2019

Studies of sustainable pavement maintenance: Waste management and innovative preservation materials

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Studies of sustainable pavement maintenance: Waste management and innovative preservation materials

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Civil Engineering (Civil Engineering Materials)

Program of Study Committee:
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

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ACKNOWLEDGMENTS

Foremost, I would like to thank my major professors, Drs. Halil Ceylan and Bora Cetin, for their patience, motivation, enthusiasm, encouragement and immense help throughout my studies. Their support helped me greatly to finish my research topic, and their knowledge and work ethics also set a good example to me and will benefit my future career.

I would like to thank my committee members, Drs. Sunghwan Kim, Robert Horton, and Charles T. Jahren, for their guidance and support throughout the course of this research. It a great pleasure for me to present my research dissertation to them for reviewing and attending my final oral defense. I also have special thanks to Drs. Kasthurirangan Gopalakrishnan, Sunghwan Kim and Yang Zhang for their extra significant aid to my research.

In addition, I would also like to thank graduate students Yizhou Li and Masrur Mahedi in Civil, Construction and Environmental Engineering, and graduate student Chenyi Luo in Agronomy, Iowa State University. The good corporation with them is another important contribution for this research.

Finally, I am also grateful to Iowa Department of Transportation (IA-DOT), Minnesota Department of Transportation (MN-DOT) and Recycled Materials Research Center (RMRC), Clinton County Engineers Office and Bargen, Inc. for their support and assistance in this study.

ABSTRACT

Sustainability is a concept focusing on environmental, social, and economic factors in decision-making processes. In recent years, more and more state highway agencies (SHAs) are embracing principles of sustainability in pavement design, construction, use, maintenance, and material production. A sustainable pavement system would not only meet the basic needs of traveling, but would remain effective and environmentally friendly during highway construction, service, and preservation.

Efficient collection of pavement cracking data is essential to pavement sustainability because it aids in determining selection of optimum pavement preservation technology. While there are multiple methods for identification of pavement cracking data, some are not generally compatible, possibly complicating the sharing of cracking-data information among agencies and vendors and reporting such data to the US Federal Highway Administration (FHWA) for establishing national, state, and local performance goals. In this study, comprehensive review of existing federal and SHAs' cracking data collection practices were conducted, including how data should be collected and classified. The study's findings are summarized in the context of developing standard definitions for comparable pavement cracking data.

To seek sustainability goals for concrete pavements, a concrete slurry waste, generated from common resurfacing rehabilitation activities known as diamond grinding, was evaluated. During grinding operations, a high pH slurry comprised of removed concrete and cooling water for blades, designated as concrete grinding residue (CGR), may be generated and discharged along the roadside, resulting in potentially critical environmental issues. To understand the effects of CGR on soil chemical properties, a field site was built for applying four different CGR rates: 2.24, 4.48, 6.72 and 8.96 kg/m^2 (0, 10, 20, and 40 ton/acre), and measurements of soil pH,

electrical conductivity (EC), alkalinity, cation exchange capacity (CEC), exchangeable sodium percentage (ESP), and percent base saturation (PBS) at the site were determined and statistically analyzed both before and after CGR application. The results indicated that CGR significantly impacted the chemical properties of soil, and this impact became greater with increase in CGR application rates. The results indicated that, while CGR can be discharged along roadsides at up to 8.96 kg/m^2 (40 ton/acre), the CGR's unreacted cement and high pH have potential for being reused to stabilize roadbed soil. To investigate reuse of CGR, this study mixed 10%, 20%, 30%, and 40% samples of CGR by weight with soil to stabilize two types of Iowa soils. Strength and penetration tests for CGR-treated soil showed that a 20% CGR addition was the optimum content in that it resulted in the greatest strength, and other laboratory testing results revealed that CGR treatment could reduce the maximum values of dry density and plasticity.

Asphalt pavements can also be made sustainable by using innovative preservation methods. Fog seal is a commonly used pavement preservation technology that involves spraying petroleum-based emulsion on a road surface to maintain skid resistance, prevent oxidation and reduce water infiltration. In recent years, bio-based fog sealants have received increased attention in the United States, and RePLAY, a soy-based sealant derived from an agricultural agent, has been successfully used in some areas. To evaluate the effectiveness of RePLAY as an alternative for preserving Iowa roads, a 5.3 km (3.3 mile) long asphalt pavement section was selected for application of RePLAY followed by a two-year investigation of the pavement's marking retroreflectivity, surface friction, water absorption, and air permeability. An untreated section and three treated sections using spray rates of 0.091, 0.113, and 0.136 l/m^2 (0.020, 0.025, and 0.030 gal/yd^2) were set up for this purpose, and field results showed that retroreflectivity and skid resistance decreases due to application of bio-sealant were restored to their original levels within two weeks and eleven months, respectively. The laboratory results revealed that the bio-sealant-treated specimens with the highest application rate exhibited the lowest water absorption and air permeability.

CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

Pavement systems represent one of the main infrastructure-related assets in the United States, as there are more than 6.4 million kilometers (4 million miles) of roads in the US. To meet human needs, billions of dollars are spent annually on pavement network construction and preservation. The concept of sustainability was proposed in 1972, defining a compilation of social, environmental and economic factors in the decision-making process (Babashamsi et al., 2016). In recent years, the Federal Highway Administration (FHWA) and state highway agencies (SHAs) have expended considerable effort to embrace principles of sustainability, including material production, design, construction, use, maintenance and end of life (FHWA, 2014), related to pavement life-cycle phases). A sustainable pavement would not only meet basic human needs, but would also use resources effectively while restoring and preserving the surrounding environment (FHWA, 2014).

Pavements will deteriorate over time, and to determine pavement condition for proper selection of appropriate maintenance and preservation technologies, effective pavement cracking data collection practices becomes an important point of making pavement systems sustainable. Pavement condition determines what kind of maintenance practice should be used, and cracking data collection and while sharing among agencies and vendors and reporting it to FHWA can establish national, state, and local performance goals, the multiple methods for cracking identification used among various SHAs are not always compatible, leading to difficulties in managing pavement systems and improving sustainability. Therefore, a comprehensive review of existing federal and SHA cracking data collection practices is needed, including information about how data are collected and classified.

To maintain serviceability and extend pavement longevity, to achieve the goal of sustainable pavement, appropriate maintenance and preservation technologies must be executed at low cost and with low environmental impact. Different pavement surface types require different maintenance and preservation technologies. Portland cement concrete (PCC) pavement experiences multiple types of deterioration such as cracking, joint deficiencies, surface defects, and miscellaneous distresses (Miller and Bellinger, 2014). Diamond grinding is a widely used rehabilitation technique to remove irregularities of PCC surfaces and produce a smooth surface with enhanced texture, skid resistance, and less road noise. This operation generally is performed using a truck equipped with grinding heads at ground level to saw a thin layer of concrete and grind it into fine particles, mix it with cooling water, then generate a slurry byproduct known as concrete grinding residue (CGR). Since CGR in many states has no detailed guidelines for disposal, it is generally spread along the roadside. Because of its high pH and alkalinity, such spreading of CGR may result in critical environmental issues (Mamo et al., 2015; DeSutter et al., 2011). To manage CGR properly, relevant investigations about its effects on soil properties should be performed.

Asphalt pavement quality is susceptible to air in the environment because it can become brittle over time due to oxidation. Typical preservation treatments for asphalt pavement include fog seal, slurry seal, chip seal, and overlay, and each can be used for various purposes. Fog seal is a low-cost application using petroleum or coal tar-based asphalt emulsion to improve skid resistance, prevent oxidation, and seal against water infiltration. Although petroleum or coal tar-based agents have been successfully used as fog sealants to maintain road surfaces for many years, their main drawbacks, including long curing time and risks to environment and human health, cannot be ignored (Kim and Im, 2012; Ghosh et al., 2016). To make asphalt pavement preservation sustainable, a bio-based sealant called RePLAY, derived from agricultural oil, has attracted much attention from SHAs and been used successfully in many areas. The application of this bio-based product is not only cost-effective compared with that of traditional fog sealants, but also can permit the road to be open to traffic within 30 minutes. Encouraged by such anecdotal evidences, the Iowa Department of Transportation (DOT) has become interested in evaluating RePLAY as a fog seal material for Iowa mainline, shoulders, and rumble strips.

1.2 Research Objective

The primary purposes of this study are:

- To conduct a comprehensive review on existing pavement cracking data collection practices among US federal and state agencies.
- To investigate the effects of CGR on soil chemical properties.
- To review current CGR management practices throughout the United States.
- To evaluate reuse of CGR for soil stabilization purposes.
- To evaluate the effectiveness of using RePLAY agricultural oil agent as a fog sealant for preservation of asphalt pavement in Iowa.

This study is focused on improvement of pavement sustainability through understanding differences among multiple cracking identification methods and evaluating cost-effective and environmentally friendly pavement maintenance and preservation methods. Improved sustainability in pavement life cycles not only could provide well-maintained, safe, and durable pavement at lower cost, but also could minimize risks to the surrounding ecosystem.

1.3 Research Significance

The significance of this research is highlighted as follows:

- Summarize national guidelines and practices of all 50 states with respect to pavement cracking data collection and reporting and compare the national guidelines with state practices. This will provide a very useful reference for states wishing to develop or revise their guidelines for cracking data identification.
- Address the relationship between CGR rates and soil chemical properties and provide guidelines related to spreading of CGR along roadside.
- Provide a detailed review of existing technical guidelines and state management practices related to CGR. This will provide a very useful reference to states wishing to develop or revise their specifications with respect to CGR management.
- Exhibit the potential of CGR recycling for soil stabilization purposes and provide laboratory evidence about how CGR can improve soil engineering properties and recommend an optimum CGR application rate to the studied soils.
- Demonstrate the construction process of bio-fog sealant installation on Iowa pavement surfaces. Present a two-year evaluation of both field and laboratory performance of a RePLAY treated road.

1.4 Dissertation Organization

This dissertation, written in the alternative journal paper format, is organized into seven chapters.

- Chapter 1 presents background, motivation, objectives, and general approach of this study.

- Chapter 2 provides a review of pavement cracking identification practices, then summarizes a literature review of CGR, including CGR properties, its effects on soil and vegetation properties, typical management practices, and reuse and recycling practices for different applications.
- Chapter 3 presents a conference article entitled: *Review of pavement cracking data collection practices* that summarizes all cracking identification practices throughout fifty states as and the Long-term Pavement Performance Program (LTPP) distress identification manual. Current practices adopted by each agency are also compared to other interim standardization protocols.
    - Chapter 4 presents the first journal article: *Evaluation of the Effects of Concrete Grinding Residue (CGR) on Soil Properties*. This journal article characterizes the chemical properties of soil before and after CGR application through a control field study. The different CGR application rates, application periods, and soil depths at the selected site are discussed, including how to influence pH, electrical conductivity (EC), alkalinity, and other chemical properties related to soil quality.
- Chapter 5 presents a second journal article: *Concrete Grinding Residue – Management Practices and Reuse for Soil Stabilization* that evaluates existing CGR management practices throughout America and reuse of such slurry for soil stabilization purposes. A laboratory experimental program was set up to test engineering properties and chemical properties of soil stabilized with CGR.
- Chapter 6 presents the third journal article: *Evaluation of a Bio-based Fog Seal for Low-volume Road Preservation* that discusses both field and laboratory performance

of asphalt pavement located in Clinton County, Iowa, within the first two years after installation of RePLAY. The construction process is also documented in this study.

- Chapter 7 concludes the studies completed in this dissertation and advances recommendations for future research.

1.5 References

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CHAPTER 2. SUMMARY OF LITERATURE REVIEW RESULTS AND RESEARCH GAPS

This chapter is a review of existing pavement cracking identification practices, CGR, and fog sealant, and research gaps existing in previous studies are also discussed. Both national level and state level practices with respect to crack identification are summarized. The CGR review can be classified into four categories: CGR properties, its effects on soil and vegetation, typical management practices, and its reuse in different applications, including soil stabilization. The fog seal discussion includes both traditional fog sealant and bio-based fog sealant. In addition, each paper contains its own detailed literature review related to the paper's objective.

2.1 Review of Pavement Cracking Identification Practices

2.1.1 Review of National Guidelines

2.1.1.1 LTPP

The LTPP program is a very large research project conducted by the Strategic Highway Research Program (SHRP) from 1987 to 1991. The primary purpose of LTPP was to collect pavement condition data and analyze the various factors that can influence pavement performance. A detailed review of LTPP history, research methodology, and publications is presented in Chapter 3 "Review of Pavement Cracking Data Collection Practices" Section 3.3.1. One of the most significant achievements in this program is the LTPP distress identification manual that gives general definitions and recording methods related to common cracking. Table B.1 in Appendix B explains how this manual categorizes pavement cracking and related data collection and reporting methods. As a national guideline, eight states, including Connecticut, Delaware, Indiana, Mississippi, Missouri, Nevada, Oklahoma, and Vermont use it as a baseline to rate their pavement performance.

2.1.1.2 AASHTO

Over the past several decades, AASHTO has conducted many efforts intended to provide standard guidelines with respect to cracking identification. AASHTO PP 67, "Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods" and AASHTO PP 68, "Collecting Images of Pavement Surfaces for Distress Detection" are major achievements published in 2016 and 2014, respectively. A detailed review of these two documents is presented in Chapter 3, Section 3.3.2 and 3.3.3, summarizing the basic requirements related to quantifying pavement cracking based on automatic survey methods that differ from the manual survey methods provided in the LTPP program. While an automatic survey method provides an alternative way of efficiently, quickly, and safely collecting pavement condition data, a lack of baseline guidelines restricts SHAs to developing automatic imaging technology based only upon local conditions, so AASHTO PP 67 and AASHTO PP 68 can be a helpful reference to those states wishing to develop an automatic or semi-automatic survey method.

2.1.1.3 NCHRP

NCHRP is a program administered by the Transportation Research Board (TRB) to conduct highway research. One of the primary objectives of this program is to provide solutions for issues faced by states Departments of Transportation (DOTs) and private sectors, and generally NCHRP maintains a close relationship with AASHTO and FHWA on highway research. Of on-going projects, NCHRP 1-57 (2016) is the one that tries to define comparable pavement performance data. NCHRP has also conducted other research about pavement condition evaluation, such as NCHRP Synthesis 334 conducted by McGhee (2004), "Automated Pavement Distress Collection Techniques", NCHRP Synthesis 401 conducted by McGhee and Flintsch (2009), "Quality Management of Pavement Condition Data Collection", and NCHRP

Project 20-24(37)J conducted by Spy Pond Partners, LLC (2013), “Measuring Performance Among State DOTs: Sharing Good Practices – Pavement Structural Health”.

NCHRP Synthesis 334 was published in 2004; it is a comprehensive review of automated techniques including their benefits, contracting procedures, QC/QA, equipment, cost, case studies, and limitations. In 2009, another important product, NCHRP Synthesis 401, discussed SHA quality management practices. It evaluated all three data collection methods: automated, semi-automated, and manual. Cambridge Systematic Inc. conducted a study about identification of common indicators of pavement performance from a group of SHAs in 2013. It was not only a comprehensive study about pavement condition evaluation, but also a good review of practices about data collection in some SHAs. The work of NCHRP is not to create specifications for pavement data collection, but to focus more on technical areas in pavement condition data collection.

During these decades a great many research projects about pavement data collection, such as LTPP and NCHRP, have been conducted. Before 1990 the primary pavement data collection methods were manual, and windshield and walking surveys were very common. At that time, different SHAs and vendors exhibited great variability in crack recording, processing, and reporting and this resulted in creation of a collection of incompatible databases among the 50 states in America. FHWA and SHRP therefore developed the LTPP distress identification manual in the early 1990s to provide standards and references for their member departments. After a few years, considering the limitations of manual survey methods, safety and survey efficiency, semi-automated and automated data collection methods came into wide use. NCHRP conducted some practices in utilization of automated methods after 2000, and AASHTO published some related specifications in 2015 for further reference. Presently, a few SHAs already have their own automated data collection practices, and undoubtedly more and more SHAs will turn to automated survey in the future. Practices vary significantly from state to state for several reasons, and conducting an overall review is already becoming an issue.

2.1.2 Review of State Guidelines

In the United States, pavement condition is monitored by local SHAs, and each state has its own practices related to surveying pavement performance. To perform a comprehensive review about existing survey practices in each state, available documents related to cracking survey were checked through an online search of SHAs' official website, and a detailed summary table of practice in each state is presented in Appendix B.1, including pavement categorization, cracking type, cracking severity and extent, and others. An overview of state practice is shown in Chapter 3, Section 3.4, and Appendix B.2 provides detailed summary figures in Figure B. 1 to Figure B. 34. These figures show differences among state practices related to pavement surface type and cracking type categorizations as well as data collection and reporting methods. Differences result from many factors such as historical practice, environment, pavement design and construction, preservation strategy, and highway management systems. Since the LTPP distress identification manual is referenced by many states, some similarities can be found in the different documents. As for the other significant specifications at the national level, while AASHTO PP 67 and 68 are not presently followed by the SHAs, it is possible to foresee that these two documents will be very useful and significant for those states that plan to develop new specifications based on automated technology.

2.1.3 Research Gaps in Previous Studies

Pavement cracking identification practices are critical to pavement sustainability. While each SHA has successfully surveyed their pavement performance for many years, different practices in different states have resulted in complexity of sharing and reporting data to other

SHAs as well as to FHWA. Previous studies conducted by LTPP, AASHTO, and NCHRP focused on standardization of cracking identification methods, and in recent years they recommended appropriate automatic survey methods. In this study, the primary objective is to develop a comparable summary for each cracking identification guideline. The pavement surface categorization, cracking types, sampling method, survey collection method, survey frequency, and other important information for each state ae presented in Chapter 3 and Appendix B, where comparable results of different SHAs and FHWA to set up long-term performance goal are described. Moreover, the review summary provided in this study can be an important reference to states wishing to develop or update their cracking identification guidelines.

2.2 Review of Concrete Grinding Residue

2.2.1 Properties of Concrete Grinding Residue (CGR)

Concrete pavement typically has many surface irregularities that can negatively affect its serviceability. To create a smooth surface, a truck equipped with spaced bottom-located blade heads is used to perform diamond grinding. CGR is the slurry byproduct generated during the diamond grinding operation on a concrete pavement surface, and it is comprised of a removed concrete thin layer and cooling water for blades. Several studies have been conducted with various CGR slurries to determine the characteristics of CGR. Holmes and Narver (1997) reported that CGR samples collected from a grinding operation in California had initial pH values in ranges of 9.4 to 11.1, and exhibited no toxicity based on the 96-hour Acute Toxicity test. While volatile organic compounds both in the solid phase and the liquid phase of CGR did not exceed detection limits of the equipment, semi-volatile compounds were detected in the liquid phase of the samples. In addition, cation and anion concentrations of aluminum (Al), iron (Fe), and SO_4 (sulfate) exceeded the California Drinking Water Standard.

DeSutter et al. (2010) and DeSutter et al. (2011) analyzed CGR slurry samples from grinding practices in California, Minnesota, Nebraska, Washington, and Michigan. The CGR pH in those studies ranged from 11.6 to 12.5, with detected concentrations of arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), selenium (Se), and silver (Ag) that were below the 40 CER 261 standard toxic limits. The concentration values of toxic elements in the slurry solid phase were smaller than the values reported for the surface soil at the sampling locations, indicating that CGR slurry was not the soil dominant contaminant. Based on particle size distribution analysis, silt-sized particles were the major constituent of the CGR samples (Figure 2.1).

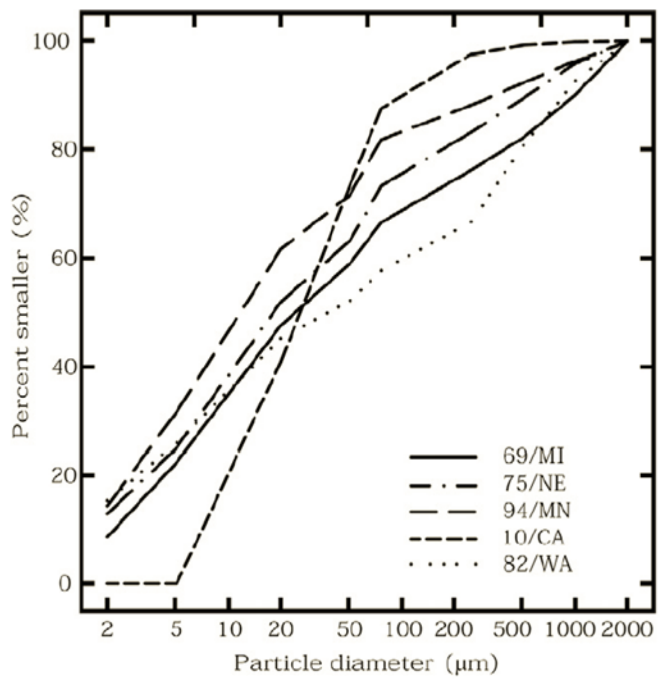

Figure 2.1 *Particle size distributions for five CGR samples from five roadway sites (DeSutter et al., 2010).*

Other researchers have reported similar results regarding the properties of concrete residues. For example, in a study on concrete residue recycling, Goodwin and Roshek (1992) reported the pH of concrete residues from multiple sources to lie within the range of 12 to 12.6.

Hanson et al. (2010) reported pH values of CGR samples from Washington State to be 10.2 and 10.9. Druschel et al. (2012) reported several concrete residue properties, including those of CGR slurry in Minnesota, in their project on concrete wastewater and best management practices. The pH of a reconstituted slurry sample was 9.4, and it predominantly contained silt-sized or finer particles. Chini and Mbwambo (1996) reported pH values of 11 to 12 in concrete wastewater samples. Sulfates, hydroxides, chlorides, and small quantities of both hydrocarbons and admixture compounds were also found in concrete wastewater. Young and Shanmugam (2005) reported that pH values of slurry in Washington State ranged from 11.9 to 12.1 in a slurry neutralization experiment. Based on previous investigations, it should be noted that CGR is a fine material with high pH and alkalinity, and its improper disposal may result in a critical environmental issue.

2.2.2 Soil and Plant Responses to CGR Application

While spreading of CGR along a roadside is a common disposal method adopted in many states, the high pH and alkalinity caused by CGR composition may be a concern with respect to vegetated soil. To understand how CGR can affect the environment, some efforts have been made to analyze soil and plant responses to CGR offloading. Young and Shanmugam (2005) investigated the long term (6 to 10 years) effects of slurry on soil pH. The pH values of soil without CGR slurry were 6.3 to 7.2, while the pH values of soil with CGR slurry were increased by 1 to 2 units, as shown in Figure 2.2. The concentration of Pb (Lead), Cu (Copper), Zn (Zinc) and Cd (Cadmium) were measured at different soil depths, and there were no significant differences between the soil background value and the values of soil in the slurry disposal areas. However, the concentrations of Mg (magnesium) and Ca (Calcium) increased due to the slurry application.

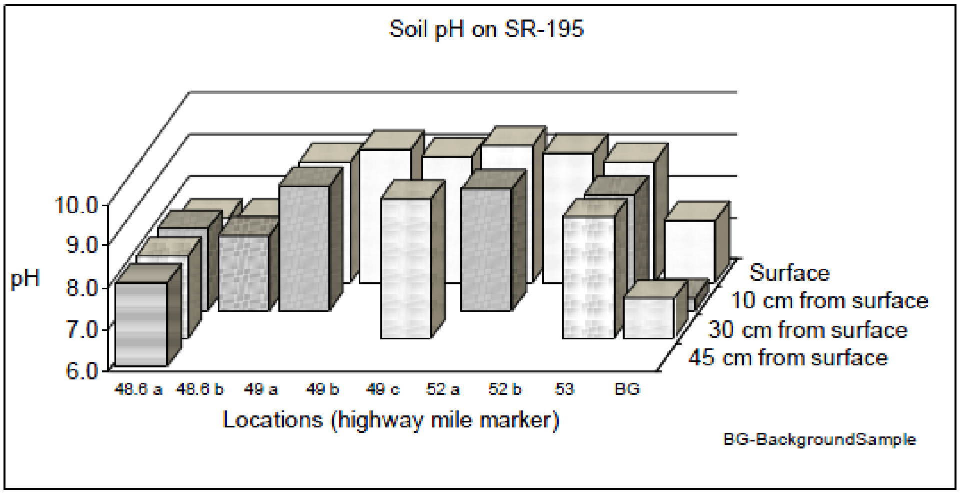

Figure 2.2 *Soil pH at I-90 sample sites as a function of depth. In this figure, a, b and c refer to replicate samples collected within in 1 ft. of each other (Young and Shanmugam, 2005).*

DeSutter et al. (2010) summarized the effects of CGR on water infiltration time in soil, showing that the infiltration time of soil with slurry was longer than that of the soil alone. DeSutter et al. (2011) reported short-term (99 days) soil and plant responses to CGR slurry, and shoot growth was promoted for low slurry rates (8%), while it was inhibited for high slurry rates (25%). Soil pH after CGR application was higher than that of soil alone, while EC increased significantly at higher CGR application rates. Concentrations of non-trace (Ca, Cd, Pb and Sr) and trace metals (Cr) in smooth brome grass were also significantly increased by CGR application, and the factor of CGR type only significantly increased Ca and Sr concentrations. Soil types also showed registered significant effects of Cd, Cr, Pb and Sr in biomass, but Hg concentration was not affected. Mamo et al. (2015) studied both short-term (one month) and long-term (one year) effects of CGR on soil properties and roadside plants located at HWY 31 Milepost 34 and 36 in Nebraska. This study indicated that slurry, slope, depth, and slurry-depth interaction were the most significant factors affecting soil pH, EC, Ca, K, Mg, and Na concentrations for the first month after slurry application. After a one-year period, the slurry effects shown in Table 2.1 were not significant ($p < 0.05$).

Table 2.1 *Consequences of one time CGR slurry application effects based on two site experiments, with loam and silt loam soil textures, at NE State HWY 31 sites (Mamo et al., 2015).*

CGR kg/m^2 (ton/acre)	pH	EC dS m^{-1}	K mg Kg^{-1}	Ca mg Kg^{-1}	Mg mg Kg^{-1}	Na mg Kg^{-1}
0	8.1	0.74	259	3835	162	1031
1.12 (5)	8.1	0.57	300	4434	206	647
2.24 (10)	8.2	0.58	305	4390	175	638
4.48 (20)	8.2	0.59	301	4498	179	736
6.72 (40)	8.2	0.60	314	4946	197	681
Effect	P > F					
Slurry	0.5927	0.1867	0.4896	0.0078	0.4225	0.1970
Slope	0.0008	0.3171	0.0002	0.0325	<0.0001	0.2236
Depth	<0.0001	0.4920	0.0003	0.0007	<0.0001	<0.0001
Slurry*Slope	0.8609	0.7677	0.6685	0.9023	0.8778	0.0184
Slurry*Depth	0.7901	0.0011	0.7768	0.0002	0.1726	0.8506

Kluge et al. (2017) discussed environmental concerns related to disposal of CGR along the roadside by conducting X-ray fluorescence (XRF), X-ray diffraction (XRD), and leaching tests on CGR samples collected from Jacksonville, Florida, with test results indicating that leached concentrations of 25 elements (Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Sn, Sr, Ti, V and Zn) did not exceed the Florida soil clean-up target levels (SCTLs), and that direct exposure should not be a major limitation to CGR management, especially when it is placed next to a roadway or on an agricultural area. Wingeyer et al. (2013) reported that, after a four-week period following the application of slurry at a rate of 9 kg/m^2 (40 ton/acre), the soil pH increased by 0.11 units compared to the control site. Compared to the control site, there was also a significant decrease in Mg and K concentrations at a depth of (0-20 cm (0-7.9 in.), while the exchangeable Na level at the 0-20 cm (0-7.9 in.) depth increased due to CGR application. In addition, the exchangeable Ca level compared to the control site increased at a 0-10 cm (0-3.9 in.) depth. The botanical compositions of the treated plots were not affected by the slurry application.

Overall, previous studies have indicated that CGR slurries could increase soil pH, EC, and concentrations of metals (Ca, Mg, Na, etc.) in soils. Based on these results, CGR should be managed properly to avoid the contamination of soil and bodies of water.

2.2.3 Management Practices of CGR Application

2.2.3.1 Technical guidance

The International Grooving and Grinding Association (IGGA) is a non-profit industry trade association consisting of contractors, manufacturers, suppliers, consultants, and public officials representing all facets of the industry. In consideration of the potential environmental contamination by CGR, IGGA developed best management practices IGGA BMPs (2013) related to disposal of CGR properly. Chapter 5, Section 5.3.1, introduces the history of IGGA and describes detailed procedures with respect to CGR management (Table 5.1a). In CGR BMPs, three disposal methods are suggested: (1) spreading of CGR along roadsides in rural area, (2) decanting CGR into specific ponds, and (3) processing in waste facilities. A selection of CGR disposal method should consider all factors such as area sensitivity, cost, and measured properties of CGR. In BMPs, recommended pH is in the range of 2 to 12.5.

2.2.3.2 State management practices

To investigate how local SHAs and contractors dispose of CGR, a comprehensive review was conducted of the study of CGR. All available guidelines throughout United States were collected from official SHAs websites and are summarized in Chapter 5.3.2. Table 5.1b presents details of CGR disposal practices in 42 states, while the other eight states have no available documents related to CGR management on their official websites. Typical CGR disposal methods proposed in IGGA BMPs (2013), including spreading along roadsides, decanting in ponds and processing in waste facilities, are followed by 12, 11, and 8 states, respectively. In fact, the review results show that detailed guidelines to proper disposal of CGR in many states are lacking, and discharge rate of CGR into roadside has most especially not been determined in most states due to lack of scientific evidence.

2.2.3.3 Survey responses

To seek understanding of DOT and industry contractor perspectives, a survey created at Iowa State University (ISU) was sent to 50 state DOTs (Appendix A.1) and 30 contractors (Appendix A.2) and responses were received from 12 state DOTs (Arkansas, Florida, Idaho, Iowa, Louisiana, Nebraska, Nevada, Ohio, Pennsylvania, Washington, West Virginia, and Wyoming) and 7 contractors (Girard Resources and Recycling LLC, Quality Saw and Seal Inc., and others). The survey questions covered specifications, methods, control actions, and recycling practices regarding CGR management, and the results are shown in Figure A. 1 through Figure A. 20. Survey questions can be found in Appendix A. Based on the survey responses, CGR is regarded as a hazardous waste in three states (Figure A. 1). The personnel from local SHAs in two states responded that they did not have guidelines for managing CGR (Figure A. 2). Only one of the state DOTs indicated that they followed IGGA BMPs (Figure A. 3), and only two of the state DOTs indicated that they recycled CGR for other purposes (Figure A. 5). As seen in Figure A. 4 and Figure A. 6, all states indicated that they did not monitor the long-term impacts of CGR when it was offloaded onto soil and could not estimate how much money was spent to dispose of CGR. Figure A. 7 indicates that 6 contractors follow state guidelines in disposal of CGR, and if those guidelines are not available, the contractors would choose to dump slurries along roadside, decanting them in ponds or haul them to processing in waste facilities (Figure A. 8). Figure A. 9 presents how SHAs and contractors dispose of CGR if state guidelines are not available, and two states and one contractor chose to dump it along roadsides. Figure A. 10 and Figure A. 11 exhibit that some states try to control the pH, metal concentrations, and total suspended solids (TSS) of CGR. Figure A. 12 through Figure A. 20 show that many DOTs and contractors have no control action plan to manage the disposal of CGR slurries, and lack detailed guidelines for activities such as dumping areas and distance from road surfaces when they offloaded CGR along roadsides. Although some studies (DeSutter et al., 2011, Kluge et al., 2017) did not expressly describe the negative impacts of CGR on plant growth, the variable characteristics of CGR may create environmental issues, depending on the materials used during concrete production. In conclusion, survey results show that the overall majority of DOTs and contractors have no proper guidelines for managing or mitigating the effects of CGR on its surrounding environment. Based on the results of this survey, it is recommended that CGR disposal should be managed by following the IGGA BMPs or by recycling for other applications in combination with a pH control plan, or, if needed, with other control plans (TSS and Metals) to minimize risk to the environment.

2.2.4 Reuse of CGR in Various Applications

2.2.4.1 Reuse of CGR as construction materials

In addition to the common CGR disposal methods (offloading along roadside, decanting in ponds, or processing in waste facilities), recycling and reuse of CGR are strongly recommended for achieving the goal of sustainable pavements. Some studies were carried out to evaluate the reuse of CGR or other recycled concrete fines as an additive in construction materials or liming products.

Concrete waste can typically be used for partial replacement in concrete mixing or filling materials in construction. Goodwin and Roshek (1992) evaluated recycling of CGR as a filler into a cement-treated base course in Utah. CGR was collected at the grinding project site and hauled to the temporary storage for filtering, and pH control action was performed through addition of acid to reduce pH to a range between 7 to 9. The separated slurry water was hauled to a wastewater treatment plant for treatment and discharge, and the solid waste was reused into construction of a cement-treated base. This study concluded that recycling of CGR as a filler in a cement-treated base resulted in lower construction cost, with similar mechanical performance, compared to industrial treatment and disposal such as processing in waste facilities.

Kluge et al. (2017) examined CGR collected from Jacksonville, Florida for potential use as partial replacement of cement in new mortar, and found no dramatic reactivity or improvement in mortar strength, as shown in Figure 2.3. Ravindrarajah and Tam (1987) obtained similar results when they used recycled concrete fines for concrete mixing. The results of this study showed that early-age strength and modulus of elasticity of cement paste were reduced with addition of recycled concrete fines, while dry shrinkage and creep potential increased. Conversely, the studies of Hanson et al. (2010) and Janssen et al. (2012) described opposite trends than those of Kluge et al. (2017) and Ravindrarajah and Tam (1987).

Amin et al. (2015) investigated the reuse of recycled concrete fines from demolished concrete for strength gain within a cement mortar matrix (Figure 2.4), and showed that the rehydration of these fines, observed through electron microscopy in the mortar, resulted in strength gain.

Cavalline and Albergo (2017) performed a benefit-cost analysis on CGR disposal to investigate potential savings. They concluded that use of decanting ponds was the most cost-effective method of handling CGR slurries. Disposal options for CGR solids vary across the country and are highly dependent on waste disposal facilities fees. Based upon this study, the disposal of CGR as a solid beneficial fill material was determined to be the least expensive alternative.

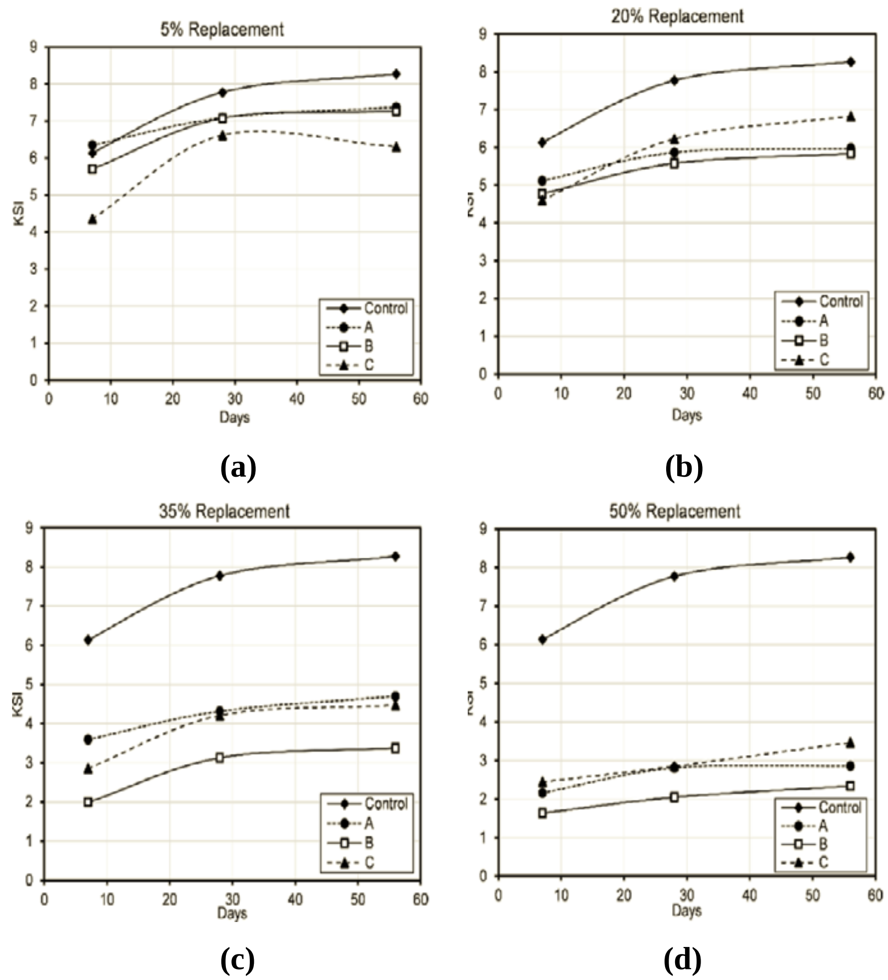

Figure 2.3 *Three CGR samples (A, B and C) were used as cement replacements in 2-inch cubes and subjected to compressive strength tests (Kluge et al., 2018).*

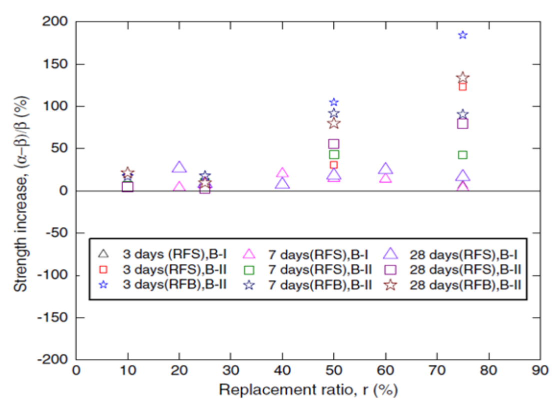

Figure 2.4 *Percentage strength increases caused by replacement of recycled fines from brick aggregate concrete (RFB) and stone aggregate concrete (RSB) at different ages (Amin et al., 2015).*

Other studies also evaluated the use of recycled concrete fines for soil stabilization applications. Kerni et al. (2015) concluded that use of demolished concrete waste in soil stabilization not only helped reduce the hazardous environmental impact of the waste, but also improved the engineering properties of soil, ultimately reduced cost of construction, and increased the life of a structure built on the stabilized soil. Lindeman et al. (2016) investigated the use of recycled crushed concrete (RCC) fines for soil stabilization and found that the compressive strength of the soil with 3% RCC waste material suffered no significant effect with respect to soil mechanical characteristics. Ransinchung et al. (2013) reported reduction in dry densities and plasticity indices of clayey soils mixed with both cement and recycled concrete fines. On the other hand, that study observed that admixing of concrete fines improved the soaked CBR value, unconfined compressive strength, and split-tensile strength of soil. Twagirimana et al. (2017) determined the optimum lime and concrete contents that should be added to maximize the CBR of silty sand to 6% and 8% respectively. At these percentages, improvements in shear strength, fatigue cracking, and rutting resistance of soil were observed. Engelsen et al. (2012) monitored release of major and trace elements from recycled concrete aggregates used in an asphalt-covered road sub-base over 4 years. Based upon their findings, the levels of Cd, Ni, Pb and Zn in the subbase did not exceed the acceptance criteria for groundwater and surface water. They also observed that levels of Cr and Mo were increased in the winter, and they assumed this was caused by the use of de-icing salt. Townsend et al. (2016) evaluated the possible impact of using recycled concrete aggregate as a road base in the subsurface environment, and a reduction of pH in recycled concrete aggregates due to environmental factors such as carbonation from atmospheric carbon dioxide, neutralization with soil acidity, and neutralization with groundwater was observed.

2.2.4.2 Reuse CGR for soil amendment

In addition to the investigation of using CGR as construction material, some studies evaluated the use of CGR as a soil amendment. Berger and Carpenter (1981) suggested the reuse of recycled concrete waste to neutralize acidic soils. Scott (1985) and Scott (1986) investigated a forest site covered with concrete dust derived from resurfacing operations for an overpass. The thickness of concrete dust was about 2 mm (0.079 in.), and the covered forest exhibited a flourishing condition probably caused by the addition of Ca from the concrete dust into the soil. Hansen (2004) discussed a variety of potential uses for CGR, including wastewater treatment filters, poultry grit, limestone substitution in SO_2 scrubbers, and stabilizing sewage sludge. Hanson and Angelo (1986) concluded that the addition of crushed concrete fines may have improved engineering properties of clayey soils for earthwork purposes. While the literature indicates that CGR can have a beneficial utilization in soil amendment, soil testing and risk assessment is strongly recommended to determine an optimum application rate at each specific site prior to applying CGR. The literature shows that CGR composed of concrete fines from cooling water for blades may be a useful waste product for many applications, including producing new concrete, filling road base, and stabilizing subgrade soil. Due to its composition, the solid phase of CGR can be utilized in similar applications. In addition to reuse of CGR in construction materials, the previous studies also highlight that it can be reused as a soil amendment. Reuse of waste materials like CGR in different applications not only reduces possible environmental risks due to improper disposal methods, but also contributes to the sustainability of concrete pavement designs.

2.2.5 Research Gaps in Previous Studies

During recent decades, there has been considerable effort directed toward understanding the properties of CGR and in particular soil and vegetation responses to addition of CGR. These studies claimed that different CGR sources had pH values ranging from 9.4 to 12.6 (Goodwin and Roshek, 1992; Holmes and Narver, 1997; Hanson et al. 2010; Desutter et al., 2010; Desutter et al., 2011), and some of them displayed that CGR added no toxicity to soil and vegetation (Holmes and Narver, 1997; Desutter et al., 2011). Other studies investigated recycling of CGR in concrete and soil amendments indicate that CGR could provide benefits when used as construction materials (Goodwin and Roshek, 1992; Kluge et al., 2017). However, the findings in these studies were more based on local conditions, and a relevant study based on general Iowa conditions is lacking. In fact, Iowa allows CGR to be spread along roadsides (Table 5.1b), but a suggested discharge rate is unavailable in related documents (IA-DOT, 2012; IA-DOT, 2018), so a scientific study to explore the effects of CGR on Iowa soil is needed. Moreover, this CGR study evaluated changes in other important soil properties such as CEC and ESP due to addition of CGR. In consideration of the nature of CGR, the following study with respect to CGR recycling in soil stabilization was also conducted, but has not as yet been highlighted in previous studies.

2.3 Review of Fog Sealant

2.3.1 Review of Traditional Fog Sealant

Asphalt pavement is very susceptible to environmental conditions and traffic, and several maintenance technologies have been developed and successfully used for many years to prevent pavement deterioration. Fog seal is the application of liquid asphalt emulsion to preserve asphalt pavement, and it is generally used to seal micro-cracks and prevent raveling and oxidation (Chehovits and Galehouse, 2010; Jahren et al. 2007). In some cases, fog seal has been applied as a top surface of chip seals to reduce aggregate loss and improve aggregate retention to extend pavement service life. A detailed literature review about traditional fog sealant is presented in Chapter 6, Section 6.3.1. Previous studies have focused more on modification of petroleum-based emulsion, emphasizing and promoting performance such as aggregation retention for the modified binder (Prapaitrakul et al. 2010; Im and Kim, 2013). As a common preservation technology, many states have developed guidelines regarding the application of traditional fog seal. Six states published fog seal specifications in terms of emulsion grade, dilution rate, application rate, equipment and application instruction are summarized in Table 6.1, illustrating the different fog seal methods.

While the literature review results indicate that traditional fog sealants exhibit good performance for road surface treatment and aggregation retention, especially if they include polymer modification, some authors also pointed out the drawbacks of traditional fog sealants. Kim and Im (2012) summarized the advantages and disadvantages of fog seal in Table 2.2, indicating main disadvantages of long curing time and reduced friction. In addition, coal-tar sealant was reported to contain polycyclic aromatic hydrocarbons (PHAs) that are generally carcinogenic (Ghosh et al., 2016). In consideration of these drawbacks, bio-based sealant could be an attractive alternative for improving pavement sustainability.

Table 2.2 *Advantages and disadvantages of traditional fog sealants (Kim and Im, 2012).*

Advantages	**Disadvantages**
• Cost-effectiveness • Ease of construction • Extension of the service life of the pavement • Desirable black appearance	• Long curing time (delayed traffic opening) • Reduction in skid resistance

2.3.2 Review of Bio-based Fog Sealant

In recent years, a few bio-based products have been invented and introduced as fog sealants for pavement preservation purposes. RePLAY, a bio-based fog sealant developed by BioSpan Technologies (Medina and Clouser, 2009), is a black liquid containing 88% bio-based compounds, 40% of which are sourced from soybean oil. This bio-based product also contains some polymers, including SBS (styrene-butadiene-styrene) and SBBS (styrene-butadiene-butadiene-styrene), common admixtures used in traditional asphalt emulsion to improve pavement flexibility under colder conditions. Making use of agricultural and recycled materials, this bio-sealant is a non-toxic and environmentally friendly alternative to petroleum-based sealing agents. Some studies have been conducted to evaluate the effectiveness of bio-sealants, and an overview of current practices about pavement maintenance are presented in this study.

Medina and Clouser (2009) conducted a field study in Pennsylvania on evaluating the effectiveness of RePLAY. The company representatives provided help in applying this product to the road. Based on their description, the surface became wet and soft within minutes after spraying, and after 15 minutes only some coarse aggregates still remained wet. When the installation had been completed, the road spent about one hour open to traffic. Skid resistance and retroreflectivity of pavement marking were conducted before, two weeks, and 18 months after application. The field results indicated that the bio-based sealant caused a significant loss in skid resistance and retroreflectivity. Six cores were taken to evaluate the laboratory permeability, with three of them RePLAY treated cores, the other three untreated specimens, and all cores exhibited impermeability.

Olson (2011) selected two different pavements for evaluating the performance of RePLAY treated road. The first pavement, a cracked and raveled bicycle and pedestrian trail, had an age of about 15 years. The second pavement was five years old and in excellent condition. Both pavements were treated with the RePLAY product, and their behavior with respect to water was observed before and after surface sealing. At the stage before installation of RePLAY, water found it easy to penetrate into the old pavement, while after fog sealing both pavements exhibited rapid water run-off from the surface. In addition, when the sealed asphalt surface was observed by the author, there was additional benefit to high-traffic pavement under hot weather conditions because traditional sealant could become soft and sticky.

Nagabhushana et al. (2010) performed field and laboratory tests to evaluate the effects of RePLAY. In their report, a road with six lanes was selected in 2009 for application of RePLAY. After approximately eight weeks, 12 treated cores and 12 control cores were collected for testing their stability, flow, indirect tensile strength, accumulated strain, penetration, and other properties. The results revealed that RePLAY improved the bitumen properties of a pavement surface.

Huang and Shu (2010) studied several sealants, including joint adhesives and infrared heating and joint sealers such as Jointbond and RePLAY, whose purpose was improvement of longitudinal joints in hot mix asphalt (HMA). These products were applied to road surfaces, using spray rates of 0.362 and 0.136 l/m^2 (0.08 and 0.03 gal/yd^2), respectively, for Jointbond and RePLAY. The experiment was intended to measure laboratory air voids, permeability, indirect tensile strength, water absorption, and X-ray CT for cores taken from field sites. This project concluded that Jointbond and RePLAY produced a significant reduction in water absorption.

Ghosh et al. (2016) reported evaluation of four fog sealants used for treating road sections in Minnesota. The selected road was paved in 2013, and CSS-1h, RePLAY, Biorestor and Jointbond were sprayed on it between August and October 2014 at rates of 0.453, 0.091, 0.905, and 0.330 l/m^2 (0.1, 0.02, 0.2 and 0.073 gal/yd^2), respectively. Four cores were then collected from each treated section and the control section, and three of the four cores were taken a few days after treatment and one was taken 8 months later. Several binder properties were examined, including rheological properties, low temperature stiffness, and relaxation, and creep and strength tests for the asphalt mixtures were also conducted. The results showed that oil-based sealant can soften control binder significantly compared to water-based sealants. For asphalt mixtures, the installation of sealant did not significantly affect creep and strength, and sealant products were not detected through Fourier transform infrared spectroscopy (FTIR) analysis in the treated specimens.

Johnson (2018) performed a field study subsequent to that by Ghosh et al. (2016) to investigate the effects of the same four fog sealants on retroreflectivity, friction, and permeability of pavement within four years after fog sealing at the same site. This study reported that retroreflectivity and friction of treated section were temporarily decreased at an early stage after fog sealing but were subsequently restored, and CSS-1h experienced the longest time for recovery of skid resistance, but CSS-1h displayed the greatest protection after two years of service with respect to permeability

Although traditional fog sealants exhibit good performance for pavement surface treatment, bio-based products can provide extra benefits related to pavement maintenance. As a bio-based seal agent, RePLAY has been proven to prolong asphalt pavement surface life, protect pavement against water damage, maintain skid resistance, introduce polymer to asphalt binder, and strengthen the asphalt matrix (Table 6.2, in Section 6.3.2), meaning that bio-sealants like RePLAY can extend the lives of asphalt roadways by penetrating and filings the voids near the surface, protecting against water penetration, minimizing freeze/thaw damage, and making asphalt more resilient. Table 6.2 summarizes the limitations of RePLAY, indicating that this agent is not suitable for wet surfaces or surfaces exhibiting alligator cracking. The recommended spray rate of RePLAY can range from 0.045 to 0.091 l/m^2 (0.01 to 0.02 gal/yd^2) and typically it can penetrate on average 1.9 to 3.2 cm (0.75 to 1.25 in.) deep into asphalt within a matter of minutes (BioSpan, 2010). RePLAY not only reduces the need to use petroleum-based products in pavement maintenance, but it also reduces the need to use bitumen in the manufacture of new asphalt to make the road surface last longer. Moreover, this bio-based product is a competitively priced and environmentally-benign alternative to traditional petroleum-based asphalt sealers. The application of bio-sealant is comparable in cost to other asphalt seal coat treatment and it represents the only bio-based, non-toxic, and carbon negative solution. It is also easy to apply and extends the life of asphalt pavement much longer.

2.3.3 Research Gaps in Previous Studies

Previous studies of fog seal investigated the effects of polymer modification on asphalt emulsion. Although the performance of such sealants was promoted, the important drawbacks of traditional fog sealant cannot be ignored. The use of a bio-sealant like RePLAY to achieve pavement sustainability is a potential alternative to use of fog seal, and while previous studies have described both advantages and disadvantages of using this product as fog sealant, the evaluated spray rates of RePLAY in their studies ranged from 0.045 to 0.091 l/m^2 (0.01 gal/yd^2 to 0.02 gal/yd^2), and, based on pavement conditions, higher rates should be evaluated. In this study, the evaluation of RePLAY treatment was conducted on an Iowa road using higher that ranged from 0.091 to 0.136 l/m^2 (0.02 gal/yd^2 to 0.03 gal/yd^2). This study also continuously monitored pavement marking retroreflectivity and surface friction to seek understanding of changes during application. This study can be a good reference in developing proper guidelines with respect to using bio-based fog sealant.

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CHAPTER 3. REVIEW OF PAVEMENT CRACKING DATA COLLECTION PRACTICES

A conference paper submitted and accepted for publication in *Tenth International Conference on the Bearing Capacity of Roads, Railways and Airfields*

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3.1 Abstract

While there are multiple methods available for identification of pavement cracking data, these methods and cracking data are not always compatible, possibly complicating the sharing of cracking data in-formation among agencies and vendors as well as reporting of such data to the US Federal Highway Administration (FHWA) to establish national, state, and local performance goals. In this study, comprehensive reviews on existing federal and state highway agencies' cracking data collection practices were conducted, including how data are collected and classified. Current practices adopted by each agency have also been com-pared to interim standardization protocols, building upon work reported in American Association of State

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Highway and Transportation Officials (AASHTO), PP 67, “Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods”, and PP 68, “Collecting Images of Pavement Surfaces for Distress Detection”. The study’s findings are summarized in the context of developing standard definitions for comparable pavement cracking data.

3.2 Instruction

For effective maintenance and design of pavements, the collection of pavement condition data becomes an important aspect of a pavement management system. Generally, pavement surface assessment involves collection of surface distress and ride quality information. Surface distress is related to poor and unsatisfactory pavement performance because of cracking, surface defects, and deterioration. Ride quality is typically characterized using an international roughness index (IRI). Among the various information elements, cracking plays an important role an overall pavement rating because it not only is very common but also can be quite complex under a variety of different conditions.

The US FHWA considers cracking data collection to be very important. National level guidelines provided in documents such as Long-term the Pavement Performance Program (LTPP) distress identification manual and AASHTO specifications were created to achieve data consistency. Some local state highway agencies (SHAs) have also employed such documents as routine practice, while in other states, SHAs developed their own cracking data collection methods based on local conditions. The definition, classification, measurement, and reporting methodology of cracking using these methods are not always comparable, so information sharing among different agencies and vendors can become problematic, possibly resulting in inconvenience of reporting to the FHWA for the purpose of setting performance goals at both national and state levels.

The primary goal of this study is to present comprehensive reviews of existing cracking data collection practices among both US federal and state agencies. To achieve this goal, the SHA official website of each state was searched to identify and study the available documents related to collection of cracking data, identification of cracking type, recording the severity, extent, and quantity of cracking, and other related factors. The LTPP manual developed by FHWA was also reviewed because some SHAs use it as a baseline for cracking data collection.

3.3 Review of National Level Guidelines and Studies

3.3.1 LTPP

LTPP program is a comprehensive pavement performance database initiated by the Strategic Highway Research Program (SHRP) from 1987 to 1991. As one of SHRP's major research projects related to pavement performance, LTPP was established to collect pavement performance data for exploring extension of pavement life. After the first five years, FHWA made another effort to manage and fund the LTPP for the next 15 years. Pavement performance is affected by various factors, including design methods, loading, materials, environment, and maintenance. LTTP collected pavement performance data from more than 2,500 pavement sections to evaluate the influence of these factors.

To obtain reliable and consistent information, the first version of the LTPP distress identification manual was published in 1993, producing specifications for collection of pavement performance data. As one of the most important LTPP products and publications, this manual was adopted and used by many SHAs, and was also frequently used as a reference when some SHAs developed their own distress identification manuals. So far, this manual has gone through five editions; the latest version is the fifth edition developed by Miller and Bellinger (2014).

The LTPP distress identification manual provides specifications defining the common cracking types of asphalt concrete (AC): surfaced pavement, jointed plain concrete pavement (JPCP), and continuously reinforced concrete pavement (CRCP). For AC surfaced pavement, the six common cracking types are fatigue cracking, block cracking, edge cracking, longitudinal cracking, reflection cracking, and transverse cracking. For JPCP, this manual defines corner breaks, durability cracking (D-cracking), longitudinal cracking, transverse cracking, and map cracking. For CRCP, the four common types of cracks are D-cracking, longitudinal cracking, transverse cracking, and map cracking. The LTPP distress identification manual not only provides the definition, severity levels, measurement methods, and photos describing each cracking type, but also provides distress survey guidelines, including data reporting and survey sheets. As a comprehensive guideline and reference, the LTPP distress identification manual is very significant because historical practices, various environments, and different construction materials and design methods reflect the wide variation in distress identification practices in different states.

