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Performance Evaluation of Seal Coat Materials and Designs

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INDIANA DEPARTMENT OF TRANSPORTATION
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Performance Evaluation of Seal Coat Materials and Designs

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16. Abstract
This project presents an evaluation of seal coat materials and design method. The primary objectives of this research are 1) to evaluate seal coat performance from various combinations of aggregates and emulsions in terms of aggregate loss; 2) to evaluate how the properties of aggregates and emulsions affect seal coat performance; 3) to evaluate current seal coat design methods based on INDOT seal coat practice; and 4) to develop seal coat design software incorporating Indiana practice.

To evaluate the effects of aggregate and emulsion types on aggregate loss performance of seal coat, three emulsions and eight aggregates including CRS-2P, RS-2P, and AE-90S for emulsions and Trap Rock, Sandstone, Blast Furnace Slag, Steel Slag, Limestone, Dolomite, Crushed Gravel (one face), and Crushed Gravel (two faces) were tested utilizing the sweep test and Vialit test. In addition, to explore influential factors (i.e., electrical surface charge interaction, water evaporation change in emulsion, water affinity of aggregate, etc.), the Zeta potential, water content, and X-ray deflection (XRD) tests were also conducted.

According to the Zeta potential test results, the electrical surface charge of an aggregate in emulsions varies with the type of emulsion (i.e., with the pH of the emulsifier). From the water content test, among the emulsions, CRS-2P was the earliest emulsion to have enough bond strength to retain aggregates in open traffic. In addition, aggregate can retard the water evaporation process of emulsions. Based on the XRD test results, Sandstone and Dolomite have the highest and smallest content of SiO_2, respectively among the eight aggregates. This means that Sandstone and Limestone have the highest and lowest water affinity (hydrophilic and hydrophobic), respectively.

In the sweep test with Limestone with various curing time, CRS-2P showed superior aggregate loss performance among the emulsions. Comparing the sweep test results to the water contents of emulsions, faster water evaporation presented better aggregate loss performance. This finding indicates that the bond strength of emulsion to retain aggregate can be mainly a function of water evaporation in emulsion. Based on the sweep test at 77 °F after 24 hours of curing, CRS-2P performed the best regardless of aggregate type. The Vialit test at a temperature range of 35 °F to -22 F° after 24 hours of curing shows the most aggregate loss at lower testing temperatures. AE-90S had the strongest resistance in losing aggregate among the three emulsions at lower temperatures, which is an opposite trend comparing to the sweep test results. Also, Crushed Gravel with two faces outperformed Crushed Gravbel with one face. According to statistical analysis results, it was concluded that AE-90S and Crushed Gravel with two faces showed the best performance among the emulsions and aggregates, respectively. In addition the best-performing aggregate-emulsion combinations were AE-90S with most of the aggregates, except for Steel Slag. Thus, the aggregate type in terms of mineral/chemical composition is not a major factor affecting the aggregate loss performance.

To develop a seal coat design, seal coat performance was evaluated for various emulsion (EAR) and aggregate application rates (AAR) by using three different evaluation methods: the IRI, friction, and visual inspection. Based on these performance tests, immediate failure occurring locally during construction due to incorrect application rate (e.g., insufficient aggregate rate) can cause total failure of the seal coat road resulting from a chain reaction. Employing a factor to compensate for AAR discrepancies between target and actual is critical for seal coat survival during construction. This study confirms the irrelevance of seal coat application to IRI values due to the thin coat and the limitation of the IRI measurement (e.g., 250 mm moving average). The friction test results show an adequate skid resistance performance on all seal coat test sections. In addition, friction improvements due to seal coat applications were confirmed within a range of seal coat rates applied in this study. Overall, IRI, friction, and visual inspection did not show distinct differences in seal coat performance in terms of application rates. A methodology in selecting an equipment factor for correcting any difference between a target rate and a measured rate was developed considering reliability and a designed rate using the McLeod equation.

Design software, "INDOT SEAL COAT DESIGN (iSeal)", was developed as part of the study to aid the seal coat design process and incorporates INDOT seal coat practice. The software was largely based on the McLeod design method which includes factors that the INDOT seal coat specification lacks. Furthermore, an additional factor, an equipment factor, was implemented into the design process to resolve issues due to discrepancies between designed rate and applied rate.

17. Key Words
Surface Treatment, Seal Coat, Aggregate Loss, Low Temperature, Vialit Test, Sweep Test, Performance-based Design, Application Rate, Equipment Correction Factor, Influence Factor

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Introduction

A seal coat is a durable and functional pavement surface treatment technique that requires minimal traffic disruption. Additional benefits include sealing the existing pavement's surface cracks, providing a skid resistant surface, and preventing pavement surface damages from further aging or oxidation.

Data and literature have suggested that seal coats constructed with high quality materials provide better initial and long-term performance and extend the overall service life of the pavement being treated. However, no research or data exist on quantifying the overall performance of different seal coat materials currently available in the Indiana seal coat industry. Evaluating the performances of seal coat materials and updating/expanding standard specifications based on their performance is needed in order to provide proper guidelines to the pavement maintenance engineers in each district. Furthermore, introducing new and better performance materials from other states to Indiana, considering life cycle cost, can expand current seal coat material selection.

Although typical aggregate and asphalt application rates are available in specifications such as ASTM D1369-84 and INDOT standard specifications (Chapter 404), design method, and guidelines are still needed to compute an optimum seal coat application rate for specific aggregate, emulsion, and pavement condition on a project-specific basis.

The primary objectives of this research are: 1) To evaluate seal coat performance of various combinations of aggregates and emulsions in terms of aggregate loss; 2) To evaluate how each of the properties of theses aggregates and emulsions affect seal coat performance; 3) To evaluate current seal coat design methods based on INDOT seal coat practice; and 4) To develop a seal coat design program incorporating Indiana practice.

Findings

To evaluate the effects of aggregate and emulsion types on aggregate loss performance of seal coat, three emulsions and eight aggregates including CRS-2P, RS-2P, and AE-90S for emulsions and Trap Rock, Sandstone, Blast Furnace Slag, Steel Slag, Limestone, Dolomite, Crushed Gravel (one face), and Crushed Gravel (two faces) were tested utilizing the sweep test and Vialit test. In addition, to explore influence factors (i.e., electrical surface charge interaction, water evaporation change in emulsion, water affinity of aggregate, etc.), the Zeta potential, water content, and X-ray deflection test were conducted.

According to the Zeta potential test results, the electrical surface charge of an aggregate in emulsions varies with the type of emulsion (i.e., with the pH of emulsifier). From the water content test, CRS-2P is the earliest emulsion to have enough bond strength among the emulsions to retain aggregates in open traffic. In addition, aggregate can slow the water evaporation process of emulsions. Based on the XRD results, Sandstone and Limestone have the highest and lowest water affinity (hydrophilic and hydrophobic), respectively.

The sweep test with Limestone, which varied curing time, revealed that faster water evaporation presents better aggregate loss performance. This finding indicates that the bond strength of emulsion, or its ability to retain aggregate, is mainly a function of water evaporation in emulsion. Based on the sweep test after 24 hours of curing, CRS-2P performs the best, regardless of the type of aggregate used. On the other hand, AE-90S showed the poorest performance with large variations in aggregate loss despite the type of aggregate used. The Vialit test at a low temperature with 24 hours of curing resulted in the most aggregate loss at lower testing temperatures. Another finding was that the Crushed Gravel with two faces outperforms that with one face. In addition, AE-90S outperforms other emulsions in the Vialit test.

To develop a seal coat design, seal coat performance was evaluated for various emulsion and aggregate application rates by using three different evaluation methods: the IRI, friction, and visual inspection. Employing a factor to compensate for AAR discrepancies between target and actual is critical for seal coat survival during construction. This study confirms the lack of relevance between seal coat application and IRI values due to the thin coat and the limitation of the IRI measurement (e.g., 250 mm moving average). The friction test results showed adequate skid resistance performance on all seal coat test sections. In addition, friction improvements due to seal coat applications were confirmed within a range of seal coat rates applied in this study. Overall, IRI, friction, and visual inspection did not reveal distinct differences in seal coat performance in terms of application rates. A methodology for selecting an equipment factor for correcting any difference between a target rate and a measured rate was developed considering reliability and a designed rate using the McLeod equation.

Design software, "INDOT SEAL COAT DESIGN (iSeal)," was developed as part of the study to aid seal coat design process and to address a few problems existing with the INDOT seal coat specification. The software was largely based on the McLeod design method which includes factors that the INDOT seal coat specification lacks. Furthermore, an additional factor, an equipment factor, was implemented into the design process to resolve issues due to discrepancies between the designed rate and the applied rate.

Implementation

The findings and iSeal software will be introduced to the INDOT Pavement Preservation Subcommittee Chapter in order to assist with district level preservation treatment practices. The details in the report and software are intended for reference only, not as specifications or design guidance. In the event that any information presented herein conflicts with the Indiana Design Manual, INDOT's Standard Specifications, or any other INDOT policy, said policy will take precedence and the software will be managed by the Asset Preservation Engineer so that conflicts do not arise.

1. INTRODUCTION

1.1 Research background

A seal coat is a durable and functional pavement surface treatment technique that requires minimal traffic disruption. It is typically constructed by spreading a thin asphalt emulsion followed by spreading small size aggregates. Additional benefits include sealing the existing pavement's surface cracks, providing a skid resistant surface, and preventing pavement surface damages from further aging or oxidation.

In terms of cost effectiveness, seal coat is outperforms other surface treatments. The typical, performance life of seal coat in Indiana is four years while hot mix asphalt (HMA) overlay over built-up asphalt for preventive maintenance is 9 years. The cost of a seal coat is about 12 % to 25 % of HMA overlays, but the life of seal coat is 44.4 % of HMA overlay's life. In the case of INDOT, seal coat application has been done almost exclusively by in-house maintenance forces and costs about $1.25/yd^2 as of 2011, which is significantly cheaper than other surface treatments done by contractors. As a result, the practice of using seal coat as a pavement preservation treatment in place of HMA overlay has become more widespread. Although seal coats were originally used mostly as surface wearing courses on rural and urban low traffic volume roads, the seal coat has evolved into a pavement preservation treatment for both low and high traffic volume roads. Seal coats in Indiana are applied to roads that have an average daily traffic (ADT) count of up to 10,000 and INDOT applied over 1200 lane miles in the fiscal year 2011. These numbers illustrate the effectiveness of seal coat as a cost effective method for restoring pavement surface to meet the demand of the traveling public for good roads.

Research has also shown that state DOTs are satisfied with the overall performance of seal coat. According to the survey conducted by Ksaibati, Cole, and Farrar (1996), state DOTs were asked to evaluate the overall performance of surface treatment applications on a scale of 1 (poor) to 5 (excellent). From the 35 responses, more than 90 % of state DOTs (including INDOT) rated their seal coats as 3 (average) or better, while less than 10 % of state DOTs rated them as 2(fair). It should be noted that not a single DOT believed its seal coat performance was either 5 (excellent) or 1 (poor). These survey results indicated that a majority of state DOTs were satisfied with the performance of seal coat, yet there are still areas of seal coat performance that need improvements. In a review by the National Center for Pavement Preservation in 2005, the best INDOT seal coat project in a northern district was rated only as "fair."

Data and literature have suggested that seal coats constructed with high quality materials provide better initial and long-term performance and extend the overall service life of the pavement being treated. However, no research or data exist on quantifying the overall performance of different seal coat materials currently available in the Indiana seal coat industry. Evaluating the performances of seal coat materials and updating/expanding standard specifications based on their performance is needed to provide proper guidelines to pavement maintenance engineers of the districts. Furthermore, introducing new and better performance materials from other states to Indiana can expand current seal coat material selection.

In North America, the most generally accepted seal coat design methods are the modified Kearby method (1953) and the McLeod method (1969). Although typical aggregate and asphalt application rates are available in specifications such as ASTM D 1369-84 (2006) and INDOT standard specifications (2010), it is recommended that a design method and guidelines are needed to compute optimum seal coat application rate for specific aggregates, emulsions, and pavement conditions on a project-specific basis. The existing INDOT materials specification was adopted from other state DOTs' specifications. However, it has been proven many times in both the literature as well as in INDOT practice that "one size does not fit all". Design methods and specifications that work well in one state may not be easily adapted to another state, or even another district. Evaluation of current design methods, recommended application rates, materials, and construction practices are needed to improve the performance of INDOT seal coat projects. Also, testing methods cannot be easily adopted from state to state. The existing seal coat testing procedure used by ASTM should be simplified in order to be better implemented by the workforce in INDOT Sub-districts.

1.2 Research objectives

The primary objectives of the proposed research project are:

1. to evaluate seal coat performances of various combinations of aggregates and emulsions in terms of aggregate loss;
2. to evaluate how the properties of aggregates and emulsions affect seal coat performance;
3. to evaluate current seal coat design methods based on INDOT seal coat practice; and
4. to develop seal coat design software incorporating Indiana seal coat practice.

1.3 Report organization

This report is composed of five chapters plus appendices. Chapter 1 presents the research needs and objectives. Chapter 2 describes various factors affecting the seal coat performance and design methods previously developed as well as Indiana seal coat performance survey results. Chapter 3 reports the performance evaluation of seal coat materials including, sweep and Vialit test results along with other influential factor test results. Chapter 4 discusses the performance evaluation of seal coat design by three evaluation methods, namely IRI, friction and visual inspection; this chapter also covers the development of the "INDIANA SEAL COAT DESIGN" software. Chapter 5 summarizes the findings, and provides recommendations for future research. Appendices offer all test results with pictures and detailed calculations and evaluation methods employed in the study. In addition, a design software manual is included.

2 LITERATURE REVIEW

Seal coat is referred to using several terms in the literature: chip seal, asphalt seal coat, bituminous asphalt surface treatment (ASTM D 1369-84) (1), straight seal, surface dressing (United Kingdom), and sprayed seal (Austria). INDOT uses the terms chip seal (INDOT Design Manual Chapter 52) (2) and seal coat (INDOT Standard Specification and INDOT Field Operations Handbook for Crew Leaders) (3) (4). Seal coat will be used for the purpose of this study.

2.1 Seal coat performance

A common critical mode of seal coat failure is aggregate loss. Early traffic on a road with newly applied seal coat is the primary cause of aggregate loss. However, aggregate loss may also occur due to other factors including unexpected cold or wet weather, excessive aggregate amounts, insufficient traffic control, lack of proper aggregate embedment into asphalt, poor aggregate characteristics and dusty or dirty aggregate (5) (6). Also, errors in construction cause aggregate loss to occur within a few months of the placement of a seal coat; such seal coats should typically be repaired instead of resealed. Resealing will usually yield a shorter seal coat life than what is intended (7). Aggregate properties, including gradation, shape, moisture content, and fines contents, also significantly affect seal coat performance.

2.1.1 Influence of aggregate

In a seal coat application, aggregate constitutes about 80 % of the seal coat by volume, and is an important influence on the properties and performance of a seal coat.

Influence of traffic

When a pavement treated with a seal coat is open to the traffic while the seal coat is still curing, passing vehicles spread some of the cover aggregate off the road or even pick up aggregates along the wheel path. The McLeod design method recognizes this "whip-off" effect, which depends on the volume and speed of traffic on the newly coated road. The aggregate design equation addresses this effect by including a traffic whip-off factor, which typically ranges from 5 % to 10 %. Lower whip-off factors correspond to low volume residential traffic while higher values are used for higher speed roadways such as county roads (8).

Influence of fines contents

Since asphalt may not properly adhere to dusty or dirty aggregate, it is essential to use clean aggregate. When particles are covered with silt or clay, the dust creates a film that reduces the ability of the asphalt to stick to the aggregate. Therefore, desirable adhesion is less likely to be obtained when dusty or dirty aggregate is used (9).

One method of improving adhesion is to wash the aggregate with clean, potable water in order to remove fine particles (6). Another way to reduce aggregate loss is to use aggregate that is precoated with asphalt. Aggregate that is somewhat dusty may be successfully used with high-float and polymer-modified emulsions, as these allow the aggregate to gather a thicker and tackier asphalt film (8).

The amount of dust, which is commonly defined as the percentage of fines passing the No. 200 sieve, is often controlled by state seal coat specifications. Many states allow a maximum of 2 % fines passing the No. 200 sieve upon manufacture, whereas some specify less than 0.5 % passing the No. 200 sieve in order to improve seal coat performance (10) (8). TABLE 2.1 summarizes the maximum allowable fines contents as required by various states.

According to Kandhal (10), in most cases the rate of increase in aggregate loss due to increasing fines content grows significantly as the dust content exceeds about 3 %. Consequently, Kandhal calls 3 % a threshold value. Kandhal agrees that most states' maximum of 2 % dust for unwashed aggregates is reasonable for low volume traffic roads and is even more justifiable if washing or precoating is expensive.

According to Yazgan (11), the effect of the fines content on aggregate retention is independent of the embedment depth. Therefore, seal coat material specification, not seal coat design, should deal with the fines content problem.

TABLE 2.1
Specifications for maximum percentage of fines content

State	Maximum Percentage Passing No. 200
Alabama	1.0
Florida	3.75
Indiana	2.0
Kansas	2.0
Maryland	1.0
North Carolina	1.5
North Dakota	4.0
Ohio	3.0
Pennsylvania	2.0
South Carolina	0.0
South Dakota	2.0
Tennessee	1.0
Average	1.9

Influence of gradation

Another major factor in seal coat design and performance is aggregate gradation. An ideal aggregate gradation is one that has single-sized particles with less than 2 % fines contents passing the No. 200 sieve (6).

Using aggregate that is close to uniform in size is necessary to form a seal coat that has only one layer of aggregate with uniform height. If the particles are not uniformly sized, the asphalt film may cover the smaller particles and prevent larger particles from being properly embedded. For surface treatment application, the largest aggregate size should typically be no more than twice the size of the smallest particles, although some variation is allowed in order to maintain economical production (Asphalt Institute 2007). However, as the allowed variation is increased, the performance of the seal coat is generally believed to weaken. As a result, spending more money initially to obtain uniformly sized aggregate may be a better option economically than purchasing cheaper but less effective aggregate that requires greater maintenance expenses (McLoed 1969).

According to Kandhal (1987), use of well graded cover aggregates reduces aggregate retention. Smaller particles typically occupy the voids between the larger particles, which prevents the larger particles from embedding into the asphalt.

The use of uniformly sized aggregate also has the advantage of maximizing contact between the road surface and the tires of a vehicle. Improving tire contact increases the frictional area, which in turn improves skid resistance when the correct amount of asphalt is used (Herrin, Marek, and Majidzadeh 1968).

Lee et al. evaluated aggregate retention performance with different types of aggregates. They eliminated the effects of gradation and fines content differences by matching the gradations. The aggregates showed essentially the same aggregate retention performance. Although these aggregates have different aggregate shapes, different levels of electrostatic interactions among aggregates and emulsions, and different asphalt absorption levels, the effects of these characteristics on the aggregate retention performance seems to be minor. Therefore, the researchers concluded that aggregate gradation is the most significant factor affecting aggregate retention performance (Lee 2007).

Lee and Kim developed a new chip seal performance indicator called the *performance-based uniformity coefficient* (PUC). The PUC uses the concepts of McLeod's failure criteria for chip seals and the uniformity coefficient used for soil, sand, and aggregate. They found that McLeod's failure criteria could serve as tools for narrowing the aggregate specifications required for chip seal construction (Lee and Kim 2007).

2.1.2 Influence of emulsion

Emulsion makes up approximately 13 % to 17 % of a seal coat volume and emulsion residue makes up approximately 9 % to 12 % of the volume based on the McLeod design method. Compatibility between emulsion and aggregate is a key factor affecting seal coat performance.

Influence of surface charge

An asphalt emulsion for seal coat consists of the following three components: asphalt cement, water, and emulsifier (surfactant). In some cases, latex or polymer modified asphalt is used to make an emulsion. These modified emulsions are used primarily to improve early aggregate retention (adhesion) and seal coat durability (Wood, Janisch, and Gaillard 2006).

The adhesion between aggregate and emulsion is a function of mechanical, chemical, and electrostatic properties (Yazgan and Senadheera 2004). Possible mechanical- and chemical-related factors include aggregate dust, moisture content, porosity (specific gravity), and temperature. Different types of aggregate are better suited to certain emulsions as a result of electrical surface charges (Gransberg and James 2005).

It is important to choose an emulsion with an electrical surface charge that is opposite that of the aggregate. If this is not the case, the emulsion will not form a strong bond with the aggregate and it will ravel. In his research, Roberts observed that the contribution of electrostatic force to the adhesion of the rubber surface was less than 10% (12). Therefore, local aggregate is critical to determining which type of seal coat to use, which type of emulsion to design for, and which type of construction procedures to specify (6).

The emulsifier determines the electrical surface charge of the emulsion (cationic (+), anionic (-) or nonionic). Since like charges exhibit repelling force between particles, the emulsion will not bind well to aggregates with the same surface charge (13). It is noteworthy that Limestone aggregate and AE-90S are the most widely used combination for seal coat application in Indiana. Limestone aggregate is known to have a positive surface charge. Thus, AE-90S, the anionic medium set emulsion, can have an electrostatic interaction with Limestone aggregate.

In order to find the electrostatic force, surface charges of both aggregates and emulsions should be known. Hefer and Little (14) have stated that the surface charge of aggregates can be approximated with Zeta potential. The surface charge existing on a particle surface attracts other particles with an opposite surface charge, resulting in the creation of an electric double layer around a particle as shown in Figure 2.1. The region surrounding the particle can then be divided into two regions, an inner region and a diffuse region (an outer region), based on the distance from the particle surface. The smaller the distance between the ion and particle surface, the larger the bond strength becomes between them. Consequently, ions that are beyond a certain distance in the outer region do not move the particle travels. The Zeta potential is a potential at this boundary, is called the slipping plane.

