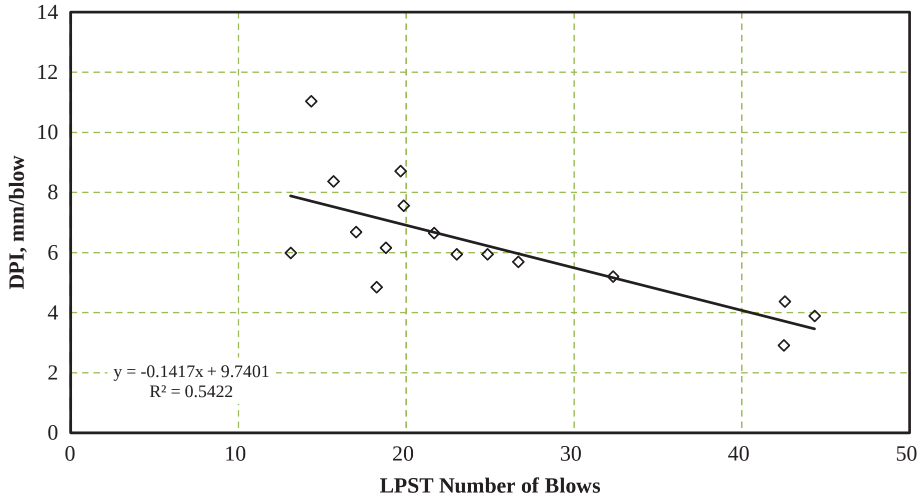


Figure 3.85. Relationship between long-pin shear test number of blows and DPI.

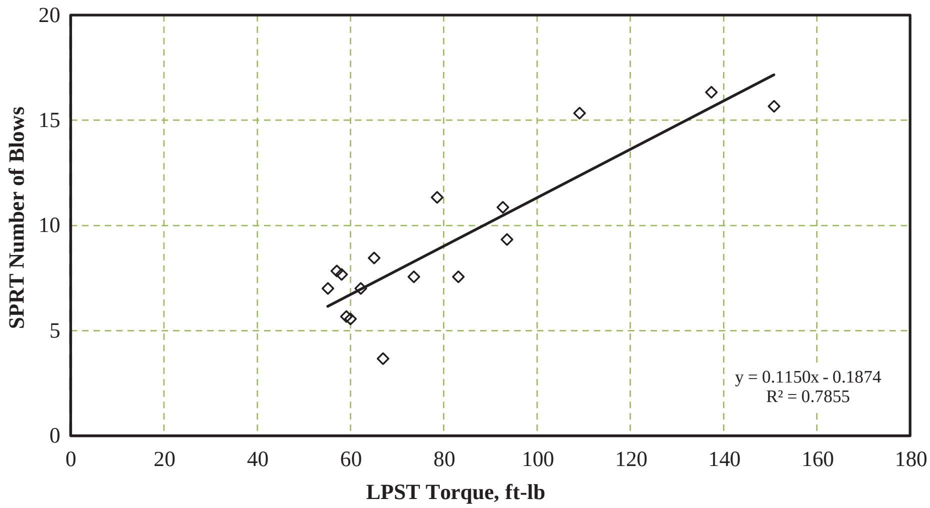


Figure 3.86. Relationship between long-pin shear test torque value and short-pin raveling test number of blows.

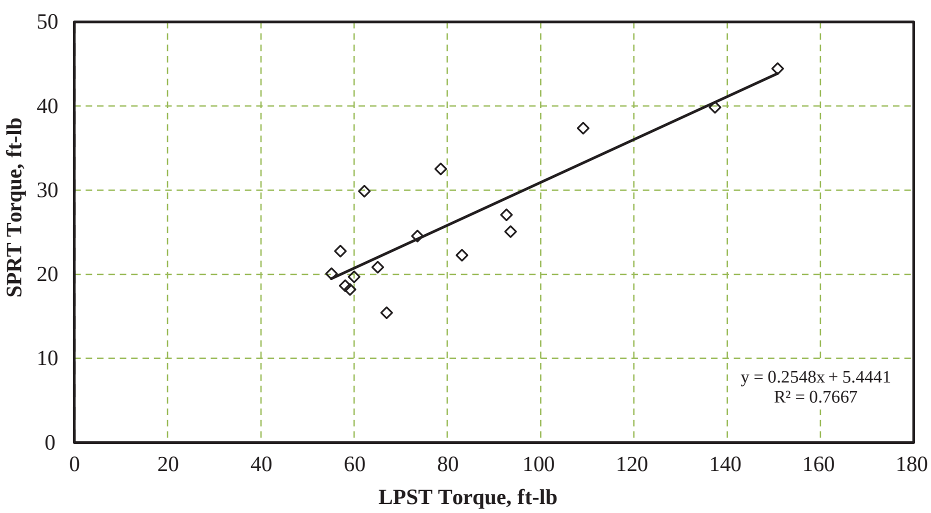


Figure 3.87. Relationship between long-pin shear test torque value and short-pin raveling test torque value.

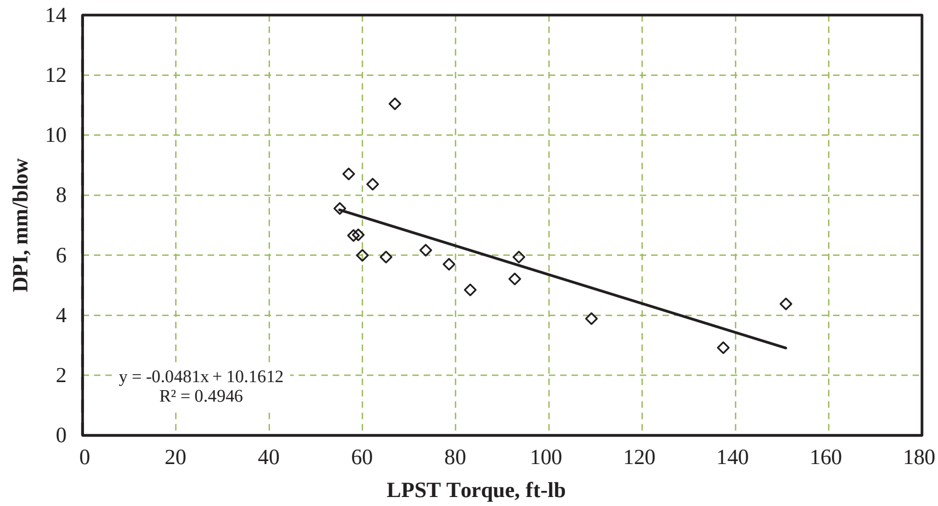


Figure 3.88. Relationship between long-pin shear test torque value and DPI.

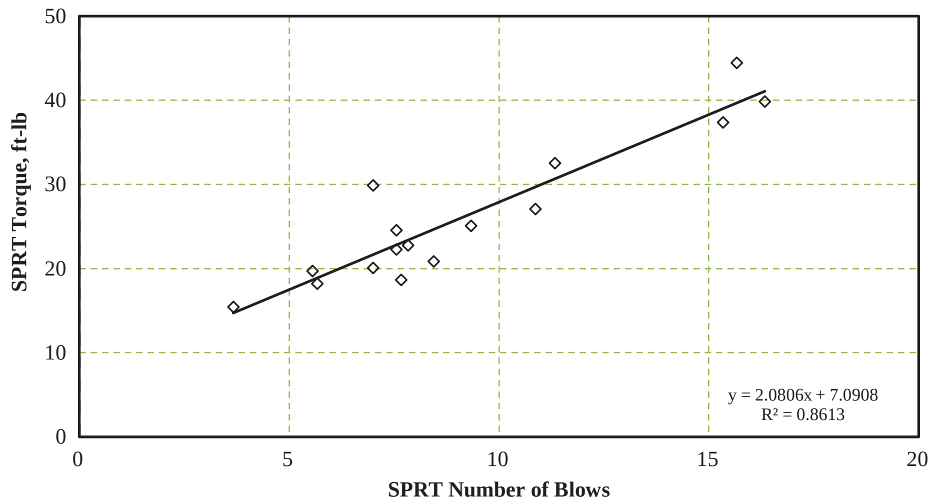


Figure 3.89. Relationship between short-pin raveling test number of blows and short-pin raveling test torque value.

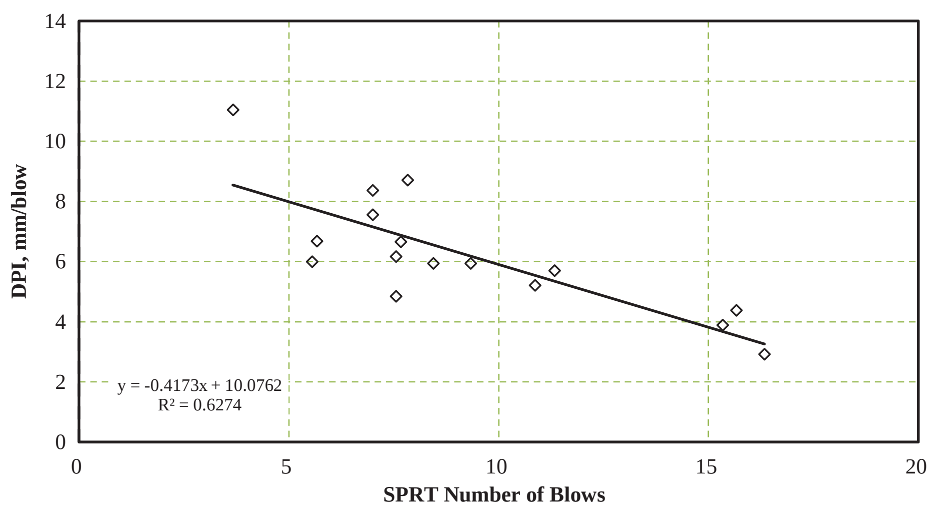


Figure 3.90. Relationship between short-pin raveling test number of blows and DPI.

Penetration resistance testing using the DCP was completed by ensuring that the DCP handle was kept plumb and that testing was not started on a large piece of aggregate at the pavement surface. DCP testing could be conducted by two operators, but a third was helpful: one holding the handle, one operating the weight, and a third reading the penetration depth. Recent commercial developments to the DCP include automated counters, which could reduce the number of operators needed. Operating the DCP by recording the distance to a predetermined number of blows was considered as an option but ultimately was not selected for reasons discussed Section 3.6.1: Proposed Tests.

Shear and raveling resistance tests were completed by including a 1-in.-diameter bubble level to ensure that the base plate was kept parallel to the surface of the recycled layer while the shear and raveling fixtures were driven into the recycled material. For both tests, the operator listened for a change in the sound while driving the fixture to note when the base plate was touching the surface of the recycled layer. The rate at which the torque was applied was kept constant from location to location by drawing a line (using a lumber crayon on the recycled surface) 12 in. long from the center of the base plate. Perpendicular to this 12-in. line, and at the end farthest from the center of the base plate, a 4-in. line was drawn in the direction the torque wrench was to be pulled by the operator. During testing, the operator counted 4 seconds and, during this time, swung the arm of the torque wrench along the entire length of the 4-in. line. This method allowed the operator to apply a consistent torque rate, and the maximum value was always obtained within this distance. Figure 3.91 shows an illustration of this process.

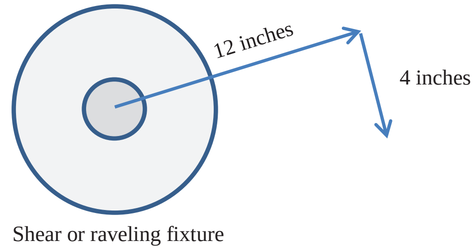


Figure 3.91. Plan view of torque application.

During initial stages of the field testing, there was concern that the recycled material might be susceptible to raveling after completion of the field tests given that most of the projects were opened to traffic soon after the tests were completed. The most destructive test devices included the DCP and the shear and raveling fixtures. Following each of these tests, any disturbed material could be tamped back into place by the operator simply stepping on and compressing the disturbed material. Figure 3.92 shows the typical condition of the pavement surface just after testing and again after the disturbed material had been tamped. Figure 3.93 shows the condition of the pavement surface 4 days after testing having no deterioration caused by the testing.

Figure 3.92. Recycled material after a torque test (left) ***and after tamping*** (right)***.***

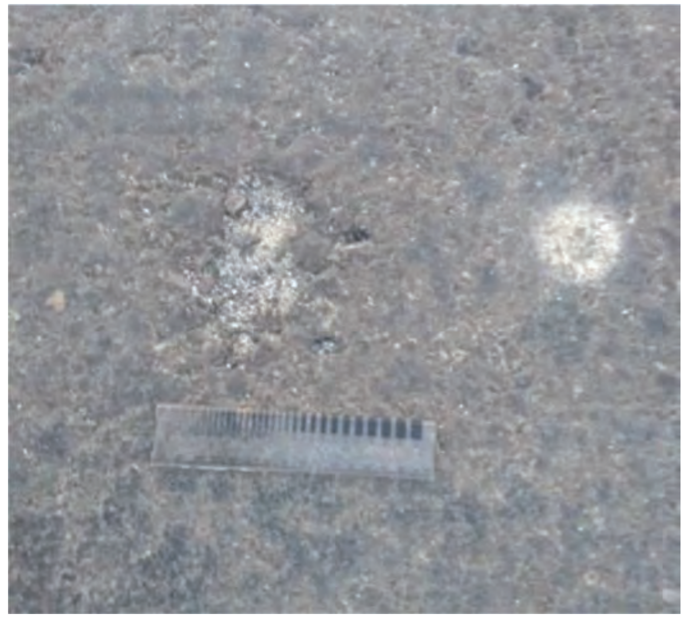


*Figure 3.93. Test area four days after a torque test (*left*) and close-up of the same location (*right*).*

3.5.7 Preliminary Precision Statements as Determined During Interlaboratory Study

As part of the field testing, the research team conducted an ILS to develop preliminary precision statements for the shear and raveling tests developed in this study. The term "preliminary" is used since only three laboratories participated in the ILS and the ILS was conducted in the field. The ILS was conducted to develop preliminary precision statements for penetration resistance testing using the DCP, number of blows and torque value for the LPST, and number of blows and torque value for the SPRT. Following a presentation of the data for each test, details of determining the data consistency, the form of the precision statement, and the final precision statements are provided.

3.5.7.1 Preliminary Precision Statement for DCP Testing

The average DPI value from the ILS testing by all participating laboratories and test cells is shown in Table 3.60. Testing using the DCP was conducted in only four of six test cells.

Prior to the collected data being analyzed, the single-operator and between-laboratory consistency were investigated with respect to the average and dispersion of the results. This check was performed to prevent effects of any potential inconsistent data on the precision of the test method. Data consistency was checked in accordance with the procedure outlined in ASTM C802.

Two statistical parameters are defined in ASTM C802 to evaluate data consistency: the *k*-value and the *h*-value. The *k*-value is used to check the consistency of the single-operator variability for each laboratory for a given material. The *k*-values are always positive numbers and indicate how the variability of a laboratory might be different from the variability of other laboratories in a study (i.e., pooled variability). High *k*-values denote high single-operator variability. The *h*-value is used to investigate whether the average value of a laboratory is consistent with the overall average of the other laboratories for a given material. Unlike the *k*-values, the *h*-values can be positive or negative numbers. Positive or negative *h*-values show that an average property measure of a laboratory is larger or smaller than the average property measures of other laboratories. In addition, outliers are determined on the basis of checking the variability values (*k*-value and *h*-value) of a laboratory (or material) with respect to critical values (*k*-value and *h*-value) determined at a given significance level (e.g., 0.5%).

These calculated *k*- and *h*-values were checked with respect to the critical *k*- and *h*-values determined on the basis of the

Table 3.60. Summary of DPI from ILS.

Laboratory	Replicates	DPI, mm/blow			
		Cell 1 FDR E-C	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 7 CCPR F-C
Lab 1	1	5.3	4.6	5.1	5.5
	2	4.8	4.4	5.0	5.2
	3	4.6	4.1	5.5	5.8
Lab 2	1	5.1	3.8	6.2	4.9
	2	4.4	5.0	7.5	5.3
	3	5.3	4.0	8.7	5.2
Lab 3	1	4.7	4.5	6.2	6.1
	2	4.7	4.8	5.7	6.0
	3	4.7	4.2	5.6	6.0

Table 3.61. *k*-values for single-operator data consistency for DPI.

Laboratory	DPI, mm/blow			
	Cell 1 FDR E-C	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 7 CCPR F-C
Lab 1	1.07	0.64	0.35	1.42
Lab 2	1.36	1.46	1.65	0.97
Lab 3	0.07	0.69	0.38	0.23

Note: Critical k-value equals 1.67.

Table 3.62. *h*-values for between-laboratory data consistency for DPI.

Laboratory	DPI, mm/blow			
	Cell 1 FDR E-C	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 7 CCPR F-C
Lab 1	0.50	0.05	–0.83	–0.11
Lab 2	0.65	–1.02	1.11	–0.94
Lab 3	–1.15	0.98	–0.29	1.05

Note: Critical *h*-value equals ± 1.15.

number of replicates used and the number of laboratories participating in the ILS. ASTM C802 provides a table of critical values of *k* and *h* statistics at a 0.5% significance level. The critical *k*-values are a function of the number of participating laboratories and the number of replicate test measurements. On the other hand, the critical *h*-values depend only on the number of participating laboratories. Throughout this study, there were three participating laboratories for any of the tests considered, with three replicate measurements for each test unless otherwise indicated. Hence, the critical *k*-value for this ILS was determined to be 1.67, whereas the critical *h*-value equals ± 1.15. Both values were determined in accordance with ASTM C802.

Tables 3.61 and 3.62 show the analysis of data consistency for DPI in terms of the calculated *k*-values and *h*-values, respectively. The results show that all laboratory/material combinations were within acceptable limits when compared to the critical values and therefore indicate consistency in the collected data.

The data were also investigated to identify if any interactions among laboratories and test cells existed. The presence of interactions was investigated by determining whether the pattern of the test results obtained on the section by one laboratory differed notably from the pattern obtained by the other laboratories. Figure 3.94 shows the DPI values for each laboratory and material combination with respect to the test cell from lowest to highest values. The average DPI values and the value from each laboratory with respect to the test cell followed a similar trend. However, the DPI value for Laboratory 2 and Cell 4 was significantly higher than for the other laboratories. Although it is unclear as to why such a trend was observed, the data were included in the analysis as the consistency statistics (*k*- and *h*-values) of single-operator and between-laboratory conditions were within the acceptable limits, as presented previously, and the number of participating laboratories was already limited.

The single-operator and multi-laboratory standard deviation and COV for DPI with respect to test cells are presented in Table 3.63, as calculated in accordance with ASTM C802.

To determine the form of the precision statements, the relationship between the average DPI values and the standard deviation and the COV for single-operator and multi-laboratory conditions was investigated and is shown in Figures 3.95 and 3.96, respectively.