3.3.2 AASHTO PP 67

AASHTO has made many efforts to standardize cracking data collection over the past several decades. AASHTO PP 67 (2016), "Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods", represents a very important achievement supporting agencies in standardizing their cracking data collection procedures. AASHTO PP 67 defines only three types of cracking in asphalt pavement: longitudinal cracking, transverse cracking, and pattern cracking. This differs from the LTPP distress identification manual by focusing on quantifying cracks, including activities of data reduction, data analysis, data reporting, data interpretation, and data quality control/quality assurance (QC/QA). Actually, the guidelines in the AASHTO PP 67 anticipate automated data collection methods by featuring pavement image scanning and collection, and no earlier standardized specifications were available at the national level.

3.3.3 AASHTO PP 68

AASHTO PP 68 (2014), "Collecting Images of Pavement Surfaces for Distress Detection" describes the other important standard list of practices for automated data collection methods. It provides detailed requirements on pavement image size and quality. The content in this document has some overlap with AASHTO PP 67-6, "Data Reduction – Crack Detection" whose utilization can contribute to consistency in pavement condition data.

In US, although manual data collection is currently the main method for surveying pavement performance, automated data collection method has attracted more and more attention from SHAs in recent years, leading to the desire of some SHAs to update their pavement data collection and processing methods. AASHTO PP 67 and 68 will be the very good references to those wishing to switch to automated techniques.

3.3.4 National Cooperative Highway Research Program (NCHRP)

A primary objective of NCHRP is to provide solutions for highway-related issues faced both by state Departments of Transportation (DOTs) and private sectors. NCHRP has conducted other research regarding evaluation of pavement condition. For example, McGhee (2004) developed NCHRP Synthesis 334, "Automated Pavement Distress Collection Techniques". McGhee and Flintsch (2009) developed NCHRP Synthesis 401, "Quality Management of Pavement Condition Data Collection". Spy Pond Partners, LLC et al. (2013) conducted the NCHRP Project 20-24(37) J, "Measuring Performance among State Dots: Sharing Good Practices – Pavement Structural Health".

NCHRP Synthesis 334 provides a comprehensive review of automated technique, including its benefits, contracting procedures, QC/QA, equipment, cost, case studies, and limitations. The NCHRP Synthesis 401 discussed quality management practices for SHAs and evaluated automated, semi-automated, and manual collection methods. NCHRP Project 20-24(37) J conducted research on the identification of common indicators of pavement performance from a group of SHAs. It is not only a comprehensive study about pavement condition evaluation, but also a good review of practices about data collection in some SHAs. The work of these NCHRP projects was not only intended to create specifications for pavement data collection; the objectives were more focused on the technical areas of pavement condition data collection.

3.3.5 Summary of Literature Review

Over the previous decades many research projects on pavement data collection have been conducted through LTPP and NCHRP. Before 1990, pavement data collection was commonly done manually using windshield and walking surveys. During that time, different SHAs and vendors exhibited great variability in crack recording, processing, and reporting, resulting in production of non-comparable databases among the fifty states. FHWA and SHRP then developed the LTPP distress identification manual in the early 1990s to provide standards and references for their member departments. After a few years, semi-automated and automated data collection methods were much more greatly valued than manual methods. NCHRP engaged in some research projects related to utilization of automated methods after 2000. AASHTO published relevant specifications in 2015 for further reference. Presently, only a few SHAs provide their own automated data collection guidance, but there is no doubt that more and more SHAs will turn to automated surveys in the future. Practices have varied significantly from state to state for several reasons. An overall review of current pavement cracking data collection practices is needed prior to establishing standard and discrete definitions for common cracking types.

3.4 Review of State Practices

3.4.1 Categorization of states

In the US, each of the fifty states has its own SHA. A check on the availability of documents related to distress identification in the official websites leads to categorizing these fifty states into four groups with respect to pavement cracking data collection and reporting practice specifications or references used in this study. The SHAs in group 1 follow the LTPP Pavement Distress Identification Manual; SHAs making their pavement distress identification manuals available online are categorized into group 2; SHAs with their pavement distress survey methodologies not officially available online but referred to in other online documentation (i.e., pavement preservation guideline or research reports) are categorized in group 3; In group 4, the SHAs do not have their own pavement distress identification manual and do not follow the LTPP Pavement Distress Identification Manual. Detailed information about this grouping is shown in Table 3.1.

Table 3.1 *Categorization of states*.

Group	States	Total amount
Group 1	Connecticut, Delaware, Indiana, Mississippi, Missouri, Nevada, Oklahoma, Vermont;	8 states
Group 2	Alabama, Alaska, California, Colorado, Florida, , Idaho, Kentucky, Michigan, Minnesota, Nebraska, North Carolina, Ohio, Oregon, Pennsylvania, South Dakota, Texas, Utah, Virginia, Washington, Wisconsin;	20 states
Group 3	Arizona, Georgia, Illinois, Louisiana, Massachusetts, New Jersey, New Mexico, New York;	8 states
Group 4	Arkansas, Hawaii, Iowa, Kansas, Maine, Maryland, New Hampshire, Montana, North Dakota, Rhode Island, South Carolina, Tennessee, West Virginia, Wyoming.	14 states

From Table 3.1, there are thirty-six states in groups 1, 2, and 3 providing online documents about cracking identification practice, while fourteen states do not. Twenty-eight states in groups 2 and 3 have their own related documents that do not follow the LTPP distress identification manual. It should be noticed that some SHAs in group 4 may have official distress identification manuals, but they have not yet been published online.

3.4.2 Pavement types

Pavement surfaces can be categorized into two types, AC surface and Portland cement concrete surface (PCC) with the categorization based only on surface material. For example, flexible pavement and AC overlay PCC would be identified as AC surfaced pavement. Cracking types vary with pavement surface type, so SHAs in groups 1, 2, and 3 (in a total of thirty-six states) generally categorize cracking types into AC surface and PCC surface. Figure 3.1 shows how SHAs categorize pavement types. In general, thirty-three states have cracking identification for both AC surfaced and PCC surfaced pavements, while Arizona, Alaska, and Massachusetts have specifications only about cracking for AC-surfaced pavement.

Figure 3.2 shows the detailed categorizations: seventeen states have cracking identification guidelines for flexible pavement and rigid pavement; fourteen states have them for flexible pavement, JPCP and CRCP; two states have them for flexible pavement, composite pavement, JPCP, and CRCP. In addition, South Dakota identifies other pavement types like aggregate road.

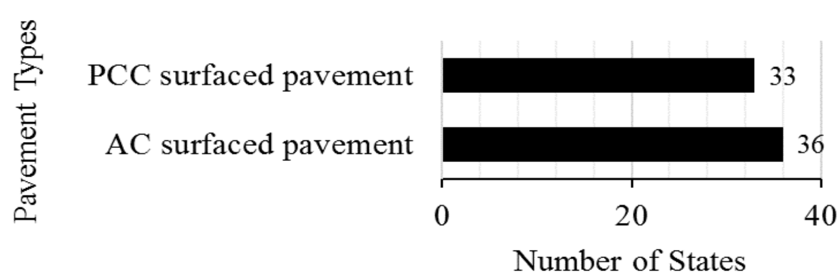

Figure 3.1 *Pavement surface categorization in group 1, 2 and 3.*

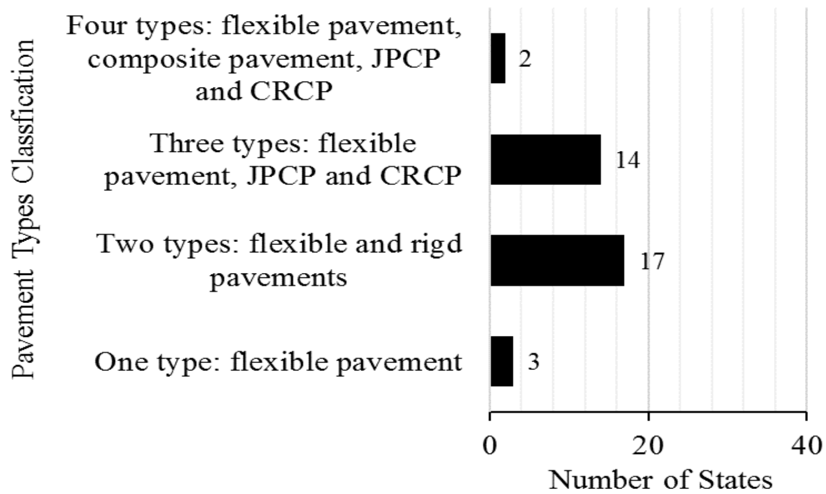

Figure 3.2 *Pavement categorization in group 1, 2 and 3.*

3.4.3 Cracking types

Figure 3.3 shows that many states in groups 1, 2, and 3 identify the common cracking types introduced in the LTPP distress identification manual for AC surfaced pavement. Twenty-eight states identify longitudinal cracking and another eight states combine it into other cracking types such as single cracking and load cracking. For transverse cracking, thirty-two states identify it and another four states combine it into other cracking types. Among these thirty-six states, twenty-nine states identify alligator cracking, twenty-six states identify block cracking, seventeen states identify edge cracking, and sixteen states identify reflection cracking. It should be noticed that Ohio identifies corner breaks and broken panels for AC overlay PCC; these two cracking types generally are associated with PCC surfaced pavement.

Some states identify the special cracking types shown in Figure 3.4. Michigan identifies transverse tear as different from transverse cracking; Ohio identifies thermal cracking; Alabama identifies both non-load and load associated cracking; Pennsylvania identifies miscellaneous cracking; Wisconsin and New York identify slippage cracking; Florida identifies combination cracking; California defines XF cracking. In addition, Kentucky, Massachusetts, and New York use "other cracking" to identify some uncommon cracking types. These crack types are totally different from the common ones, limited to only in a few states, and not introduced in the LTPP distress identification manual.

Figure 3.5 provides statistical data about common cracking types for PCC surfaced pavement. Twenty-four states in group 1, 2, and 3 identify longitudinal cracking for PCC surfaced pavement. Other states such as Alabama and Idaho do not include longitudinal cracking in their manuals, while some states like Kentucky and Nebraska use other terms to identify it. Transverse cracking is identified by twenty-five states, some states such as Georgia and South Dakota do not have related identification guidelines, and other states like New Jersey and Nebraska use other terminology. For other common cracking types, twenty-two states identify corner breaks, fourteen states identify durability cracking, and thirteen states identify map cracking.

As with AC surfaced pavement, some states have their own special cracking types for PCC surfaced pavement, as shown in Figure 3.6. For example, North Carolina and Virginia identify clustered cracks; broken-panels cracking is identified by eight states; cracked panels are identified only by Minnesota; Nebraska and New York identify slab cracking; California identifies XC, XJ, 1st stage, and 3rd stage cracks; Oregon and Wisconsin identify corner cracking; Texas identifies spalled cracking; Idaho and Wisconsin identify meander cracking. In addition, Kentucky, Texas, Washington and New Jersey use the term of "other cracking" to identify many cracking types not explicitly specified in their manuals.

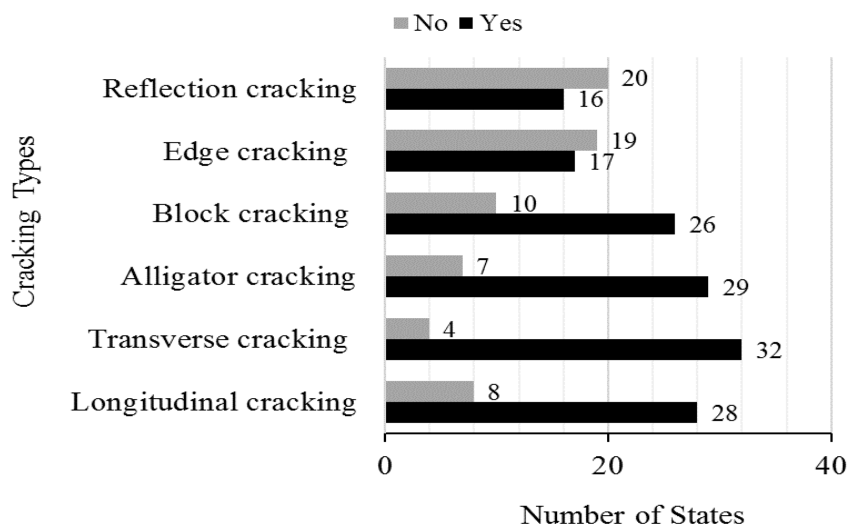

Figure 3.3 *Common cracking types summary for AC surfaced pavement in group 1, 2 and 3.*

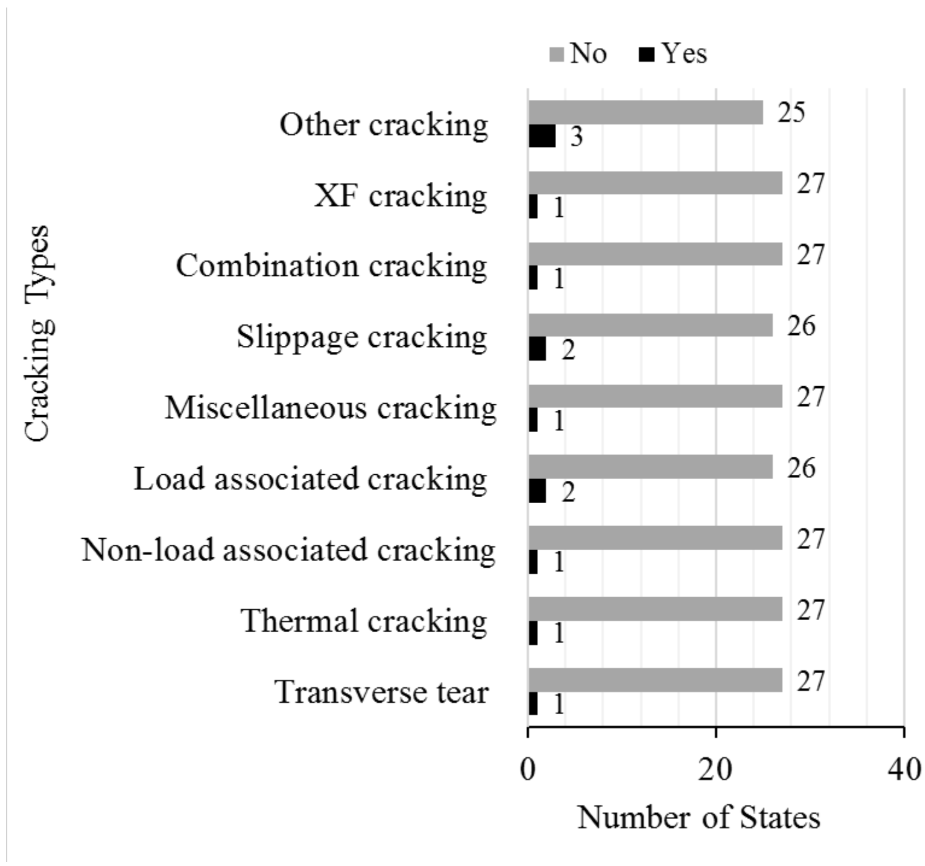

Figure 3.4 *Special cracking types summary for AC surfaced pavement in group 1, 2 and 3.*

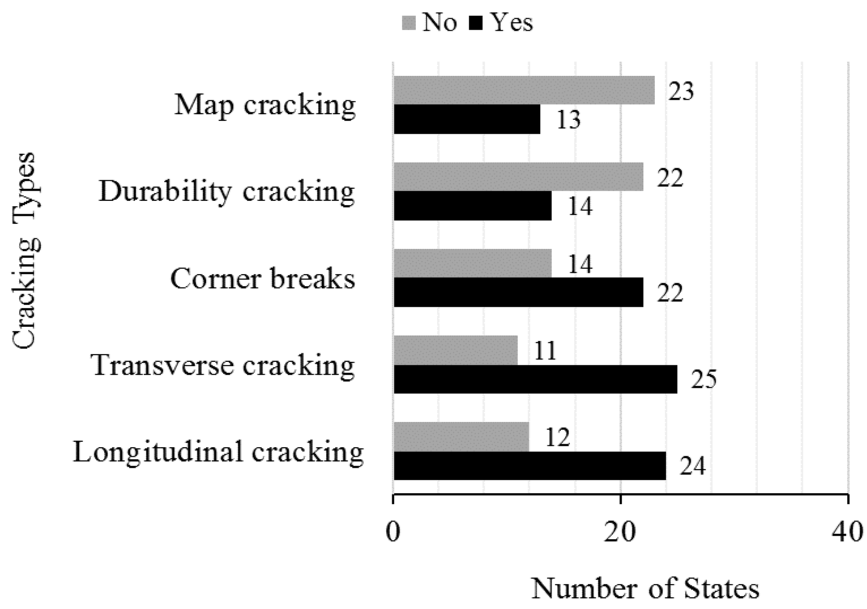

Figure 3.5 *Common cracking types summary for PCC surfaced pavement in group 1, 2 and 3.*

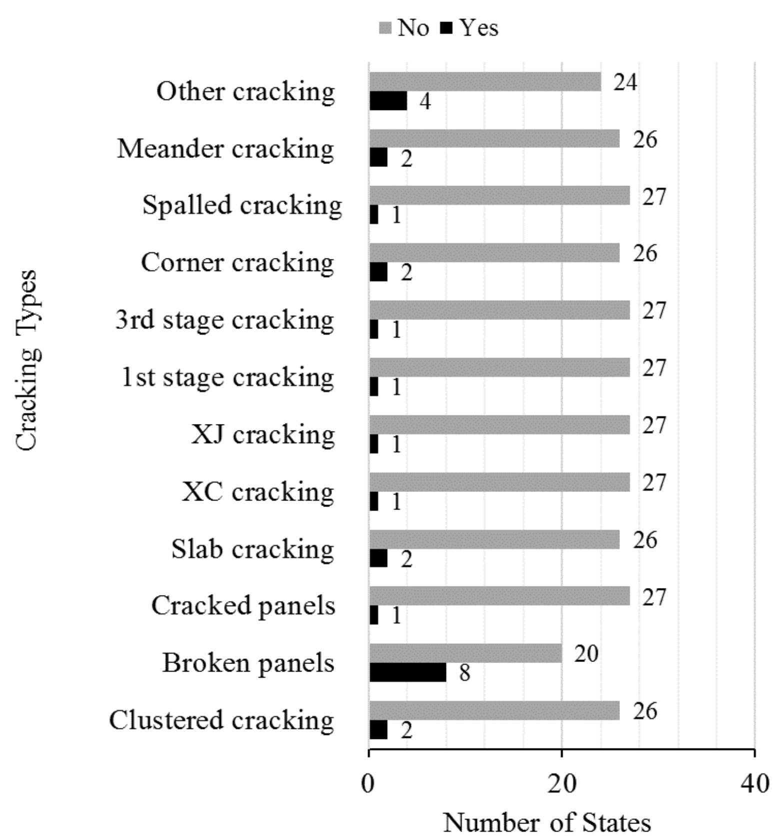

Figure 3.6 *Special cracking types summary for PCC surfaced pavement in group 2 and 3.*

3.4.4 Data collection method

A summary of data collection methodology is given in Figure 3.7. There are three data collection methods: manual, semi-automated, and fully-automated. For the states in groups 2 and 3, the manual method is most common, currently used by seventeen states. Automated methods have also been found to be effective in many states, and six have already produced guidelines. North Carolina accepts both semi-automated and fully automated methods. States that accept semi-automated methods also accept other methods, but no state uses only semi-automated methods. Illinois, Louisiana and New Mexico do not specify the data collect methods, but they accept manual, semi-automated, or fully automated methods. Massachusetts provides no information about its data collection method. As mentioned in NCHRP Synthesis 334, automated methods are safer and more efficient data collection methods than others, and this has become a trend that is recommended to many states currently using manual methods. A potential limitation of an automated method is its high cost.

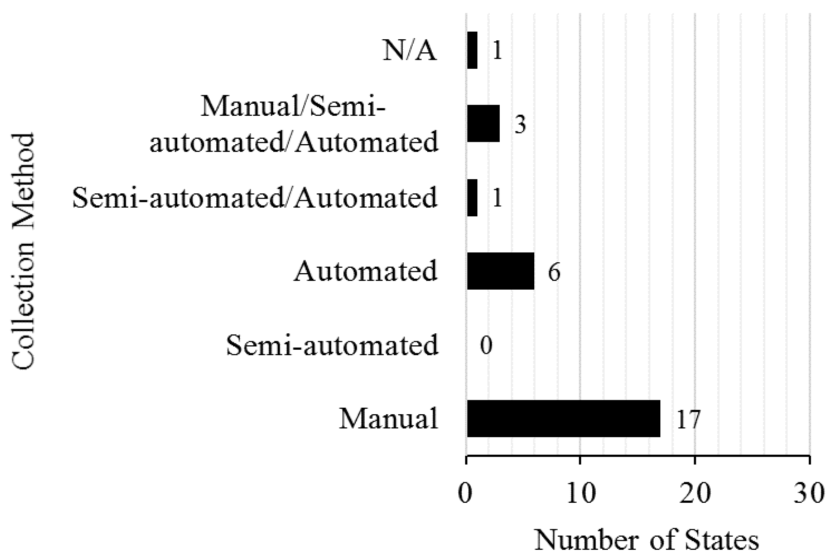

Figure 3.7 *The summary of data collection methods for the states in group 2 and 3. (Note: N/A is not available).*

3.4.5 Sampling method

The choice of sampling method in a distress survey focuses on two points. The first point relates to what percentage of the entire pavement system should be surveyed, and the other is the choice of pavement length for each survey form. Many SHAs do not make clear statements in their manuals about the first point. Only six states survey their pavements continuously (i.e., the entire pavement system). Figure 3.8 shows that twenty-nine states in groups 1, 2, and 3 regulate the surveyed length for AC surfaced pavement and twenty-seven states do this for PCC. Only Alaska and Arizona have guidelines about surveyed length for AC surfaced pavement, while seven other states such as Massachusetts do not address this issue for either AC and PCC surfaced pavements. Generally, the surveyed length is less than 1.6 km (1 mile) but for JPCP some states specify a number of slabs. It is also should be noted that a section generally may be divided into different traffic directions and different surveyed lanes. Although the section length is regulated, this is flexible in most states and can be changed based on local pavement conditions.

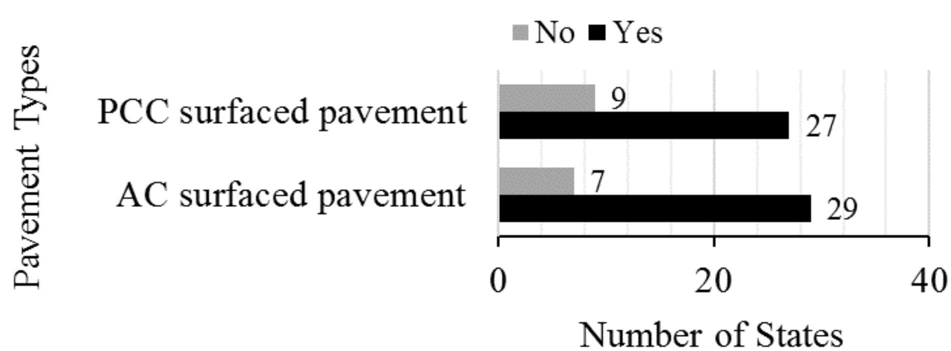

Figure 3.8 *The summary of surveyed section length for the states in group 1, 2 and 3.*

3.4.6 Measurement zone

The pavement surface can be divided into different zones for cracking identification and measurement. It is well known that some types of cracking are caused by repeated vehicle loads, so these cracks generally occur in the wheel path. Figure 3.9 shows that eighteen states in group 1, 2, and 3 provide no statement about how to separate pavement surface into different zones. For the other eighteen states, fourteen have two zones, wheel path and non-wheel path; one of them, New Mexico, has three zones, wheel path, mid-lane, and center line; another state, Pennsylvania, specifies five zones, the distance between wheel paths, inside wheel path, outside wheel path, lane center, and the center of outside wheel path on the lane; two states, North Carolina and Virginia, specify a variable number of zones based on the pavement width. Pavement surface zone separation for most states is used only for cracking identification. A few states require that crack data should be recorded for each zone. The other remarkable fact is that some states specify only a measurement zone for longitudinal cracking because this cracking type can occur in both wheel path and non-wheel path areas.

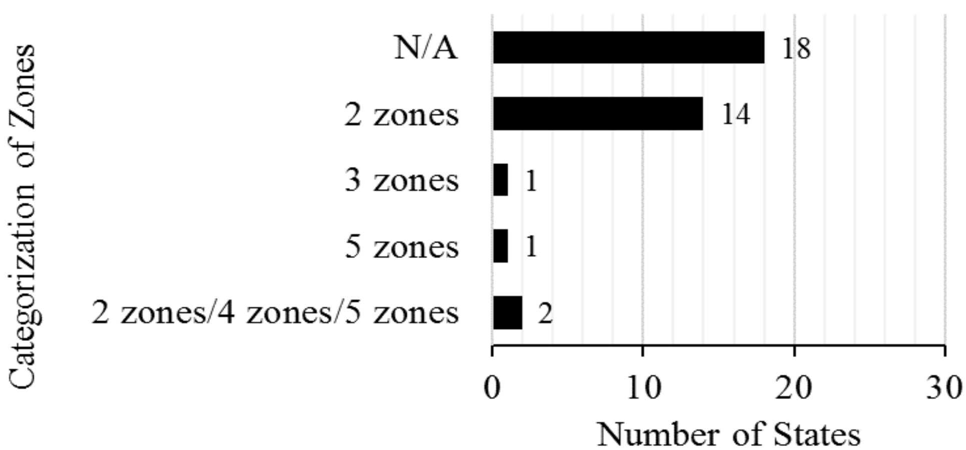

Figure 3.9 *The summary of measurement zone for the states in group 1, 2 and 3.*

3.4.7 Severity and extent categorizations

Severity and extent are important aspects of cracking data. In Figure 3.10, thirty-three states in groups 1, 2, and 3 define cracking severity for AC surfaced pavement; for PCC surfaced pavement the number decreases to twenty-nine. Three states, Louisiana, Texas, and Wisconsin, have no severity categorization for either AC and PCC surfaced pavements, and Alaska, Arizona, Massachusetts, and Minnesota do not have one for PCC surfaced pavement. The most common severity categorization is three levels: low, medium, and high, generally based on the cracking length, width, and visual assessment.

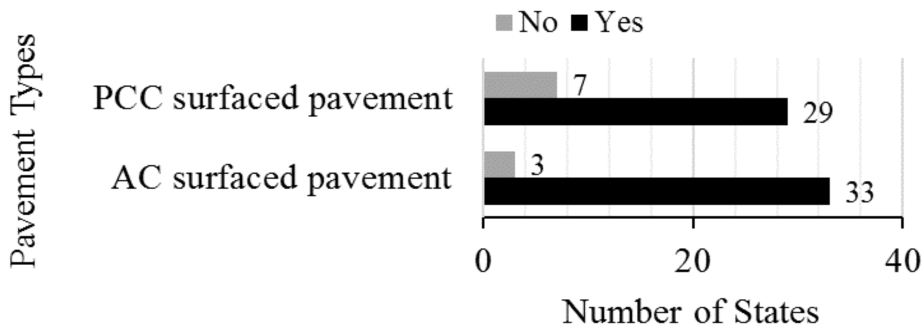

Figure 3.10 *The summary of severity for the states in group 1, 2 and 3.*

Several states also specify recording extent data of cracks, but in practice the extent of cracks usually gets less attention from SHAs than the severity of cracks. In Figure 3.11, thirteen and eleven states, respectively, define extent of cracking for AC and PCC surfaced pavements. The common categorization of extent also has three levels, similar to the categorization of severity.

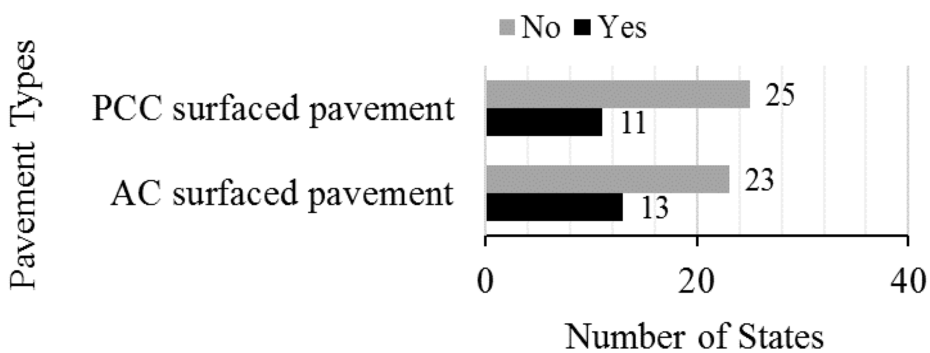

Figure 3.11 *The summary of extent for the states in group 1, 2 and 3.*

3.4.8 Pavement overall rating

Pavement overall rating is a scoring system used to comprehensively evaluate the pavement surface. Some, but not all, SHA manuals describe what kind of pavement scoring they utilize. The LTPP distress identification manual also does not introduce any pavement scoring. The statistical data shown in Figure 3.12 indicates that ten states in groups 2 and 3 utilize pavement scoring. Although each of these states describes how they evaluate pavement scores, their scoring systems are different. For example, the scoring systems may reflect pavement condition index (PCI), pavement serviceability rating (PSR), pavement condition rating (PCR), and others. Papagiannakis et al. (2009) summarized pavement scores synthesis for all fifty states and reported that only Oklahoma and Rhode Island have no clear statement about their pavement condition rating. The differences seen in this practice is reasonable because some state DOTs introduce their pavement scores in other documents rather than their distress identification manuals.

Figure 3.12 *The summary of pavement overall rating for the states in group 2 and 3.*

3.4.9 Survey frequency

Some states set their own regular schedules to survey their pavement conditions. A summary of survey frequency is given in Figure 3.13 that shows that eleven states in groups 2 and 3 have their own survey frequencies specified in their distress identification manuals. Among these eleven states, Louisiana, New York, and Wisconsin perform the survey every two years while the other eight states perform it annually. Although the Wisconsin manual specifies a survey frequency of two years, it also recommends an annual survey. In the LTPP distress identification manual, the survey frequency is not mentioned. The other eighteen states in groups

2 and 3 that provide no information about pavement survey frequency in their manuals may give related information in other documents.

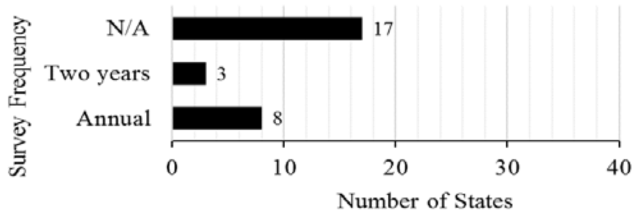

Figure 3.13 *The summary of survey frequency for the states in group 2 and 3.*

3.4.10 Verification

The cracking data verification process is an important part of QC/QA. Figure 3.14 shows that ten states in groups 2 and 3 indicate that their manuals provide verification processes for collecting data. Although these ten states give a clear statement about they have data verification, most of them give no details about how to verify collected data. As with the survey frequency, the LTPP distress identification manual provides no related specification.

Figure 3.14 *The summary of cracking data verification for the states in group 2 and 3.*

3.5 Comparison check with AASHTO PP 67and68

3.5.1 Comparison to AASHTO PP 67

AASHTO PP 67 and 68 provide detailed specifications about quantifying cracks and collecting images. Comparability between the current distress identification manual for each state and AASHTO PP 67 and 68 can be checked, although these two standard practices are used for AC surfaced pavement using automated data collection methods.

Comparability can focus on issues like terminology, data reduction, data analysis, data reporting, data interpretation, and data QC/QA. With respect to terminology, no state in groups 1, 2, and 3 follows AASHTO PP 67. Thirty-four states have their own terminologies that are partially similar to those of AASHTO PP 67. The other two states, Arizona and Massachusetts, provide no description of terminology in their distress identification documents. Data reduction is not discussed in many state manuals, and only four: Alabama, North Carolina, Virginia, and New Jersey, have their own specifications in this regard. In other words, no state follows AASHTO PP 67 with respect to data reduction. The data analysis described in AASHTO PP 67 includes surveyed section length, measurement zones, and crack measurement. With respect to these three aspects, no state totally conforms to AASHTO PP 67. The data reporting recommended in AASHTO PP 67 indicates how to record the severity and extent for each crack and how to report the pavement score, but still no state follows AASHTO PP 67 totally. Discussion of any erratic cracking data refers to data interpretation. AASHTO PP 67 considers the dramatic shift in severity and extent of cracks caused by the natural variation. This study has found that only four states: Arizona, California, Kentucky and Washington, treat data interpretation. As shown in Figure 3.14, ten states have a verification process, an important part of data QC/QA. However, manuals for these states lack details about QC/QA and are difficult to compare to AASHTO PP 67, so again data QC/QA in AASHTO PP 67 is not totally followed by these states. The conclusion is that AASHTO PP 67 is currently not followed and utilized as a reference by states.

3.5.2 Comparison to AASHTO PP 68

AASHTO PP 68 provides specifications for collecting images of pavement surfaces, and it provides detailed specifications for aspects such as dimensions of reported images and image resolution. A check of SHA specifications finds that while only four states: Alabama, North

Carolina, Virginia, and New Jersey have the related specifications, no state exactly follows AASHTO PP 68.

Comparability results show that the official documents for distress identification do not follow AASHTO PP 67 and 68 for any state. One of the most important reasons for this deficiency is that these are very new standard practices, published as late as 2016 and 2014, respectively, before which most states had already developed their own standard practices. Another reason is that manual data collection is still utilized by many states, and this method reflects few requirements regarding image quality, QC/QA, etc. Some states, however, have already recognized the advantages of using automated data collection methods, and when these states decide to switch to these newer methods, AASHTO PP 67 and 68 will be very useful references for them.

3.6 Conclusion

In conclusion, twenty-eight states specify their own individual practices for distress identification, and eight of them utilize LTPP distress identification manuals as their baseline. Each of the twenty-eight states uses a different method to survey their pavement surface condition. The differences are caused by a number of factors such as historical practice, environment, pavement design and construction, preservation strategy, and highway management systems. Since the LTPP distress identification manual is referenced by many states, some similarities can be found in different state documents. As with other significant national-level specifications, while AASHTO PP 67 and 68 are not followed by the SHAs, it is possible to foresee that these documents will be very useful and significant for those states planning to develop new specifications based on automated technology. In summary, the comparison between state practices and national standard practices made in this study can provide a significantly useful reference for developing new cracking identification practices or revising current ones for all fifty states in America.

3.7 References

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CHAPTER 4. EVALUATION OF THE EFFECTS OF CONCRETE GRINDING RESIDUE (CGR) ON SOIL PROPERTIES

A journal paper submitted to *Journal of Environmental Management*

Bo Yang[1], Bora Cetin[2,*], Yang Zhang[3,*], Chenyi Luo[4], Halil Ceylan[5], Sunghwan Kim[6], Masrur Mahedi[7], Sunghwan Kim[5]

4.1 Abstract

Diamond grinding of fresh concrete pavement surfaces is a widely-used concrete pavement rehabilitation technique for the correction of surface irregularities of concrete such as faulting and roughness. During grinding, slurries composed of cooling water, concrete and aggregate (referred to as Concrete Grinding Residue (CGR)) are generated. During this process, CGRs are mostly disposed along the roadside which can impact the chemistry of soils and vegetation growth along the roadways. To understand the effects of CGR on soil chemical properties, a controlled field study site was established with sixteen 2-m by 2-m (6.6 ft. by 6.6 ft.) experimental plots. CGR was applied at four different rates of 0, 2.24, 4.48, and 8.96 kg/m^2 (0, 10, 20 and 40 ton/acre). Each CGR rate was applied on four different plots at the site and soil sample was conducted at various time, one month, six months, and twelve months, after CGR

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application to measure pH, electrical conductivity (EC), alkalinity, metal concentration, water-extracted cation exchange capacity (WE-CEC), exchangeable sodium percentage (ESP), and percentage base saturation (PBS). Statistical analyses were performed to analyze the impacts of CGR on soil chemical properties. The results of statistical analyses indicated that the CGR application impacted the chemical properties of soil, and the impact of CGR became greater with an increase in the CGR application rates. In addition, the CGR impact decreased with soil depth. Soil pH, alkalinity, and EC increased with an increase in the CGR application rate. Concentrations of Ca, K, Mg, Na, Al, and Fe in soil increased with CGR, while such increases were not observed for Ba, Cr, Cu, Mn, and Zn. In general, the WE-CEC of soil increased after the CGR application. However, the changes in soil properties such as pH and PBS did not persist twelve months after the CGR application. The primary findings indicate that CGR can change soil chemical properties significantly, but these changes may not be negative to soil and plant environment.

4.2 Introduction

Diamond grinding of Portland Cement Concrete (PCC) pavement is a maintenance operation carried out to remove surface irregularities on concrete surfaces which ultimately improves the ride quality and longevity of highways. It is typically performed using a machine equipped with a rotating cutting head comprised of a series of closely spaced, diamond-tipped saw blades and spacers. During grinding operations, the water introduced to cool the diamond blades mixes with cut concrete residue. This process generates a high pH slurry byproduct referred to as concrete grinding residue (CGR). CGR composition can vary considerably depending on its concrete source and water quality. As a waste material, CGR should be handled properly, and allowable disposal methods vary across the United States. The three most common management practices for CGR disposal are; (1) spreading the slurry along the roadsides, (2) collecting the slurry, and (3) pond decanting of the slurry for recycling, or for transporting the slurry to treatment facilities (IGGA, 2013). While some states currently allow offloading of CGR along roadside foreslopes in rural areas (Iowa DOT, 2012; MPCA, 2012; NDEQ, 2016), the spreading of CGR below the shoulder may have long-term impacts on soil properties and may threat on the soil and plant environment due to the high pH, alkalinity, and possible metal leaching of CGR materials (Mamo et al., 2015; Kluge et al., 2017).

Recently, some efforts have been made to characterize the nature of CGR and its impact on soil after slurry application. Holmes and Narver (1997) analyzed CGR samples collected from a surface grinding operation in California, and they reported that the pH and toxicity characteristics of CGR with a 10% solids content did not exceed the California Title 22 hazardous waste standards. Yonge and Shanmugam (2005) reported that pH values of CGR slurry used in Washington State in a slurry neutralization experiment ranged from 11.9 to 12.1. This study also indicated that soil pH increased by 1 to 2 units after CGR was applied. This study also observed that the concentrations of Mg and Ca in soil were increased with CGR application. DeSutter et al. (2010 and 2011) collected CGR slurry samples from multiple sites representing various geographical distributions in the United States. In this study, slurry pH values ranged from 11.6 to 12.5, and trace metal concentrations were below the EPA toxicity limits (U.S. EPA 2018). DeSutter et al. (2010) also observed that shoot growth was promoted in small slurry application rates and inhibited for large slurry application rates. Mamo et al. (2015) reported that the pH values of reconstituted slurry ranged from 9 to 10, and the effective calcium carbonate equivalent (ECCE) ranged from 13% to 28%. This study also highlighted that the effects of applied slurry up to 8.96 kg/m^2 (40 ton/acre) on roadside soil pH, EC, and levels of Ca, Mg, Na and K were not significant after 12 months of slurry application. Kluge et al. (2017) reported that pH values of slurry samples provided by the Florida Department of Transportation (FDOT) were in the range of 11.4 to 11.8, and the results of X-ray fluorescence (XRF) and X-ray diffraction (XRD) in their study indicated that the contributors of high CGR pH values were lime (CaO) and magnesia (MgO). The measurements carried out by Wingeyer et al. (2013) showed that, after a four-week period following the application of slurry (9 kg/m^2 (40 ton/acre), the soil pH increased by 0.11 units compared to that of the control site. Soil electrical conductivity (EC) and exchangeable Na, Ca contents were also increased, while Mg and K levels were significantly decreased in the area to which slurry was applied. Although these studies provided information about the properties of CGR and its effects on soil and vegetation, more studies on different CGR sources and native soil responses should be performed because CGR quality can vary, and the impacts of CGR on alkalinity, soil WE-CEC, ESP and PBS have not been well studied. The current study, not only quantifies the effects of CGR on several soil chemical properties, but also investigates the variations in CGR effects at various soil depths and at various times after application. In the current study, a controlled field site was established. Different rates of CGR were applied on the same soil to characterize the impacts of CGR on soil properties under local conditions. Samples were taken at different depths in each plot. pH, EC, alkalinity, metal contents, WE-CEC, ESP, and PBS of each sample were measured.

4.3 Materials and Experimental Plan

4.3.1 Concrete Grinding Residue and Soil

Fresh concrete grinding residue was obtained from a diamond grinding operation on McAndrews Road in Apple Valley, Minnesota. The slurry was offloaded into 5 gallon buckets and transported to the laboratory. Due to the different solid contents in each bucket, all collected slurry samples were mixed together in a single tank to obtain a homogenous mixture for application. The physicochemical properties of the CGR are given in Table 4.1. The specific gravity (G_s) of the CGR, determined by a water pycnometer (ASTM D 854-14, 2014), was 2.4. The mixed slurry had a solid content of 44%, and its sand, silt and clay mass fractions were 43%, 42.8% and 14.2%, respectively. The pH, EC, and alkalinity of the CGR were 11.7, 13.7 dS/m and 300 mg/L of calcium carbonate ($CaCO_3$), respectively. These measurements showed that CGR was a fine material with high pH (>11) and alkalinity. XRF analyses were carried out to identify elemental constituents of the CGR sample. Table 4.2 shows the chemical compositions, including specific oxides of the CGR and soil, respectively. The two most prevalent compounds in the CGR were Silica (SiO_2) (53.12%) and lime (CaO) (16.82%) which were also the major compounds in the concrete materials (Table 4.2).

4.3.2 Experimental Site and Soil Properties

The Kelly Farm, located at 1119 Xl Ave, Ames, Iowa (Northwest of Ames, Iowa), was chosen as the site to establish field test plots to evaluate the impact of CGR slurry on soil chemical properties. This site (Kelly Farm) was selected due to the presence of a mixed uniformly distributed prairie species including legumes and forbs which are commonly found plants on roadsides. In addition, the location of the Kelly Farm was not nearby a roadway which avoided automotive emissions and human activities from interfering with the study. The research site had a slope of about 6% in the southeast direction, and its total area of 196 m^2 (2110 ft^2) was divided into sixteen plots designated from 1 to 16, as shown in Figure 4.1. Each plot was a 2 m by 2 m (6 ft. by 6 ft.) square, and the closest distance (both in horizontal and vertical directions) between any two adjacent plots was 2 m (6.6 ft.). CGR slurry was applied on the sixteen sites at four different rates (dry slurry weight/area), i.e., A = control (no slurry), B = 2.24 kg/m^2 (10 ton/acre), C = 4.48 kg/m^2 (20 ton/acre), and D = 8.96 kg/m^2 (40 ton/acre). The properties of the Kelly Farm soil before application of CGR are provided in Table 4.1. Soil was classified as clayey sand according to the Unified Soil Classification System (USCS). It had a pH of 5.6, EC of 0.6 ds/m, and an alkalinity of 25.3 mg/L as $CaCO_3$. Additionally, WE-CEC, exchangeable sodium (ESP), and percent base saturation (PBS) of the soil were determined as 1.1 meq/100 gm, 5.4% and 94.4%, respectively.

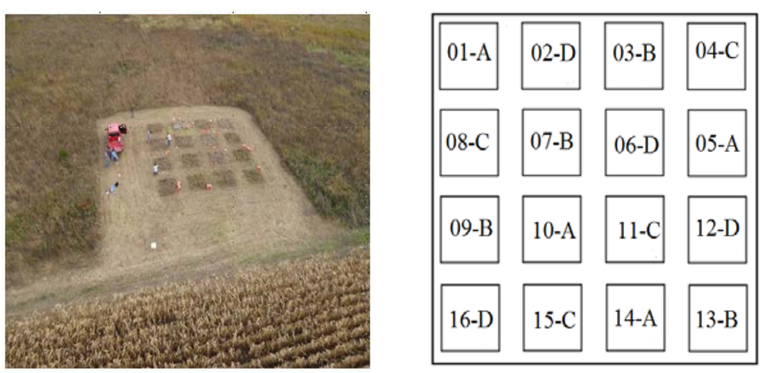
Table 4.1 *Characterization of CGR and soil at Kelly Farm site.*

Characterizations	**Soil**	**CGR**
AASHTO Soil Classification	A-2-6 (silty or clayey gravel and sand)	-
Unified Soil Classification	SC (clayey sand)	-
Specific Gravity	2.8	2.4
Sand (%): 0.074 mm - 4.76 mm	69.4	43.0
Silt (%): 0.074 mm - 0.002 mm	23.1	42.8
Clay (%): < 0.002 mm	7.5	14.2
Plasticity Index (%)	16.5	
$pH_{1:1}$	5.6	11.7
Electrical $Conductivity_{1:1}$ (ds/m)	0.6	13.7
$Alkalinity_{1:10}$ (mg/L of $CaCO_3$)	25.3	300
Cation Exchange Capacity (meq/100 gm)	1.1	
Exchangeable Sodium Percentage (%)	5.4	
Percent Base Saturation (%)	94.4	

Table 4.2 *XRF analysis of elemental abundances of soil sample.*

	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)	P_2O_5 (%)	TiO_2 (%)	BaO (%)	SrO (%)	Mn_2O_3 (%)	LOI[a] (%)	Sum (%)
CGR	53.12	7.87	3.81	0.68	16.80	2.84	1.51	1.82	0.10	0.44	0.04	0.04	0.07	10.87	100.00
Soil	78.10	8.62	2.44	0.02	1.06	0.52	1.59	1.33	0.08	0.41	0.04	0.02	0.06	5.20	100.00

a. LOI: Loss on ignition.



(a) **(b)**

Figure 4.1 *The aerial picture and layout of the test plots: (a) aerial picture of site and (b) layout of CGR application.*

4.3.3 Experimental Plan

The experimental plan included taking soil samples for comparison purposes from each plot at the times of one month, six months, and twelve months after the application of CGR. Soil samples were obtained from the 0 to 30 cm (12 in.) soil layer using a steel probe sampler. Samples were divided into three layers, i.e., topsoil from 0 to 10 cm, middle soil from 10 to 20 cm (4 to 8 in.), and bottom soil from 20 to 30 cm (8 to 12 in.). The soil samples were air-dried at 25°C, and a No. 10 sieve (2 mm) was used to remove plant residue and coarse particles. Soil samples were stored in clean plastic bags for further analyses.

4.3.4 Sample Analysis

Soil samples from different plots, layers, and time stages were analyzed for pH and EC using an Oakton PC2700 Meter. They were prepared with a 1:1 ratio of soil to deionized water (S/DI), and the measurements of pH and EC were performed in accordance with ASTM D4972-13 and C1A/3, respectively. Alkalinity of specimens was measured using the Hach alkalinity test kit No. 24443-01. After these three measurements, batch water leach tests were performed on the remaining portion of each sample (ASTM D 4793-93 (2004)). Samples were prepared at 1:10 S/DI ratio and were agitated for 18 hours at the rate of 30 rpm. Then, pH and EC were measured, and the supernatant solutions were filtered through 0.2 μm membrane filter. All filtered samples were acidified with 10% trace metal grade nitric acid. Acidified leachate was analyzed for metal concentrations, including Ca, K, Mg, Na, Al, Ba, Cr, Cu, Fe, Mn and Zn. Inductively coupled plasma atomic emission spectroscopy (ICP-AES) was used to measure the metal concentrations. These eleven elements were selected due to their importance for the plant growth, or because they may pose threats to the environment when leached at higher concentrations (Mengel and Kirkby, 1978). Three replicates for each specimen were analyzed. Equivalent mass of four exchangeable basic cations Ca, K, Mg, and Na were determined by a water extraction method to analyze the WE-CEC, ESP, and PBS (Midwest Laboratories, 2016; Sonon et al., 2012) after metal analyses were completed (Equation 1 to Equation 4). In addition to the soil chemical measurements after application of CGR, scanning electron microscope (SEM) and X-ray diffraction (XRD) measurements were performed to understand the microstructure and element contents of the specimens.

$$[X^{+a}] = M/[Z/A/10] \quad \text{(Equation 4.1)}$$

$$WE - CEC = [Ca^{2+}] + [K^{+}] + [Mg^{2+}] + [Na^{2+}] + [H^{+}] \quad \text{(Equation 4.2)}$$

$$ESP = [Na^{2+}]/CEC \times 100 \quad \text{(Equation 4.3)}$$

$$PBS = ([Ca^{2+}] + [K^{+}] + [Mg^{2+}])/\ CEC \times 100 \quad \text{(Equation 4.4)}$$

Where, $[X^{a+}]$ represents the milligram-equivalent weight of cation per 100g sample and is expressed as meg/100 gm; *X* represents the symbol of a cation; *M* represents the concentration of the cation and is expressed as mg/kg. *Z* represents the atomic weight of the element; *A* represents the number of valance.

4.3.5 Statistical Analysis

Data obtained from the soil chemical measurements were analyzed using a two-way analysis of variance (ANOVA). In this statistical model, CGR application rate, sampling depth and their interaction (CGR × Depth) were fixed, replication of offloading the same CGR rate on four different plots was considered as a random effect, and an $\alpha = 0.05$ level was set up to calculate the probability value (p value). The influence of a factor was considered significant when its p value was lower than 0.05.

4.4 Results and Discussion

4.4.1 pH

The pH results and corresponding p values are shown in Figure 4.2a and in Table 4.3, respectively. Figure 4.2a shows that soil pH is affected by the CGR rate and depth one-month after application, while it does not change considerably with depth after six months. The soil pH was elevated after CGR application, and this indicated that the soil pH was positively correlated with CGR rate at early stages, a result similar to that from Yonge and Shanmugam (2005), DeSutter et al. (2011) and Wingeyer et al. (2013). Increases in soil pH were due to the presence of high CaO content in CGR. As shown in Figure 4.2a, CGR application of 2.24, 4.48, and 8.96 kg/m^2 (10, 20 and 40 ton/acre) increased the topsoil pH values to 5.94, 5.86, and 6.01, respectively, after twelve months. This indicated that the liming effect of CGR produced a moderate improvement in pH. The essence of the increase in soil pH after application of CGR resulted from the high content of CaO along with the dissolution of MgO (Table 4.3). These compounds can form hydroxide compounds such as $Ca(OH)_2$ and $Mg(OH)_2$. In the presence of water, these compounds dissolve into hydroxides and ultimately raise the pH of the soil solution. Although an increase in soil pH due to CGR was found in Figure 4.2a, the pH at the middle and bottom soil layers was not significantly elevated ($p \leq 0.05$) six months after the CGR application. Most of the directly-dumped CGR solids were retained in the top soil layer due to the particle size of the CGR solid phase (43% of sand size particles). Thus, the top soil layer characteristics were more influenced by the CGR than the deeper soil (middle and bottom) layers. In addition to describing the effects of soil depth, Figure 4.2a also indicates that the pH of the top soil layer decreases from between 0.51 and 0.99 between 6 and 12 months after CGR application. The decrease in pH over time was due to CO_2 in the atmosphere which could dissolve in the soil and water to form carbonic acid and generate hydrogen ions to neutralize the elevated pH. Another reason for the reduction in pH over time was due to infiltration of rainwater and snow. These environmental processes caused some of the CGR to penetrate into the deeper soil layers with time. As a result, the relative content of CGR in the middle and bottom layers increased, which elevated the soil pH during the first six months. In summary, the application of CGR onto soil increased the topsoil pH by 1 unit or less.

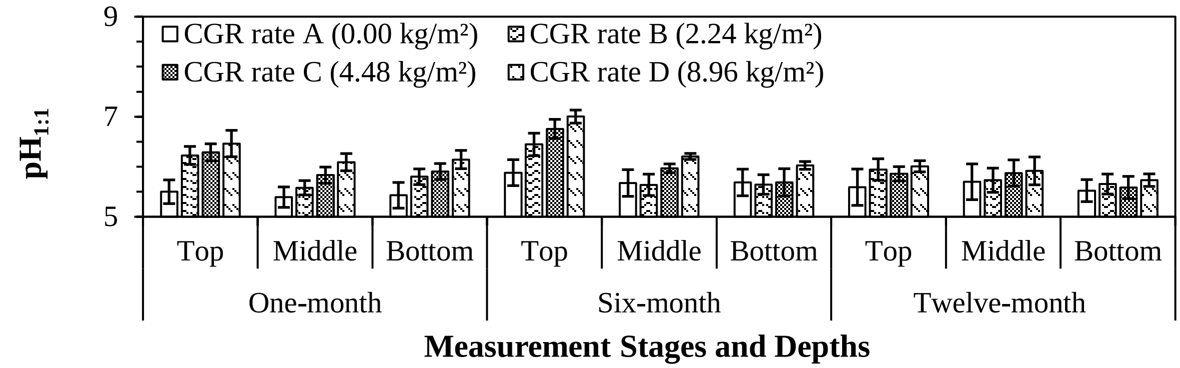
4.4.2 Alkalinity

Alkalinity represents the ability of a soil to neutralize its acidic pH that occurs due to rainfall or wastewater (EPA, 1994). Table 4.3 shows the statistical results for alkalinity. The p values lower than 0.05 indicate that the alkalinity at all stages is significantly influenced by the CGR rate and soil depth and the two-way interaction of both. Figure 4.2b shows that an increase in CGR application rate and application time increase the alkalinity of soil dramatically up to 160 mg/L as $CaCO_3$. The top soil layer exhibited higher alkalinity than the middle and bottom layers of soil. Scott (1985) and Scott (1986) indicated that CGR application could mitigate the effects of acidity within soil and improve the growth of plant species. CGR is a concrete waste which is rich in alkali and alkaline earth metals such as K, Na, Ca, and Mg. Therefore, it was expected that alkalinity would increase in soils exposed to CGR. K and Na are monovalent and the strongest alkalinity elements since they completely dissociate in aqueous solution. In addition, their hydroxide compounds can dissociate to form hydroxide ions which can float freely in aqueous solutions (Dye and Tepper, 2018). Ca and Mg are divalent and relatively soluble in water, meaning that, while they cannot be completely ionized as monovalent elements, they can form more hydroxide ions compared to other alkali metals such as Na and K (Kantor, 2016). Thus, CGR additions significantly elevated the alkalinity of the top soil layer, and with longer times after the CGR application more alkaline earth and alkali metal cations leached into the soil and strengthened its ability to neutralize acidity. Concentrations of these elements will be explained in detail in the metal analyses section.