In addition, the Zeta potential value is often used as an indication of how stable suspension is (15). If the

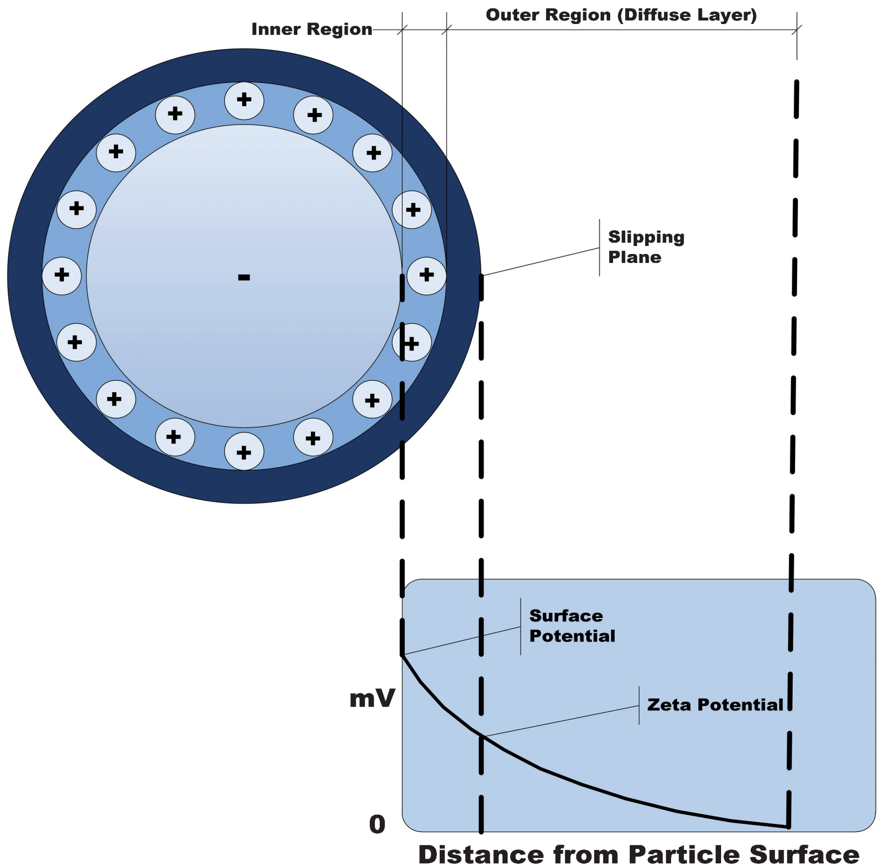


Figure 2.1 Schematic representation of Zeta potential

Zeta potential is either larger than 30 mV or smaller than -30mV, it is regarded stable. As stated previously regarding electrostatic theory, particles in suspension tend to repel each other strongly as the absolute value of the Zeta potential increases. As a result, a repelling force existing between particles in suspension prevents flocculation before it is mixed with aggregates for its application, including seal coat.

Influence of water content

Water consists of approximately 30 % of an emulsion in order to provide storability and workability, but begins to evaporate once the emulsion is sprayed. In order to obtain appropriate adhesion between the aggregate and emulsion, water in the emulsion should be minimal once applied. Schuler investigated the relationship between water content and adhesion and indicated that enough adhesion which can withhold the brooming as well as uncontrolled traffic is developed once water content ranges between 15 % and 25 %. In addition, his study found that 90 % of aggregates were retained during the sweep test (ASTM D7000) with the same water content range, which is referred to as "critical moisture content" in the study (16).

2.2 Seal coat design methods

The primary components of seal coat design are emulsion application rate (EAR) and aggregate application rate (AAR). Hanson developed the earliest seal coat design procedure (17). His design procedure was originally adopted in New Zealand, and is now a framework for all major seal coat design methods currently used. New Zealand's 2004 Chipseal design is the newest method that has been created based on the Hanson design method. In North America, the most commonly used design methods are the modified Kearby design method and the McLeod method (6). Descriptions of the Hanson, 2004 Chipseal design, McLeod, Kearby, and modified Kearby design methods are listed in the following subchapters. TABLE 2.2 provides a summary of the modified Kearby, McLeod, and 2004 Chipseal design methods. The characteristics of the Hanson, McLeod, 2004 Chipseal, Kearby, and modified Kearby design methods are provided in the following subchapters, and the modified Kearby design method, McLeod method, and 2004 Chipseal design method are summarized in TABLE 2.2.

TABLE 2.2
Summary of design methods (Lee 2007)

	Modified Kearby	McLeod	2004 Chipseal Design
Factors for aggregate application rate (AAR)	• Board test	• Aggregate gradation • Flakiness index • Bulk-specific gravity of aggregate • Loose unit weight of aggregate • Wastage	• Aggregate gradation • Flakiness index • Bulk-specific gravity of aggregate • Wastage
Factors for emulsion application rate (EAR)	• AAR • Bulk-specific gravity of aggregate • Loose unit weight of aggregate • Traffic correction • Surface condition correction • Seasonal adjustment • Percentage of residual asphalt in emulsion	• Aggregate gradation • Flakiness index • Traffic correction • Bulk-specific gravity of aggregate • Loose unit weight of aggregate • Surface condition • Aggregate absorption • Percentage of residual asphalt in emulsion • Traffic volumes	• Aggregate gradation • Flakiness index • ADT • Percentage of heavy commercial vehicles per day • Texture depth • Soft substrate • Absorptive surfaces • Steep grades • Aggregate shape • Traffic volumes
Reference voids for AAR	Voids at the board test condition, approximately 50 %	Voids at ultimate compacted seal coat state, 20 %	Voids at two-year light traffic volumes, approximately 40 %
Reference voids for EAR	Voids at the board test condition, approximately 50 %	Voids at ultimate compacted seal coat state, 20 %	Voids at the first major frost day, normally higher than 40 %
Embedment depth (%)	Variable in terms of seal coat mat thickness and aggregate type	65–80	35
Synthetic aggregate	Considered in EAR	Not considered	Not considered
Multilayer	N.A.	Available with empirical guideline	Available with empirical guideline

2.2.1 Hanson design method

The Hanson design method was mainly developed for use with liquid asphalt, or cutback asphalt. The average least dimension (ALD) of the cover aggregate is the most important factor in this method. The ALD was determined by manually callipering a sample of the cover aggregate and measuring the smallest dimension. Hanson discovered that the voids between particles were about 50 % when the cover aggregate was distributed by an aggregate spreader. He concluded that the voids most likely dropped to around 30 % after rolling and 20 % after traffic compaction. Hanson suggested that between 60 % and 75 % of the voids should be filled with residual asphalt, depending on the type of aggregate used and the level of traffic on the surface (17).

2.2.2 New zealand design method

The 2004 Chipseal design of New Zealand is an evolution of the Hanson method. In this method, the total volume of voids between particles is actually significantly greater than 20 % in a compacted seal. They also concluded that the voids are continually decreased under the weight of traffic. The 2004 Chipseal design method, which is a performance-based design method, considers both the first winter aggregate loss and the seal coat voids reduction model (7). Dealing with substrate non-uniformity is one major challenge involved with the design of material application rates. The 2004 Chipseal design uses the sand circle (sand patch) test for the substrate texture depth and the ball penetration test for soft substrate in order to obtain a substrate correction factor. Lee developed a performance-based seal coat design equation using a lab loading simulator (i.e., the third-scale Model Mobile Loading Simulator). The study provided a voids reduction factor generated by traffic loading for the McLeod design method (18).

2.2.3 Mcleod design method

With Hanson's previous work as a guide and empirical relationships and observations to draw from, McLeod (19) created another seal coat design method in the 1960s. McLeod's design method includes procedures for determining quantity of aggregate, quantity and type of asphalt, and rate of asphalt application. This method deals with both single and multiple layers of seal coat applications. McLeod created several equations in order to establish a system for calculating the standard seal coat design parameters (19).

Quantity of aggregate

The quantity of aggregate required for a seal coat application is determined from equations based on three main assumptions:

- Approximately 80 % of the ALD will be embedded into the road surface;
- Aggregate is uniformly sized (when graded aggregates are used, the equation requires a slight modification); and
- The aggregate will eventually become oriented so that the thickness of the seal coat layer becomes the same as the aggregate ALD.

When deciding on the quantity of aggregate, additional factors, such as the type of aggregate, the type of supporting layer, and climatic variations, must also be considered.

Quantity of asphalt

There are also several assumptions that underlie the equation determining the quantity of asphalt:

- Voids will make up approximately 20 % of the seal coat volume, and approximately 80 % of the voids will be asphalt;
- Aggregate is uniformly sized (when graded aggregates are used, the equation requires a slight modification); and
- Measurement is taken at a temperature of 60 °F (a correction is necessary if different than 60 °F).

A chart constructed by McLeod determines the asphalt type and grade based on aggregate size and surface temperature. McLeod's design method has been further refined by the Asphalt Emulsion Manufacturers Association and the Asphalt Institute. Both offer further recommendations according to different asphalt type and grades based on aggregate gradations and supply asphalt application rate correction factors to balance the effects of existing surface conditions.

2.2.4 Modified kearby design method

Jerome P. Kearby (1953) was one of the first to introduce seal coat mix design in the United States. He developed a monograph that used the values of average thickness, percentage of aggregate embedment, and percentage of voids to determine the asphalt application rate in gallons per square yard. Kearby's design curve was studied by Epps and his associates in 1974 through the use of synthetic aggregates (20). Epps et al. proposed a new design curve that showed approximately 30 % more embedment than the Benson-Gallaway curve (21) due to the high porosity of synthetic aggregates. Epps et al. (22) continued to study the work done by Kearby (1953) and Benson and Gallaway (1954) by testing Kearby's design method through field validation. Epps et al. concluded that the asphalt application rates predicted by the Kearby method were actually lower than the rates used in practice in Texas. Therefore, two changes to the design procedure were proposed. First, the asphalt application rates were adjusted to account for the level of traffic and existing pavement conditions. Second, the original design curve from the Kearby and Benson-Gallaway methods was shifted as suggested for lightweight aggregates so that it followed the proposal in the Epps' study from 1974.

For this method, the AAR is determined by using the laboratory board test. In a 1/2 yd^2 area, a single layer of aggregate is applied. The amount of aggregate needed to cover the 1/2 yd^2 area is then converted to a field AAR using the aggregate dry loose unit weight and bulk specific gravity. Plywood or Masonite is used to construct the test board, which has sides framed by 1/2 in. (12 mm) molding strips. Finally, several factors influence the asphalt application rate: the number of vehicles using each lane per day, the existing surface conditions, the amount of asphalt present in the emulsion or cutback, and the field factor, which is determined through field experience.

2.3 Standard specifications

Among state departments of transportation (DOTs), seal coat practices vary by construction technique, material availability, climate, and other factors. Nine state DOTs, including Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin, have been reviewed for this study. A summary of findings from the specifications review indicated the following:

- "Seal coat" is the most commonly used term in neighboring states except Ohio and Michigan. While the INDOT standard specification uses the term "seal coat", the INDOT Design Manual uses the term "chip seal".
- The specified fines content for seal coat aggregates is 2 % in Minnesota and Ohio.
- The surface of the aggregate is typically not allowed to contain free water; otherwise, the amount of free water is limited. Additionally, damped seal coat aggregates are recommended by some state DOTs.
- The current INDOT specification specifies the time allowed between emulsion and aggregate application as being less than one minute. Three states (Michigan, Ohio and Iowa) specifies the maximum distance allowed between distributor and spreader, while others either does not specify or uses the term, "immediately."
- The pneumatic-tired roller is typically used for seal coat compaction in all states except Wisconsin, which uses a steel wheel roller for initial rolling then and uses both a steel wheel roller and a pneumatic-tired roller.
- An initial rolling is required immediately after the aggregate application in most states while INDOT specifies an initial rolling to be done within two minutes after the aggregate application.
- Indiana requires at least three roller applications, defined as one pass of the roller over the width sealed, as most states do.
- Maximum roller speed is specified in some states as to be 5 mph, but Indiana specifies the maximum roller speed as at which will not displace aggregates from the asphalt material.
- Brooming is typically applied within one day following seal coat rolling.
- Missouri and Ohio include strip tests that evaluate short term seal coat performance based on visual inspection before the actual seal coat application. Indiana has a similar test method specified in ITM No. 579-94P, but it is not included in the state's seal coat standard specification.

TABLE 2.3
Seal coat standard specificationô comparison

State	Minnesota	Iowa	Missouri	Wisconsin
Name	Bituminous seal coat	Bituminous seal coat	Seal coat	Seal Coat
Aggregate Condition	• Fines: < 2 % (by mass) • Free surface moisture: < 4 %	• Must be washed • Fines: < 4 % (by mass)	• Fines: < 3.5 % (by mass) • Free from objectionable coatings	• Dry or moisten the aggregate to ensure that it is damp to surface dry
Temp. or Time Restrictions	• May 15 - August 31 • Pavement and air temp above 70 °F. • Relative humidity: < 75 % • Dry and clean surface	• Not after September 15 • Pavement temp above 60 °F	• Pavement and air temp above 60 °F • Dry and clean surface	• Air temp above 60°F • Dry and clean surface
Distance between Distributor and Spreader	• Immediately	• Less than 150 ft.		
Rolling	• Self-propelled, smooth-tread pneumatic-tired rollers • Initial rolling within 5 min • Five coverages within 30 min • A minimum of two rollers • Max speed: < 5 mph • Begin at the edges and continue to the center	• Self-propelled pneumatic-tired rollers • A minimum of two rollers • Rolling within 30 min • Initial coverage shall be as close to the aggregate spreader as possible, not to exceed 200 ft. (60 m) • Initial rolling within 2 min • Five coverages • Max speed: < 5 mph		• Self-propelled steel-wheel roller weighing between 6 and 9 tons • Self-propelled, pneumatic-tire roller • Roll the surface immediately after spreading the aggregate with a steel-wheel roller • Begin at the edges and continue to the center, lapping 1/2 the roller width on each successive pass. After this initial rolling, perform subsequent rolling using both steel-wheel rollers and pneumatic-tire rollers
Traffic Control	• No traffic allowed until the completion of all rolling and bituminous materials is cured to a degree satisfactory to the engineer	• Control traffic not to exceed 25 mph (40 km/h) for a minimum of 2 hrs		• Closed until cover aggregate is applied
Brooming after rolling	• On the morning following each day of seal coat operations	• Early the next morning		• Lightly broom the surface to remove excess loose material
Test				
Payment	• Binder: liter (gallon) • Aggregate: metric ton (ton)	• Binder: gallon • Aggregate: ton	• By unit price	• By cubic yard or ton

2.4 Survey of seal coat performance in indiana

Seal coat practice varies state by state and even district by district. Knowing current INDOT seal coat practice is essential for improving or developing seal coat technology. A state-wide survey was conducted including seven districts (Crawfordsville, Fort Wayne, Greenfield, La Porte, Seymour, Vincennes, and Central Office). The research team visited each district and several district engineers participated in the survey,

TABLE 2.3
Extended

Illinois	Michigan	Ohio	Kentucky	Indiana (2011)
Bituminous Surface Treatment	Chip seals	Chip Seal	Asphalt seal coat	Seal coat
• No free moisture.	• Natural aggregate or Blast Furnace Slag and Blast Furnace Slag for shoulder seal coats	• Washed Limestone or Dolomite, • A max of 2.0 % fines	• Surface dry	
• May 1 - October 1 • Air temp in the shade above 60°F • Dry and clean surface.	• Pavement and air temp above 55 °F. • June 1-August 15 for the Upper Peninsula • May 15-September 1 for the Lower Peninsula north of M-46 • May 15-September 15 for the Lower Peninsula south of M-46	• Pavement and air temp above 60 °F • May 1 -September 1	• Air temp above 45 °F	• Pavement or air temp above 60°F • May 1-October 1 (exception for shoulder)
• Immediately	• 150 ft.	• 150 ft.	• Immediately	• Within 1 min.
• Roll immediately with a pneumatic-tired roller • Begin at the edges and continue to the center, overlapping on successive trips by at least 1/2 the width of the roller	• Self-propelled, pneumatic-tired rollers • Roll within 5 mins • Max speed: < 5 mph • Make a minimum of two complete passes (one trip, forward and backward, over the same path) • Overlap each pass by one-half the width of the roller • A minimum of two rollers	• Roll immediately with a pneumatic-tired roller • Make a minimum of two complete passes (one trip, forward and backward, over the same path) • Overlap each pass by one-half the width of the roller • A minimum of three rollers • Max speed: < 5 mph	• Roll immediately with a pneumatic-tired roller (steel-wheel roller may be allowed on slopes) • Make a minimum of three complete passes	• At least three complete roller coverages • First roller: within 2 min. of aggregate application • Last Roller: within 30 min
• The surface may be opened to traffic as soon as it has cured sufficiently to prevent the material from being picked up by the wheels of vehicles passing over it	• Allow the new surface sufficient cure time to prevent damage by vehicle tires before opening to traffic • The speed of vehicles in the open lane at a maximum speed of 35 miles per hours	• Control traffic not to exceed 35 mph		• Closed until cover aggregate is applied
• The surface shall be swept clean, removing all dirt, debris, and loose material	• Before the end of each day's work or within 24 hrs	• Within 4 hrs • Additional sweeping in subsequent days	• After the asphalt material has cured sufficiently	• No later than the morning following placement of the seal coat
		• Test Strip: 1000 ft. (300 m) long and the width of one lane. Review the test strip the next workday.		
• Binder: gallon or ton • Aggregate: ton	• By square yard of seal coat in place	• Square yard of seal coat in place	• Binder: ton • Aggregate: ton	• Square yard of seal coat in place

which occurred in January and February 2008. It is a noteworthy that, as of May 2011, seal coat practice surveyed in this study is generally outdated due to practice improvement, training, specification change, etc.

2.4.1 Survey summary

The survey questionnaire was developed based on information gained from a review of the literature review several state DOT specifications and a chip seal best practice study completed by the National Cooperative Highway Research Program (NCHRP) (6). The survey consisted of six categories of questions: general, design, material, equipment, construction, and performance. In the general question category, some background information was collected from survey participants. This information was then used to screen for the highest quality data by establishing a ranking system based on seal coat project involvement and familiarity. Accordingly, 12 responses among 47 total responses were selected for data analysis. Only 15 of the 47 total survey participants reported that they had more than 5 years experience working on seal coat related projects in their respective INDOT districts. Of the 12 responses that were chosen for data analysis, 8 were from participants that had more than 5 years of seal coat experience in their district and 4 were from respondents who did not have at least5 years of experience in their districts.

The critical findings are listed below. In addition, all response histograms and details follow this report. Researchers noted that some answers were not available or lacked statistical meaning; therefore, these are not shown in the survey results.

The following abbreviations are used for each district in this report:

- CV for Crawfordsville
- FW for Fort Wayne
- GF for Greenfield
- LP for La Porte
- SM for Seymour
- VC for Vincennes
- C/O for Central Office

2.4.2 Survey analysis results

General

According to the 12 responses to the survey, the average seal coat lifetime was 5.2 years. The Vincennes district had the highest lifetime response with an average of 6.5 years. The longest overall reported lifetime was 8 years and was also from Vincennes. The shortest seal coat lifetime came from the Seymour district with an average of 4 years.

The most typical response to question 5 (“What are the major reasons for your district’s decision to apply a chip seal?”) about the district’s performance in handling seal coat operations was “Good: minor difficulties”. The Fort Wayne (FW) district reported option 5 “Excellent: Very Little Difficulty.” The most frequent response to question 6 (“What are the major reasons for your district’s decision to apply a seal coat?”) was the option “Improving skid resistance.” That option was chosen 10 times by survey respondents. However, the option “distress (cracking)” and “oxidation” each had a frequency of 9. The options “Prevent water infiltration” and “Provide wearing surface” each had a frequency of 8 responses. Based on this, it is likely that each of these aforementioned reasons to apply a seal coat carry approximately equal weight. Other options, including “meeting annual work plan”, “improving night vision,” and “eliminating surface rutting,” each had fewer than 2 responses, indicating a lesser degree of weight in the decision-making process. Some reasons specified in the “Other” category included covering the edge line and extending pavement lifetime.

TABLE 2.4
Summary of results from general category

Average seal coat life in Indiana is approximately five years.
Major reasons to apply a seal coat are cracking, skid resistance, oxidation, and water infiltration.
Major “trigger point” for doing a seal coat is the age of existing pavement.
Average level of distress on a pavement that will receive a seal coat is moderate condition.

The most frequent response to question 7 (“What is the trigger point in your seal coat decision-making process?”) was the choice “age of the surface.” The next most frequent choices were “pavement condition rating,” “oxidation,” and “no trigger,” each of which had an equal number of responses. One respondent wrote into the “Other” category that his district did not consider a single factor but instead considered all of the above.

The most frequent response to question 8 (“How would you describe the level of distress on roads that generally receive a seal coat?”) was “Moderate”. The least frequent response was “severe.” There was only one uniquely “severe” response. Two responses marked both “severe” and “moderate” on their questionnaire and both responses were counted towards the total.

The most frequent response to question 9 (“What is the major problem associated with seal coat work in your district?”) was both “Early chip loss” and “Other”. Both received a frequency of 4 responses. Overall, the reasons specified in the “Other” response were very different from each other.

Design

In determining the application rates of both aggregate and emulsion for seal coat placement in the field, most districts appear to rely primarily on the INDOT standards and specifications. For emulsion application rates (question 10), the option “INDOT standard specification” had a frequency of 7, while “using the design procedure” and “based on past experience” each had a frequency of 4.

For aggregate application rates (question 11), similar results were seen. Use of the INDOT specifications received a frequency of 7, while use of past experience

TABLE 2.5
Summary of results from design category

Most districts rely on INDOT specifications for application rates of emulsion and aggregate
Typical ADT of a road in consideration for a seal coat is no more than 5000 vehicles

TABLE 2.6
Summary of results for materials category

All districts use Indiana aggregate No. 11 and No. 12
Limestone and Crushed Gravels are most typical for seal coat aggregates
Cleanness, size and gradation, were of frequent concern regarding seal coat aggregate
The majority of districts use AE-90S for asphalt emulsion

received a frequency of 6, suggesting a more even split between use of experience and the specifications in determination of the aggregate application rate.

Regarding the maximum amount of traffic volume allowed on roads that will be given seal coats (question 14), most of the respondents marked that roads with ADT less than 5000 vehicles were appropriate.

Materials

All of the survey participants noted that their districts use Indiana aggregate No. 11 and/or No. 12 for their seal coat jobs. Regarding the type of aggregate, almost every district responded that Limestone and Crushed Gravels were typical for seal coat projects. The most frequent concern regarding aggregate for seal coat jobs (question 18) was cleanness, which had 9 responses. Size and gradation were also important (frequency of 4).

For question 19 ("How do you select the emulsion type for seal coat jobs?") the survey results were highly variable and perhaps inconclusive. The most frequent response was "other" with a frequency of 5. Some of the responses written-in included choosing based on the standard specification or choosing based on the engineer's experience. The second most frequent response that plays a role in selecting emulsion type was traffic level of the road.

Question 20 asked for the names of the emulsions most often used for seal coats in the various districts. The majority of responses were AE-90S, which had a frequency of 8.

Equipment

The first question regarding equipment asked each participant to list the number of spreaders, distributors, rollers, and brooms each district owns and uses during a seal coat job. All district had only 1 spreader, 9 out of 12 Districts had 2 distributors, 6 Districts had 2 brooms, and 5 Districts had 3 rollers. The average number of distributors for a given district was 2.18, the average number of rollers was 2.45, and the average number of brooms was 1.73.

TABLE 2.7
Summary of results from equipment category

Most districts had 1 spreader, 2 distributors, 2 or 3 rollers, and 2 brooms
The majority of districts had distributors with computerized controls
Half of the districts had aggregate spreaders with computerized controls, and half dis not
The static pneumatic-tire roller was most frequently used for seal coat rolling

The majority of Districts had emulsion distributors with computerized controls and calibrated their distributors periodically. As for aggregate spreaders (question 25), half of the districts had computerized gate controls on their aggregate spreaders, and half dis not. All survey participants reported that their aggregate spreaders were calibrated periodically, except for one (question 26). The roller that most often used in the districts that participated in this survey was the static pneumatic-tire roller. Eleven of the survey participants chose this roller in their responses.