The single-operator standard deviation and COV increased slightly with increasing DPI values. The multi-laboratory standard deviation and COV also increased with increasing DPI values. However, there were only four observations, and the increasing trend for the multi-laboratory condition is highly affected by the observation from the Laboratory 2

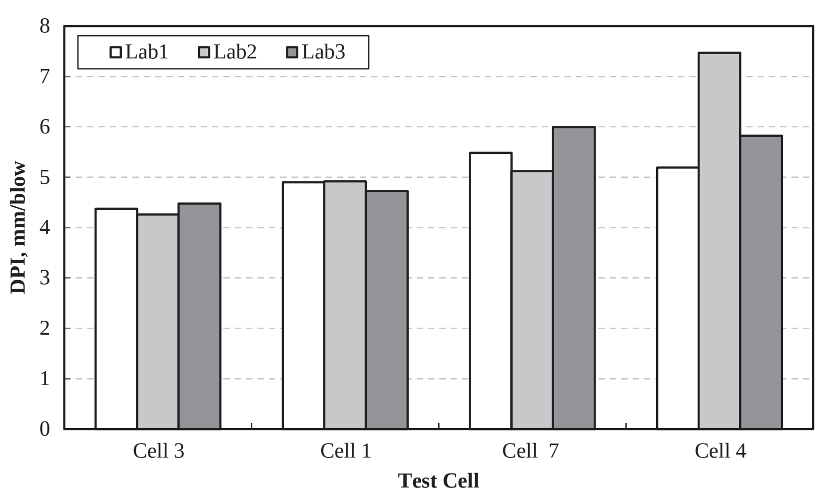


Figure 3.94. Average DPI values arranged from least to greatest.

Table 3.63. DPI average, standard deviation, and coefficient of variation.

Test Cell/Material	DPI, mm/blow				
	Average	Standard Deviation		Coefficient of Variation, %	
		Single Operator	Multi-Laboratory	Single Operator	Multi-Laboratory
Cell 3 CIR F-C	4.4	0.43	0.43	9.8	9.8
Cell 1 FDR E-C	4.8	0.34	0.34	7.0	7.0
Cell 7 CCPR F-C	5.5	0.22	0.47	4.0	8.6
Cell 4 CIR E-N	6.2	0.76	1.33	12.3	21.6

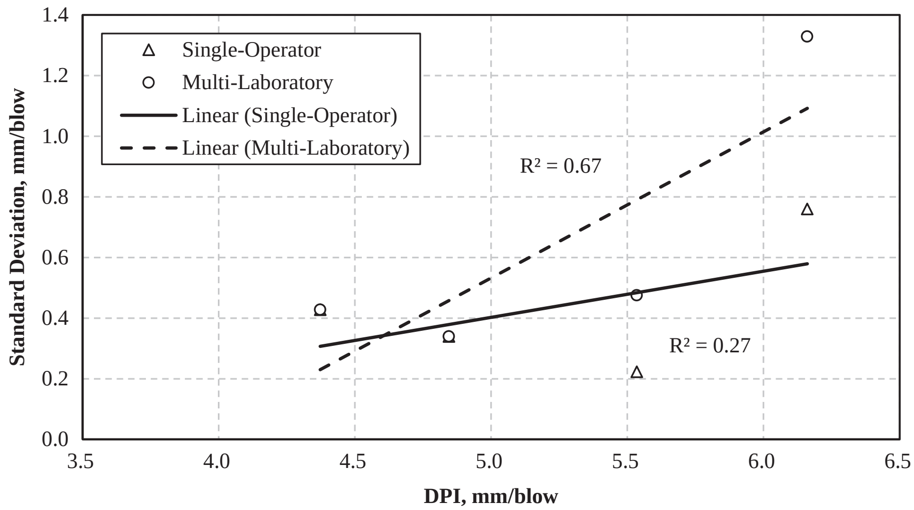


Figure 3.95. Relationship between average DPI measurements and standard deviation.

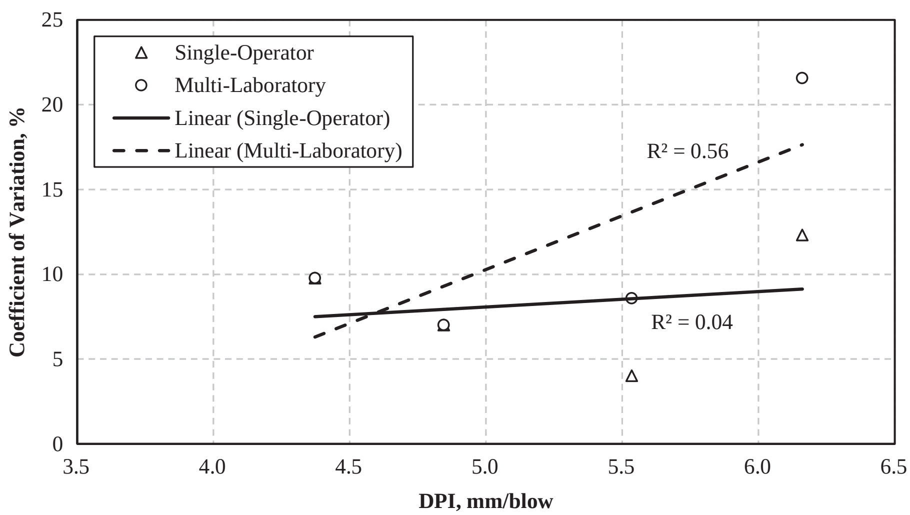


Figure 3.96. Relationship between average DPI measurements and coefficient of variation.

Table 3.64. Summary of LPST number of blows from ILS.

Laboratory	Replicates	Number of Blows Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1	17	9	44	20	21	30
	2	16	12	40	19	22	30
	3	18	16	40	20	22	30
Lab 2	1	17	10	42	18	21	29
	2	17	11	37	18	23	28
	3	17	11	43	18	22	28
Lab 3	1	18	17	47	19	28	36
	2	24	16	47	19	24	34
	3	20	16	43	18	24	32

measurement on Cell 4. Given this slight increase and effect of the one observation in Cell 4, the assumption of constant standard deviation or COV was made. Since the COV tends to be more independent than the standard deviation, the use of a constant COV is appropriate for developing the precision statements for DCP test results. The pooled single-operator and multi-laboratory COV values from Table 3.63 were used to develop the precision statements for DCP measurements.

The precision statements for DCP measurements were developed in accordance with ASTM C670 and are presented here.

- Single-operator precision: The single-operator COV was 8.3%. Therefore, the results of two properly conducted tests by the same operator on the same material are not expected to differ by more than 23.2%[A] of their average.
- Multi-laboratory precision: The multi-laboratory COV was 11.7%. Therefore, the results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ by more than 32.8%[A] of their average.

[A]These numbers represent the difference limits in % (d2s%) as described in ASTM Practice C670.

Note: These precision statements are based on an ILS that involved three laboratories, four materials, and three replicate tests per operator, with DPIs ranging from 3.8 to 8.7 mm/blow.

3.5.7.2 Preliminary Precision Statement for Shear Tests

The average number of blows and torque value from testing from the LPST are shown in Tables 3.64 and 3.65, respectively.

Summaries of calculated *k*-values and *h*-values for the LPST number of blows for each test cell are shown in Tables 3.66 and 3.67, respectively. The values that exceeded the critical values are highlighted and bolded in the tables. The only laboratory/material combination that exceeded a critical statistic parameter (*k*-value in this case of more than 1.67) was Laboratory 1 for Cell 1 (FDR E-C LD). A parameter exceeding the critical value normally calls for elimination of the data from the remaining part of the analysis. However, the high variability for this section was attributed to likely nonhomogenous characteristics of the section. This particular test area was an unintended construction anomaly identified by the research team within a planned test section, and thus higher variability might be expected. Given the limited number of laboratories and sections, the research team opted to include these data for further analysis. It was expected that the resulting precision values would not be adversely affected by the inclusion of these data in the analysis.

Similarly, Tables 3.68 and 3.69 show the calculated *k*-values and *h*-values for the LPST torque values for each test cell, respectively. All the *h*- values and *k*-values were within the acceptable range except the *k*-value for Cell 1 (FDR E-C LD)

Table 3.65. Summary of LPST torque values from ILS.

Laboratory	Replicates	Torque, ft-lb Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1	68.9	47.3	133.3	76.9	54.5	91.9
	2	89.9	39.5	161.1	78.0	52.2	93.7
	3	83.1	73.3	157.7	66.3	62.3	92.0
Lab 2	1	72.1	49.1	154.4	66.5	54.8	77.0
	2	82.0	51.1	162.5	71.8	55.6	83.0
	3	80.7	52.4	165.6	64.9	63.4	84.1
Lab 3	1	92.4	75.0	133.4	76.7	100.2	113.0
	2	101.0	76.8	149.4	81.8	71.7	108.2
	3	78.0	75.1	139.8	79.3	70.9	106.8

Table 3.66. *k*-values for single-operator data consistency for LPST number of blows.

Laboratory	Number of Blows					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	0.54	**1.69**	0.87	1.22	0.39	0.00
Lab 2	0.00	0.28	1.21	0.00	0.67	0.48
Lab 3	1.65	0.28	0.87	1.22	1.55	1.66

Notes: Critical *k*-value equals 1.67; bold/highlight = critical value exceeded.

Table 3.67. *h*-values for between-laboratory data consistency for LPST number of blows.

Laboratory	Number of Blows					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	–0.58	–0.27	–0.45	1.06	–0.66	–0.27
Lab 2	–0.58	–0.84	–0.70	–0.93	–0.49	–0.84
Lab 3	1.15	1.11	1.15	–0.13	1.15	1.11

Note: Critical *h*-value equals ± 1.15.

by Laboratory 1, with a *k*-value of 1.69, the same observation as with the case of number of blows measurements. For the same reasons as stated previously, the data associated with this observation were not removed from the analysis.

To evaluate interactions among laboratories and test cells, the LPST number of blows and torque value are shown in Figures 3.97 and 3.98, respectively. The data are arranged from least to greatest value. The trends from each laboratory were similar for both the number of blows and torque value. From the results shown in Figures 3.97 and 3.98, no data were excluded because of interactions.

Tables 3.70 and 3.71 show the single-operator and multi-laboratory standard deviation and COV for LPST number of blows and torque value, respectively, as calculated for each test cell in accordance with ASTM C802.

To determine the form of the precision statements, the relationship between the average LPST number of blows and the standard deviation and the COV for single-operator and multi-laboratory conditions is shown in Figures 3.99 and 3.100, respectively. The figures indicate that the standard deviation is also the appropriate basis for developing the precision statements for LPST number of blows measurements. That is because the standard deviation tends to be relatively more independent of LPST number of blows measurements than the COV for both single-operator and multi-laboratory conditions. Thus, the pooled single-operator

Table 3.68. *k*-Values for single-operator data consistency for LPST torque values.

Laboratory	Torque Value, ft-lb					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1.11	**1.72**	1.45	1.39	0.50	0.34
Lab 2	0.56	0.16	0.55	0.78	0.45	1.29
Lab 3	1.21	0.10	0.77	0.67	1.60	1.10

Notes: Critical *k*-value equals 1.67; bold/highlight = critical value exceeded.

Table 3.69. *h*-values for between-laboratory data consistency for LPST torque values.

Laboratory	Torque Value, ft-lb					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	–0.38	–0.48	–0.01	0.05	–0.64	–0.13
Lab 2	–0.75	–0.67	1.00	–1.02	–0.52	–0.93
Lab 3	1.14	1.15	–0.99	0.97	1.15	1.06

Note: Critical *h*-value equals ± 1.15.

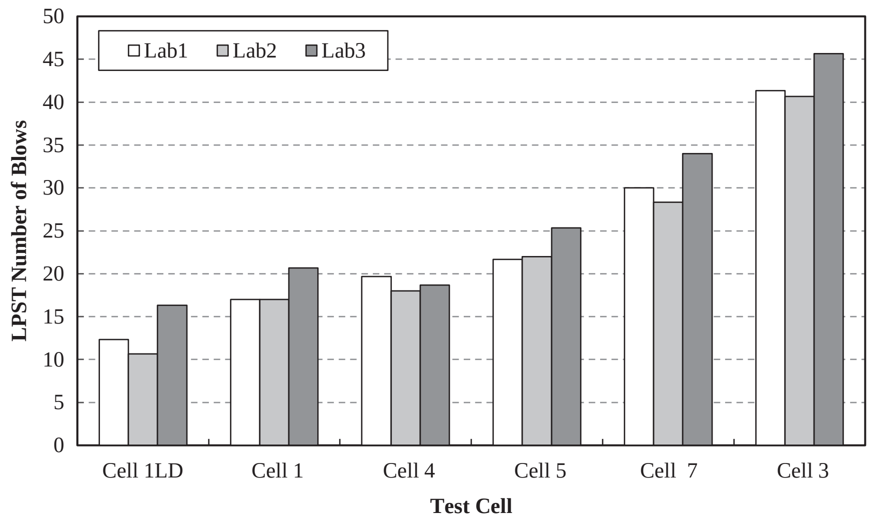


Figure 3.97. Average LPST number of blows arranged from least to greatest.

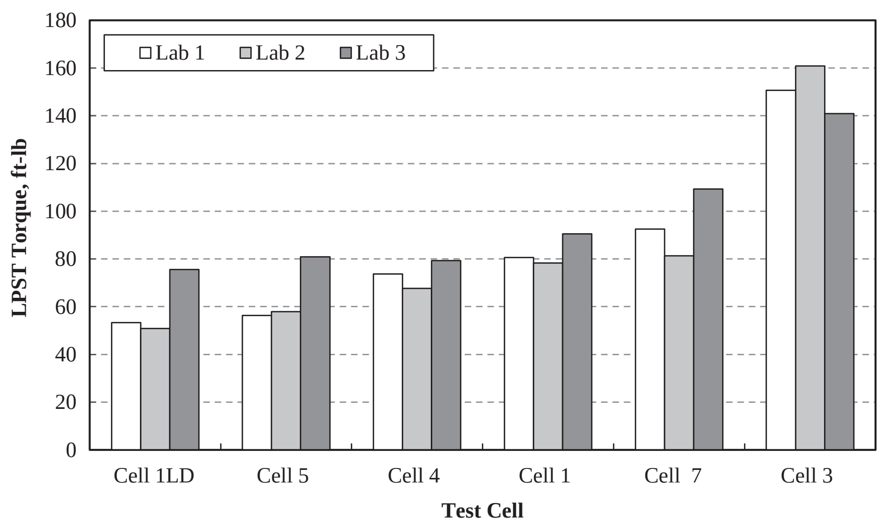


Figure 3.98. Average LPST torque arranged from least to greatest.

Table 3.70. LPST number of blows average, standard deviation, and coefficient of variation.

Test Cell/Material	Number of Blows				
	Average	Standard Deviation		Coefficient of Variation, %	
		Single Operator	Multi-Laboratory	Single Operator	Multi-Laboratory
Cell 1 FDR E-C LD	13.1	2.1	3.4	15.9	25.7
Cell 1 FDR E-C	18.2	1.9	2.6	10.2	14.3
Cell 4 CIR E-N	18.8	0.5	0.9	2.5	4.9
Cell 5 CCPR E-N	23.0	1.5	2.4	6.5	10.3
Cell 7 CCPR F-C	30.8	1.2	3.1	3.9	10.0
Cell 3 CIR F-C	42.6	2.6	3.5	6.2	8.2

Table 3.71. LPST torque value average, standard deviation, and coefficient of variation.

Test Cell/Material	Torque Value, ft-lb				
	Average	Standard Deviation		Coefficient of Variation, %	
		Single Operator	Multi-Laboratory	Single Operator	Multi-Laboratory
Cell 1 FDR E-C LD	60.0	10.3	16.0	17.2	26.7
Cell 5 CCPR E-N	65.1	10.6	16.2	16.2	24.8
Cell 4 CIR E-N	73.6	4.6	6.8	6.3	9.2
Cell 1 FDR E-C	83.1	9.6	10.2	11.6	12.3
Cell 7 CCPR F-C	94.4	3.0	14.3	3.1	15.1
Cell 3 CIR F-C	150.8	10.5	13.1	6.9	8.7

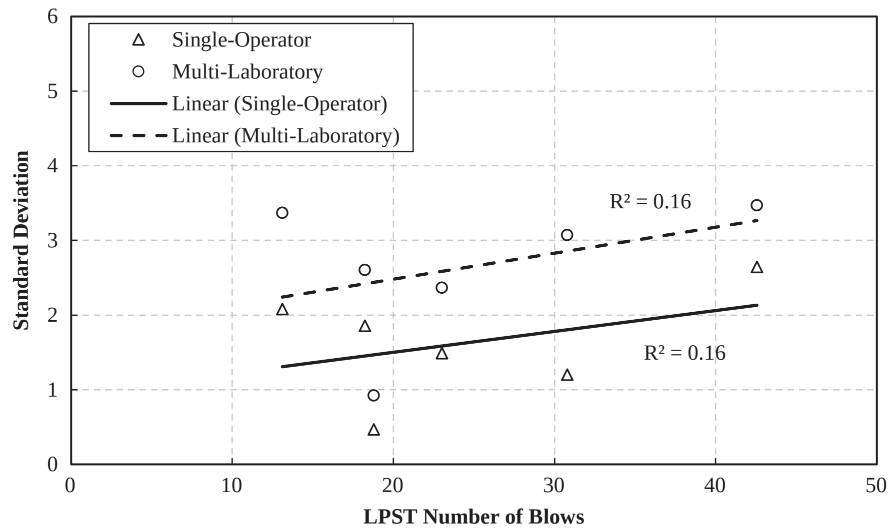


Figure 3.99. Relationship between average LPST number of blows and standard deviation.

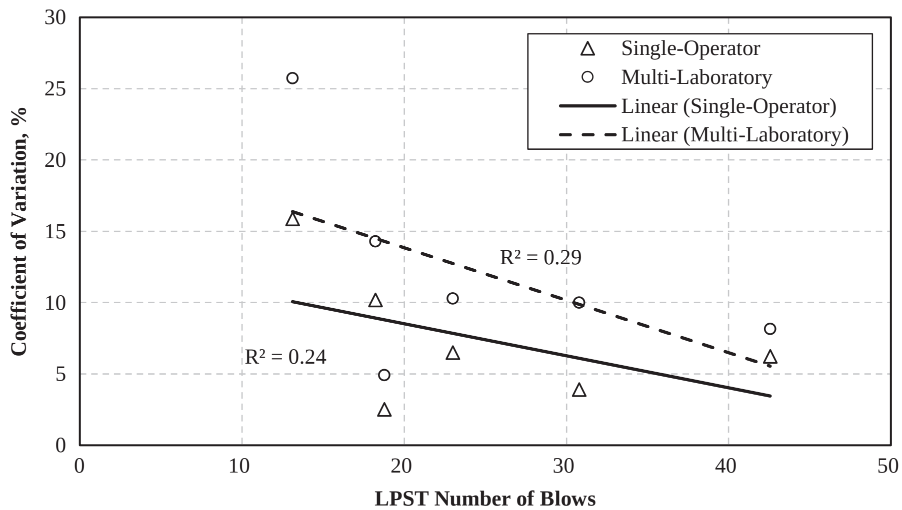


Figure 3.100. Relationship between average LPST number of blows and coefficient of variation.