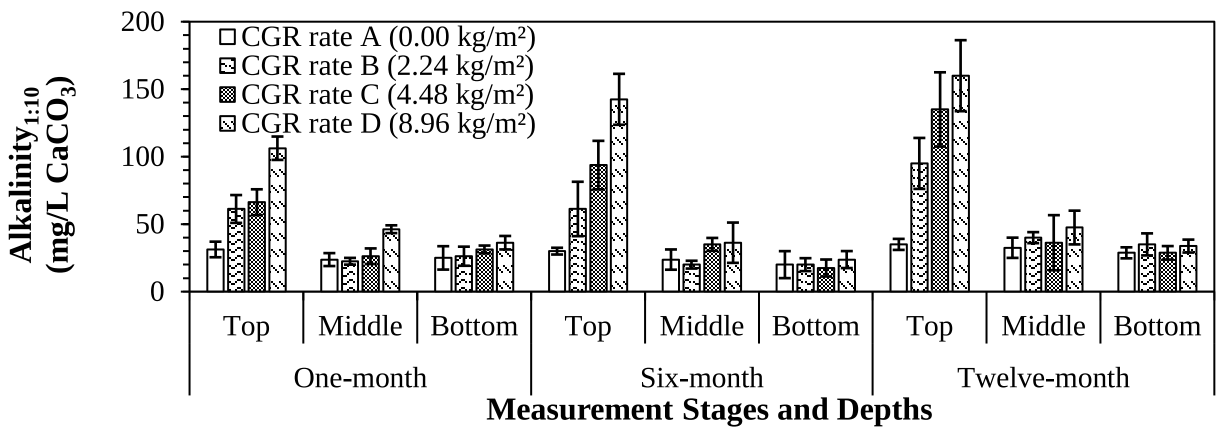
Table 4.3 *P values of two-way ANOVA for soil chemical properties after CGR application.*

Stages	Factors	*Pr > F*					
		pH	*EC*	*Alkalinity*	*CEC*	*ESP*	*PBS*
One month	CGR rate	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.875	0.931
	Soil depth	0.193	**<0.001**	**<0.001**	**<0.001**	0.064	0.061
	Interaction	0.984	**<0.001**	**<0.001**	**0.036**	0.913	0.916
Six months	CGR rate	0.085	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Soil depth	**0.014**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Interaction	0.868	**<0.001**	**<0.001**	**<0.001**	0.963	0.904
Twelve months	CGR rate	0.418	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.604
	Soil depth	0.276	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Interaction	0.919	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.492

Note: P values that are in bold are less than 0.05 (effect of factor is significant).

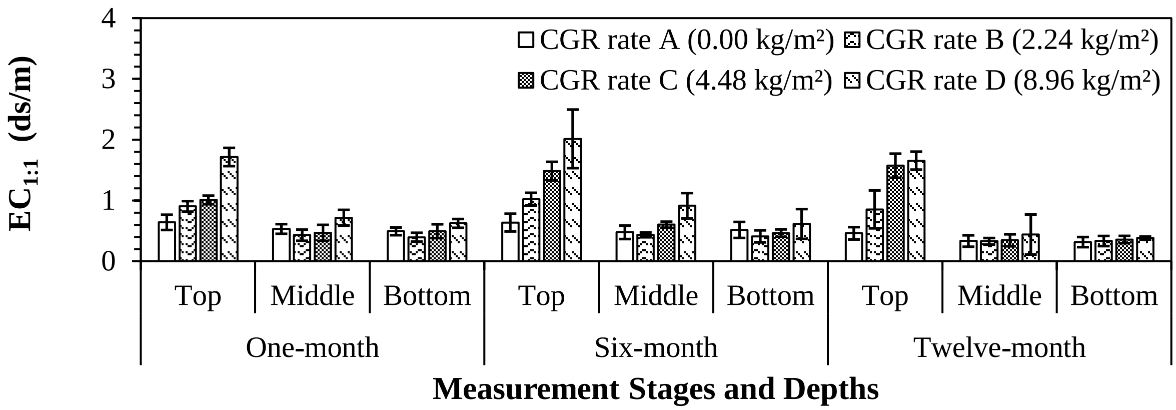


(a)



(b)

Figure 4.2 *Measurements of (a) pH, (b) alkalinity and (c) electrical conductivity of soil at different stages and depths.*



(c)

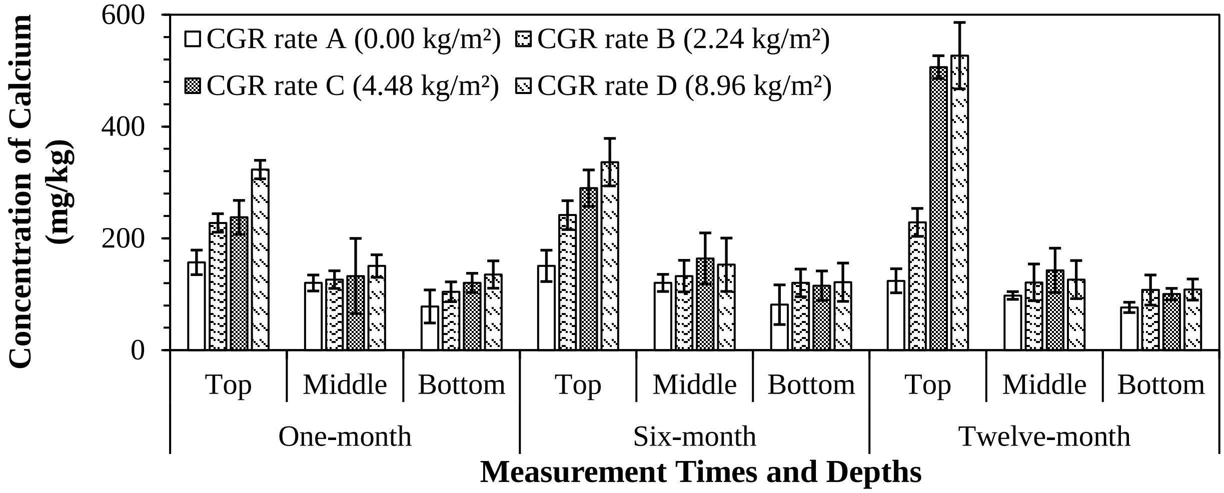
Figure 4.2 (continued).

4.4.3 Electrical Conductivity (EC)

Soil electrical conductivity (EC) is a measure of soil salinity and is an important indicator of soil health. CGR rate, soil depth, and their two-way interaction had significant effects on soil EC at all times after the CGR application (p values < 0.05, shown in Figure 4.2). EC results showed that the highest CGR rate could increase the soil EC from 0.55 to 2.01 dS/m. Figure 4.2c shows that higher EC values are observed with higher CGR application rates and in the top soil layer. Desutter et al. (2011), Mamo et al. (2015) and Wingeyer et al. (2013) also found that soil EC increased when CGR was applied. For the field plots with 2.24 and 8.96 kg/m^2 (10 and 40 ton/acre) of CGR slurry, the respective EC reductions of 0.15 and 0.35 dS/m were observed after six months and twelve months. The primary contributor of higher EC was the massive amount of soluble salts derived from metallic oxides (e.g., CaO, MgO, K_2O) introduced from CGR. Because CGR had a large fraction of fines, its salts could easily dissolve in water to form an abundance of cations and anions, which increased the concentrations of total ions leading to increased soil EC. When CGR penetrated deeper into soil, EC values were also elevated. From the perspective of vegetation growth, high EC may have negative impacts, because higher osmotic potential around roots can decrease the ability of a plant to absorb water (Warrence et al., 2002). Waskom et al. (2014) pointed out that plants could grow at soil EC below 4 dS/m, and in this study the EC was below this threshold, indicating that the addition of CGR up to 8.96 kg/m^2 (10 ton/acre) should not limit plant growth.

4.4.4 Concentrations of Metals

CGR contains a number of metals which come from the cement, fly ash and/or slags used during concrete and cement productions. Determination of increases in metal contents is important for risk assessment of dumping CGR slurry on the soil surface. While the presence of excessive metals (Fe, Mn, Zn) may be toxic and contaminate soil and groundwater, some metals (Ca, K, Mg, Cu, Fe, Mn, and Zn) that are defined as nutrients may have positive impacts on vegetation growth (Barker and Pilbeam, 2015; Tchounwou et al., 2012). Figure 4.3a through Figure 4.3f lists the concentrations of six metals and Table 4.4 presents the p values of factors with respect to these elements and another five elements. The CGR rate, soil depth and their interaction exhibited significant effects on the Ca level of soil at all times after CGR application. Impacts of these factors were also significant for K, Al, and Fe after one month and six months. Mg was significantly affected by the CGR rate after one month and twelve months, and Na was influenced by CGR rate at all stages. For the other metals (Ba, Cr, Cu, Mn and Zn), CGR rate, soil depth and their interaction were not significant (Table 4.4), resulting from their low contents in CGR materials. Calcium compounds are major constituents in Portland cement production and combined with other metal compounds containing K, Mg, Na, Al, and Fe. Thus, concentrations of these elements in soils can increase through CGR offloading. As shown in Figure 4.3a and Figure 4.3c, the highest Ca and Mg contents, 526.8 and 56.1 mg/kg respectively, occur in the plots twelve months after the highest CGR rate (8.96 kg/m^2 (40 ton/acre)) was applied. K reflected the highest level of 90.6 mg/kg and this occurred for the highest CGR application rate after six months Figure 4.3b). At one month after CGR application, Na, Al, and Fe concentrations increased to 35.8 mg/kg, 9.7 mg/kg, and 6.9 mg/kg, respectively, in the highest CGR rate (Figure 4.3d through Figure 4.3f). Increases in metal concentrations were generally observed in the top soil layer. Weather events including rainwater and snow water could also alter the levels of metals. Results of this study showed that CGR slurry was likely to release metal over a year. Environmental effects (rainfall, dust, snow, and freezing and thawing) and anthropogenic effects in adjacent sites (such as application of fertilizers and emissions of farm vehicles) also had a potential to increase metals in the soil, as mentioned by Ho and Tai (1988) and Sutherland et al. (2000). Moreover, metals could penetrate into soil with water infiltration, or could be absorbed by plant roots, thus being reduced in the soil. Na is a functional nutrient for plants in soil, but an excessive amount of Na can cause the dispersion of soil particles based on the theory of electrical diffuse double-layer, resulting in restricted plant growth. Warrence et al. (2002) stated that Na ions could deflocculate fine-grained soil particles (particularly clay soil) because sodium was a monovalent and the dispersed clay particles could plug soil pores to cause lower permeability. Although divalent ions such as Ca and Mg could help to aggregate clay particles and could have the ability to nullify the soil dispersion caused by Na. From the perspectives of plant nutrient and soil behavior, the increased number of metal cations derived from CGR could play a positive role in soil condition and plant growth, and such conditions were supported by previous studies carried out by Desutter et al. (2011) and Mamo et al. (2015).



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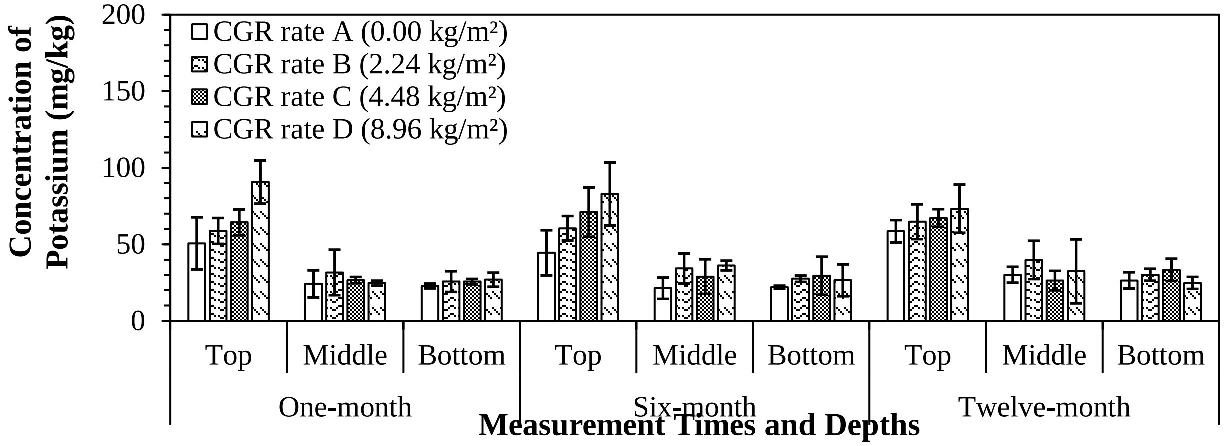

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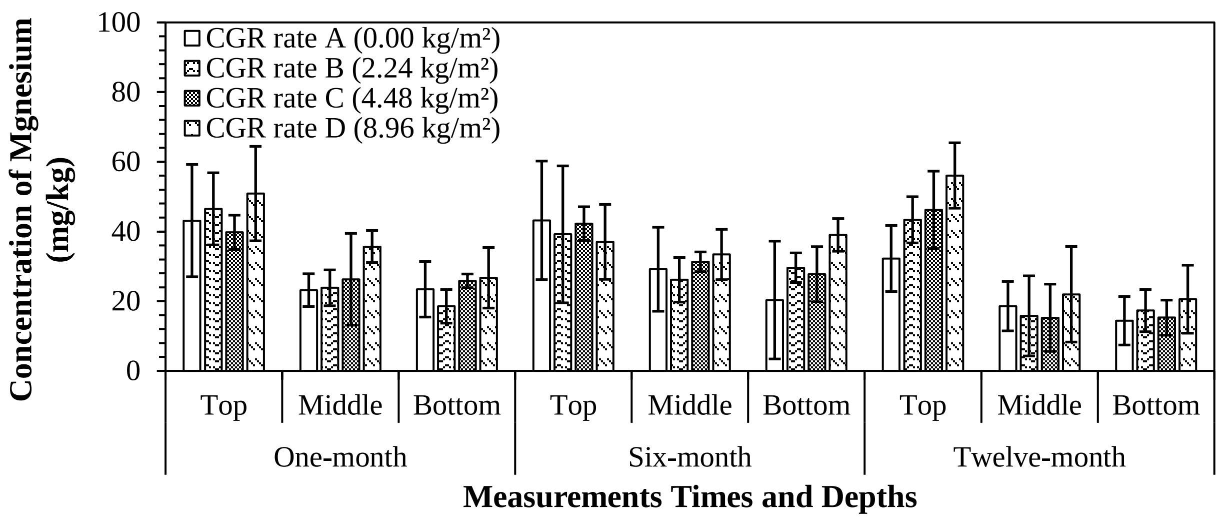
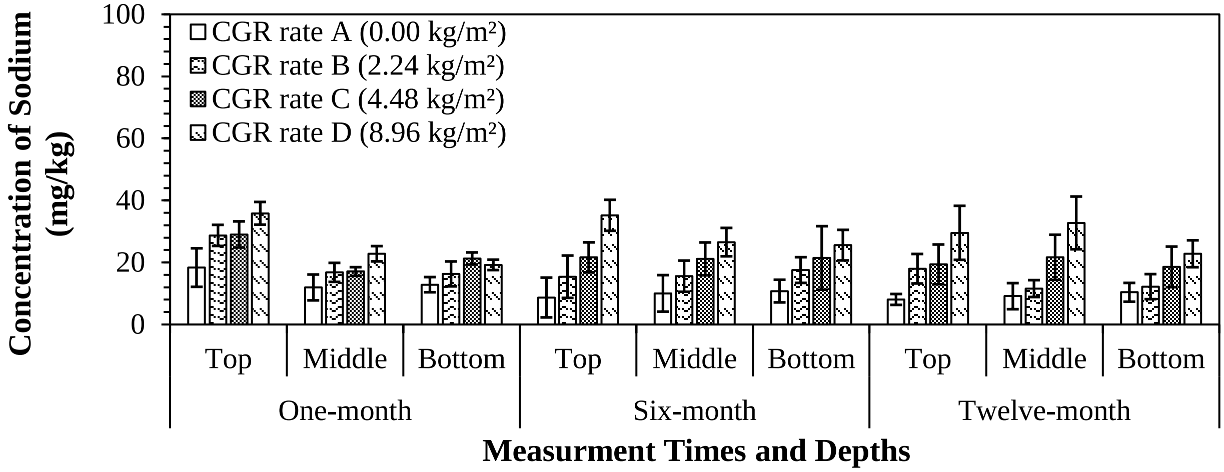


(c)

Figure 4.3. *Water extracted concentrations of (a) calcium, (b) potassium, (c) magnesium, (d) sodium, (e) aluminum (f) iron.*



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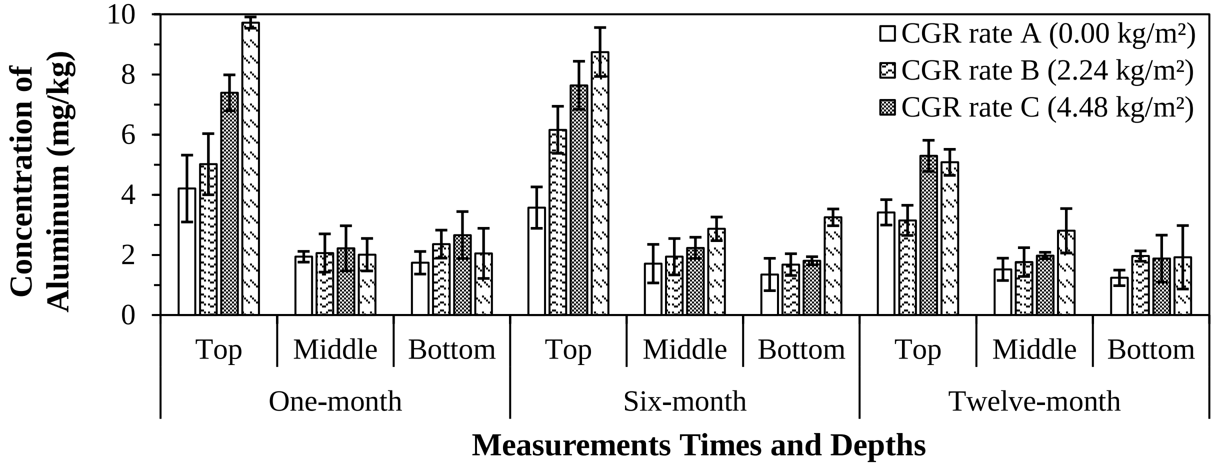

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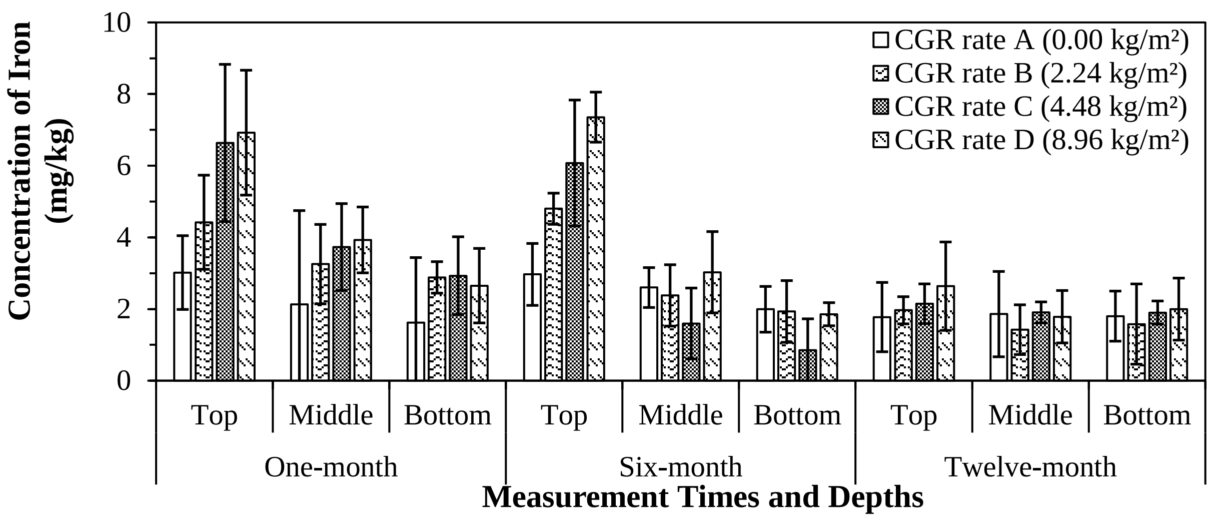
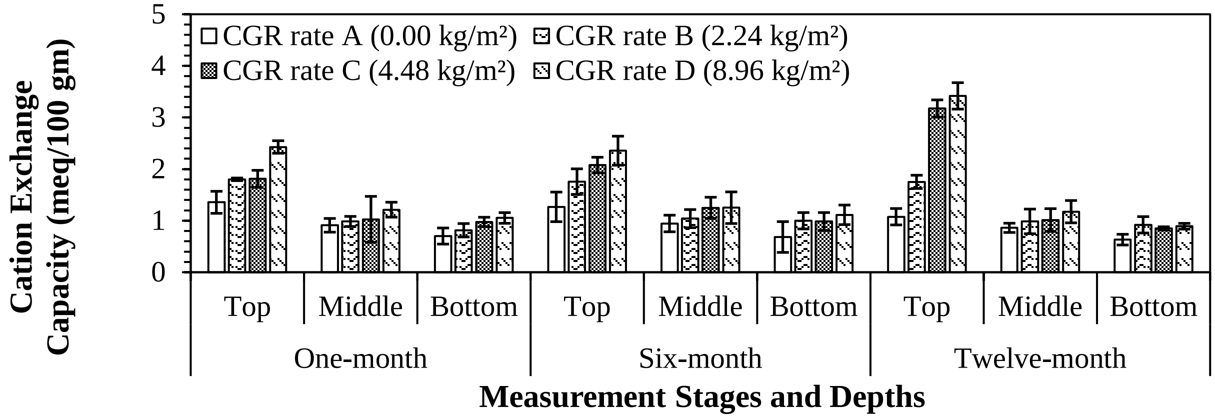


(f)

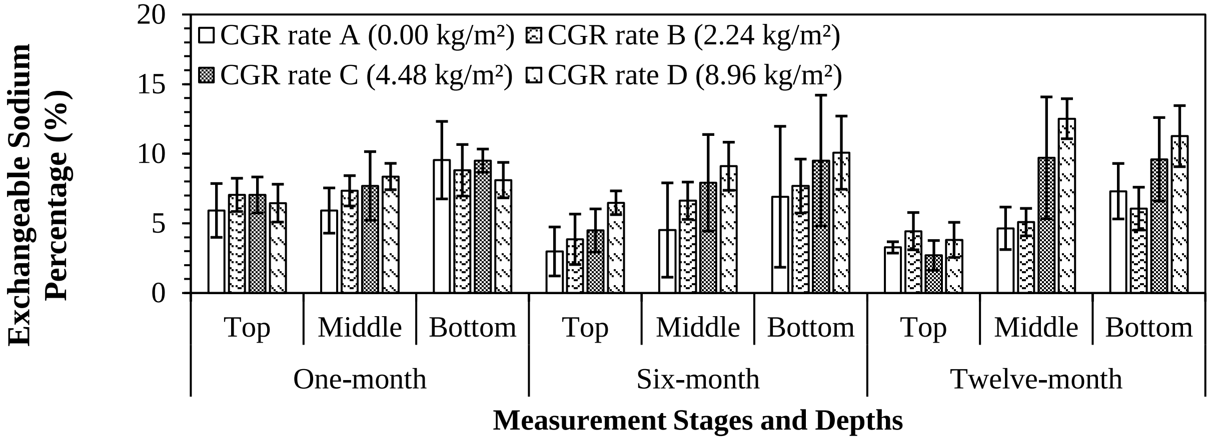
Figure 4.3 (continued).

4.4.5 Water Extraction Cation Exchange Capacity

The capacity of soil to hold exchangeable cations (nutrients) with respect to cation exchange capacity (CEC) was measured with a water extraction method. WE-CEC was significantly affected by CGR rate, soil depth, and two-way interaction at all sampling times, as shown in Table 4.3 (p value ≤ 0.05). As an important soil property, WE-CEC can influence the soil structure stability and nutrient availability for plants. Figure 4.4a shows the soil WE-CEC at the Kelly Farm site. Those plots received CGR exhibited higher WE-CEC, up to 3.42 meq/100 gm, than the WE-CEC value of 1.04 meq/100 gm for plots without CGR (soil alone). This indicated that the application of slurry increased the soil (especially the top soil layer) WE-CEC. The main contribution for such an increase in WE-CEC probably resulted from the chemical composition of CGR which could elevate soil pH and introduce metal cations in soil. Sonon et al. (2014) stated that WE-CEC was a pH-dependent property which could increase with an increase in pH by liming. At higher pH conditions, acidic elements such as Al^{3+} tend to dissolve in solutions, thereby improving the ability of the soil particles to hold the exchangeable cations such as Ca^{2+}, Mg^{2+} and K^{+} which ultimately increases the soil WE-CEC. Furthermore, cement fines and its hydration products (calcium-silicate-hydrate (C-S-H)) have high specific surface areas and negative surface charges (Labbez et al, 2006; Dhir and McCarthy, 1999; Gartner et al., 2017), reflecting a good ability to hold cations. In consideration of these influences, the addition of CGR to soil has a potential for increasing the soil WE-CEC. Thus, this practice can be beneficial for vegetation growth due to an enhanced ability to hold nutrients as WE-CEC increases.



(a)



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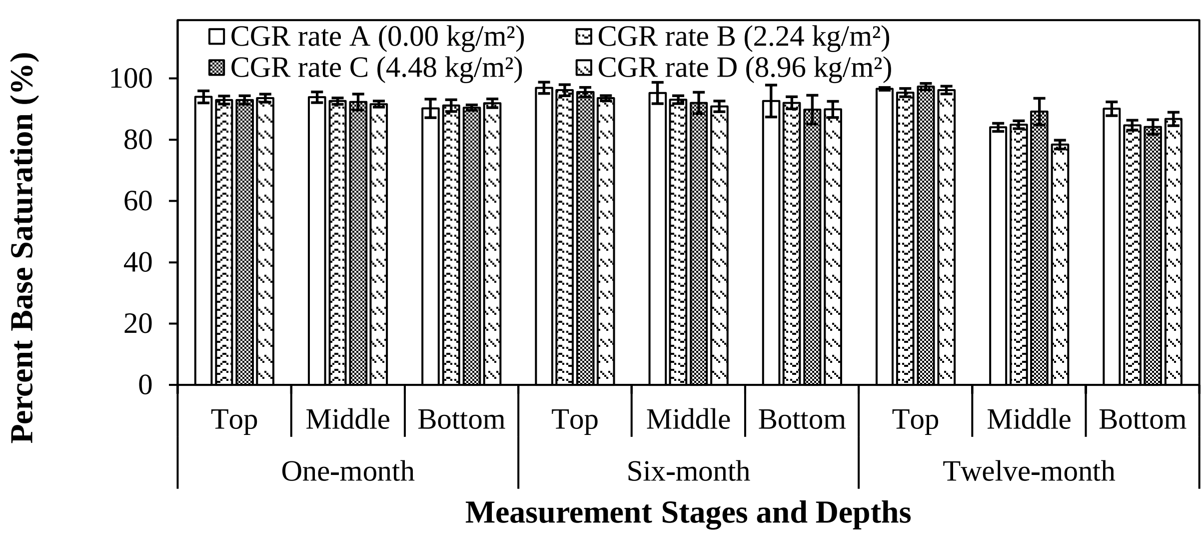


(c)

Figure 4.4 *Measurements of (a) cation exchange capacity, (b) exchangeable sodium percentage and (c) percent base saturation of soil at different stages and depths*.

Table 4.4 P *values of two-way ANOVA for levels of metals in soil after application of CGR.*

Stages	Factors	*Pr > F*										
		Ca	*K*	*Mg*	*Na*	*Al*	*Ba*	*Cr*	*Cu*	*Fe*	*Mn*	*Zn*
One month	CGR rate	**<0.001**	**0.024**	**0.233**	**<0.001**	**<0.001**	0.775	0.289	0.141	**<0.001**	0.095	0.815
	Soil depth	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.071	0.074	0.758	**<0.001**	0.336	0.989
	Interaction	**0.014**	**0.013**	0.871	0.528	**<0.001**	0.322	0.053	0.421	**<0.001**	0.870	0.201
Six months	CGR rate	**<0.001**	**<0.001**	0.456	**<0.001**	**<0.001**	0.098	0.308	0.123	**<0.001**	0.655	0.525
	Soil depth	**<0.001**	**<0.001**	**0.002**	0.617	**<0.001**	0.944	0.427	0.197	**<0.001**	0.197	0.687
	Interaction	**<0.001**	**0.049**	0.252	0.367	**<0.001**	0.415	0.108	0.106	**<0.001**	0.092	0.988
Twelve months	CGR rate	**<0.001**	0.380	**0.008**	**<0.001**	**0.003**	0.169	0.326	0.937	0.181	0.733	0.525
	Soil depth	**<0.001**	**<0.001**	**<0.001**	0.076	**<0.001**	0.178	0.753	0.700	0.126	0.080	0.687
	Interaction	**<0.001**	0.257	0.157	**0.022**	0.150	0.989	0.980	0.935	0.766	0.334	0.988

Note: P values that are in bold are less than 0.05 (effect of factor is significant).

4.4.6 Exchangeable Sodium Percentage

Exchangeable sodium percentage (ESP) is defined as the concentration of Na as a percentage of WE-CEC, and it is an indicator of soil sodicity. Sodic soils have negative impacts on plant growth (Warrence et al., 2002). The ANOVA results of ESP are shown in the Table 4.3. It was observed that the impact of CGR rate and soil depth significantly changed the ESP of soils at six-month and twelve-month stages. Figure 4.4b shows that ESP values increase in CGR-applied soil due to the increased proportion of Na in WE-CEC. At the six-month stage, the top, middle and bottom layer soil at the plot associated with the highest CGR rate had the highest ESP values of 6.48%, 9.10% and 10.08%, respectively. The ESP of the top soil layer was generally lower than those of the middle and bottom soil layers, which may have been caused by Ca, K, and Mg uptake by plant roots in the deep soil layer (Barker and Pilbeam, 2015). Most of the applied CGR was retained in the top soil layer, resulting in higher WE-CEC than in the deeper soil. As a result, the ratio of Na^+ to WE-CEC, i.e., ESP in the top soil layer became lower. High ESP is an indicator of more sodic soil (dispersion caused by Na) which can lead to a reduction in soil quality for plant growth and water infiltration (Subbarao et al., 2003; Shainberg and Letey, 1984). In this study, the ESP of soils with CGR ranged from 3.81% to 12.51%, and was categorized as low (<10) and intermediate (10<ESP<20) sodicity (Shainberg and Letey, 1984), indicating that CGR had a minimum to medium impact on soil water infiltration and quality.

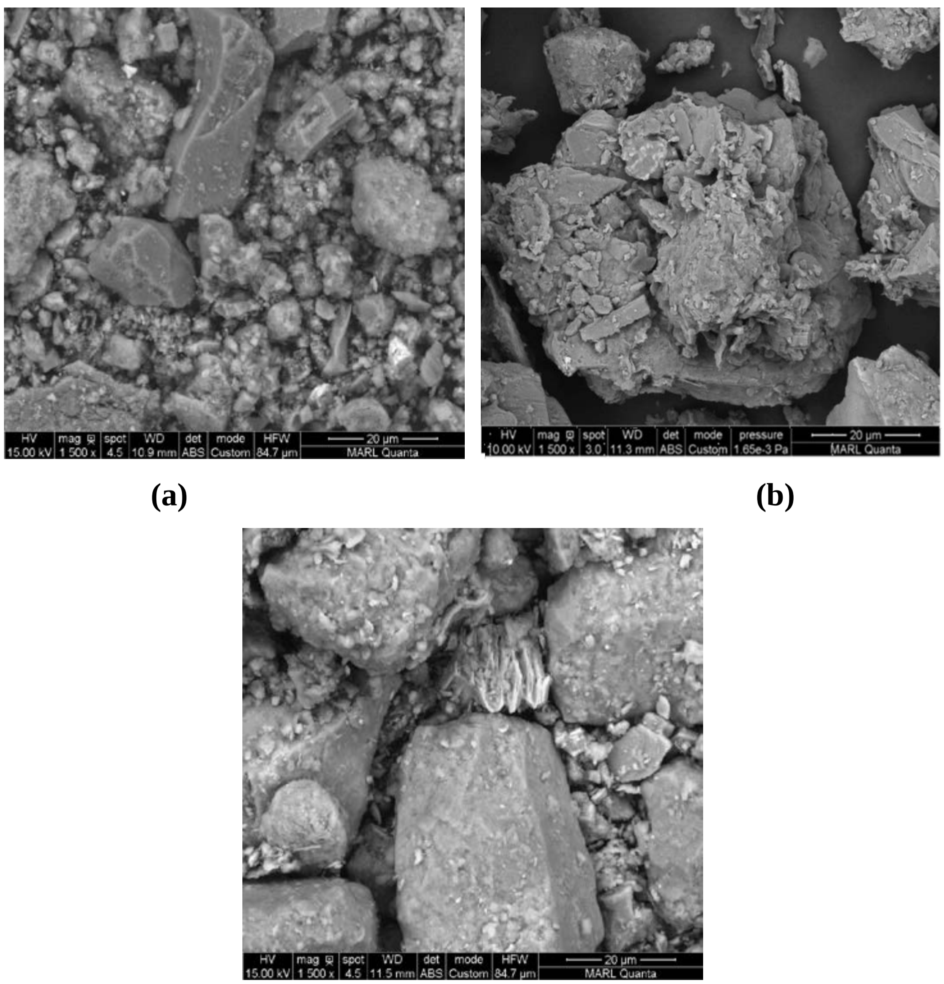
4.4.7 Percent Base Saturation

Percent base saturation (PBS) represents the percent of soil WE-CEC occupied by nutrient cations such as Ca, Mg, and K. In this study PBS was significantly influenced by the CGR rate after six months, as shown in Table 4.3. Another factor in this model was the soil depth which also had a significant effect on soil PBS after six-months and twelve-months. Figure 4.4c shows that the lowest PBS observed in the top soil layer was 93.52% at six months for the highest CGR rate. Middle and bottom soil layers exhibited lower PBS than those measured in top soil layers (Figure 4.4c). The reduction of PBS with the increased soil depth after applying of CGR was caused by the higher proportions of cations (Ca^{2+}, Mg^{2+} and K^{+}) in top soil layer WE-CEC. In general, higher PBS indicates more fertile soil since it reflects lower contents of acidic cations such as Al, neutral pH (5.5 to 7.0), and more nutrient cations (Sonon et al., 2014). Therefore, the addition of CGR did not cause significant reductions in soil PBS and soil fertility.

4.4.8 Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) Analyses

The morphologies of CGR and soil before and after application of CGR are shown in Figure 4.5. It shows that clear crystalline structures and boundaries are observed for CGR alone and soil alone particles. For the top soil layer after twelve-months, the presence of CGR can be identified (Figure 4.5c). However, no clear visual evidence about the formation of new compounds due to the chemical reactions between soil and CGR was observed in SEM images.

X-ray diffraction (XRD) is an analytical technique used for the identification of the crystal structure in materials (Borie, 1965). Figure 4.6 exhibits the representative parts of XRD patterns for CGR alone, soil along, and top, middle and bottom soil layers twelve months after CGR was applied. The common compounds in CGR and in a soil were identified as quartz (SiO_2), albite ($NaAlSi_3O_8$) and microcline ($KAlSi_3O_8$) (Figure 4.6a). CGR had a significant amount of calcite resulting in high calcite content in the top soil layer. Figure 4.6b shows that only the top soil layer has the highest calcite content twelve months after CGR application compared to those in the middle and bottom soil layers. These results indicated that CGR particles were not able to penetrate into the deep soil layer.



(a) **(b)**

(c)

Figure 4.5 *SEM images with 1500-x magnification for: (a) pure CGR; (b) topsoil before application of CGR and (c) topsoil at the stage of twelve-month after application of CGR.*

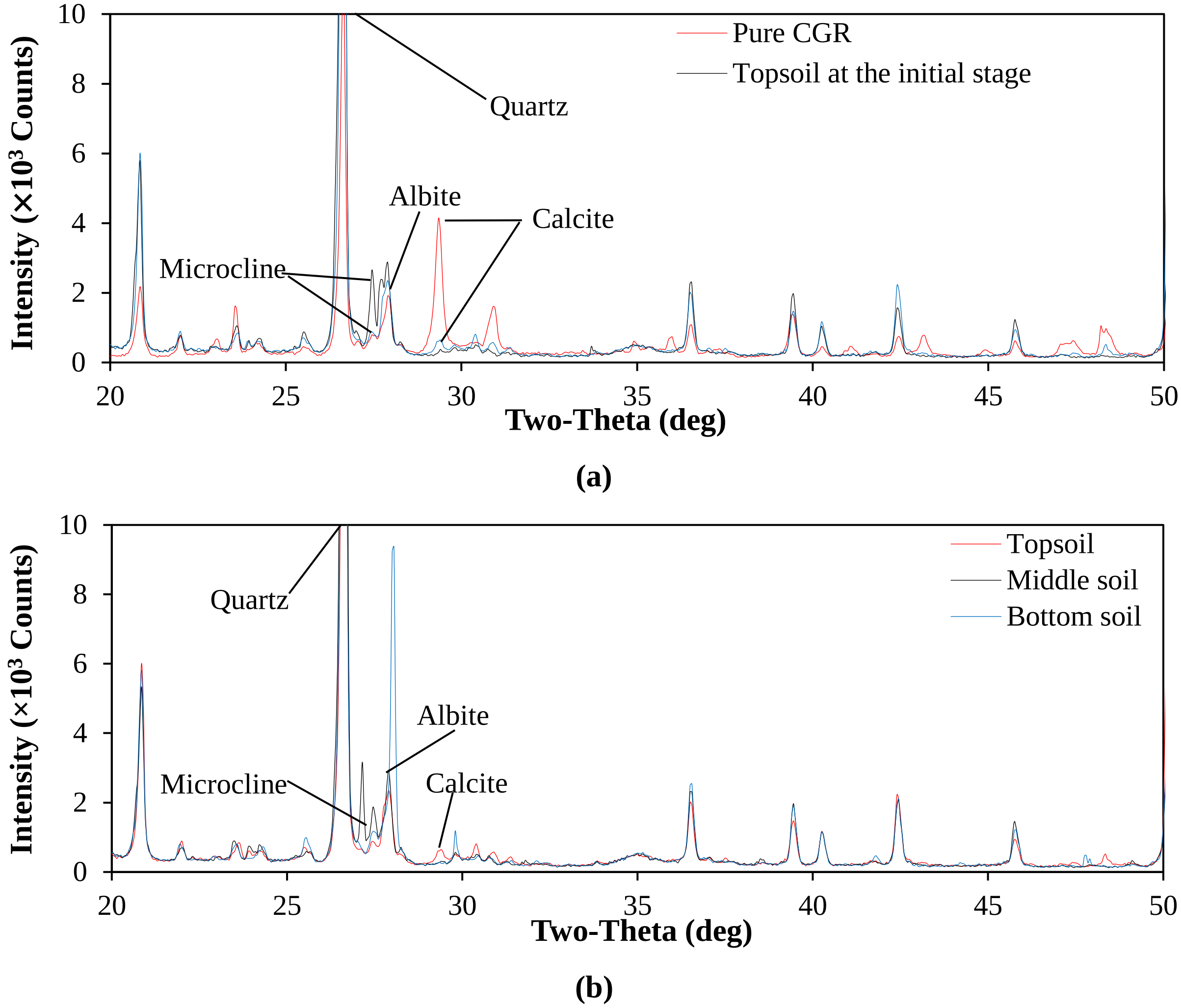


Figure 4.6 *XRD patterns for: (a) overlay patterns between CGR and the top soil layer and (b) overlay patterns between different soil layers twelve-months after application of CGR.*

4.5 Conclusions and Recommendations

Because the constituents of CGR depend on concrete composition and water used for blade cooling, its environmental impact can vary considerably. This study quantified the effects of different application rates of CGR on various soil chemical properties, including pH, alkalinity, EC, concentrations of certain metals, WE-CEC, ESP, and PBS at various soil depths. The findings and recommendations of this research study can be summarized as follows:

- Soil pH, alkalinity, and EC increased with an increase in CGR application rate, and the increase was caused by the liming and salinity effects of CGR. However, the impacts of CGR on the soil properties including pH, alkalinity and EC were lower at deeper soil layers because the solid phase of slurry did not penetrate deep into soil. This study also revealed that the effects of a CGR application on pH did not persist after twelve months.
- Concentrations of Ca, K, Mg, Na, Al, and Fe in soil increased after applying of CGR, but other metals like Ba, Cr, Cu, Mn, and Zn were not significantly impacted due to their relative low contents in CGR.
- Soil WE-CEC increased after the slurry application due to raised pH values and the negatively charged cement particles in CGR.
- CGR increased soil ESP after six months and twelve months, and the middle and bottom soil layers had higher ESP than those for the top soil layer. This may have been due to uptake by plant roots in the deeper soil layers. PBS was significantly decreased by CGR only at the six-month stage, probably due to the combined effects of changed cation contents and plant uptake activities in soils.
- CGR applied onto soil continuously increased the soil pH, alkalinity and EC within the first six months due to an on-going release of metals (Ca, Mg, K, Na, etc.), although after some time (probably more than twelve months) its effects would most likely be mitigated due to environmental influences (weather, plant and microorganism activities).
- Increases in pH, alkalinity, nutrient metals (Ca, Mg and K) and WE-CEC caused by application of dry CGR, up to 8.96 kg/m^2 (40 ton/acre), indicated a potential to benefit plant growth in CGR offloading area. Changes in other soil properties such as EC, ESP,

PBS, and levels of Al and Na indicated a potential negatively affect to plant growth and soil structure.

Even though concrete pavement diamond grinding has been widely used over the past several decades, the environmental impacts of applying CGR to soil have not been thoroughly studied. From this field study, CGR was concluded to be a nonhazardous materials when the application rate was lower than 8.96 kg/m^2 (40 ton/acre), and its liming effects may help to improve the soil quality in acidic soil. Because both positive and negative influences of CGR additions to soil were identified in this study, proper management practices of CGR should be developed to maximize benefits and minimize the environment risks.

4.6 Acknowledgments

The authors gratefully acknowledge the Minnesota Department of Transportation (MN-DOT) for financial support (MN-DOT Contract No. 99004 Work Order No. 20). The MN-DOT Technical Liaison, Mr. David Hanson is greatly appreciated for his professional guidance on this study. The findings and opinions in this study are solely those of the authors. Endorsements by the MN-DOT and are not implied and should not be assumed.

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CHAPTER 5. CONCRETE GRINDING RESIDUE – MANAGEMENT PRACTICES AND REUSE FOR SOIL STABILIZATION

A journal paper submitted to *Transportation Research Board (TRB), Journal of the Transportation Research Board*

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5.1 Abstract

Concrete grinding residue (CGR) is a slurry byproduct produced from diamond grinding operations used to smooth concrete pavement surface. As a waste material, CGR consists of cooling water for blades and concrete fines from the removed concrete layer. Since the composition of CGR reflects high pH, it can be a critical environmental issue and should be managed properly to reduce its impact to the ecological system. To understand the current management practices of CGR throughout the United States, a comprehensive review of state regulations and a survey of Departments of Transportation (DOTs) and contractors were conducted in this study, with results showing that in many states detailed guidance for disposal of CGR to reduce risks was lacking. In addition, this study investigated the potential use of CGR for roadbed soil stabilization. To evaluate the performance of CGR for soil stabilization purpose, this study mixed 10%, 20%, 30%, and 40% of CGR by weight with two types of soils classified as A-4 and A-6 according to the American Association of State Highway and Transportation Officials (AASHTO). Unconfined compressive strength (UCS) and California bearing ratio

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(CBR), pH, electrical conductivity (EC), alkalinity, and cation exchange capacity (CEC) tests were conducted on specimens. Results of the strength tests showed that the soils treated with 20% of CGR had the highest strength. Other laboratory tests revealed that CGR treatment could reduce the maximum dry unit weight (γ_{dmax}) and plasticity and increase the pH, alkalinity, EC and CEC of soils.

5.2 Introduction

Diamond grinding is a widely-used rehabilitation technique usually referred to as resurfacing of Portland cement concrete (PCC) pavement. As a maintenance operation, diamond grinding can provide a smooth PCC surface with enhanced texture and skid resistance and less road noise. Typically, this operation uses a truck equipped with grinding heads at the ground level to saw the thin layer of concrete and grind it into fine particles, mix with cooling water for blades, then generate a slurry byproduct known as concrete grinding residue (CGR).

The composition of CGR can vary widely due to use of different Portland cement products and supplementary materials in concrete. Generally, CGR has high a pH and rich in metal content (e.g. chromium (Cr), iron (Fe)) due to the addition of fly ash and/or steel slag during cement production or concrete mix preparation. Thus, their inappropriate disposal may cause critical environmental issues on environmentally sensitive nearby areas (farmlands, lakes, creeks, rivers, and high groundwater table presence, etc.). On the other hand, CGR has a significant potential for reuse as construction material, liming products, or soil stabilizer due to its high pH and rich CaO content.

To understand the characteristics of CGR, several studies have been conducted with various CGR slurries. Holmes and Narver (1997) reported that CGR samples collected from a grinding operation in California had initial pH at the range of 9.4 to 11.1, and the cation and anion concentrations of aluminum (Al), iron (Fe), and SO_4 (sulfate) exceeded the California

Drinking Water Standard. DeSutter et al. (2010) and DeSutter et al. (2011) analyzed CGR slurry samples from grinding practices in California, Minnesota, Nebraska, Washington and Michigan, and the CGR pH measurements in those studies ranged from 11.6 to 12.5, with detected concentrations of arsenic (As), Barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), selenium (Se), and silver (Ag) below toxic limits, based on the 40 CER 261 standard. Other studies (Goodwin and Roshek, 1992; Hanson et al., 2010; Chini and Mbwambo, 1996) have reported similar results with respect to the pH of CGR slurries generated from multiple sites, ranging from 11 to 12.6. In addition to studies of nature identification of CGR, some researchers have also investigated its impact on soil properties. Measurements performed by Yonge and Shanmugam (2005) showed that both pH and concentrations of Ca and Mg of soil loaded with CGR slurry increased, while concentrations of lead (Pb), copper (Cu), zinc (Zn), and cadmium (Cd) were not significantly affected. DeSutter et al. (2010) summarized the effects of CGR on water infiltration time in soil, soil pH and EC, and change in metal concentrations of soils such as calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), chromium (Cr), lead (Pb) and strontium (Sr). Mamo et al. (2015) studied both short-term (1 month) and long-term (1 year) effects of CGR on soil properties and roadside plants in Nebraska, summarizing that slurry, slope, depth, and slurry-depth interaction were the most significant factors affecting the soil pH and electrical conductivity (EC), Ca, K, Mg, and Na concentrations for the first month after slurry application.

A summary based upon several literature reviews shows that CGR may pose some environmental concerns even though in some cases it seems to be environmentally friendly. In this study, a comprehensive review related to state regulations governing CGR management practices in all 50 state was conducted to understand the issues and concerns regarding the CGR use in the concrete industry and DOTs. In considering the properties of CGR, recycling of slurry waste in soil, concrete, and other applications could be an attractive alternative for ultimately improving roadway sustainability, long-term performance, and reducing life-cycle cost of pavement designs. For this purpose, this study also evaluated the possibilities for reuse of CGR in several applications, particularly highlighting CGR recycling for soil stabilization suggested by laboratory tests including unconfined compressive strength (UCS), California bearing ratio (CBR), Atterberg limits, pH, alkalinity, EC, and cation exchange capacity (CEC) tests. Microscopy technologies including scanning electron microscope and energy dispersive spectroscopy (SEM/EDS) were carried out as well to understand the mechanisms of soil stabilization through the addition of CGR.

5.3 Review of CGR Management Practices

5.3.1 Technical Guidance

Grooving and grinding pavement surfaces developed into global activities during the previous century. In 1972, International Grooving and Grinding (IGGA), a non-profit industry trade association, was founded to provide technical and professional guidance for properly grinding and grooving pavement surfaces. Based on several studies related to CGR characteristics, the major negative consideration related to slurry waste is the contamination of the local environment, especially bodies of water (Kluge et al., 2017). To prevent such contamination, the IGGA developed the best management practices (BMPs) for proper disposal of slurry by-products. The IGGA BMPs (2013) provided three methods shown in Table 5.1a to manage the CGR disposal. In some cases, CGR can be spread along roadsides in rural areas, while CGR generated in the urban area can be hauled and transported to chosen ponds for decanting or to waste treatment facilities for processing. It should be noticed that spreading of CGR to sensitive areas or drainage facilities (e.g., culverts, drain inlets) is prohibited by the

BMPs due to its high pH and metal contents. In fact, numerous previous tests have verified that CGR is a nonhazardous material (Holmes and Narver, 2015; Correa and Wong, 2001), and other studies conducted by DeSutter et al. (2011) and Mamo et al. (2015) pointed out that CGR application of may even have the positive impact on plant growth. In addition to the recommended proper disposal methods of CGR, the BMPs also proposed that pH values of CGR should be monitored and maintained at the ranges of 2 to 12.5.

5.3.2 State Management Practices

A survey to summarize the current CGR management practices of state DOTs and industrial contractors were conducted by authors. Results of the survey showed that some states had their own regulations for guiding CGR disposal which varied slightly from each other. Variations in CGR management practices in different states were a result of historical practices and variation in environments, construction materials, and design methods. Table 5.1b summarizes the local regulations for CGR disposal in all 50 state DOTs. Based upon the review of the survey results and current guidelines of DOTs, 8 of the 50 states, including Indiana, Maryland, and a few others, had no regulations for managing CGR. For the other 42 states, cleaning CGR from the road surface was a basic requirement, with 19 states requiring continuous CGR removal, and 29 states emphasized the prohibition of CGR flow into drainage facilities or sensitive areas. The purpose of the cleaning requirement was to avoid CGR remaining on a pavement surface becoming airborne by the wind. Of the 42 states, 12, 11, and 8 states, respectively, allowed the roadside offloading, pond decanting and waste-facility processing. In other 12 states, contractors and engineers were required to provide a methodology for CGR disposal to minimize the risk to the environment. In this study, a survey distributed to the grinding contractors showed that following the state guidelines to manage CGR was a priority. If no state regulations were available, contractors generally either offloaded the CGR along the roadsides or disposed it to pond or waste facilities. Since CGR slurry in general had high pH, 7 states asked contractors to control the CGR pH (general below 12.5) prior to its disposal.

Table 5.1 *Guidelines of CGR disposal methods in (a) IGGA BMPs and (b) state regulations*.

(a)

Disposal Methods	Applicable Cases	Precautions
Spread CGR along roadsides.	In rural areas, CGR can be dumped along vegetated roadsides.	• Do not allow CGR to flow across the roadway into adjacent lanes. • Do not allow CGR to enter a closed drainage system. • Identify the wetlands and other sensitive areas before discharge of CGR. • CGR shall be spread with a minimum 0.3 m (1ft) distance from shoulder. • Do not spread CGR within 30.5 m of sensitive areas or within 0.9 m (3 ft.) of water-filled ditch.
Collect slurry for pond decanting.	In urban area and other areas with closed drainage system or sensitive environment, CGR can be disposed in a constructed pond.	1. The location of pond shall be approved by engineer. 2. Water in the pond can be decanted for reuse in the grinding operation. 3. Solids in the pond after drying can be reused as fill material or other useful applications. 4. The pond area shall be reclaimed and vegetated to avoid erosion.
Collect slurry for plant processing.	In urban area and other areas with closed drainage system or sensitive environment, CGR can be disposed in a constructed pond.	1. The plant processing shall be in accordance with state regulation. 2. The processed water and solids can be reused in the same applications as the decanting pond.

(b)

State	Reference	Prohibitive area to offload CGR	Disposal methods of CGR	Road surface clean	Control CGR properties
AK	AK-DOT and PF (2017)			Remove CGR continuously.	
AL	AL-DOT (2012)	Drainage facilities	Determine by contractor and engineer.	Remove CGR continuously.	
AR	AR-HTD (2014)	Drainage facilities and sensitive areas	Determine by contractor and engineer; Disposal in pond*; Disposal in pre-approved flat vegetated area*.	Clean CGR.	
AZ	AZ-DOT (2008)	Drainage facilities and sensitive areas	Determine by contractor and engineer.	Clean CGR.	
CA	Caltrans (2012a, 2012b)	Drainage facilities	Disposal in pond.	Clean CGR.	
CO	CO-DOT (2017)		Disposal off-site.	Remove CGR continuously.	

Table 5.1 (continued).

State	Reference	Prohibitive area to offload CGR	Disposal methods of CGR	Road surface clean	Control CGR properties
DE	DE-DOT (2016)		Determine by contractor and engineer.	Remove CGR continuously.	
FL	FL-DOT (2016)	Drainage facilities and sensitive areas	Determine by contractor and engineer; Follow IGGA BMPs*.	Remove CGR continuously.	Metal concentrations*; pH*
GA	GA-DOT (2013)	Drainage facilities		Clean CGR.	
HI	HI-DOT (2005)			Remove CGR continuously.	
IA	IA-DOT (2012, 2018)	Drainage facilities	Spread along roadsides.	Remove CGR continuously.	
ID	ID-DOT (2017)	Drainage facilities	Determine by contractor and engineer; Disposal in pond*; Disposal in waste plant*.	Clean CGR.	
IL	IL-DOT (2012)		Follow general waste management practices.	Remove CGR continuously.	
KS	KS-DOT (2007)	Drainage facilities and sensitive areas		Remove CGR continuously.	
KY	KY-TC (2012)	Drainage facilities	Determine by contractor and engineer.	Clean CGR.	
LA	LA-DOTD (2016)	Drainage facilities	Spread along roadsides; Disposal in pond*.	Clean CGR.	
MI[a]	MI-DOT (2011); MI-DEQ (2003)	Drainage facilities and sensitive areas	Spread along roadsides ($\geq$ 1.5-m from curb); Disposal in pond; Disposal in waste plant.	Clean CGR.	pH: $\leq$ 12.5
MN	MN-PCA (2012)		Spread along roadsides; Disposal in pond; Disposal in waste plant.	Clean CGR.	pH: 6 - 12
MO	MO-DOT (2018)	Drainage facilities and sensitive areas	Disposal off-site; Spread along roadsides.	Clean CGR.	
MS	MS-DOT (2017)	Drainage facilities	Determine by contractor and engineer.	Clean CGR.	
MT	MT-DT (2015)	Drainage facilities and sensitive areas	Disposal in pond.	Clean CGR.	
NE[a]	NE-DEQ (2016)	Drainage facilities and sensitive areas	Discharge along roadsides ($\leq$ 8.96 kg/m^2 (40 ton/acre) by CGR dry weight).	Clean CGR.	pH: $\leq$ 12.5*; TSS*
NV	NV-DOT (2014)	Drainage facilities and sensitive areas	Disposal off-site; Disposal in pond; Disposal in waste plant*.	Clean CGR.	
NJ	NJ-DOT (2007)		Follow general waste management practices.	Remove CGR continuously.	
NM	NM-DOT (2014)	Drainage facilities		Remove CGR continuously.	

Table 5.1 (continued).