Construction

The typical seal coat construction season varied slightly from district to district, but the prime season were the months of June, July, August, and September. Some districts also included April and October as appropriate times for seal coat placement.

The typical ambient air temperature range for seal coat placement across the districts was about 50 to 100 ℉. Every district in the survey reported that they broomed the surface prior to emulsion application.

After the emulsion is sprayed, the aggregate is spread at varying times depending on each district. However, most districts spread the aggregate very soon after emulsion is spread. A frequency of 4 was reported for spreading aggregate less than one minute after emulsion and a frequency of 3 was reported for both 1 and 2 minutes after emulsion is sprayed. One response from the Vincennes district reported that aggregate was spread 30 minutes after emulsion. The most common time period between aggregate spreading and initial rolling was around 2 to 5 minutes.

The most important control for each district's roller operations was the number of passes, which had a frequency of 10 responses. Rolling patterns and speed limits were also quite important, with frequencies of 7 and 6, respectively. The most typical speeds for a roller in a seal coat job across the districts were in the range

TABLE 2.8
Summary of results from construction category

The typical seal coat placement season was June – September
The acceptable ambient air temperature range to perform a seal coat was approximately 50 to 100 ℉
In the majority of districts, aggregate was spread within 2 minutes or less of spraying emulsion
The most important control regarding rolling was the number of passes, followed by patterns and speed
The average speed of a roller across the districts was 4.43 mph
The average weight of a roller was 8.63 tons
The most important factors regarding broom timing were weather and humidity
In the majority of districts, 24 hours were allowed to pass between final rolling and initial brooming
The most frequent broom coverage was 2
Flaggers, pilot vehicles, safety cones, and reduced speeds were most often used for traffic control

TABLE 2.9
Summary of results from performance category

Crack reflection, streaking, and raveling were the most common distresses observed in seal coats
Supplying better aggregate was the most important factor in improving a seal coat
The most frequent public complaint regarding a seal coat was visible loose stone
The most likely cause of seal coat failure was dirty aggregate
Original pavement quality, materials, and climate/environment conditions were critical to the life of the seal coat
The majority of districts did not perform field tests to monitor the quality of the seal coat

of 3 to 5 mph. The average speed of a roller in all the districts was 4.43 miles per hour. The range of roller weights was between 5 and 10 tons with an average of 8.63 tons. The rolling patterns were split evenly between pattern 1 and pattern 2 with 2 responses falling in the "other" category.

The most important factor in determining the optimum timing of brooming after final rolling (question 38) were weather and humidity with a frequency of 5. The most frequent amount of time in between final rolling and initial brooming during seal coat placement was 24 hours. The most frequent number of broom coverage was 2 and all districts used either 2 or 3 broom coverages. The most typical traffic control measures used were flaggers, pilot vehicles, safety cones, and reduced speeds.

Performance

According to the survey, the most common distresses observed in seal coats across the districts were crack reflection (frequency of 7), streaking (frequency of 6), and raveling (frequency of 6). Other distresses such as bleeding, transverse joints, and potholes were reported in lesser numbers.

According to the survey, the most important factor in improving seal coat performance was better aggregate. A better design method was the second-most important, followed by better emulsion. The most frequent public complaint regarding a seal coat was loose stone. Road noise and appearance were also important, but not to the same degree. The majority of survey participants described the pavement ride on roads with a seal coat as "good" in general.

The most likely cause of a seal coat failure was dirty or dusty aggregate, followed by inclement weather or environmental conditions. The survey participants were relatively undecided among three factors when determining the most critical factor affecting the life of seal coats. These factors were "original quality of pavement" (frequency of 6), "materials of seal coat" (frequency of 5), and "cold climate considerations" (frequency of 5). Finally, the majority of the districts reported that they did not perform field tests to monitor the quality of the seal coat.

3 PERFORMANCE EVALUATION OF SEAL COAT MATERIALS

To evaluate aggregate and emulsion types on aggregate loss and seal coat performance, three emulsions and eight aggregates including CRS-2P, RS-2P, and AE-90S for emulsions and Trap Rock, Sandstone, Blast Furnace Slag, Steel Slag, Limestone, Dolomite, Crushed Gravel (one face), and Crushed Gravel (two faces) were tested utilizing the sweep and Vialit tests. In addition, to explore influential factors (i.e., electrical surface charge interaction, water evaporation change in emulsion, water affinity of aggregate, etc.), the Zeta potential, water content, and X-ray deflection test were also conducted.

3.1 Materials

The materials used in this research include eight different aggregates and three types of asphalt emulsions. Different types of aggregates and emulsions were selected based on accessibility and availability in the state of Indiana for Indiana seal coat.

3.1.1 Emulsions

The emulsions, including AE-90S, RS-2P, and CRS-2P, were obtained from Asphalt Materials Inc. in Indianapolis, Indiana. AE-90S, which is a polymer-modified rapid-setting anionic emulsion, is widely used for seal coat application in the state of Indiana and is specified in the INDOT Standard Specification (3). According to ASTM D 977 and D 2397, RS-2P and CRS-2P are respectively polymer-modified rapid-setting anionic and cationic emulsions, which are used primarily for spray applications, such as seal coat (23) (24). These two emulsions are not specified in the INDOT Standard Specification (3). The emulsifier used for AE-90S and RS-2P is a mixture of crude tall oil and sodium hydroxide (NaOH), and the emulsifier for CRS-2P is an amine and Hydrochloric acid (HCl). The standard routine emulsion tests using the three emulsions were conducted at the INDOT Fort Wayne district lab. The tests included Saybolt Furol, residue test by distillation, oil distillate by distillation, demulsibility test, Penetration test, solubility test, ductility test, and sieve test. The standard tests and test results are summarized in TABLE 3.1 and Appendix 1.2.

3.1.2 Aggregate

In this study, eight different types of aggregates including, Trap Rock, Sandstone, Blast Furnace Slag, Steel Slag, Limestone, Dolomite, Crushed Gravel (one face), and Crushed Gravel (two faces) were used. Their water absorption and bulk specific gravity obtained from the AASHTO T 85 test are shown in Figure 3.2.

Two types of Crushed Gravels were included in order to examine whether there is a direct correlation between seal coat performance and the number of cut faces.

TABLE 3.1
Standard emulsion test results

Test	AASHTO	AE-90S	CRS-2P	RS-2P
Saybolt Furol Viscosity, 50 ℃ SFS	T 72	127	67	56
Residue by Distillation, %	T 59	65.8	69.8	68.8
Oil Distillation, ml/100g Emulsion	T 59	0.5	0.5	0.5
Demulsibility, 35 ml. 0.02M $CaCl_2$, %	T 59	96	78	28
Penetration, 25 ℃, 100 g, 5 sec, 0.1 mm	T 49	119	106	106
Solubility in organic solvents, %	T 44	99.94	99.92	99.89
Ductility, 25 ℃ exceeds mm.	T 51	-	400	400
Sieve Test, % retained	T 59	0.19	0.88	0.07

*INDOT Standard Specification employs metric unit in the requirements for asphalt emulsion (3)

Throughout the experiment, only aggregates passing the 3/8 in. sieve and retained on the 1/4 in. sieve with a Flakiness Index of 0 % were used to limit the factors affecting the seal coat performance including gradation, size, and shape. This specific size of aggregates makes up a major portion of the gradation of the seal coat aggregate (No. 12) used in Indiana. The Flakiness Index (British Standard EN 933-3) determines the percentage of flat and elongated coarse aggregates by mass. Each aggregate sample was tested using a metal plate with slotted openings (25). As a result, the aggregates that passed through the slots were separated. The equation used to calculate the Flakiness Index and the metal plate are shown in EQUATION 3-1 and TABLE 3.2, respectively.

$$\text{Flakiness Index} = \frac{\text{Mass of Passing Particle}}{\text{Mass of Passing Particle} + \text{Mass of Retained Particle}} \times 100 \quad (3.1)$$

3.2 Test methods

3.2.1 Zeta potential test

The pH (acidity or basicity) is an important factor in the measurement of the Zeta potential (15). Assume a particle with a negative Zeta potential. When base is added to this system, the OH^- becomes more available resulting in a more negative Zeta potential. When acid is introduced into the system then H^+ neutralizes any negative charges up to a certain point, called the isoelectric point. The Zeta potential becomes positive if more acid is added beyond the isoelectric point at which point the system was neutralized.

The emulsion used in this study was an "oil in water" type. Thus, the electrical surface charge characteristic of the emulsion particles was more likely governed by the pH of the solution (water and emulsifier). Also, the electrical surface charge of an aggregate in emulsion depends on the pH of the solution. Therefore, it is critical to match

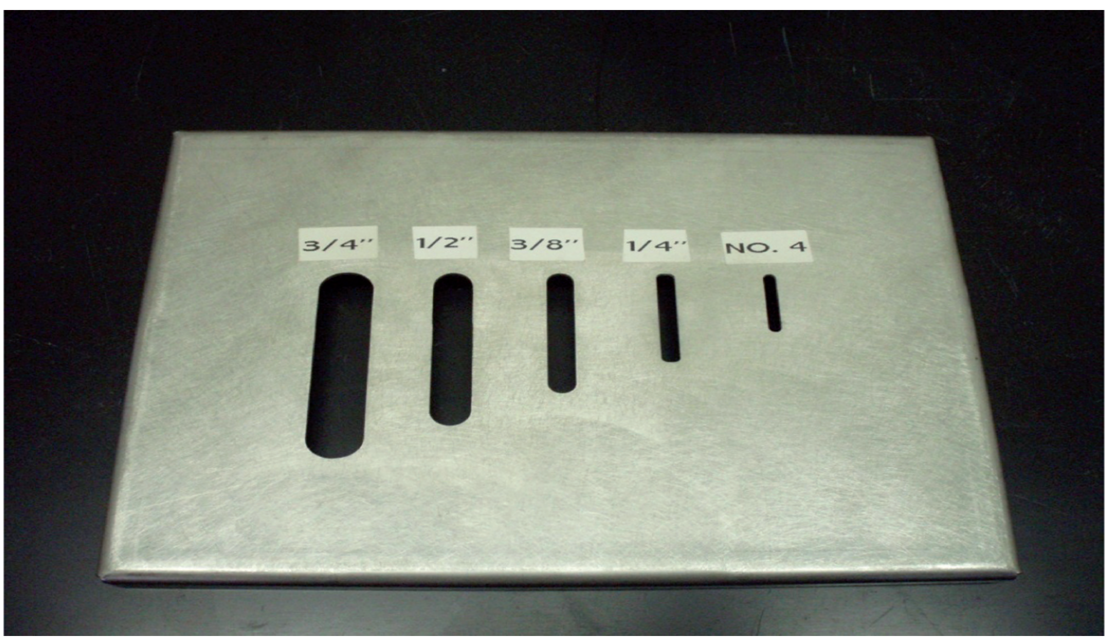
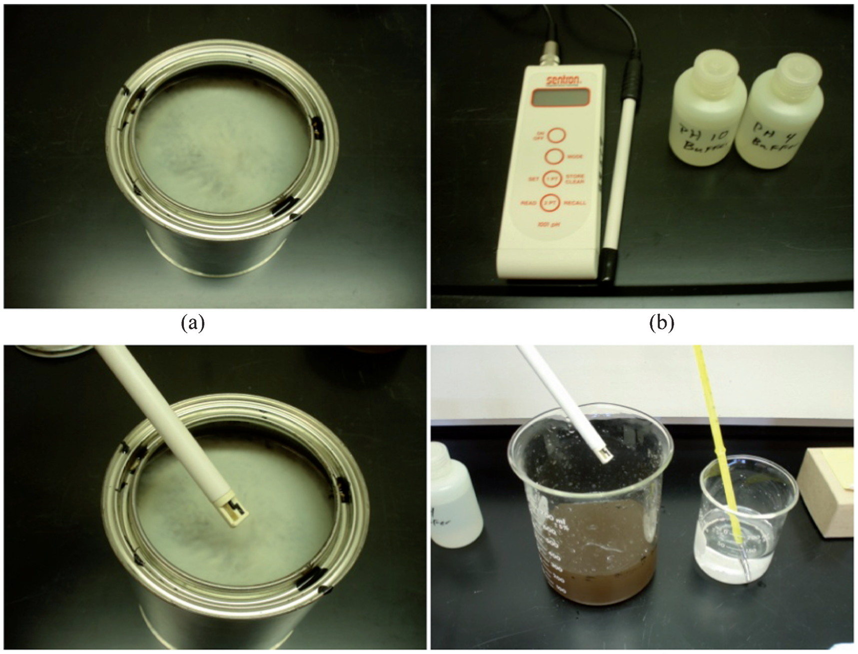


Figure 3.1 Slotted sieve openings for flakiness index testing



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

Figure 3.2 pH measurement procedure: (a) RS-2P asphalt emulsion; (b) pH meter and buffers; (c) pH measurement of emulsion; (d) Rinsing the probe with deionized water

the pH of a solution for the Zeta potential test to the pH of the emulsion used in this study.

Primary process for emulsion Zeta potential test:

1. pH (acidity or basicity) measurements of emulsions
2. Preparation of solution pH-matched with emulsion types
3. Zeta potential tests with the emulsions in the solutions

Primary process for aggregate Zeta potential test:

1. Aggregate specimen preparation
2. Preparation of solution pH-matched with emulsion types
3. Zeta potential test with the aggregates in the solutions.

Details about the Zeta potential test for aggregate and emulsion are introduced in the following subchapter.

Zeta potential test for emulsion

pH Meter Calibration: The pH of a solution is first determined with a pH meter (Sentron Model 1001 pH system). The pH meter is recommended to be calibrated at least once on the day of use. The standard buffers used for calibration are pH 4.0, pH 7.0, and pH 10.0. A small amount is dispensed into a smaller container for 2-point calibration. (It is recommended that the probe be placed in a potassium chloride (KCl) solution at room temperature for 30 minutes prior to the calibration). During the experiment, a pH meter should be calibrated between testing.

pH (acidity or basicity) measurements of emulsions: Asphalt emulsion samples have been stored at room temperature at 77 °F for more than 48 hours until a thinner layer of emulsion appears on the top. In order to prevent the probe from damaging, the probe tip is held horizontally and the sample material is placed onto the sensor surface. The reading is recorded followed by rinsing with deionized water. Repeat procedure 2, 3 and 4 as required, until each asphalt emulsion sample has been measured three times.

As shown in TABLE 3.3, the pH of AE-90 S and RS-2P are about 11, and the ph of RS-2P is approximately 2. The pH values are appropriate representation of the emulsifiers used for each type of emulsion, Hydrochloric acid (HCl, strong acid) for CRS-2P and sodium hydroxide (NaOH, strong base) for AE-90S and RS-2P.

TABLE 3.2
Aggregate types and properties

Aggregate Type	Water Absorption (AASHTO T 85)	Bulk Specific Gravity (AASHTO T 85)
Trap Rock	0.49	2.90
Sandstone	1.43	2.59
Blast Furnace Slag	3.99	2.37
Steel Slag	1.45	3.51
Limestone	1.25	2.67
Dolomite	1.29	2.71
Crushed Gravel (one face)	1.57	2.62
Crushed Gravel (two faces)	2.09	2.58

TABLE 3.3
Summary of pH test result of emulsions

Sample Name	Replicate 1st [pH]	2nd [pH]	3rd [pH]	Average [pH]
AE-90S	10.5	10.4	10.4	10.5
CRS-2P	2.1	2.1	2	2.1
RS-2P	10.8	11	10.8	10.9

Preparation of solution pH-matched with emulsion types: Aqueous solutions with the pH 2 and 11 are prepared prior to the testing as determined. Five Molar of HCl (pH 1) and 5 Molar of NaOH (pH 14) are first prepared depending on the desired pH of the final solution. Once the moles of H^+ or OH^- ions appear in the prepared solutions, a calculated amount of deionized water (pH 7) is added to the desired molarities of the final solution (pH 2 or pH 11). The final solution is once again checked with a pH meter to determine whether additional adjustments are needed. If the final pH is a bit off, add either 5 Molar of HCl (to lower pH) or 5 Molar of NaOH (to increase pH).

Zeta potential tests with emulsions in solutions: The Zeta potential test starts with filling the cuvette with 2 ml of solutions with specific pH values, as shown in Figure 3.3-(c), and then emulsion specimens are added into the cuvette. Deionized water is used for a Zeta potential measurement at pH 7. The deionized water and solutions are mixed with emulsions; the cuvette with the specimen is placed in the testing machine. Each set of specimens is measured 10 times using the Zetasizer Nano Series and analyzed with the PALS Zeta potential Analyzer Ver. 3.29.

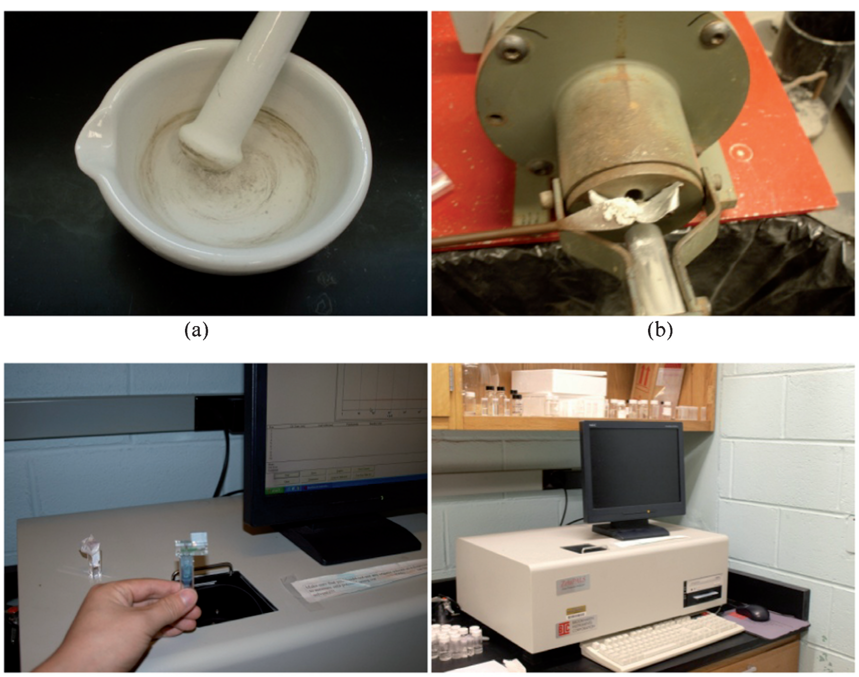
Zeta potential test for aggregate

Aggregate specimen preparation: The specimen preparation for the Zeta potential test starts by pulverizing 1/4 in. aggregates into fine powder with an effective diameter less than 1000 nm. Aggregates of 1/4 in. are first processed with the crusher into coarse powders and further processed with the pulverizer, generating fine aggregate powders as shown in Figure 3.3-(a). Finally, fine aggregate powders are ground using a mortar and pestle as shown in Figure 3.3-(b).

The same steps are repeated for each different aggregate sample. Throughout the grinding process, the components of each instrument are thoroughly cleaned using both an air blower and tap water after each use to protect from cross-contamination.

Preparation of solution pH-matched with emulsion types: Aqueous solutions with a pH of 2 and 11 are prepared prior to the testing as determined. Five Molar of HCl (pH 1) and 5 Molar of NaOH (pH 14) are first prepared depending on the desired pH of the final solution. Once the moles of H^+ or OH^- ions appear in the prepared solutions, calculated amount of deionized water (pH 7) is added to the desired molarities of the final solution (pH 2 or pH 11). The final solution is once again checked with the pH meter to determine whether additional adjustments are needed. If the final pH is a bit off, add either 5 Molar of HCl (to lower pH) or 5 Molar of NaOH (to increase pH).

Zeta potential tests with aggregates in the solutions: The Zeta potential test starts with filling the cuvette with 2 ml of solutions with specific pH values, as shown in Figure 3.3-(c), and then aggregate specimens are added into the cuvette. Deionized water at pH 7 is used for a solution for the Zeta potential measurement. Once the cuvette is mixed until the aggregate specimen particles are evenly dispersed, let particles settle to the bottom of the cuvette. By then, smaller aggregate specimen particles are dispersed in the solution as a colloidal although the solution may appear to be clear since all other larger particles are at the bottom of the



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

Figure 3.3 Zeta potential test procedure: (a) Pulverization of specimens; (b) Mortar and pestle for final grinding; (c) Cuvette contacting the aqueous solution and specimen (d) Zeta potential measurement cuvette. Finally, the cuvette is placed in the testing machine. Each set of specimens is measured 10 times using the Zetasizer Nano Series and analyzed with the PALS (Phase Analysis Light Scattering) Zeta potential Analyzer Ver. 3.29.

3.2.2. Emulsion water contents testing

The emulsion water content testing by evaporation is carried out to examine how the water contents of an emulsion changes over a period of time unlike the standard test method for residue by evaporation of emulsified asphalt (ASTM D 6934), which only determines the quantitative composition of the residue content in the emulsion (26). In this study, emulsion water contents tests were conducted both with and without aggregate.

Specimen preparation

The specimen preparation for the emulsion water contents test closely resembles the specimen preparation procedure of the sweep test (ASTM D7000) (27). The specimen for the emulsion water contents test is prepared by first having a felt disk firmly glued onto a steel disk with a diameter of 13.8 in. The felt disk is then placed in the oven under a flat-bottomed weight to keep the felt disk pressed against the steel disk for 1.5 hours or longer. The emulsion is also placed in the oven at 140 ℉ until sufficient workability of the emulsion sample is achieved.