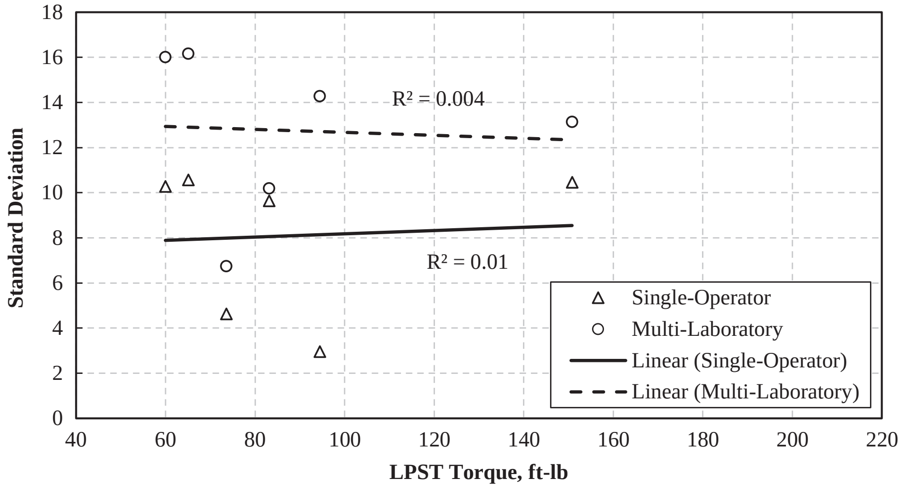


Figure 3.101. Relationship between average LPST torque value and standard deviation.

and multi-laboratory standard deviations from Table 3.70 were used to develop the precision statements for LPST number of blows measurements.

Similarly, the relationship between the average LPST torque value and corresponding standard deviation for single-laboratory and multi-laboratory conditions is shown in Figure 3.101. The relationship between average LPST number of blows and COV for single-laboratory and multi-laboratory conditions is shown in Figure 3.102. From these two figures, it is evident that the standard deviation was independent of the LPST torque measurements for both single-operator and multi-laboratory conditions, whereas (although not a strong relationship) the single-operator and multi-laboratory COV tended to decrease with an increase in LPST torque measurements. Hence, the use of a constant standard deviation is appropriate for developing the precision statements for LPST torque results. Therefore, the pooled single-operator and multi-laboratory standard deviations from Table 3.71 were used to develop the precision statements for LPST torque values.

The following precision statements for LPST number of blows and torque value were developed in accordance with ASTM C670.

Number of Blows

- Single-operator precision: The single-operator standard deviation was 1.6 blows. Therefore, the results of two properly conducted tests by the same operator on the same material are not expected to differ by more than five blows.[A]

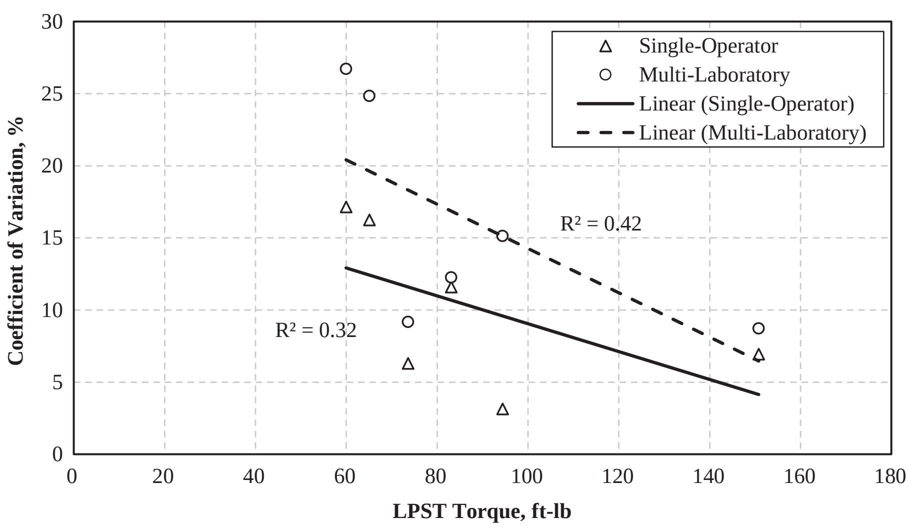


Figure 3.102. Relationship between average LPST torque value and coefficient of variation.

Table 3.72. Summary of SPRT number of blows from ILS.

Laboratory	Replicates	Material					
		Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1	8	7	15	8	9	11
	2	7	6	19	8	9	13
	3	10	7	16	8	9	14
Lab 2	1	6	4	16	8	7	9
	2	6	4	15	7	8	10
	3	7	4	15	7	8	10
Lab 3	1	8	6	16	7	8	11
	2	8	6	15	8	9	10
	3	8	6	14	7	9	10

- Multi-laboratory precision: The multi-laboratory standard deviation was 2.6 blows. Therefore, the results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ by more than seven blows.[A]

[A]These numbers represent the difference limits (d2s) as described in ASTM C670.

Note: These precision statements are based on an ILS that involved three laboratories, six materials, and three replicate tests per operator, with number of blows values ranging from nine to 54.

Torque Value

- Single-operator precision: The single-operator standard deviation was 8.1 ft-lbf. Therefore, the results of two properly conducted tests by the same operator on the same material are not expected to differ by more than 22.6 ft-lbf.[A]
- Multi-laboratory precision: The multi-laboratory standard deviation was 12.7 ft-lbf. Therefore, the results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ by more than 35.7 ft-lbf.[A]

[A]These numbers represent the difference limits (d2s) as described in ASTM C670.

Note: These precision statements are based on an ILS that involved three laboratories, six materials, and three replicate tests per operator, with torque values ranging from 39.5 ft-lbf to 165.6 ft-lbf.

3.5.7.3 Preliminary Precision Statement for Raveling Tests

Tables 3.72 and 3.73 show the SPRT number of blows and torque value, respectively.

Summaries of calculated *k*-values and *h*-values for the SPRT number of blows for each test cell are shown in Tables 3.74 and 3.75, respectively. The values that exceeded the critical values are highlighted and bolded in the tables. For reasons stated previously, the data associated with this observation were included in the analysis.

Similarly, Tables 3.76 and 3.77 show the calculated *k*-values and *h*-values for the SPRT torque values for each test cell, respectively. As shown, none of the *k*-values and *h*-values exceeded the critical values, indicating consistency in the collected data.

To evaluate interactions among laboratories and test cells, the SPRT number of blows and torque value are shown in Figures 3.103 and 3.104, respectively. The data are arranged from least to greatest value. As seen from the figures, the trends from each laboratory were similar for both the number of blows and torque value. No data were excluded because of interactions.

Table 3.73. Summary of SPRT torque value from ILS.

Laboratory	Replicates	Torque Value, ft-lb					
		Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1	26.1	22.9	39.4	25.6	20.7	27.2
	2	26.2	17.8	46.3	22.5	23.3	24.0
	3	23.9	15.2	42.0	18.8	21.0	28.8
Lab 2	1	18.5	18.1	50.6	29.7	21.9	26.1
	2	19.7	15.9	44.5	21.7	16.6	23.2
	3	20.6	16.6	40.9	26.5	20.0	23.8
Lab 3	1	22.8	21.8	50.8	24.8	25.9	30.2
	2	22.9	27.4	45.7	26.8	18.9	28.6
	3	19.8	21.8	40.0	24.8	19.6	25.3

Table 3.74. *k*-values for single-operator data consistency for SPRT number of blows.

Laboratory	Number of Blows					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1.62	**1.73**	1.51	0.00	0.00	1.53
Lab 2	0.61	0.00	0.42	1.22	1.22	0.58
Lab 3	0.00	0.00	0.73	1.22	1.22	0.58

Notes: Critical *k*-value equals 1.67; bold/highlight = critical value exceeded.

Table 3.75. *h*-values for between-laboratory data consistency for SPRT number of blows.

Laboratory	Number of Blows					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	0.73	0.80	1.13	1.15	0.80	1.13
Lab 2	–1.14	–1.12	–0.38	–0.58	–1.12	–0.78
Lab 3	0.41	0.32	–0.76	–0.58	0.32	–0.35

Note: Critical *h*-value equals ± 1.15.

The single-operator and multi-laboratory standard deviation and COV for SPRT number of blows and torque value are presented in Tables 3.78 and 3.79, respectively, as calculated for each test cell in accordance with ASTM C802.

To determine the form of the precision statements, the relationship between the average SPRT number of blows and the standard deviation and the COV for single-operator and multi-laboratory conditions is shown in Figures 3.105 and 3.106, respectively. The figures show that the COV is the appropriate basis for developing the precision statements for SPRT number of blows as the COV overall tended to be relatively more independent than the standard deviation for both single-operator and multi-laboratory conditions. Thus, the pooled single-operator and multi-laboratory standard deviations from Table 3.78 were used to develop the precision statements for SPRT number of blows.

The relationship between average SPRT torque values and the standard deviation and the COV for single-operator and multi-laboratory conditions is presented in Figures 3.107 and 3.108, respectively. The standard deviation tended to increase with an increase in the SPRT torque value for both single-operator and multi-laboratory conditions, and the single-operator and multi-laboratory COV stayed relatively constant with changes in the LPST torque value. Thus, the use of a constant COV is appropriate for developing the precision statements for SPRT torque values. The pooled single-operator and multi-laboratory COVs from Table 3.79 were used to develop the precision statements for SPRT torque values.

Table 3.76. *k*-values for single-operator data consistency for SPRT torque values.

Laboratory	Torque Value, ft-lb					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	0.93	1.30	0.75	1.09	0.50	1.11
Lab 2	0.75	0.37	1.05	1.29	0.95	0.69
Lab 3	1.26	1.08	1.16	0.37	1.36	1.13

Note: Critical *k*-value equals 1.67.

Table 3.77. *h*-values for between-laboratory data consistency for SPRT torque values.

Laboratory	Torque Value, ft-lb					
	Cell 1 FDR E-C	Cell 1 FDR E-C LD	Cell 3 CIR F-C	Cell 4 CIR E-N	Cell 5 CCPR E-N	Cell 7 CCPR F-C
Lab 1	1.07	–0.31	–1.15	–1.15	0.66	0.17
Lab 2	–0.92	–0.81	0.53	0.70	–1.15	–1.07
Lab 3	–0.15	1.12	0.63	0.45	0.49	0.91

Note: Critical *h*-value equals ± 1.15.

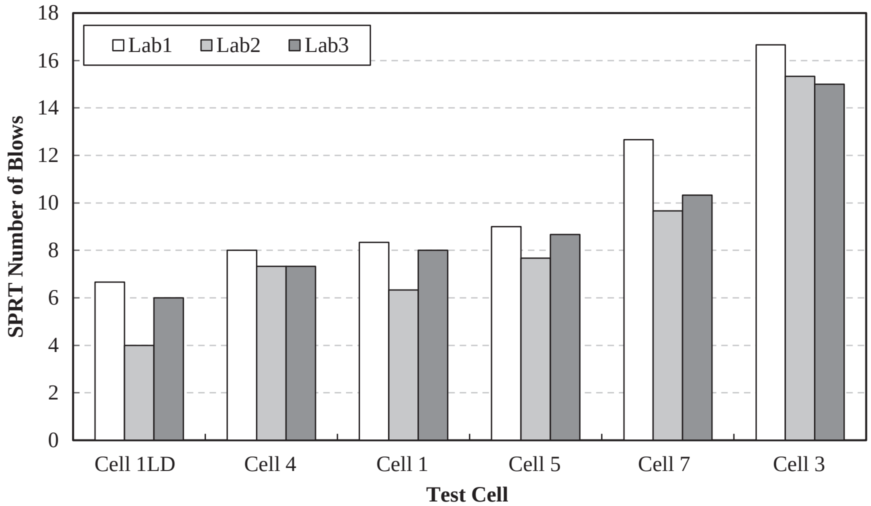


Figure 3.103. Average SPRT number of blows arranged from least to greatest.

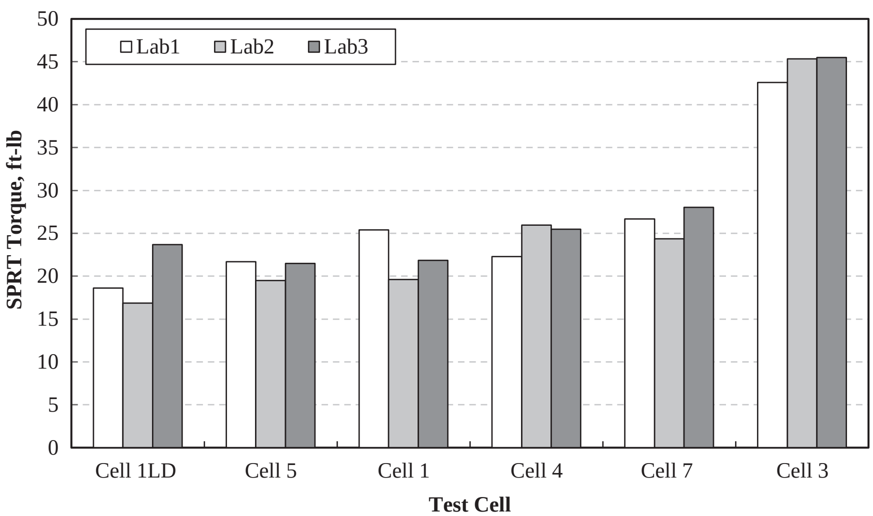


Figure 3.104. Average SPRT torque value arranged from least to greatest.

Table 3.78. SPRT number of blows average, standard deviation, and coefficient of variation.

Test Cell/Material	Number of Blows				
	Average	Standard Deviation		Coefficient of Variation, %	
		Single Operator	Multi-Laboratory	Single Operator	Multi-Laboratory
Cell 1 FDR E-C LD	5.6	0.3	1.4	6.0	25.5
Cell 4 CIR E-N	7.6	0.5	0.5	6.2	7.2
Cell 1 FDR E-C	7.6	0.9	3.3	12.5	43.4
Cell 5 CCPR E-N	8.4	0.5	0.8	5.6	9.4
Cell 7 CCPR F-C	10.9	1.0	1.8	9.2	16.3
Cell 3 CIR F-C	15.7	1.4	1.4	8.8	9.1

Table 3.79. SPRT torque value average, standard deviation, and coefficient of variation.

Test Cell/Material	Torque Value, ft-lb				
	Average	Standard Deviation		Coefficient of Variation, %	
		Single Operator	Multi-Laboratory	Single Operator	Multi-Laboratory
Cell 1 FDR E-C LD	19.7	3.0	4.3	15.2	21.8
Cell 5 CCPR E-N	20.9	2.8	2.8	13.6	13.6
Cell 1 FDR E-C	22.3	1.4	3.1	6.3	14.1
Cell 4 CIR E-N	24.6	3.1	3.2	12.7	13.1
Cell 7 CCPR F-C	26.4	2.2	2.6	8.4	9.8
Cell 3 CIR F-C	44.5	4.7	5.4	10.5	12.3

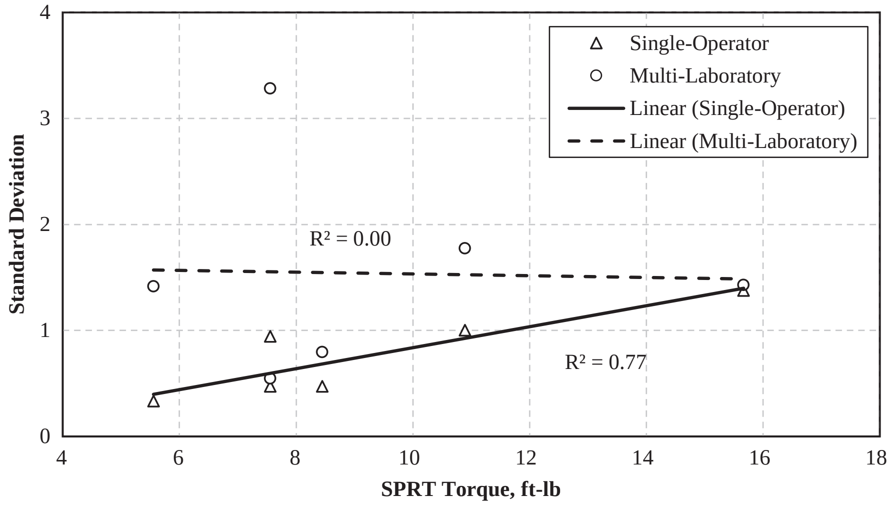


Figure 3.105. Relationship between average SPRT number of blows and standard deviation.

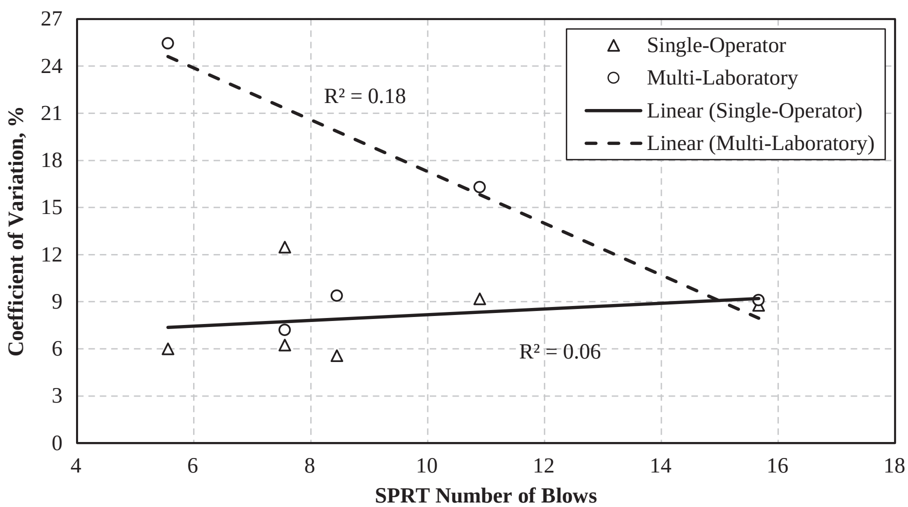


Figure 3.106. Relationship between average SPRT number of blows and coefficient of variation.