State	Reference	Prohibitive area to offload CGR	Disposal methods of CGR	Road surface clean	Control CGR properties
NY	NY-DOT (2014)	Drainage facilities and sensitive areas	Disposal off-site.	Remove CGR continuously.	
NC[a]	NC-DOT (2015)	Drainage facilities and sensitive areas	Disposal off-site; Spread along roadsides; Disposal in waste plant	Clean CGR.	pH: 10 - 12
ND	ND-DOT (2014)		Follow general waste management practices.	Remove CGR continuously.	
OH	OH-DOT (2013)	Drainage facilities	Soil testing prior to a disposal plan needs to be provided and approved*.	Clean CGR.	PH: ≤ 11.5*
OK	OK-DOT (2009)		Spread along roadsides.	Remove CGR continuously.	
OR	OR-DOT (2018)		Follow general waste management practices.	Clean CGR.	
PA	PA-DOT (2016)	Drainage facilities	Follow general waste management practices (≥ 15.2-m from bodies of water or sewer system).	Remove CGR continuously.	
RI	RI-DOT (2013)	Drainage facilities	Disposal off-site.	Remove CGR continuously.	
SC	SC-DOT (2016)	Drainage facilities	Follow IGGA BMPs.	Clean CGR.	pH: 2 - 12.5
SD	SD-DOT (2015)			Clean CGR.	
TN	TN-DOT (2015)	Drainage facilities	Spread along roadsides; Disposal in pond.	Clean CGR.	
TX	TX-DOT (2014)	Drainage facilities	Determine by contractor and engineer.	Remove CGR continuously.	
UT	UT-DOT (2017)		Determine by contractor and engineer.	Clean CGR.	
WA	WS-DOT (2018)	Drainage facilities and sensitive areas	Disposal off-site.	Remove CGR continuously.	
WI	WI-DOT (2018)	Drainage facilities and sensitive areas	Disposal off-site.	Clean CGR.	
WV	WV-DOT (2010)	Drainage facilities	Determine by contractor and engineers; Spread along roadsides*; Disposal in waste plant*.	Clean CGR.	TSS*
WY	WY-DOT (2010)		Determine by contractor and engineer.	Remove CGR continuously.	

Statements with superscript "*" are responses from survey distributed to DOT engineers.
States with superscript "a" mean they recycle and reuse of CGR in some applications.

The review of state practices revealed that in many states CGR disposal methods were flexible and lack of detailed guidelines and control actions. Based on survey responses from few DOTs, CGR was regarded as a hazardous waste in Washington, Ohio, and Arkansas. Although some studies (DeSutter et al., 2011; Mamo et al., 2015)) did not expressly describe its negative impacts on plant growth, the variable characteristics of CGR may have caused environmental issues depending on the materials used during concrete production. In consideration of these concerns, it was recommended that CGR disposal could be managed by following the IGGA BMPs in combination with a pH control plan, or, if needed, with other control plans (TSS and Metals) to minimize the risk to the environment.

While the results of the survey and the review of current management practices of CGR of DOTs provide valuable information to the transportation agencies and industrial contractors, this study also started investigating the potential reuse of CGR in soil applications for strength gaining which had not been a practice for any state DOTs or industrial contractors. The current study is the first research to authors' knowledge that CGR is investigated to be reused in such applications.

5.3.3 Applications of CGR Recycling

In addition to the more common CGR disposal methods, recycling and reuse is strongly recommended for achieving the goal of sustainable pavements. There are three states providing relevant guidelines with respect to land application of CGR. Michigan (2003) not only allows reuse of CGR solids as a construction fill material or a liming product with a maximum rate of 1.12 kg/m^2 (5 dry ton/acre), but also approves their reuse after decanting for blade cooling. In Nebraska, the permit (2016) allows the use of CGR up to 8.96 kg/m^2 (40 dry ton/acre) for land application. North Carolina (2015) approves recycling of CGR for land application, irrigation, or dust control on NC-DOT projects. In addition, some efforts have been made to evaluate the reuse of CGR in various applications such as its use in construction material or in liming products.

Concrete waste can typically be used for partial replacement in concrete mixing or filling materials in construction. While Ravindrarajah and Tam (1987) reported a reduction in early-age strength in cement paste from the addition of recycled concrete fines, the studies of Hanson et al. (2010) and Janssen, et al. (2012) presented opposite results with the use of optimal percentage of fines within the cement paste. Goodwin and Roshek (1992) concluded that recycling of CGR as a filler in cement-treated base resulted in lower construction cost with a similar mechanical performance compared with the traditional industrial treatments such as processing in waste facilities. Amin et al. (2015) investigated the reuse of recycled concrete fines for strength gain within a cement mortar matrix, and showed that the rehydration was observed in the mortar which resulted in strength gain. On the other hand, Kluge et al. (2017) examined the CGR for potential use as a partial replacement of cement in new concrete and found no dramatic reactivity or improvement in mortar strength. Cavalline and Albergo (2017) performed a cost analysis and concluded that the use of CGR as a fill was the least expensive option for CGR disposal. Based on these studies, the use of concrete wastes, including CGR, as construction materials may be a cost-effective option for their disposal.

In addition to the investigation of recycled concrete as construction materials, some studies evaluated the use of CGR as a soil amendment. Berger and Carpenter (1981) suggested the use of recycled concrete waste to neutralize acidic soils due to its high pH and alkalinity. Hansen (2004) discussed a variety of potential uses for CGR, including wastewater treatment filters, poultry grit, limestone substitution in SO_2 scrubbers, and stabilizing sewage sludge. Hanson and Angelo (1986) concluded that the addition of crushed concrete fines may improve the engineering properties of clayey soils for earthwork purposes. While the literature indicates that CGR can have a beneficial utilization in soil amendment, soil testing and risk assessment at each specific site prior to applying CGR is strongly recommended to determine an optimum application rate.

The literature shows that while concrete fines may be a useful waste product for many applications. The solid phase of CGR can also be utilized in similar applications due to its chemical composition. However, applications of the CGR recycling may be restricted by a number of factors such as construction schedule, cost, existing environmental conditions, and local regulations. Thus, there is a need to enlarge the range of application areas of CGR. Soil stabilization is a common practice related to the application of additives (e.g. cement, lime, fly ash) to improve the engineering properties of subgrade soil for supporting pavement structures. The reuse of waste materials such as CGR in soil stabilization contributes to the reduction in hazardous environmental impact and strengthening the engineering properties of soils which can ultimately reduce the cost of construction and increase the service life of the pavement structure built on the stabilized soil. In this study, laboratory tests were carried out to evaluate the utilization of CGR as a soil stabilizer.

5.4 Use of CGR for Soil Stabilization

5.4.1 Materials

Two types of Iowa soils (Soil 1 and Soil 2) were collected in the current study. Index properties of these soils along with their pH values are given in Table 5.2. Soil 1 and Soil 2 were classified as A-6 and A-4, respectively, according to the AASHTO while they were classified as SC and CL-ML, respectively, according to the Unified Soil Classification System (USCS). Fresh CGR materials were obtained from an ongoing concrete pavement grinding project located in Apple Valley, Minnesota (MN). Table 5.2 also shows the properties of CGR materials. CGR slurry discharge was collected into water-tight tanker unit and then transported to the laboratory for further testing. All slurry was agitated in the water-tight tanker to ensure uniform/homogenous distribution of solids in the slurry before it was poured on a tray for air drying. After air drying process completed, the CGR was added into soils at 10%, 20%, 30%, and 40% by weight and mixed uniformly and compacted with standard Proctor energy at their corresponding optimum moisture content (OMC). CGR used in this study is a fine material with a pH value of 11.65. Table 5.3 shows that CGR is rich in SiO_2 (53%) and CaO (16.8%) contents. Other detected specific metallic oxides, including Al_2O_3, Fe_2O_3, and MgO, were probably introduced by the supplementary materials such as fly ash and steel slag used during cement production or concrete mixture preparation (Figure 5.1). Table 5.3 also shows that both soils have higher SiO_2 and lower CaO than that of CGR. Figure 5.1a shows that the major crystal structures of CGR consist of calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), quartz (SiO_2), albite ($NaAlSi_3O_8$), and microcline ($KAlSi_3O_8$) while it does not contain any major clay minerals. On the other hand, both soils had presences of montmorillonite, illite and kaolinite clay minerals (Figure 5.1).

Table 5.2 *Properties of soil and CGR investigated*.

Characterizations		**Soil 1**	**Soil 2**	**CGR**
Classification	AASHTO	A-6	A-4	-
	USCS group symbol	SC	CL-ML	-
	USCS group name	Clayed sand	Sandy silty with clay	-
Grain size distribution	Gravel (> 4.75 mm), %	7.1	0.1	0
	Sand (4.75–0.075 mm), %	54.9	37.2	43
	Silt and clay (< 0.075mm), %	38.0	54.9	57
Engineering properties	Specific gravity, G_s	2.70	2.76	2.4
	Liquid limit, %	32.8	29.1	-
	Plastic limit, %	17.4	22.9	-
	Plastic index, %	15.4	6.2	non-plastic
	Optimum moisture content, %	14.4	18.2	-
	Maximum dry density, kg/m^3	1,728	1,631	-
Chemical properties	$pH_{1:1}$	7.19	7.91	11.65

5.4.2 Experimental Plan

The experimental plan for this study consisted of conducting Atterberg limits, compaction, UCS, soaked and unsoaked CBR, alkalinity tests and measuring the EC, pH and

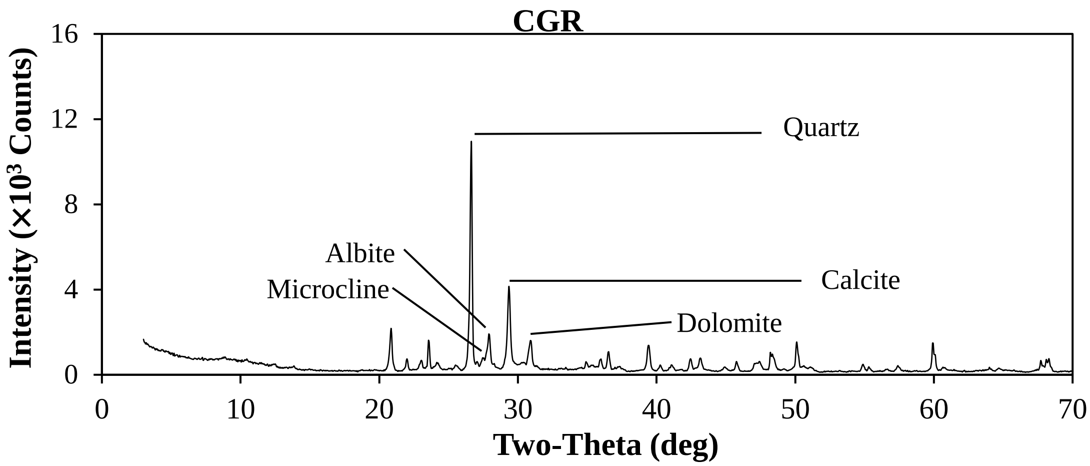
CEC values. In addition to these tests, SEM and EDS tests were conducted to analyze the reactions between soil and CGR at particle level. Soils were mixed with CGR at four different rates by weight: (a) 10%; (b) 20%; (c) 30%; and (d) 40%. For the measurements of index and engineering properties, appropriate ASTM standards including D4318, D698 and D2166 were followed to measure the Atterberg limits (liquid limit (LL), plastic limits (PL) and plasticity index (PI), compaction properties (γ_{dmax} and OMC), and UCS of soils treated with CGR. For CBR tests, both soaked and unsoaked CBR values of specimens were measured in accordance with ASTM D1883 along with the swelling potential of soaked CBR specimens.

Table 5.3 *X-ray fluorescence analysis for CGR and soil materials.*

	SiO_2 (%)	**Al_2O_3 (%)**	**Fe_2O_3 (%)**	**SO_3 (%)**	**CaO (%)**	**MgO (%)**	**K_2O (%)**	**Na_2O (%)**	**P_2O_5 (%)**	**TiO_2 (%)**	**BaO (%)**	**SrO (%)**	**Mn_2O_3 (%)**	**LOI[a] (%)**
CGR	53	8	3.8	0.68	16.8	2.8	1.5	1.8	0.1	0.4	0.04	0.04	0.07	11
Soil 1	66.7	9.5	3.16	0.25	5.89	2.54	1.75	1.2	0.11	0.44	0.06	0.02	0.12	8.21
Soil 2	66	9.85	3.32	0.02	6.21	2.37	1.95	1.23	0.15	0.59	0.07	0.02	0.13	7.76

LOI[a]: Loss on ignition.

The 7-day air-dried specimens were prepared with a 1:1 ratio of soil to deionized water (S/L) for pH and EC measurements using an Oakton PC2700 meter in accordance with the ASTM D4972 and C1A/3, respectively. For alkalinity and CEC measurements, specimens were prepared with a 1:10 S/L ratio and then rotated at a rate of 30 rpm/min for 18 hours and filtered through the 0.2-um membrane filter in accordance with the ASTM D3987. The alkalinity of the filtered leachate was measured via Hach alkalinity test kit No. 24443-01 (titration method) by following the test kit manual, and the levels of Ca^{2+}, K^{+}, Mg^{2+} and Na^{+} in the remaining leachate were measured by using inductively coupled plasma atomic emission spectroscopy (ICP-AES) which was ultimately used to determine the CEC of specimens (Midwest Laboratories, 2016)). For all tests, three replicates were carried out in this study.



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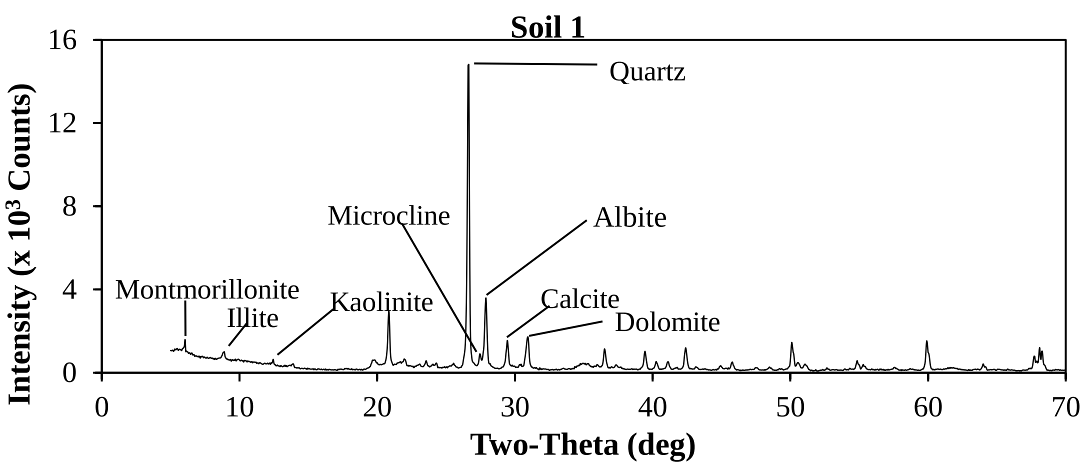

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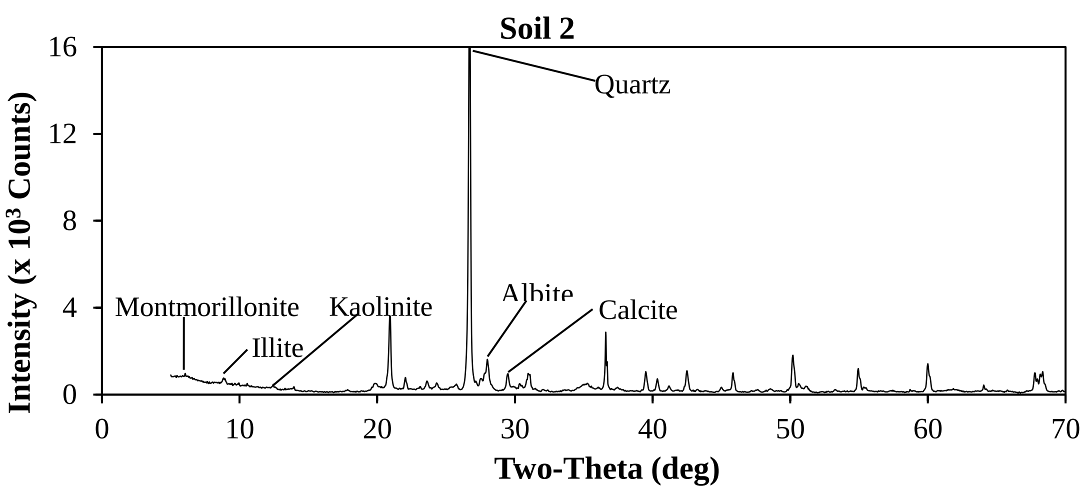


(c)

Figure 5.1 *X-ray diffraction pattern for (a) CGR, (b) Soil 1 and (c) Soil 2.*

5.4.3 Specimen Preparation

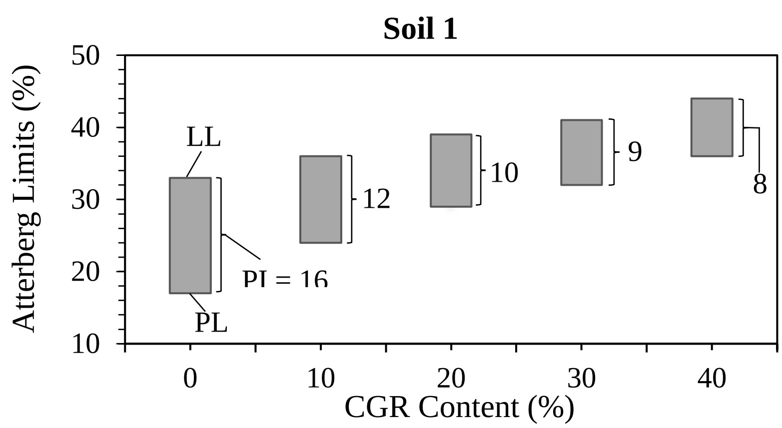
In this study, the compacted specimens were required for UCS and CBR tests, however, their preparation methods were different. For UCS test, the air-dried (at 25°C) soils and CGR materials were mixed at three different moisture contents (OMC-4%. OMC, and OMC+4%) and compacted at standard Proctor compaction energy in 5.08 cm (2 in.) diameter and 5.08 cm (2 in.) in height for UCS testing. This compaction method, developed by O'Flaherty (1963), has the primary benefit of producing more specimens with less effort. The compaction procedures involved loading loose soil-CGR mixture into a 5.08 cm (2 in.) diameter steel mold and dropping a 2.27 kg (5 lb.) hammer from a 30.48 cm (12 in.) height with 6 and 7 blows for the Soil 1 and the Soil 2, respectively. After compaction, the fabricated specimens were sealed in a plastic wrap and an aluminum foil, then stored in Ziploc bags at 25°C for 7-day and 28-day curing periods.

The CBR specimens were prepared by following the ASTM D1883. Specimens were compacted at OMC level in 15.2 cm (6 in.) diameter and in 12.7 cm (5 in.) height. After compaction, all specimens were sealed in a plastic wrap and an aluminum foil and stored at 25°C for 7-day for curing. After curing period, another set of specimens were soaked for 4-days in water tank to conduct swelling potential and soaked CBR tests afterwards.

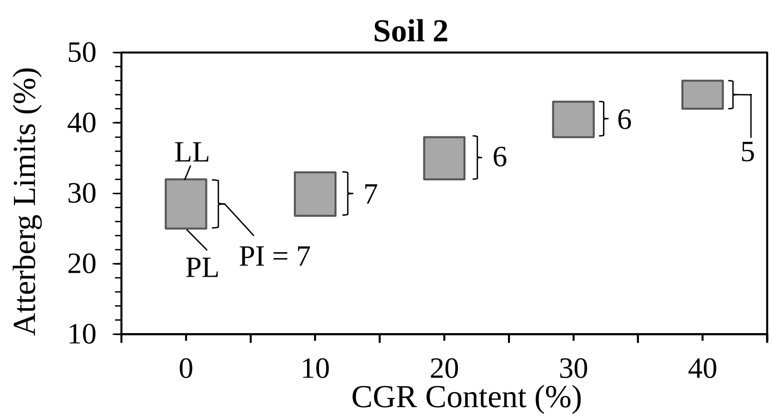
5.5 Results and Discussion

5.5.1 Atterberg Limits

All specimens were subjected to the Atterberg limits tests. The effects of different CGR application rates on Atterberg limits of the soils are shown in Figure 5.2. For Soil 1, both liquid limit (LL) and plastic limit (PL) increased with an increase in CGR rate while the plasticity index (PI) of the soil 1 decreased from 16 to 8 (Figure 5.2a). Soil 2 showed a similar trend with the addition of CGR with relatively lower impact compared to those of Soil 1 mixtures (Figure 5.2b). The change in the plasticity of soil after CGR treatment can be attributed to the cation exchange activities between the divalent ions (e.g. Ca^{2+}) derived from CGR and the monovalent ions (e.g. K^+, Na^+ and H^+) surrounding the surface of clay particles in soils, resulting in flocculation of clay particles (Schwieger, 1965; Arman and Munfakh, 1972). The other factors related to clay mineralogy such as CEC, specific surface area, and hygroscopic moisture may result in the different effects of CGR addition on different soil types (Smith et al., 1985). Figure 5.2 shows that CGR addition does not impact the PI of soils when soils have lower PIs. This effect of CGR on the reduction of the plasticity of soils suggests that CGR is a promising additive to be used for stabilization purposes (Smith et al., 1965). Dayioglu et al. (2017) showed that a decrease in PI of fine-grained soils yielded an increase in shear strength of those soils.



(a)

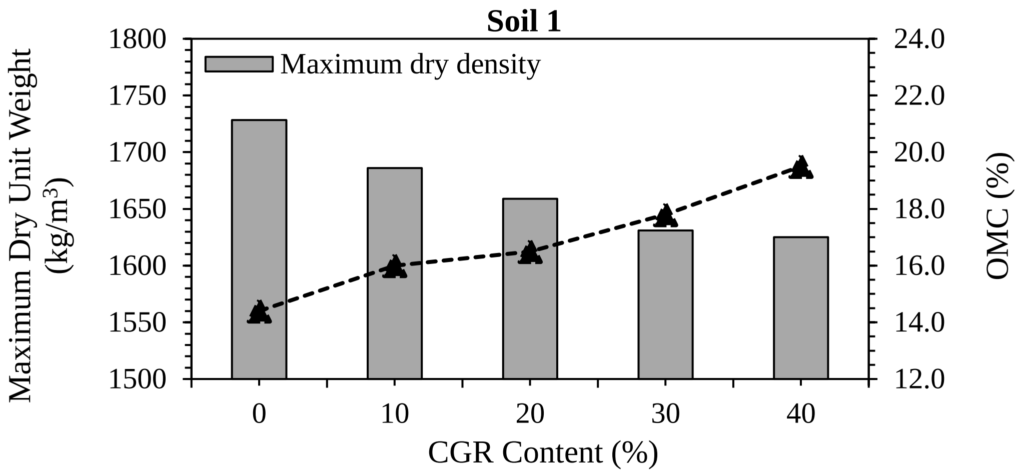


(b)

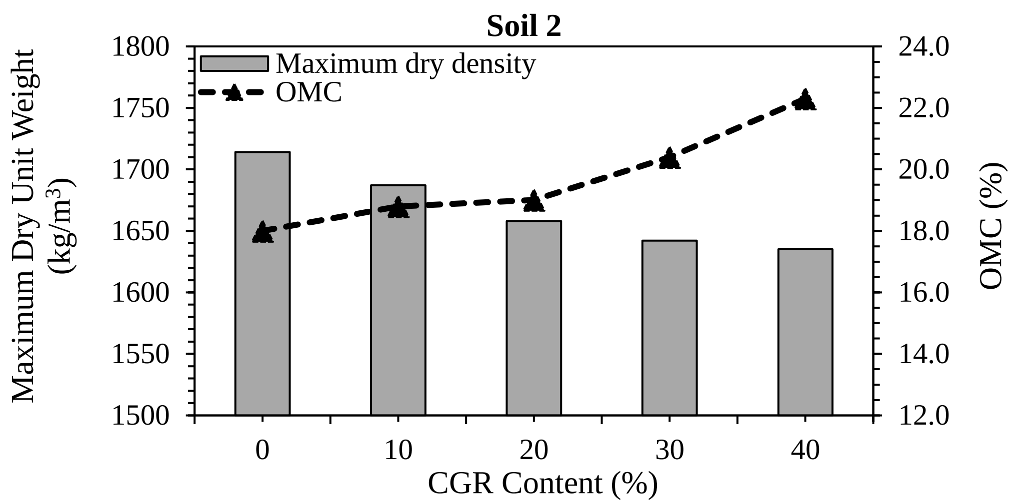
Figure 5.2 *Effects of CGR on Atterberg limits of (a) Soil 1 and (b) Soil 2.*

5.5.2 Compaction Characteristics

Figure 5.3 shows that the addition of CGR reduces the γ_{dmax} and increases the OMC of soils. Untreated Soil 1 had a γ_{dmax} of 1728 kg/m^3 (107.8 pcf) with 14.4% of OMC, and 40% CGR reduced γ_{dmax} to 1625 kg/m^3 (101.4 pcf) and increased the OMC to 19.5%. For Soil 2, the highest rate (40%) of CGR additions caused 79 kg/m^3 (4.9 pcf) reduction in γ_{dmax} and 4.3% increase in OMC. The different angularities and mineralogy of soil particles in Soil 1 and Soil 2 may result in the different changes of compaction characteristics after addition of CGR. The coarser material (Soil 1) was likely to have higher angular materials due to its higher sand and gravel contents (Table 5.1) which could influence the compaction characteristics of Soil 1 with the addition of CGR compared to the Soil 2. The decreased densities of soils were caused by the light weight of CGR since the specific gravity (G_s) of CGR is 2.44 (Table 5.2), lower than those of two soils. On the other hand, more flocculated structures were formed due to Ca derived from CGR which increased the resistance against the compaction process and resulted in lower γ_{dmax} (Santos et al., 2011). Moreover, the formed flocculated structures increased the void ratio of soil matrix, combined with the enlarged specific area of particles due to finer CGR materials, resulted in additional water required to reach the OMC (Santos et al., 2011). For soil stabilization purposes, an increase in γ_{dmax} and a decrease in OMC of soil is desired for stabilizers, so CGR could be added into the soil at a proper rate to minimize its negative impacts on compaction characteristics of original soils.



(a)



(b)

Figure 5.3 *Effects of CGR on moisture-density relationship of (a) Soil 1 and (b) Soil 2.*

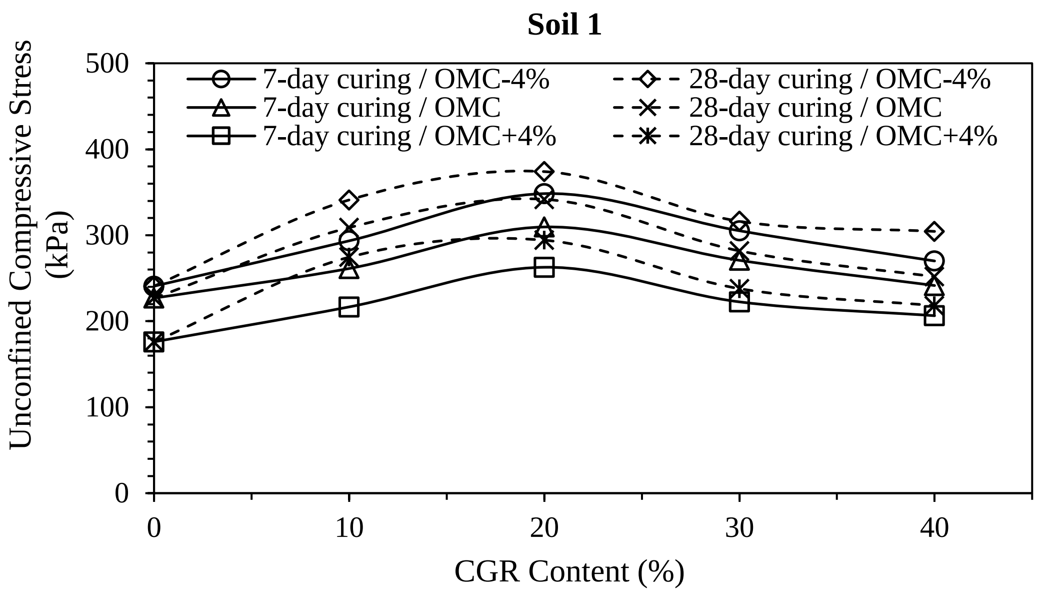
5.5.3 Unconfined Compressive Strengths (UCS)

Figure 5.4 shows the effects of CGR on strength of both soils. UCS tests were conducted to evaluate the impact of soil types, CGR rates, moisture contents, and curing periods on the CGR-treated soils. UCS results showed that Soil 1-CGR mixtures had higher strength for all treatment rates than those of Soil 2-CGR mixtures (Figure 5.4). All CGR-treated specimens showed higher UCS values than the UCS of Soil 1 and Soil 2 alone. The highest UCS for both soils (374 kPa for Soil 1 and 305 kPa for Soil 2) were observed at 20% CGR addition rate

(Figure 5.4). Both laboratory UCS and CBR tests results showed that 20% CGR addition provided the highest UC strength and CBR. This was observed most probably due to the contribution of rehydration of cement particles in CGR while it was not altering the OMC and γ_{dmax} of mixtures significantly (Figure 5.3). Figure 5.3 shows that CGR addition beyond this rate increases the OMC and decreases the γ_{dmax} of the mixtures. Thus, a strength loss was observed at Soil-CGR mixtures prepared with 30% and 40% CGR by weight. With respect to the fines content of soils, CGR is more effective on the relatively “finer” soil because it produced up to a 139% increase in UCS of Soil 2 compared to the untreated Soil 2 specimen, while for Soil 1, only a 57% increase in strength was observed with CGR addition. Different moisture levels also seemed to influence the UCS of Soil-CGR mixtures. While all specimens showed a reduction in UCS with an increase in moisture content, Soils mixed with 20% CGR by weight at OMC+4% exhibited the highest UCS than those untreated specimens compacted at the dry side of OMC, suggesting that CGR treatment at a proper rate could help to keep the soil strength even at higher moisture contents. Curing-period is another factor that influences the strength of CGR-treated soils. In this study, UCS of all CGR-treated specimens improved with longer curing periods. This behavior was attributed to both the physical and chemical reactions occurring between soil and CGR particles.

With reflect the CGR composition (e.g. CaO, MgO, SiO_2), a combination of the following mechanisms involved in the stabilization of a subgrade are proposed: (a) cation exchange; (b) flocculation; (c) hydration and rehydration; and (d) pozzolanic reaction. In general, the surface of clay particles is negatively charged due to the isomorphic substitutions, resulting in the attraction to the cations to neutralize the negatively-charged surface. When CGR is added to the soil, strong cations from CGR such as Ca^{2+} and Mg^{2+} can be attracted to the surface of clay particles to replace H^+, Na^+, and K^+, regarded as weak cations. Furthermore, strong cations such as Ca^{2+} can contribute to the flocculation process between particles due to the reduced double diffuse layer (DDL) and their divalence, resulting in more flocculated structures and higher surface tension that can improve soil strength, especially early strength (Kumar et al., 2007). Soil with the higher specific area can also benefit more in terms of strength improvement due to Ca^{2+} absorption on soil particles and this can explain why CGR is more effective in improving the strength of finer soils (Soil 2). Long-term strength improvement was also observed in CGR-treated specimens, and hydration and rehydration of cementitious materials and unreacted cement in CGR were hypothesized to be the contributor (Amin et al., 2015). Pozzolanic reactions between Ca, Si and Al (calcium silicate hydrate (C-S-H) and calcium aluminum hydrate (C-A-H)) may be another contributor to achieving long-term strength. On the other hand, it should be pointed out that since an excessive amount of CGR could limit the strength gain in soil, UCS tests with varied CGR rates are recommended to identify the optimum content of CGR for the soil stabilization purpose.

The results of the UCS tests indicated that the addition of CGR could increase the soil bearing capacity, and 20% CGR addition by weight was the optimum rate for the soils tested in the current study. Although CGR treatment exhibited a relatively lower soil strength improvement than those observed with other traditional additives such as cement and lime, it could still be used to stabilize the subgrade soil of roadways.



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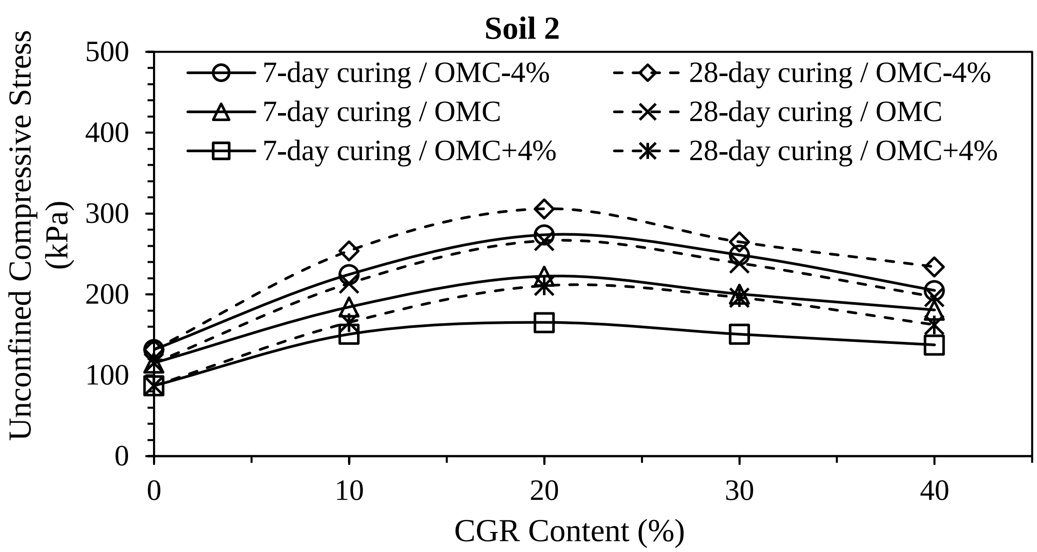


(b)

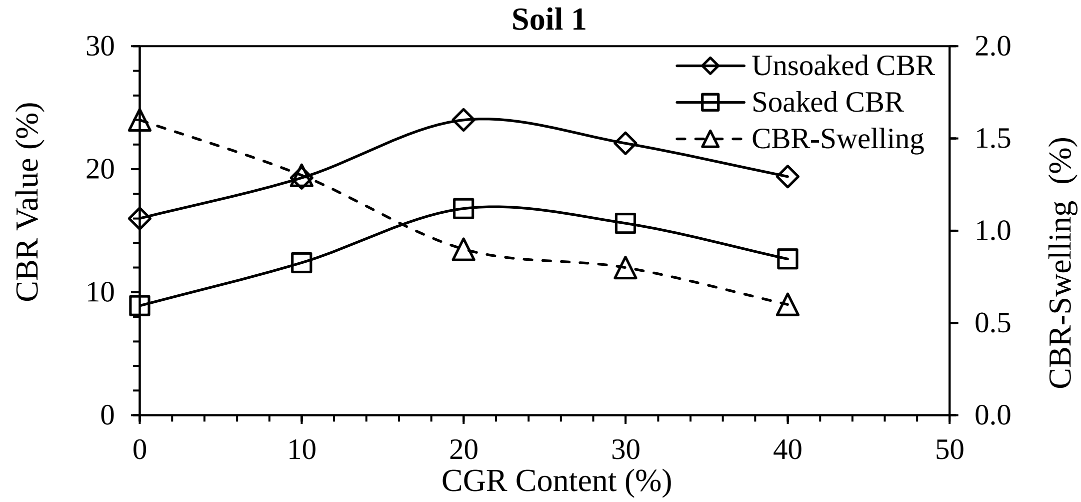
Figure 5.4 *Effects of CGR on unconfined compressive strength of (a) Soil 1 and (b) Soil 2.*

5.5.4 California Bearing Ratio (CBR)

The effects of CGR on unsoaked and soaked CBR and swelling potential after 7-day curing time are shown in Figure 5.5. The results showed that the unsoaked CBR values of untreated Soil 1 and Soil 2 were 16 and 6.7, respectively. The addition of 20% CGR led to the maximum increases in the unsoaked CBR of Soil 1 (CBR = 24) and Soil 2 (CBR = 19.3). The soaked CBR values exhibited a similar trend with the unsoaked CBR values, indicating that 20% of CGR was the optimum rate to increase the CBR of soils under soaking conditions. The swelling potential illustrated in Figure 5.5 showed that the untreated Soil 1 and Soil 2 experienced 1.6% and 1.1% swelling, respectively. Increasing the application rate of CGR in Soil 1 and Soil 2 resulted in a decrease of swelling at the range of 0.6% and 0.7%, respectively. The results of the CBR tests indicated that CGR could improve the strength and reduce the swelling potential of natural soils. The improved CBR performance of soils due to the addition of CGR could be explained by a combination of newly formed strong flocculated structures, hydration and pozzolanic products (C-S-H and C-A-H) due to presence of cementitious and pozzolan minerals in CGR.

5.5.5 pH

The pH results shown in Figure 5.6 indicated that the CGR rate positively correlated with the soils` pH values, a result similar to that of previous studies (Desutter et al., 2011; Yonge and Shanmugam, 2005). The CaO and MgO compounds in CGR are soluble in water, resulting in the generation of a massive number of hydroxide ions to elevate pH to basic conditions (Desutter et al., 2011; Mamo et al., 2015). The addition of CGR increased the pH of soil from 7.19 to 9.83 after 0 days (Figure 5.6a), while a pH reduction was observed for the same CGR rate after 7 days and 28 days curing periods. The elevated pH did not only provide alkaline environment for hydration and pozzolanic reactions (Nazer et al., 2016), but also improved the cation exchange activity in the soil matrix to cause flocculation and aggregation (Sonon et al., 2014; Shi and Day, 2000). The reduction of pH in Soil-CGR mixtures with time could be caused by the adsorption of Ca^{2+} cations onto the surface of clay particles and/or hydration and pozzolanic reactions occurring the soil matrix (Shon et al., 2010), indicating the formation of strong compounds (C-S-H and C-A-H) to improve the strength of soil with curing longer time.



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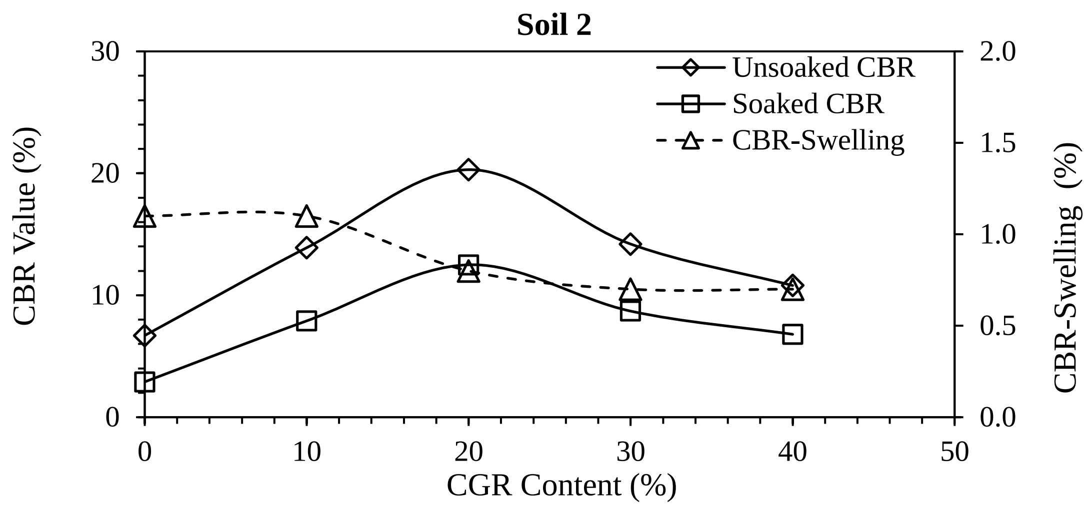
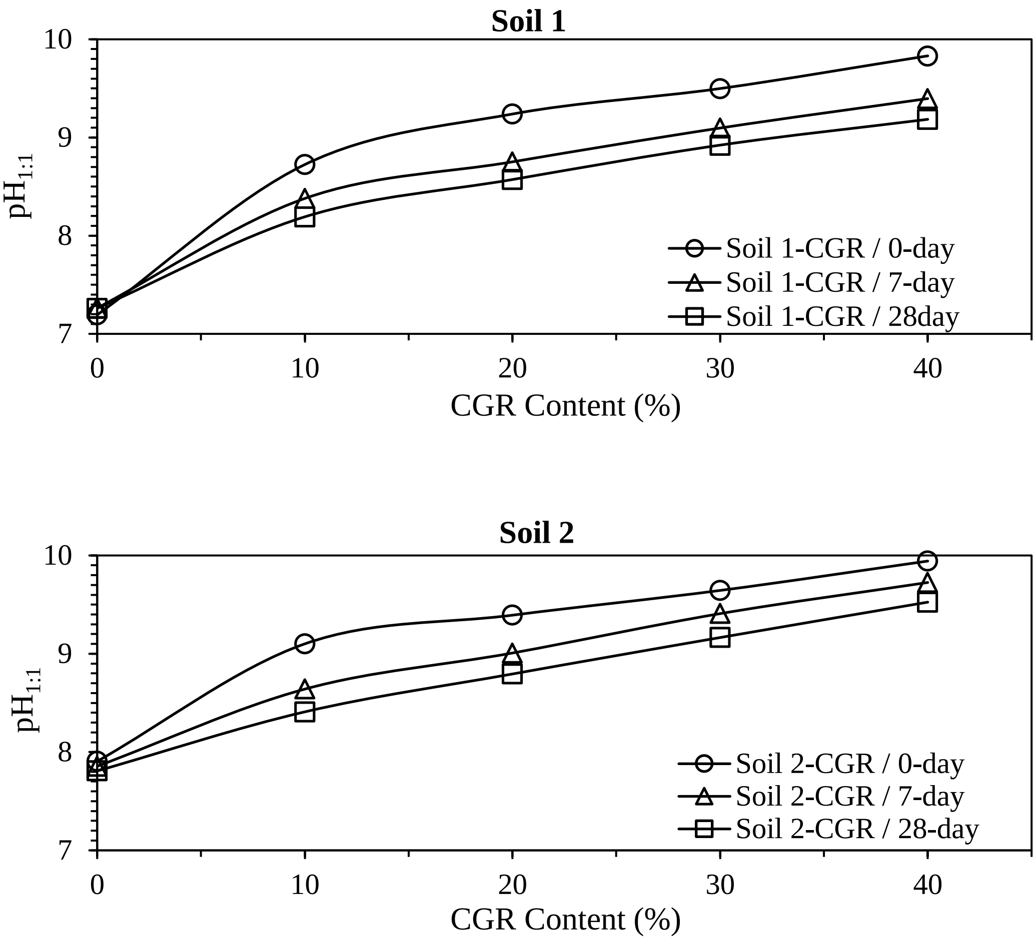


(b)

Figure 5.5 *Effects of CGR on California bearing ratio of (a) Soil 1 and (b) Soil 2 after 7-day curing.*



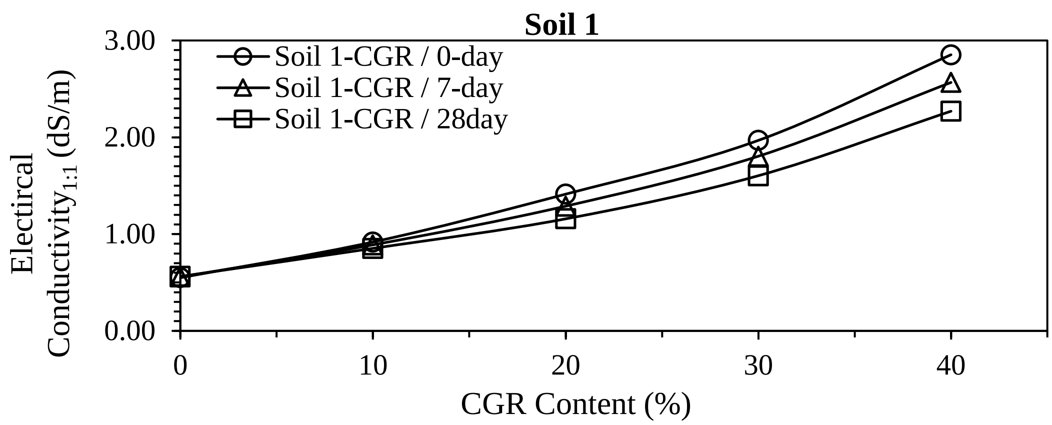
(a)

(b)

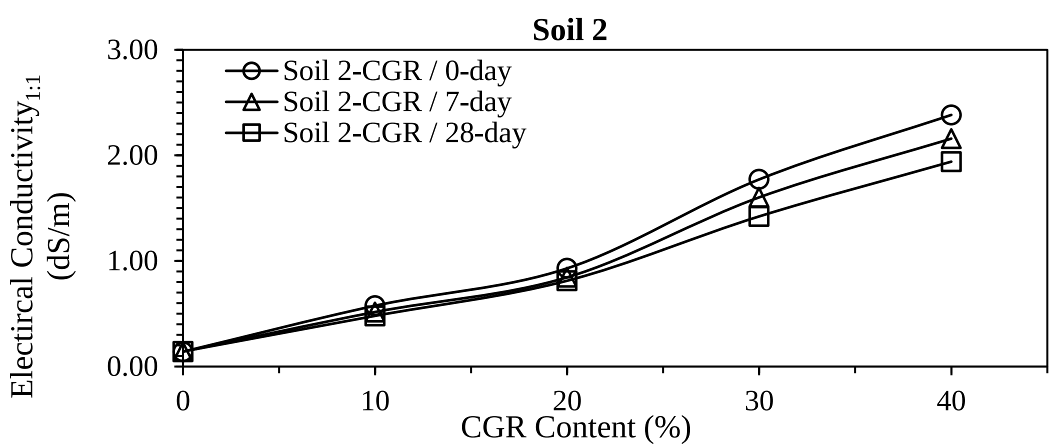
Figure 5.6 *Effects of CGR on soil pH.*

5.5.6 Electrical Conductivity (EC)

Electrical conductivity (EC) of soils is used as a measure of salt content in soils. Figure 5.7 shows that the highest CGR rate (40% of CGR) increase the soil EC from 0.55 to 2.85 and 0.14 to 2.38 dS/m for Soil 1 and Soil 2, respectively. Similar to the results of pH measurements, the highest EC values occurred with the highest CGR rate and at the stage of 0-day, and then EC decreased with an increase in curing time. The increase in soil EC was attributed to the massive soluble salts such as NaCl and KCl from CGR and massive alkali salts derived from the hydration of abundant metallic oxides such as CaO, MgO, K_2O and others in CGR (Desutter et al., 2011; Mamo et al., 2015), and the reduction in EC with time could be due to the absorption of metal cations (Ca^{2+} and Mg^{2+}) through cation exchange, hydration, rehydration and pozzolanic reactions (Shi and Day, 2000; Shon et al., 2010; Langan et al., 2002). The salts from CGR could initiate the chemical reactions in soil matrices, and the decreased EC with time indicated the consumption of ions in solution due to the multiple reactions occurrence which ultimately led to an increase in UCS after 28-day curing period (Zhang et al., 2014).



(a)



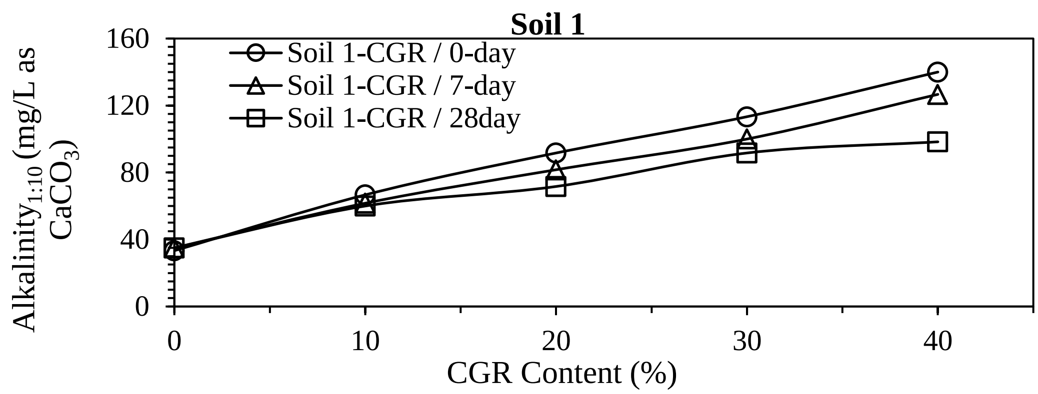
(b)

Figure 5.7 *Effects of CGR on soil electrical conductivity.*

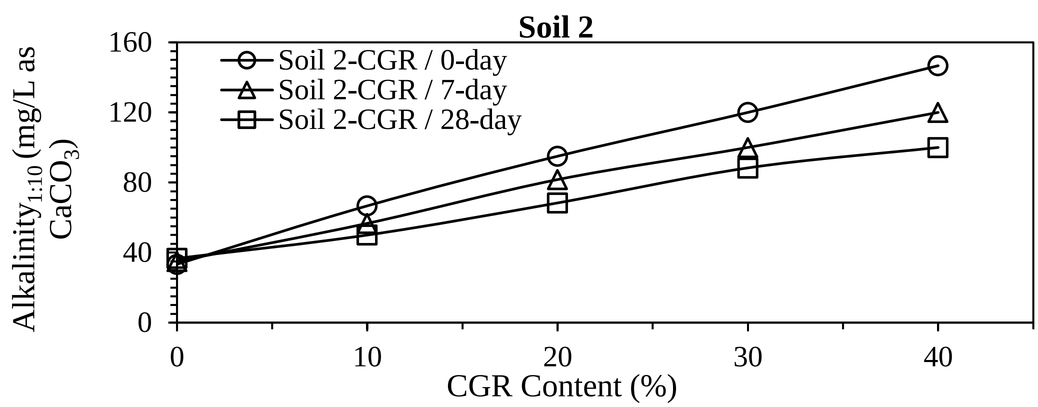
5.5.7 Alkalinity

Alkalinity is the ability of a soil to neutralize the acidity of a solution and generally expressed as the measurement of a concentration of $CaCO_3$. Figure 5.8 presents the alkalinity measurements for both soils treated with varied rates of CGR, showing that CGR rate increased the alkalinity for both Soil 1 and Soil 2 dramatically, up to 140 and 147 mg/L as $CaCO_3$, respectively. The alkalinity of all mixtures decreased with higher curing time. The primary contributor of the high alkalinity is the presence of alkaline earth (e.g. Ca and Mg) minerals and alkali metals (e.g. Na and K) in CGR which can highly dissociate in aqueous solution to form the ions float freely. The increased alkalinity can provide the applicable environment to occur hydration and pozzolanic reactions in soil. Moreover, the increase in alkalinity indicates the increased free alkaline metals which can improve the activity of hydration and pozzolanic reactions. The reduced alkalinity after long-term could be explained with the same reasons for pH and EC which could be due to the chemical reactions occurring in the soil matrices, indicating the formation of hydration and pozzolanic products to improve the strength of soils with longer curing times.

Trends of pH, EC, and alkalinity for all Soil-CGR mixtures were similar that increases in CGR contents yielded increases in these parameters of the mixtures. This indicated that the CGR addition caused an increase in basic elements such as Ca and Mg which were the main elements for hydration and pozzolanic reactions for strength gain. Thus, there was a high potential for these elements to react with CO_2 (aq), OH^- ions and Si^{4+} from soils and form calcite, portlandite, C-S-H, respectively. In addition, formation of C-S-H in soils took longer time (Dayioglu et al., 2017). These three parameters of all Soil-CGR mixtures decreased slightly with an increase in curing times indicating that Ca^{2+} cation were used by the hydration reactions to form higher amount of C-S-H. Figure 5.4 shows that UCS of all mixtures are higher when cured longer periods proving that the formation of C-S-H continues with curing time.



(a)



(b)

Figure 5.8 *Effects of CGR on soil alkalinity*.

5.5.8 Cation Exchange Capacity (CEC)

CEC is the total capacity of a soil to hold the exchangeable cations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}). The measured CEC values for pure soils and soils treated with 20% CGR by weight after 7-day curing are shown in Figure 5.9. The results indicated that the CEC of Soil 1 and Soil 2 were increased from 1.96 meq/100 g and 4.16 meq/100 g to 2.89 meq/100 g, and 6.27 meq/100 g after addition of CGR, respectively. Soil 2 was a finer soil with the higher specific surface area which resulted in higher CEC than that of Soil 1. Observing an increase in CEC with CGR addition was attributed to the increase of pH of the soil media and the release of Ca^{2+} and Mg^{2+} cations from CGR to the soil media. Thus, CEC of mixtures increased. An increase in pH in the soil media also resulted in desorption of acidic cations (H^{+} and Al^{3+}) from the soil particles to dissolve into solution which also contributed to an increase in CEC increase (Shi and Day, 2000). Furthermore, as a result of this increase in CEC of Soil-CGR mixtures, more divalent cations were attracted to the soil particles and caused the flocculation and aggregation of soils which could yield an increase in strength (Kumar et al., 2007). Thus, the Soil 2-CGR mixtures had higher UCS and CBR improvements than those of Soil 1-CGR mixtures.

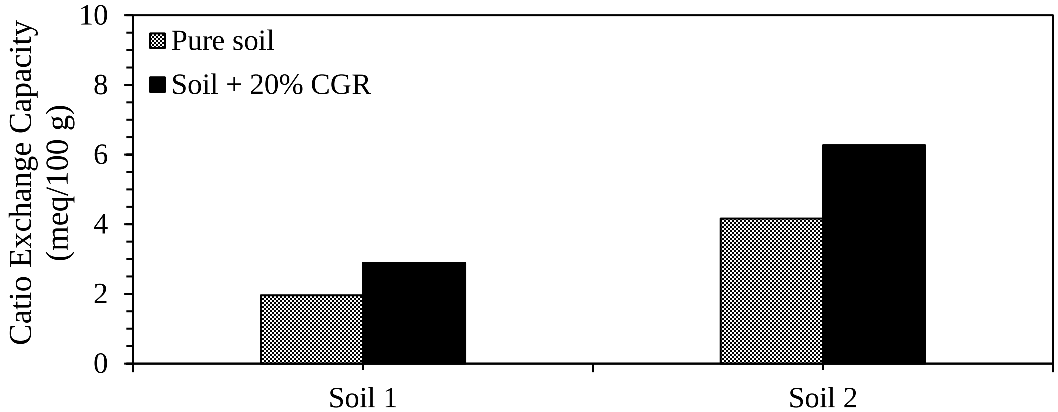
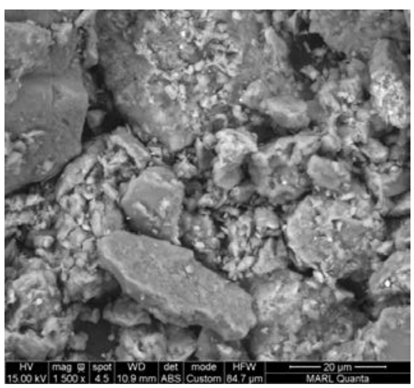


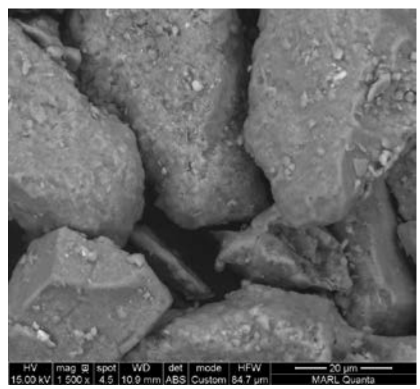
Figure 5.9 *Effects of CGR on soil cation exchangeable capacity*.