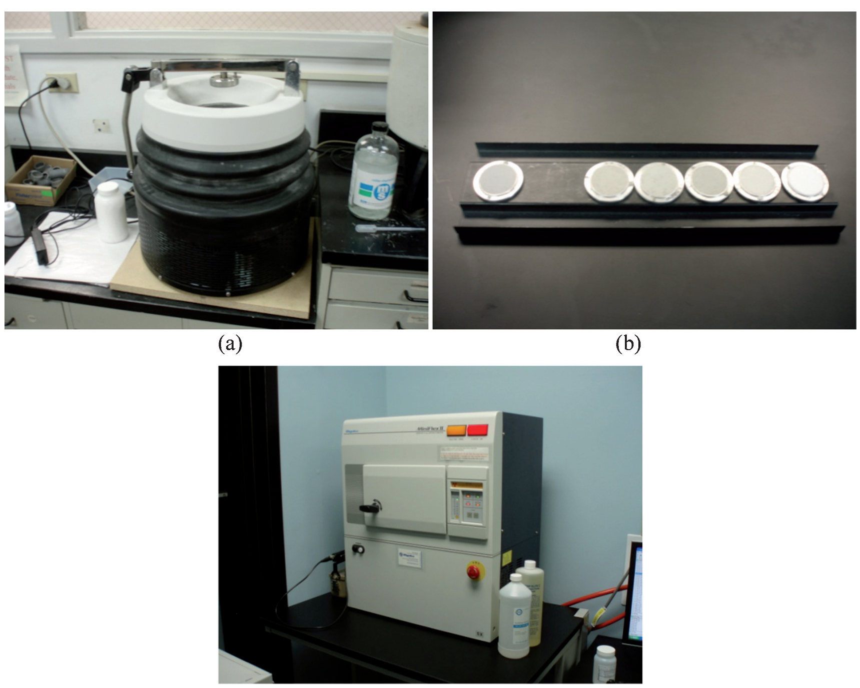
Once the emulsion sample is sufficiently fluid, the felt disk is removed from the oven and a strike-off template is placed over the felt disk while being centered over the felt disk. The emulsion is then poured slowly over the top of the felt disk. A strike-off is used to remove the excess emulsion thereby creating a uniform layer of emulsion over the surface of the felt disk. The emulsion application rate on the felt disk was 0.35 gal/yd^2 based on the dimension of the template (i.e., thickness = 0.06 in. and diameter = 11 in.). For specimens with aggregates, Limestone (200 g per each felt disk) passing 3/8 in. sieve and retained on a 1/4 in. sieve with a Flakiness Index of 0 % were used. The detailed procedure regarding aggregate placement is explained in Chapter 3.2.4

Testing procedure

The felt disk is weighed before applying the emulsion sample. Once the specimen is prepared, the initial weight (felt disk and emulsion) is again measured. The felt disk is then placed in the oven for curing at 113 ℉. After a specified period of time, the felt disk is removed from the oven for weight measurement and then placed back in the oven. The testing is repeated for 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, 7 hours, 15 hours, 23 hours, 31 hours, 47 hours, and 71 hours.

3.2.3 X-ray defflection test

The X-ray diffraction (XRD) tests are generally distinguished among single crystal, polycrystalline, and powder applications. Among the three applications, the powder application is mainly used for identification of chemical compositions of various solid materials. A



(a) (b)

(c)

Figure 3.4 XRD test procedure: (a) specimen preparation by grinding aggregates; (b) preparing specimen onto the steel template; (c) XRD testing instrument study by A.W.Hull in 1919 suggested that about 95 % of solid materials can be described as crystalline and every crystalline produces a unique pattern consistently, regardless of its mixture (28). The International Center for Diffraction Data (ICDD) is the organization, responsible for maintaining the data base of inorganic and organic spectras. As a result, the XRD test can reveal the chemical compositions and the solid materials can then be classified by comparing the result to the known spectras provided by the ICDD.

In the study, each aggregate was tested by Heritage Transport LLC in Indianapolis based on ASTM C 295 to determine its mineral composition. Figure 3.4 shows the general procedures employed at Heritage Transport LLC. The testing procedure started with transforming sample aggregates into fine powder since the main purpose of XRD testing is to determine a sample's chemical composition as described above. Once a powered sample is packed onto the metal template, specimens are presented to the testing machine.

3.2.4 Sweep test

The sweep test (ASTM D 7000) measures the curing performance, characteristics of bituminous emulsion, and aggregates by simulating the brooming action of a surface treatment in the laboratory. Although the test method is useful for classifying rapid-setting bituminous emulsions and applicable to surface treatments that require a quick return to traffic, this performance test required modifications for the following reasons:

- The sweep test method specifies the mass of aggregates used for each specimen. However, the volume of aggregates used for each specimen varies due to different specific gravity. Aggregates with low specific gravity require the use of a larger volume of aggregate, which produces multiple layers of aggregates on the felt disk when applied onto the emulsion. As a result, a certain portion of the aggregates are not embedded even after the compaction of the aggregates with the sweep test compactor. The mass loss measured after the testing contains the mass of aggregates that are not embedded properly. This excessive aggregate loss is related to the application rate. To avoid the problem, aggregates are applied by placing individual aggregates by hand onto the felt disk.
- Any loose aggregates occurred by abrading force contains emulsions attached to them; therefore, any emulsions on the surface of loss aggregates are included in the mass loss. The modified sweep test method counts the aggregate particles in order to correct for the misrepresentation in the mass loss.
- The survey of seal coat performance in Indiana was conducted in January and February of 2008. The survey revealed that 24 hours were allowed to pass between final rolling and initial brooming in the majority of Indiana districts. To address this practice, the tests were conducted after 24 hours of curing.

Specimen preparataion

The specimen for the sweep test is prepared by first having a felt disk firmly glued onto a steel disk with a diameter of 13.8 in. The felt disk is then placed in the oven under a flat-bottomed weight to keep the felt disk pressed against the steel disk for 1.5 hours or longer. The emulsion is also placed in the oven at 140 ℉ until sufficient workability of the emulsion sample is achieved.

Once the emulsion sample is sufficiently fluid, the felt disk is removed from the oven and a strike-off template is placed over the felt disk while being centered over the felt disk. The emulsion is then poured slowly over the top arc of the felt disk, as shown in Figure 3.5. A strike-off is used to remove the excess emulsion thereby creating a uniform layer of emulsion over the surface of the felt disk. The emulsion application rate on the felt disk was 0.35 gal/yd^2 based on the dimension of the template (i. e., thickness = 0.06 in. and diameter = 11 in.).

The aggregates are placed on the disk upon application of the emulsion by dropping individual aggregates on the disk by hand. The aggregates are placed on the disk in a circular pattern, as shown in Figure 3.5-(c). The aggregates are arranged in such a way that only a single layer of aggregates are formed.

The felt disk is covered with a wax-coated piece of paper for the compaction. A hand compactor is passed over the surface of the specimen three times consecutively in the same direction, as shown in Figure 3.5-(d). Then the compactor is rotated perpendicular to the initial direction for an additional three passes. Finally, the felt disk is placed in the oven for curing at 113 ℉ before testing. The completed specimen is shown in Figure 3.5-(e).

Testing procedure

After curing is completed, the felt disk is removed from the oven and securely attached to the mixer table. The specimen is exposed to one minute of sweeping at 0.8 cycles per second.

Determination of aggregate loss

Pictures of each specimen were taken before and after each testing. The pictures were then evaluated to determine the number of particles retained on the specimen during each stage of the test. By subtracting the number of particles retained after testing from the number of particles originally embedded on the felt disk before testing, the number of particles lost during the test can be obtained. Once the number of particles lost during the test was known, the percentage aggregate of loss was then calculated by dividing with number of particles on the felt disk before the test.

$$\%\,\text{Aggregate Loss} = \frac{\text{Number of Particles before testing-Number of Particles retainad after testing}}{\text{Number of Particles before testing}} \times 100 \qquad (3.2)$$

3.2.5 Vialit test

The Vialit test method (British Standard EN 12272-3) is an indicator of aggregate retention for seal coat

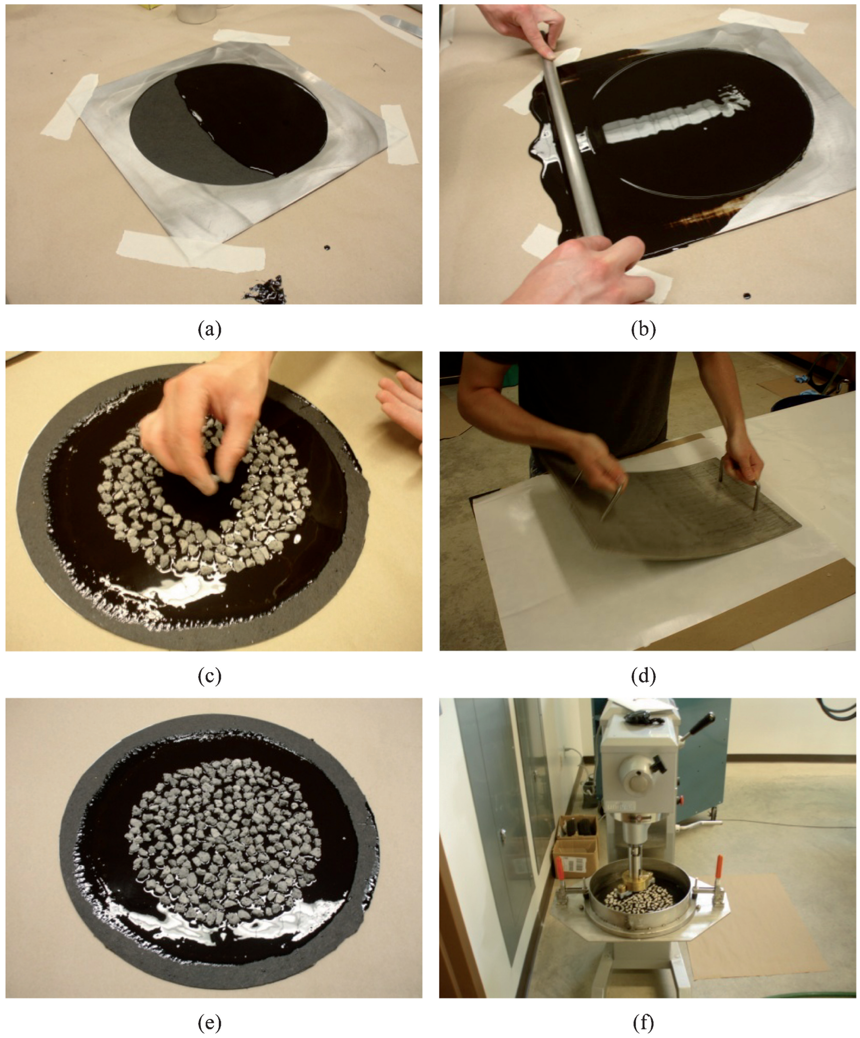


Figure 3.5 Sweep test procedure: (a) emulsion application; (b) excess emulsion removal; (c) placement of aggregate (d) specimen compaction with compactor; (e) sweep test specimen prior to testing; (f) specimen secured in the sweep test machine

(29). Although the Vialit test method is one of many testing methods developed for measurements of seal coat performance, the testing method is found to be useful for the following reason: Most aggregate loss failure in seal coat occurs in the first frost season of seal coat life. Evaluating the low temperature performance is imperative in predicting long term performance. The sweep test has a limitation in inducing the aggregate loss at a temperature below 32 ℉ due to a lack of mechanical force in sweeping aggregates using a steel brush. The Vialit test applies impact force by dropping a 1.12 lb ball, causing aggregate loss at a temperature below 32 ℉.

Specimen preparation

The specimen preparation for the sweep test closely resembles the specimen preparation procedure of the sweep test with a few distinctions. The Vialit test utilizes a square steel plate with a rim that extends 0.1 inches above the flat surface, containing the applied emulsion. Once the emulsion is poured over the top of the plate, as shown in Figure 3.6-(a), a strike-off is used to remove the excess emulsion thereby creating a uniform layer of emulsion over the surface of the steel plate. The emulsion rate was determined to be 0.55 gal/sy^2 based on the square steel plate's dimensions (i. e. thickness of rim = 0.09 in. and Area = 63.2 in^2). A total of 196 particles are placed on the plate in rows with even spacing, as shown in Figure 3.6-(c). The steel plate is then compacted using a 55 lb roller, used in the same manner as the specimen for the sweep test, as shown in Figure 3.6-(d). The completed specimen is finally placed in the oven at 113 ℉.

Testing procedure

After curing, the specimen is moved to a chamber as shown in Figure 3.6-(e), where the specimen is conditioned at specific sub-freezing temperatures. The specimen is placed in the chamber for two hours, and then placed upside down on the testing apparatus as shown in Figure 3.6-(f). A steel ball is released from the ramp three times on the testing apparatus to strike the back

Figure 3.6 Vialit test procedure: (a) emulsion application; (b) excess emulsion removal; (c) placement of aggregate (d) specimen compaction; (e) specimen compaction with a roller; (f) release point of steel ball

of the specimen. Once the testing is done, the specimen is placed back in the chamber for two hours at a new temperature. The testing procedure is repeated at 32 ℉, 18.5 ℉, 5 ℉, -8.5 ℉, and -22 ℉.

Determination of aggregate loss

As discussed in the sweep test chapter, the same method was applied to the Vialit test to calculate the percentage loss of aggregate. Pictures of each specimen were taken and after each testing. The pictures then were evaluated to determine the number of particles retained on the specimen during each stage of the test. By subtracting the number of particles retained after testing from the number of particles originally embedded on the felt disk before testing, the number of particles lost during the test can be obtained. Once the number of particles lost during the test were know, percentage aggregate loss was then calculated by dividing the number of particles on the felt disk before the test.

$$\%\,\text{Aggregate Loss} = \frac{\text{Number of Particles before testing g. number of Particles lost during the test}}{\text{Number of Particles before testing}} \times 100 \quad (3.3)$$

3.3 Test results and discussions

3.3.1 Zeta potential test

Zeta potential of aggregate

The Zeta potential test was conducted with eight different types of aggregates at various pre-determined pH levels (pH 2, 7 and 11) based on the pH of emulsions used and the results are shown in Figure 3.7 and TABLE 3.4. The pH value of 2 represents CRS-2P and the pH value of 11 represents RS-2P and AE-90S.

Overall, all aggregates adhere to a general trend of having positive Zeta potentials at low pH and negative Zeta potentials at high pH. It should be noted that the Blast Furnace Slag is the only aggregate having

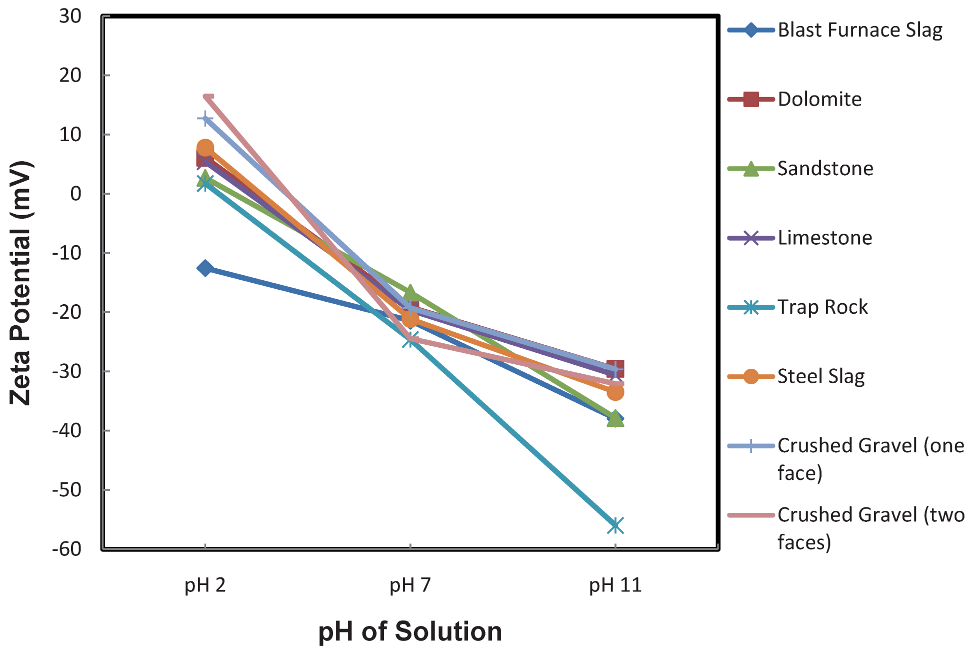


Figure 3.7 Zeta potential of each aggregate at different pH solutions

a negative Zeta potential value throughout the pH ranges from 2 to 11. Among the eight aggregates, the Zeta potentials of Trap Rock and Blast Furnace Slag are the most sensitive and insensitive in terms of pH, respectively. Limestone aggregate is known to have a positive surface charge; however, the results presented in TABLE 3.5 show that the Zeta potential of Limestone fluctuates from positive in a low pH to negative in a high pH.

Zeta potential of emulsion

The Zeta potential test was also conducted with three different types of emulsions and the results are shown in TABLE 3.5. CRS-2P showed a positive Zeta potential and others including RS-2P and AE-90S, showed a negative Zeta potential, which corresponds to the ironical characteristics of emulsifiers used for the emulsions (e.g., cationic (+), anionic (-) or nonionic). The emulsifier for CRS-2 is Hydrochloric acid (HCl, strong acid), which resulted in positive Zeta potential. On the other hand, the emulsifier for AE-90S and RS-2P is crude tall oil and sodium hydroxide (NaOH, strong base), which resulted in a negative Zeta potential.

In addition, Zeta potential value is often used as an indication of how stable suspension is (15). If the Zeta potential is either larger than 30 mV or smaller than -30mV it is regarded as stable; otherwise, it is regarded as unstable. As stated previously regarding electrostatic theory, particles in suspension tend to repel each other strongly as the absolute value of Zeta potential increases. As a result, the repelling force existing

TABLE 3.4
Zeta potentials of aggregates

	Zeta Potential (mV)		
Aggregate Name	pH 2	pH 7	pH 11
Blast Furnace Slag	-12.55	-21.43	-37.96
Dolomite	6.09	-19.15	-29.56
Sandstone	2.69	-16.67	-37.86
Crushed Gravel (two faces)	16.45	-24.47	-32.08
Trap Rock	1.73	-24.61	-55.99
Crushed Gravel (one face)	12.71	-19.26	-29.61
Steel Slag	7.79	-21.15	-33.48
Limestone	5.42	-19.67	-30.6

TABLE 3.5
Zeta potential of emulsions

Emulsion Type	Zeta Potential (mV)
CRS-2P	73.72
RS-2P	-92.51
AE-90S	-145.92

TABLE 3.6
Electrostatic interaction (attraction and repulsion)

	Zeta Potential of Emulsions (mV)		
	CRS-2P	RS-2P	AE-90S
Aggregate Name	73.72	-92.51	-145.92
Blast Furnace Slag	-925	1982	5539
Dolomite	449	1772	4313
Sandstone	198	1542	5525
Crushed Gravel (two faces)	1213	2264	4681
Trap Rock	128	2277	8170
Crushed Gravel (one face)	937	1782	4321
Steel Slag	574	1957	4885
Limestone	400	1820	4465

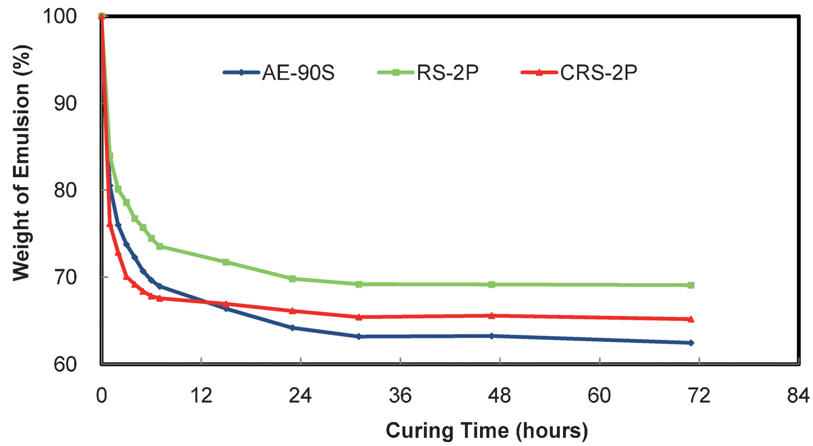


Figure 3.8 Weight change characteristics of emulsions

between particles in a suspension prevents flocculation before it is mixed with aggregates for its application, including the seal coat. The test results, as shown in TABLE 3.5, reveal that all three emulsions are stable with high Zeta potentials (i.e. >30 mV or <-30 mV).

Electrical surface charge interaction

Another factor that many believe affect the performance of a seal coat is the electrostatic interaction between aggregate and emulsifier in emulsions. The breaking process occurs right after the seal coat placement and the electrostatic interaction is known to play an important role in breaking/curing emulsion.

To present the electrostatic interaction, the Zeta potentials from aggregates and emulsions were multiplied and the results are tabulated in TABLE 3.6. The negative and positive interactions represent an attraction and repulsion, respectively, between aggregate and emulsion particles. In general, AE-90S and CRS-2P showed the strongest and the weakest repulsion, respectively. Blast Furnace Slag and CRS-2P were the only aggregate-emulsion combination having an attraction to each other. Trap Rock with AE-90S showed the strongest repulsion among the 24 aggregate-emulsion combinations.

3.3.2 Water contents of emulsion

Critical water content

Knowing how the percentage of water in emulsion changes during the course of curing is critical to early seal coat performance. The adhesion of asphalt in emulsion, that is its ability to retain aggregate particles, depends mainly on the water content of an emulsion during the setting or curing process. The typical water content of an emulsion ranges from 30 % to 40 %. Once curing begins, stronger adhesion developed as water contents reached closer to 0 %. Schuler found that if an emulsion contains less than approximately 7 % water content based on fresh emulsion weight (approximately 80 % of water is evaporated), referred to as "critical moisture content", then it can generate enough adhesion to the aggregate particle for vehicle traffic (16).

The quantitative composition of residue of the emulsions in terms of time was evaluated to investigate the emulsion setting and curing characteristics using three replicates. Figure 3.8 presents how the average weight of each emulsion specimen changes over time in comparison to their initial weights. The percent weights of emulsions, calculated using EQUATION 3.4, decreased as the curing time increased and were stabilized at 62 %, 65 %, and 69 % for AE-90S, CRS-2P, and RS-2P, respectively. Accordingly, water contents for emulsion were 38 %, 35 %, and 31 % for AE-90S, CRS-2P, and RS-2P, respectively. The stabilized percent weights of emulsions were the residues of emulsions. These residue contents were slightly different from the AASHTO T 59 results, shown in TABLE 3.1, due to the different testing condition (i.e., temperature and time).

$$\%\,\text{Weight of emulsion}_r = \frac{\text{Weight of emulsion}_r}{\text{Weight of emulsion}_{r=0}} \times 100 \tag{3.4}$$

To evaluate the critical moisture content for each emulsion, the percent weight of water were calculated using EQUATION 3.5. In general, CRS-2P and AE-90S showed the fastest and slowest water evaporations, respectively as shown in Figure 3.9. The critical moisture content (7 % water content) is equivalent to 20 % weight of water. CRS-2P took around 2 hours to reach the critical moisture content point. RS-2P and AE-90S took approximately 3 hours and 4 hours, respectively, longer than CRS-2P. Accordingly, CRS-2P can allow traffic to open earlier than AE-90S based on critical water content.

$$\%\,\text{Weight of water}_t = \frac{\text{Weight of emulsion}_t - \text{Weight of emulsion}_{t=72\ \text{hrs}}}{\left(1 - \frac{\%\,\text{Weight of emulsion}_{t=72\ \text{hours}}}{100}\right)} \times 100 \tag{3.5}$$

It is noteworthy that emulsion curing time is controlled by emulsifier concentration and type. In detail, the breakdown of emulsions is comprised of four

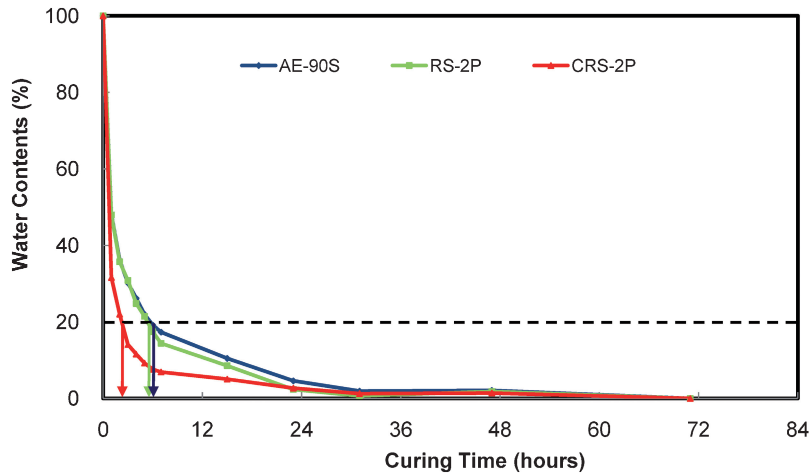


Figure 3.9 Water contents change of emulsions

stages: initial, flocculation, coalescence (curing) and final (30). At the initial stage, particles are separated by repelling forces produced by same the charges on the surfaces. Once applied, particles approach each other closely as water starts to evaporate, which comprises the flocculation stage. Although the flocculation stage can sometimes be reversed by agitation, dilution or addition of more emulsifiers (30), anionic and cationic emulsions break in different ways from this stage (31). As anionic emulsion is applied to a negatively charged surface, all particles repel each other. As a result, coalescence (curing) cannot begin until a sufficient amount of water evaporates; thus, particles are forced to merge. On the other hand, cationic emulsions (e.g., CRS-2P) begin curing once applied to pavement, which is typically a negatively charged surface (like a felt disk used in this study). In addition, water starts to evaporate and go through the same process as the anionic emulsion. As a result, there are two breaking processes occurring at the same time, which accelerate the curing process as compared to the slower curing process of an anionic emulsion (e.g., RS-2P and AE-90S).