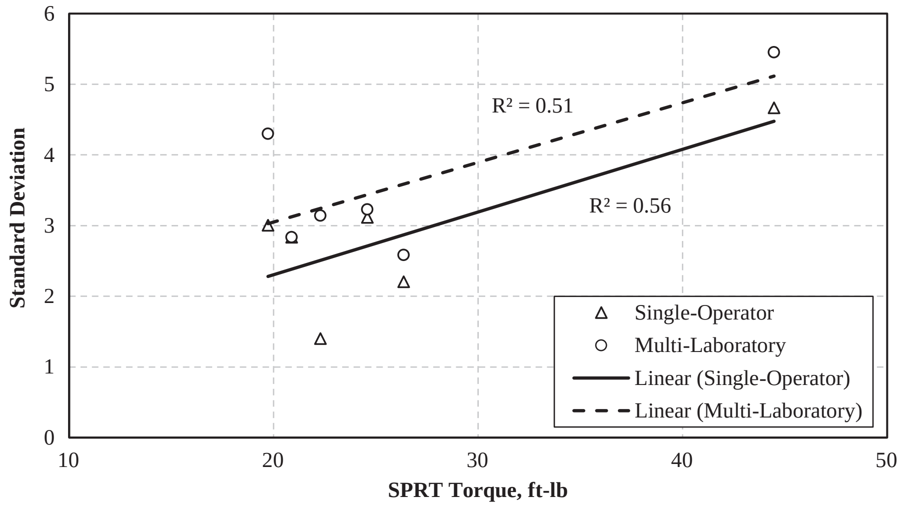


Figure 3.107. Relationship between average SPRT torque value and standard deviation.

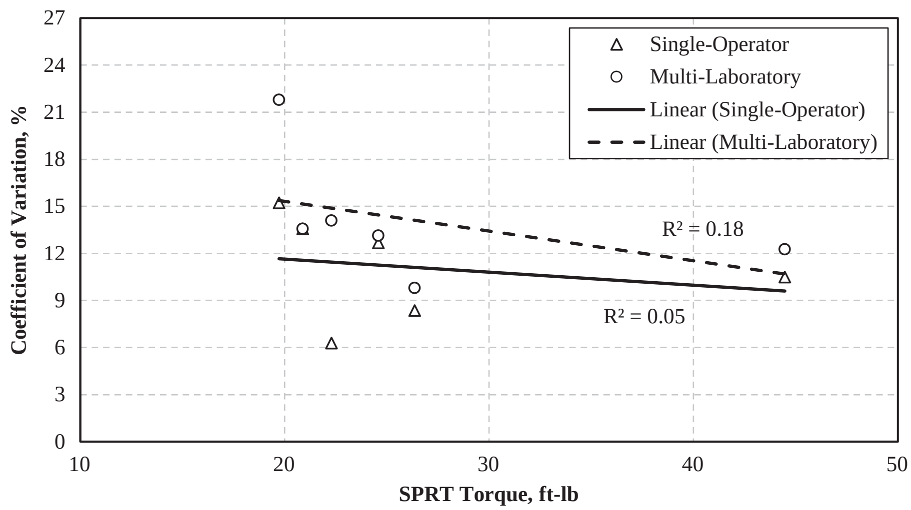


Figure 3.108. Relationship between average SPRT torque value and coefficient of variation.

The following precision statements for SPRT number of blows and torque value were developed in accordance with ASTM C670.

Number of Blows

- Single-operator precision: The single-operator COV was 8%. Therefore, the results of two properly conducted tests by the same operator on the same material are not expected to differ by more than 22.5%[A] of their average.
- Multi-laboratory precision: The multi-laboratory COV was 14.2%. Therefore, the results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ by more than 39.6%[A] of their average.

[A]These numbers represent the difference limits in % (d2s%) as described in ASTM C670.

Note: These precision statements are based on an ILS that involved three laboratories, six materials and three replicate tests per operator, with number of blows ranging from four to 19.

Torque Value

- Single-operator precision: The single-operator COV was 11.1%. Therefore, the results of two properly conducted tests by the same operator on the same material are not expected to differ by more than 31.1%[A] of their average.
- Multi-laboratory precision: The multi-laboratory COV was 13.8%. Therefore, the results of two properly conducted

tests by two different laboratories on specimens of the same material are not expected to differ by more than 38.7%[A] of their average.

[A]These numbers represent the difference limits in % (d2s%) as described in ASTM C670.

Note: These precision statements are based on an ILS that involved three laboratories, six materials, and three replicate tests per operator, with torque values ranging from 15.2 to 50.8 ft-lbf.

3.6 Selection of Recommended Tests and Threshold Values

Selecting the recommended tests and their corresponding threshold values was conducted by comparing the different tests, subjectively considering the ease at which the tests could be conducted, and making a statistical evaluation of the test variability. Due to differences in the confinement conditions between laboratory testing (Phase II) and field testing (Phase III), the proposed test selection and threshold values were determined based on field test data.

3.6.1 Proposed Tests

From the findings of this study, the SSG and LWD tests were not recommended since they were found to be influenced by the properties of the pavement foundation and not just the recycled layer. This was evidenced by the large difference in measured stiffness properties of the Indiana SR 1 project having good and poor underlying support layers. If the goal of this project were to include an overall structural capacity assessment that included the foundation, the SSG and LWD tests would have been good candidates.

The DPI was found to be somewhat correlated with the remaining tests (LPST number of blows and torque value, SPRT number of blows and torque value) when considering the coefficient of determination (calculated by squaring the values shown in Table 3.59a). The coefficient of determination (R^2) when considering the DPI versus the remaining tests was found to range from 0.44 to 0.63, indicating that approximately 44% to 63% of the variation in the other tests was explained by the DPI values. Because of this lower explanatory power, and because the DPI is only a measure of penetration resistance and not any type of shearing force, the DPI was not recommended.

Because of their ability to measure independent material properties and the ease at which the test can be conducted, the LPST number of blows and torque and the SPRT number of blows and torque were recommended. Despite the good correlation shown during the Phase III field testing between the number of blows and torque value for each fixture, these two components of each test are recommended since the number of blows can easily be counted while preparing to assess the torque value. In addition, as shown in the next section, not all projects respond to the number of blows and torque threshold values the same way despite the good correlation. This added a level of conservatism to the testing.

The LPST number of blows and torque are thought to be an indicator of the material's ability to withstand the loading from traffic and from paving equipment when the recycled material is surfaced. The SPRT is thought to be an indicator that the recycled material can be trafficked without experiencing deterioration of the surface of the recycled layer.

3.6.2 Proposed Threshold Values

A statistical approach was used to establish the threshold values for each recommended test. The threshold value is that value that defines the separation between deficient material and adequate material. Threshold values were calculated using the mean and variability of each test from Phase III using an approach similar to the percent within limits (PWL) concept. The PWL is the proportion of test values that fall within a predetermined upper and lower specification limit. Hughes (1996) and Muench and Mahoney (2001) state that when agencies work to develop statistical-based quality assurance programs, these specification limits are set most often based on two factors: engineering judgment and statistical analysis. In an ideal case, the proportion considered acceptable should be set such that the maximum amount of accepted defective material will not substantially degrade the overall quality of the pavement. Typical levels of acceptable quality for pavement materials are often set such that 90% or 95% of test values from a given population are identified as adequate (Muench and Mahoney, 2001). Using these concepts, a lower specification limit was calculated for each test and was considered as the threshold value.

Using engineering judgment and concepts from Hughes (1996), the threshold values for each test were calculated by considering the left-side tail of the field dataset distribution as shown in Figure 3.109. The threshold value was calculated

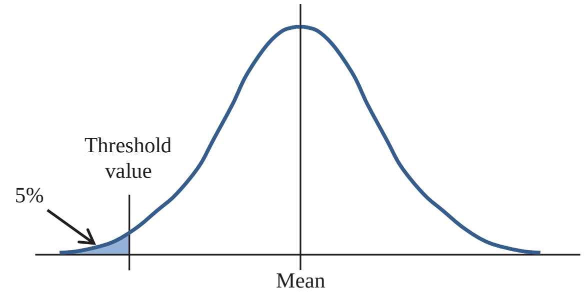


Figure 3.109. Example normal distribution with threshold value at a left-tail area of 5%.

Table 3.80. Recommended test mean, pooled standard deviation, and threshold value.

Recommended Test		Mean	Pooled Standard Deviation	Threshold Value (Average of Three Tests)
Short-pin raveling test	Number of blows	8.4	0.8	7.1
	Torque, ft-lb	24.3	2.5	20.2
Long-pin shear test	Number of blows	22.8	2.1	19.3
	Torque, ft-lb	76.4	8.2	62.9

by first determining the mean value from all 50 observations of each test. Next, the standard deviation from each project (termed "project standard deviation") was calculated based on their respective replicate measurements. Finally, the pooled standard deviation was calculated as the average of the project standard deviations. The threshold value was calculated such that 95% of the test observations would be found adequate (5% deficient) as follows:

$$TV = Mean - 1.645(PSD)$$

Where TV = threshold value, mean = mean value, 1.645 = *z*-statistic for a left-tail area of 5%, and PSD = pooled standard deviation. Table 3.80 shows the mean, pooled standard deviation, and threshold values for each test. Given the relatively low number of projects for each recycling process and stabilizing/recycling agent combination, the same threshold values were suggested regardless of recycling process and stabilizing/recycling agent combination. To add a layer of conservatism, a material must pass both the number of blows and torque component to be considered as adequate.

The threshold values shown in Table 3.80 were compared to the test results from two field projects that had the lowest values and from two additional trials where 100% RAP was placed but no additional binder was added. The two 0% binder trials, one conducted in the laboratory and one in the field, were used to simulate a worst-case scenario with respect to cold recycled materials—the case where no additional binder is added.

Table 3.81 shows the test results from the Phase III field projects that, while constructed successfully, had the lowest measured values for three of the four recommended tests. The CA SR 22 project was tested at three curing times while the MN Cell 1-LD site was only tested at one curing time. Comparing the test results from these two projects to the proposed threshold values shows that the results of the four tests did not meet the threshold value when testing was conducted at the earliest curing time. This suggests that both surfacing and trafficking should wait to see if additional curing improves the test results. Only the CA project was assessed at longer curing intervals and Table 3.81 also shows that the test results met or exceeded all threshold values after 24 hours.

Table 3.82 shows the test results from the two 0% binder trials. For the laboratory assessment, RAP from a CIR project was sampled and mixed with water to reach the optimum moisture content. The wetted RAP was placed into wood molds having dimensions of 54 in. × 23 in. × 3.25 in. The material was compacted using a plate compactor until a density of approximately 123 lbs/ft^3 was achieved. For the testing conducted in the field, a fine-graded 100% RAP mixture was placed using a paver and compacted with a 12-ton double steel drum roller in an effort to assess the potential of using 100% RAP as a surfacing alternative to treat unsurfaced rural roads. The material was rolled for approximately seven to nine vibratory passes, but no density information from the field trial was available. No standard deviation was calculated for the SPRT torque value during

Table 3.81. Threshold values and Phase III results from two sites.

Test		Threshold Value	CA SR 22 CIR F-C (Single Observation)			MN Cell 1-LD FDR E-C (Average of Three Replicates)
			2 Hours Curing	6 Hours Curing	24 Hours Curing	3 Hours Curing
Short-pin raveling test	Number of blows	7.1	3.7	5.7	11.0	5.6
	Torque, ft-lb	20.2	15.4	20.2	30.2	19.7
Long-pin shear test	Number of blows	19.3	14.3	15.7	26.0	13.1
	Torque, ft-lb	62.9	67.0	78.9	123.7	60.0

Table 3.82. Results of laboratory and field trials using 0% binder material.

Test		Threshold Value	Laboratory Trial			Field Trial		
			Mean	Pooled Standard Deviation	Zero-Binder Upper Limit (Mean + 1.645 Standard Deviations)	Mean	Pooled Standard Deviation	Zero-Binder Upper Limit (Mean + 1.645 Standard Deviations)
Short-pin raveling test	Number of blows	7.1	3.7	0.8	5.0	2.4	0.8	3.7
	Torque, ft-lb	20.2	12.6	2.5	15.6	15.4	2.5	19.5
Long-pin shear test	Number of blows	19.3	7.3	2.1	9.8	6.2	2.1	9.7
	Torque, ft-lb	62.9	42.2	8.2	51.9	26.1	8.2	39.6

the field trial since the test value was near the lower limit of the torque wrench.

When evaluating the 0% binder trial test results with respect to the threshold values, a direct comparison between the mean values of the test results and the threshold values was not made; rather, a more conservative approach was undertaken to eliminate the probability of accepting a deficient material. Given that the 0% binder trials were to represent a worst-case scenario, it was decided that the upper end of the distribution of test results, assumed to be at the 95th percentile, should be less than the threshold value (since the threshold value was considered a minimum acceptable test result). The zero-binder upper limit for both the laboratory and field trials was then calculated by adding 1.645 times the pooled standard deviation to the mean test value, as is shown in Table 3.82. The pooled standard deviation was used since there were more observations (50) in the study population than the zero-binder trials (three). The zero-binder upper limits from the laboratory and field trials were found to be less than the threshold values from each test. The zero-binder trials were considered an acceptable verification of the threshold values and indicated a good level of conservatism and a low risk that rejectable material would be found adequate.

3.7 Proposed AASHTO Standard Practice

A proposed AASHTO standard practice guide was developed to assist agencies with implementing the proposed tests. A draft of the proposed standard practice is provided in Appendix B.

CHAPTER 4

Conclusions and Suggested Research

Following the completion of this research study, conclusions and suggested research topics were developed and are included in the following sections.

4.1 Conclusions

Based on the information obtained from the literature review and the online stakeholder survey, the most used methods for assessing the quality of constructed recycled pavement layers are not adequate for determining the time to opening to traffic or the time to surfacing. Assessing the moisture content and density were found to be the most used tests in current practice. However, the moisture content value is more of a surrogate for the amount of curing that has taken place within the recycled layer than an actual measure of the curing progress. Similarly, low density is often considered to be an indicator of poor quality, and thus poor expected performance, but high density values do not necessarily predict good performance.

During this study, a series of tests that could be used to describe performance properties of an FDR, CIR, or CCPR layer were evaluated in laboratory and field settings. These tests were assessed based on their potential to quantify expected changes in mixture properties with respect to curing time and presence of cement as an active filler, their variability, and their correlation with other tests. As part of the laboratory study, a ruggedness evaluation was conducted and showed that certain physical dimensions of the test fixtures and the angular rate at which the torque was applied were significant factors. During the field study, an ILS was completed. The ILS was used to develop precision statements for each of the recommended tests. Following the work in the laboratory and the field, the study recommended that the shear and raveling properties of recycled materials be assessed to quantify the time to opening to traffic and surfacing. Specifically, the number of blows and the torque value from a long-pin shear test and a short-pin raveling test were proposed to quantify the material behavior. Based on a statistical analysis of the collected data, threshold values for each of the four tests were proposed, as shown in Table 4.1.

The long-pin shear test requirements (both number of blows and torque value) would be used to determine the appropriate time to surface a recycled layer. The short-pin raveling test requirements (both number of blows and torque value) would be used to determine the appropriate time to allow traffic on a recycled layer. Given the length of the pins, the shear and raveling tests are appropriate only for recycled layers having a thickness greater than 3 in.

4.2 Suggested Research

One limitation of a civil engineering research study is the ability to collect enough data on field-produced and field-placed materials. During this study, the research team was able to assess the properties of 16 recycled pavement sections where each section exhibited a unique combination of a recycling process, a stabilizing/recycling agent, the presence of an active filler, or another property expected to influence the test results. The development of the threshold values for each of the recommended tests was based on an analysis of the data collected. However, each project, by virtue of being part of a constructed facility for public use, was constructed with the best possible materials and construction practices. For the purposes of this study, it would have been beneficial to construct some sections purposefully having known defective material properties in addition to the two 0% binder trials. This would allow for the assessment of the response of the recommended tests to these defects. Future testing should be undertaken on such materials in an effort to verify the threshold values for each of the recommended tests. This verification could either be conducted on special test sections in the field or be completed as part of a typical recycling project where the reclaimer or cold recycler would process adjusted materials or other modifications.

Table 4.1. Recommended test threshold values.

Recommended Test		Threshold Value (Average of Three Tests)
Short-pin raveling test	Number of blows	7.1
	Torque, ft-lb	20.2
Long-pin shear test	Number of blows	19.3
	Torque, ft-lb	62.9

CHAPTER 5

Training and Implementation

This chapter:

- Provides recommendations on how best to put the research findings/products into practice,
- Identifies possible institutions that might take leadership in applying the research findings/products,
- Identifies issues affecting potential implementation of the findings/products and recommends possible actions to address these issues, and
- Recommends methods of identifying and measuring the impacts associated with implementation of the findings/products.

This information is presented as the following implementation plan with sections on each topic.

5.1 Implementation Plan

To put the research findings/products into practice, a well-developed implementation plan will be important for the successful implementation of the research products. Issues that need to be addressed in the implementation plan include defining the research product market so that the applicability of the research product to improving current practice can be communicated. A realistic assessment of impediments to successful implementation, along with identification of marketing opportunities and potential deployment leadership, will also be conducted. Finally, tactical items that will need to be addressed in the plan will include revisions of related policies, standards, and guideline documents and training and knowledge transfer for stakeholders at multiple levels. Knowledge transfer for this study began during the project at multiple technical meetings and conferences that helped promote interest and understanding along the way.

For any new test method to be used as part of the bid documents for a construction project, the equipment associated with the new test methods will need to be available commercially. The research team has been contacted by two potential equipment manufacturers to date, demonstrating an interest in commercial production of the equipment. Since ruggedness experiments were performed for the proposed test methods that were developed in AASHTO's standard format, the only item needed to complete them is follow-up, complete ILS studies; submission to AASHTO for balloting can then occur.

The market for the research products is primarily the AASHTO member states; other public agencies; FHWA, to some degree; and other industry stakeholders. It includes highway agencies and other entities involved in specifying, accepting, and paying for construction materials. The market for the presentation materials includes the broader industry stakeholders and specifically those entities and individuals that will serve as deployment leaders. Every state, county, and city road agency, and many other agencies, are stakeholders and potential users of the products of this research. These stakeholders need to be engaged in the process of implementation by recognizing the benefits the research will provide them. Communication and dissemination of the research products to stakeholders are essential for successful implementation. This involves development of knowledge-transfer materials that can be used by agencies, contractors, universities, local technical assistance program centers, and trade organizations such as ARRA. These will be in the form of the technical memoranda and the revised test methods. Dissemination of the research results will need to occur through the presentation and publication of research findings at conferences such at the TRB Annual Meeting; in peer reviewed journals; and presentations of the research findings at expert task group meetings, annual user-producer groups, and other industry meetings.