5.5.9 Scanning Electron Microscope and Energy Dispersive Spectroscopy (SEM/EDS)

SEM and EDS analyses were also conducted on soils alone, CGR alone, and Soil-20% CGR mixture to characterize the microstructures of materials and analyze the changes on soil particle surface due to CGR addition. Figure 5.10 shows the morphologies of CGR alone and two soils (Soil 1 and Soil 2), while Figure 5.11 focuses on the morphologies of the soil mixtures treated for 7 days with 20% CGR by weight. The untreated soil images and CGR image (Figure 5.10) showed clear particle surfaces and boundaries and porous structures under 1500x magnification. As seen in the images of the CGR-treated soil specimen (Figure 5.11), the grains were coated by some crumbs of floccules which were different from the CGR and the soil alone particles, and the voids between particles were filled by this same material. Figure 5.12 exhibits the chemical characterization of the areas in Figure 5.11 and showing that the floccules are calcium-rich. Figure 5.12 shows that the concentrations of Ca, Na, Mg and S of both soils increase with addition of 20% CGR by weight, and the concentrations of Si and K decrease at the same time. The changed levels of elements in the Soil-20% CGR mixture compared to the untreated soils were due to the chemical composition of the CGR. Moreover, the level of Ca of untreated soil was significantly elevated after the addition of 20% CGR (Figure 5.12), resulting in possible chemical precipitates as shown in Figure 5.11 (crystalline structures). Thus, it was speculated that the floccules in CGR and the Soil-20% CGR mixtures were most probably the cementitious compounds (calcite and/or C-S-H and C-A-H) produced by calcite precipitation and or hydration/pozzolanic reactions to gain strength.



(a)



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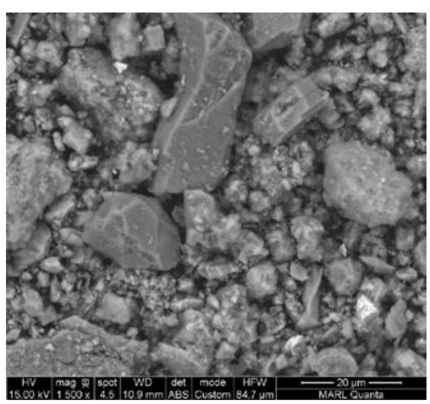
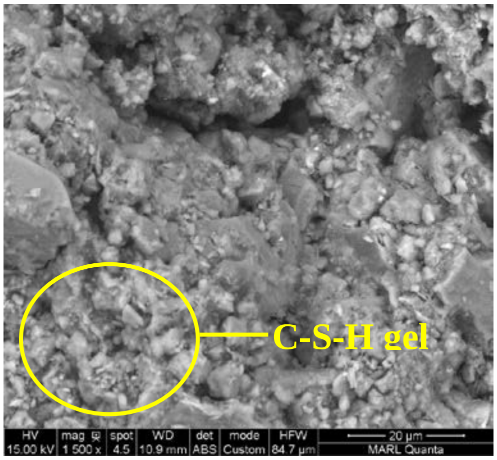


(c)

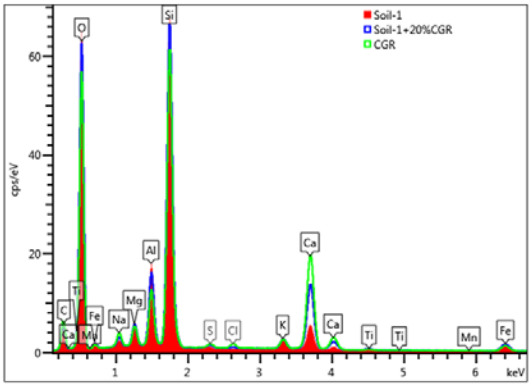
Figure 5.10 *Images of SEM for specimens with 1500-x magnification: (a) pure Soil 1, (b) pure Soil 2 and (c) pure CGR.*



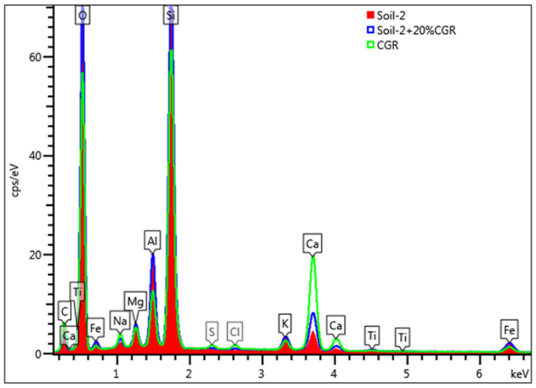
(a)

(b)

Figure 5.11 *Images of SEM for specimens with 1500-x magnification: (a) Soil 1 + 20% CGR and (b) Soil 2 + 20% CGR.*



(a)



(b)

Figure 5.12 *EDS results of (a) Soil 1 set and (b) Soil 2 set.*

5.6 Conclusions and Recommendations

This paper reviewed the current practices of the CGR management throughout the United States in an effort to evaluate the reuse of CGR for soil stabilization purposes. A comprehensive summary was developed to understand the different disposal methods of CGR recommended by different DOTs, and environmental concerns were discussed. Several practices for properly managing of CGR with respect to its reuse through soil and concrete amendment were discussed, and laboratory tests related to the stabilization of soils with CGR were evaluated. Based upon the results, the primary findings and recommendations were provided as follows:

- The management methods of CGR varied between states, and many states did not have detailed guidelines for dealing with its associated environmental concerns. Following the IGGA BMPs is recommended for disposal of CGR if detailed state guidelines are lacking.
- Based on the literature review it is recommended that the fresh CGR should be disposed to a specific pond for future uses such as soil and concrete amendment and soil stabilization.
- CGR treatment increased the soil strength, CBR values, OMC, pH, EC, alkalinity and CEC and decreased the γ_{dmax}, PI and swelling potential of soils. 20% CGR addition by weight was determined as the optimum rate gain strength for both soils tested in the current study. It was also determined that CGR was more effective for improving the engineering properties of finer soils.
- The strength and CBR gains for CGR-stabilized soils were observed due to a combination of cation exchange, flocculation, hydration, and rehydration and pozzolanic

reactions. The SEM and EDS analyses confirmed the formation of cementitious compounds in CGR-stabilized soils.

- Future studies related to the evaluation of the combination of cementitious materials and CGR in soil stabilization is recommended.
- The investigation about the effect of CGR on stabilizing some other types of soils such as fat clay is recommended.

5.7 Limitations and Recommendations

- It should be noted that this study focused on using one type of CGR for stabilization of two different soils. It is recommended to conduct further research to test the possible application of CGR with different physicochemical properties on different types of soils including fat clay and coarser materials (highway base/subbase layer materials).
- Cost-benefit analyses were not the scope of this study. However, detailed cost-benefit and life cycle cost analyses should be conducted to evaluate the feasibility of reuse of CGR for soil improvement compared to the traditional stabilizers such as cement, lime, and fly ash.

5.8 Acknowledgments

The authors gratefully acknowledge the Recycled Materials Research Center (RMRC) for financial support of this study. The authors are also grateful to the Minnesota Department of Transportation (MN-DOT) for providing the CGR materials. The findings and opinions in this study are solely those of the authors. Endorsements by the MN-DOT and/or the RMRC are not implied and should not be assumed.

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CHAPTER 6. EVALUATION OF A BIO-BASED FOG SEAL FOR LOW-VOLUME ROAD PRESERVATION

A conference paper submitted to *12th TRB International Conference on Low-Volume Roads: Patron Support Information*

Bo Yang[1], Yang Zhang[2,*], Halil Ceylan[3], Sunghwan Kim[4]

6.1 Abstract

While asphalt pavement is one of the most commonly used surface types for low-volume roads in the United States, it is susceptible to oxidation as being exposed to environmental effects, making the pavement layer brittle and leading to formation of cracks. To maintain the performance of a road surface and extend its service life, pavement preservation is needed. Fog seals are a common preservation technology used for asphalt pavements to mitigate micro-cracking, prevent oxidation and reduce water infiltration. Traditional fog sealers such as asphalt-based or coal tar-based products have been successfully used for many years, to achieve the goal of sustainable pavement development, in recent years. The use of bio-based products as fog sealers has attracted more and more attention. Some new bio-based sealants derived from agricultural oil have been used as fog sealers in many states. To evaluate the effectiveness of a bio-sealant as an alternative to preserve asphalt pavements, a 5.3 km (3.3 mile) test section was selected for application of a soy-based fog sealant with three different application rates to

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conduct a two-year investigation of pavement marking retroreflectivity, surface friction, laboratory water absorption, and air permeability. A control section without bio-sealant was also set up for comparison purposes. The field results revealed that, after application, a short-term decrease in retroreflectivity and skid resistance was restored to the original condition after two weeks and several months, respectively. The laboratory results indicated that the bio-sealant treated specimens applied at the highest application rate exhibited the lowest water absorption and air permeability.

6.2 Introduction

All types of roads, including those with asphalt pavements, steadily deteriorate over time due to repeated mechanical (traffic) and climatic loadings. Pavement preservation consists of applying a suitable treatment on deteriorated roads to maintain good conditions and extend their service lives (Johnson, 2000; Mamlouk and Zaniewski, 1998). Typical preservation approaches for low-volume asphalt pavements include fog seal, crack sealing, slurry seal, chip seal, and overlay, and each can be used for various purposes in preventive maintenance projects. Fog seal is a low-cost application of liquid asphalt or emulsion derived from petroleum or coal tar, sometimes followed by a cover of fine aggregate or sand, to slow down micro-cracking propagation, prevent oxidation, and seal against water infiltration. While such petroleum-based traditional fog sealers have been successfully used to maintain road surfaces for many years, they not only need a long curing time that results in delayed traffic opening (Kim and Im, 2012), but they can also cause health issues from chemical components such as polycyclic aromatic hydrocarbons (Ghosh et al., 2016). Furthermore, the use of fossil fuel-based products increases the risks associated with an energy crisis and environmental contamination (IPCC, 1996; IPCC, 2014).

In recent years, a few bio-based fog sealers have been developed as sustainable alternatives to traditional petroleum-based sealers; soy-based fog sealant derived from agricultural oil is one such product. The manufacturers of bio-sealant claim that it protects asphalt from oxidation, pot-holing, edge rutting, and cracking, and can extend the life of paved asphalt surfaces when applied every 3-5 years (Shatnawi, 2014). States such as Missouri and Ohio have reported success in using bio-based products for county road preventive maintenance (BioSpan, 2010; Shatnawi, 2014). While the reported observations include quick shedding of water from roadways treated with bio-sealant while retaining the skid resistance of normal pavement, documentation of construction and performance experience is limited.

Based on successful use of bio-sealant in other states, this study aimed at evaluating a bio-based product as a fog sealant for low-volume asphalt pavements in Iowa. With the intent of checking the effect of such bio-sealant on skid resistance, pavement marking retroreflectivity, water absorption, and permeability, the construction process and consequent field and laboratory investigations based on varied sealant spray rates over a two-year period were documented.

6.3 Background

6.3.1 Literature review of fog seal

Fog seal is a treatment using diluted slow-setting or medium-setting asphalt emulsion without aggregates, applied on a pavement surface by an asphalt distributor (Estakhri and Agarwal, 1991; Johnson, 2000). It is used to seal and enrich the pavement surface, seal micro-cracks, prevent raveling and oxidation, and provide shoulder delineation with the least amount of energy consumption (Chehovits and Galehouse, 2010; Jahren, Smith, and Plymesser, 2007; Janisch and Gaillard, 1998; Johnson, 2000; Thomas, 2002). Fog seal can be used on both low- and high-volume roads, especially for raveling prevention on open-graded friction courses. The recommended spray temperature should be between 52°C and 71°C (125°F and 160°F) at a surface temperature of at least 10°C (50°F) and rising. The performance life of fog seal treatment is about one to two years. Because the greatest limitation of fog seal treatment is its reduction of pavement friction after spraying, it is not recommended to use fog seal on heavy-traffic roads. The prices of fog seal varies with the type of emulsion, the binder application rate, and the size of the project, and is usually about US $0.12 to US $0.24 per square meter (US $0.10 to US $0.20 per square yard).

Some literature has reported that fog seal has been applied as a top surface on chip seal (Kim and Im, 2010). Because the major concern of chip seal is aggregate loss, fog seal could possibly be used to reduce the potential for aggregate loss, improve aggregate retention, and extend pavement service life. Polymer-modified emulsions (PMEs) are recommended over unmodified emulsion since PMEs can not only improve emulsion bond strength, shorten curing rates, decrease temperature susceptibility, and increase emulsion adhesion, but also provide better aggregate retention and bleeding performance (Im and Kim, 2013; Janisch and Gaillard, 1998; Lawson, Leaverton, and Senadheera, 2007).

While fog-seal treatments are widely used throughout the world, there is a lack of documentation comparing fog-seal applications in state specifications in different states in terms of materials, equipment, application instructions, and opening to traffic. The details of applying fog seal have been documented on the basis of state highway agency standard specifications. The most important criteria for preparing and applying fog seal onsite based on six state highway agency specifications in the US are summarized in Table 6.1.

Suggested quality assurance/quality control (QA/QC) tests to be employed in the laboratory or in the field for estimating performance of fog seals include Vialet test, indirect tension test, evaporation test, bitumen bond strength test, rolling ball test, damping test, aggregate loss test, bleeding analysis, third-scale model mobile load simulator test, the British pendulum test, and use of a three-dimensional (3-D) laser scanner (Im and Kim, 2013; Janisch and Gaillard, 1998; Lawson, Leaverton, and Senadheera, 2007). The six state highway agency specifications on fog seal application all suggest a slow-setting asphalt emulsion, the most often used being CSS-1 or SS-1 at a dilution rate of 1:1 and an application rate between 0.09 to 0.9 l/m^2 (0.02 to 0.2 gal/yd^2). All six states use a bituminous distributor for fog-seal application equipment with roadway condition requirements of dry and clean surfaces with either the pavement temperature or the air temperature above 10°C (50°F) and rising.

To assess the effectiveness of fog seal treatments, Prapaitrakul et al. (2010) measured the stiffness of recovered pavement binder and compared treated and untreated binders through a paired t-test analysis. Test specimens were cored from selected pavement sites with both treated and untreated sections. The core samples were trimmed and sliced into three 0.64 cm (¼ in.) thick layers. Asphalt binder composed of a blend of fog seal material and the original *in situ* pavement binder was extracted and recovered from each core layer so that a flowing measurement could effectively determine the presence of the fog seal materials at a certain layer depth. A gel permeation chromatograph (GPC) was used to measure the molecular size distribution of asphalt materials, and overall test results indicated that the fog seal penetrated mostly into the top layer at 0.64 cm (¼ in.) thickness and could therefore affect only the top layer properties. According to the statistical analysis, only EB44 coal tar-type had a statistically significant effect on the binder rheology, bystiffening only the top layer of the binder (Prapaitrakul et al., 2010).

Table 6.1 *Summary of state highway agency specifications on fog seal*.

State	Reference	Material			Equipment	Application Instruction
		Emulsion Grade	Dilution Rate (AE/W ratio)	Application Rate, gal/yd^2		
IA	IA-DOT (2015)	CSS-1,SS-1	1:4	0.12	Bituminous distributor	One-half of the roadway with an overlap of about 4 in. at the middle; do not place on a damp or wet surface; do not apply either when the pavement temperature or the air temperature is below 60°F
CA	Caltrans (2010)	slow-setting asphalt emulsion	1:1	0.02 to 0.06	Bituminous distributor	Do not start fog seal when precipitation is been forecast during the application and curing period; do not apply when either the pavement temperature or the air temperature is below 40°F
MO	MO-DOT (2016)	SS-1, SS-1h, CSS-1, or CSS-1h	given by engineer	0.20	Bituminous distributor	Sand dams may be necessary to prevent emulsion from being applied outside of designated areas; asphalt emulsion shall not be placed on a damp or wet surface, and the surface shall be free of objectionable material prior to sealing
OR	OR-DOT (2015)	CSS-1, CSS-1h, HFRS-P1	≥1:1	0.10 to 0.15	Bituminous distributor, hauling vehicles	Apply emulsified asphalt to only one designated traffic lane at a time; do not place fog seal when the air temperature is below 60°F
TX	TX-DOT (2014)	SS-1, SS-1h, CSS-1, CSS-1h	–	–	Bituminous distributor	Apply the mixture when the air temperature is at or above 60°F or above 50°F and rising
WA	WA-DOT (2014)	CSS-1, CSS-1h	1:1	0.10 to 0.18	Bituminous distributor	–

Note: AE/W Ratio indicates asphalt emulsion-water ratio; – indicates not specified. 1 gal/yd^2 = 4.53/m^2; 1 in. = 2.54 cm; (1°F − 32) × 5/9 = -17.22°C.

Im and Kim (2013) reported a study using fog seal as a potentially cost-effective method to enhancing aggregate retention, and investigating the curing and adhesive properties of fog seal for determination of traffic opening times in the field. The emulsions that were selected in that study were CSS-1h, CQS-1h, and modified PME-A and PME-B, and performance tests were conducted on chip seal texture using CRS-2L emulsion with EARs (emulsion application rates) of 1.132 l/m^2 (0.25 gal/yd^2) and 5.4 kg/m^2 (10 lb/yd^2) of lightweight aggregate in comparison with different emulsion types. The results showed that all four types of emulsions exhibited a short curing time once placed with low EARs at a high temperature. PME-A and PME-B exhibited shorter curing time than unmodified CSS-1h and CQS-1h. Rolling-ball test results showed that the curing rate of PME-B was faster than that of the other emulsions. While PMEs can be cured within one hour, however, the unmodified emulsions required more than 1.25 hours. Aggregate loss test results indicated that the PMEs samples experienced less than 5% aggregate loss while the unmodified emulsions experienced a 15% aggregate loss. The samples with PME-B exhibited the best aggregate retention performance (Im and Kim, 2013).

6.3.2 Fog seal using bio-sealant

The soy-based bio-sealant used in this study is a black liquid with a non-descript slightly citrus odor, with the physical and chemical properties presented in Table 6.2. This product has a viscosity of 5 to 20 seconds at room temperature, similar to the flowability of water. It is 88% bio-based, with 40% obtained from soybean oil. By making use of agricultural and recycled materials, this bio-sealant is a non-toxic and environmentally friendly alternative to petroleum-based sealing agents. It contains some polymers, including SBS (styrene-butadiene-styrene) and SBBS (styrene-butadiene-butadiene-styrene), common admixtures in traditional asphalt emulsion used to improve pavement flexibility under colder conditions.

Table 6.2 *Physical and chemical properties of bio-fog sealant (Shatnawi, 2014).*

Property	**Value/Description**
pH range	5.0–6.0
Specific gravity	0.87-0.88
Saybolt viscosity	5-20 seconds at 25°C (77°F)
Boiling point	154-166°C (310-330°F)
Solubility in water	Immiscible
Residue by distillation	12% min and 18% max

The soy-based sealant is a pavement preservation agent that has proven to prolong asphalt pavement surface life when applied every 3-5 years, to protect pavement against water damage, and to maintain skid resistance. It also stabilizes the asphalt binder and strengthens the asphalt matrix. As a result, application of bio-sealant prolong the lifespan of asphalt roadways as it penetrates and fills voids near the surface, protects against water penetration, minimizes freeze/thaw damage, and makes the asphalt more resilient. The typical spray rate of bio-sealant can vary from 0.045 to 0.091 l/m^2 (0.01 to 0.02 gal/yd^2). When applied to an asphalt surface, the patented solution reverses the oxidation process, on average penetrating 1.9 to 3.2 cm (0.75 to 1.25 in.) deep into the asphalt in a matter of minutes. Bio-sealant can not only reduce the need to use petroleum-based products in pavement maintenance, but can also reduce the need for using bitumen in the manufacture of new asphalt by causing the road surface to last longer. Bio-sealant is a competitively priced, environmentally-benign alternative to traditional petroleum-based asphalt sealers. The application of bio-sealant is cost-comparable to other asphalt seal coat treatment, but it is the only solution that is bio-based, non-toxic, and carbon negative. It is also easier to apply and extends the life of asphalt pavements. Table 6.3 summarizes the benefits and limitations of applying bio-based fog seal.

Table 6.3 *Benefits and limitations of using bio-sealant for fog seal (BioSpan, 2010; Shatnawi, 2014).*

Benefits of using bio-sealant	Limitations of using bio-sealant
• Resistance to deterioration o 3-5 additional years of service life. o Reduces oxidation. o Penetrates deep into asphalt. (2-3cm) o Adding polymers to the asphalt cement. • Improvements to surface o Seals hairline cracks. o Helps maintain skid resistance. o Reduces moisture penetration. o Reduces potholing and edge rutting. • Financial considerations o Does not affect line stripping. o Is not removed by snowplowing. o No heating, carbon negative. o Reduces lifecycle costs.	• If a road is in good shape, bio-sealant should be applied every four to five years. If it is in fair shape, it should be applied every two to three years, as long as the road is not ravelling. If the road has alligator cracking, bio-sealant cannot repair the damage and should not be used. • Applying bio-sealant calls for dry conditions, and a dry road with temperatures above 40ºF (4ºC). Bio-sealant should never be applied in wet, freezing conditions.

6.4 Construction and Experimental Approaches

The sites selected for bio-sealant installation were located near Toronto in Clinton County, IA, including a 4,506-m (2.8-mile) section road in E63/Y32 with a 7.6 cm (3 in.) hot mix asphalt (HMA) overlay on a 8.9 cm (3.5 in.) cold-in-place recycling (CIR) layer and a 805-m (0.5-mile) long section through the City of Toronto with a 5.1 cm (2 in.) HMA overlay (Figure 6.1). It was a two-lane low-volume road with annual average daily traffic (AADT) of less than 400 vehicles. Each lane was 3.05 m (10 ft) wide with a 0.91-m (3-ft) wide sand-paved shoulder on each side. Based on previous construction information, the HMA overlay was replaced in 2011. The test sections at the installation site were divided into five sub-sections: 30.5 m (100 ft) of untreated section (control, 0 l/m^2), 305 m (1,000 ft) of treated section No. 1 (TS 1) with a spray rate of 0.136 l/m^2 (0.030 gal/yd^2), 305 m (1,000 ft) of treated section No. 2 (TS 2) with a spray rate of 0.113 l/m^2 (0.025 gal/yd^2), 305 m (1,000 ft) of treated section No. 3 (TS 3) with a spray rate of 0.091 l/m^2 (0.020 gal/yd^2), and the remaining roads as other treated sections with a spray rate of 0.091 l/m^2 (0.020 gal/yd^2).

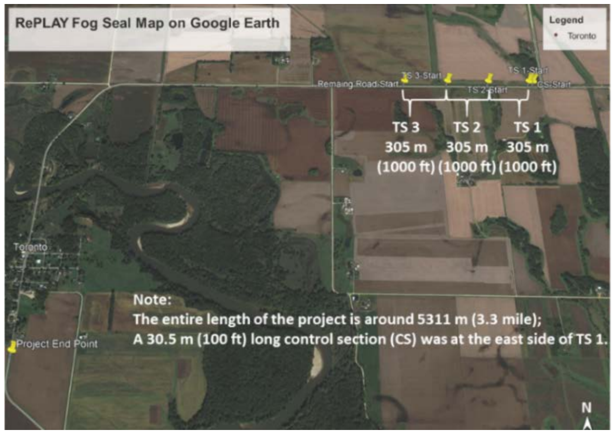


Figure 6.1 *Location of the bio-fog seal construction and test sections in 2016.*

6.4.1 Fog seal construction using Bio-fog sealant

The application of fog seal using bio-sealant in Clinton County, IA began on June 29, 2016 during dry and clear weather with an ambient temperature ranging from 15 to 26ºC (59 to 79ºF). Before application, all road surfaces were swept and cleaned, and the boundary marking lines for each section were painted. Figure 6.2a shows a vehicle equipped with an automatic bio-sealant spray machine equipped with a system for controlling the application rate. The adjustable spray bar with evenly-spaced nozzles was set to totally treat a width of 3.05 m (10 ft). During application, the vehicle speed typically ranged from 8 to 16 km/h (5 to 10 mph). In addition to the automatic spraying system, a spray gun was also used for some edge areas where nozzles of the automatic spraying system could not reach. Since this bio-based agent needs no heating before spraying, the sprayer was not equipped with a heating system. During the spraying, county secondary road department personnel controlled traffic in both lanes of the road, allowing only one lane to be open for traffic while spraying was occurring in the other lane. After bio-sealant application to the first lane, it was immediately opened to traffic, with the second lane then closed for subsequent spraying work.

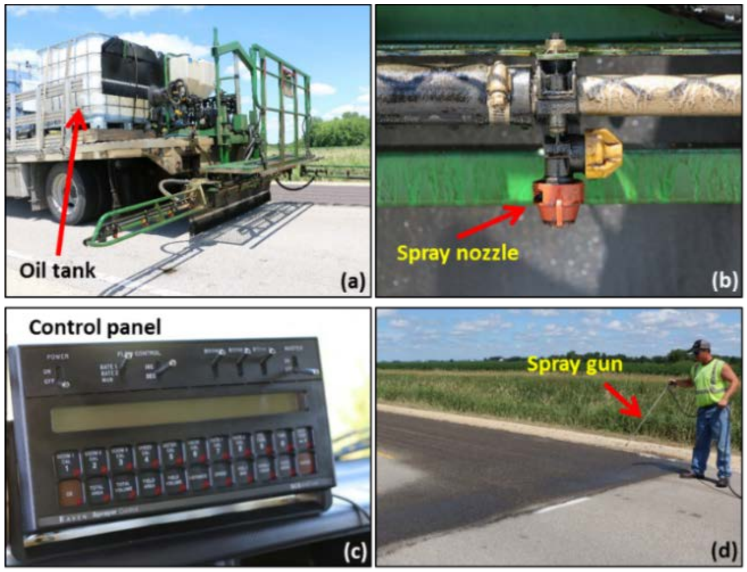


Figure 6.2 *Construction equipment for fog seal*.

For purposes of comparison, Figure 6.3 provides images of both a bio-sealant treated lane and an untreated lane on the day of construction. While the bio-sealant treated lane exhibited a darker color than the untreated lane, this difference in appearance disappeared after a few days. During construction, the pavement marking (centerline and edgeline) was applied along with the bio-sealant materials, but no obvious reduction in visibility of the marking was observed. In fact, the darkened pavement appearance could possibly make the pavement marking more visible due to increased contrast. As shown in Figure 6.3, the bio-sealant treated section did not exhibit free liquid standing on its surfaces, indicating that the bio-sealant could be quickly absorbed by the pavement surface due to its natural properties. Based upon this characteristic, a bio-sealant treated road can be opened to traffic within 30 minutes after application, somewhat more rapidly than when applying traditional fog sealers (Kim and Im, 2012). In summary, the documented construction process showed that the application of bio-sealant is easy to perform, does not require extra energy for heating of the sealant, and the treated road section can be opened to traffic quickly. From these perspectives, it is a cost-effective technology.

Figure 6.3 *Appearance of bio-sealant treated pavement surfaces*.

6.4.2 Field investigations on retroreflectivity, skid number, and British pendulum number

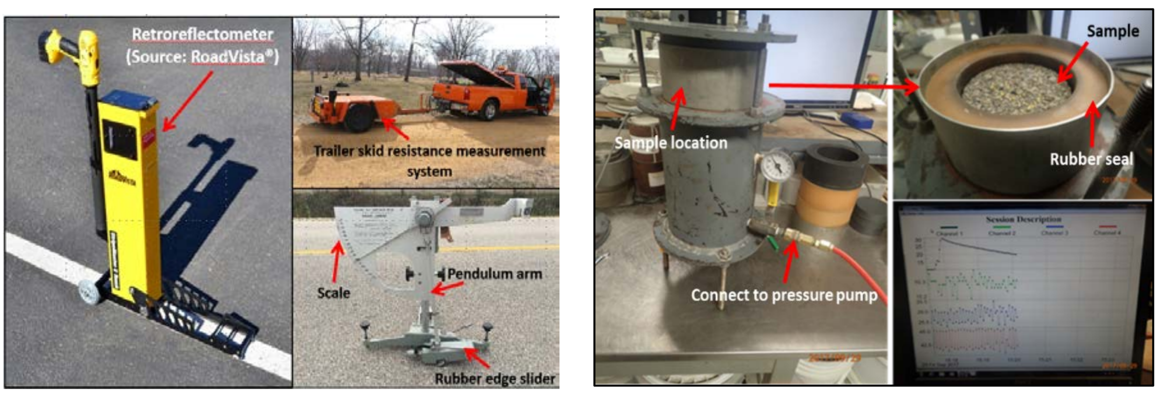
To document the performance of bio-sealant treated roads, several field visits were conducted to measure retroreflectivity, skid number (SN) and British pendulum number (BPN) for the bio-sealant installation site within the first two years after application. Pavement marking on a road can provide guidance and helpful information to drivers, and a road's retroreflectivity plays an important role in safe driving (Austin and Schultz, 2009). Retroreflectivity is a measure of the amount of light returned back from an illuminated object for a given amount of illuminance. In this study, a Roadvista Stripemaster 2 Touch D35229 retroreflectometer (Figure 6.4a) was used to measure the retroreflectivity of two selected spots at the white edgeline on each test section before and after bio-sealant installation in accordance with Materials I.M. 386, with measurement units of mcd/m^2/lux (i.e. millicandelas per square meter per lux, how much light will be reflected at a given illuminance).

Skid resistance is an important field measurement for evaluating the force developed when a tire prevented from rotating slides along a pavement surface. Figure 6.4a shows a locked wheel skid tester consisting of a truck and a special trailer used for skid resistance measurement. This locked wheel test requires driving the vehicle at a speed of 64 km/h (40 mph) to collect discontinuous data points during measurement in accordance with ASTM E274 (2015). Because it provides automatic data collection during driving, and this test is an efficient test for a long road, it is difficult to perform repeated measurements at the same point. In this study, skid resistance of treated sections, including sections remaining before and after installation of bio-sealant, was measured for both eastbound and westbound lanes, and the collected data points can be plotted to provide an overview of SN levels for all sections.

The British pendulum test is a common test for surface friction measurement both in the laboratory and in the field. As shown in Figure 6.4a, the tester consists of a pendulum arm with a standard rubber slider. In accordance with ASTM E303 (2013), the measurement requires swinging the arm to propel the slider edge over a test surface to obtain BPN on the scale. Although the British pendulum test has a similar purpose to that of the locked wheel skid measurement, it can perform repeated measurements at specific points in each test section. This study performed British pendulum measurement after bio-sealant installation for the control section and three treated sections (the remaining section after TS 3 was not included), and two points were tested in each section, including one in the eastbound lane and another in the westbound lane. Each selected point was located in the right wheel path 3.05 m (10 ft) from the section beginning, and each point measurement was repeated four times.

6.4.3 Specimen Coring

To perform the laboratory testing for HMA specimens, sixteen cores with 10.16 cm (4 in.) diameter were taken through electric core drill from the bio-sealant treated sections (the remaining section after TS 3 was not included) and control section in the site every year. Each section had four cores, and two of them from the eastbound lane and the other two from the westbound lane. Until November of 2018, there were two specimen coring activities completed, and the first one was performed on May 8, 2017. After coring, all HMA specimens were brought to the laboratory and sawed into 5.08 cm (2 in.) thickness, and then were oven-dried at 52°C (125°F) to obtain the constant mass. Since four cores were taken from each section, the experiments planned to use the one from the eastbound lane and another one from the westbound lane for permeability measurements, and the other two were used for water absorption measurements. The second specimen coring was performed on April 11, 2018, and the coring plan and experimental plan were the same as those of the first coring activity.



(a) (b)

Figure 6.4 *Images of devices of (a) retroreflectometer, locked wheel skid resistance tester, and British pendulum tester; (b) laboratory air permeability tester.*

6.4.4 Laboratory testing – water absorption and air permeability

Water absorption is a measure of percentage of water on a volume basis absorbed by a specimen during immersion. For asphalt mixture, capability for water absorption is an important indicator about presence of voids. In general, high water absorption in bituminous pavements is associated with many voids and permeability, resulting in more oxidation and pavement structural damages. In this study, dry weight, weight in water, and saturated surface-dry weight (SSD) of specimens were measured to calculate water absorption, following ASTM D2726 (2014).

Permeability is an important property of HMA for evaluating asphalt pavement durability. To measure the permeability of HMA, this study used the air chamber device shown in Figure 6.4b, originally developed by the University of Innsbruck in Austria (Paulini, 2010) and modified at Iowa State University (ISU) in the United States; it was used on specimens under laboratory conditions. A specimen core was inserted into a compressible collar within a rigid sleeve, then was fixed in the steel chamber. The upper surface of the specimen was open to the atmosphere, and its underside was connected to an inlet through which an air gun inserted air to pressurize the chamber. Once the pressure had been loaded to 150 kPa (21.75 psi), the outlet was closed and the measurement initiated. The pressure gauge could record falling pressure in the chamber and output the pressure-time relationship to the computer. After data had been obtained, it was plotted as $\ln(P_0/P_t)$ versus t, with P_0 as the initial pressure and P_t the pressure at time t. $k = \frac{\omega V g d z}{R A \varphi}$, Equation 6.1 was then used to calculate the coefficient of permeability k (m/s) was then calculated for each sample.

$$k = \frac{\omega V g d z}{R A \varphi}, \qquad \text{Equation 6.1}$$

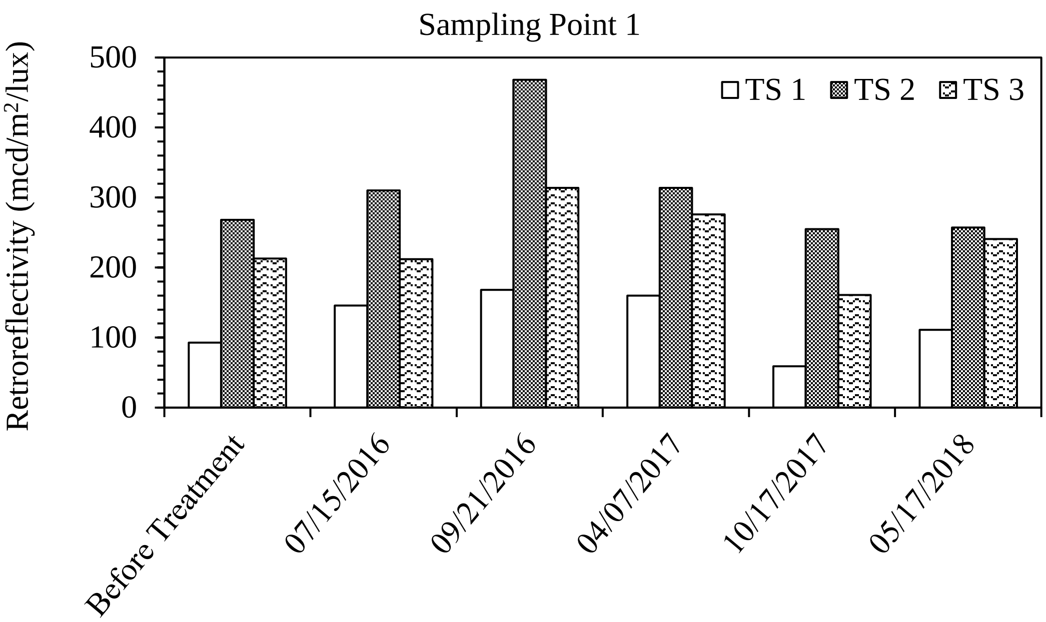
where, ω – molecular mass of air (28.97 g/mol (1.02 oz/mole)), V – volume of air under pressure (m^3), g – acceleration due to gravity (9.81 m/s^2 (32.2 ft/s^2)), A – cross sectional area of specimen (m^2), d – average specimen thickness (m), φ – temperature (k), z – slope of the $\ln(P_0/P_t)$ vs t line.

6.5 Results and Discussion

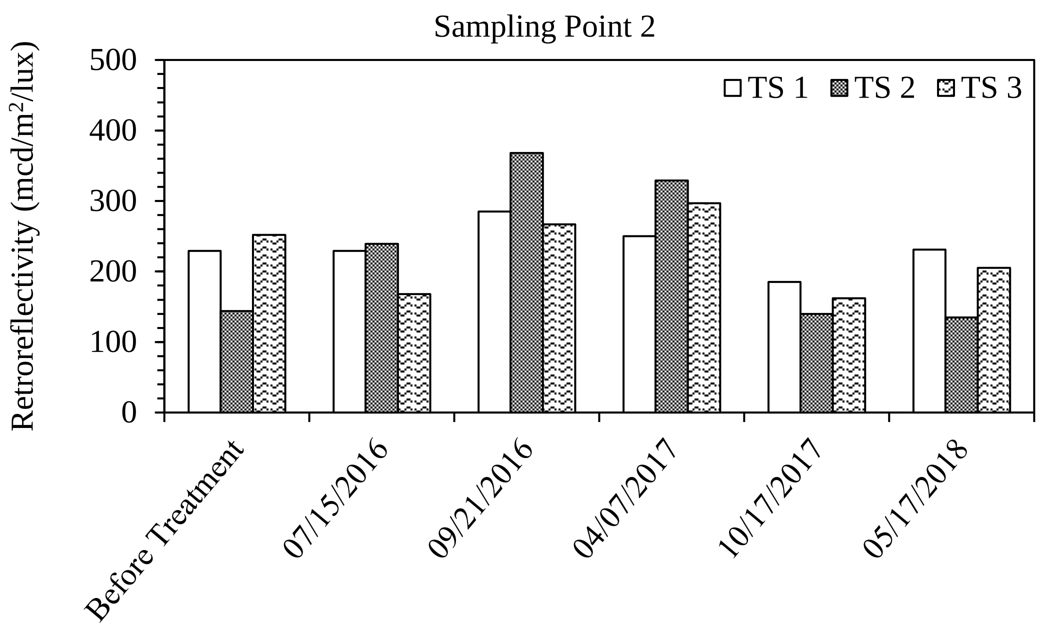
6.5.1 Retroreflectivity

The results for retroreflectivity of white edgelines on all treated sections are shown in

Figure 6.5, which shows the recovered retroreflectivity about two weeks (July 15, 2016) after the date of bio-fog sealant application on June 29, 2016. The original markings were durable paint pavement markings. In this study, TS 1 and TS 2 showed no decrease in retroreflectivity at both two sampling points two weeks after construction, but the lowest spray rate of 0.091 l/m^2 (0.020 gal/yd^2) resulted in a reduction of 84 $mcd/m^2/lux$ (84 $mcd/ft^2/ft\text{-}cd$) at the second sampling point. The lane markers are retroreflective because the painting materials contain special glass beads. Generally, based on these results, fog seal may cause a reduction in retroreflectivity because it can cover the beads and block the light retroreflection. Johnson (2018) reported decreased retroreflectivity of pavement markings after applying different fog sealers, including some bio-based products, and he also observed retroreflectivity recovery for bio-based fog sealed pavement markings after 1,600 truck passes. In this field test, while the bio-sealant application should have resulted in a reasonable loss of retroreflectivity, possible abrasion from tire wear and environmental effects (rain and wind) could have removed the fog seal from the markings after about two weeks to recover retroreflectivity. However, the results for TS 3, reflecting the lowest spray rate, indicated that the bio-based fog sealants were removed faster, resulting in earlier tire wear and reduction of retroreflectivity at sampling point 2. From the perspective of postponing a decrease in retroreflectivity, the higher spray rates are better in providing protection from abrasion for pavement marking. Because of the negative impacts of bio-sealant on retroreflectivity at the initial stage, to achieve driving safety, repainting of pavement marking before seal application is recommended to meet the required retroreflectivity level after application of bio-sealant.



(a)



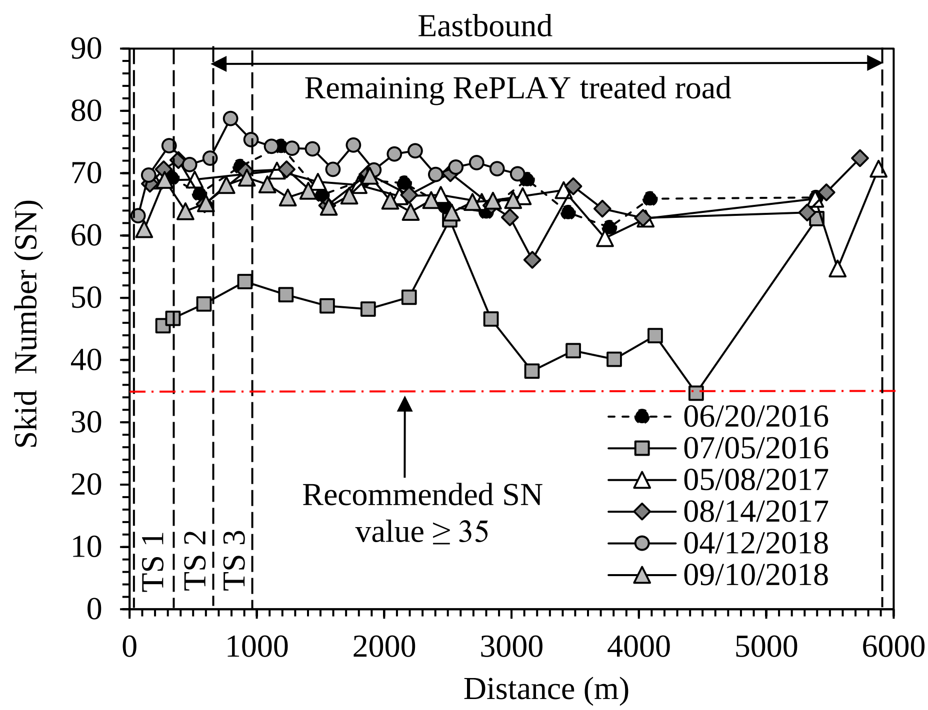
(b)

Figure 6.5 *The measured retroreflectivity on (a) sampling location 1 and (b) sampling location 2.*

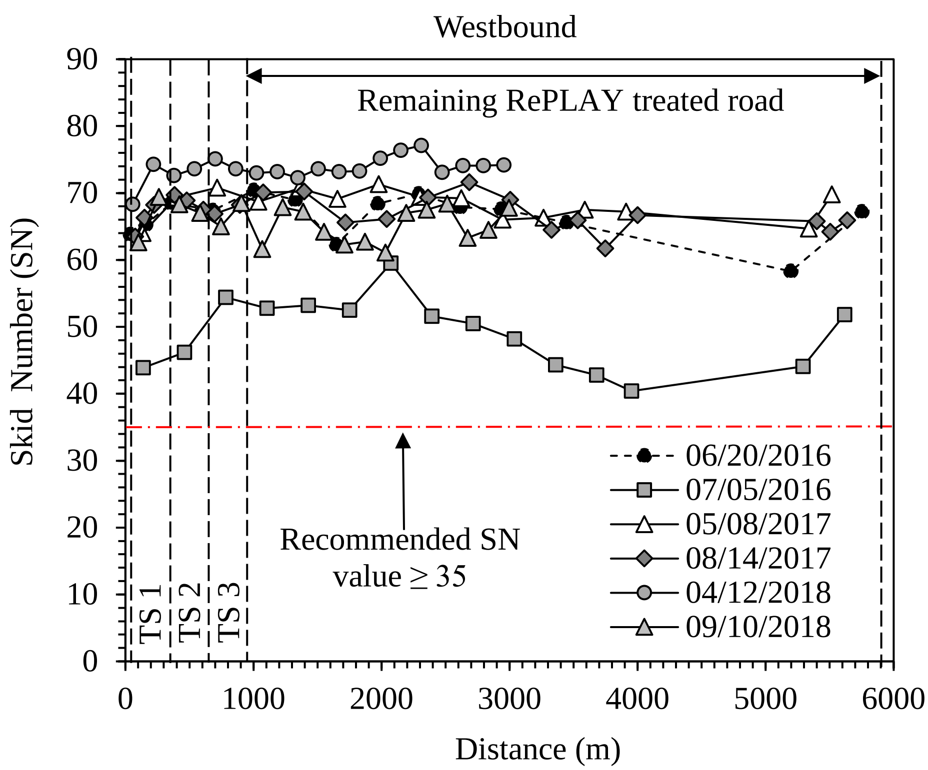
6.5.2 Friction

The results due to friction from locked-wheel tests and British pendulum tests are shown in Figure 6.7. For measurements of skid numbers, both the eastbound lane (Figure 6.7a) and the westbound lane (Figure 6.7b) exhibited significant decreases in skid resistance within the first week after application. While the original average SN of the entire road without bio-sealant was 63, and approximately one week after bio-sealant application (July 5th, 2016), the average SN significantly decreased to 49), after several months (between July 2016 and May 2017), the skid resistance was restored to its original condition. Decreased surface friction because of the use of fog sealants has been reported in several studies (Abaza et al., 2017; Lu and Steven, 2006), suggesting that filling in the pavement surface texture by fog sealant was the primary reason reducing the skid resistance. With continuous tire wear, the fog sealants were worn away from the surface, resulting in an increase in friction (Prapaitrakul et al., 2005). In this study,however, a higher spray rate led to a reasonably larger reduction in skid resistance at initial stage, with all measured SN above the recommended value of 35 (Wambold, 1988), and after eleven months, in all the treated sections the SN returned to the original level.

As shown in Figure 6.7c and Figure 6.7d, the British pendulum test results were compared in terms of BPN using standard deviations (Std) between the control section and the other three bio-sealant treated sections. For both eastbound and westbound lanes, the treated sections presented higher BPN values than the control section, although the differences were slight and all measured numbers were significantly higher than the recommended BPN of 55 (Wambold, 1988). Since the first measurement of BPN was performed about 11 months after the bio-sealant application (May 8, 2017), the results did not exhibit a reduced BPN at the early stage as did the reduced SN on July 5, 2017 (Figure 6.7a and b). The presented BPN values from the first measurement indicated restoration of friction. Figure 6.7c and d also indicate that the latest measurement on March 22, 2018, produced higher BPN values than those from previous measurements.

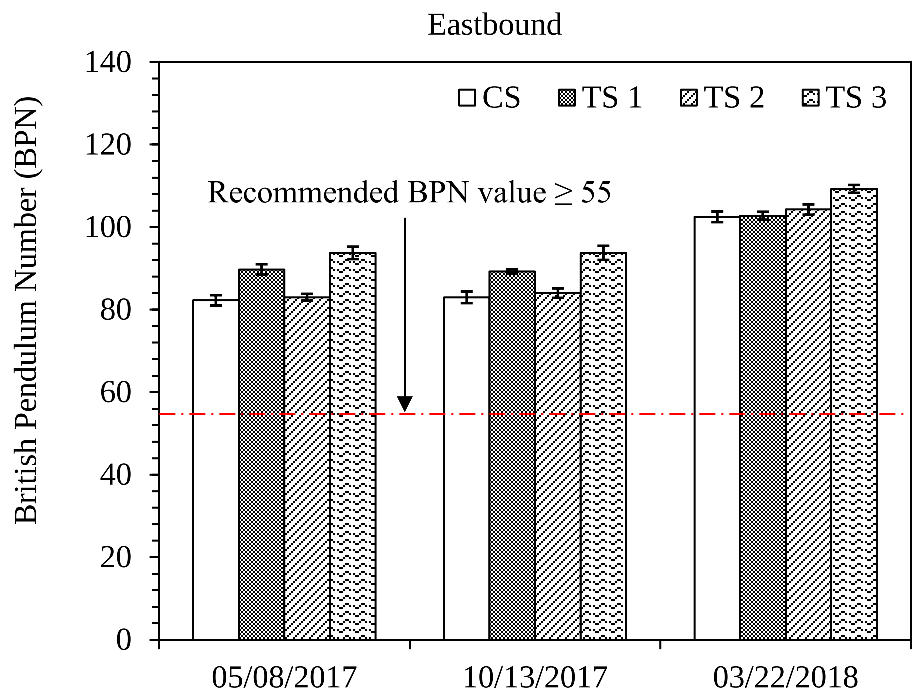


(a)

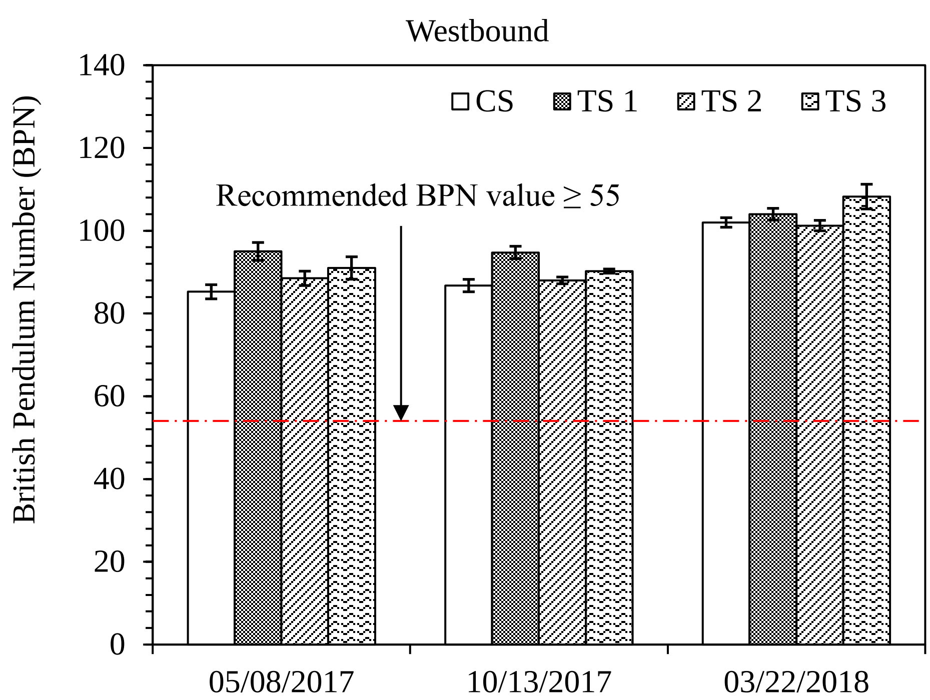


(b)

Figure 6.6 *Results of (a) SN of eastbound, (b) SN of westbound, (c) BPN of eastbound, and (d) BPN of westbound*.



(c)



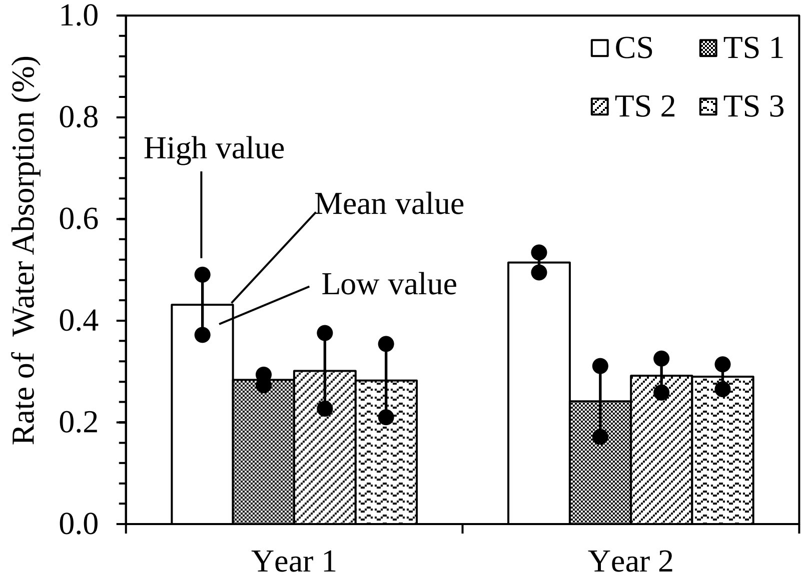
(d)

Figure 6.7 (continued)

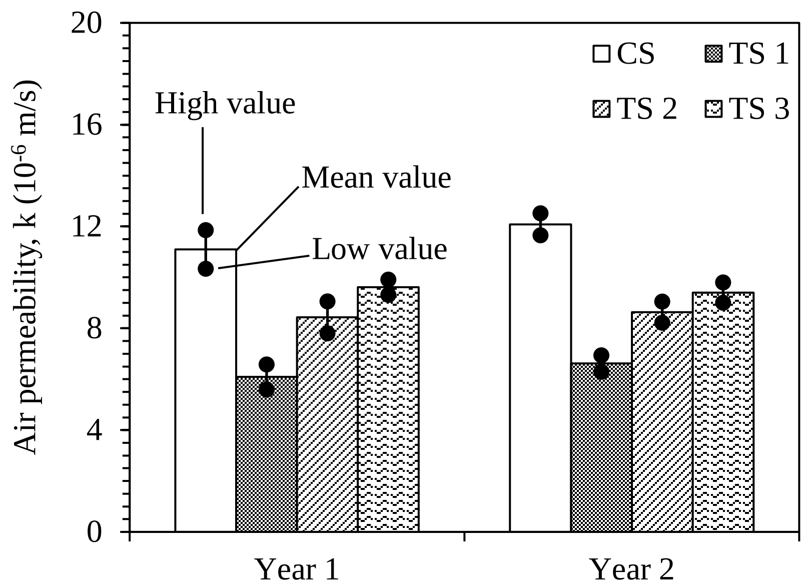
The combined results from locked wheel tests and British pendulum tests indicated that the application of bio-sealant could lead to a reduction in surface friction at an early stage, although after several months the friction could be restored. In a newly constructed pavement system, the friction typically increases during the first two years due to the loss of asphalt binder, then decreases due to polished aggregates (Prapaitrakul et al., 2005). In this study, reduced friction was observed in the measurements of July 5, 2017, 11 months after application, and the highest friction was exhibited on March 22, 2018, (Figure 6.7c and d) and April 12, 2018 (Figure 6.7a and b), with another reduction detected on September 10, 2018, (Figure 6.7a and b). In consideration of the typically higher skid resistance in fall and winter (Prapaitrakul et al., 2005), the site was assumed currently to be in a stage of decreased friction, so more friction measurements were recommended for evaluation of bio-sealant effectiveness on maintenance of skid resistance. In summary, while pavements treated with bio-sealant at rates up to 0.136 l/m2 (0.03 gal/yd^2) displayed an acceptable short-term decrease in skid resistance, they resumed their previous skid performance after several months.

6.5.3 Laboratory water absorption

Figure 6.7a shows water absorption for cores taken in 2017 and 2018. For the cores taken in 2017, one specimen in TS 2 and one in TS 3 displayed absorption similar to the control section specimen. Follow-up testing to the specimen taken in the second year continued to reveal lower water absorption capability for all bio-sealant treated specimens, indicating that the studied bio-sealant can decrease water absorption of pavement cores for at least two years. As mentioned, bio-sealant has good flowability that results in satisfactory void-filling voids in HMA concrete, reducing the likelihood of asphalt binder directly contacting air or moisture. The testing results revealed that the highest spray rate along with TS 1 displayed the lowest absorption.



(a)



(b)

Figure 6.8 *Test results of: a – water absorption; b – air permeability (1 m/s = 3.28 ft/s).*

6.5.4 Laboratory air permeability

The results from air permeability tests shown in Figure 6.8b reflect lower permeability in TS 1 and TS 2 compared to that in specimens from the control section. The thickest/highest rate of application resulted in the lowest air permeability for specimens taken both from the first year (2017) and the second year (2018), reflecting the greater void-filling in bio-sealant- treated specimens. The results from permeability tests exhibited trends similar to those obtained from the water absorption tests. From the perspective of pavement preservation, lower permeability is desirable since it can prevent water infiltration into pavement structures and thereby minimize damage caused by seasonal variations such as freeze-thaw cycles.