Influnce of aggregate on water content

To evaluate the effect of aggregate on the water content change of emulsions, the water content tests were conducted using a total of 18 specimens, comprised of six replicates for each type of emulsions (three replicates with aggregates and three replicates without aggregates). Figure 3.10 presents how the average weight of each emulsion specimen with and without aggregate changes in terms of log time. The percent weight change in terms of time does not have a linear relationship, so transformation was attempted by taking the log curing time in order to have a normal linear regression model for statistical analysis.

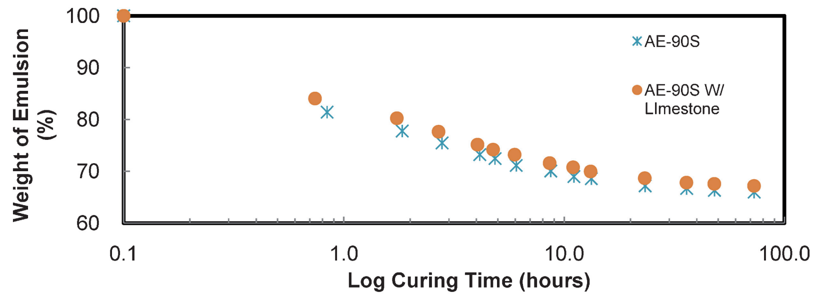
Each type of emulsion was tested separately since the main objective of the test was to find the effect of aggregate application in the curing process. Thus, data from specimens without aggregates were considered as the baseline and compared to it. Consequently, analysis was focused on comparison between the slope of each fitted line. The results are shown in TABLE 3.7.

The parameter estimates for specimens without aggregates represent the slope of the best fitted line while that of specimens with Limestone represent the difference in slopes compared to the other. For instance, the parameter estimate for AE-90S without Limestone is -3.75, and the parameter estimate for AE-90S with Limestone is -3.46 (addition of -3.75 + 0.29). Accordingly, the fitted slopes with aggregates are gentler compared to those without aggregate. Thus, the aggregate application to emulsion retards the water evaporation process. AE-90S and CRS-2P had the smallest and the largest differences in slope between with and without aggregate among the emulsions, respectively.

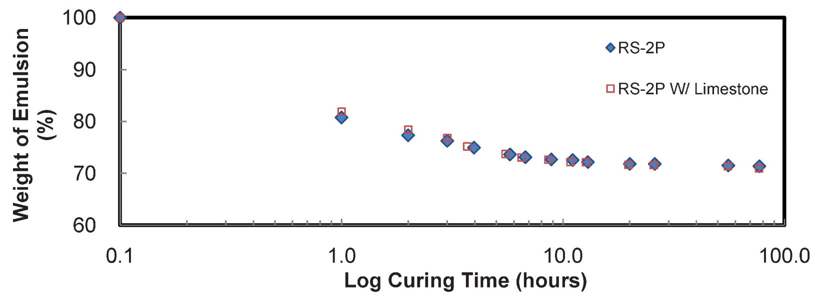
To evaluate the significance of slope difference, the cumulative probability of t distribution ($Pr > |t|$) were observed. In the case of AE-90S, the value of $<.0001$ represents that the probability of the parameter estimate for AE-90S being 0 is less than 0.01 % thus rejecting the null hypothesis of the parameter estimate being 0. This supports the plot shown in Figure 3.10, which clearly shows that the weight of the AE-90S specimen changes over time.

When the same analysis is applied to the case of AE-90S with Limestone application, it can be interpreted that $Pr > |t|$ of the parameter estimate being 0 is about 21.15 %. Thus, the slopes of AE-90S with and without Limestone application are not significantly different from each other. Also, the slopes of RS-2P with and without Limestone application are not significantly different from each other.

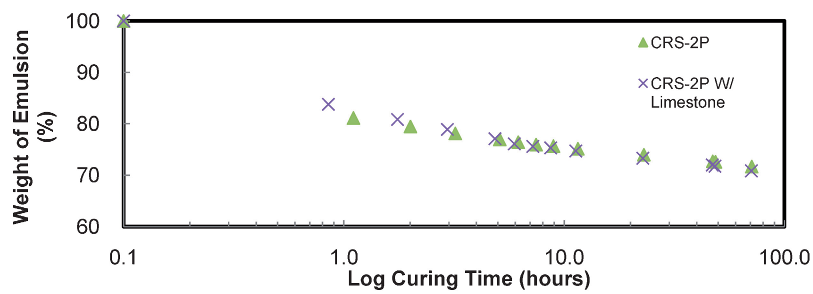
However, the $Pr > |t|$ of the parameter estimates of the CRS-2P specimen with Limestone is 0.04. In other words, the probability of the slope difference being 0 between specimens with and without Limestone is less than 4 %. Considering that 0.05 is generally used as the threshold value for determination of significance, the result can be interpreted thus: there is a significant difference between specimens with and without Limestone applications. Consequently, it can be concluded



(a)



(b)



(c)

Figure 3.10 Weight change characteristics of emulsions with and without Limestone: (a) AE-90S, (b) RS-2P; (c) CRS-2P

that the application of aggregate retards the water evaporation of CRS-2P.

Researchers also observe that the higher the electrostatic repulsion that exists between the Limestone and the emulsions, as shown in TABLE 3.6, the less effect the aggregate had on the water content change of emulsions; however, the effects for RS-2P and AE-90S are statistically insignificant. The Limestone with CRS-2P, having the weakest repulsion to each other among the three emulsion-Limestone combinations, presented the largest effect which was also the only statistically significant.

3.3.3 X-ray defflection test

Aggregates are commonly classified as either acidic or basic and hydrophilic or hydrophobic (32), while most asphalt is an acidic organic compound. Accordingly, the basic aggregate mixed with the acidic asphalt were expected to have stronger bonding or adhesion between aggregate and asphalt than the acidic aggregate mixed with the acidic asphalt. Furthermore, the basic aggregate with the acidic asphalt should have fewer water stripping problems due to the hydrophobic characteristics of aggregate (33). Hydrophobic aggre-

TABLE 3.7
Result of standardized linear regression model analysis

Emulsion Type	Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
AE-90S	W/O Limestone	1	-3.75517	0.16471	-22.80	<.0001
	W/Limestone	1	0.29641	0.23519	1.26	0.2115
CRS-2P	W/O Limestone	1	-2.75622	0.19837	-13.89	<.0001
	W/Limestone	1	0.59516	0.28738	2.07	0.0422
RS-2P	W/O Limestone	1	-2.30978	0.19338	-11.94	<.0001
	W/Aggregate	1	0.32781	0.27379	1.20	0.2350

TABLE 3.8
Chemical composition of aggregate from the XRD testing

	BF Slag	Steel Slag	Trap rock	CG One Face	Sand stone	Lime stone	CG Two Faces	Dolo-mite
Al_2O_3	13.85	5.31	15.50	4.12	3.87	0.80	4.87	0.48
CaO	34.10	26.28	9.02	23.03	13.76	57.98	15.57	31.20
Cr_2O_3	0.00	0.95	0.03	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	0.20	37.96	7.12	2.15	0.87	0.30	1.87	0.35
K_2O	0.47	0.00	0.80	0.84	1.14	0.13	1.05	0.05
MgO	11.14	11.74	7.05	9.81	1.38	2.04	7.07	21.88
Mn_2O_3	0.42	4.93	0.19	0.05	0.01	0.00	0.05	0.03
Na_2O	0.21	0.00	2.21	0.69	0.00	0.00	0.89	0.00
P_2O_5	0.00	0.61	0.08	0.04	0.02	0.00	0.04	0.00
SO_3	0.30	0.10	0.03	0.04	0.03	0.08	0.01	0.01
SiO_2	35.20	10.85	50.98	33.71	67.11	4.28	51.62	0.38
SrO	0.05	0.00	0.02	0.03	0.02	0.05	0.02	0.02
TiO_2	0.56	0.64	0.86	0.22	0.30	0.05	0.24	0.06
V_2O_5	0.00	0.14	0.04	0.00	0.00	0.00	0.00	0.00
ZrO_2	0.01	0.00	0.00	0.01	0.03	0.00	0.01	0.00
Total	96.48	99.43	93.94	74.72	88.40	65.57	83.30	54.39

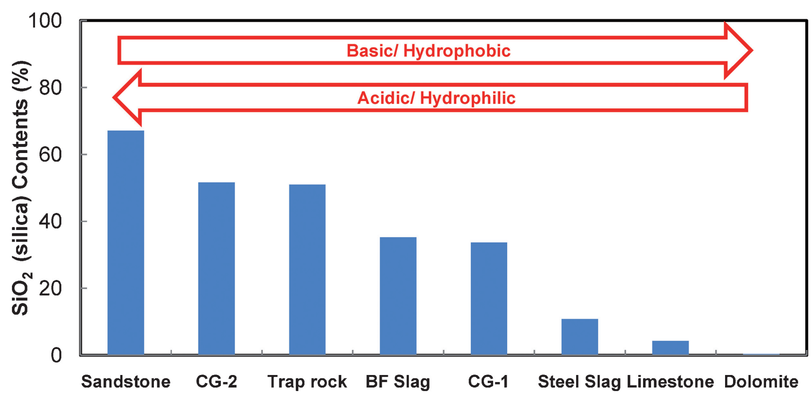


Figure 3.11 Contents of SiO_2 in percentages

gates tend to have greater affinity for asphalt than water. Among the many chemical characteristics of each mineral, the silica (SiO_2) contents were often examined due to their effect on the acidity/basicity and water-affinity. This is because the surface of silica is commonly formed with OH^-, which is highly hydrophilic.

Based on the XRD test results, the major chemical compositions of aggregates are SiO_2 for BFS, Trap Rock, Crushed Gravel, and Sandstone; Fe_2O_3 for Steel Slag; and CaO for BFS, Limestone, and Dolomite as shown in TABLE 3.8. As shown in Figure 3.11, Sandstone and Dolomite have the highest and smallest percent of SiO_2, respectively among the eight aggregates. The SiO_2 contents were within the typical range.

3.3.4 Absorption

Absorption of asphalt (emulsion residue) is a factor used to design the emulsion application rate. Many reports that fail to recognize this fact and correct for it can lead to excessive aggregate loss due to a lack of embedment (13). While controversial, researchers expect that aggregates with higher absorption would have better aggregate loss performance due to the wider surface contact area between the emulsion and aggregate.

The Rice method (ASTM D 2041) can measure the amount of asphalt absorption (34). However, the method is not applicable to emulsion absorption due to limitations, including differences in the mixing process between seal coat and hot-mix asphalt; weight change during curing; uncontrollable mass loss during the mixing process, etc. As a result, the water absorption

TABLE 3.9
Water absorption of aggregates

Aggregates	Absorption (Mass-based) [%]	Absorption (Volume-based) [%]
Trap rock	0.49	1.42
Limestone	1.25	3.34
Dolomite	1.29	3.50
Sandstone	1.43	3.70
Steel Slag	1.45	5.09
Crushed Gravel (one face)	1.57	4.11
Crushed Gravel (two faces)	2.09	5.39
Blast Furnace Slag	3.99	9.46

TABLE 3.10
Aggregate loss measured in percentage from the sweep test at various curing time

	Curing Time (hours)					
	1.5	3	5	10	16	24
CRS-2P	10.16	7.24	0.46	0.0	-	-
RS-2P	F	F	F	4.38	0.41	0.37
AE-90S	F	F	F	F	2.06	0.79

was used instead while assuming that aggregates having higher water absorption would absorb more emulsion. The water absorption tests with two replicates were conducted in accordance with AASHTO T 85. The average absorptions are summarized in TABLE 3.9.

It should be noted that the absorption values in the table are mass based, while aggregates have different specific gravities of their own. Therefore, the absorptions, which were converted based on the volume, are also presented in TABLE 3.9. Trap Rock showed the lowest absorption and Blast Furnace Slag showed the highest absorption, which confirmed that sedimentary aggregates such as Limestone can absorb more water than igneous aggregate such as granite or Trap Rock (13).

3.3.5 Sweep test with various curing time

The short-term performance of a seal coat is important especially in planning the opening of traffic and brooming application since early opening or

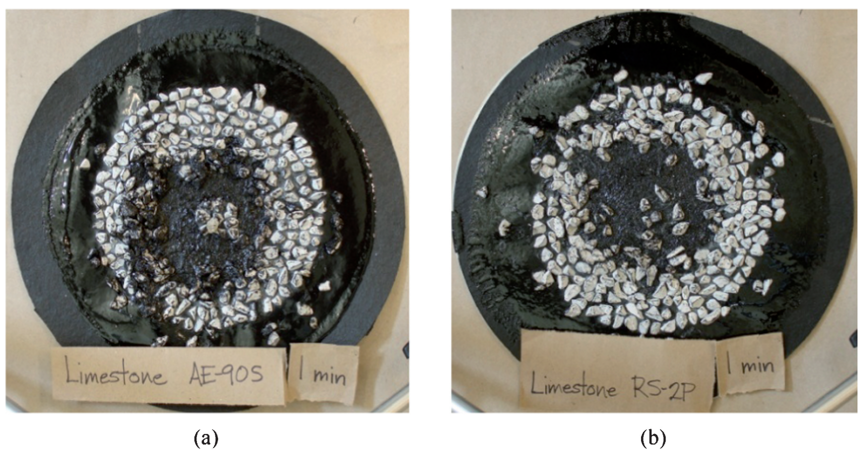


Figure 3.12 Failure by excessive loss of aggregates with 3 hours of curing after one minute sweep test (a) AE-90S and (b) RS-2P

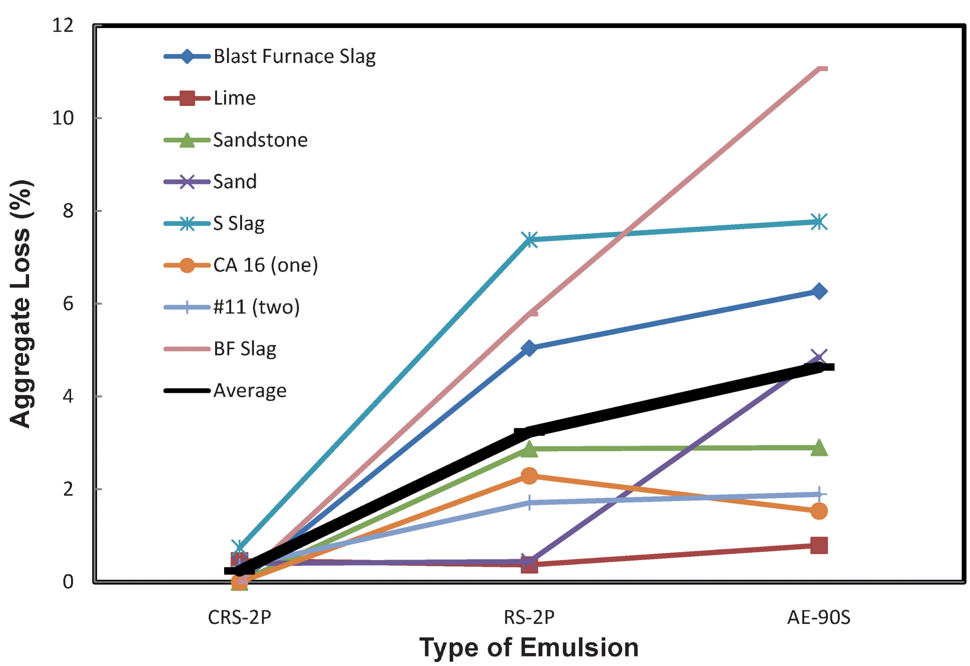


Figure 3.13 Aggregate loss performance of emulsions by sweep test (24 hours curing)

brooming without ensuring proper adhesion between aggregate and emulsion will cause failure of the entire seal coat application. Furthermore, the asphalt area exposed by the aggregate loss is tracked by the vehicles and causes bleeding failure which results in friction reduction.

The INDOT Standard Specification specifies that "the seal coat shall be protected by the restriction of traffic or by controlling traffic speed until the asphalt material has cured or set sufficiently to hold the cover aggregate without displacement." To address the restrictions, it is specified that the broom should be applied on the day following placement (INDOT Standard Specification, 2010). Thus, the sweep tests, which simulate brooming action, were conducted to quantify the aggregate loss performance for each emulsion with Limestone while varying curing times.

The sweep test results are summarized in TABLE 3.10. Aggregate loss is presented as a percentage loss, calculated using the equation presented in Chapter 3.2.4. F represents the failure, which was defined as exhibition of aggregate loss more than approximately 20 %. Examples are shown in Figure 3.12. The main reason for this type of failure is a result of the brush attached to the testing machine. The brush not only sweeps the aggregates, but also tracks the uncured emulsion. The emulsion then adheres to the brush which accelerates aggregate loss. As a result, the aggregate particles in the middle of the specimen are completely removed.

In general, the most aggregate loss occurred with shorter curing times as shown in TABLE 3.10. However, CRS-2P showed superior aggregate loss performance as it did not exhibit any failure regardless of curing time. On the other hand, RS-2P and AE-90S required 10 and 16 hours of curing time, respectively, to reach a point which did not yield failure. Specifically, AE-90S took almost 14 hours longer than CRS-2P before it started to exhibit almost no aggregate loss performance. This aggregate performance behavior is

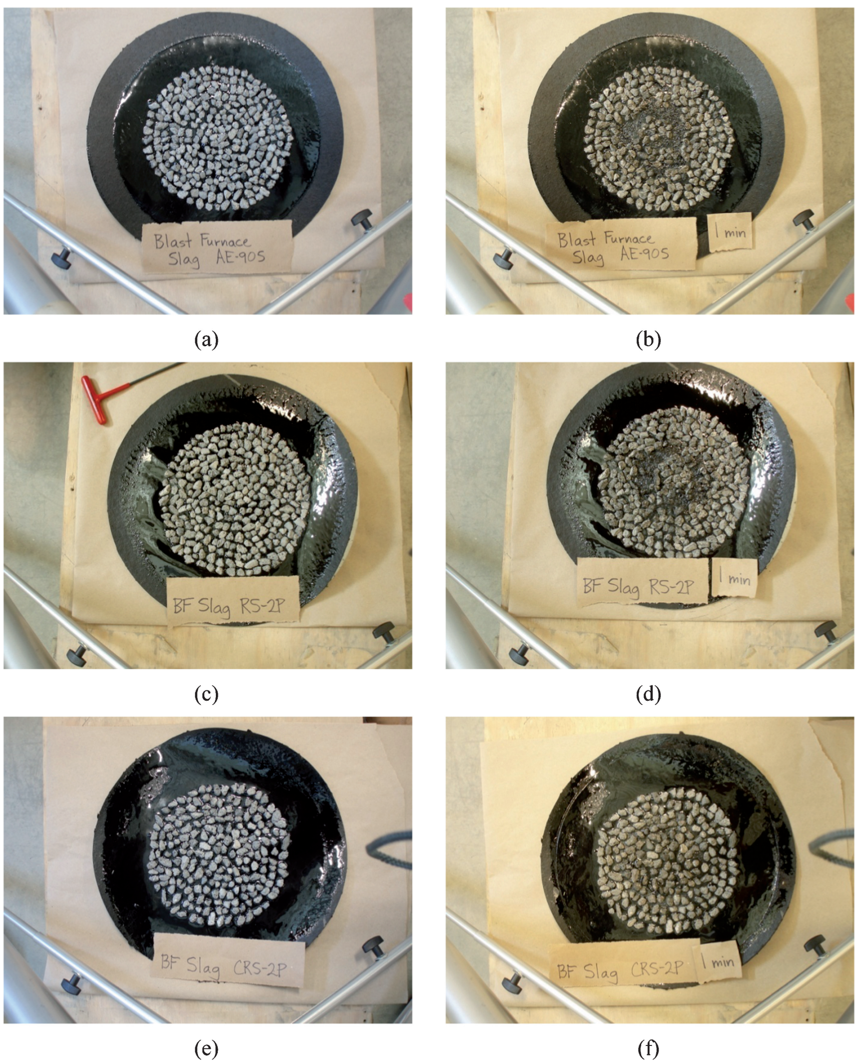


Figure 3.14 Sweep test results with AE-90S, RS-2P, and CRS-2P with Blast Furnace Slag: (a) prior to test; (b) after one minute sweep; (c) prior to test (d) after one minute sweep; (e) prior to test; and (f) after one minute sweep

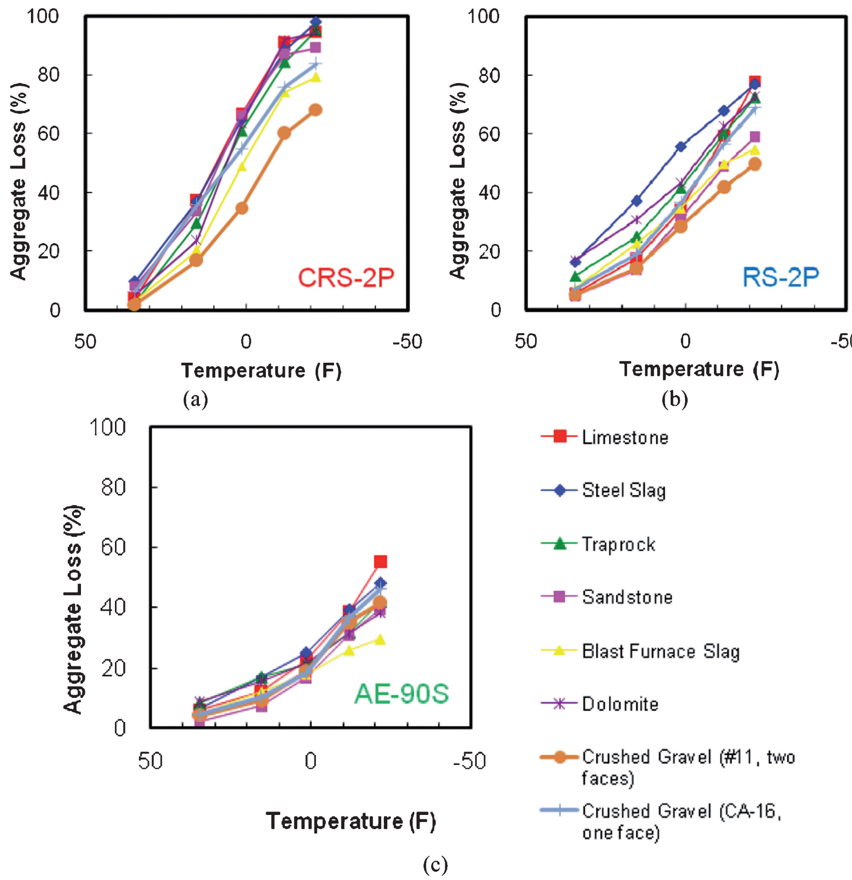


Figure 3.15 Aggregate loss performance of emulsions by Vialit test: (a) CRS-2P; (b) RS-2P; (c) AE-90S

similar to the water content change of emulsions shown in Figure 3.9. The faster the water contents of emulsion, the less aggregate loss it exhibited. Specifically, CRS-2P showed the fastest water evaporation and the best performance among the three emulsions.