5.2 Potential Institution and Individual Research Product Deployment Leaders

Potential institution deployment leaders include the project research team, ARRA, AASHTO, consulting engineering firms or consultants that specialize in pavement engineering, and FHWA. AASHTO will be a key institution since the proposed guide specification and test methods will need to be published as AASHTO standards for ultimate implementation of the research findings. FHWA has historically played a significant role in knowledge transfer, training, and implementation support. ARRA also has a significant knowledge transfer and implementation support function that should be leveraged.

FHWA has a cooperative agreement titled Development and Deployment of Innovative Asphalt Pavement Technologies that has as its purpose to stimulate, facilitate, and expedite the deployment and rapid adoption of new and innovative technology relating to the design, production, testing, control, construction, and investigation of asphalt pavements. It is structured in tasks, and a task could be proposed to assist with implementation. Finally, NCHRP could play a role with a subsequent implementation support project that provides for training materials and regional workshops. Potential individual deployment leaders include key staff at the institutions referenced previously.

5.3 Assessment of Impediments to Successful Implementation

Impediments to successful implementation would be those typical of most change-management activities and could be grouped into the following categories relative to the research outcomes of this project: policy and documentation, knowledge transfer and training, and operational stakeholder impediments.

5.3.1 Policy and Documentation

Policy and documentation impediments are items that would need to be developed, revised, or deleted for successful implementation. Examples are revisions or updates to existing agency policies, standard specifications and special provisions, standard test methods, and acceptance-related documents such as quality-control plan requirements and acceptance criteria. Change does take effort, and at some public agencies there may be a desire not to make changes.

5.3.2 Knowledge Transfer and Training

Knowledge transfer and training are central to the successful implementation of any new technology. They will need to take place with management, engineering and operational agency staff, and other industry stakeholders. Fortunately, the research topic is of significant interest, and industry will likely be supportive of agency changes to implement the products. Therefore, knowledge transfer and training will need to be developed in such a manner that they are scalable to the audience and include easily communicated examples. Delivery will have to be done in such a manner that the interest of stakeholders is maintained, including practitioner audiences using appropriate materials and communication techniques. Past FHWA and National Highway Institute knowledge transfer relative to specifications has been effective. Many of the techniques historically used by them could be used successfully to assist with implementation of the research products. Knowledge-transfer opportunities to consider include:

- Webinars;
- Presentation conferences or meetings at the national, regional, state, and local government levels and industry trade association events;
- Workshops; and
- Demonstration projects.

5.3.3 Operational Stakeholders

Impediments at the operational level would likely occur because of resistance to change and lack of understanding as to why the change is needed. A practical example of this at the construction-project level would be changes in testing requirements. Additional testing would be required to perform shear and raveling tests. Some contractor staff could interpret this as additional work with no value to them. They could also view the change as additional risk in that projects could get delayed if the time to opening were extended compared to current practices. However, with an explanation that the time would be reduced relative to the times in most specifications today (i.e., a specified number of days before opening to traffic or surfacing), the perceived risk would be reduced, and transition to the new testing approach would be embraced.

5.4 Methods of Identifying and Measuring the Implementation Impacts

The ability to measure impacts associated with implementation of the findings and products of the research is straightforward. The following is a list of key measurable impacts:

1. Do the three documents delivered in AASHTO standard format (AASHTO Standard Guide Specification,

AASHTO Standard Method of Test for Evaluating Shear Resistance, and AASHTO Standard Method of Test for Evaluating Raveling Resistance) as part of the research ultimately become published AASHTO documents?

2. Does one or more equipment manufacturer produce commercially available shear and raveling fixtures?
3. How many agencies make documented changes to requirements associated with:
   - The findings/products of the project,
   - Standard test methods used,
   - Quality control requirements, and
   - Standard specifications related to time to opening to traffic or surfacing?

References

Al-Qadi, I., Z. Leng, S. Lahouar, J. Baek. In-Place Hot-Mix Asphalt Density Estimation Using Ground Penetrating Radar. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2152, 2010, pp. 19–27.

Alghamdi, H. Dynamic Cone Penetrometer (DCP) Based Evaluation of Sustainable Low Volume Road Rehabilitation Techniques. Master of Science thesis, Ohio University, Athens, 2016.

Alshibli, K. A., M. Abu-Farsakh, and E. Seyman. Laboratory Evaluation of the Geogauge and Light Falling Weight Deflectometer as Construction Control Tools. *Journal of Materials in Civil Engineering*, Vol. 17, No. 5, 2005, pp. 560–569.

Apeagyei, A. K., and B. K. Diefenderfer. Evaluation of Cold In-Place and Cold Central-Plant Recycling Methods Using Laboratory Testing of Field-Cored Specimens. *Journal of Materials in Civil Engineering*, Vol. 25, No. 11, 2013, pp. 1712–1720.

Asphalt Academy. *Technical Guideline: Bitumen Stabilised Materials*, 2nd Edition. Pretoria, South Africa, 2009.

Asphalt Recycling and Reclaiming Association. *Basic Asphalt Recycling Manual,* 2nd Ed. Annapolis, MD, 2015.

Bemanian, S., P. Polish, and G. Maurer. Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1949, 2006, pp. 54–71.

Berthelot, C., B. Marjerison, G. Houston, J. McCaig, S. Werrener, and R. Gorlick. Mechanistic Comparison of Cement- and Bituminous-Stabilized Granular Base Systems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026, 2007, pp. 70–80.

Betti, G., G. Airey, K. Jenkins, A. Marradi, and G. Tebaldi. Active Fillers' Effect on In Situ Performances of Foam Bitumen Recycled Mixtures. *Road Materials and Pavement Design*, Vol. 18, No. 2, 2017, pp. 281–296.

Bowers, B. F., B. K. Diefenderfer, and S. D. Diefenderfer. Evaluation of Dynamic Modulus in Asphalt Paving Mixtures Utilizing Small-Scale Specimen Geometries. *Journal of the Association of Asphalt Paving Technologists*, Vol. 84, 2015, pp. 497–526.

Bowers, B. F., B. K. Diefenderfer, and C. W. Schwartz. Assessment of Permanent Deformation Properties of In-Place Recycled Pavement Mixtures. *Journal of the Association of Asphalt Paving Technologists*. Vol. 87, 2018, pp. 241–273.

Chen, D., and C. Jahren. Evaluation of Long-Term Field Performance of Cold In-Place Recycled Roads: Field and Laboratory Testing. Publication IHRB TR-502. Iowa Department of Transportation, Ames, 2007.

Chen, D. H., J. H. Wang, and J. Bilyeu. Application of the DCP in Evaluation of Base and Subgrade Layers. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1764, 2001, pp. 1–10.

Columbus, City of. Subgrade Compaction and Proof Rolling and Test Rolling, Construction and Materials Specifications, Section 204, Accessed: https://www.columbus.gov/Templates/Detail.aspx?id=47655, 2012.

Cross, S. A., and Y. Jakatimath. Evaluation of Cold In-Place Recycling for Rehabilitation of Transverse Cracking on US 412. Publication AA-5-11816. Oklahoma State University, Stillwater, 2007.

Crovetti, J. A. Construction and Performance of Fly Ash-Stabilized Cold In-Place Recycled Asphalt Pavement in Wisconsin. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1730, 2000, pp. 161–166.

Crovetti, J. A., and J. Schabelski. *Development of Comprehensive Subgrade Deflection Acceptance Criteria – Phase 3 Report*. Publication WI/SPR-02-01. Wisconsin Department of Transportation, Madison, 2002.

Diefenderfer, B. K., and A. K. Apeagyei. Time-Dependent Structural Response of Full-Depth Reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2253, 2011, pp. 3–9.

Diefenderfer, B. K., A. K. Apeagyei, A. A. Gallo, L. E. Dougald, and C. B. Weaver. In-Place Pavement Recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2306, 2012, pp. 21–27.

Diefenderfer, B. K., and S. D. Link. Temperature and Confinement Effects on the Stiffness of a Cold Central-Plant Recycled Mixture. Proceedings: 12th International Society for Asphalt Pavements Conference on Asphalt Pavements, Raleigh, N.C., 2014.

Diefenderfer, B. K., B. F. Bowers, and A. K. Apeagyei. Initial Performance of Virginia's Interstate 81 In-Place Recycling Project. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2524, 2015, pp. 152–159.

Diefenderfer, B. K., B. F. Bowers, C. W. Schwartz, A. Farzaneh, and Z. Zhang. Dynamic Modulus of Recycled Pavement Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2575, 2016a, pp. 19–26.

Diefenderfer, B. K., M. D. Sanchez, D. H. Timm, and B. F. Bowers. Structural Study of Cold Central Plant Recycling Sections at the

National Center for Asphalt Technology (NCAT) Test Track. Publication VTRC 17-R9. Virginia Transportation Research Council, Charlottesville, 2016b.

Dong, Q., H. Wu, B. Huang, X. Shu, and K. Wang. Development of a Simple and Fast Test Method for Measuring the Durability of Portland Cement Pervious Concrete. Publication SN3149. Portland Cement Association, Skokie, IL. 2010.

Emery, J. T. Practical Experience with Cold In-Place Asphalt Recycling and Foamed Asphalt Full Depth Reclamation. Proceedings of the 51st Annual Conference of the Canadian Technical Asphalt Association, Charlottetown, Prince Edward Island, 2006, pp. 423–444.

Evans, J. D. *Straightforward Statistics for the Behavioral Sciences*. Brooks/Cole Publishing, Pacific Grove, CA, 1996.

Federal Aviation Administration. Standards for Specifying Construction of Airports, Advisory Circular 150/5370-10G. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC-150-5370-10G-updated-201605.pdf, 2014.

Forsberg, A., E. Lukanen, and T. Thomas. Engineered Cold In-Place Recycling Project: Blue Earth County State Aid Highway 20, Minnesota. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1813, 2002, pp. 111–123.

Fu, P., D. Jones, and J. T. Harvey. Micromechanics of the Effects of Mixing Moisture on Foamed Asphalt Mix Properties. *ASCE Journal of Materials in Civil Engineering*, Vol. 22, No. 10, 2010a, pp. 985–995.

Fu, P., D. Jones, J. T. Harvey, and F. A. Halles. Investigation of the Curing Mechanism of Foamed Asphalt Mixes Based on Micromechanics Principles. *ASCE Journal of Materials in Civil Engineering*, Vol. 22, No. 1, 2010b, pp. 29–38.

Guthrie, W. S., A. V. Brown, and D. L. Eggett. Cement Stabilization of Aggregate Base Material Blended with Reclaimed Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026, 2007, pp. 47–53.

Hilbrich, S. L., and T. Scullion. Evaluation of the Laboratory Mix-Design and Field Performance of an Asphalt Emulsion and Cement Stabilized Full-Depth Reclamation Project in Texas. Presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

Holzschuher, C., H. S. Lee, and J. Greene. Accuracy and Repeatability of Ground Penetrating Radar for Surface Layer Thickness Estimation of Florida. Publication FL/DOT/SMO/07-505. Florida Department of Transportation, Gainesville, 2007.

Howard, I. L., and B. C. Cox. Multiyear Laboratory and Field Performance Assessment of High-Traffic US-49 Full-Depth Reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2573, 2016, pp. 86–97.

Hughes, C. S. *NCHRP Synthesis 232: Variability in Highway Pavement Construction*. TRB, National Research Council, Washington, D.C., 1996.

Jahren, C., D. Chen, H. D. Lee, and J. J. Kim. *Evaluation of Long-Term Field Performance of Cold In-Place Recycled Roads: Summary Report*. Publication IHRB TR-502. Iowa Department of Transportation, Ames, 2007.

Jersey, S., and L. Edwards. Stiffness-Based Assessment of Pavement Foundation Materials Using Portable Tools. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2116, 2009, pp. 26–34.

Johanneck, L., and S. Dai. Responses and Performance of Stabilized Full-Depth Reclaimed Pavements at the Minnesota Road Research Facility. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2368, 2013, pp. 114–125.

Johannes, P., E. Mahmoud, and H. Bahia. Sensitivity of ASTM D7000 Sweep Test to Emulsion Application Rate and Aggregate Gradation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2235, 2011, pp. 95–102.

Jones, D., P. Fu, and J. T. Harvey. *Full-Depth Reclamation with Foamed Asphalt in California: Final Report*. Publication UCPRC-RR-2008-07. University of California Pavement Research Center, Berkeley, 2008.

Kazmee, H., E. Tutumluer, and S. Beshears. Evaluating Constructed Aggregate Layers of Working Platforms and Flexible Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2655, 2017, pp. 1–12.

Kim Y., S. Im, and H. Lee. Impact of Curing Time and Moisture Content on Engineering Properties of Cold In-Place Recycling Mixtures Using Foamed and Emulsified Asphalt. *Journal of Materials in Civil Engineering*, Vol. 23, No. 5, 2011, pp. 542–553.

Lane, B., and T. Kazmierowski. Implementation of Cold In-Place Recycling with Expanded Asphalt Technology in Canada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1905, 2005, pp. 17–24.

Lane, B., and T. Kazmierowski. Ten-Year Performance of Full-Depth Reclamation with Expanded Asphalt Stabilization on Trans-Canada Highway, Ontario, Canada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2306, 2012, pp. 45–51.

Lee, H. D., and S. D. Im. Examination of Curing Criteria for Cold In-Place Recycling. Publication IHRB TR-553. University of Iowa, Iowa City, 2008.

Lee, H. D., Y. T. Kim, and S. D. Im. Examination of Curing Criteria for Cold In-Place Recycling. Phase 2: Measuring Temperature, Moisture, Deflection and Distress From CIR Test Section. Publication IHRB TR-590. University of Iowa, Iowa City, 2009.

Leng Z., I. Al-Qadi, P. Shangguan, and S. Son. Field Application of Ground Penetrating Radar for Measurement of Asphalt Mixture Density. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2304, 2012, pp. 133–141.

Lewis, D. E., D. M. Jared, H. Torres, and M. Mathews. Georgia's Use of Cement-Stabilized Reclaimed Base in Full-Depth Reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1952, 2006, pp. 125–133.

Li, X., and N. Gibson. Using Small Scale Specimens for AMPT Dynamic Modulus and Fatigue Tests. *Journal of the Association of Asphalt Paving Technologists*, Vol. 82, 2013, pp. 579–615.

Loizos, A. In-Situ Characterization of Foamed Bitumen Treated Layer Mixes for Heavy-Duty Pavements. *International Journal of Pavement Engineering*, Vol. 8, No. 2, 2007, pp. 123–135.

Loizos, A., and C. Plati. Ground Penetrating Radar as an Engineering Diagnostic Tool for Foamed Asphalt Treated Pavement Layers. *International Journal of Pavement Engineering*, Vol. 8, No. 2, 2007, pp. 147–155.

Loizos, A., and V. Papavasiliou. Evaluation of Foamed Asphalt Cold In-Place Pavement Recycling Using Nondestructive Techniques. *Journal of Transportation Engineering*, Vol. 132, No. 12, 2006, pp. 970–978.

Loizos, A., V. Papavasiliou, and C. Plati. Early-Life Performance of Cold In-Place Pavement Recycling with Foamed Asphalt Technique. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2005, 2007, pp. 36–43.

Loria, L., P. Sebaaly, and E. Hajj. Long-Term Performance of Reflective Cracking Mitigation Techniques in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2044, 2008, pp. 86–95.

Ma, W., R. C. West, B. K. Diefenderfer, A. J. Taylor, and M. A. Heitzman. Characterization of Cold Recycled Asphalt Mixtures on US 280 in Alabama. Presented at the Transportation Research Board Annual Meeting, Washington, D.C., 2017.

Mallick, R. B., D. S. Bonner, R. L. Bradbury, J. O. Andrews, P. S. Kandhal, and E. J. Kearney. Evaluation of Performance of Full-Depth Reclamation Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1809, 2002, pp. 199-208.

Mallick, R. B., K. Maser, and S. Nazarian. Guidelines for the Use of Ground Penetrating Radar (GPR) and Portable Seismic Property Analyzer (PSPA) in Full Depth Reclamation. Publication ME 06-13. Maine Department of Transportation, Augusta, 2007.

Maser, K. R., and T. Scullion. Automated Pavement Subsurface Profiling Using Radar: Case Studies of Four Experimental Field Sites. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1344, 1992, pp. 148–154.

Maser, K. R., T. J. Holland, R. Roberts, and J. Popovics. NDE Methods for Quality Assurance of New Pavement Thickness. *International Journal of Pavement Engineering*, Vol. 7, No. 1, 2006, pp. 1–10.

Maurer, G., S. Bemanian, and P. Polish. Alternative Strategies for Rehabilitation of Low-Volume Roads in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1989, 2007, pp. 309–320.

Meocci, M., A. Grilli, F. La Torre, and M. Bocci. Evaluation of Mechanical Performance of Cement-Bitumen Treated Materials Through Laboratory and In-Situ Testing. *Road Materials and Pavement Design*, Vol. 18, No. 2, 2017, pp. 376–389.

Mohammad, L. N., M. Y. Abu-Farsakh, Z. Wu, and C. Abadie. Louisiana Experience with Foamed Recycled Asphalt Pavement Base Materials. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1832, 2003, pp. 17–24.

Morian, D. A., J. Oswalt, and A. Deodhar. Experience with Cold In-Place Recycling as a Reflective Crack Control Technique: Twenty Years Later. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1869, 2004, pp. 47–55.

Muench, S. T., and J. P. Mahoney. A Quantification and Evaluation of WSDOT's Hot-Mix Asphalt Concrete Statistical Acceptance Specification. Publication WA-RD 517.1, Washington State Department of Transportation, Olympia, 2001.

Nataatmadja, A. Some Characteristics of Foamed Bitumen Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1767, 2001, pp. 120–125.

Ohio Department of Transportation. Subgrade Compaction and Proof Rolling, Construction and Materials Specification, Item 204, http://www.dot.state.oh.us/Divisions/ConstructionMgt/Specification%20Files/2013%20CMS%2011142012%20FINAL.PDF, 2013.

Pakes, A., T. Edil, M. Sanger, R. Olley, and R. Klink. Environmental Benefits of Cold In-Place Recycling. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2672, 2018, pp. 11–19.

Pennsylvania Department of Transportation. Placement and Compaction of Embankment and Fill, Specifications, Section 206, http://www.dot.state.pa.us/public/PubsForms/Publications/Pub_408/408_2016/408_2016_3/408_2016_3.pdf, 2016.

Piratheepan, M., P. E. Sebaaly, and E. Y. Hajj. Mix Design of Cold In-Place Recycling, Proceedings of the 2nd International ISAP Symposium on Asphalt Pavements and Environment, Fortaleza, Brazil, 2012.

Robinette, C., and J. Epps. Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2179, 2010, pp. 10–22.

Saleh, M. F. New Zealand Experience with Foam Bitumen Stabilization. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1868, 2004, pp. 40–49.