6.6 Concluding Remarks

Traditional petroleum-based fog sealers have been successfully used for many years, while alternative non-traditional fog sealers derived from agricultural matter have not yet been properly investigated. In this study, current practice in use of fog seal was reviewed and summarized. Additionally, a bio-based fog sealer derived from agricultural oil was applied to a selected asphalt pavement section at various spray rates over a two-year evaluation interval. The detailed construction procedures were documented, and the key findings from both field investigations and laboratory tests can be summarized as following.

- Retroreflectivity of pavement marking decreased immediately after fog seal application using bio-sealant, but was restored to its pre-construction level in two weeks.
- While a short-term decrease in friction was observed after bio-sealant application, friction requirements were met throughout and returned to their original levels within 11 months.
- Laboratory results indicate that specimens treated with a higher bio-sealant spray rate are associated with the lower water absorption and permeability.
- The highest bio-sealant spray rate of 0.136 l/m^2 (0.030 gal/yd^2) is practically applicable based on field and laboratory performance test results.
- Although the two-year evaluation indicated that bio-sealant could seal voids in pavement

and resulting negative impact on retroreflectivity and friction could be restored, their function on friction maintenance should be evaluated in the following years.

6.7 Acknowledgement

The authors gratefully acknowledge the IA-DOT for financial support of this study. The authors are also grateful to Roger Boulet (IA-DOT), Chris Brakke (IA-DOT), Khyle Clute (IA-DOT), Kent Ellis (IA-DOT), Vanessa Goetz (IA-DOT), Kevin Jones (IA-DOT), Todd Kinney (Clinton County), Mark McCulloh (Bargen, Inc.), Jason Omundson (IA-DOT), Jeffrey Schmitt (IA-DOT), Jim Schnoebelen (IA-DOT), Doug Standerwick (Bargen, Inc.), Fred Thiede (IA-DOT), Francis Todey (IA-DOT), Danny Waid (IA-DOT), Bob Younie (IA-DOT) for providing their comments and assistance in this study. The findings and opinions in this study are solely those of the authors. Endorsements by the Iowa DOT are not implied and should not be assumed.

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CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 General Summary

The primary objective of this study was to review cracking data collection methods and evaluate specific pavement maintenance and preservation practices related to sustainable pavement purposes. An overview of existing cracking identification practices can form a significantly useful reference either while developing a new cracking identification practice or revising the current ones for all 50 states in America. The proposed methods for disposal of concrete slurry waste or using bio-based agent can represent cost-effective and environmentally-friendly alternatives to achieve the goals of suitability sustainable pavement system.

Both national guidelines and state practices with respect to pavement cracking data identification have been summarized in this study. Documents from LTPP, AASHTO, and NCHRP were discussed, and related practices in all 50 states were described as well. The detailed review shows that 28 states have different approaches to surveying their pavement surface condition, and differences can be the result of many factors such as historic practice, environment, pavement design and construction, preservation strategy, and highway management systems.

The effects of CGR collected from an ongoing diamond grinding operation on soil chemical properties were identified in this study. A control field site was created in 2016 at an ISU research unit located in Ames, Iowa, then tested to determine how the chemical properties of soil were affected. Four different application rates of CGR were selected: 0, 2.24, 4.48, 6.72, and 8.96 kg/m^2 (0, 10, 20 and 40 dry ton/acre). The soil samples were taken at stages before, and one month, six months, and one year after CGR application, and were separated into layers ranging from the top, ranging from 0-10.16 cm (0-4 in.), the middle, ranging from 10.16 to 20.32 cm (4-8 in.), and the bottom, ranging from 20.32 to 30.48 cm (8-12 in.), for analysis. Several important chemical properties related to soil quality were examined, including pH, EC, alkalinity, metal concentration, CEC, ESP, and PBS. A statistical model was built to help in understanding the significance of fix factors in terms of CGR rate and soil depth, and results indicated that CGR can significantly affect soil chemical properties.

A comprehensive review of technical guidance and state management practices of CGR was also presented in this study. The literature indicates that CGR has high pH and rich CaO, most likely resulting in flocculation, hydration, rehydration, and pozzolanic reactions in soil matrix that can improve mechanical properties. To evaluate the effectiveness of using CGR in stabilizing soils, two types of soils, classified as A-6 and A-4, respectively were treated with 10%, 20%, 30% and 40% of CGR by dry weight, in accordance to the AASHTO. A series of experimental tests related to Atterberg limits, compaction characteristics, unconfined strength, CBR, pH, alkalinity, EC, and CEC were also conducted, with results that revealed that CGR can benefit soil strength capacity. Micro-structural characterization consisting of SEM and EDS was also performed to identify the mechanism of CGR soil stabilization, and particle-level images showed that soil grains were bonded through newly-formed C-S-H or C-A-H gels.

Construction processes and performance of RePLAY application was also demonstrated. This bio-based fog sealant was used on a 3.3-mile asphalt pavement with in Clinton County, Iowa, in 2016. The road was categorized into five sections: a 30.5-m (100-ft) control section, a 305-m (1000-ft) section using a 0.136 l/m^2 (0.03 gal/yd^2) spray rate, a 305-m (1000-ft) section using a 0.113 l/m^2 (0.020 gal/yd^2) spray rate, another 305-m (1000-ft) section using a 0.091 l/m^2 (0.03 gal/yd^2) spray rate, and the remaining road with a spray rate of 0.091 l/m^2 (0.03 gal/yd^2) . Field tests of pavement-marking retroreflectivity, locked-wheel skid resistance and British pendulum measurements were conducted before and after RePLAY installation. The cores taken from each section were collected in 2017 and 2018 to evaluate laboratory performance in terms of water absorption and air permeability. The field data showed that reduction in retroreflectivity and surface friction due to application of RePLAY were restored to their original levels after some period of time, and laboratory results also indicated that RePLAY can fill voids in cores, thereby decreasing water absorption and permeability.

7.2 Conclusion

The following discussion gives preliminary findings corresponding to each study:

7.2.1 Review of Pavement Cracking Data Identification Practices

This study presented comprehensive reviews of existing cracking data collection practices among both US federal and state agencies, specific findings as follows:

- 28 states specify their own individual practices for distress identification, and 8 of them utilize LTPP distress identification manuals as their baseline.
- Each of the 28 states uses a different method to survey pavement surface conditions, and the differences are caused by a number of factors, including historical practice, environment, pavement design and construction, preservation strategy, and highway management systems.
- Since the LTPP distress identification manual is referenced by many states, similarities can be found in different state documents.
- As with other significant national-level specifications, while AASHTO PP 67 and 68 are not always followed by the SHAs, it is possible to foresee that these documents will be very useful and significant for those states planning to develop new specifications based on automated technology.

7.2.2 Soil Chemical Responses to CGR Application

This study quantified the effects of different offloading rates of CGR on different soil chemical properties, including pH, alkalinity, EC, concentrations of certain metals, CEC, ESP, and PBS at different soil depths. The findings and recommendations of this part of the study can be summarized as follows:

- The increased CGR application rate increased soil chemical properties such as pH, alkalinity, and EC due to its liming and salinity effects. The impacts of CGR on these properties were mitigated with the increase in soil depth and application time.
- Due to the composition of CGR, the offloading of slurry caused the elevated concentrations of Ca, K, Mg, Na, Al, and Fe in soil, but it didn't significantly affect other metals like Ba, Cr, Cu, Mn, and Zn.
- The elevated pH in soil-CGR mixture increased soil CEC.
- Soil ESP was increased at the middle and bottom layers after application of CGR due to the uptake activity of plant roots in deeper soil layer. The soil PBS was significantly influenced by CGR as well, and the significant decrease was caused by the combined effects of changed cation contents and plant uptake activities in soils.
- The elevated soil pH, alkalinity, nutrient metals including Ca, Ma and K, and CEC due to the applied dry CGR up to 8.96 kg/m^2 (40 ton/acre), may be beneficial to the vegetation growth. The other changed properties such as EC, ESP, PBS, and levels of Al and Na have a potential to negatively affect plant growth and soil structure if relevant thresholds are exceeded.

7.2.3 CGR-Soil Stabilization

This study reviewed current practices of the CGR management throughout the United States in an effort to evaluate the reuse of CGR for soil stabilization purposes, and laboratory tests related to the stabilization of soils with CGR were evaluated, with primary findings as follows:

- The different states regulated the different CGR management methods. However, most of these methods didn't present the detailed guidance to engineers or contractors. IGGA BMPs are good reference to follow in these cases.
- Because CGR showed the potential to be reused in different applications, the construction of specific pond for CGR decanting is recommended to get it ready for reuse.
- The laboratory test results indicated that CGR could elevated the soil strength, CBR values, OMC, pH, EC, alkalinity, and CEC. The other results revealed that CGR could decrease the maximum dry unit weight, PI, and swelling potential of soils. In this study 20% CGR is the optimum rate for studied soils due to the highest strengths obtained.
- CGR was more effective in improving the engineering properties of finer soils.
- The SEM-EDS analyses indicated that the improved soil properties after application of CGR is due to a combination of cation exchange, flocculation, hydration, and rehydration and pozzolanic reactions were observed.

7.2.4 Evaluation of Bio-based Fog Sealant

In this study, a bio-based fog sealer, RePLAY, derived from agricultural oil, was applied to a selected asphalt pavement section at various spray rates over a two-year evaluation interval. Detailed construction procedures were documented, and key findings from both field investigations and laboratory tests can be summarized as follows:

- Based on the literature review, the application of RePLAY was supposed to decreased retroreflectivity of pavement marking. The measurements taken after two weeks showed the retroreflectivity was restored to its pre-construction level.
- Based on the literature review and field testing, the application of RePLAY could cause the reduction of pavement surface friction. The field measurement taken after 11 months indicated that the friction returned to its original level.
- The results from laboratory testing indicate that the cores treated at a higher RePLAY rate are associated with lower water absorption and permeability. It is due to the void filling in specimens.
- The manufacturer suggested that the application rate of RePLAY is from 0.01 gal/yd^2 to 0.02 gal/yd^2, however, in this study the results of measurement indicates that rate of 0.030 gal/yd^2 is practically applicable.

7.3 State of the Art Contributions to Engineering Research and Practice

The contributions of this study to engineering research and practice is are as follows:

- Conducted a comprehensive review on pavement cracking data identification practices throughout United States. Discussed differences between national guidelines and local state practices. Provided a detailed summary to help states seeking to develop or revise cracking data identification practices.
- Demonstrated the effects of CGR rate and soil depth on soil chemical properties at different time stages using the two-way ANOVA statistical model. Based on the findings in this study, an acceptable CGR spreading rate can be proposed.
- Developed a comprehensive summary to help understand different CGR disposal methods recommended by different DOTs and also discussed environmental concerns.

Reviewed several practices for properly management of CGR with respect to its reuse through soil and concrete amendment. Provided a very useful reference for use by states seeking to develop or revise CGR management practices.

- Evaluated engineering properties of soil stabilized with various application rates of CGR. Used micro-characterization technology to confirm the CGR mechanisms of with respect to improvement in strength capacity. Based upon results in this study, proposed recycling CGR on stabilizing soil to improve pavement sustainability.
- Documented the bio-sealant application process and provided both field and laboratory evaluations of RePLAY with respect to its use as an alternative for asphalt pavement preservation.

7.4 Recommendations

Recommendations corresponding to each part of the study are as follows:

7.4.1 Recommendation for Pavement Cracking Data Identification

The recommendations for pavement cracking data identification are:

- States without guidelines with respect to cracking identification are encouraged to develop their own guidelines.
- All states should use the LTPP manual as a reference in developing consistent definitions and reporting methods for common cracking types.
- FHWA should update the LTPP manual to include more cracking types common in some states. For example, broken panels are defined in eight states, but not defined in the LTPP manual. Categorizations of severity and extent should be updated as well.
- Longitudinal cracking is a special case because some states record it based on categorization of zones (i.e. wheel path and non-wheel path). It is recommended that

FHWA and SHAs develop a general definition for zone based on width of lane, then use a consistent method for identification of longitudinal cracking.

- Since automated or semi-automated survey methods attract more and more attention from SHAs, AASHTO PP 67 and PP 68 should be updated and finalized for use as a reference to SHAs.

7.4.2 Recommendation for CGR Management

Recommendations for reducing the negative effects of CGR on environment are as follows:

- pH values and heavy metal concentrations in fresh CGR should be monitored. If they exceed a particular threshold, actions such as addition of an agent should be executed to control CGR properties within a safety range based on local requirements.
- While CGR discharge along roadsides can be allowed if there are no nearby sensitive areas (farmlands, lakes, creeks, rivers, and high groundwater table presence, etc.), the maximum allowable discharge rate of CGR should be 8.96 kg/m^2 (40 dry ton/acre). While recycling and reuse of the solid phase of CGR to be in concrete and soil amendments and soil stabilization is strongly recommended, pretests to determine the proper application rate should be performed, and a specific pond should be designated to separate solid phase from CGR slurries.
- The separated liquid phase of CGR should be reused for cooling diamond blades.
- The local SHA should develop detailed CGR disposal guidelines, including cleaning, spreading along roadsides, decanting in ponds, processing in waste facilities, or recycling for multiple applications. Monitoring and control actions should be specified as well.

- Future studies regarding evaluation of higher CGR spray rates (over 8.96 kg/m^2 (40 dry ton/acre)) are recommended. Different CGR sources with longer experimental periods (more than one year) are recommended as well.
- Future studies related to evaluation combinations of cementitious materials and CGR in soil stabilization are recommended.
- Investigation regarding the effects of CGR on stabilizing other types of soils such as fat clay is recommended.

7.4.3 Recommendation for Bio-based Fog Sealant

The recommendations for using RePLAY as fog sealant are as follows:

- RePLAY can be used on an asphalt pavement where permeability is a critical issue.
- RePLAY should be avoided in a road exhibiting low surface friction because it can cause loss of skid resistance at its early stage, possibly resulting in safety issues.
- Surface friction of pavement with newly-constructed RePLAY should be monitored until the skid resistance has been restored to its original condition. The speed limit during the monitoring period can be lowered in consideration of driving safety.
- Retroreflectivity should be monitored and maintained until it is restored to its original condition.
- Future studies evaluating both field and laboratory performance of RePLAY for longer periods (more than two years) are recommended.
- Selection of a new pavement site for RePLAY installation is recommended for the purpose of monitoring changes in surface friction and marking retroreflectivity after RePLAY installation, and more precisely recording the number of days needed to restore original conditions.

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APPENDIX A. SURVEY QUESTIONS

A.1 Survey Questions for Engineers in DOTs

1. Concrete grinding residue (CGR) is a slurry consisting of water, concrete and aggregate generated from diamond grinding of concrete pavement. Is this material considered hazardous waste by the local state highway administration (SHA)?
   a. Yes ☐
   b. No ☐

2. Does the local SHA have their own specifications to dispose of the CGR? If yes, please specify the documents (e.g., highway construction manual, waste management practice and environmental protection regulation).
   a. Yes
      a) Highway construction manual ☐
      b) Waste management practice ☐
      c) Environmental protection regulation ☐
      d) Others: ____________________
   b. No ☐

3. Does the local SHA follow any national guidelines if they do not have their own specifications?
   a. Yes ☐
   b. No ☐

4. How CGR disposed of if the local SHA does not have their own specifications and does not follow the national guidelines?
   a. Offloading slurry along the roadside, ☐
   b. Decanting in pond, ☐
   c. Disposal in waste facility? ☐
   d. Other:________

5. Does the local SHA especially the environment division require control of the pH of CGR before its disposal? If yes, what is the accepted pH value?
   a. Yes – pH: _______
   b. No ☐

6. What other properties of CGR should be controlled before disposal besides pH??
   a. Metal concentrations ☐
   b. Total suspended solids (TSS) ☐
   c. Other:__________

7. Does the disposal method of CGR take the distance from the dumping area to the body of water or sewer system into account? If yes, what is the allowed distance?
   a. Yes – allowed distance:__________
   b. No ☐

8. Where is the suggested place to dispose of CGR? Median swale, shoulder, roadside ditch, or specific pond for storage and decanting?
   a. Median swale ☐
   b. Shoulder ☐
   c. Roadside ditch ☐
   d. Specific pond ☐
   e. Others:_____________

9. Does the local SHA allow the disposal of the CGR within the right-of-way?
   a. Yes ☐
   b. No ☐

10. Does the local SHA have any long-term monitoring for environmental impact when CGR is discharged on the roadside, median swale, or any other soil-based areas? If yes, what is it?

a. Yes

   a) pH ☐

   b) Metal concentrations ☐

   c) Total suspended solids (TSS) ☐

b. No ☐

11. Does the local SHA have any further treatment and/or operation when CGR is discharged on the roadside, median swale, or any other soil-based areas? If yes, what is it?

   a. Yes: __________

   b. No ☐

12. If the CGR is discharged into a specific pond, are there any further treatment and operation? If yes, what is it?

   a. Yes: __________

   b. No ☐

13. Does the local SHA require separating the wastewater from CGR and transporting it to wastewater treatment facilities?

   a. Yes ☐

   b. No ☐

14. Does the local SHA have any specifications about recycling or reusing CGR?

   a. Yes ☐

   b. No ☐

15. Are any pretreatments applied to CGR before it is recycled or reused? If there is, please explain. (For example, some DOTs ask to control the pH of CGR below 12 (pH<12) for reusing and recycling)

a. Yes: __________

b. No ☐

16. What's the annual cost of disposal of CGR?

a. $100K to $500K, ☐

b. $500K to $1 million, or ☐

c. >$1 million. ☐

d. Other: __________

e. Not applicable ☐

17. Does the local concrete industry recycle and reuse CGR and other concrete slurries? If yes what's the application?

a. Yes: ___________

b. No ☐

18. Does the generation, disposal and application of CGR require a permit by any governing agencies?

a. Yes ☐

b. No ☐

A.2 Survey Questions for Industrial Contractors

1. Does the contractor follow any guidelines to dispose of CGR? If yes, what kind of guidelines are followed?
   a. Yes
      a) Own specifications ☐
      b) State guidelines ☐
      c) National guidelines ☐
   b. No ☐

2. How CGR disposed of if the contractor follow their own specifications and does not follow the state and national guidelines?
   a. Offloading slurry along the roadside, ☐
   b. Decanting in pond, ☐
   c. Disposal in waste facility? ☐
   d. Other:________
   e. Not applicable ☐

3. How CGR disposed of if the contractor does not have their own specifications and does not follow the state and national guidelines?
   a. Offloading slurry along the roadside, ☐
   b. Decanting in pond, ☐
   c. Disposal in waste facility? ☐
   d. Other:________
   e. Not applicable ☐

4. Does the contractor need to control of the pH of CGR before its disposal? If yes, what is the accepted pH value?
   a. Yes – pH: _______
   b. No ☐

5. What other properties of CGR should be controlled before disposal besides pH?
    a. Metal concentrations ☐
    b. Total suspended solids (TSS) ☐
    c. Other:__________
    d. No ☐

6. Does the disposal method of CGR take the distance from the dumping area to the body of water or sewer system into account? If yes, what is the allowed distance?
    a. Yes – allowed distance:__________
    b. No ☐

7. Where is the suggested place to dispose of CGR? Median swale, shoulder, roadside ditch, or specific pond for storage and decanting?
    a. Median swale ☐
    b. Shoulder ☐
    c. Roadside ditch ☐
    d. Specific pond ☐
    e. Others:_____________

8. Does the contractor allow the disposal of the CGR within the right-of-way?
    a. Yes ☐
    b. No ☐

9. Does the contract need to do any further treatment and/or operation when CGR is discharged on the roadside, median swale, or any other soil-based areas? If yes, what is it?
    a. Yes:_______
    b. No ☐

10. If the CGR is discharged into a specific pond, are there any further treatment and operation? If yes, what is it?
    a. Yes:_______
    b. No ☐

11. Does the contractor need to separate the wastewater from CGR and transport it to wastewater treatment facilities?
    a. Yes ☐
    b. No ☐

12. Does the contractor recycle or reuse CGR? If yes, what is the application?
    a. Yes:_______
    b. No ☐

13. Are any pretreatments applied to CGR before it is recycled or reused? If there is, please explain. (For example, some DOTs ask to control the pH of CGR below 12 (pH<12) for reusing and recycling)
    a. Yes: __________
    b. No ☐

14. Does the generation, disposal and application of CGR require a permit by any governing agencies?
    a. Yes ☐
    b. No ☐

A.3 Summary Figures of Survey Responses

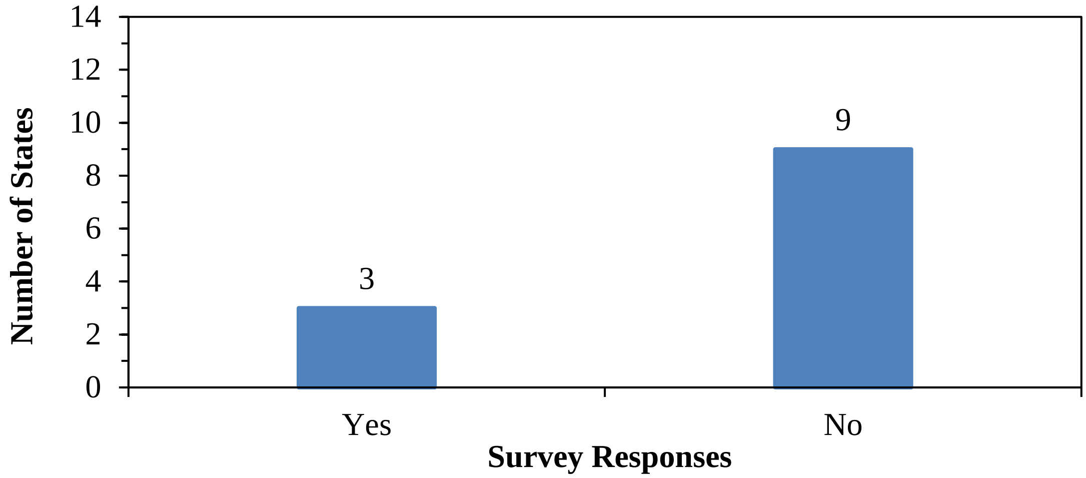


Figure A. 1 Survey question for DOTs: how many local SHAs consider CGR as the hazardous waste?

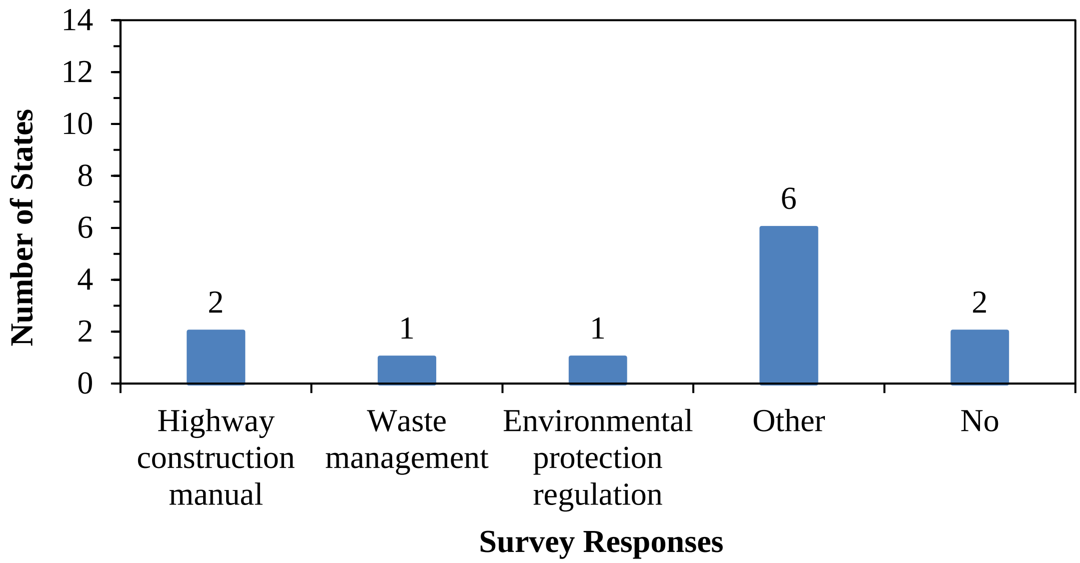


Figure A. 2 Survey question for DOTs: what specifications were followed to dispose of CGR?

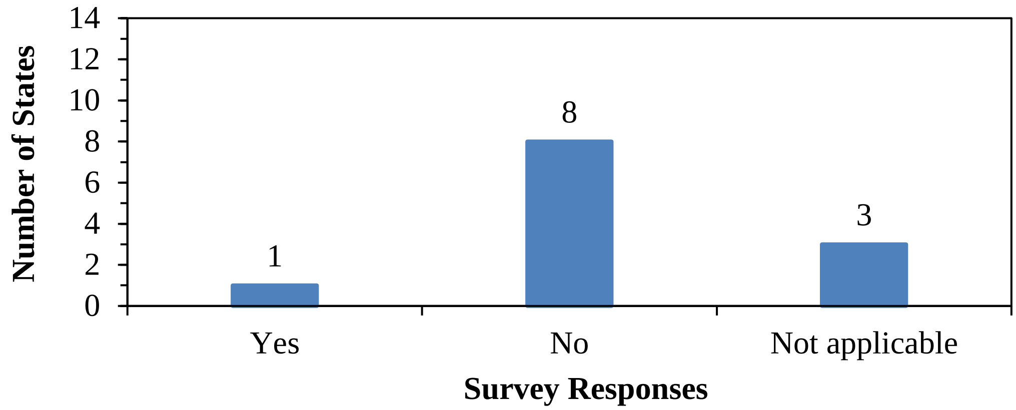


Figure A. 3 Survey question for DOTs: how many local SHAs follow IGGA BMP if they do not have their own specifications?

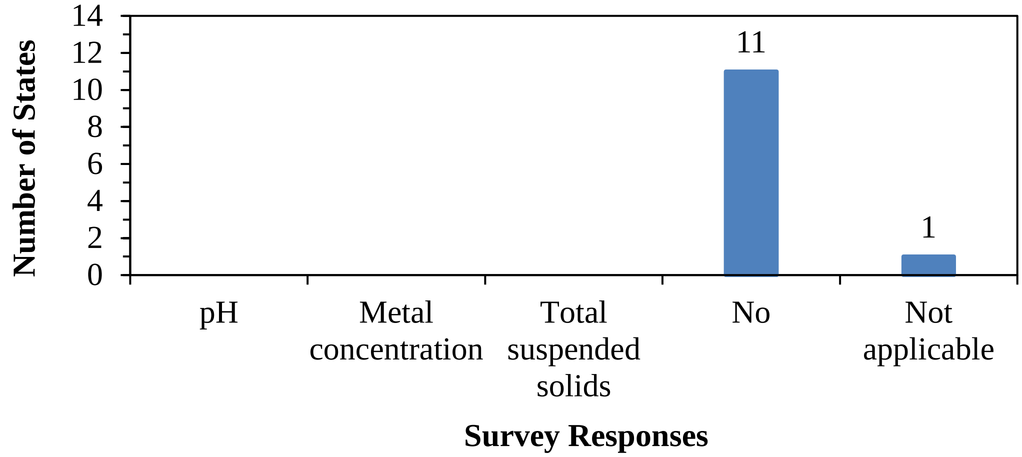


Figure A. 4 Survey question for DOTs: what long-term environmental impacts are required to be monitored when CGR is discharged on the roadside, median swale, or any other soil-based areas?

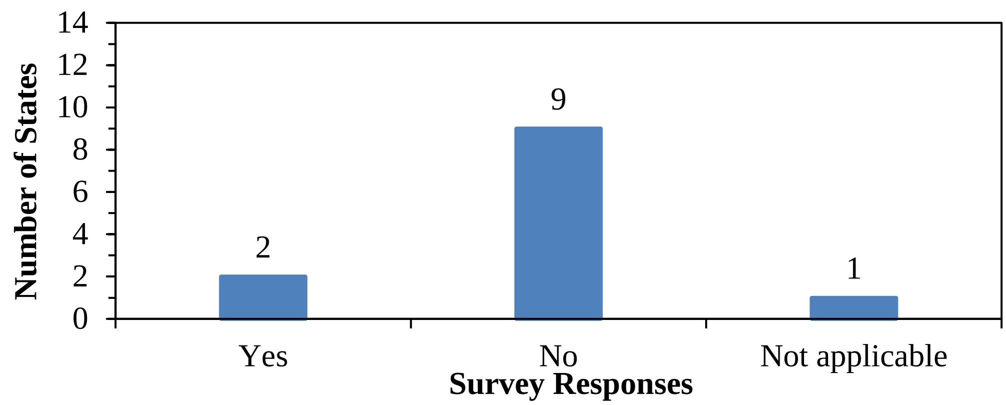


Figure A. 5 Survey question for DOTs: how many local SHAs have specifications about recycling or reusing CGR?

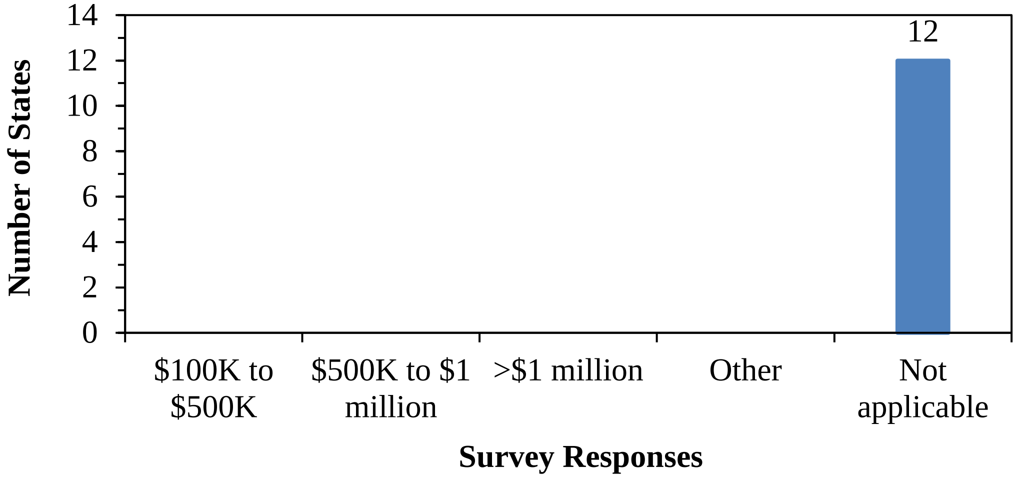


Figure A. 6 Survey question for DOTs: what is the annual cost of disposal of CGR?

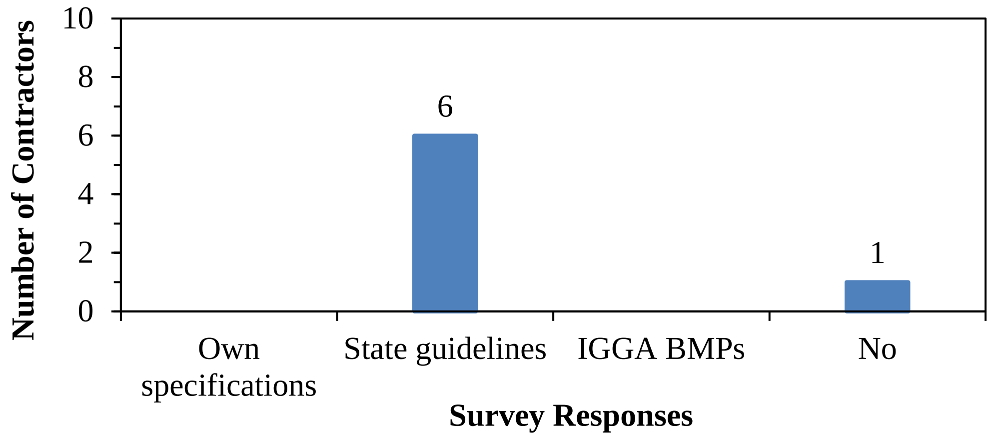


Figure A. 7 Survey question for contractors: what specifications are followed to dispose of CGR?

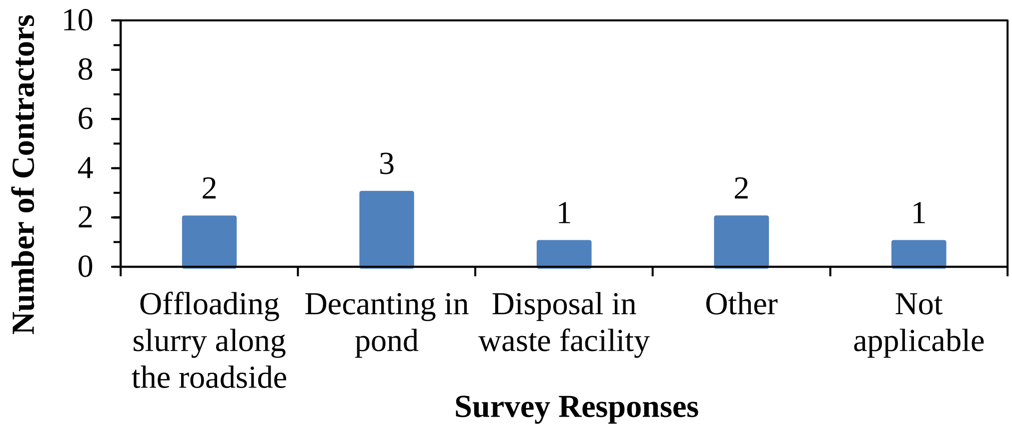


Figure A. 8 Survey question for contractors: how to dispose of CGR if the contractor follows their own specifications and does not follow the state guidelines?

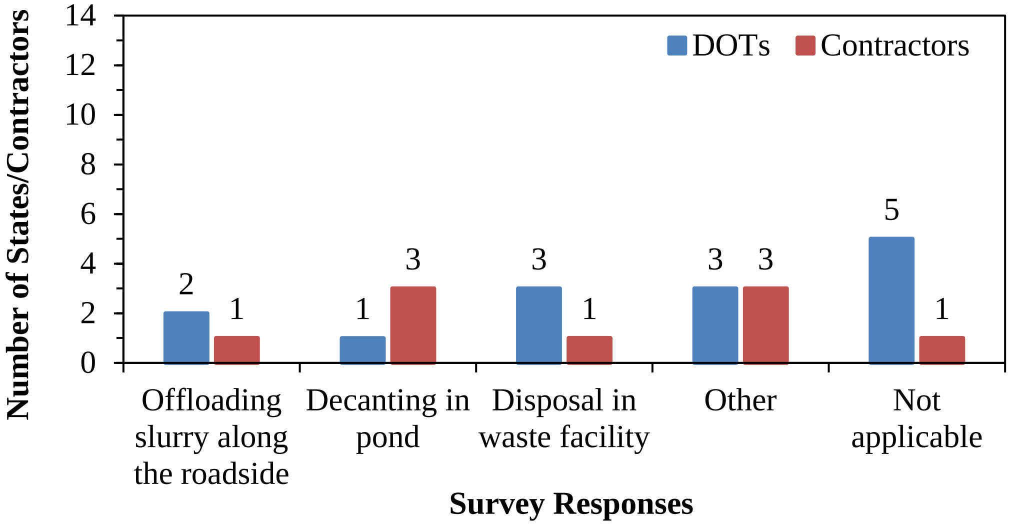


Figure A. 9 Survey question for DOTs and contractors: how to dispose of CGR if the SHAs/contractors do not have their own specifications and do not follow the state guidelines?

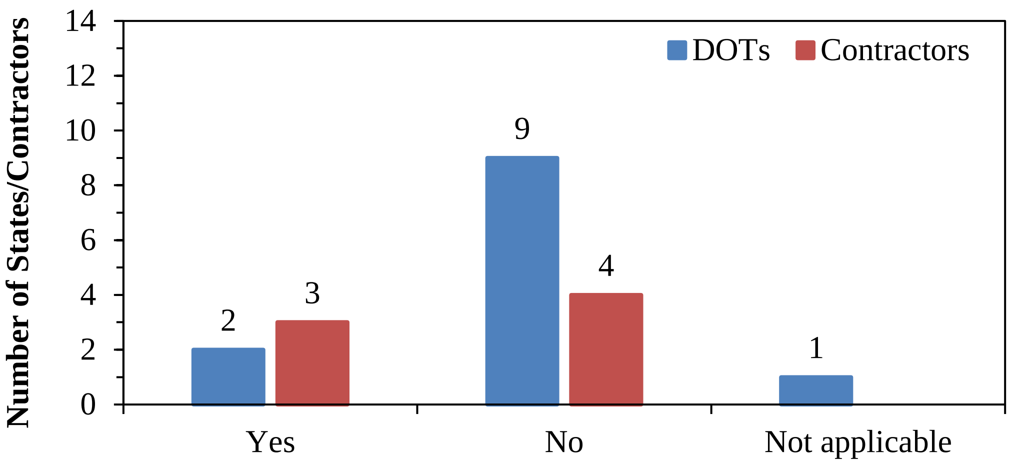


Figure A. 10 Survey question for DOTs and contractors: do they need to control pH of CGR before its disposal?

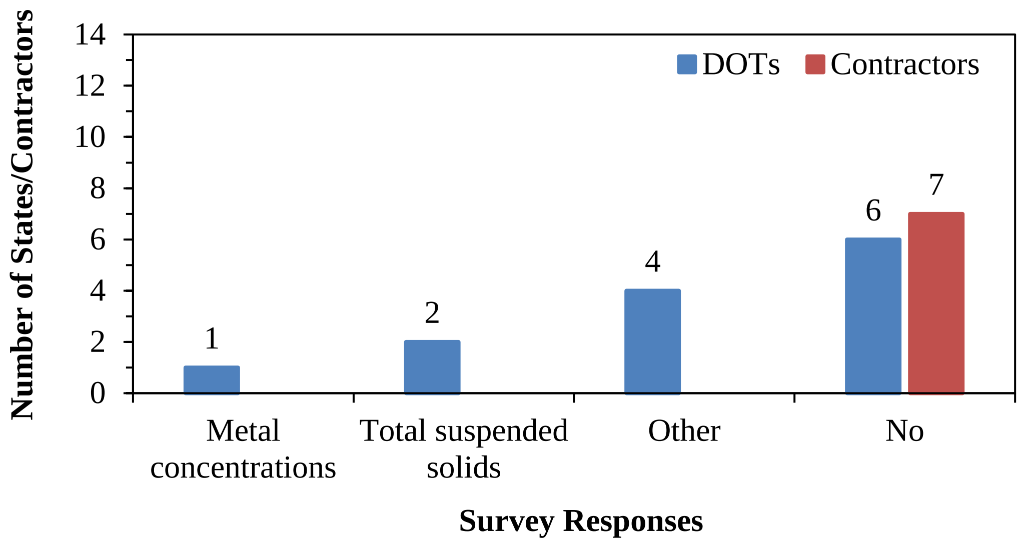


Figure A. 11 Survey question for DOTs and contractors: what other properties of CGR should be controlled before disposal except pH?

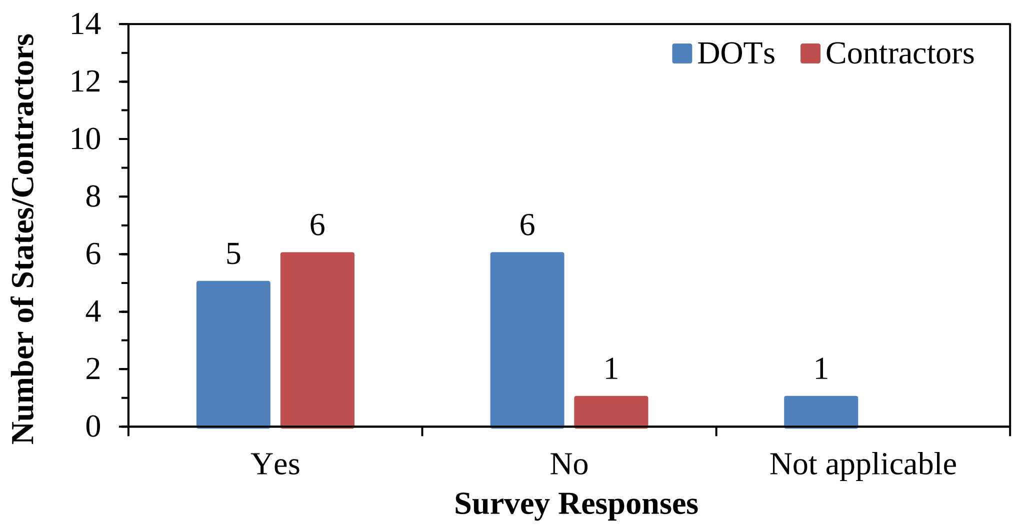


Figure A. 12 Survey question for DOTs and contractors: does the disposal method of CGR take the distance from the dumping area to the body of water or sewer system into account?

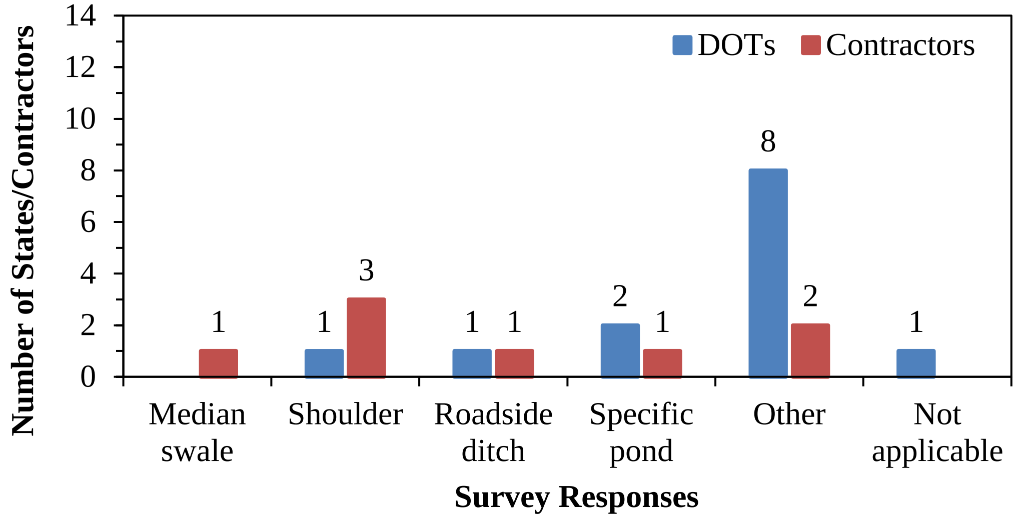


Figure A. 13 Survey question for DOTs and contractors: where is the suggested place to dispose of CGR?

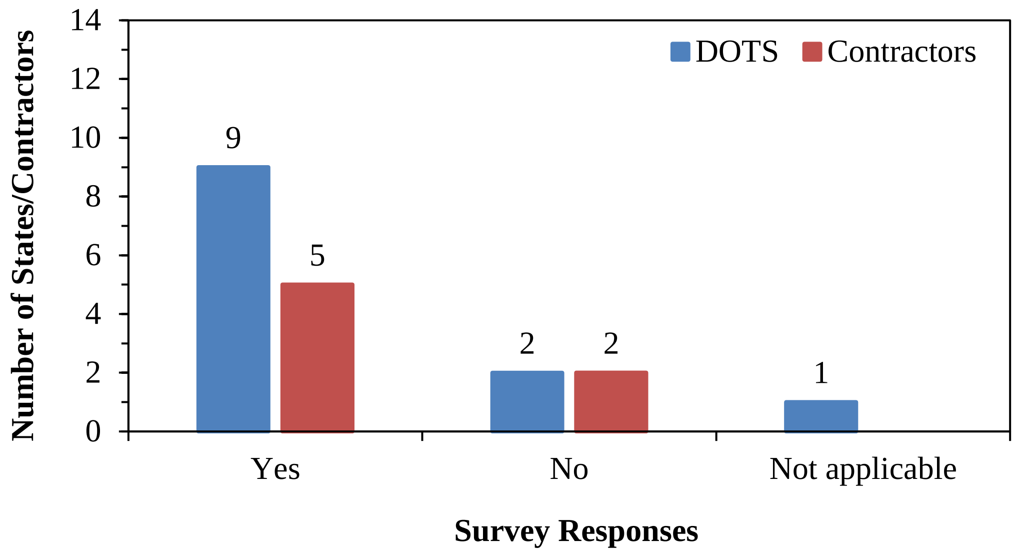


Figure A. 14 Survey question for DOTs and contractors: do they allow to dispose of the CGR within the right-of-way?

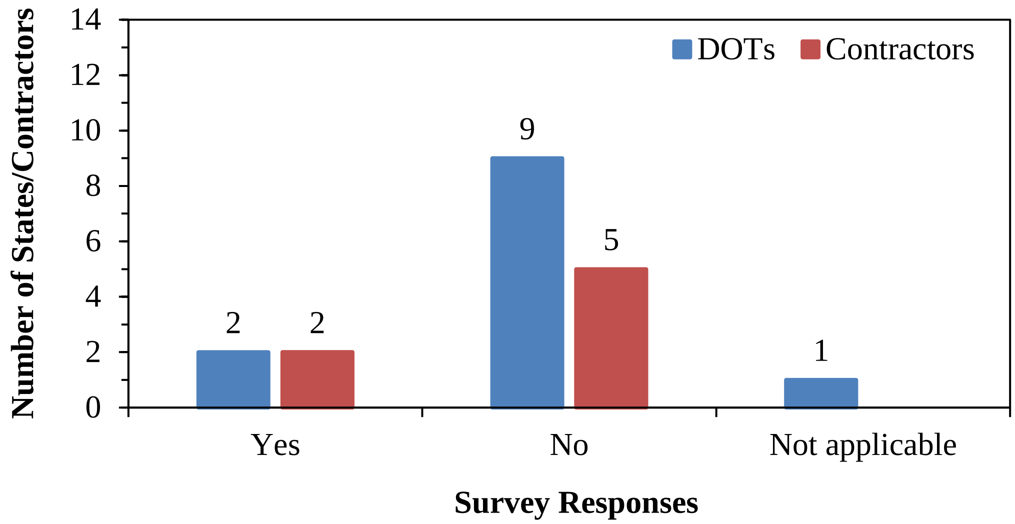


Figure A. 15 Survey question for DOTs and contractors: do they have any further treatment and/or operation when CGR is discharged on the roadside, median swale, or any other soil-based areas?

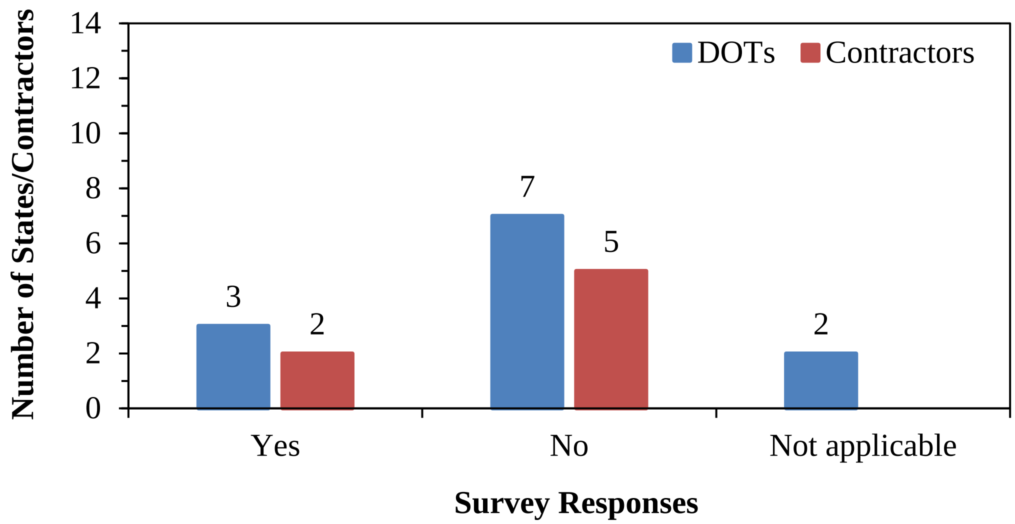


Figure A. 16 Survey question for DOTs and contractors: if the CGR is discharged into a specific pond, are there any further treatment and operation?

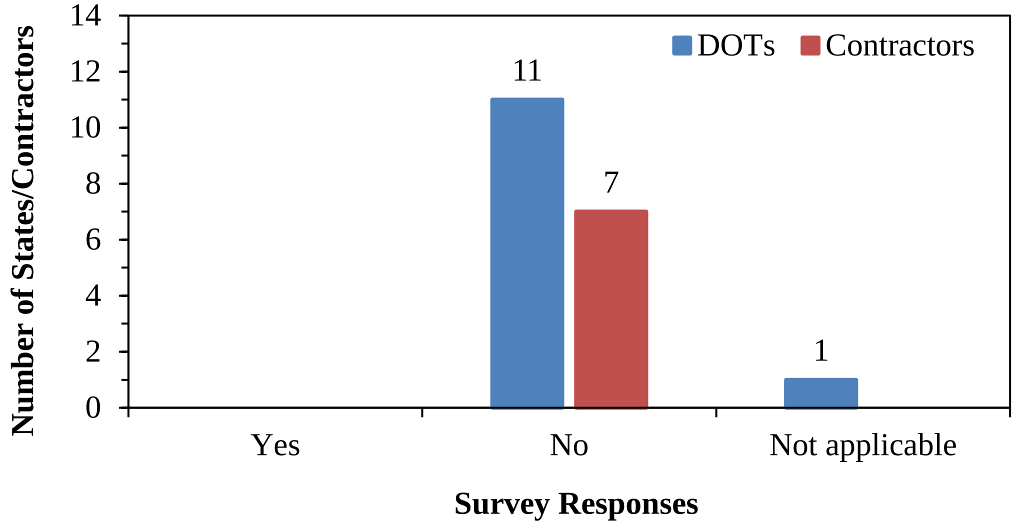


Figure A. 17 Survey question for DOTs and contractors: do they require to separate the wastewater from CGR and transport it to wastewater treatment facilities?

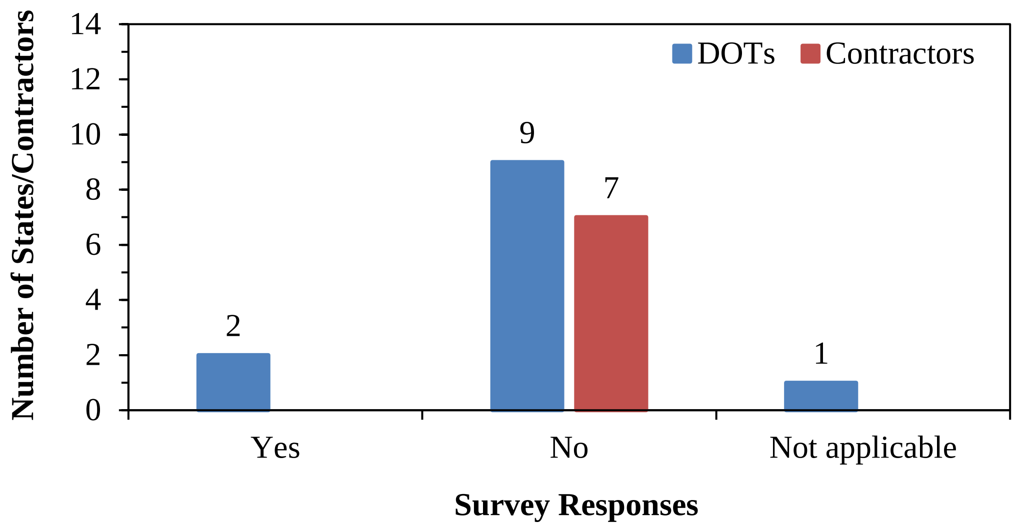


Figure A. 18 Survey question for DOTs and contractors: are any pretreatments applied to CGR before it is recycled or reused?

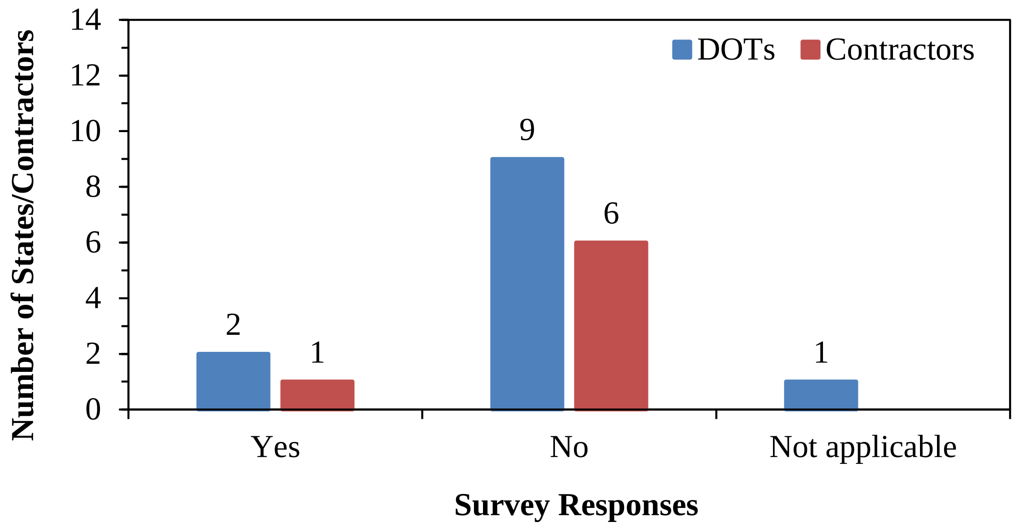


Figure A. 19 Survey question for DOTs and contractors: do they recycle and reuse CGR and other concrete slurries?

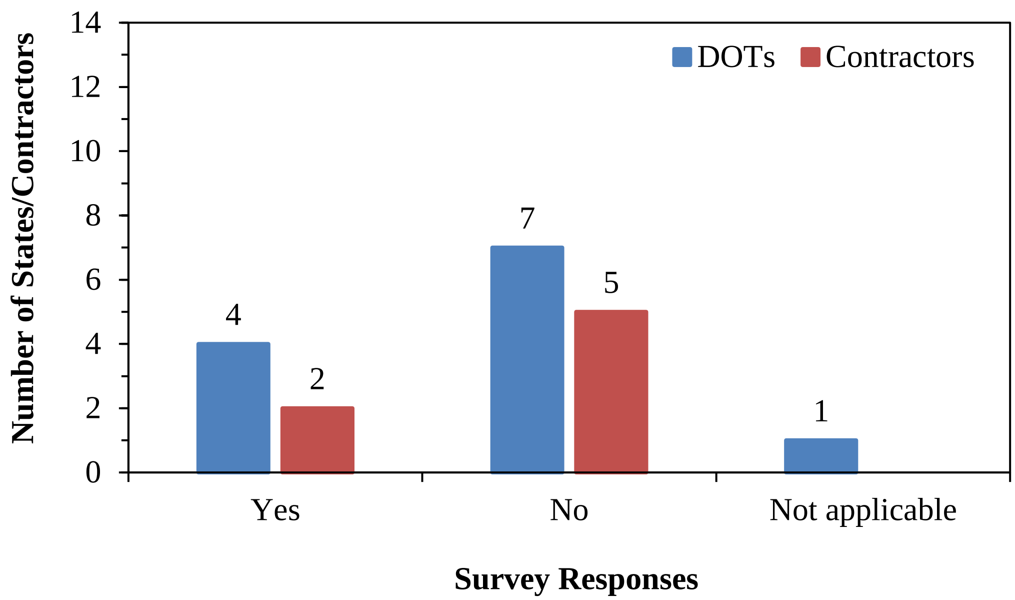


Figure A. 20 Survey question for DOTs and contractors: does the generation, disposal and application of CGR require a permit by any governing agencies?