3.3.6 Sweep test after 24 hour curing

The sweep tests were conducted at the fully evaporated state (24 hours curing) of the seal coat specimens to quantify the aggregate loss performance using 24 combinations of aggregates and emulsions as shown in Figure 3.13.

Based on the test results, Limestone had the best aggregate loss performance among the aggregates. On the other hand, Steel Slag and Trap Rock showed relatively poor performance. Additionally, Crushed Gravels shows relatively good performance. There was no significant effect of the number of cut-faces on the sweep test results. Blast Furnace Slag was the most sensitive aggregate type in the test results. Figure 3.13 shows the sweep test results of Blast Furnace Slag.

The aggregate embedment depth into the emulsion mainly represents emulsion application rate. The higher application rate implies a deeper embedment depth of aggregates. It was noted that the different aggregate embedment depths due to different residues were applied to the sweep test specimens. During the sweep test specimen fabrication process, the volume of applied emulsion was controlled using a template and a strike-off; thus, constant emulsion volumes were applied to each specimen. However, different amounts (volume) of residue remained on each specimen after 24 hours of curing since each type of emulsion had different residue contents which also caused various embedment depths of aggregates. As indicated in the previous chapter, the residue contents of each emulsion were 62 %, 65 %, and 69 % for AE-90S, CRS-2P, and RS-2P, respectively. Accordingly, aggregate with RS-2P and AE-90S had the highest and lowest embedment depths upon reaching the state where water in the emulsion was fully evaporated. Therefore, assuming that embedment depth is a major factor affecting aggregate loss performance, it can be expected that RS-2P and AE-90S show the least and the most aggregate loss, respectively. However, the sweep test results revealed that CRS-2P outperformed both RS-2P and AE-90S, regardless of the type of aggregates used. In general, RS-2P performed slightly better than AE-90S.

3.3.7 Vialit test

One of the major causes of seal coat failure is aggregate loss at low temperatures. When the temperature decreases, a seal coats shrinks. As the temperature

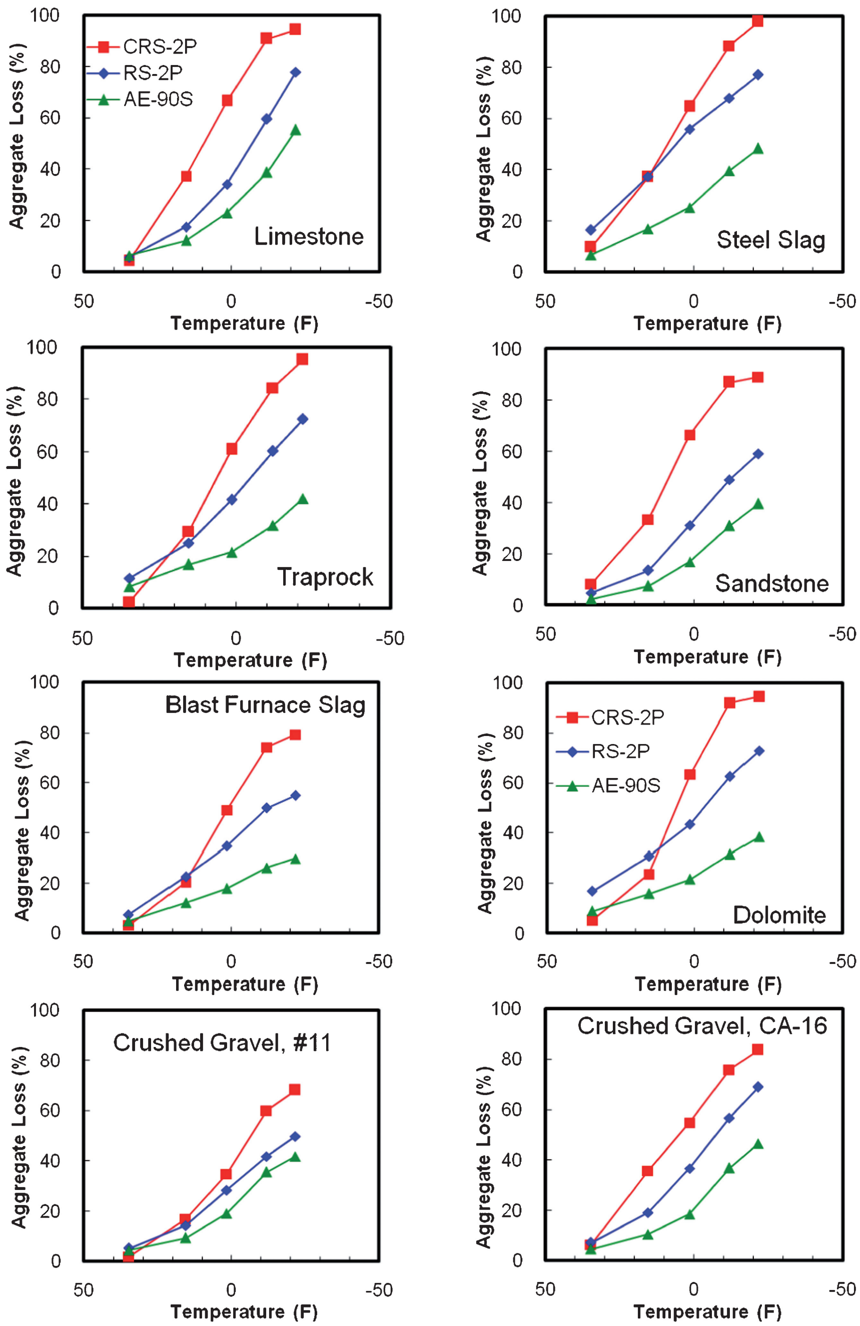


Figure 3.16 Aggregate loss performances of aggregates by Vialit test

drops, the asphalt contracts to a much greater degree than the aggregate, causing thermal stresses to develop in the seal coat. When these stresses exceed the tensile strength (adhesion) between aggregate and asphalt, micro cracks are initiated at the asphalt-aggregate interface.

In this state, asphalt is too weak to retain the seal coat aggregate with the impact of vehicle trafficking. Furthermore, impacts from snow plow blades in the winter season can also cause severe aggregate loss.

To evaluate aggregate loss performance at low temperatures, the Vialit test was conducted for all 24 combinations of aggregates and emulsions (i.e., combinations comprised of three emulsions with eight aggregates) at 35˚F, 16˚F, 2˚F, -12˚F, and -22˚F using seal coat specimens that had cured for 24 hours. The test results, as shown in Figure 3.15, reveal that most aggregate loss occurred as the testing temperature became lower, regardless of aggregate and emulsion types. Steel Slag showed the worst performance in general. The Crushed Gravel with two faces shows the best performance with RS-2P and AE-90S. When the two types of crushed gravel were compared to each other, the Crushed Gravel with two faces outperformed that with one face.

Figure 3.17 Vialit test results with AE-90S and Limestone at various testing temperatures: (a) prior to test; (b) 32 ℉; (c) 16 ℉ (d) 2 ℉; (e) -12 ℉; and (f) -22 ℉

TABLE 3.11
Factors used in the aggregate-emulsion combination model

Name of Factor	Levels	Values
Emulsion	3	AE-90S, RS-2P and CRS-2P
Aggregate	8	Trap rock, Sandstone, Blast Furnace Slag, Steel Slag, Limestone, Dolomite, Crushed Gravel (one face) and Crushed Gravel (two faces)
Temperature	6	77 ℉, 32 ℉, 18.5 ℉, 5 ℉, -8.5 ℉ and -22 ℉.

TABLE 3.12
Aggregate loss least square means of each combination of emulsion and aggregate

Emulsion Type	Blast Furnace Slag	Crushed Gravel (2-faces)	Crushed Gravel (1-face)	Dolo-mite	Lime Stone	Sand Stone	Steel Slag	Trap Rock
AE-90S	**16.99**	18.68	19.69	19.81	22.73	17.02	24.03	21.11
CRS-2P	37.64	30.33	42.72	46.41	48.93	47.41	49.75	45.44
RS-2P	29.15	23.53	31.76	38.21	32.48	25.33	43.63	35.96

TABLE 3.13
Aggregate loss least square means of emulsions

CRS-2P	RS-2P	AE-90S
43.58	32.63	**20.00**

When aggregate loss was compared considering emulsions as shown in Figure 3.16, aggregate loss performance differed by as much as 60 % at the lowest testing temperature (-22℉). AE-90S performed the best and CRS-2P showed the poorest performance, more apparent at the lower temperatures.

Another valuable finding was that aggregate loss performance among the three emulsions from the Vialit test showed an opposite trend compared to that from the sweep test. Specifically, CRS-2P outperformed other in relatively high temperature (sweep test), while AE-90S had the best resistance to aggregate loss among the three emulsions at lower temperatures. Selection of emulsion should be performance-based while considering the climate condition of the seal coat location.

3.3.8 Statistical analysis

The purpose of this chapter is to present the statistical analysis of the test results. As discussed in the previous chapter, the performance of each combination of aggregate and emulsion was evaluated by the sweep and Vialit tests in terms of aggregate loss. The relative performances among emulsions was clearly distinguished; AE-90S and CRS-2P revealed superior performances in the Vialit test (temperatures lower than 32 ℉) and the sweep test at 72 ℉ respectively. However, performance among aggregate was difficult to compare as it varied with temperature and the type of emulsion used, much less the performance of different combinations of emulsion and aggregate as a whole. Furthermore, it is appropriate to consider performance in both the sweep test and Vialit test in order to compare the performance of different combinations in various temperatures.

For the means of statistical analysis, two-way analysis of variance (ANOVA) test and standardized linear regression test were used, while focusing on the following objectives.

- To determine the best-performing emulsion-aggregate combination
- To determine the best-performing type of emulsion and aggregate

Aggregate-emulsion combination

The combined test results were analyzed using ANOVA test (also called a two-factor analysis of variance). The two-way ANOVA test was suitable for the experiments since it enabled the measurement of the effects of two factors, aggregates and emulsions, simultaneously. In addition, the two-way ANOVA was also able to assess the effects of both factors separately in the same test.

The total number of samples analyzed in the test was 384. There were three classes, namely emulsion, aggregate and temperature. Then each class was also categorized into three, eight and six categories, respectively, for emulsion, aggregate and temperature. Finally, a dependent variable was set to represent the aggregate loss of each corresponding combination of aggregate, emulsion and testing temperature. A summary of the factors used in the model is presented in TABLE 3.11.

The aggregate loss least square mean is shown in TABLE 3.12. The best-performing aggregate-emulsion combination was Blast Furnace Slag with AE-90S. However, it should be noted that most specimens made with AE-90S also provide similar performance results as compared to the best performed combination. In addition, another finding is that crushed gravel with two faces outperformed crushed gravel with one face regardless of emulsion types.

Emulsion and aggregate

Performance results of emulsions and aggregates were also separately analyzed adopting the same procedures as were used for the aggregate-emulsion combination analysis. The analysis results for emulsion and aggregate are summarized in TABLE 3.13 and TABLE 3.14, respectively. For aggregate loss square means of emulsions, AE-90S shows the best performance and CRS-2P presents the poorest performance. Among different type of aggregates, crushed gravel with two faces and Steel Slag are the best and poorest performing aggregates, respectively when aggregate performances were compared to each other without considering type of emulsions.

4 PERFORMANCE EVALUATION OF SEAL COAT DESIGN

This chapter evaluates seal coat field performance over a range of aggregate and emulsion application rates and proposes a design equation. The performance was measured and quantified using the International Roughness Index (IRI), friction, and surface condition

TABLE 3.14
Aggregate loss least square means of each type of aggregate

Blast Furnace Slag	CG One Face	CG Two Faces	Dolomite	Lime Stone	Sand Stone	Steel Slag	Trap Rock
27.93	**24.18**	31.39	34.81	34.72	30.26	39.14	34.17

evaluation prior to seal coat construction and after construction each year for a period of two years. Based on performance, an optimum application rate was determined, and accordingly, a new design was suggested.

4.1 Experimental program

The test road sections selected in this research included two state roads and one US highway. Different AAR and EAR were applied based on the design calculated by the McLeod design method. The materials used were AE-90S and Limestone.

4.1.1 Locations

The seal coat test roads were located on, US-421, SR-14, and SR-110 in the INDOT Winamac Sub-district near Winamac, Indiana, as shown in Figure 4.1. The Winamac Sub-district area has a humid continental climate and, like most cities in the Midwest, it has four distinct seasons. The rainiest months are in the spring, early summer, and fall. The Winamac climate, including average daily temperature, precipitation, and snow depth from July 1, 2008 to July 1, 2010, is presented in Figure 4.2. The test roads were selected as part of the Winamac Sub-district's normal sealing schedule. The Winamac Sub-district has three units. Each unit has roads that should be seal coated, and each unit receives its aggregate from a different source. Therefore, one road from each unit was selected for the evaluation. TABLE 4.1 summarizes the test road information, including reference posts and levels of average daily traffic (ADT). US-421 and SR-110 had the highest and lowest ADT, respectively. SR-14 and SR-110 were resurfaced in 2006, and US-421 was resurfaced in 2001.

4.1.2 Materials

The emulsion used in the study was AE-90S, a polymer-modified rapid setting emulsion, obtained from SEM Materials in Warsaw, Indiana. The aggregate used in this study was Indiana aggregate No. 12 size Limestone. Its nominal maximum aggregate size was No. 4 sieve size. Each test road used aggregate obtained from a different quarry. Aggregates used for US-421, SR-14, and SR-110 were from Vulcan Materials in Monon, Indiana, Engineering Aggregate in Logansport and Rock Industries in Peru, Indiana,

Figure 4.1 Location of evaluation roads

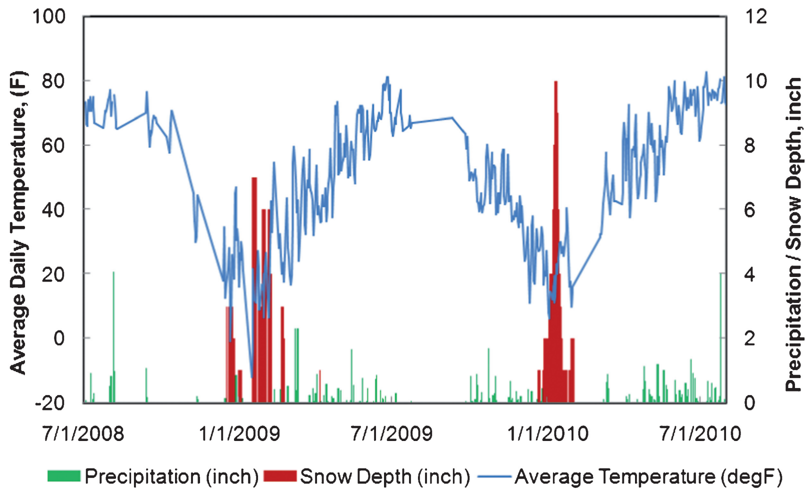


Figure 4.2 Climate condition of Winamac (The Indiana State Climate Office)

TABLE 4.1
Test road information

Road	From RP	To RP	Location		Sub District	ADT	ADT Year
SR-14	39.0	43.0	From SR-39	LaPorte	Winamac	2300	2002
US-421	201.0	206.0	SR-8 to SR-10 North	LaPorte	Winamac	4000	2007
SR-110	3.0	7.0	From SR-17	LaPorte	Winamac	1000	2007

respectively. Their gradations and physical properties are summarized in TABLE 4.2 and TABLE 4.3. Detailed lab test results of the aggregate are also presented in Appendix 1.3.

4.1.3 Existing pavement condition

As of July 2008, the existing pavement surfaces were six years old on US-421 and two years old on both SR-14 and SR-110. The US-421 surface showed moderate to high severity of aging and cracking, while most cracks were sealed in accordance with INDOT Performance Standard Activity 207, Filling Cracks. SR-14 and SR-110 were light to moderately aged and cracked. All cracks were also sealed in accordance with INDOT Performance Standard Activity 207, Filling Cracks. The existing pavement conditions of each road are shown in Figure 4.3, Figure 4.4 and Figure 4.5.

TABLE 4.2
Gradation of aggregates

Sieve Size	Percent Passing		
	US-421	SR-14	SR- 110
1/2″	100.00	100.00	100.00
3/8″	99.84	100.00	100.00
1/4″	94.15	91.26	90.21
No. 4	78.64	70.13	63.59
No. 8	30.73	8.86	16.53
No. 16	11.59	1.49	4.74
No. 30	4.33	1.26	3.01
No. 50	2.07	1.13	2.45
No. 100	1.42	0.99	2.14
No. 200	0.96	0.72	1.56

4.1.4 Application rate design

The McLeod design equations presented below were utilized to design the application rate for both aggregate and emulsion. Factors used for calculation and designed rates are presented in TABLE 4.4. In the design, a wastage factor of 10 % was used throughout each road. Average surface condition factors applied to the designs were 0.03 gal/yd^2 to reflect slightly porous and oxidized asphalt surface conditions on the test roads. It should be noted that the absorption value used for the calculation was based on a water absorption test of aggregates (AASHTO T85), not asphalt absorption.

The designed aggregate application rate (AAR) and emulsion application rate (EAR) for US-421 were the lowest among the three test roads due to the following reasons: 1) the smallest median aggregate size; 2) the lightest aggregate specific gravity from the lab test results; and 3) the least embedment depth (i.e., the least

TABLE 4.3
Aggregate Information

	US-421	SR-14	SR-110
Quarry	Volcan Materials	Engineering Aggregate	Rock Industries
Decant (%)	1.0	1.9	2.8
Bulk Specific Gravity	2.506	2.421	2.485
Water Absorption (%)	3.629	4.711	3.683

(a) (b)

Figure 4.3 SR-14 Existing Pavement Condition: (a) texture view; (b) road view

(a) (b)

Figure 4.4 US-421 Existing Pavement Condition: (a) texture view; (b) road view

(a) (b)

Figure 4.5 SR-110 Existing Pavement Condition: (a) texture view; (b) road view

ADT). Detailed McLeod design calculations for the three test roads are in Appendix 1.9.

$$AAR = 46.8(1 - 0.4V)HGE \qquad (4.1)$$

Where

AAR = aggregate application rate, lb/yd^2

V = voids in loose aggregate, expressed as decimal

H = average least dimension (ALD), in.

G = bulk specific gravity of aggregate

E = wastage factor for traffic whip-off

$$EAR = \frac{2.244HTV + S + A}{R} \qquad (4.2)$$

Where

EAR = emulsion application rate, gal/yd^2

H = average least dimension (ALD), in.

T = percentage of embedment depth of aggregate in emulsion (traffic correction factor), expressed as decimal

V = voids in loose aggregate, expressed as decimal

S = Surface condition factor, gal/yd^2

A = Aggregate absorption factor, gal/yd^2

R = percentage of residue of emulsion, expressed as decimal

4.1.5 Application rate modification

Each test road was divided into multiple one lane-mile evaluation sections. US-421, SR-14, and SR-110 contained seven, four and seven test sections, respectively. Various aggregate and emulsion application rates were applied based on the designed AAR and EAR as summarized in TABLE 4.5. Seal coast was first

TABLE 4.4
Factors used for McLeod design and designed application rates

	SR-14	US- 421	SR- 110
Median Particle Size [M, in.]	0.16	0.13	0.16
Flakiness Index [FI, %]	17.91	18.35	19.1
Avg. Least Dimension [H, in.]*	0.14	0.114	0.14
Loose Unit Weight [W, lb/ft^3]	88.84	87.52	82.64
Bulk Specific Gravity	2.421	2.506	2.469
Voids in Loose Agg. [V]**	0.412	0.44	0.464
Wastage Factor [E]	1.1	1.1	1.1
Traffic Factor [T]	0.6	0.6	0.65
Surface Correction Factor [S, gal/yd^2]	0.03	0.03	0.03
Absorption [gal/yd^2]	0.056	0.056	0.056
Residual of AE-90S [R]	0.66	0.66	0.66
AAR [C, lb/yd^2]	14.59	12.11	14.51
EAR [B, gal/yd^2]	0.25	0.23	0.27

*The average least dimension (H) is calculated with the median particle size (M) and the Flakiness Index (FI).

**The voids in loose aggregate is calculated with the loose unit weight and the bulk specific gravity of the aggregate.

applied on test sections of US-421 while varying AAR and EAR based on the designed values. SR-14 and SR-110 test section design values were refined based on the findings from the construction results of US-421.

4.1.6 Equipment and calibration

For the seal coat application, one aggregate spreader, three emulsion distributors, two pneumatic tire rollers and two brooms were used, as summarized in TABLE 4.6. Each distributor was only used for its specific application rate considering its capacity and consistency. The aggregate spreader was capable of applying a maximum width of 11 ft. If emulsions were applied to cover this width with the maximum emulsion application rate (0.35 gal/yd^2) in the experimental program, the 3,500-gallon distributors would have enough capacity to cover 1.55 lane-miles, which is longer than each test section, which spanned only one lane-mile. The 3,500-gallon distributor (64666) was used to apply a rate of 0.35 gal/yd^2. The 2,500-gallon distributors 64462 and 64185 applied 0.30 gal/yd^2 and 0.25 gal/yd^2, respectively. The distributors and aggregate spreader, shown in Figure 4.6, were calibrated at the Sub-district prior to commencing sealing operations on July 1, 2008.