Salomon, A., and D. E. Newcomb. Cold In-Place Recycling Literature Review and Preliminary Mixture Design Procedure. Publication MN/RC-2000-21. Minnesota Department of Transportation, St. Paul, 2000.

Sanjeevan, S., M. Piratheepan, E. Hajj, and A. Bush. Cold In-Place Recycling in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2456, 2014, pp. 146–160.

Sargand, S., R. Green, A. Burhani, H. Alghamdi, and B. Jordan. Investigation of In-Situ Strength of Various Construction/Widening Methods Utilized on Local Roads. Publication FHWA/OH-2016/02, Ohio Department of Transportation, Columbus, 2016.

Schwartz, C. W., and S. Khosravifar. *Design and Evaluation of Foamed Asphalt Base Materials*. Final Report, Project No. SP909B4E. Maryland Department of Transportation State Highway Administration, Baltimore, 2013.

Schwartz, C. W., B. K. Diefenderfer, and B. F. Bowers. *NCHRP Report 863: Material Properties of Cold In-Place Recycled and Full-Depth Reclamation Asphalt Concrete*. Transportation Research Board, Washington, D.C., 2017.

Scullion, T. Precracking of Soil-Cement Bases to Reduce Reflection Cracking: Field Investigation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1787, 2002, pp. 22–30.

Sebaaly, P. E., G. Bazi, E. Hitti, D. Weitzel, and S. Bemanian. Performance of Cold In-Place Recycling in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1896, 2004, pp. 162–169.

Sebesta, S., T. Scullion, and C. Estakhri. Field and Laboratory Investigations for Full Depth Reclamation Projects. Publication FHWA/TX-10/0-6271-1. Texas Department of Transportation, Austin, 2009.

Siddiki, N., A. Khan, D. Kim, and T. Cole. Use of In Situ Tests in Compaction Control of a Bottom Ash Embankment. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2045, 2008, pp. 10–18.

Stroup-Gardiner, M. *NCHRP Synthesis 421: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods*. Transportation Research Board of the National Academies, Washington, D.C., 2011.

Tebaldi, G., E. V. Dave, P. Marsac, P. Muraya, M. Hugener, M. Pasetto, A. Graziani, A. Grilli, M. Bocci, A. Marradi, L. Wendling, V. Gaudefroy, K. Jenkins, A. Loizos, and F. Canestrari. Synthesis of Standards and Procedures for Specimen Preparation and In-Field Evaluation of Cold-Recycled Asphalt Mixtures. *Road Materials and Pavement Design*, Vol. 15, No. 2, 2014, pp. 272–299.

Texas Department of Transportation. Proof Rolling and Base Curing Advisory. https://ftp.dot.state.tx.us/pub/txdot-info/cmd/tech/ta103101.pdf, 2001.

Texas Department of Transportation. Full Depth Reclamation Using Foamed Asphalt. Special Specification 3063, Austin, 2018.

Thenoux, G., A. Gonzalez, and R. Dowling. Energy Consumption Comparison for Different Asphalt Pavements Rehabilitation Techniques Used in Chile. *Resources, Conservation, and Recycling*, Vol. 49, 2007, pp. 325–339.

Thomas, T., A. Kadrmas, and J. Huffman. Cold In-Place Recycling on US-283 in Kansas. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1723, 2000, pp. 53–56.

Thompson, M. R., L. Garcia, and S. H. Carpenter. Cold In-Place Recycling and Full-Depth Recycling with Asphalt Products. Publication ICT-09-036. Illinois Center for Transportation, Rantoul, 2009.

Timm, D. H., B. K. Diefenderfer, and B. F. Bowers. Cold Central Plant Recycled Asphalt Pavements in High Traffic Applications. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2672, 2018, pp. 291–303.

Tingle, J., and S. Jersey. Evaluation of In Situ Pavement Layers with the Dynamic Cone Penetrometer. U.S. Army Engineer Research and Development Center, Vicksburg, MS, 1999.

Utah DOT. Guidelines for Evaluation, Mix Design, and Field Acceptance of Cold Recycling of Asphalt Pavements using Solventless Emulsion. Section 965, Materials Manual of Instruction. https://www.udot.utah.gov/connect/business/materials-testing/, accessed November 5, 2020. Salt Lake City, 2007.

VanFrank, K. Cold In-Place Recycle Phase III, Supplemental Field Protocol: Short Term Field Stability. Publication UT-15.08. Utah Department of Transportation, Salt Lake City, 2015.

VanFrank, K., M. VanMiligen, and T. Biel. Cold In-Place Recycle Phase III: Mix Design. Publication UT-14.08. Utah Department of Transportation, Salt Lake City, 2014.

White, D., P. Becker, P. Vennapusa, M. Dunn, and C. White. Assessing Soil Stiffness of Stabilized Pavement Foundations, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2335, 2013, pp. 99–109.

Williams, R., and S. Nazarian. Correlation of Resilient and Seismic Modulus Test Results. *Journal of Materials in Civil Engineering*, Vol. 19, No. 12, 2007, pp. 1026–1032.

Wilson, B. T., and W. S. Guthrie. Strength and Deformation Characteristics of a Cement-Treated Reclaimed Pavement with a Chip Seal. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2212, 2011, pp. 100–109.

Wirtgen. *Cold Recycling Technology*, 3rd Ed. Wirtgen GmbH, Windhagen, Germany, 2010.

Woods, A., Y. Kim, and H. Lee. Determining Timing of Overlay on Cold In-Place Recycling Layer: Development of New Tool Based on Moisture Loss Index and In Situ Stiffness. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2306, 2012, pp. 52–61.

APPENDIX A

Stakeholder Survey Questions

Introduction and Survey Consent

Do you give your consent?
( ) Yes, I consent
( ) No, I do not consent

Page exit logic: Skip/Disqualify Logic **IF:** #1 Question “Do you give your consent?” is one of the following answers (“No, I do not consent”) **THEN:** Disqualify and display: “Thank you for starting the survey.”

Demographics

1. Which of the following most accurately describes your organization?
( ) General Highway Contractor ( ) Pavement Recycling contractor ( ) State Agency ( ) Local Agency ( ) Industry Association ( ) Academic ( ) Materials Supplier ( ) Design Engineering ( ) Testing/Inspection ( ) Other

2. Which of the following most accurately describes your role in your organization?
( ) Senior Manager ( ) Operations Manager ( ) Plant Manager ( ) Engineer ( ) Field Operations (superintendent, foreman, operator) ( ) Quality Inspector or Tester ( ) Technical Salesperson ( ) Researcher or Academic

3. Which of the following best describes the years of experience your agency/company has with cold pavement recycling?
( ) Less than 2 years
( ) 2–5 years
( ) 5–10 years
( ) 10–20 years
( ) 20 years or more

4. Where does your organization do work or supply products in (select all that apply)?
[ ] Northwest US
[ ] Southwest US
[ ] Northcentral US
[ ] Southcentral US
[ ] Northeast US
[ ] Southeast US
[ ] Canada
[ ] Other

Logic: Hidden by default. Hidden unless: #5 Question "4. Where does your organization do work or supply products in (select all that apply)?" is one of the following answers ("Other")
If other: Please specify
____
____
____
____

5. Please indicate if you are willing to participate in a 30-minute maximum telephone interview regarding your responses to this survey?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #6 Question "5. Please indicate if you are willing to participate in a 30-minute maximum telephone interview regarding your responses to this survey?" is one of the following answers ("Yes")
Please provide your phone number.
____

Logic: Hidden by default. Hidden unless: #6 Question "5. Please indicate if you are willing to participate in a 30-minute maximum telephone interview regarding your responses to this survey?" is one of the following answers ("Yes")
Please enter your email address (optional)
____

Specifications and Practices

1. Please check the cold recycling technique(s), recycling/stabilizing agent(s), and chemical additive(s) that your organization has used in the last 5 years.

	Foamed Asphalt			**Asphalt Emulsion**		
	Cement	**Lime**	**Others**	**Cement**	**Lime**	**Others**
Full-Depth Reclamation (FDR)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Cold in-Place Recycling (CIR)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Cold Central-Plant Recycling (CCPR)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

2. What challenges have you encountered with implementing public-agency specifications for cold recycling (Please select all that apply)?
[ ] Previous unsuccessful experiences
[ ] Lack of quality tests with quick results
[ ] Unreasonable quality tests requested
[ ] Ability to meet the required quality test requirements
[ ] Lack of specification uniformity across different agencies
[ ] Constraints in the means and methods
[ ] Excessive time required before opening to traffic/surfacing
[ ] Lack of experienced local contractors
[ ] Lack of agency experience
[ ] Other

Logic: Hidden by default. Hidden unless: #8 Question "2. What challenges have you encountered with implementing public-agency specifications for cold recycling (Please select all that apply)?" is one of the following answers ("Other")
If other: Please list or describe.
____
____
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3. Can you recommend any **rapid** test(s) for process control or product acceptance for cold recycled pavement materials that could be used by public agencies or industry?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #9 Question "3. Can you recommend any rapid test(s) for process control or product acceptance for cold recycled pavement materials that could be used by public agencies or industry?" is one of the following answers ("Yes")
If yes: Please describe the test(s) and/or provide reference(s) (e.g., link to test method or specification)

____
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4. Can you recommend any changes to existing and widely used **rapid** test(s) for process control or product acceptance for cold recycled pavement materials to make them more rapid, efficient, and/or effective?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #10 Question "4. Can you recommend any changes to existing and widely used rapid test(s) for process control or product acceptance for cold recycled pavement materials to make them more rapid, efficient, and/or effective?" is one of the following answers ("Yes")
If yes: Please describe the test(s) and/or provide reference(s) (e.g., link to test method or specification)

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5. Can you recommend any **time to trafficking/surfacing** test(s) for cold recycled pavement materials that could be used by public agencies or industry?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #11 Question "5. Can you recommend any time to trafficking/surfacing test(s) for cold recycled pavement materials that could be used by public agencies or industry?" is one of the following answers ("Yes")
If yes: Please describe the test(s) and/or provide reference(s) (e.g., link to test method or specification)

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6. Can you recommend any changes to existing and widely used **time to trafficking/surfacing** test(s) for cold recycled pavement materials to make them more rapid, efficient, and/or effective?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #12 Question "6. Can you recommend any changes to existing and widely used time to trafficking/surfacing test(s) for cold recycled pavement materials to make them more rapid, efficient, and/or effective?" is one of the following answers ("Yes")
If yes: Please describe the test(s) and/or provide reference(s) (e.g., link to test method or specification)

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7. Can you recommend any test(s) to estimate **long-term performance** for cold recycled pavement materials that could be used by public agencies or industry?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #13 Question "7. Can you recommend any test(s) to estimate long-term performance for cold recycled pavement materials that could be used by public agencies or industry?" is one of the following answers ("Yes")
If yes: Please describe the test(s) and/or provide reference(s) (e.g., link to test method or specification)
____
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8. Can you recommend any changes to existing and widely used test(s) to estimate **long-term performance** for cold recycled pavement materials to make them more rapid, efficient, and/or effective?
( ) Yes
( ) No

Logic: Hidden by default. Hidden unless: #14 Question "8. Can you recommend any changes to existing and widely used test(s) to estimate long-term performance for cold recycled pavement materials to make them more rapid, efficient, and/or effective?" is one of the following answers ("Yes")
If yes: Please describe the test(s) and/or provide reference(s) (e.g., link to test method or specification)
____
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Methods

1. Please rate the importance of the listed items for test methods used for the following purposes:

	Process Control/Product Acceptance			**Time to Trafficking/Surfacing**			**Long-Term Performance**		
	3 Very important	**2 Somewhat important**	**1 Not important**	**3 Very important**	**2 Somewhat important**	**1 Not important**	**3 Very important**	**2 Somewhat important**	**1 Not important**
Time to available test results	( )	( )	( )	( )	( )	( )	( )	( )	( )
Location of test (in-place, laboratory)	( )	( )	( )	( )	( )	( )	( )	( )	( )
Total test time (preparation, curing, testing, & analysis)	( )	( )	( )	( )	( )	( )	( )	( )	( )
Material condition (loose, molded, in-place)	( )	( )	( )	( )	( )	( )	( )	( )	( )
Equipment required, availability, portability, and cost	( )	( )	( )	( )	( )	( )	( )	( )	( )
Application of test results (mix design, construction PC/QC/QA, structural design validation)	( )	( )	( )	( )	( )	( )	( )	( )	( )
Insensitivity to external conditions that negatively impact accuracy of test result (e.g. ambient temperature, humidity, underlying materials)	( )	( )	( )	( )	( )	( )	( )	( )	( )
Operator/data analysis skill level required	( )	( )	( )	( )	( )	( )	( )	( )	( )
Accuracy, Precision & Bias of the test	( )	( )	( )	( )	( )	( )	( )	( )	( )
Applicability to different materials (CIR, CCPR, FDR)	( )	( )	( )	( )	( )	( )	( )	( )	( )

2. What is your maximum acceptable turnaround time for a test that determines when a cold recycled pavement may be open to traffic?
( ) 0–30 min
( ) 30–60 min
( ) 1–4 hours
( ) 4–12 hours
( ) 1 day
( ) 2 days
( ) 3 days
( ) 7 days
( ) 14 days

3. What is your maximum acceptable turnaround time for a test that determines when a cold recycled pavement may be surfaced?
( ) 0–30 min
( ) 30–60 min
( ) 1–4 hours
( ) 4–12 hours
( ) 1 day
( ) 2 days
( ) 3 days
( ) 7 days
( ) 14 days

4. What is your preference for the location of test(s) to determine time to trafficking/surfacing of cold recycled pavement materials?
( ) Field
( ) Laboratory
( ) No preference

5. Which test(s) does your agency/industry typically use to determine **resistance to deformation**? (select all that apply)
[ ] Modified ball penetration
[ ] Modified falling hammer
[ ] Dynamic cone penetrometer
[ ] Other
[ ] None

Logic: Hidden by default. Hidden unless: #19 Question "5. Which test(s) does your agency/industry typically use to determine resistance to deformation? (select all that apply)" is one of the following answers ("Other")
If other: Please identify test method(s) or idea(s) for test method(s).
____
____
____
____

6. Which test(s) does your agency/industry typically use to determine **raveling resistance**? (select all that apply)
[ ] Raveling test using a stand mixer
[ ] Other
[ ] None

Logic: Hidden by default. Hidden unless: #20 Question "6. Which test(s) does your agency/industry typically use to determine raveling resistance? (select all that apply)" is one of the following answers ("Other")
If other: Please identify test method(s) or idea(s) for test method(s).
____
____
____
____

7. Which test(s) does your agency/industry typically use to determine **density**? (select all that apply)
[ ] Nuclear gauge
[ ] Non-nuclear gauge
[ ] Water balloon
[ ] Sand cone
[ ] Other
[ ] None

Logic: Hidden by default. Hidden unless: #21 Question "7. Which test(s) does your agency/industry typically use to determine density? (select all that apply)" is one of the following answers ("Water balloon")
If other: Please identify test method(s) or idea(s) for test method(s).
____
____
____
____

8. Which test(s) does your agency/industry typically use to determine **stiffness**? (select all that apply)
[ ] Falling weight deflectometer
[ ] Light weight deflectometer
[ ] Seismic pavement analyzer
[ ] Dynamic cone penetration
[ ] Other
[ ] None

Logic: Hidden by default. Hidden unless: #22 Question "8. Which test(s) does your agency/industry typically use to determine stiffness? (select all that apply)" is one of the following answers ("Dynamic cone penetration")
If other: Please identify test method(s) or idea(s) for test method(s).
____
____
____
____

9. Which test(s) does your agency/industry typically use to determine **curing has initiated**? (select all that apply)
[ ] Deflectometer testing
[ ] Stiffness gauge
[ ] Dynamic cone penetration
[ ] Clegg hammer
[ ] Other
[ ] None

Logic: Hidden by default. Hidden unless: #23 Question "9. Which test(s) does your agency/industry typically use to determine curing has initiated? (select all that apply)" is one of the following answers ("Clegg hammer")
If other: Please identify test method(s) or idea(s) for test method(s).
____
____
____
____

10. Which test(s) does your agency/industry typically use to determine **moisture content**? (select all that apply)
[ ] Nuclear gauge
[ ] Speedy
[ ] Microwave oven
[ ] Standard drying oven
[ ] Ohaus moisture analyzer
[ ] Other
[ ] None

Logic: Hidden by default. Hidden unless: #24 Question "9. Which test(s) does your agency/industry typically use to determine moisture content? (select all that apply)" is one of the following answers ("Other")
If other: Please identify test method(s) or idea(s) for test method(s).
____
____
____
____

Future Field Projects

1. Please identify (by agency, contractor, location, recycling process) potential cold recycling project(s) to be constructed in 2018 or 2019 that the project team could sample and test.
____
____
____
____

2. Please provide contact information for key personnel the research team may contact.
Name: ____
Email: ____
Phone number: ____

Thank You!

APPENDIX B

Proposed AASHTO Standard Practice

1 SCOPE

1.1 The document is to provide guidance on how the rapid test methods for asphalt-treated cold recycled pavement can be used to make time-critical decisions regarding opening to traffic and surfacing of the recycled pavements. It also indicates how the variability can be reduced to obtain consistent and accurate test measurements.

1.2 This guide is applicable to asphalt-treated (emulsified or foamed asphalt) cold recycled pavement materials with or without active fillers such as lime and cement. Specifically included are the processes of full-depth reclamation (FDR), cold in-place recycling (CIR), and cold central-plant recycling (CCPR). This guide provides recommended procedures and performance criteria. This document cannot be used for acceptance purposes, but rather used as a guide to develop acceptance performance criteria by agencies.

1.3 This document should also be used in conjunction with current agency testing practices for inspection and testing practices for acceptance of cold recycled materials (for example: in-place density, moisture content, etc.).

1.4 This document may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory regulations prior to use.

2 REFERENCED DOCUMENTS

2.1 *AASHTO Standards and Publications*

- T 256, Pavement Deflection Measurements.
- TP XXX, Evaluating Shear Resistance of Asphalt Treated Recycled Pavements.
- TP XXX, Evaluating Raveling Resistance in Asphalt Treated Recycled Pavements.

2.2 *ASTM Standards*

- D6951/D6951M - 18, Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications.
- E2583, Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD).

2.3 *Others.*

- *NCHRP Research Report 960* (Project 09-62).
- Basic Asphalt Recycling Manual (FHWA-HIF-14-001)

3 TERMINOLOGY

3.1 Full-Depth Reclamation – Full-depth reclamation (FDR) is defined as those processes in which all of the asphalt pavement layers and some portion of the underlying bound and unbound layers are pulverized, stabilized, and compacted in place. This is most commonly performed using hydraulic cement, lime, foamed asphalt, or asphalt emulsion as the primary stabilizing additives.