APPENDIX B. SUMMARY OF STATE CRACKING DATA COLLECTION AND REPORTING PRACTICES

B.1 State Practice of Cracking Data Identification

Group 1: The SHAs following FHWA LTPP Pavement Distress Identification Manual – 8 states: Connecticut, Delaware, Indiana, Mississippi, Missouri, Nevada, Oklahoma, and Vermont

Reference:

Miller, J. S., and Bellinger, W. Y. (2014). Distress identification manual for the long-term pavement performance program, FHWA-HRT-13-092, available in: https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/13092/13092.pdf (Accessed on March 03, 2016)

Note:

The reference about the states are categorized in Group 1 is listed below:

- Report FHWA-RD-01-096: Application Note: LTPP Distress Identification Manual Sets A Standard for States indicates that Mississippi, Missouri, Nevada and Oklahoma use LTPP Distress Identification Manual as the baseline.
- CT DOT Pavement Preservation Manual (Page 16) indicates Connecticut uses LTPP Distress Identification Manual.
- DE DOT Highway Performance Monitoring System Field Manual (Page 5-11) indicates Delaware uses LTPP Distress Identification Manual.
- IN DOT 2013 Design Manual (Page 33) indicates Indianan uses LTPP Distress Identification Manual.
- VTrans Pavement Design Guide indicates (Page 7) Vermont uses LTPP Distress Identification Manual.

Table B. 1. Summary of cracking data collection and reporting practices in FHWA LTPP Manual

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	JPCP	CRCP
Crack type		Block crack; Edge crack; Fatigue crack; Longitudinal crack; Reflection crack; Transverse crack.	Corner break; Durability crack; Longitudinal crack; Map crack; Transverse crack.	Durability crack; Longitudinal crack; Map crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey and distress map; No detailed specifications.	No, it uses survey and distress map; No detailed specifications.	No, it uses survey and distress map; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Block crack: record affected area (m^2); Edge crack: record length (m); Fatigue crack: record affected area (m^2); Longitudinal crack: record length (m); Reflection crack: recorded as longitudinal or transverse cracks. Transverse crack: record length (m) and number, min. dimension is 0.3 m.	Corner break: record the number, no dimension; Durability crack: record the affected area (m^2) and number; Longitudinal crack: record length (m); Map crack: record the number of occurrences and the affected area (SF); Transverse crack: record length (m) and number.	Durability crack: record the affected area (m^2) and number; Longitudinal crack: record length (m); Map crack: record the number of occurrences and the affected area (SF); Transverse crack: record length (m) and number.
	Surveyed section length	Surveyed section should be divided into 30.5 m (100 ft) long subsections.	Surveyed section should be divided into 30.5 m (100 ft) long subsections.	Surveyed section should be divided into 30.5 m (100 ft) long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	Longitudinal cracking has two zone (wheel path and non-wheel path); Other crack types do not have	No, it does not.	No, it does not.

		different zones.		
	Severity categorization	Block crack: three levels based on visual assessment and crack width; Edge crack: three levels based on visual assessment and percent of the length of the affected portion of the pavement; Fatigue crack: three levels based on visual assessment; Longitudinal crack: three levels based visual assessment and on crack width; Reflection crack: three levels based on visual assessment and crack width; Transverse crack: three levels based on visual assessment and crack width.	Corner break: three levels based on visual assessment; Durability crack: three levels based on visual assessment; Longitudinal crack: three levels based crack width, spalling length and faulting height; Map crack: the number of occurrences and the affected area; Transverse crack: three levels based on crack width, spalling length and faulting height.	Durability crack: three levels based on visual assessment; Longitudinal crack: three levels based crack width, spalling length and faulting height; Map crack: the number of occurrences and the affected area; Transverse crack: three levels based on visual assessment.
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67. Block crack: affected area at each severity level; Edge crack: length of pavement edge affected at each severity level; Fatigue crack: affected area at each severity level; Longitudinal crack: crack length at each severity level; Reflection crack: N/A. Transverse crack: length and number of cracks at each severity	It does not follow AASHTO PP 67. Corner break: number of crack at each severity level; Durability crack: number of slab has cracks and area affected at each severity level; Longitudinal crack: crack length at each severity level; Map crack: N/A; Transverse crack: length and number of cracks at each severity level.	It does not follow AASHTO PP 67. Durability crack: number of slab has cracks and area affected at each severity level; Longitudinal crack: crack length at each severity level; Map crack: N/A; Transverse crack: length and number of cracks at each severity level.

		level.		
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A	N/A
	System validation	N/A	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Alabama

Reference:

Alabama DOT (2015), Data Collection Manual-Level of Service Condition Assessments, available in http://www.dot.state.al.us/maweb/frm/ALDOT%20Condition%20Assessment%20Data%20Collection%20Manual.pdf (Accessed on March 26, 2016)

Alabama DOT (2009), ALDOT-392 Project Level Pavement Condition Data Collection Procedure, available in http://www.dot.state.al.us/mtweb/Testing/testing_manual/doc/pro/ALDOT392.pdf (Accessed on March 26, 2016)

Alabama DOT (2015), ALDOT-414-04 Network-Level Pavement Condition Data Collection Procedure, available in http://www.dot.state.al.us/mtweb/Testing/testing_manual/doc/pro/ALDOT414.pdf (Accessed on March 26, 2016)

Note:

ALDOT-392 "*Project Level Pavement Condition Data Collection Procedure*" follows FHWA LTPP Pavement Distress Identification Manual except that Alabama DOT (AL DOT) uses 1 mile or 1 km length of segment for rating instead of 0.1 mile length of segment specified in the FHWA LTPP manual. Two additional specifications are added:

- The overall quantity of fatigue cracking on flexible pavement shall be reported as a percentage of the wheel path area within the surveyed segment.
- In addition to the amount of distress specified in FHWA LTPP Pavement Distress Identification Manual, the overall quantity of transverse cracking shall be reported as a percentage of the surveyed pavement segment.

Table B. 2. Summary of cracking data collection and reporting practices for Alabama (Network Level)

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Non-load associated crack; Load associated crack; Transverse crack.	Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Non-load associated</u>	<u>Transverse crack</u>: record

		crack: record total length (ft), min. width is 1/25 inch (1 mm) and min. length is 1 inch (25.4 mm); Load associated crack: record total length (ft.), min. width is 1/25 inch (1 mm) and min. length is 1 inch (25.4 mm); Transverse crack: record total length (ft.), min. width is 1/25 inch (1 mm).	total length (ft.).
	Surveyed section length	Surveyed section should be divided into 0.01mile long subsections in network level and 1 mile (or 1 km) long subsections in project level.	Surveyed section should be divided into 0.01mile long subsections in network level and 1 mile (or 1 km) long subsections in project level.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	Required data precision is specified.	Required data precision is specified.
	Does it separate pavement into five zones for cracking summary?	No, it does not; It separates pavement into wheel path zone for load associated cracks and non-wheel path zone for non-load associated cracks.	No, it does not.
	Severity categorization	Non-load associated crack: three levels based on crack width; Load associated crack: three levels based on crack width; Transverse crack: three levels based on crack width.	Percent cracked slabs: N/A; Transverse crack: three levels based on visual assessment and crack width.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Non-load associated crack: segment length has crack and crack length at each severity	It does not follow AASHTO PP 67; Percentage of slabs in JPCP have cracks over segment should be reported;

		level; Load associated crack: segment length has crack and crack length at each severity level; Transverse crack: crack length per segment.	Transverse crack: crack length per segment.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	It has data verification process.	It has data verification process.
	Validation/acceptance report	It does not follow AASHTO PP 67; It has its own report format.	It does not follow AASHTO PP 67; It has its own report format.

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Alaska

Reference:

Wisconsin Transportation Center (2009), Pavement Distress Identification Manual-for the NPS Road Inventory Program, available in http://www.wistrans.org/mrutc/files/Distress-ID-Manual.pdf (Accessed on March 03, 2016)

Note:

Alaska uses Wisconsin Transportation Information Center Pavement Surface Evaluation and Rating (PASER) manual. However, Wisconsin DOT does not use this manual. They use different one as the distress survey manual. This document only has guidelines for AC surfaced pavement.

Table B. 3. Summary of cracking data collection and reporting practices for Alaska

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Longitudinal crack; Transverse crack.	N/A
Data collection	Manual/Automated/ Semi-automated	Automated	N/A
	Is data collected according to AASHTO PP 68?	No, it uses ARAN; No detailed specifications.	N/A
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	N/A
	Data record	<u>Alligator crack</u>: record affected area (SF); <u>Longitudinal crack</u>: record length (ft.); <u>Transverse crack</u>: record length (ft.) and number.	N/A
	Surveyed section length	Surveyed section should be divided into 0.02 mile long subsections.	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	<u>Alligator crack</u>: three levels based on visual assessment and crack	N/A

		width; Longitudinal crack: three levels based on visual assessment and crack width; Transverse crack: three levels based on visual assessment and crack width.	
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report PCR (0-100, and 100 means good) Alligator crack: percent of lane per section; Longitudinal crack: percent of lane per section; Transverse crack: number of lane per section.	N/A
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/acceptance report	N/A	N/A
Others		Propose crack index formulas.	

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – California

Reference:

California DOT (2008), Maintenance Technical Advisory Guide - Volume II - Rigid Pavement Preservation, available in: http://www.dot.ca.gov/hq/esc/oe/project_ads_addenda/04/04-1637U4/Reference%20Documents/Operations%20and%20Maintenance/Maintenance%20Technical%20Advisory%20Guide%20-%20Volume%20II%20-%20Rigid%20Pavement%20Preservation.pdf (Accessed on March 03, 2016)

California DOT: Guidelines for Identifying and Repairing Localized Areas of Distress in Asphalt Concrete Pavements Prior to Capital Preventive Maintenance or Rehabilitation Repairs, Available at: http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/PDF/guidelines-for-ac-pavements.pdf (Accessed on March 03, 2016)

California DOT (2009): Interim Caltrans Automated Pavement Condition Survey, Available at: http://www.bidsync.com/DPXViewer/45a0002f.pdf?ac=auctionandauc=853985andrndid=682044anddocid=2555370 (Accessed on March 03, 2016)

Note:

Interim Caltrans Automated Pavement Condition Survey is a draft version.

Table B. 4. Summary of cracking data collection and reporting practices for California

Pavement type		Flexible Pavement	JPCP	CRCP
Crack type		Longitudinal crack; (non-wheel path); Transverse crack; Wheel path crack; XF-crack.	Corner break; Longitudinal crack; Transverse crack; XJ-crack; 1st stage crack; 3rd stage crack.	Longitudinal crack; Transverse crack; XC-crack.
Data collection	Manual/Automated/ Semi-automated	Automated	Automated	Automated
	Is data collected according to AASHTO PP 68?	No, it uses survey, surface images and surface profile; No detailed specifications.	No, it uses survey, surface images and surface profile; No detailed specifications.	No, it uses survey, surface images and surface profile; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology
	Data record	<u>Longitudinal crack (non-wheel path)</u>: record length ratio of sealed, unsealed narrow and unsealed	<u>Corner break</u>: record number per slab; <u>Longitudinal crack</u>: record number per slab;	<u>Longitudinal crack</u>: record longitudinal crack length ratio; <u>Transverse crack</u>: record number per

		wide cracks; Transverse crack: record number of sealed, unsealed narrow and unsealed wide cracks; Wheel path crack: record wheel path crack length ratio; XF-crack: record XF-crack crack length ratio.	Transverse crack: record number per slab; XJ-crack: record number per slab; 1st stage crack: record it based on definition; 3rd stage crack: record it based on definition.	data segment; XC-crack: record XC-crack length ratio.
	Surveyed section length	Date segment : 10 m length based on both pavement images and pavement surface profile; Pavement management segment: The minimum length is 150 m (0.1 mile), or about 15 data segments per lane.	Date segment : 10 m length based on pavement images, and per slab based on pavement surface profile; Pavement management segment: The minimum length is 150 m (0.1 mile), or about 35 JPCP slabs per lane.	Date segment : 10 m length based on both pavement images and pavement surface profile; Pavement management segment: The minimum length is 150 m (0.1 mile), or about 15 data segments per lane.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not. It separates pavement into left wheel path zone and right wheel path zone for all cracks.	No, it does not.	No, it does not.
	Severity categorization	Longitudinal crack (non-wheel path): three levels based on visual assessment and crack width; Transverse crack: three levels based on visual assessment and crack width; Wheel path crack: four levels based on the wheel path crack length ratio; XF-crack: four levels	Corner break: three levels based on visual assessment; Longitudinal crack: three levels based on visual assessment; Transverse crack: three levels based on visual assessment; XJ-crack: three levels based on visual assessment; 1st stage crack: N/A; 3rd stage crack: N/A.	Longitudinal crack: N/A; Transverse crack: N/A; XC-crack: four levels based on XC-crack length ratio.

		based on XF-crack length ratio.		
	Data interpretation	It follows AASHTO PP 67; Consider pavement structure (materials and layer thicknesses), maintenance and rehabilitation history, traffic volume, and climate conditions.	It follows AASHTO PP 67; Consider pavement structure (materials and layer thicknesses), maintenance and rehabilitation history, traffic volume, and climate conditions.	It follows AASHTO PP 67; Consider pavement structure (materials and layer thicknesses), maintenance and rehabilitation history, traffic volume, and climate conditions.
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Longitudinal crack (non-wheel path): average crack length ratio at each severity level; Transverse crack: average number per 100 m lane length for each severity level; Wheel path crack: percentage data segments at each severity level and percentage of total crack length sealed; XF-crack: percentage data segments at each severity level, percentage of total crack length sealed, and percentage of unsealed wide cracks.	It does not follow AASHTO PP 67; Corner break: percentage of slabs with break at each severity level, percentage of sealed breaks, and percentage of breaks with spalling; Longitudinal crack: percentage of slabs with cracks at each severity level, percentage of sealed cracks and percentage of cracks with spalling; Transverse crack: percentage of slabs with cracks at each severity level, percentage of sealed cracks and percentage of cracks with spalling; XJ-crack: percentage of slabs with cracks at each severity level, percentage of sealed cracks and percentage of cracks with spalling; 1st stage crack: percentage of slabs	It does not follow AASHTO PP 67; Longitudinal crack: percentage data segments with cracks, average crack length ratio, percentage of sealed cracks and percentage of cracks with spalling; Transverse crack: average number per 100 m lane length, percentage of sealed cracks and percentage of cracks with spalling; XC-crack: percentage data segments at each severity level, percentage of sealed cracks and percentage of cracks with spalling.

			with cracks; 3rd stage crack: percentage of slabs with cracks.	
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A	N/A
	System validation	It has data verification process.	It has data verification process.	It has data verification process.
	Validation/ Acceptance Report	N/A	N/A	N/A
Others		Propose mixed lane.	Propose mixed lane.	Propose mixed lane.

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Colorado

Reference:

Colorado DOT (2004), Colorado DOT Distress Manual for HMA and PCC Pavements, available in: https://www.codot.gov/business/designsupport/materials-and-geotechnical/archive-references/cdot-distress-manual-oct-2004.pdf (Accessed on March 03, 2016)

Table B. 5. Summary of cracking data collection and reporting practices for Colorado

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	Rigid Pavement
Crack type		Block crack; Edge crack; Fatigue crack; Longitudinal crack; Reflection crack; Transverse crack.	Corner break; Durability crack; Longitudinal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it does not follow AASHTO PP 68.	No, it does not follow AASHTO PP 68.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	N/A	N/A
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	Longitudinal cracking has two zones (wheel path and non-wheel path), but no description about recording; Other Crack type do not have different zones.	No, it does not.
	Severity categorization	Only longitudinal and transverse cracks follow AASHTO PP 67; Block crack: three levels based on visual assessment and crack	Only longitudinal and transverse cracks follow AASHTO PP 67; Corner break: three levels based on visual assessment;

		width; Edge crack: three levels based on visual assessment and percent of the length of the affected portion of the pavement; Fatigue crack: three levels based on visual assessment; Longitudinal crack: three levels based on crack width; Reflection crack: three levels based on crack width; Transverse crack: three levels based on crack width.	Durability crack: three levels based on visual assessment; Longitudinal crack: three levels based crack width, spalling length and faulting height; Transverse crack: three levels based crack width, spalling length and faulting height.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/acceptance report	N/A	N/A

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Florida

Reference:

Florida DOT (2015), Flexible Pavement Condition Survey Handbook, available in: http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/researchreports/pavement/flexiblehandbook.pdf (Accessed on March 03, 2016)

Florida DOT (2015), Rigid Pavement Condition Survey Handbook, available in: http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/researchreports/pavement/rigidhandbook.pdf (Accessed on March 03, 2016)

Table B. 6. Summary of cracking data collection and reporting practices for Florida

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Block crack; Combination crack.	Corner break; Longitudinal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey, video, maps, straight line diagram, etc. No detailed specifications.	No, it uses survey, video, maps, straight line diagram, etc. No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Record percent of pavement area affected by cracks for all types.	Record total number of cracks for all types.
	Surveyed section length	Rated section length depends on county line, county section, etc. No less than 0.5 miles.	Rated section length depends on county line, county section, etc. No less than 0.5 miles.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not. It separates pavement into wheel path zone and non-wheel path zone for all cracks.	No, it does not.
	Severity categorization	Three severity levels for all crack types are evaluated by crack width, total liner length,	Three severity levels for all crack types are evaluated by crack width and visual assessment.

		affected area and visual assessment.	
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report percent of pavement area affected by cracks for all types.	It does not follow AASHTO PP 67; Report total number of cracks for all types.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	It has data verification process.	It has data verification process.
	Validation/acceptance report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Numerical deductions for cracking method.	Numerical deductions for cracking method.

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Idaho

Reference:

Idaho DOT (2011), Idaho Transportation Department Pavement Rating Manual, available in: http://www.itd.idaho.gov/newsandinfo/docs/PavementManual.pdf (Accessed on March 03, 2016)

Table B. 7. Summary of cracking data collection and reporting practices for Idaho

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Block crack; Edge crack; Longitudinal crack; Transverse crack.	Corner break; Meander crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey, video, maps, straight line diagram, etc. No detailed specifications.	No, it uses survey, video, maps, straight line diagram, etc. No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Record amount per 500 ft., depth, width and thickness of all crack types.	Record amount per 10 slabs, depth, width and thickness of all crack types.
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	<u>Alligator crack</u>: three levels based on size; <u>Block crack</u>: three levels based on size and visual assessment; <u>Edge crack</u>: three levels based on visual	<u>Corner break</u>: three levels based on visual assessment; <u>Meander crack</u>: three levels based on crack width and depth; <u>Transverse crack</u>: three

		assessment; Longitudinal crack: three levels based on crack width, dip width and visual assessment; Transverse crack: three levels based on crack width, dip width and visual assessment	levels based on crack width.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report Crack Index Ratings (0-5.0, and 5.0 means good).	It does not follow AASHTO PP 67; Report Crack Index Ratings (0-5.0, and 5.0 means good).
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/acceptance report	N/A	N/A
Others		Three levels for crack extent based on the number of cracks.	Three levels for crack extent based on the number of cracks.

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Kentucky

Reference:

Kentucky Transportation Cabinet (2009), Pavement Management Field Handbook - KYTC Pavement Distress Identification Manual and Guideline for Preventive Maintenance Treatments, available in: http://transportation.ky.gov/Maintenance/Documents/PavementOperations/PM%20Field%20Manual09.pdf (Accessed on March 03, 2016)

Table B. 8. Summary of cracking data collection and reporting practices for Kentucky

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Fatigue crack; Other cracks.	Other cracks.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	N/A	N/A
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	<u>Fatigue crack</u>: three levels based on visual assessment and crack width; <u>Other cracks</u>: three levels based on visual assessment and crack width.	<u>Other cracks</u>: three levels based on visual assessment and crack width.
	Data interpretation	It follows AASHTO PP 67; Consider time of year and weather condition.	It follows AASHTO PP 67; Consider time of year and weather condition.
Data reporting	Is it according to	It does not follow	It does not follow

	AASHTO PP 67?	AASHTO PP 67; Report extent of each severity of each type of crack by using finite values.	AASHTO PP 67; Report extent of each severity of each type of crack by using finite values.
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual
	System validation	N/A	N/A
	Validation/ Acceptance Report	N/A	N/A
Others		Crack extent categorization. <u>Fatigue crack</u>: three levels based on percentage of potential cracking area; <u>Other cracks</u>: three levels based on spacing between transverse cracks.	Crack extent categorization. <u>Other cracks</u>: three levels based on percentage of panels have cracks.

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Michigan

Reference:

Michigan DOT (2010), MDOT Pavement Management System - Current Distress Manual, available in: http://www.michigan.gov/documents/mdot/RC-1594_-_Appendices_D_432766_7.pdf (Accessed on March 03, 2016)

Table B. 9. Summary of cracking data collection and reporting practices for Michigan

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Block crack; Longitudinal crack; Transverse tear; Transverse crack.	Longitudinal crack; Transverse crack; Map crack.
Data collection	Manual/Automated/ Semi-automated	Automated	Automated
	Is data collected according to AASHTO PP 68?	No, it uses computer based survey and images; No detailed specifications.	No, it uses computer based survey and images; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Alligator crack: record its location (mile point); Block crack: record its location (mile point); Longitudinal crack: record its location (mile point); Transverse Tear: record its location (mile point); Transverse crack: record its location (mile point).	Longitudinal crack: record its location (mile point); Map crack: record its location (mile point); Transverse crack: record its location (mile point).
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity/Extent	Alligator crack: three	Longitudinal crack: five

	categorization	levels based on maximum width; Block crack: N/A; Longitudinal crack: five levels based on seal condition and maximum width; Transverse tear: N/A Transverse crack: matrix based on seal condition, transverse length and maximum width.	levels based on seal condition and maximum width; Map crack: five levels based on transverse length; Transverse crack: matrix based on seal condition, transverse length and maximum width.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67.
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual
	System validation	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Principal distress and associated distress; Associated distress matrix combined severity and extent.	Principal distress and associated distress; Associated distress matrix combined severity and extent.

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Minnesota

Reference:
Minnesota DOT (2011), Mn/DOT Pavement Distress Identification Manual, available in:
http://www.dot.state.mn.us/materials/manuals/pvmtmgmt/Distress_Manual.pdf
(Accessed on March 03, 2016)

Table B. 10. Summary of cracking data collection and reporting practices for Minnesota

Pavement type		Flexible Pavement	JPCP	CRCP
Crack type		Alligator crack; Block crack (Multiple crack); Longitudinal crack; Longitudinal joint crack Transverse crack.	Broken panel; Cracked panel; Durability crack.	Durability crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Alligator crack: record lineal feet; Block crack: record lineal feet; Longitudinal crack: record length (ft.); Longitudinal joint crack: record length (ft.); Transverse crack: record the number of cracks.	Broken panel: record the number of panels broken; Cracked panel: record the number of panels cracked; Durability crack: record the number of panels has crack.	Durability crack: record the number of cracks; Transverse crack: record the number of cracks.
	Surveyed section length	Surveyed section should be divided into 500 ft. long subsections.	Surveyed section should be divided into 500 ft. long subsections.	Surveyed section should be divided into 500 ft. long subsections.
Data analysis, crack classification,	Data reduction and crack detection	N/A	N/A	N/A
	Does it separate	No, it does not.	No, it does not.	No, it does not.

and evaluation	pavement into five zones for cracking summary?			
	Severity categorization	Alligator crack: N/A; Block crack: N/A; Longitudinal crack: three levels based on visual assessment and the distance from the adjacent cracks; Longitudinal joint crack: three levels based on visual assessment and the distance from the adjacent cracks; Transverse crack: three levels based on visual assessment and the distance from the adjacent cracks.	Broken panel: N/A; Cracked panel: N/A; Durability crack: N/A.	Durability crack: N/A; Transverse crack: N/A.
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Convert crack number into percent crack by formula; Calculate total weighted distress; Report Surface Rating (0-4.0, and 4.0 means good); Longitudinal crack: crack length at each severity level; Longitudinal joint crack: crack length at each severity level; Transverse crack: the number of cracks at each severity level.	It does not follow AASHTO PP 67; Report percent slab has cracks; Calculate total weighted distress; Report Surface Rating (0-4.0, and 4.0 means good).	It does not follow AASHTO PP 67; Convert crack number into percent crack by specific Table A-; Calculate total weighted distress; Report Surface Rating (0-4.0, and 4.0 means good).
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual	Annual
	System validation	N/A	N/A	N/A
	Validation/ Acceptance Report	N/A	N/A	N/A

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Nebraska

Reference:

Nebraska DOR (2012), Surface Distress Survey Manual, available in:
http://www.transportation.nebraska.gov/mat-n-tests/pdfs-docs/surfacedistresssurveymanual.pdf (Accessed on March 03, 2016)

Table B. 11. Summary of cracking data collection and reporting practices for Nebraska

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Edge crack; Grid block crack; Longitudinal crack; Transverse crack.	Slab crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey and digital photo; No detailed specifications.	No, it uses survey and digital photo; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Alligator crack</u>: N/A; <u>Edge crack</u>: N/A; <u>Grid block crack</u>: N/A; <u>Longitudinal crack</u>: N/A; <u>Transverse crack</u>: N/A.	<u>Slab crack</u>: N/A.
	Surveyed section length	Pavement segment for detailed survey is no longer than 1 mile and no less than 0.04 mile.	Pavement segment consists of ten lane joints and panels (five joints and panels in each lane); Pavement segment for detailed survey is no longer than 1 mile and no less than 0.04 mile.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity	<u>Alligator crack</u>: three	<u>Slab crack</u>: two levels

	categorization	levels based on visual assessment and crack width; Edge crack: three levels based on visual assessment and crack width; Grid block crack: three levels based on visual assessment, crack width and crack spacing; Longitudinal crack: three levels based on crack width; Transverse crack: three levels based on visual assessment and crack width.	based on visual assessment.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67.
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual
	System validation	It has data verification process.	It has data verification process.
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Safety; Crack extent categorization; Alligator crack: six levels based on the percentage of area has cracks; Edge crack: six levels based on the percentage of area has cracks; Grid block crack: six levels based on the percentage of area has cracks; Longitudinal crack: six levels based on the percentage of area has cracks; Transverse crack: six	Safety.

	levels based on the distance between cracks.	

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – North Carolina

Reference:

North Carolina DOT (2011), NCDOT Digital Imagery Distress Evaluation Handbook, available in:https://connect.ncdot.gov/resources/Asset-Management/AssetManagementDocs/NCDOT%20High%20Speed%20Distress%20Manual%20V1.0%2011-15-2011.pdf (Accessed on March 03, 2016)

Note:

This manual is developed by North Carolina DOT and Virginia DOT. Therefore they have very similar specifications about pavement distress identification.

Table B. 12. Summary of cracking data collection and reporting practices for North Carolina

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	JPCP	CRCP
Crack type		Alligator crack; Longitudinal crack; Longitudinal lane joint crack; Transverse crack; Transverse and longitudinal reflection crack over joints.	Corner break; Longitudinal crack; Transverse crack; Shattered slab.	Clustered crack; Longitudinal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Semi-automated/Automated	Semi-automated/Automated	Semi-automated/Automated
	Is data collected according to AASHTO PP 68?	No, it uses survey and surface image; It has detailed specifications which are very similar to AASHTO 68.	No, it uses survey and surface image; It has detailed specifications which are very similar to AASHTO 68.	No, it uses survey and surface image; It has detailed specifications which are very similar to AASHTO 68.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Alligator crack</u>: record affected area (SF), min. width is 1 ft; <u>Longitudinal crack</u>: record length, min. length is 1 ft; <u>Longitudinal lane joint</u>	<u>Corner break</u>: record the number of slabs containing one or more corner break; <u>Longitudinal crack</u>: record the number of cracks per slab, min.	<u>Clustered crack</u>: record the affected area (m^2) and number; <u>Longitudinal crack</u>: record the number of cracks and length (m), min. length is 1 ft;

		crack: record length (ft), min. dimension is 1 ft; Transverse crack: record length; Transverse and longitudinal reflection crack over joints: record length for transverse reflection crack; record length for longitudinal reflection crack, min. length is 1 ft.	length is 1 ft; Shattered slab: record the number of shattered slabs per section; Transverse crack: record the number of cracks per slab, min. length is 1 ft.	Transverse crack: record the number of cracks and length (ft) and, min. length is half a lane width.
	Surveyed section length	Surveyed section (continuous) should be divided into 0.1 mile long subsections.	Surveyed section (continuous) should be divided into 0.1 mile long subsections.	Surveyed section (continuous) should be divided into 0.1 mile long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	Automated reduction of images.	Automated reduction of images.	Automated reduction of images.
	Does it separate pavement into five zones for cracking summary?	It separates pavement up to five zones based on lane width but not used for separated data recording.	No, it does not.	No, it does not.
	Severity categorization	Alligator crack: three levels based on visual assessment and crack width; Longitudinal crack: two levels based on visual assessment and crack width; Longitudinal lane joint crack: two levels based on visual assessment; Transverse crack: three levels based on visual assessment, crack width, the distance from the adjacent cracks, and area of blocks (SF); Transverse and longitudinal reflection	Corner break: two levels based on visual assessment and spalling length; Longitudinal crack: two levels based on visual assessment; Shattered slab: N/A; Transverse crack: two levels based on visual assessment.	Clustered crack: two levels based on average spacing; Longitudinal crack: three levels based on spalling length; Transverse crack: three levels based on visual assessment.

		crack over joints: three levels based on visual assessment, crack width, the distance from the adjacent cracks, and area of blocks (SF).		
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67. Alligator crack: affected area at each severity level; Longitudinal crack: total length at each severity level; Longitudinal lane joint crack: total length at each severity level; Longitudinal reflection crack over joint: total length at each severity level.	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67. Transverse crack: total length and number at each severity level.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A	N/A
	System validation	It has data verification process.	It has data verification process.	It has data verification process.
	Validation/ Acceptance Report	N/A	N/A	N/A

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Ohio

Reference:

Ohio DOT (2006), Pavement Condition Rating System, available in: https://www.dot.state.oh.us/Divisions/Planning/TechServ/TIM/Documents/PCRManual/2006PCRManual.pdf (Accessed on March 26, 2016)

Table B. 13. Summary of cracking data collection and reporting practices for Ohio

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	JPCP	CRCP
Crack type		**For flexible pavement**: Block and transverse crack; Edge crack; Longitudinal crack; Wheel track crack; Thermal crack; **For composite pavement (AC over PCC):** Corner break; Longitudinal crack; Shattered slab; Transverse crack and Reflection crack .	Corner break; Longitudinal crack; Transverse crack (plain concrete); Transverse crack (reinforced concrete).	Longitudinal crack; Transverse crack spacing.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology
	Data record	Only record severity and extent levels.	Only record severity and extent levels.	Only record severity and extent levels.
	Surveyed section length	Surveyed section (continuous) should be divided into 3 to 5 km (2 to 3 miles) long subsections.	Surveyed section (continuous) should be divided into 3 to 5 km (2 to 3 miles) long subsections.	Surveyed section (continuous) should be divided into 3 to 5 km (2 to 3 miles) long subsections.
Data analysis,	Data reduction and	N/A	N/A	N/A

crack classification, and evaluation	crack detection			
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.	No, it does not.
	Severity categorization	**For flexible pavement:** Block and transverse crack: three levels based on block size; Edge crack: three levels based on visual assessment and crack width; Longitudinal crack: three levels based on visual assessment and crack width; Wheel track crack: three levels based on visual assessment and crack width; Thermal crack: three levels based on visual assessment and crack width. **For composite pavement (AC over PCC):** Corner break: three levels based on visual assessment and crack area depression depth; Longitudinal crack: three levels based on visual assessment and crack width; Shattered slab: three levels based on visual assessment and crack width; Transverse crack and reflection crack: three levels based on visual assessment and crack width.	Corner break: three levels based on visual assessment and crack width; Longitudinal crack: three levels based on visual assessment and crack width; Transverse crack (plain concrete) : three levels based on crack width; Transverse crack (reinforced concrete): three levels based on the number of failed cracks, min. width is 3/16 inches.	Longitudinal crack: three levels based on visual assessment and crack width,; Transverse crack spacing: three levels based on visual assessment and crack spacing.

	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report PCR (0-100, and 100 means good).	It does not follow AASHTO PP 67; Report PCR (0-100, and 100 means good).	It does not follow AASHTO PP 67; Report PCR (0-100, and 100 means good).
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A	N/A
	System validation	N/A	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Local pavement distress; Crack extent categorization for; **flexible pavement**: Block and transverse crack: three levels based on the percentage of section length is affected by cracks; Edge crack: three levels based on the percentage of section length is affected by cracks; Longitudinal crack: three levels based on the average crack length per 100 ft (30 m); Wheel track crack: three levels based on percentage of the wheel track length within the section has crack; Thermal crack: three levels based on crack spacing. **Crack extent categorization for flexible pavement**: Corner break: three levels based on the	Local pavement distress; Crack extent categorization; Corner break: three levels based on the number of corner breaks/mile (per 1.6 km); Longitudinal crack: three levels based on the percentage of slabs have crack; Transverse crack (plain concrete) : three levels based on the percentage of slabs have crack; Transverse crack (reinforced concrete): three levels based on the percentage of slabs have failed crack.	Local pavement distress; Crack extent categorization; Longitudinal crack: three levels based on percentage of section length has cracks; Transverse crack spacing: three levels based on percentage of section length has cracks.

	number of corner breaks/mile (per 1.6 km) of section length; Longitudinal crack: three levels based on the average crack length per 100 ft (30 m); Shattered slab: three levels based on the number of shattered slab areas/mile (per 1.6 km) of section length; Transverse crack: N/A.		

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Oregon

Reference:

Oregon DOT (2010), Pavement Distress Survey Manual, available in: http://www.oregon.gov/odot/hwy/construction/docs/pavement/distress_survey_manual.pdf (Accessed on March 03, 2016)

Table B. 14. Summary of cracking data collection and reporting practices for Oregon

Pavement type		Flexible Pavement	JPCP	CRCP
Crack type		Block crack; Fatigue crack; Longitudinal crack; Transverse crack.	Corner break; Corner crack; Longitudinal crack; Transverse crack; Shattered slab.	Longitudinal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual survey currently, but automated survey is accepTable A-.	Manual survey currently, but automated survey is accepTable A-.	Manual survey currently, but automated survey is accepTable A-.
	Is data collected according to AASHTO PP 68?	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.	No, it uses survey; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67. It has its own cracking terminology.	It does not follow AASHTO PP 67. It has its own cracking terminology	It does not follow AASHTO PP 67. It has its own cracking terminology
	Data record	<u>Block crack</u>: record affected area (SF), max. quantity is 6,000 SF per segment; <u>Fatigue crack</u>: record area (SF) and length (ft), max. quantity is 1,000 ft per segment; <u>Longitudinal crack</u>: record length (ft), max. quantity is 1,500 ft per segment; <u>Transverse crack</u>: record length (ft) and the number of cracks, max. quantity is 44 per segment.	<u>Corner break</u>: record the number of cracks, max. quantity is 32; <u>Corner crack</u>: record the number of cracks and length, max. quantity is 32; <u>Longitudinal crack</u>: record length (ft), max. quantity is 1500 ft; <u>Shattered slab</u>: record the number of cracks, max. quantity is 32; <u>Transverse crack</u>: record length (ft) and the number of cracks, max. quantity is 44.	<u>Longitudinal crack</u>: record length (ft), max. quantity is 1500 ft; <u>Transverse crack</u>: record the number of cracks per 100 ft.
	Surveyed section	Surveyed section	Surveyed section	Surveyed section

	length	(continuous) should be divided into 0.1 mile long subsections.	(continuous) should be divided into 0.1 mile long subsections.	(continuous) should be divided into 0.1 mile long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.	No, only longitudinal crack has two zones (wheel path and non-wheel path).
	Severity categorization	Block crack: three levels based on visual assessment and crack width; Fatigue crack: three levels based on visual assessment; Longitudinal crack: three levels based on visual assessment and crack width; Transverse crack: three levels based on visual assessment, crack width.	Corner break: three levels based on visual assessment, spalling length and faulting height; Corner crack: three levels based on crack width, spalling length and faulting height; Longitudinal crack: three levels based on crack width, spalling length and faulting height; Shattered slab: three levels based on how many pieces the slab is broken into, spalling length and faulting height; Transverse crack: three levels based on crack width, spalling length and faulting height.	Longitudinal crack: three levels based on visual assessment, crack width, spalling length and faulting height; Transverse crack: three levels based on the percentage of total length spalled.
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67; Corner break: the number of cracks at each severity level; Corner crack: the number of cracks at each severity level; Longitudinal crack: the length (ft) at each severity level;	It does not follow AASHTO PP 67; Longitudinal crack: the length (ft) at each severity level; Transverse crack: the crack spacing (100/number of cracks).

			Shattered slab: the number of cracks at each severity level; Transverse crack: the length (ft) at each severity level.	
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A	N/A
	System validation	N/A	N/A	N/A
	Validation/ Acceptance Report	N/A	N/A	N/A

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Pennsylvania

Reference:

Pennsylvania DOT (2015), Automated Pavement Condition Survey Field Manual, available in: http://www.dot.state.pa.us/public/PubsForms/Publications/Pub%20336.pdf (Accessed on March 03, 2016)

Table B. 15. Summary of cracking data collection and reporting practices for Pennsylvania

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Edge Deterioration; Fatigue crack; Miscellaneous crack; Transverse crack.	Broken slab; Longitudinal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Automated	Automated
	Is data collected according to AASHTO PP 68?	No, it uses survey and surface profile; No detailed specifications.	No, it uses survey and surface profile; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Edge crack: record the length; Fatigue crack: record the length; Miscellaneous crack: record the length, max. total length cannot exceed 1,000 ft; Transverse crack: record number and length, min length is 1 ft.	Broken Slab: record the number of slabs; Longitudinal crack: record the number of slabs; Transverse crack: record the number of slab.
	Surveyed section length	Surveyed section (continuous) should be divided into 0.5 mile long subsections.	Surveyed section (continuous) should be divided into 0.5 mile long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	It separates pavement into five zones but not used for separated data recording.	It separates pavement into five zones but not used for separated data recording.

	Severity categorization	Edge crack: three levels based on visual assessment and crack width; Fatigue crack: three levels based on visual assessment and crack width; Miscellaneous crack: three levels based on crack width; Transverse crack: three levels based on crack width.	Broken Slab: three levels based on crack width, faulting height and IRI; Longitudinal crack: three levels based on crack width and spalling width; Transverse crack: three levels based on crack width, spalling width and faulting height.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67. Edge crack: the length at each severity level; Fatigue crack: the length at each severity level; Miscellaneous crack: the length at each severity level; Transverse crack: number and length at each severity level.	It does not follow AASHTO PP 67. Broken Slab: the number of slabs at each severity level; Longitudinal crack: the number of slabs at each severity level; Transverse crack: record the number of slabs at each severity level.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/ Acceptance Report	N/A	N/A

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – South Dakota

Reference:

South Dakota DOT (2009), SDDOT's Enhanced Pavement Management System - Visual Distress Survey Manual, available in: http://www.sddot.com/resources/Manuals/DistressManual.pdf (Accessed on March 03, 2016)

Table B. 16. Summary of cracking data collection and reporting practices for South Dakota

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Block crack; Fatigue crack; Transverse crack.	Corner crack; Durability crack. Longitudinal crack
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey, surface images and compute programmed form; No detailed specifications.	No, it uses survey, surface images and compute programmed form; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Record the extent of each severity of each type of distress.	Record the extent of each severity of each type of distress.
	Surveyed section length	Surveyed section (continuous) should be divided into 0.25 mile long subsections.	Surveyed section (continuous) should be divided into 0.25 mile long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	<u>Block crack</u>: three levels based on visual assessment and block size; <u>Fatigue crack</u>: three levels based on visual	<u>Corner crack</u>: three levels based on visual assessment and faulting height; <u>Durability crack</u>: three levels based on visual

		assessment; Transverse crack: three levels based on crack width and depression depth.	assessment. Longitudinal crack: N/A.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report the extent of each severity of each type of distress; Transverse crack: total extent.	It does not follow AASHTO PP 67; Report the extent of each severity of each type of distress.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Crack extent categorization; Block crack: three levels based on percentage of section affected; Fatigue crack: four levels based on percentage of wheel path affected; Transverse crack: four levels based on crack spacing.	Crack extent categorization; Corner crack: four levels based on percentage of slabs affected; Durability crack: four levels based on percentage of slabs affected; Longitudinal crack: four levels based on percentage of slabs affected.

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Texas

Reference:

Texas DOT (2015), Pavement Management Information System - Rater's Manual, available in:ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/raters_manual.pdf (Accessed on March 03, 2016)

Table B. 17. Summary of cracking data collection and reporting practices for Texas

Pavement type		Flexible Pavement	JPCP	CRCP
Crack type		Alligator crack; Block crack; Longitudinal crack; Transverse crack.	Shattered slab; Slab with longitudinal cracks; Failure (corner break, durability crack, etc.).	Spalled crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses visual evaluation with two logging the data collected methods: a laptop computer programs and automated rating forms.	No, it uses visual evaluation with two logging the data collected methods: a laptop computer programs and automated rating forms.	No, it uses visual evaluation with two logging the data collected methods: a laptop computer programs and automated rating forms.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology
	Data record	Alligator crack: record the percentage of the rated lane's total wheel path area is affected; Block crack: record the percentage of the rated lane's total surface area is affected; Longitudinal crack: record the length (ft) per 100 ft, min. width is 1/8 inch; Transverse crack: record the number per	Failure: record the number of failure observed; Shattered slab: record the number of shattered slab; Slab with longitudinal cracks: record the number of slabs have cracks.	Spalled crack: record the number of cracks, min. spalling length is 3 inch.

		100 ft, min. width is 1/8 inch.		
	Surveyed section length	The surveyed section is identified by using Reference Markers with 0.5 mile average length, some sections may be shorter or longer.	The surveyed section is identified by using Reference Markers with 0.5 mile average length, some sections may be shorter or longer.	The surveyed section is identified by using Reference Markers with 0.5 mile average length, some sections may be shorter or longer.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.	No, it does not.
	Severity categorization	N/A	N/A	N/A
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67.	It does not follow AASHTO PP 67.
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual	Annual
	System validation	N/A	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Reference Marker; Safety; AccepTable A- rating values and special cases for each crack type.	Reference Marker; Safety; AccepTable A- rating values and special cases for each crack type.	Reference Marker; Safety; AccepTable A- rating values and special cases for each crack type.

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Utah

Reference:

Utah DOT (2002), Maintenance and Pavement Management - FY 2003 UDOT Distress Manual, available in: http://www.udot.utah.gov/main/uconits_owner.gf?n=1917011012244345562 (Accessed on March 03, 2016)

Table B. 18. Summary of cracking data collection and reporting practices for Utah

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Block crack; Longitudinal crack; Transverse crack; Wheel path crack.	Corner break; Shattered panel; Longitudinal or diagonal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey and surface images; No detailed specifications.	No, it uses survey and surface images; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Transverse crack</u>: N/A, min. length is 4 ft; Record the extent of each severity of each type of distress.	<u>Corner break</u>: N/A, the length of side is less than 6 ft and greater than 1 ft; <u>Shattered panel</u>: N/A, min. pieces is 3; Record the extent of each severity of each type of distress.
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	<u>Block crack</u>: three levels based on crack width; <u>Longitudinal crack</u>: three levels based on crack	<u>Corner break</u>: three levels based on number of pieces, spalling length and faulting height;

		width; Transverse crack: three levels based on crack width; Wheel path crack: three levels based on visual assessment and alligator pattern dimension.	Shattered panel: three levels based on the number of pieces per slab; Longitudinal or diagonal crack: three levels based on crack width, spalling length and faulting height; Transverse crack: three levels based on crack width, spalling length and faulting height.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67. Report the extent of each severity of each type of distress.	It does not follow AASHTO PP 67. Report the extent of each severity of each type of distress.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	It has data verification process.	It has data verification process.
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Surveyor training; Crack extent categorization; Block crack: three levels based on length of section has cracks, max. length is 500 ft; Longitudinal crack: three levels based on crack length (ft); Transverse crack: three levels based on number of cracks; Wheel path crack: three levels based on crack length (ft).	Surveyor training; Crack extent has no categorization, only record the number of slabs have cracks.

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Virginia

Reference:
Virginia DOT (2012), A Guide to Evaluating Pavement Distress Through the use of Digital Images, available in: http://www.virginiadot.org/business/resources/local_assistance/A_Guide_to_Evaluating_Pavement_Distress_Through_the_Use_of_Digital_Images_v2.6_1.pdf (Accessed on March 03, 2016)

Table B. 19. Summary of cracking data collection and reporting practices for Virginia

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	JPCP	CRCP
Crack type		Alligator crack; Longitudinal crack; Longitudinal lane joint crack; Reflection crack over joints; Transverse crack.	Corner break; Divided slab; Longitudinal crack; Transverse crack.	Clustered crack; Longitudinal crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	Automated survey currently, but semi-automated survey is accepTable A-.	Automated survey currently, but semi-automated survey is accepTable A-.	Automated survey currently, but semi-automated survey is accepTable A-.
	Is data collected according to AASHTO PP 68?	No, it uses survey and surface image; It has detailed specifications which are very similar to AASHTO 68.	No, it uses survey and surface image; It has detailed specifications which are very similar to AASHTO 68.	No, it uses survey and surface image; It has detailed specifications which are very similar to AASHTO 68.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology
	Data record	Alligator crack: record affected area (SF), min. width is 1 ft; Longitudinal crack: record length, min. length is 1 ft; Longitudinal lane joint crack: record the length (ft), min. length is 1 ft; Reflection crack over	Corner break: record the number of slabs containing one or more corner break; Divided slab: record the number of shattered slabs per section; Longitudinal crack: record the number of cracks per slab, min.	Clustered crack: record the affected area (m^2) and number; Longitudinal crack: record the number of cracks and length (m), min. length is 1 ft; Transverse crack: record the number of cracks and length (ft) and, min. length is half

		joints: record length for transverse reflection crack; record the length for longitudinal reflection crack, min. length is 1 ft; Transverse crack: record length.	length is 1 ft; Transverse crack: record the number of cracks per slab, min. length is 1 ft.	a lane width.
	Surveyed section length	Surveyed section (continuous) should be divided into 0.1 mile long subsections.	Surveyed section (continuous) should be divided into 0.1 mile long subsections.	Surveyed section (continuous) should be divided into 0.1 mile long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	Image resolution is specified.	Image resolution is specified.	Image resolution is specified.
	Does it separate pavement into five zones for cracking summary?	It separates pavement up to five zones based on lane width but not used for separated data recording.	No, it does not.	No, it does not.
	Severity categorization	Alligator crack: three levels based on visual assessment; Longitudinal crack: two levels based on visual assessment; Longitudinal lane joint crack: two levels based on visual assessment; Reflection crack over joints: three levels based on visual assessment; Transverse crack: two levels based on visual assessment.	Corner break: two levels based on visual assessment and spalling length; Divided slab: N/A; Longitudinal crack: two levels based on visual assessment; Transverse crack: two levels based on visual assessment.	Clustered crack: two levels based on average spacing; Longitudinal crack: three levels based on spalling length; Transverse crack: three levels based on visual assessment.
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report Critical Condition Index (0-100, and 100 means good); Alligator crack: affected area at each	It does not follow AASHTO PP 67; Report Critical Condition Index (0-100, and 100 means good).	It does not follow AASHTO PP 67; Report Critical Condition Index (0-100, and 100 means good); Transverse crack: total length and number at

		severity level; Longitudinal crack: total length at each severity level; Longitudinal lane joint crack: total length at each severity level; Longitudinal reflection crack over joint: total length at each severity level.		each severity level.
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual	Annual
	System validation	It has data verification process.	It has data verification process.	It has data verification process.
	Validation/ Acceptance Report	N/A	N/A	N/A

<u>Group 2</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Washington

Reference:

Northwest Pavement Management Systems Users Group (1992), Pavement Surface Condition Rating Manual, available in:http://www.wsdot.wa.gov/NR/rdonlyres/1AB0E29D-72D7-466A-9547-C9F631B4CE6C/0/PavementSurfaceConditionRatingManual.pdf (Accessed on March 03, 2016)

Northwest Pavement Management Association (1992), Pavement Surface Condition Field Rating Manual for Asphalt Pavement, available in: http://www.wsdot.wa.gov/publications/manuals/fulltext/m0000/AsphaltPavements.pdf (Accessed on March 03, 2016)

Table B. 20. Summary of cracking data collection and reporting practices for Washington

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Block crack; Longitudinal crack; Transverse crack.	Crack.
Data collection	Manual/Automated/ Semi-automated	Manual survey currently, but automated methods is accepTable A-.	Manual survey currently, but automated methods is accepTable A-.
	Is data collected according to AASHTO PP 68?	No, it use survey; No detailed specifications.	No, it uses survey; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Alligator crack</u>: record the accumulated lengths along the surveyed lane as it occurs in both wheel path; <u>Block crack</u>: record the block size and crack width; <u>Longitudinal crack</u>: record the accumulated lengths along the surveyed lane; <u>Transverse crack</u>: N/A, min. length is 4 ft.	<u>Crack</u>: record the number of slabs have cracks.
	Surveyed section length	Surveyed section should be divided into 0.1 mile	Surveyed section should be divided into 0.1 mile

		long or shorter subsections.	long or shorter long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not;	No, it does not.
	Severity categorization	Alligator crack: three levels based on visual assessment; Block crack: three levels based on visual assessment, crack width and block size; Longitudinal crack: three levels based on visual assessment and crack width; Transverse crack: three levels based on visual assessment and crack width.	Crack: three levels based on number of cracks per slab.
	Data interpretation	It follows AASHTO PP 67; Consider time of year and weather condition.	It follows AASHTO PP 67; Consider time of year and weather condition.
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Alligator crack: extent and percentage of length per section at each severity level; Block crack: block size level and crack width level; Longitudinal crack: extent and percentage of length per section at each severity level; Transverse crack: extent and number of cracks per 100 ft at each severity level;	It does not follow AASHTO PP 67; Crack: extent and percentage of sections have cracks at each severity level.
Data Quality Assurance/	Survey frequency	N/A	N/A
	System validation	It has data verification	It has data verification

Quality Control		process.	process.
	Validation/ Acceptance Report	N/A	N/A
Others		Surveyor training; Crack extent categorization; Alligator crack: four suggested ranges based on the percentage of wheel path length; Block crack: only estimate the full length per section; Crack seal condition: three suggested ranges based on the percentage of total length of cracks were sealed; Longitudinal crack: three suggested ranges based on the percentage of section length; Transverse crack: three suggested ranges based on the number of cracks per 100 ft.	Surveyor training; Crack extent categorization; Crack: three suggested ranges based on percentage of slabs cracked per section.

Group 2: The SHAs having their own pavement distress identification manuals which are officially available online – Wisconsin

Reference:

University of Wisconsin-Madison Transportation Information Center (2002), Asphalt Roads PASER Manual, available in: https://uwmadison.box.com/shared/static/15yz8a9jsiztk99jj5fjkftmkpomxryb.pdf (Accessed on April 06, 2016)

University of Wisconsin-Madison Transportation Information Center (2002), Concrete Roads PASER Manual for Asphalt Pavement, available in: https://uwmadison.box.com/shared/static/q3qqfw4y2h1yf0lbkv8xffns7hhp1ggz.pdf (Accessed on April 06, 2016)

Note:

The other documents in Wisconsin DOT indicate that they have other distress manuals but they are not available online:

- Wisconsin Department of Transportation's Pavement Surface Distress Survey Manual (1993 version).
- WisDOT Pavement Distress Index (PDI) Survey Manual.

Table B. 21. Summary of cracking data collection and reporting practices for Wisconsin

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	Rigid Pavement
Crack type		Alligator crack; Block crack; Longitudinal crack; Reflection crack Slippage crack Transverse crack	Corner crack Durability crack Map crack Meander crack Transverse slab crack;
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it use visual survey; No detailed specifications.	No, it use visual survey; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	N/A	N/A
	Surveyed section length	In rural area, the surveyed section may vary from 0.5 mile to 1.0 mile; In urban area, the	In rural area, the surveyed section may vary from 0.5 mile to 1.0 mile; In urban area, the

		surveyed section will likely be 1-4 blocks or more.	surveyed section will likely be 1-4 blocks or more.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	N/A	N/A
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Rating pavement surface condition (1-10, and 10 means excellent)	It does not follow AASHTO PP 67; Rating pavement surface condition (1-10, and 10 means excellent)
Data Quality Assurance/ Quality Control	Survey frequency	Recommended update is every two years, annual update is even better.	Recommended update is every two years, annual update is even better.
	System validation	N/A	N/A
	Validation/ Acceptance Report	N/A	N/A
Others		Pavement drainage should be considered.	Pavement drainage should be considered.