TABLE 4.6
Equipment used for the seal coat application

Type of Unit	Quantity
Aggregate Spreader	1
3500 Gallon Emulsion Distributor*	1
2500 Gallon Emulsion Distributor**	2
Pneumatic Tire Roller	2
Self-Propelled Rotary Power Broom	2

*Distributor Number 64666

**Distributor Number 64185 and 64462

4.2 Performance evaluations

Performance evaluations were conducted in terms of three different measurements including international roughness index, friction number and surface condition evaluation.

4.2.1 International Roughness Index (IRI)

The International Roughness Index (IRI) and Profilograph Index (PrI) are the two most recognized indexes used to measure smoothness. These indexes reflect the pavement roughness that affects the driving public. INDOT (INDOT Specification 2010 Chapter

TABLE 4.5
Designed and target application rates for each test section

Road	Test section Code	RP From	RP To	Direction	Designed AAR/EAR	Target AAR/EAR
US-421	421-11/0.35	201	202	NB	12/0.23	11/0.35
	421-11/0.30	202	203.35	NB		11/0.30
	421-11/0.35	203.35	204	NB		11/0.35
	421-13/0.35	204	205	NB		13/0.35
	421-17/0.30	205	206	NB		17/0.30
	421-20/0.35	206	205	SB		20/0.35
	421-17/0.25	205	204	SB		17/0.25
SR-14	14-25.3/0.25	39	40	EB	15/0.25	20/0.25
	14-19.2/0.31	40	41	EB		20/0.30
	14-21.9/0.29	41	42	EB		22/0.30
	14-18.1/0.26	42	43	EB		17/0.25
SR-110	110-21.9/0.34	7	6	WB	15/0.27	22/0.33
	110-21.9/0.27	6	5	WB		22/0.30
	110-18.5/0.30	5	4	WB		20/0.30
	110-21.1/0.30	4	3	WB		20/0.28
	110-15.7/0.27	3	4	EB		18/0.25
	110-20.1/0.28	4	5	EB		18/0.28
	110-17.0/0.27	5	5.5	EB		16/0.25

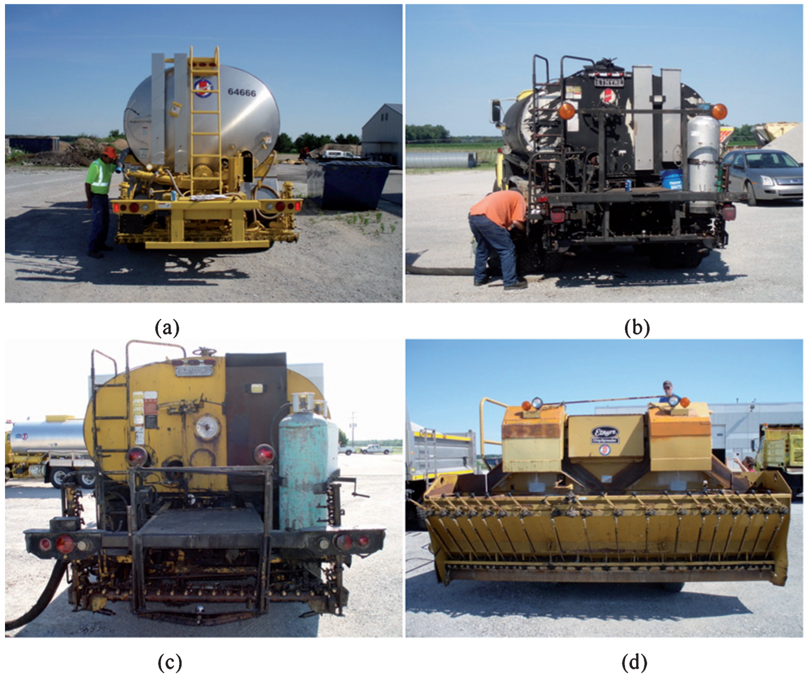


Figure 4.6 Seal coat equipment: (a) 64666 distributor; (b) 64185 distributor; (c) 64462 distributor; (d) aggregate spreader

401.22) currently provides both incentives and penalties for HMA constructions based on PrI requirements (3). To parallel the smoothness index with Mechanistic Empirical Pavement Design Guide (MEPDG) performance criteria, INDOT is currently conducting research regarding adopting IRI into the INDOT Specification.

One of the many software tools for calculating IRI, using a measured profile, is the Profile Viewing and Analysis (ProVAL) software. ProVAL is a product of joint research conducted by the US Department of Transportation, the Federal Highway Administration (FHWA), and the Long Term Pavement Performance Program (LTPP).

4.2.2 Friction

Pavement surface friction is one of the main factors that affect travel safety, particularly with wet road surface conditions. In addition, pavement surface friction has recently become one of the primary concerns in decision-making for pavement preventative maintenance. Many state highway agencies conduct pavement friction testing in accordance with ASTM E 274 using the standard rib tire. However, INDOT is one of the very few state highway agencies that utilizes the standard smooth tire because of its advantages in characterizing pavement surface friction and understanding wet pavement skidding accidents compared to testing with the rib tire. INDOT's current practice mandates that action is required for pavement having a friction number (FN) below 20 at 40 mph. The typical test frequency is four tests per mile.

4.2.3 Surface condition evaluation

The pavement distresses were evaluated by making visual observation on the first and last 50 ft. of each test section. The distresses investigated included aggregate loss, bleeding, excessive aggregate, delamination, streaking, reflected bleeding from crack sealing, and polishing. The observed distresses were scored on a scale ranging from 0 (excellent) to 10 (unacceptable) by evaluators. The evaluation sheet is in Appendix 1.12.

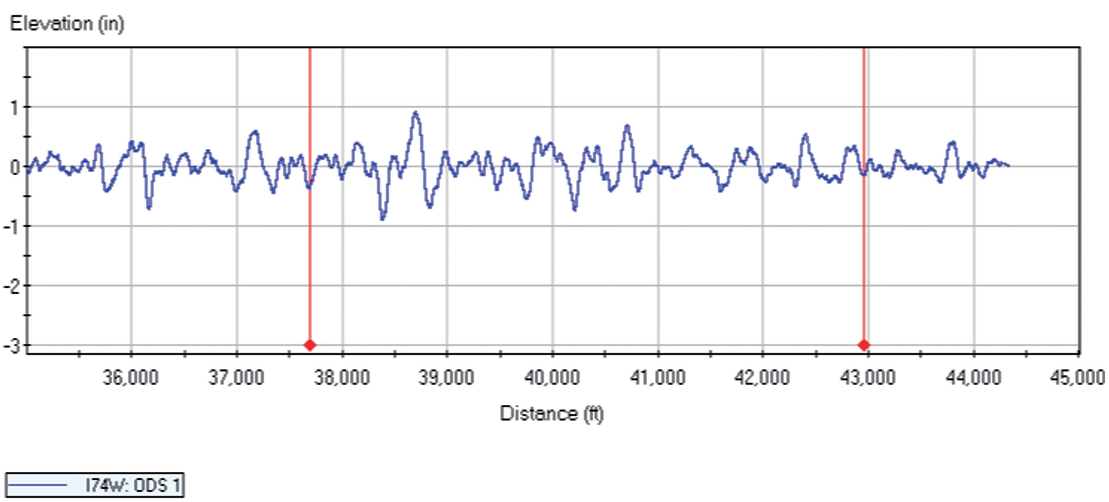
4.3 Seal coat constructions

4.3.1 US-421

The seal coat was first applied on the test sections of US-421 in this study. General information about the construction environment and time are summarized in TABLE 4.7 along with additional construction details for each section.

During construction of the first four sections, including 421-11/0.25, 421-11/0.30, 421-11/0.35 and 421-13/0.25, bleed-through was immediately observed upon application. As a result, all four sections were re-chipped with additional 11 lb/yd^2 aggregate. However, additional severe problems were reported from test sections 421-11/0.25 and 421-11/0.30, which were allowed to open for traffic within only one hour after application due to the fact that SR-49 (a parallel route) was closed and detoured onto US-421. It is believed that tires, traveling on the fresh seal coat of sections 421-11/0.25 and 421-11/0.30, picked up aggregates, resulting in exposure of bare emulsions to subsequent

(a)



(b)

Figure 4.7 INDOT Profiler: (a) Profiler; (b) example of profile data

Figure 4.8 INDOT friction test equipment

TABLE 4.7
Construction summary for US-421

Construction Time		July 14, 2008 07:35 AM	
Pavement Temperature		64 °F	
Emulsion Temperature		160 °F	
Traffic Condition		Construction sections reopened in 1 Hour	
Section	**AAR (lb/yd^2)**	**EAR (gal/yd^2)**	**Note**
421-11/0.35	11	0.25	Failed
421-11/0.30	11	0.30	Failed
421-11/0.35	11	0.35	Failed
421-13/0.35	13	0.35	Failed
421-17/0.30	17	0.30	-
421-20/0.35	20	0.35	Not Constructed
421-17/0.25	17	0.25	Not Constructed

traffic. As more tires traveled on emulsion-exposed sections, more aggregates were picked up by traveling vehicles. Consequently, the seal coats applied on the first four sections (421-11/0.25, 421-11/0.30, 421-11/0.35 and 421-13/0.25) had to be immediately removed by underbody snow plows, front mount plows, and broom blades. Upon removal of the applied seal coat, limestone sands were applied on the cleaned pavement to provide adequate traffic friction. While clearing was performed, US-421 was closed and traffic was detoured to SR-39. Due to this seal coat removal operation, the remaining test sections (421-20/0.35 and 421-17/0.25) were not constructed. Section 421-17/0.30 was the only section to survive on US-421 since the aggregate application rate was modified to be much higher than the designed rate. The removed sections were resealed in the fall of 2008. Accordingly, it should be noted that the US-421 test sections were eliminated in the seal coat performance database, which was used for developing a seal coat design equation, due to the failure.

The main cause of seal coat failure was the application rates of emulsion and aggregate. Sections 421-11/0.25, 421-11/0.30, and 421-11/0.35 had relatively low aggregate application rates and high emulsion application rates. The failures that occurred in these sections directly influenced the following sections since vehicle tires transferred aggregates from emulsion-exposed sections. From this failure it was found that aggregate loss in uncured emulsion can cause total failure of the following uncured sections through a chain reaction. A local failure can be caused by inadequate design, non-calibrated equipment, opening traffic on uncured seal coat, high truck traffic, etc.

4.3.2 SR-14

Seal coat construction on SR-14 was conducted on July 16, 2008, and the construction information is summarized in TABLE 4.8. To avoid the seal coat failure that was observed on US-421, the aggregate application rate for the test sections on SR-14 was modified to be much higher than the designed rate (i.e., 25.3 lb/yd^2 for a target AAR and 15 lb/yd^2 for a designed AAR).

4.3.3 SR-110

Seal coat construction on SR-110 was conducted on July 16, 2008, and the construction information is summarized in TABLE 4.9. Unlike the test section on SR-14, test sections on SR-110 were composed of both eastbound and westbound directions. Section 110–17.0/0.27 had a target rate closest to that of the design rate, 15 lb/yd^2 for AAR and 0.25 gal/yd^2 for EAR.

4.3.4 Seal coat application measurements

During the seal coat construction, the aggregate and emulsion application rates were measured using two different methods. One was the carpet method and the other was the gauge read method. The carpets, the size of a square yard, were placed on each test section, and then later measured for actual emulsion and aggregate application rates as shown in Figure 4.12. The details about the carpet method are in Appendix 1.13. The emulsion rates were also measured with reading gauges on the emulsion distributors prior to and after the application and converted to read the application rate (gal/yd^2). The actual emulsion and aggregate application rates are presented in TABLE 4.10. It should be noted that all of the test sections on US-421 were excluded from evaluation due to the fact that those test sections were deemed inappropriate for evaluation as explained in the construction section.

4.4 Test section evaluation

In order to represent the seal coat performance in accordance with each corresponding application rate, an IRI for smoothness, friction test for skid resistance, and visual evaluation for surface distresses were all conducted periodically between 2008 and 2010. Based on the results of these performance tests, the optimum application rate range was determined and is presented in the following chapters.

4.4.1 Snow plow and pavement temperature

The first one or two winters are a critical period during the typical life of a seal coat since seal coat which survives the initial seasons tend to fulfill its life span (e.g., four years in Indiana). In the winter, low temperatures and snow plow traffic are the main causes of damage and, shorten seal coat life. Accordingly, this research monitored winter temperatures and snow plow operation for the test roads. INDOT adopted a Maintenance Decision Support System (MDSS) in 2008, which helped with efficient resource management and decision making for snow and ice treatment. As part of the MDSS project, snowplow trucks recorded air and pavement temperatures during plowing operations beginning in 2008 and 2009.

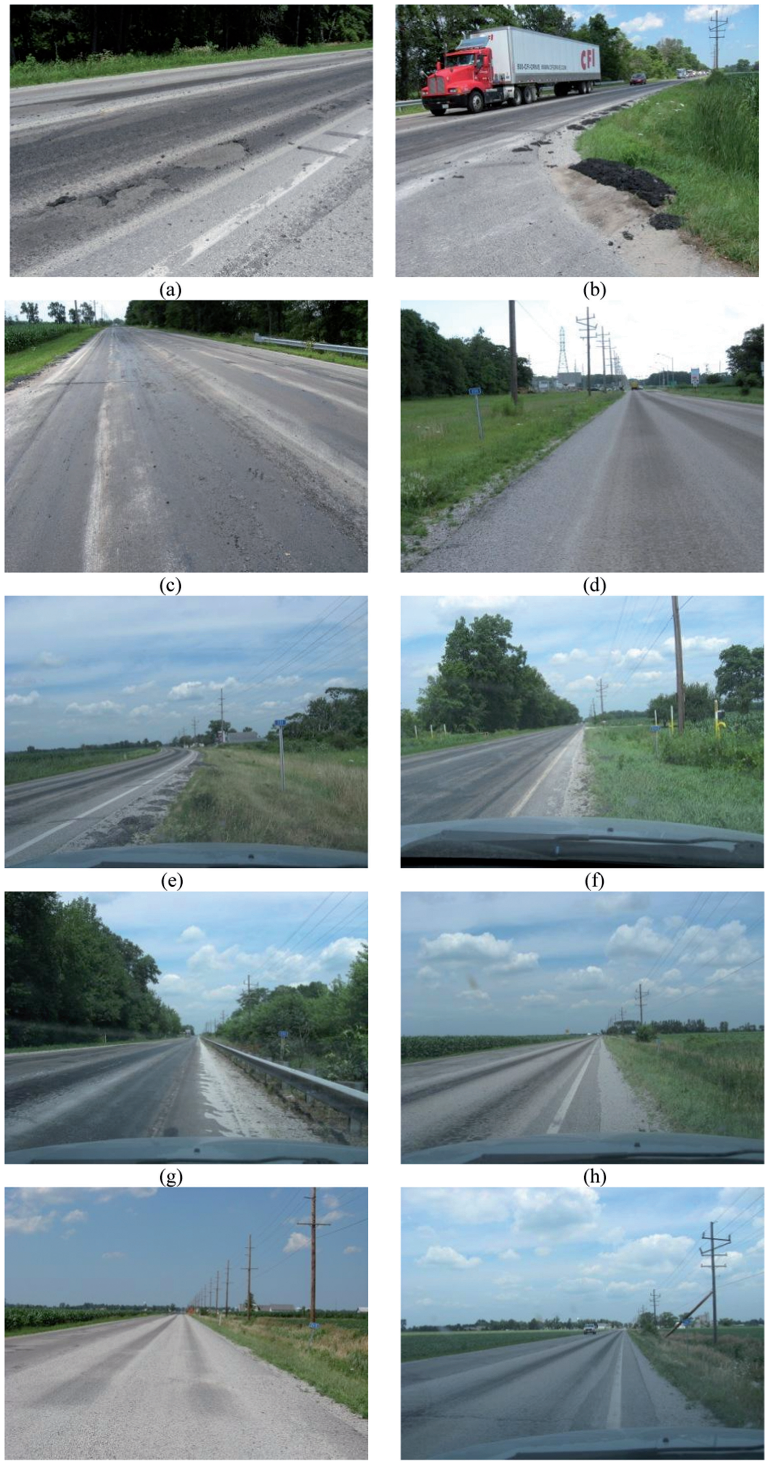


Figure 4.9 US- 421 pavement condition before seal coat application: (a) before plowing/scraping; (b) during plowing; (c) after plowing/scraping; (d) RP 200; (e) RP 201; (f) RP 202; (g) RP 203; (h) RP 204; (i) RP 205; (j) RP 206

The temperature data for SR-14 and SR-110 in Winamac, Indiana were collected from MDSS. While the focus of this research was to obtain air and pavement temperature data only when the snow plow operation occurred, the raw data from MDSS contained a wide range of temperature data. As a result, any temperature data over 40 ℉ was discarded due to the following reasons. First, an infrared thermometer takes a few minutes to adjust to a temperature swing, resulting from, for example, a truck leaving a warm garage. Second, it is unlikely for snowplow trucks to be operated when temperatures are above 40 ℉ since

TABLE 4.8
Construction summary for SR-14

Construction Time	July 16, 2008 07:20 AM
Pavement Temperature	80 ℉
Emulsion Temperature	160 ℉
Traffic Condition	Closed

section	AAR (lb/yd^2)	EAR (gal/yd^2)	Agg. Spreader Speed (ft./s)
14-25.3/0.25	20	0.25	350
14-19.2/0.31	20	0.30	320
14-21.9/0.29	22	0.30	-
14-18.1/0.26	17	0.25	-

TABLE 4.9
Construction summary for SR-110

Construction Time	July 29, 2008 09:30 AM
Pavement Temperature	81 ℉
Emulsion Temperature	160 ℉
Traffic Condition	Closed

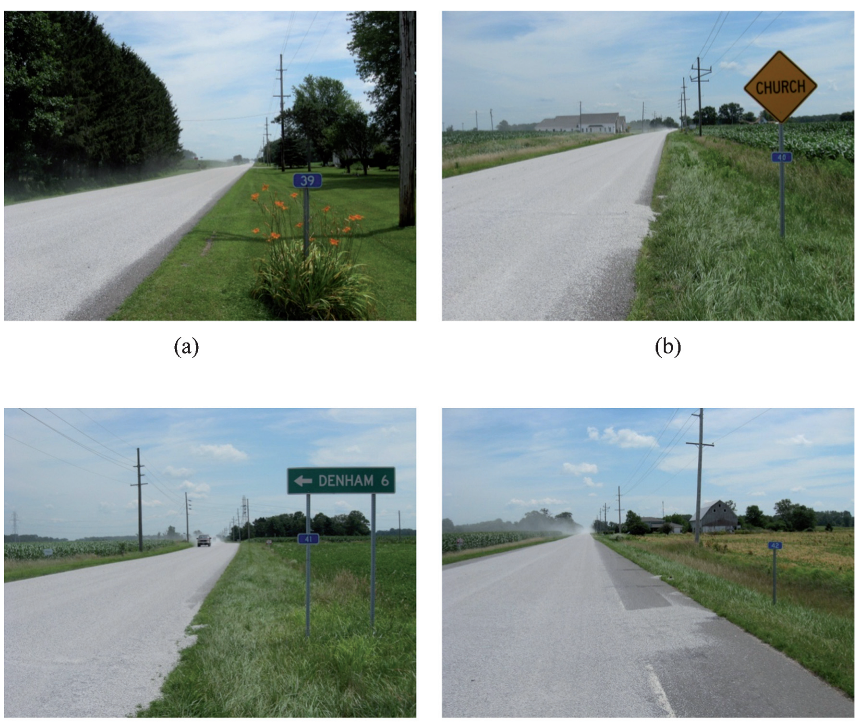
Section	AAR (lb/yd^2)	EAR (gal/yd^2)
110-21.9/0.34	22	0.33
110-21.9/0.27	22	0.30
110-18.5/0.30	20	0.30
110-21.1/0.30	20	0.28
110-15.7/0.27	18	0.25
110-20.1/0.28	18	0.28
110-17.0/0.27	16	0.25

at that temperature most snow on the pavement is assumed to have melted away. A summary of the temperature data obtained is presented in TABLE 4.11.

There are four snow routes, 4614, 4631, and 4616 and 4627, which cover the test sections on SR-14, US-421, and SR-110, respectively (the last two snow routes correspond to SR-110). Although each snow route consisted of various segments of multiple roads, the number of man-hours spent plowing the test sections could be obtained by a ratio of test road length to total mileage of each corresponding snow plow. However, man-hours spent for the test sections were not related to the number of passes made by a plow during operation. As a result, the number of passes each plow made was obtained based on the knowledge that each route takes about two hours for completion, and every section in each route was covered in each pass. For the SR-110 test sections, where two snow routes covered different portions of test sections, a larger number of passes made between two routes was selected. TABLE 4.12 summarizes man-hours spent on each test section and the number of passes made for FY 2009 and FY 2010 snow plow operation.