3.2 Cold In-Place Recycling – Cold in-place recycling (CIR) is defined as a process in which a portion of existing asphalt concrete pavement layers is pulverized, stabilized, and repaved in place. This is most commonly performed using foamed asphalt or emulsified asphalt as the primary stabilizing additive. The pavement may be milled, stabilized, and repaved using the same machine or machine train, or paved from a stabilized, windrowed material using traditional practices.

3.3 Cold Central-Plant Recycling– Cold central-plant recycling (CCPR) is a process in which recycled asphalt concrete pavement is processed and stabilized using foamed asphalt or emulsified asphalt at a plant and then placed using conventional asphalt paving equipment.

3.4 Qualified Technician – An engineering technician who is proficient at performing basic pavement materials tests and may be qualified by meeting some minimum education, experience, or qualifying body (e.g., agency, NICET) standard.

3.5 For other terminology used in the guide specification, refer to the relevant AASHTO or ASTM standards.

4 EQUIPMENT

4.1 Refer to the equipment section in the test methods. For the dynamic cone penetrometer equipment, an 8 kg (17.6 lb) DCP mass shall be used as described in ASTM D6951.

5 SIGNIFICANCE AND USE

5.1 The time required for reaching the desired properties for a new asphalt-treated cold recycled pavement changes depending on many factors. Examples include environmental conditions, emulsion composition and dose, presence of active filler, moisture and density of the compacted material, and the milled surface of the existing pavement. The test methods described in this guide specification assess the raveling potential, penetration resistance, shear resistance, and stiffness of a newly constructed cold recycled pavement and could be used to supplement current agency testing practices for inspection and testing for acceptance of cold recycled materials (for example, in-place density, moisture content).

5.2 This document can be used as guidance to developing draft standard specifications and/or special provisions for conducting the rapid tests listed below for making time-critical decisions regarding opening to traffic and surfacing of the cold recycled pavements.

- Evaluation of Raveling Resistance Using a Short-Pin Raveling Test.
- Evaluation of Shear Resistance Using a Long-Pin Shear Test.

6 EVALUATION OF RAVELING RESISTANCE USING A SHORT-PIN RAVELING TEST

6.1 The raveling test is conducted in accordance with the AASHTO standard TP XXX-XX.

6.2 **Applicability of Test Method**

6.2.1 This test method may be used on any asphalt-treated cold recycled pavements with thickness of 3 in. or more. The recommended values discussed in the guide specification may not be applicable for pavements with a thickness of less than 3 in. The test method could still be used for evaluating the raveling potential of the newly constructed cold recycled pavements at the engineer’s discretion.

6.3 **Standardization and Calibration of Equipment Assembly**

6.3.1 The weight assembly and short-pin fixture must be standardized and calibrated periodically. The torque wrench shall be calibrated following the recommended procedure by the manufacturer. The maximum interval between the consecutive calibrations of the torque wrench shall not exceed 12 months. The calibration frequency of the raveling resistance fixture can be established based on the usage of the fixture by the agency. However, the interval between two consecutive calibrations of the fixture shall not exceed 6 months.

6.3.2 The short-pin fixture, coupler, and torque wrench should be inspected for any defects before each test.

6.4 **Test Frequency and Location**

6.4.1 The raveling resistance test frequency can be similar to that of mat density measurement for recycled asphalt concrete layers set by the agency. Lot and sublot sizes should be established by the agency and used consistently for each of the test methods referenced in this guide specification. The lot and sublot definitions should be established to appropriately balance agency and contractor risk. They could be based on material quantity (volume) or roadway surface area per lift.

6.4.2 Test locations should be randomly selected and within a 4-ft radius of the location of mat density measurements. Three replicate tests should be conducted with a center-to-center spacing between tests of approximately 1 ft. The test location should be undisturbed, free from foreign objects and loose asphalt mixture, and representative of the newly constructed pavement. If loose asphalt particles are present on the surface, it can be swept with a soft brush (horsehair brush) without dislodging the fines on the pavement. Figure 1 illustrates an example of test locations when each of the test methods referenced in this guide specification are used.

6.4.3 The test location shall be 1 ft away from the edge or joint of the pavement. If the agency desires to evaluate the raveling potential of a joint, it could conduct the test within 6 in. from the joint. It is important to recognize that different criteria may be necessary for mat and joint test locations.

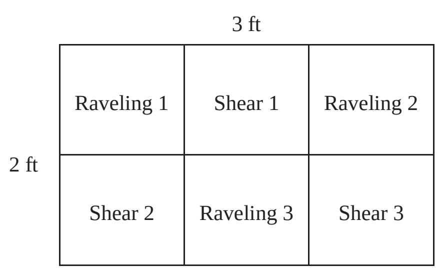

Figure 1. Illustration of rapid test locations.

6.5 **Test Criteria**

6.5.1 If the raveling test data is to be used for acceptance purposes, the agency can establish the minimum number of tests and raveling test criteria similar to that of mat density measurement for asphalt concrete layers as described in Section 6.4.

6.5.2 The agency will establish the criteria for the raveling test parameters (number of blows and torque value) obtained in accordance with the standard, based on the type of the cold recycled pavement and traffic volume. Table 1 shows the preliminary criteria (average of three replicate measurements) established as part of NCHRP Project 09-62 research.

Table 1. Raveling resistance test criteria for cold recycled pavement, average of three replicate measurements.

Recycling Process	Number of Blows	Torque Value, ft-lbs
FDR	7.1	20.2
CIR		
CCPR		

6.5.3 Alternatively, if the agency is to set the time for opening the cold recycled pavement to traffic, it can construct a test strip using representative materials in an environment close to the project location and in compliance with the project specifications. Based on the mat density and/or stiffness, the agency can establish the construction practice (lift thickness, rolling pattern, rerolling, etc.). The raveling resistance test can be conducted on the test strip at multiple intervals (0.5 hour, 1 hour, 2 hour, etc.) to determine when the raveling test criteria is met and use that to establish the time for opening the pavement to traffic as long as similar environmental conditions exist. A new test location shall be established for each time interval.

7 EVALUATION OF SHEAR RESISTANCE USING A LONG-PIN SHEAR TEST

7.1 The shear resistance test is conducted in accordance with the AASHTO standard TP XXX-XX.

7.2 **Applicability of Test Method**

7.2.1 This test method may be used on any asphalt-treated cold recycled pavements with thickness of 3 in. or more. The recommended values discussed in the guide specification may not be applicable for pavements with a thickness of less than 3 in. The test method could still be used for evaluating the shear resistance of the newly constructed cold recycled pavements at the engineer's discretion.

7.3 **Standardization and Calibration of Equipment Assembly**

7.3.1 The weight assembly and long-pin fixture must be standardized and calibrated periodically. The torque wrench shall be calibrated following the recommended procedure by the manufacturer. The maximum interval between the consecutive calibrations of the torque wrench shall not exceed 12 months. The calibration frequency of the fixture for the shear resistance test can be established based on the usage of the fixture by the agency. However, the interval between two consecutive calibrations of the fixture shall not exceed 6 months.

7.3.2 The long-pin fixture, coupler, and torque wrench should be inspected for any defects before each test.

7.4 **Test Frequency and Location**

7.4.1 The shear resistance test frequency can be similar to that of mat density measurement for recycled asphalt concrete layers set by the agency. Lot and sublot sizes should be established by the agency and used consistently for each of the test methods referenced in this guide specification. The lot and sublot definitions should be established to appropriately balance agency and contractor risk. They could be based on material quantity (volume) or roadway surface area per lift.

7.4.2 Test locations should be randomly selected and within a 4-ft radius of the location of mat density measurements. Three replicate tests should be conducted with a center-to-center spacing between tests of approximately 1 ft. The test location should be undisturbed; free from foreign objects and loose asphalt mixture; and representative of the newly constructed pavement. If loose asphalt particles are present on the surface, it can be swept with a soft brush (horsehair brush) without dislodging the fines on the pavement.

7.4.3 The test location shall be 1 ft away from the edge or joint of the pavement. If the agency desires to evaluate the shear resistance of the mat closer to a joint, it could conduct the test within 6 in. from the joint. It is important to recognize the different criteria may be necessary for mat and joint test locations. Figure 1 illustrates an example of test locations when each of the test methods referenced in this guide specification are used.

7.5 **Test Criteria**

7.5.1 If the data from the shear resistance test is to be used for acceptance purposes, the agency can establish the minimum number of tests and shear resistance test criteria similar to that of mat density measurement for asphalt concrete layer as described in Section 7.4.

7.5.2 The agency can establish the criteria for one or more shear resistance test parameters (number of blows and peak torque) obtained in accordance with the standard, based on the type of the cold recycled pavement and traffic volume. Table 2 shows the preliminary criteria (average of three replicate measurements) established as part of NCHRP Project 09-62 research.

Table 2. Shear resistance test criteria for cold recycled pavement, average of three measurements.

Recycling Process	Number of Blows	Torque Value, ft-lbs
FDR	19.3	62.9
CIR		
CCPR		

7.5.3 Alternatively, if the agency is to set the time for surfacing the cold recycled pavement, it can construct a test strip using representative materials in an environment close to the project location and in compliance with the project specifications. Based on the mat density and/or stiffness, the agency can establish the construction practice (lift thickness, rolling pattern, rerolling, etc.). The shear resistance test can be conducted on the test strip at multiple intervals (0.5 hour, 1 hour, 2 hours, 1 hour, 2 hours, etc.) to determine when the shear test criteria are met and use that to establish the time for surfacing the cold recycled pavement as long as similar environmental conditions exists. A new test location shall be established for each time interval.

8 INSPECTION AND TESTING

8.1 All the test methods discussed in this guide specification shall be conducted by technicians experienced with testing pavements and pavement materials.

8.2 The engineer shall approve the inspection and testing plan for the project prior to construction. It can be similar to the specification requirements for mat density measurements for recycled asphalt concrete layers set by the agency.

APPENDIX C

Proposed AASHTO Standard Method of Test for Evaluating the Shear Resistance of Asphalt-Treated Recycled Pavement Applications Using a Long-Pin Fixture

Standard Method of Test for

Evaluating Shear Resistance of Asphalt-Treated Recycled Pavements Applications Using a Long-Pin Fixture

AASHTO Designation: TP XXX-XX
ASTM Designation: E XXXX-XX

AASHTO

1. SCOPE

1.1. This standard covers the determination of shear resistance of asphalt-treated cold recycled pavements through the number of blows and shear torque values with a long-pin shear test. In this test method, the long-pin shear fixture is driven into a pavement using a dynamic cone penetrometer (DCP) upper assembly (an 8-kg [17.6-lb] hammer) per ASTM D 6951 - 18, and the number of blows required to drive the fixture into the pavement is recorded. The DCP upper assembly is removed and the peak torque observed while rotating a handheld torque wrench connected to the long-pin shear fixture while the number of blows is recorded. These measurements can be used to make time-critical decisions regarding opening to traffic and surfacing of the recycled pavements.

1.2. This test method is applicable for number of blows and torque measurements conducted on asphalt-treated cold pavement recycling techniques, including cold in-place recycling (CIR), cold central-plant recycling (CCPR), and full-depth reclamation (FDR). The recycled pavements may include emulsified or foamed asphalt with or without active fillers such as cement, lime, and fly ash.

1.3. The values stated in SI units are to be regarded as the standard. The values in parentheses are provided for information purposes only.

1.4. This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory regulations prior to use.

2. REFERENCED DOCUMENTS

2.1. ASTM Standards:

- D 6951/D 6951M - 18, Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications
- C1067 - 12 Standard Practice for Conducting a Ruggedness Evaluation or Screening Program for Test Methods for Construction Materials
- C670 - 15 Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
- C802 - 14 Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials

3. TERMINOLOGY

3.1. Definitions:

- *Shear resistance* – resistance of a recycled pavement to shear stress induced by rotation of a long-pin fixture driven into the pavement and rotated with a torque wrench

4. SUMMARY OF METHOD

4.1. The long-pin shear fixture is driven into compacted asphalt-treated cold recycled pavement by lifting the sliding hammer of the upper assembly of a DCP to the handle and then dropping it. The total number of blows to drive the fixture into the compacted recycled pavement is counted and recorded. The long-pin fixture, embedded in the compacted recycled pavement, is then twisted using a digital handheld wrench. The peak torque in a clockwise rotation is recorded in ft-lb, or any other unit of measure as appropriate. Three replicate tests are conducted on different locations of the same pavement of interest.

5. SIGNIFICANCE AND USE

5.1. Number of blows counted from dropping the hammer and torque measured using handheld wrench provide information that can be used to assess mixture shear resistance and make time-critical decisions regarding opening to traffic and surfacing of the recycled pavements.

6. APPARATUS

6.1. Handheld digital torque wrench: a torque wrench at least 305-mm [12-in.] in length with a digital display that can measure torque over a range of 15–300 ft-lbs with accuracy of ±1.0% to which a 19–mm [0.75-in.] socket may be attached.

6.2. The long-pin shear fixture is shown schematically in Fig. 1. It consists of a steel base plate with circular geometry: 127-mm [5.0-in.] diameter), four 10.3-mm [0.406-in.] diameter and 80-mm [3.15-in.] long pins, one 12.7-mm [0.50-in.] diameter and 75-mm [2.95-in.] pin in the center of the steel base plate, one 25.4-mm [1.00-in.] diameter upper center shaft with a hexagonal milled end.

6.3. Test template for measurement shown in Fig. 2 and illustrated with the other equipment.

6.4. The hammer used in this test method shall conform to the general requirements described in ASTM D 6951/D 6951M - 18. An 8-kg [17.6-lb] DCP hammer (upper assembly) is shown schematically in Fig. 3. This device is typically constructed of stainless steel conforming to ASTM D 6951/D6951M - 18.

- Hammer weight measurement of 8.0 kg [17.6-lb]; tolerance is 0.01 kg [0.02-lb].
- Drop of hammer measurement of 575 mm [22.6 in.]; tolerance is 1.0 mm [0.04 in.].
- Hammer weight measurement of 8.0 kg [17.6 lb]; tolerance is 0.01 kg [0.02 lb].
- Drop of hammer measurement of 575 mm [22.6 in.]; tolerance is 1.0 mm [0.04 in.].

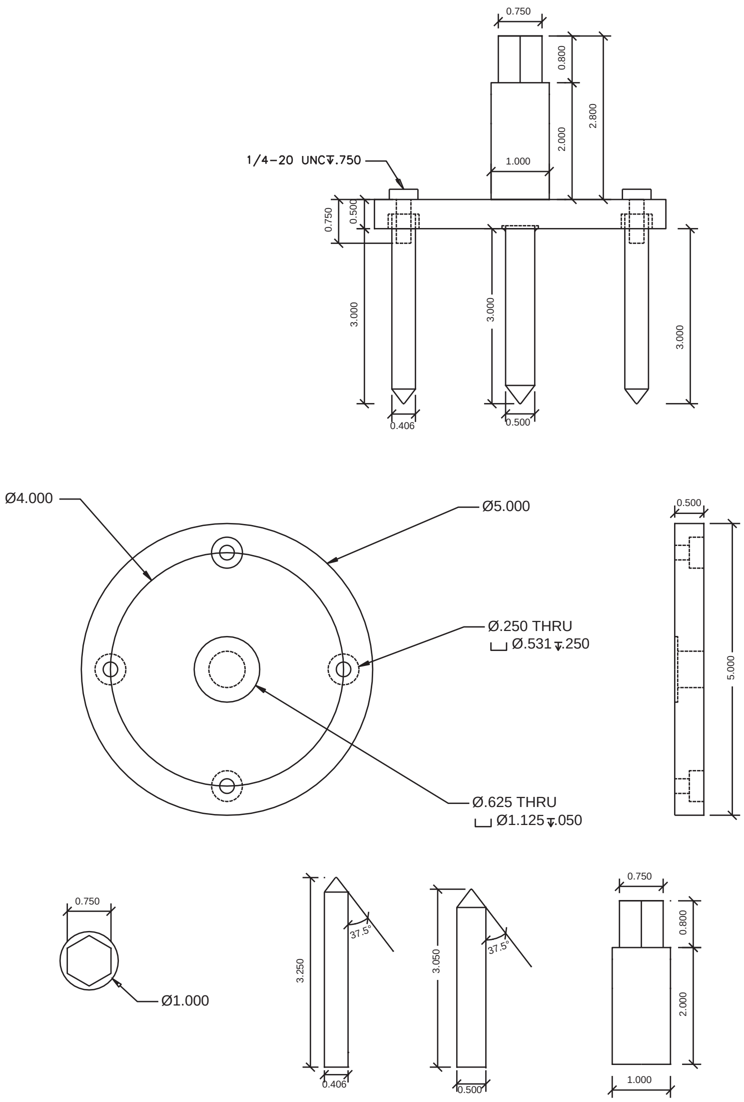

FIG. 1 Schematics of the long-pin shear fixture.

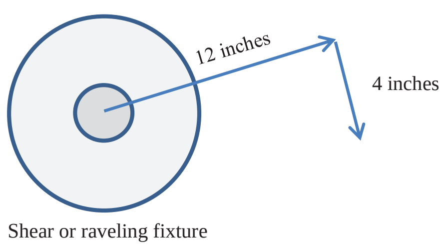

FIG 2. Template used for torque measurement.

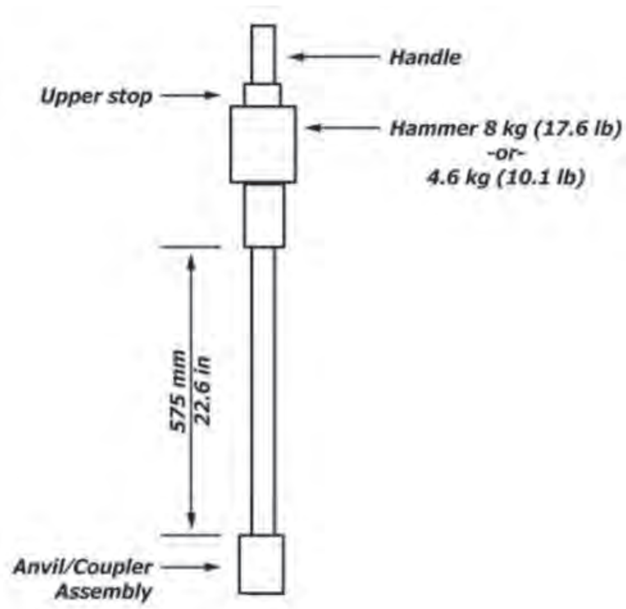

FIG. 3 Schematic of upper hammer assembly.

7. HAZARDS

7.1. Injury can occur while operating DCP upper assembly (hammer) due to lifting and dropping the falling weight. Thus, care must be taken to avoid injury.

8. PROCEDURE

8.1. Place the long-pin fixture on the recycled pavement surface. To ensure uniform contact and load distribution of the steel base plate, the test surface should be smooth to the extent possible, and free of any loose material.