Group 3: The SHAs having their own pavement distress identification manuals which are officially available online – Arizona

Reference:

Arizona DOT (1992), Preliminary Engineering and Design Manual, Chapter 3 Pavement Management and Evaluation, available in: http://www.azdot.gov/docs/businesslibraries/ped-chapter-3.pdf?sfvrsn=7 (Accessed on March 03, 2016)

Table B. 22. Summary of cracking data collection and reporting practices for Arizona

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		No cracking types	N/A
Data collection	Manual/Automated/ Semi-automated	Manual	N/A
	Is data collected according to AASHTO PP 68?	No, it use survey; No detailed specifications.	N/A
	Cracking terminology	N/A	N/A
	Data record	Cracking is estimated and recorded as a percentage of a 1,000 SF area at each milepost.	N/A
	Surveyed section length	Subdivide the pictures of road surfaces into a 1,000-compartment grid. Survey cracks at each milepost.	
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	Three levels based on percent cracking estimated.	N/A
	Data interpretation	It follows AASHTO PP 67; Consider average daily traffic, 10-year cumulative 18k ESAL, and seasonal variation.	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67. Report PSR (0-5, and 5	It does not follow AASHTO PP 67. Report PSR (0-5, and 5

		means good).	means good).
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual survey only for patching and faulting.
	System validation	N/A	N/A
	Validation/acceptance report	N/A	N/A

<u>Group 3</u>: The SHAs having their own pavement distress identification manuals which are officially available online – Georgia

Reference:

Georgia DOT (2005), Georgia Department of Transportation Pavement Design Manual – Chapter 12 - Preservation, Rehabilitation, Restoration, available in: http://www.dot.ga.gov/PartnerSmart/DesignManuals/Pavement/Pavement%20Design%20Manual.pdf (Accessed on March 03, 2016)

Table B. 23. Summary of cracking data collection and reporting practices for Georgia

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	Rigid Pavement
Crack type		Block/Transverse crack; Edge crack; Load crack; Reflection crack.	Broken slab Corner break; Durability crack; Longitudinal crack; Map crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey illustrations and photographs; No detailed specifications.	No, it uses survey, illustrations and photographs; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Block/Transverse crack</u>: N/A; <u>Edge crack</u>: record distress on curve and the percentage of total length has cracks; <u>Load crack</u>: N/A; <u>Reflection crack</u>: N/A.	<u>Broken slab</u>: record the slab which is broken; <u>Corner break</u>: record the number of slabs has cracks; <u>Durability crack</u>: N/A; <u>Longitudinal crack</u>: record the number of slabs has cracks; <u>Map crack</u>: N/A.
	Surveyed section length	Crack rating should be a 100 ft representative section in each 1 mile segment.	Crack rating should be a 100 ft representative section in each 1 mile segment.
Data analysis, crack	Data reduction and crack detection	N/A	N/A

classification, and evaluation	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	Block/Transverse crack: three levels based on visual assessment; Edge crack: three levels based on visual assessment and crack width; Load crack: four levels based on visual assessment; Reflection crack: three levels based on visual assessment.	Broken slab: two levels based on visual assessment; Corner break: two levels based on visual assessment; Durability crack: N/A; Longitudinal crack: two levels based on visual assessment; Map crack: N/A.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report Project Rating (0-100, and 100 means good).	It does not follow AASHTO PP 67; Report Project Rating (0-100, and 100 means good). Broken slab: number of broken slab at each severity level.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/acceptance report	It does not follow AASHTO PP 67; It has its own software file.	It does not follow AASHTO PP 67; It has its own software file.
Others		Safety	Safety

Group 3: The SHAs having their own pavement distress identification manuals which are officially available online – Illinois

Reference:

Illinois DOT (2012), Bureau of Local Roads and Street Manual - Chapter Forty-Five - Local Agency Pavement Preservation, available in: http://idot.illinois.gov/assets/uploads/files/doing-business/manuals-split/local-roads-and-streets/chapter%2045.pdf (Accessed on March 03, 2016)

Table B. 24. Summary of cracking data collection and reporting practices for Illinois

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Block crack; Longitudinal crack; Transverse crack.	Corner break; Durability crack; Longitudinal crack; Map crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	All of three methods are accepTable A-.	All of three methods are accepTable A-.
	Is data collected according to AASHTO PP 68?	No, because several survey methods are accepTable A-; No detailed specifications.	No, because several survey methods are accepTable A-; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Alligator crack: N/A; Block crack: record area; Longitudinal crack: N/A; Transverse crack: N/A.	Corner break: record the number of cracks; Durability crack: N/A; Longitudinal crack: N/A; Map crack: N/A; Transverse crack: N/A.
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	Alligator crack: three levels based on visual assessment; Block crack: three levels	Corner break: three levels based on visual assessment; Durability crack: three

		based on visual assessment; Longitudinal crack: three levels based on crack width, dip width and visual assessment; Transverse crack: three levels based on crack width, dip width and visual assessment.	levels based on visual assessment; Longitudinal crack: three levels based on visual assessment; Map crack: three levels based on visual assessment; Transverse crack: three levels based on visual assessment.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Pavement rating score system is based on the selected survey method (e.g., PCI, PASER, CRS, etc.).	It does not follow AASHTO PP 67; Pavement rating score system is based on the selected survey method (e.g., PCI, PASER, CRS, etc.); Corner break: the number of cracks at each severity level.
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/ Acceptance Report	N/A	N/A

Group 3: The SHAs having their own pavement distress survey methodologies which are not officially available online but are referred in other documentations – Louisiana

Reference:

Louisiana DOT (2010), Guidelines on the Application of Preventive Maintenance and Rehabilitation Practices for Pavement Perseveration – Chapter 2 Pavement Distress, available in: http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Road_Design/Systems_Preservation/Documents/Pavement%20Preservation%20Manual%20(October%202010).pdf (Accessed on March 03, 2016)

Table B. 25. Summary of cracking data collection and reporting practices for Louisiana

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	JPCP	CRCP
Crack type		Block crack; Edge crack; Fatigue crack; Longitudinal crack; Reflection crack; Transverse crack.	Corner break; Longitudinal crack; Transverse crack.	Longitudinal crack; Map crack; Transverse crack.
Data collection	Manual/Automated/ Semi-automated	All of three methods are accepTable A-.	All of three methods are accepTable A-.	All of three methods are accepTable A-.
	Is data collected according to AASHTO PP 68?	No, it uses visual survey or automated equipment (laser-video) to collect data; No detailed specifications.	No, it uses visual survey or automated equipment (laser-video) to collect data; No detailed specifications.	No, it uses visual survey or automated equipment (laser-video) to collect data; No detailed specifications.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology
	Data record	N/A	N/A	N/A
	Surveyed section length	Surveyed section should be divided into 0.004 mile (for 2008-2009 survey year) or 0.01mile (for 2006-2007 survey year) long subsections.	Surveyed section should be divided into 0.004 mile (for 2008-2009 survey year) or 0.01mile (for 2006-2007 survey year) long subsections.	Surveyed section should be divided into 0.004 mile (for 2008-2009 survey year) or 0.01mile (for 2006-2007 survey year) long subsections.
Data analysis, crack classification, and	Data reduction and crack detection	N/A	N/A	N/A
	Does it separate pavement into five	No, it does not.	No, it does not.	No, it does not.

evaluation	zones for cracking summary?			
	Severity categorization	N/A	N/A	N/A
	Data interpretation	N/A	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report PCI (0-100, and 100 means good).	It does not follow AASHTO PP 67; Report PCI (0-100, and 100 means good).	It does not follow AASHTO PP 67; Report PCI (0-100, and 100 means good).
Data Quality Assurance/ Quality Control	Survey frequency	Every two years	Every two years	Every two years
	System validation	N/A	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.

<u>Group 3</u>: The SHAs having their own pavement distress survey methodologies which are not officially available online but are referred in other documentations - Massachusetts

Reference:

Massachusetts DOT (2006), Massachusetts Highway Department Project Development and Design Guidebook - Chapter 9 Pavement design, available in: https://www.massdot.state.ma.us/Portals/8/docs/designGuide/CH_9.pdf (Accessed on March 03, 2016)

Massachusetts DOT (2006), Massachusetts Highway Department Project Development and Design Guidebook Appendix 9-A-1 available in: http://www.massdot.state.ma.us/Portals/8/docs/designGuide/ch_9_appendix_a.pdf (Accessed on March 03, 2016)

Note:

See section 9.3.2. 4 Field Inspection Report. Appendix 9-A-1: Pavement Design Checklist is referred in section 9.3.2. 4 Field Inspection Report. This section only shows the report form, the details about distress collection and evaluation are not available.

Table B. 26. Summary of cracking data collection and reporting practices for Massachusetts

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Block crack; Other crack.	N/A
Data collection	Manual/Automated/ Semi-automated	N/A	N/A
	Is data collected according to AASHTO PP 68?	N/A	N/A
	Cracking terminology	N/A	N/A
	Data record	Only record severity level and extent.	N/A
	Surveyed section length	N/A	N/A
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	N/A	N/A
	Severity categorization	Three levels for all cracks; The reason for categorization is not available.	N/A

	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67.	N/A
Data Quality Assurance/ Quality Control	Survey frequency	N/A	N/A
	System validation	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	N/A
Others		Crack extent is expressed as the percentage; No categorization.	

Group 3: The SHAs having their own pavement distress survey methodologies which are not officially available online but are referred in other documentations – New Jersey

Reference:

Nichnadowicz, V. F., Vitillo, N., Gucunski, N., Rascoe, C., and Zaghloul, S. (2009), Evaluation of the Automated Distress Survey Equipment, available in: http://www.nj.gov/transportation/refdata/research/reports/FHWA-NJ-2009-007.pdf (Accessed on March 03, 2016)

Note:

Official DOT distress manual is not available in web search but the draft of distress manual for Automated Distress Survey Equipment was developed by Rutgers University – CAIT. The research team used distress types, severity levels, and extent measurements based on the SHRP Distress Identification Manual (SHRP P-338, 1993).

Table B. 27. Summary of cracking data collection and reporting practices for New Jersey

Pavement type		Flexible Pavement and Composite Pavement (AC over PCC)	Rigid Pavement
Crack type		Fatigue crack; Longitudinal crack ; Multiple crack; Transverse crack and Reflection Cracking at Joints.	Crack.
Data collection	Manual/Automated/ Semi-automated	Automated	Automated
	Is data collected according to AASHTO PP 68?	No, it use survey, crack map and surface images; It has detailed specifications which are very similar to AASHTO 68.	No, it use survey, crack map and surface images; It has detailed specifications which are very similar to AASHTO 68.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	Fatigue crack: only record the severity level; Longitudinal crack: record the length; Multiple crack: only record the severity level; Transverse crack and Reflection Cracking at	Crack: record the number (for transverse crack) and length.

		Joints: record the number of cracks at each severity level.	
	Surveyed section length	Surveyed section should be divided into 0.1 mile long subsections.	Surveyed section should be divided into 0.1 mile long subsections.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	Image resolution is specified.	Image resolution is specified.
	Does it separate pavement into five zones for cracking summary?	No, it does not; It separates pavement into wheel path zone for load associated cracks and non-wheel path zone for non-load associated cracks.	No, it does not; It separates pavement into wheel path zone for load associated cracks and non-wheel path zone for non-load associated cracks.
	Severity categorization	Fatigue crack: three levels based on visual assessment; Longitudinal crack: three levels based on visual assessment and crack width; Multiple crack: three levels based on visual assessment; Transverse crack and Reflection Cracking at Joints: three levels based on visual assessment and crack width.	Crack: three levels based on visual assessment and crack width.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Fatigue crack: extent and the highest severity level; Longitudinal crack: extent and crack length at each severity level; Multiple crack: extent and the highest severity level; Transverse crack and Reflection Cracking at Joints: extent and the highest severity level ;	It does not follow AASHTO PP 67; Crack: extent, number of cracks (for transverse crack) at each severity level and crack length at each severity level.
Data Quality	Survey frequency	N/A	N/A

Assurance/ Quality Control	System validation	It proposes data verification process.	It proposes data verification process.
	Validation/ Acceptance Report	N/A	N/A
Others		Statistical analysis; Crack extent has no categorization, only record the percentage of section have cracks.	Statistical analysis; Crack extent has no categorization, only record the percentage of section have cracks.

Group 3: The SHAs having their own pavement distress survey methodologies which are not officially available online but are referred in other documentations – New Mexico

Reference:

New Mexico DOT, University of New Mexico and New Mexico State University (2007), Distress Evaluation Reference Chart for Visual Distress Survey, available in: https://www.pavementpreservation.org/wp-content/uploads/presentations/New%20Mexico%20Department%20of%20Transportation's%20Pavement%20Inspection%20Program.pdf (Accessed on March 03, 2016)

New Mexico State University Department of Civil Engineering (2012), Improving NMDOT's Pavement Distress Survey Methodology and Developing Correlations between FHWA's HPMS Distress Data and PMS Data, available in: http://dot.state.nm.us/content/dam/nmdot/Research/FinalReportw-apendicies-UseThisOne.pdf (Accessed on March 03, 2016)

New Mexico DOT (2007), The NMDOT's Pavement Maintenance Manual, available in: https://www.pavementpreservation.org/wp-content/uploads/presentations/New%20Mexico%20Department%20of%20Transportation's%20Pavement%20Maintenance%20Manual.pdf (Accessed on April 11, 2016)

Note:
NMDOT uses manual survey method currently, but they want to use automatic survey if it becomes more cost-effective for them.

Table B. 28. Summary of cracking data collection and reporting practices for New Mexico

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Alligator crack; Edge crack; Longitudinal crack; Transverse crack.	Corner break; Longitudinal crack; Transverse and diagonal crack.
Data collection	Manual/Automated/ Semi-automated	All of three methods are accepTable A-.	All of three methods are accepTable A-.
	Is data collected according to AASHTO PP 68?	No, it use visual survey and compute programmed form; The surface image is accepTable A-.	No, it use visual survey and compute programmed form; The surface image is accepTable A-.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	N/A	N/A
	Surveyed section length	0. 1 mile section in each 1 mile interval of the pavement.	0. 1 mile section in each 1 mile interval of the pavement.
Data analysis,	Data reduction and	N/A	N/A

crack classification, and evaluation	crack detection		
	Does it separate pavement into five zones for cracking summary?	No, it does not; only longitudinal crack has three zones (mid-lane, center line and wheel track).	No, it does not.
	Severity categorization	Alligator crack: three levels based on visual assessment and crack width; Edge crack: three levels based on visual assessment and crack width; Longitudinal crack: three levels based on visual assessment and crack width; Transverse crack: three levels based on visual assessment and crack width.	Corner break: three levels based on visual assessment, crack width and faulting height; Longitudinal crack: three levels based on visual assessment, crack width and faulting height; Transverse and diagonal crack: three levels based on visual assessment, crack width and faulting height.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67; Report PSI (0-5, and 5 means good). Alligator crack: the length at severity level; Edge crack: only record the severity level; Longitudinal crack: the length at each severity level and extent level; Transverse crack: the number of cracks at each severity level.	It does not follow AASHTO PP 67; Report PSI (0-5, and 5 means good). Crack: extent and number of cracks (for transverse crack) at each severity level and crack length at each severity level.
Data Quality Assurance/ Quality Control	Survey frequency	Annual	Annual
	System validation	It proposes data verification process.	It proposes data verification process.
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Safety; Average deviation index;	Safety; Average deviation index;

	Crack extent categorization; Alligator crack: three levels based on the percentage of section has cracks; Edge crack: three levels based on the percentage of section has cracks; Longitudinal crack: three levels based on the percentage of section has cracks; Transverse crack: three levels based on the percentage of section has cracks.	Crack extent categorization; Corner break: three levels based on the number of cracks per section; Longitudinal crack: three levels based on the number of cracks per section; Transverse and diagonal crack: three levels based on the number of cracks per section.

Group 3: The SHAs having their own pavement distress identification manuals which are officially available online – New York

Reference:

New York DOT (2000), Comprehensive Pavement Design Manual - Chapter 2 - Evaluation of Existing Pavements, available in: https://www.dot.ny.gov/divisions/engineering/design/dqab/cpdm (Accessed on March 03, 2016)

New York DOT (2013), Comprehensive Pavement Design Manual - Chapter 3 - Pavement Evaluation and Treatment Type Selection Process, available in: https://www.dot.ny.gov/divisions/engineering/design/dqab/cpdm/repository/chapter3.pdf (Accessed on March 03, 2016)

Table B. 29. Summary of cracking data collection and reporting practices for New York

Pavement type		Flexible Pavement	Rigid Pavement
Crack type		Edge crack; Longitudinal crack; Full width transverse crack; Other crack; Slippage crack; Wheel path crack.	Slab crack.
Data collection	Manual/Automated/ Semi-automated	Manual	Manual
	Is data collected according to AASHTO PP 68?	No, it uses survey.	No, it uses survey.
	Cracking terminology	It does not follow AASHTO PP 67; It has its own cracking terminology.	It does not follow AASHTO PP 67; It has its own cracking terminology.
	Data record	<u>Edge crack</u>: estimate the percentage of the 500 ft section affected; <u>Full width transverse crack</u>: record the number of cracks occurring at the 500 ft section; <u>Longitudinal crack</u>: estimate the percentage of the 500 ft section affected; <u>Other crack</u>: estimate the percentage of the 500 ft section affected;	<u>Slab crack</u>: record the number of slab has cracks.

		Slippage crack: record the section has cracks; Wheel path crack: estimate the percentage of the 500 ft section affected.	
	Surveyed section length	0. 1 mile section in each 1.5 mile interval of the pavement.	0. 1 mile section in each 1.5 mile interval of the pavement.
Data analysis, crack classification, and evaluation	Data reduction and crack detection	N/A	N/A
	Does it separate pavement into five zones for cracking summary?	No, it does not.	No, it does not.
	Severity categorization	Edge crack: three levels based on visual assessment; Full width transverse crack: three levels based on visual assessment; Longitudinal crack: three levels based on visual assessment; Other crack: three levels based on visual assessment; Slippage crack: N/A; Wheel path crack: three levels based on visual assessment.	Slab crack: three levels based on visual assessment and crack width.
	Data interpretation	N/A	N/A
Data reporting	Is it according to AASHTO PP 67?	It does not follow AASHTO PP 67. Edge crack: extent at each severity level; Full width transverse crack: extent and the number of cracks at each severity level; Longitudinal crack: extent at each severity level; Other crack: extent at each severity level; Slippage crack: extent at	It does not follow AASHTO PP 67. Slab crack: extent and the number of cracks at each severity level.

		each severity level; Wheel path crack: extent at each severity level.	
Data Quality Assurance/ Quality Control	Survey frequency	Every two years	Every two years
	System validation	N/A	N/A
	Validation/ Acceptance Report	It does not follow AASHTO PP 67; It has its own report form.	It does not follow AASHTO PP 67; It has its own report form.
Others		Crack extent is the percentage of sections have cracks, no categorization.	Crack extent is the percentage of sections have cracks, no categorization.

B.2 Summary Figures of State Practice of Cracking Data Identification

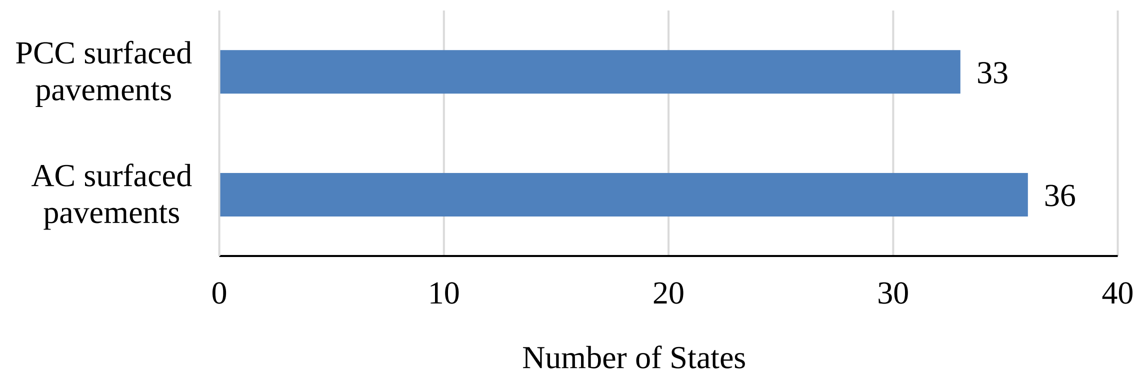


Figure B. 1 Pavement surface categorization in group 1, 2 and 3

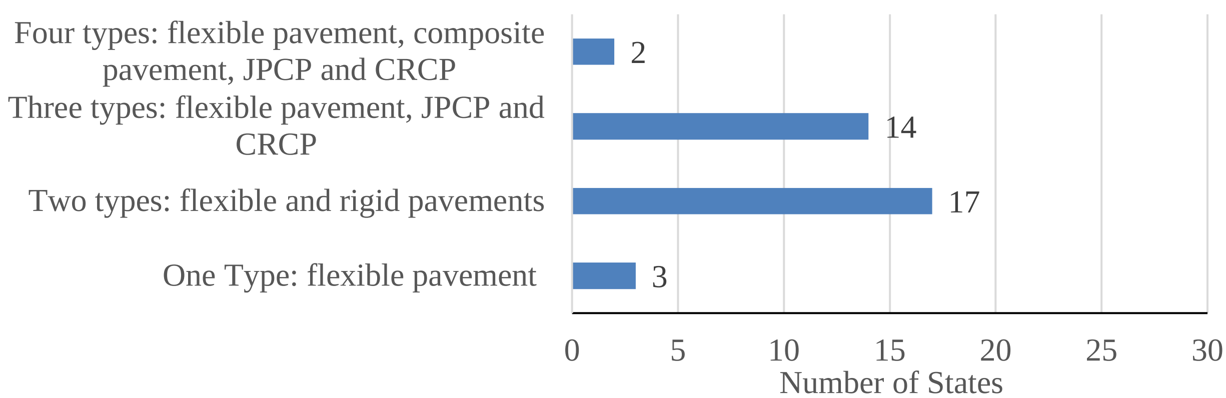


Figure B. 2 Pavement categorization in group 1, 2 and 3

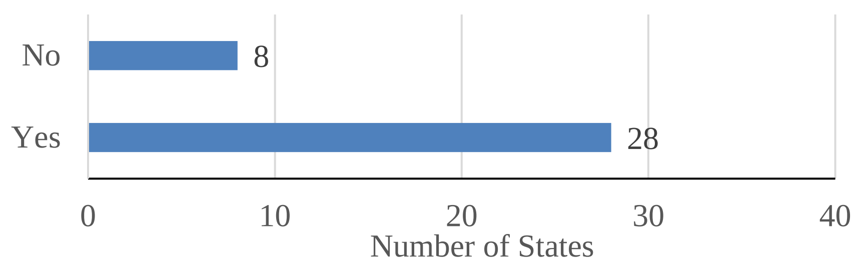


Figure B. 3 Longitudinal cracking summary for AC surfaced pavement in group 1, 2 and 3

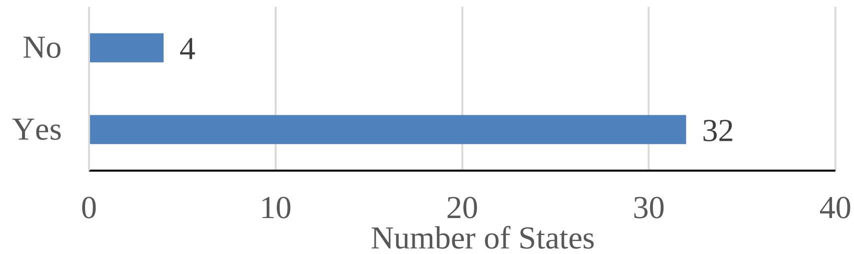


Figure B. 4 Transverse cracking summary for AC surfaced pavement in group 1, 2 and 3

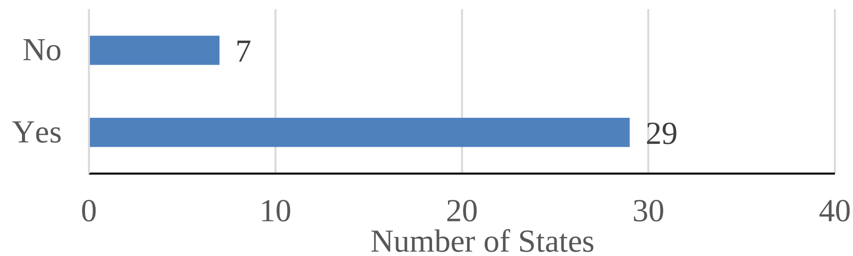


Figure B. 5 Alligator cracking summary for AC surfaced pavement in group 1, 2 and 3

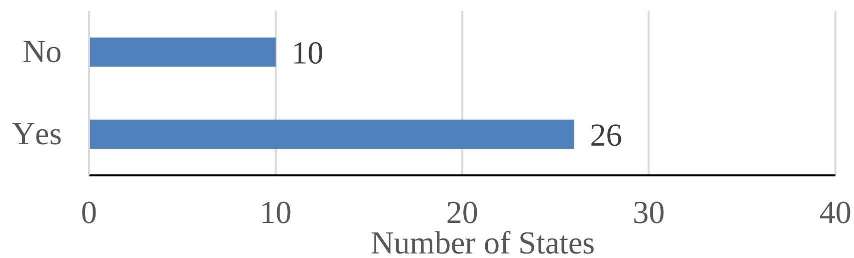


Figure B. 6 Block cracking summary for AC surfaced pavement in group 1, 2 and 3

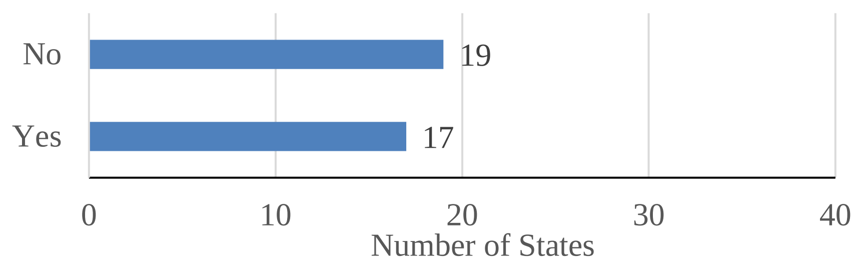


Figure B. 7 Edge cracking summary for AC surfaced pavement in group 1, 2 and 3

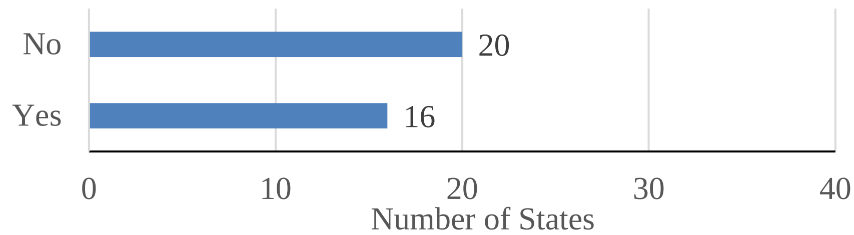


Figure B. 8 Reflection cracking summary for AC overlay PCC in group 1, 2 and 3

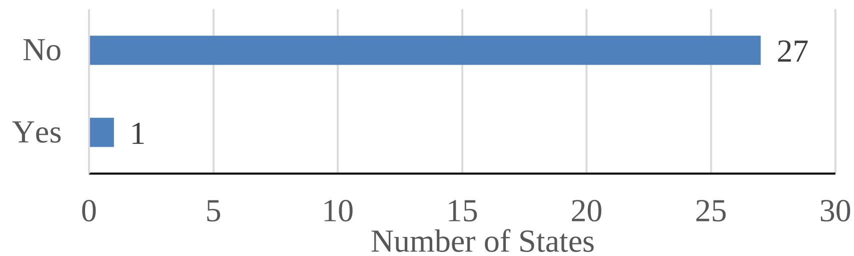


Figure B. 9 Transverse tear summary for AC surfaced pavement in group 2 and 3

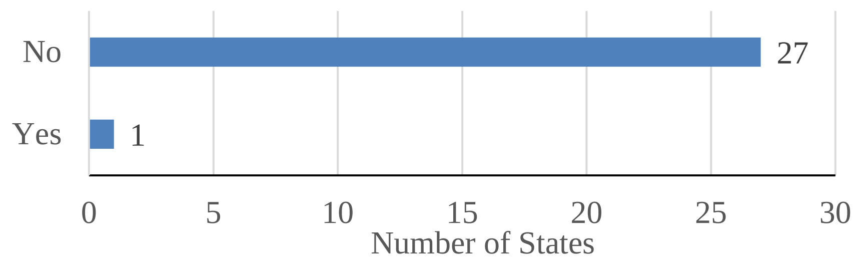


Figure B. 10 Thermal cracking summary for AC surfaced pavement in group 2 and 3

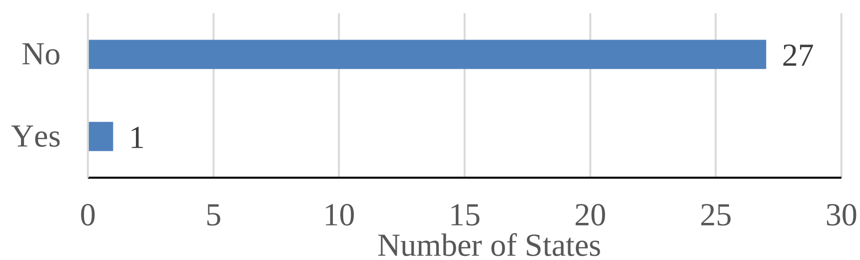


Figure B. 11 Non-load associated cracking summary for AC surfaced pavement in group 2 and 3

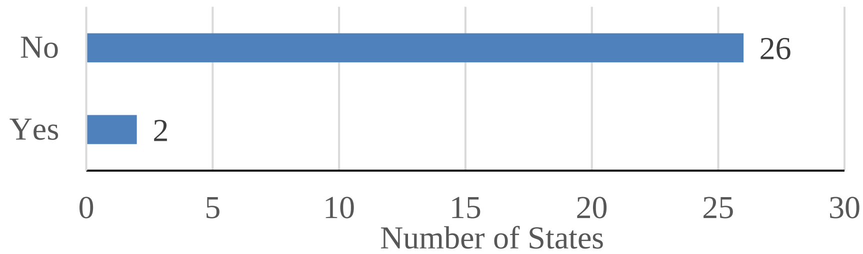


Figure B. 12 Load associated cracking summary for AC surfaced pavement in group 2 and 3

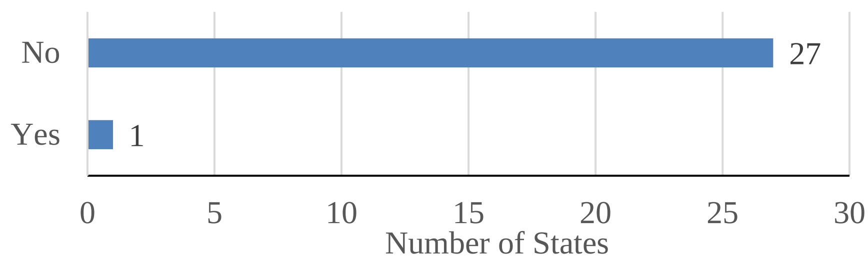


Figure B. 13 Miscellaneous cracking summary for AC surfaced pavement in group 2 and 3

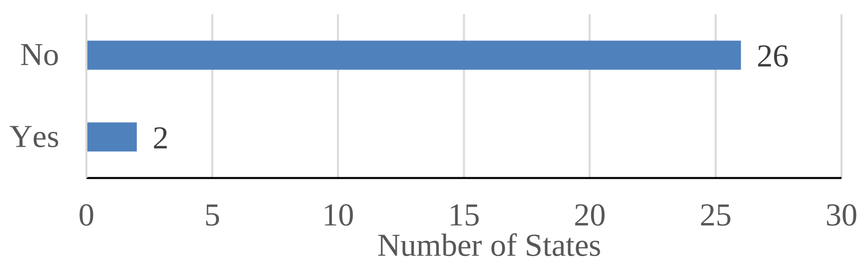


Figure B. 14 Slippage cracking summary for AC surfaced pavement in group 2 and 3

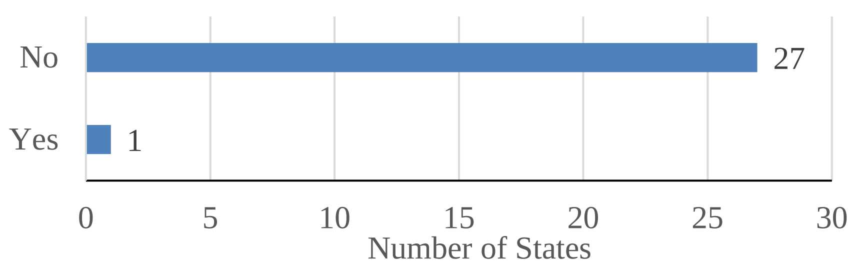


Figure B. 15 Combination cracking summary for AC surfaced pavement in group 2 and 3

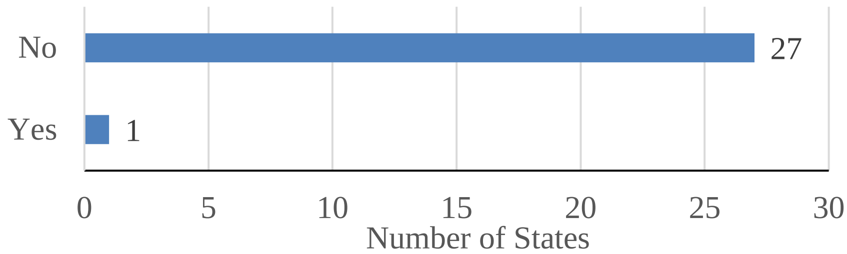


Figure B. 16 XF cracking summary for AC surfaced pavement in group 2 and 3

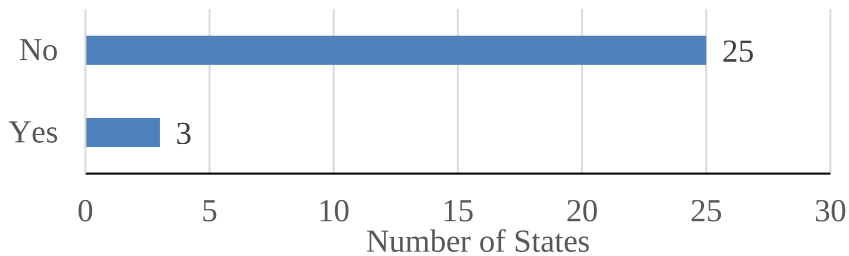


Figure B. 17 Other cracking summary for AC surfaced pavement in group 2 and 3

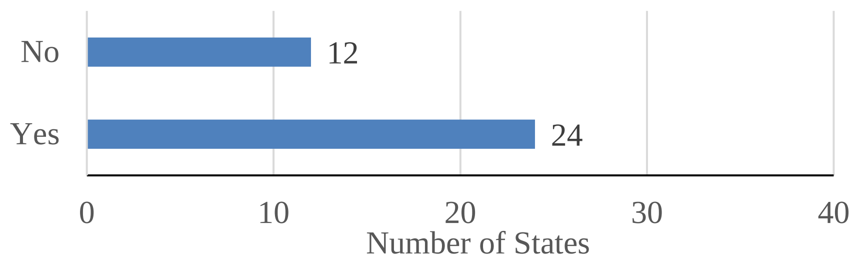


Figure B. 18 Longitudinal cracking summary for PCC surfaced pavement in group 1, 2 and 3

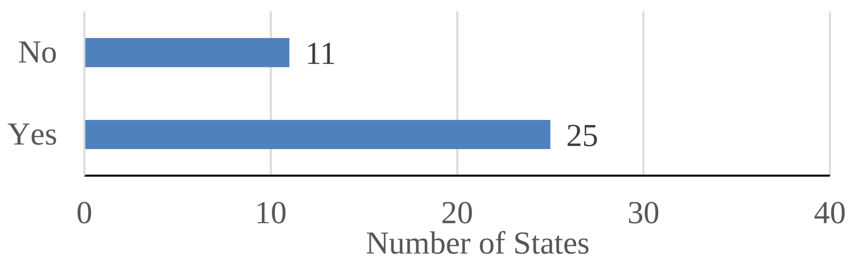


Figure B. 19 Transverse cracking summary for PCC surfaced pavement in group 1, 2 and 3

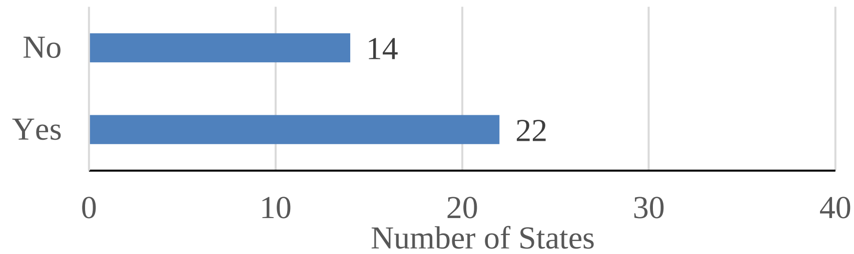


Figure B. 20 Corner breaks summary for PCC surfaced pavement in group 1, 2 and 3

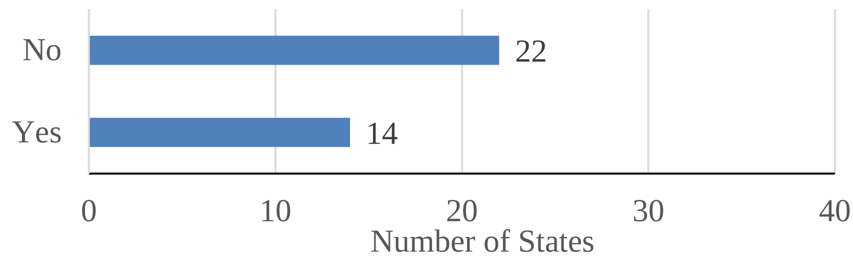


Figure B. 21 Durability cracking summary for PCC surfaced pavement in group 1, 2 and

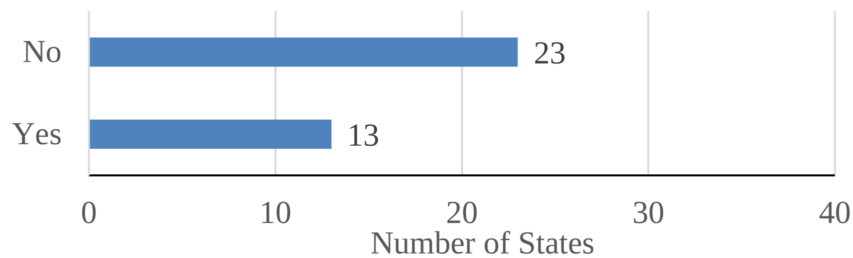


Figure B. 22 Map cracking summary for PCC surfaced pavement in group 1, 2 and 3

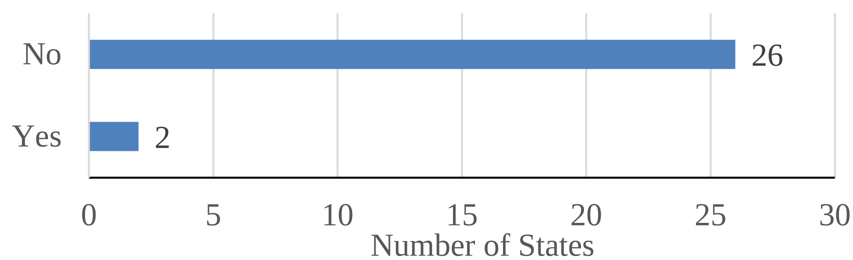


Figure B. 23 Clustered cracking summary for PCC surfaced pavement in group 2 and 3

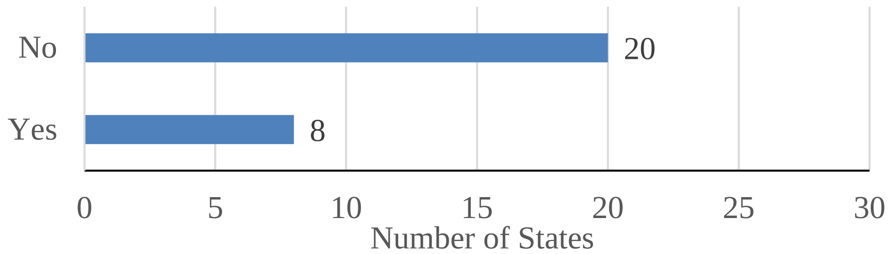


Figure B. 24 Broken panels summary for PCC surfaced pavement in group 2 and 3

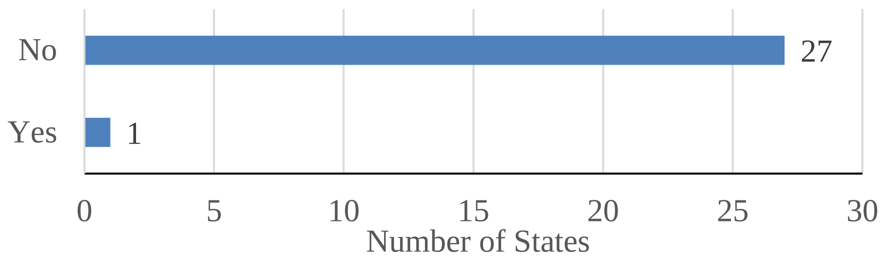


Figure B. 25 Cracked panels summary for PCC surfaced pavement in group 2 and 3

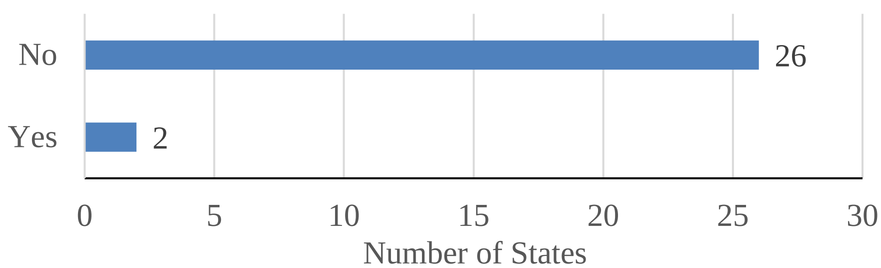


Figure B. 26 Slab cracking summary for PCC surfaced pavement in group 2 and 3

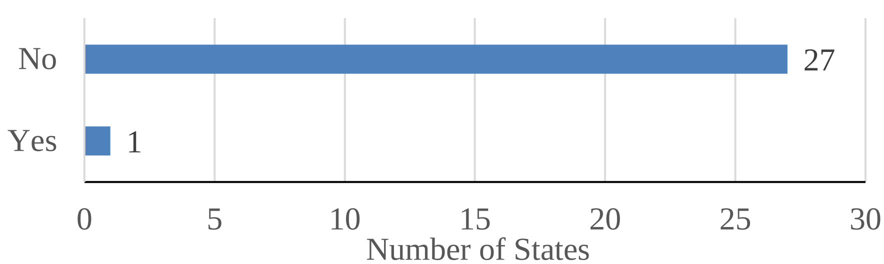


Figure B. 27 XC cracking summary for PCC surfaced pavement in group 2 and 3

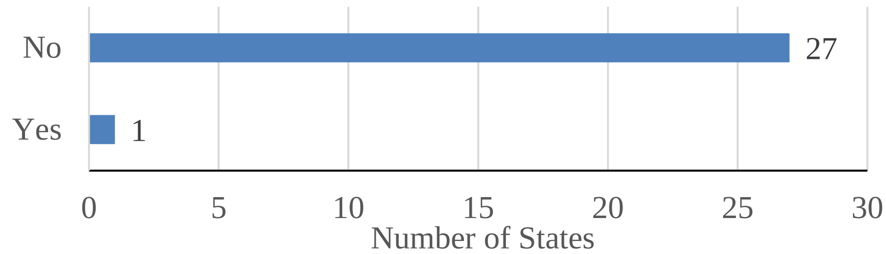


Figure B. 28 XJ cracking summary for PCC surfaced pavement in group 2 and 3

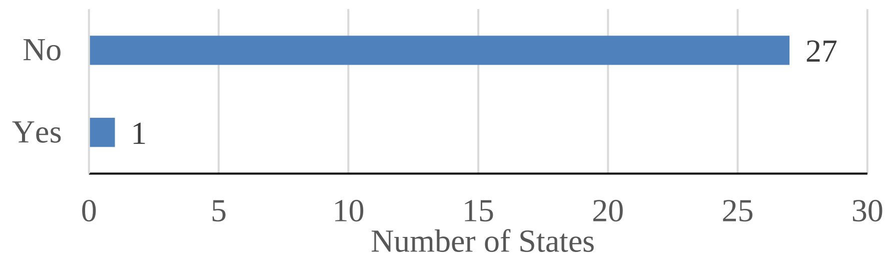


Figure B. 29 1st stage cracking summary for PCC surfaced pavement in group 2 and 3

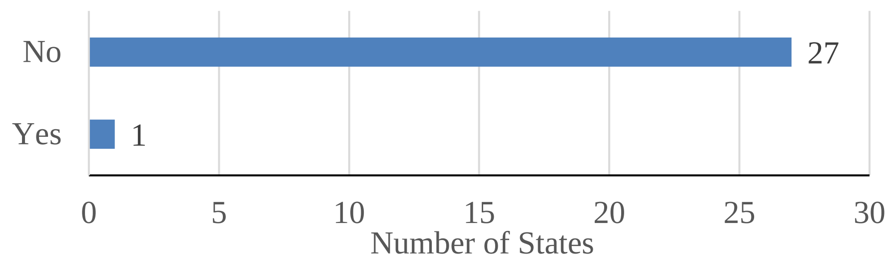


Figure B. 30 3rd stage cracking summary for PCC surfaced pavement in group 2 and 3

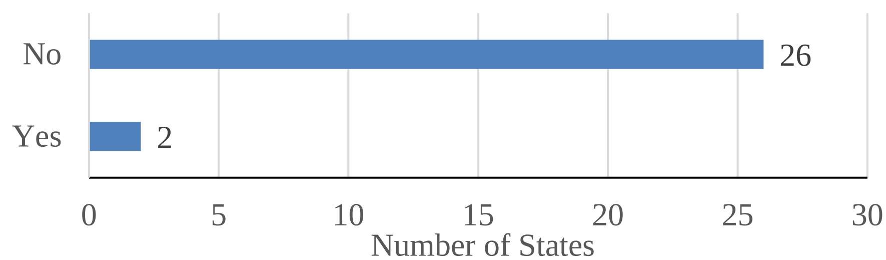


Figure B. 31 Corner cracking summary for PCC surfaced pavement in group 2 and 3

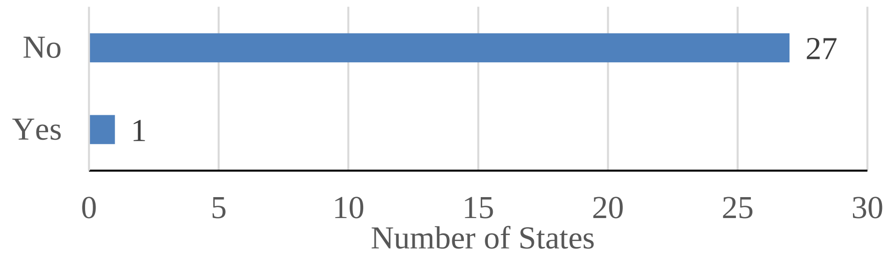


Figure B. 32 Spalled cracking summary for PCC surfaced pavement in group 2 and 3

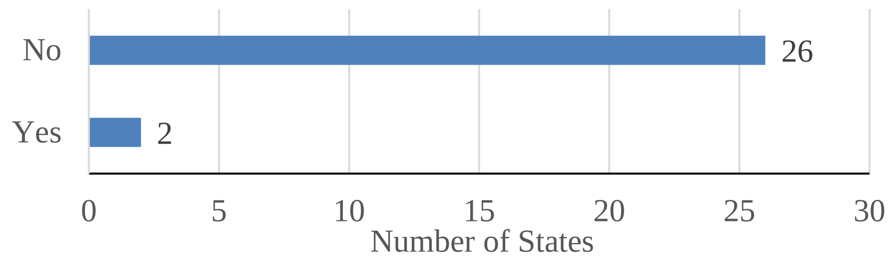


Figure B. 33 Meander cracking summary for PCC surfaced pavement in group 2 and 3

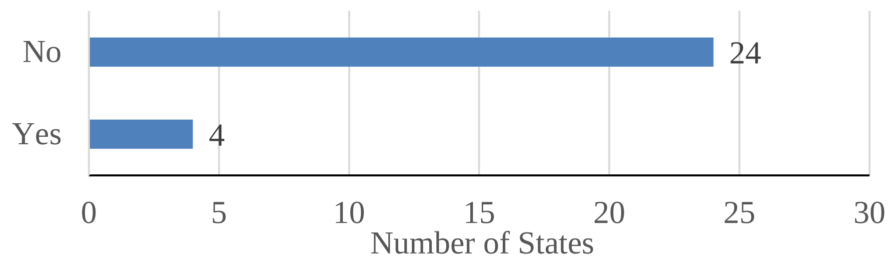


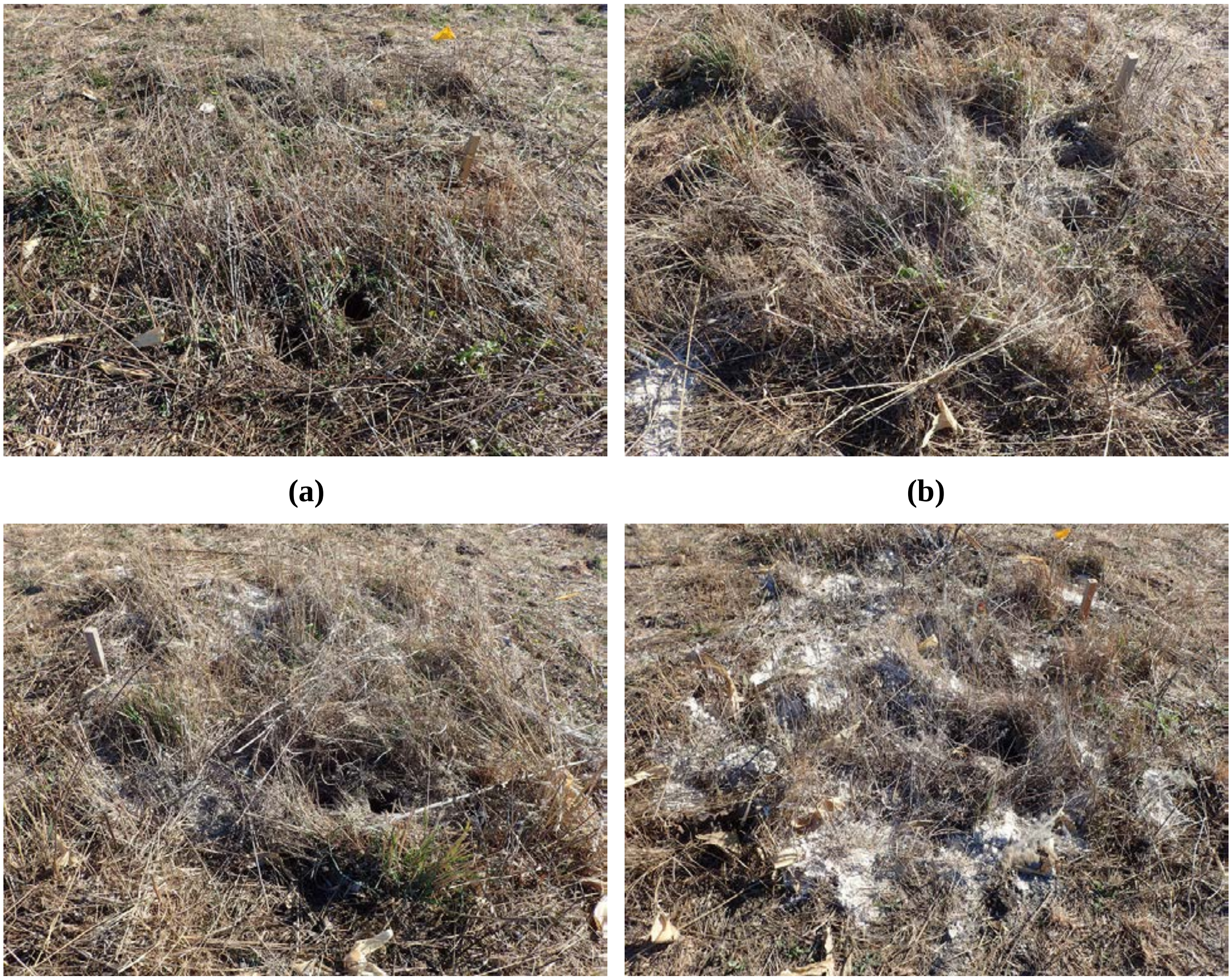
Figure B. 34 Other cracking summary for PCC surfaced pavement in group 2 and 3

APPENDIX C. IMAGES OF KELLY FARM CONTROL SITE

C.1 Images of CGR Application at Kelly Farm

Figure C. 1 Images of Applying CGR at Kelly Farm on Oct 16th, 2016

C.2 Images of Kelly Farm after CGR Application



(c) **(d)**

Figure C. 2 Images of Kelly Farm at the stage of one month after CGR application for (a) control plot, (b) plot with 10 ton/acre CGR, (c) plot with 20 ton/acre and (d) plot with 40 ton/acre.

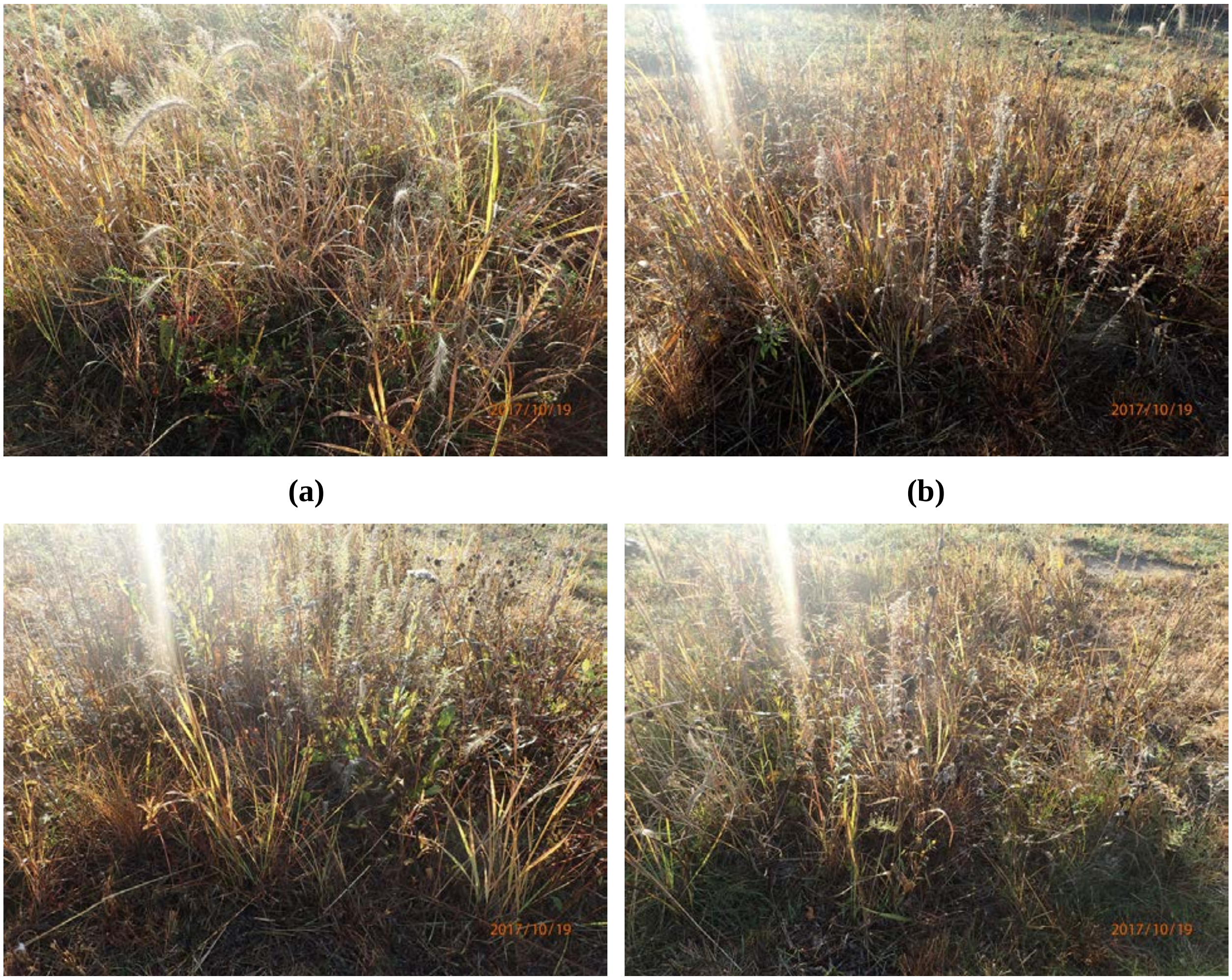
(a)

(b)

(c)

(d)

Figure C. 3 Images of Kelly Farm at the stage of six months after CGR application for (a) control plot, (b) plot with 10 ton/acre CGR, (c) plot with 20 ton/acre and (d) plot with 40 ton/acre.



(a) (b) (c) (d)

Figure C. 4 Images of Kelly Farm at the stage of one year after CGR application for (a) control plot, (b) plot with 10 ton/acre CGR, (c) plot with 20 ton/acre and (d) plot with 40 ton/acre.