8.2. The DCP hammer (upper assembly) is then placed on top of the test fixture. The hammer-fixture system should be leveled using a bubble level resting on the base plate prior to testing.

8.3. The DCP hammer is lifted to the standard drop height and then released to deliver the force that drives the fixture into the recycled pavement. During the operation, the hammer weight guide shaft should be held firmly without applying any downward pressure.

8.4. Repeat lifting and releasing the weight until the long pins of the fixture are fully embedded into the recycled pavement and the base plate is resting on the pavement surface. The fixture handle should be plumb with respect to the pavement surface; change the test location if it is not plumb.

8.5. Record the number of blows required to drive the test fixture until the bottom of the steel plate is uniformly in contact with the recycled pavement surface. Remove the DCP upper assembly.

8.6. Attach a digital handheld torque wrench device to the upper shaft of the fixture using a 19-mm (0.75-in.) socket.

8.7. On the pavement surface, draw a 12-in. line extending from the center of the base plate. Next, draw a 4-in. line perpendicular to the 12-in. line at the end furthest from the base plate.

8.8. Rotate the torque wrench clockwise through the 4-in. [304.8-mm] line at a constant rate over a 4 second period.

8.9. Record the maximum torque observed as expressed in ft-lbs.

8.10. Repeat steps 8.1–8.9 at three (3) replicate locations with a center-to-center spacing of approximately 1 ft and far enough apart from prior measurements that each measurement is not influenced by the disturbed recycled pavement surface. An example of test locations for shear and raveling resistance is shown in Figure 4.

3 ft

2 ft	Raveling 1	Shear 1	Raveling 2
	Shear 2	Raveling 3	Shear 3

FIG. 4 Illustration of rapid test locations.

9. Reporting

9.1. Report the following information:

9.1.1. Test date, test location, lane, weather, recycling process, recycling agent, recycling agent content, active filler, active filler content, lane, offset, test number, number of blows, torque, nuclear density gauge reading.

9.2. Report the individual number of blows as whole numbers and torque measurements to 0.1 ft-lbs. Report the average of three number of blows measurements and three torque measurements to the nearest 0.1 blows or 0.1 ft-lbs, respectively.

10. PRECISION AND BIAS

10.1. A ruggedness evaluation was performed for this test method in accordance with ASTM C1067 - 12, Standard Practice for Conducting a Ruggedness Evaluation or Screening Program for Test Methods for Construction Materials. The tolerances on the long-pin shear fixture in Section 6. Apparatus was determined by the ruggedness study. A partial interlaboratory study was conducted in accordance with ASTM C802, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials. However, only three laboratories participated. This was because the test is new, and commercially available equipment was not available. The ILS was conducted in the field, rather than in a laboratory, as prescribed in ASTM C802 - 14. Thus, preliminary single-operator and multi-laboratory precision that can be found in NCHRP Research Report 960 are reported, which should be replaced with an ILS when commercially available equipment is available.

10.2. *Number of Blows*

Single-Operator Precision—The single-operator standard deviation was found to be 1.6 blows. Therefore, results of two properly conducted tests by the same operator on the same material are not expected to differ by more than 5 blows.[A]

Multi-laboratory Precision—The multi-laboratory standard deviation was found to be 2.6 blows. Therefore, results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ by more than 7 blows.[A]

[A]These numbers represent the difference limits (d2s) as described in ASTM Practice C670.

Note 1—These precision statements are based on an interlaboratory study that involved three laboratories, six materials, and three replicate tests per operator, with number of blows values ranging from nine to 54.

10.3. *Torque Value*

Single-Operator Precision—The single-operator standard deviation was found to be 8.1 ft-lbf. Therefore, results of two properly conducted tests by the same operator on the same material are not expected to differ by more than 22.6 ft-lbf.[A]

Multi-laboratory Precision—The multi-laboratory standard deviation was found to be 12.7 ft-lbf. Therefore, results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ by more than 35.7 ft-lbf.[A]

[A]These numbers represent the difference limits (d2s) as described in ASTM Practice C670.

Note 2—These precision statements are based on an interlaboratory study that involved three laboratories, six materials, and three replicate tests per operator, with torque values ranging from 39.5 ft-lbf to 165.6 ft-lbf.

10.4. *Bias*—because there is no accepted reference material suitable for determining the bias in this test method, no statement on bias is made.

11. KEYWORDS

11.1. Shear resistance; asphalt-treated recycled pavement, long-pin shear fixture, number of blows; torque; dynamic cone penetrometer (DCP); cold in-place recycling (CIR); cold central-plant recycling (CCPR); full-depth reclamation (FDR); sliding hammer; driving force; destructive testing; recycled pavement testing; recycled pavement layer shear resistance.

APPENDIX D

Proposed AASHTO Standard Method of Test for Evaluating the Raveling Resistance of Asphalt-Treated Recycled Pavement Applications Using a Short-Pin Fixture

Standard Method of Test for

Evaluating Raveling in Asphalt-Treated Recycled Pavement Applications Using a Short-Pin Fixture

AASHTO Designation: TP XXX-XX
ASTM Designation: E XXXX-XX

AASHTO

1. SCOPE

1.1. This standard covers the determination of raveling resistance of asphalt-treated cold recycled pavements through the number of blows and raveling torque values with a short-pin raveling test. In this test method, the short-pin shear fixture is driven into a pavement using a dynamic cone penetrometer (DCP) upper assembly (an 8-kg [17.6-lb] hammer) per ASTM D 6951 - 18, and the number of blows required to drive the fixture into the pavement is recorded. The DCP upper assembly is removed and the peak torque observed while rotating a handheld torque wrench connected to the short-pin raveling fixture while the number of blows is recorded. These measurements can be used to make time-critical decisions regarding opening to traffic and surfacing of the recycled pavements.

1.2. This test method is applicable for number of blows and torque measurements conducted on asphalt-treated cold pavement recycling techniques, including cold in-place recycling (CIR), cold central-plant recycling (CCPR), and full-depth reclamation (FDR). The recycled pavements may include emulsified or foamed asphalt with or without active fillers such as cement, lime, and fly ash.

1.3. The values stated in SI units are to be regarded as the standard. The values in parentheses are provided for information purposes only.

1.4. This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory regulations prior to use.

2. REFERENCED DOCUMENTS

2.1. ASTM Standards:
- D 6951/D 6951M - 18, Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications
- C1067 - 12, Standard Practice for Conducting a Ruggedness Evaluation or Screening Program for Test Methods for Construction Materials
- C670 - 15, Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
- C802 - 14, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials

3. TERMINOLOGY

3.1. Definitions:
- *Raveling resistance – resistance of a recycled pavement to raveling stress induced by rotation of a short-pin fixture driven into the pavement and rotated with a torque wrench*

4. SUMMARY OF METHOD

4.1. The short-pin field shear fixture is driven into compacted asphalt-treated cold recycled pavement by lifting the sliding hammer of the upper assembly of a DCP to the handle and then dropping it. The total number of blows to drive the fixture into the compacted recycled pavement is counted and recorded. The short-pin fixture, embedded in the compacted recycled pavement, is then twisted using a digital handheld wrench. The peak torque in a clockwise rotation is recorded in ft-lb, or any other unit of measure as appropriate. Three replicate tests are conducted on different locations of the same pavement of interest.

5. SIGNIFICANCE AND USE

5.1. Number of blows counted from dropping the hammer and torque measured using handheld wrench provide information that can be used to assess mixture raveling resistance and make time-critical decisions regarding opening to traffic and surfacing of the recycled pavements.

6. APPARATUS

6.1. Handheld digital torque wrench: a torque wrench at least 305-mm [12-in.] in length with a digital display that can measure torque over a range of 15–300 ft-lbs with accuracy of ±1.0% to which a 19-mm [0.75-in.] socket may be attached.

6.2. The short-pin raveling fixture is shown schematically in Fig. 1. It consists of a steel base plate with circular geometry: 127-mm [5.0-in.] diameter), four 10.3-mm [0.406-in.] diameter and 25.4-mm [1.0-in.] long pins, one 12.7-mm [0.50-in.] diameter and 75-mm [2.95-in.] pin in the center of the steel base plate, one 25.4-mm [1.00-in.] diameter upper center shaft with a hexagonal milled end.

6.3. 10-lb plate: a 4.5-kg [10-lb] barbell plate with an external diameter not exceeding 254 mm [10.00 in.] – made of a solid cast iron with machined hole (diameter > 19 mm [0.75 in.]) and a durable finishing.

6.4. Test template for measurement shown in Fig. 2 and illustrated with the other equipment.

6.5. The hammer used in this test method shall conform to the general requirements described in ASTM D 6951/D 6951M - 18. An 8-kg [17.6-lb] DCP hammer (upper assembly) is shown schematically in Fig. 2. This device is typically constructed of stainless steel conforming to ASTM D 6951/D6951M - 18.
- Hammer weight measurement of 8.0 kg [17.6 lb]; tolerance is 0.01 kg [0.02 lb].
- Drop of hammer measurement of 575 mm [22.6 in.]; tolerance is 1.0 mm [0.04 in.].

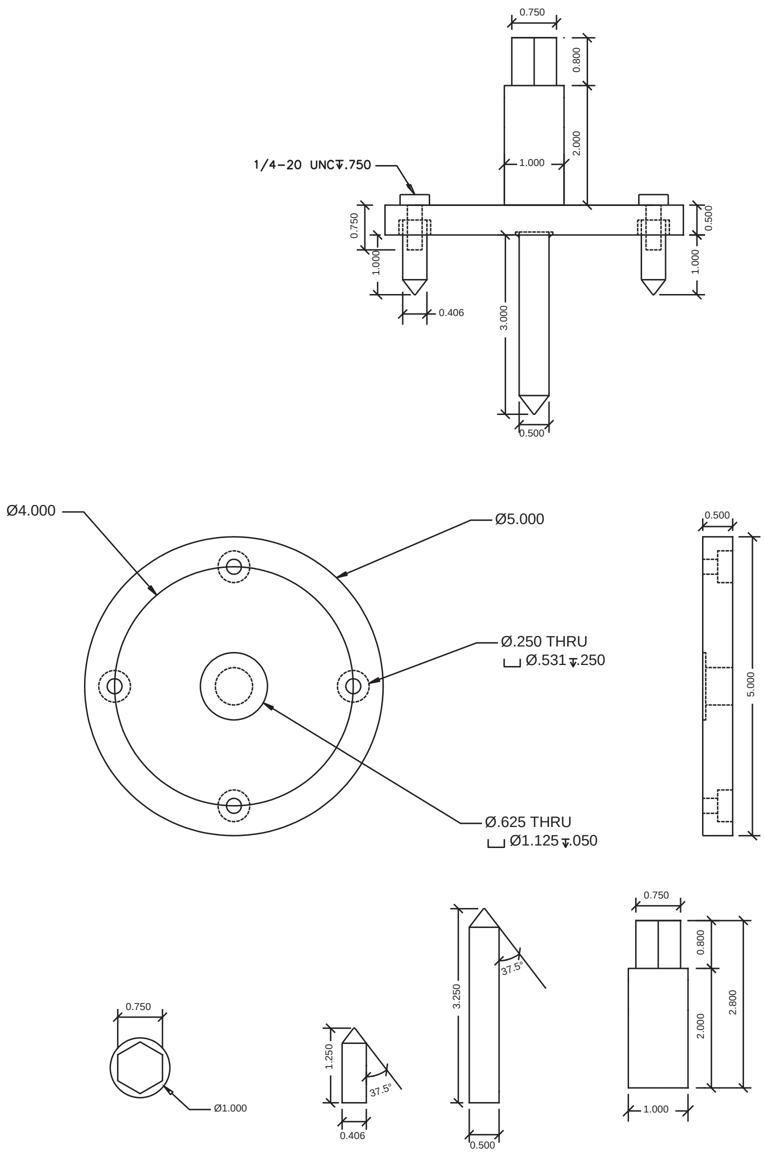

Fig. 1 Schematics of short-pin raveling fixture.

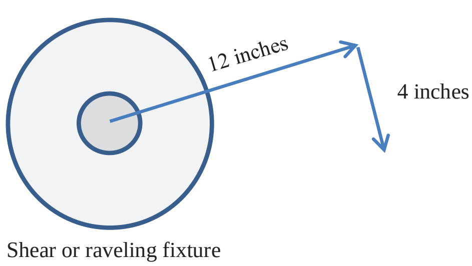

Fig 2. Template used for torque measurement.

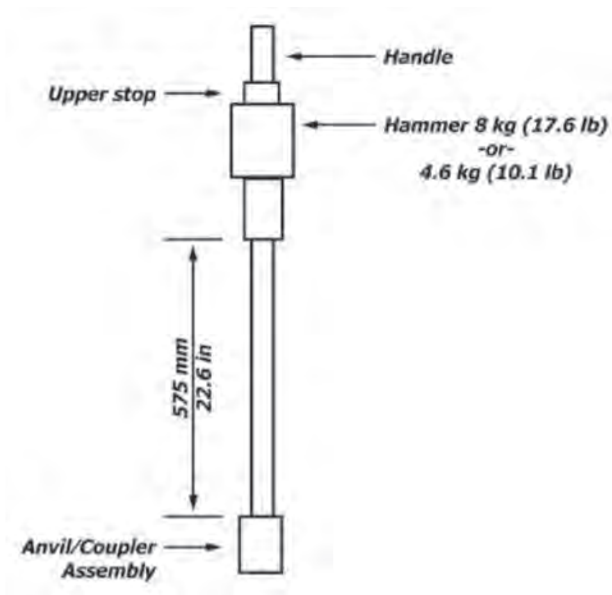

Fig. 3 Schematic of upper hammer assembly.

7. HAZARDS

7.1. Injury can occur while operating DCP upper assembly (hammer) due to lifting and dropping the falling weight. Thus, care must be taken to avoid injury.

8. PROCEDURE

8.1. Place the short-pin fixture on the recycled pavement surface. To ensure uniform contact and load distribution of the steel base plate, the test surface should be smooth to the extent possible and free of any loose material.

8.2. The DCP hammer (upper assembly) is then placed on top of the test fixture. The hammer-fixture system should be leveled using a bubble level resting on the base plate prior to testing.

8.3. The DCP hammer is lifted to the standard drop height and then released to deliver the force that drives the fixture into the recycled pavement. During the operation, the hammer weight guide shaft should be held firmly without applying any downward pressure.

8.4. Repeat lifting and releasing the weight until the long pins of the fixture are fully embedded into the recycled pavement and the base plate is resting on the pavement surface. The fixture handle should be plumb with respect to the pavement surface; change the test location if it is not plumb.

8.5. Record the number of blows required to drive the test fixture until the bottom of the steel plate is uniformly in contact with the recycled pavement surface.

8.6. Remove the DCP upper assembly and place two 4.53-kg (10-lb) plates on top of the short-pin fixture and over the 19-mm (0.75-in.) upper shaft to avoid any possible uplift of the fixture.

8.7. Attach a digital handheld torque wrench device to the upper shaft of the fixture using a 19-mm (0.75-in.) socket.

8.8. On the pavement surface, draw a 12-in. line extending from the center of the base plate. Next, draw a 4-in. line perpendicular to the 12-in. line at the end furthest from the base plate.

8.9. Rotate the torque wrench clockwise through the 4-in. [304.8-mm] line at a constant rate over a 4-second period.

8.10. Record the maximum torque observed as expressed in ft-lbs.

8.11. Repeat steps 8.1–8.10 at three replicate locations with a center-to-center spacing of approximately 1 ft and far enough apart from prior measurements that each measurement is not influenced by the disturbed recycled pavement surface. An example of test locations for shear and raveling resistance is shown in Fig. 4.

3 ft

2 ft

Raveling 1	Shear 1	Raveling 2
Shear 2	Raveling 3	Shear 3

Fig. 4 Illustration of rapid test locations.

9. Reporting

9.1. Report the following information:

9.1.1. Test date, test location, lane, weather, recycling process, recycling agent, recycling agent content, active filler, active filler content, lane, offset, test number, number of blows, torque, nuclear density gauge reading.

9.2. Report the individual number of blows as whole numbers and torque measurements to 0.1 ft-lbs. Report the average of three number of blows measurements and three torque measurements to the nearest 0.1 blows or 0.1 ft-lbs, respectively.

10. PRECISION AND BIAS

10.1. A ruggedness evaluation was performed for this test method in accordance with ASTM C1067 - 12, Standard Practice for Conducting a Ruggedness Evaluation or Screening Program for Test Methods for Construction Materials. The tolerances on the long-pin shear fixture in Section 6. Apparatus was determined by the ruggedness study. A partial interlaboratory study was conducted in accordance with ASTM C802, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials. However, only three laboratories participated. This was because the test is new, and commercially available equipment was not available. The ILS was conducted in the field, rather than in a laboratory, as prescribed in ASTM C802 - 14. Thus, preliminary single-operator and multi-laboratory precision that can be found in NCHRP Research Report 960 are reported, which should be replaced with an ILS when commercially available equipment is available.

10.2. *Number of Blows*

Single-Operator Precision—The single-operator coefficient of variation was found to be 8 percent. Therefore, results of two properly conducted tests by the same operator on the same material are not expected to differ from each other by more than 22.5 percent[A] of their average.

Multi-Laboratory Precision—The multi-laboratory coefficient of variation was found to be 14.2 percent. Therefore, results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ from each other by more than 39.6 percent[A] of their average.

[A]These numbers represent the difference limits in percent (d2s%) as described in Practice C670.

Note 1—These precision statements are based on an interlaboratory study that involved three laboratories, six materials, and three replicate tests per operator, with number of blows ranging from four to 19.

10.3. *Torque Value*

Single-Operator Precision— The single-operator coefficient of variation was found to be 11.1 percent. Therefore, results of two properly conducted tests by the same operator on the same material are not expected to differ from each other by more than 31.1 percent[A] of their average.

Multi-Laboratory Precision— The multi-laboratory coefficient of variation was found to be 13.8 percent. Therefore, results of two properly conducted tests by two different laboratories on specimens of the same material are not expected to differ from each other by more than 38.7 percent[A] of their average.

[A]These numbers represent the difference limits in percent (d2s%) as described in ASTM C670.

Note 2— These precision statements are based on an interlaboratory study that involved three laboratories, six materials, and three replicate tests per operator, with torque values ranging from 15.2 ft-lbf to 50.8 ft-lbf.

10.4. *Bias*—Because there is no accepted reference material suitable for determining the bias in this test method, no statement on bias is made.

11. KEYWORDS

11.1. Raveling resistance; asphalt-treated recycled pavement, short-pin raveling fixture, number of blows; torque; dynamic cone penetrometer (DCP); cold in-place recycling (CIR); cold central-plant recycling (CCPR); full-depth reclamation (FDR); sliding hammer; driving force; destructive testing; recycled pavement testing; recycled pavement layer raveling resistance.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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