4.4.2 IRI

Test section profile data was acquired before construction in 2008 and again after construction in the following years 2009 and 2010. Data was analyzed using ProVAL (Version 3.03.0091) with the IRI selected



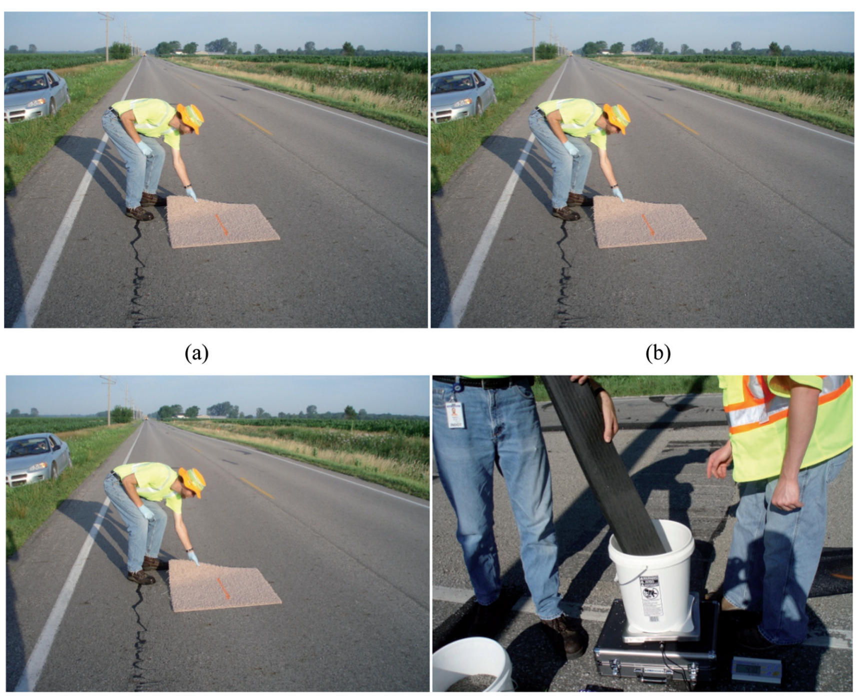
(a) (b) (c) (d)

Figure 4.10 Pictures of SR-14 on construction day: (a) RP 39; (b) RP 40; (c) RP 41; (d) RP 42

Figure 4.11 Pictures of SR-110 on construction day

TABLE 4.10
Test section summaries

Road	Test section Code	Target AAR/EAR	Measured AAR	Measured EAR	Gauged EAR
SR- 14	14-25.3/0.25	20/0.25	25.3	0.25	0.25
	14-19.2/0.31	20/0.3	19.2	0.29	0.31
	14-21.9/0.29	22/0.3	21.9	0.29	0.29
	14-18.1/0.26	17/0.25	18.1	0.22	0.26
SR- 110	110-21.9/0.34	22/0.33	21.9	0.35	0.34
	110-21.9/0.27	22/0.3	21.9	0.30	0.27
	110-18.5/0.30	20/0.3	18.5	0.30	0.30
	110-21.1/0.30	20/0.28	21.1	0.29	0.30
	110-15.7/0.27	18/0.25	15.7	0.24	0.27
	110-20.1/0.28	18/0.28	20.1	0.28	0.30
	110-17.0/0.27	16/0.25	17.0	0.27	-



(a) (b)

(c) (d)

Figure 4.12 Carpet test: (a) prior to emulsion application; (b) after emulsion application; (c) prior to aggregate application; (d) after aggregate application

TABLE 4.11
Actual air and pavement temperatures with snow plow operation

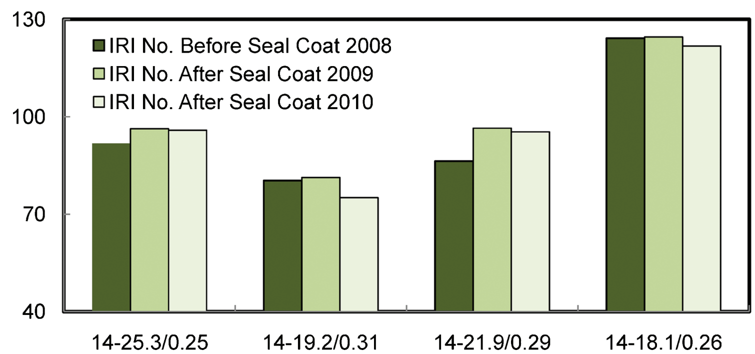
Temperature	Air Temperature [°F]	Pavement Temperature [°F]
Minimum	-13	-21
Maximum	39	32
Mean	23.11	22.37
Median	24	24
Standard Deviation	8.5	7.4
No. of Data	23153	29007

as pro-processor along with 10 in. (250 mm) moving average. The test results are summarized in Figure 4.13, in which units are reported as in/mile.

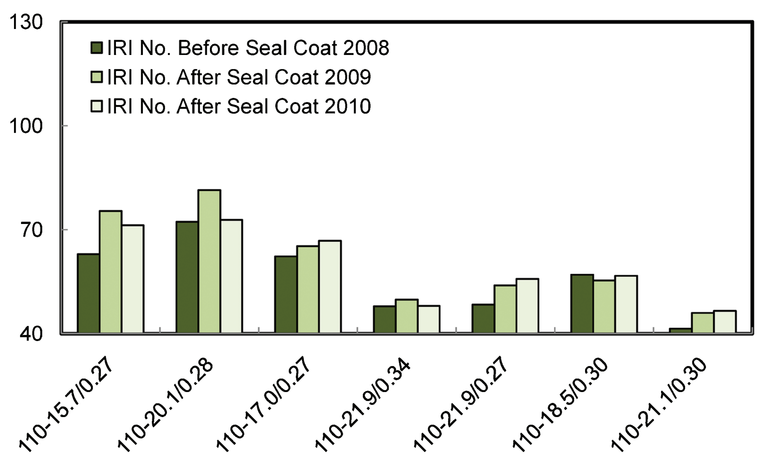
In general, the IRI of SR-110 was lower than that of SR-14. IRIs increase slightly in 2009 after seal coat applications. IRIs on SR-14 decreased in 2010 compared to the IRI values of the previous year. Additionally, changes in IRI values in each year were limited to a maximum of around 10 %. It is known that a seal coat does not improve the IRI due to its thin coat and the limitation of the IRI measurement. In detail, seal coat aggregate particle size from a major portion of aggregates used in the study (Indiana aggregate No. 12) is 0.094 in. (sieve No. 8) as shown in TABLE 4.2. The IRI is calculated using the 10 in. (250 mm) moving average filter with a profile collected by a sampling space of 3 in., which cannot properly read the very subtle profile change created by application of a seal

TABLE 4.12
Summary of snow plow passes and man-hours for each test section

				Actual		Proportional	
Road	From RP	To RP	Snow Route	Man-hours	No. of Passes	Man-hours	No. of Passes
US-421	201.0	206.0	4631	521	261	492	246
SR-14	39.0	43.0	4614	526	263	463	232
SR-110	3.0	7.0	4616	435	218	482	241
			4627	405		392	



(a)



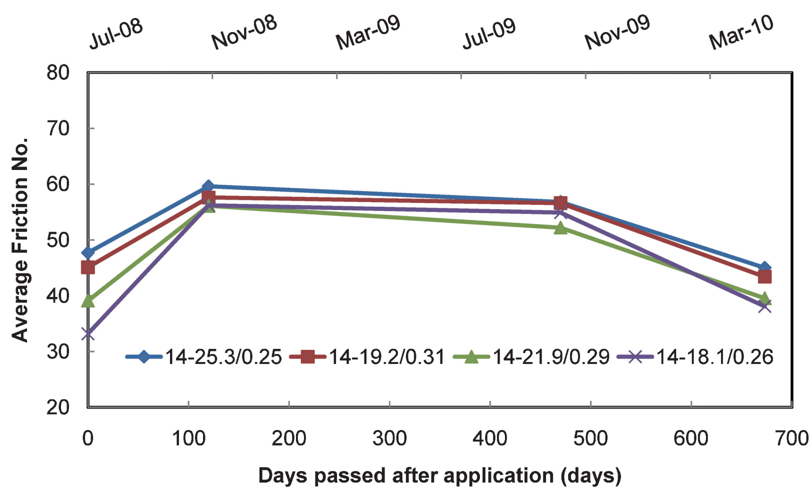
(b)

Figure 4.13 IRI test results: (a) SR-14; (b) SR-110 coat with a one-stone-thickness. The results from this study confirm the lack of correlation between seal coat application and IRI.

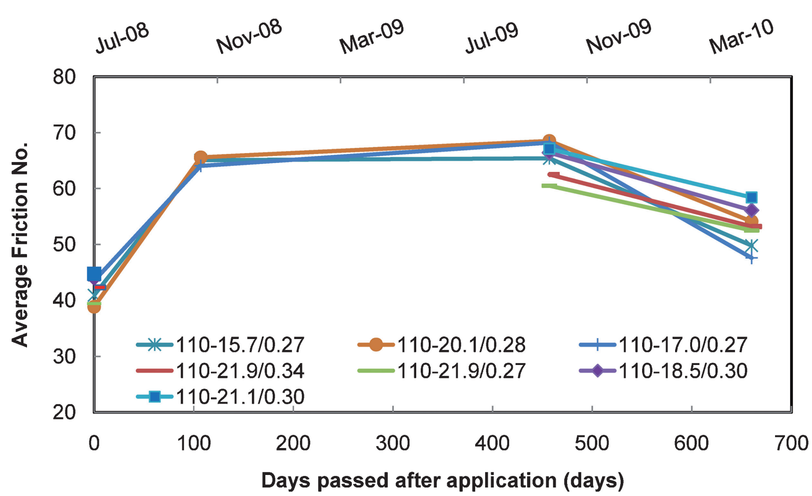
4.4.3 Friction

The first friction test was conducted on July 8, 2008, about a week prior to seal coat application. The friction tests on the test sections were measured in November 2008, after seal coat application and again in the following years, 2009 and 2010. Test results are summarized in Figure 4.14 and Figure 4.15. In general, most of the test sections prior to and after seal coating had either good or excellent friction numbers according to Figure 4.14. All friction numbers (FN) were above 20, which is INDOT's minimum FN requirement. The sections in SR-110 had higher FNs than those in SR-14. To evaluate FN improvements related to seal coat application, percent FN improvements were calculated by dividing the FN obtained in the following years by the FN measured prior to seal coating and are presented in Figure 4.14 Friction test results: (a) SR-14; (b) SR-110. There were improvements in FNs throughout all the test sections after seal coat applications. The improved FNs were maintained for approximately 500 days (passing the first winter season) and then reduced after passing the second winter. FNs in SR-110 decreased more slowly than those in SR-14. In general, FN improvement in SR-110 was greater than that in SR-14.

Aggregate application rate (AAR) and emulsion application rate (EAR) can be significant factors affecting the FNs of seal coats if the rates are inadequately designed. For instance, an acceptably high EAR can cause bleeding, resulting in a decrease of FN. Correlations between FNs and EAR were evaluated and their correlation factors (R^2) are shown in Figure 4.16. In addition, the volume ratio influence on the FNs was examined since the seal coat design optimizes the volumetric components of both the AAR and the EAR. To observe how much volumetric

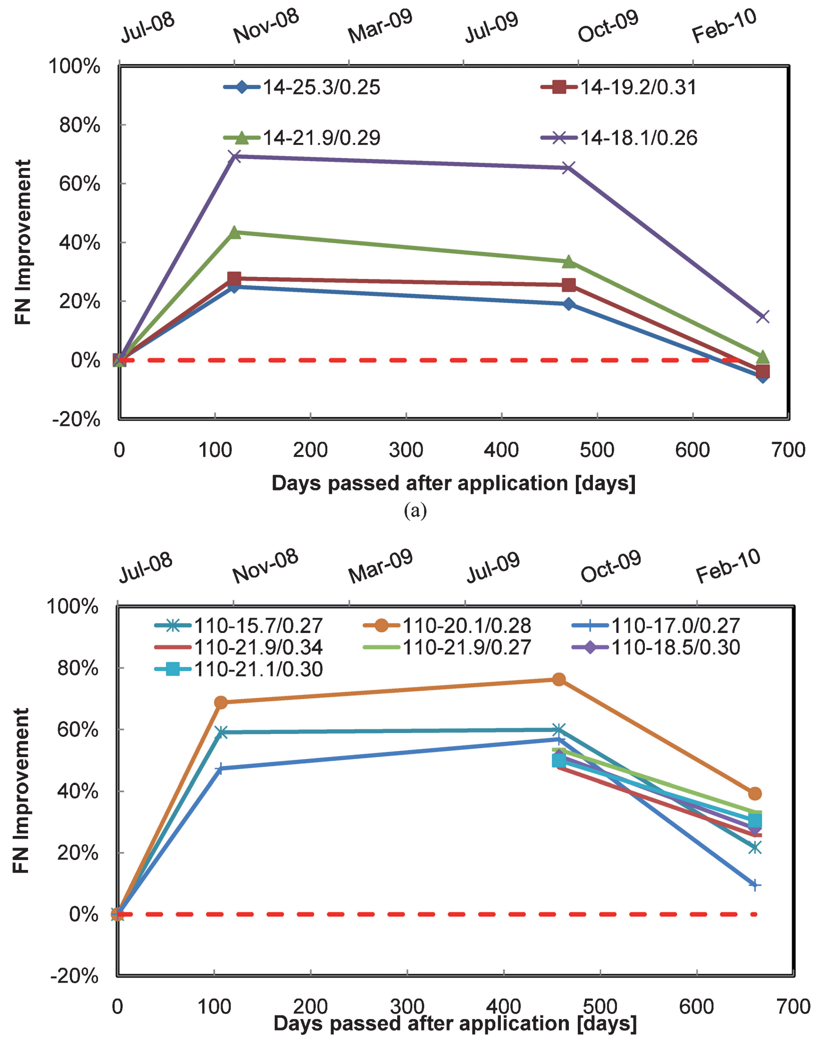


(a)



(b)

Figure 4.14 Friction test results: (a) SR-14; (b) SR-110



(a)

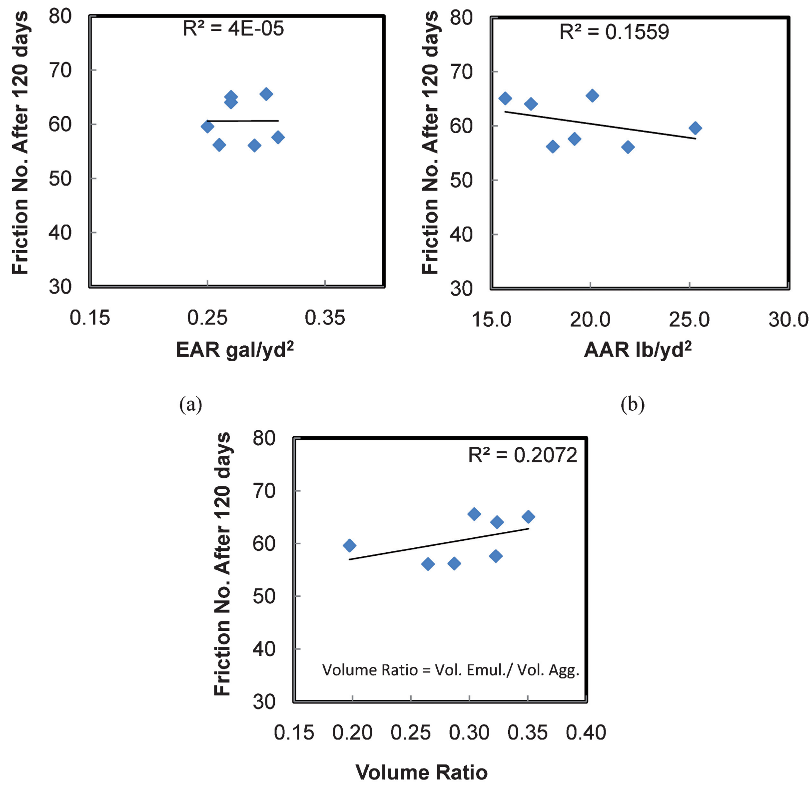
(b)

Figure 4.15 Friction improvements

ratio influences the FN, the volume ratios (ratio between applied emulsion volume and applied aggregate volume) of each section were calculated and compared with the FNs, as shown in TABLE 4.13. All correlation charts are also available in Appendix 1.14. At least within the ranges of both the AAR and the EAR used in this study, R^2 values presented in TABLE 4.13 illustrated that no significant influence was found from either the AAR/EAR or the volumetric ratio on FNs.

4.4.4. Visual observation

Visual observations were conducted by INDOT engineers after seal coat application. Each test section was subject to seven different distress types: aggregate, bleeding, excessive aggregate, delamination, streaking, reflected bleeding from crack seal, and polishing. In order to limit variations caused by having different individuals participate in the observation, two INDOT engineers consistently performed all examinations, except in 2008, in which an additional engineer was part of the inspection. Each test section was examined by the inspectors at each end of the section, while scores were given on a scale from 0 (excellent) to 10 (unacceptable). The scores obtained from the evaluators were averaged and are presented in Figure 4.17. All seal coats showed excellent performance, regardless of application rates during the observation period (i.e., overall scores were very low). The highest average score was 1.5. To identify the performance difference in terms of application rate, the volume ratios (ratio between applied emulsion volume and applied aggregate volume) of test sections were calculated and aggregate loss over the volume ratio is shown in Figure 4.18. All charts are available in Appendix 1.15. Based on observations made from Figure 4.17, Figure 4.18 and Appendix 1.15, it was determined that all sections performed well, and no clear performance difference was observed among the different test sections



(a) (b)

(c)

Figure 4.16 Correlations of friction: (a) EAR; (b) AAR; (c) volume ratio

TABLE 4.13
R^2 of correlation between rates and FNs

Days after Construction	120	470	673
AAR	0.0004	0.0462	0.1773
EAR	0.1559	0.1559	0.00005
Volume Ratio	0.2072	0.2786	0.0746

4.5 Analysis and discussions

4.5.1 Performance criteria

There are three categories describing seal coat failure: (a) immediate failure during construction; (b) short-term failure, which occurs after completion of construction prior to the first winter; and (c) long-term failure, which occurs after the first winter. In general, a seal coat surviving the first winter can be expected to have a typical life (e.g., four years in Indiana).

Immediate failure may occur during construction for several reasons, including inadequate materials, traffic volume, climate, improper equipment operation, poor design, etc. To prevent immediate failure, a seal coat design and specification should consider the above mentioned factors accordingly. The McLeod design method, which has been widely adopted in North America, addresses factors regarding materials, traffic volume, existing pavement condition, an excessive aggregate application rate. Among many factors affecting the performance of a seal coat, the excessive aggregate application rate (called wastage factor) is determined empirically and 10 % is typically assumed. This factor is considered to be critical for seal coat survival during construction.

The McLeod design calculates the EAR which is mainly based on the optimum embedment depth of aggregate and the amount of residue. The aggregate embedment depth in the residue of emulsion is represented as a function of traffic. Accordingly, a higher traffic volume generates a deeper aggregate embedment depth. In detail, the McLeod design assumes a seal coat to have a thickness, equivalent to median particle size oriented to lie on its flattest side, called the Average Least Dimension (ALD). The optimum embedment depth is then assumed to be 60 % - 85 % of the height of the ALD at a fully cured state of emulsion in terms of average daily traffic (ADT). As a result, a higher depth is expected upon application of a fresh emulsion in the construction stage, since a volume reduction from the emulsion to the residue due to water evaporation is typically 30 % - 40 % of the emulsion (e.g., approximately 34 % for AE-90S).

For instance, to have an optimum embedment depth (70 % for an ADT between 500 and 1000, as shown in Figure 4.19-(b), when AE-90S with 66 % residue content is used), all of the aggregate should be fully submerged with freshly applied AE-90S in the initial

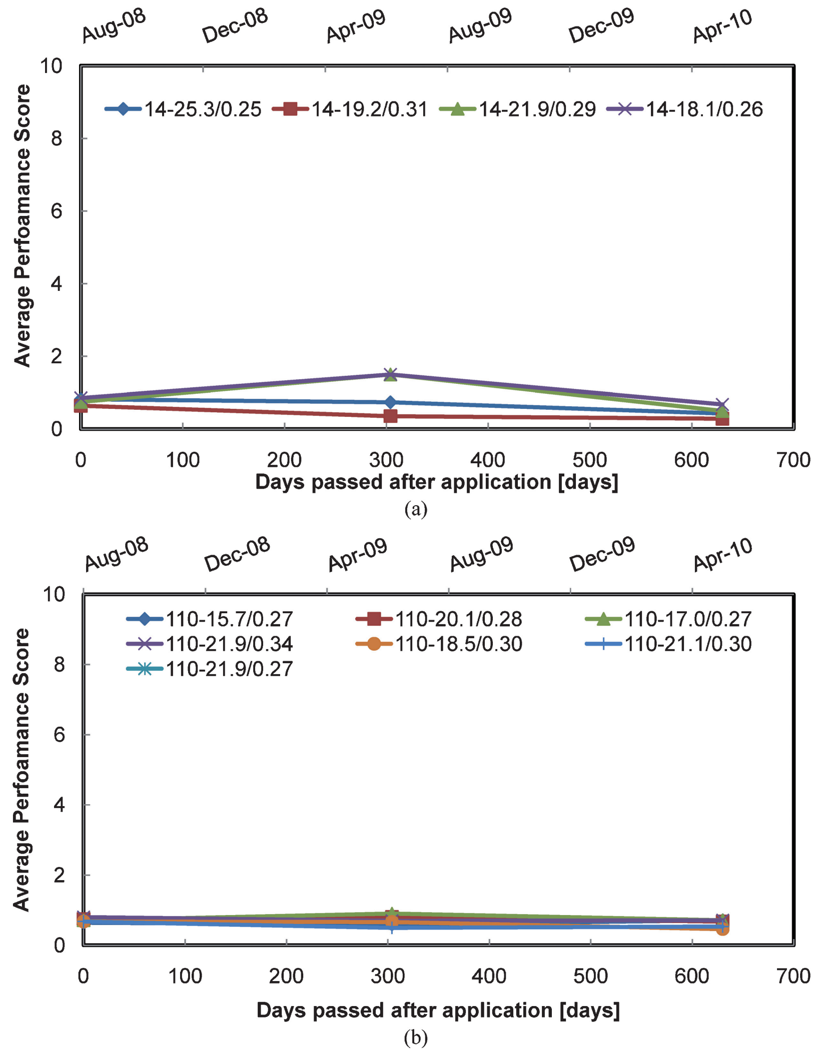


Figure 4.17 Visual observation results: (a) SR-14; (b) SR-110

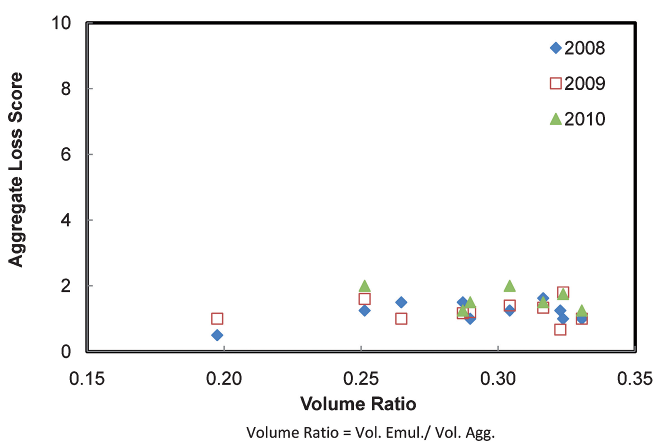


Figure 4.18 Visual observation result changes over volume ratio

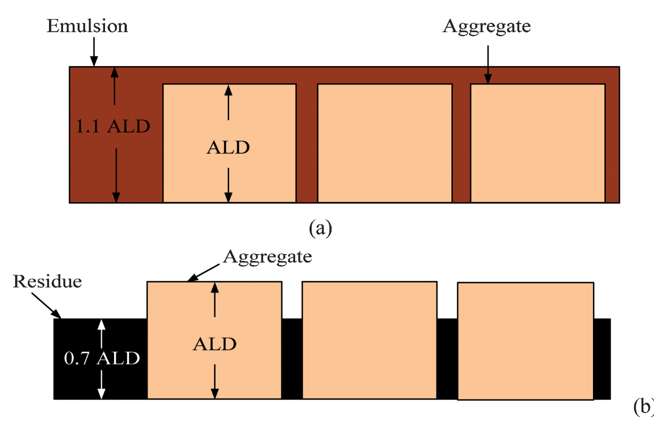


Figure 4.19 Embedment depth change: (a) fresh emulsion; (b) fully cured emulsion (residue)

seal coat construction stage with the EAR of 1.1 ALD, as shown in Figure 4.19 (a). An assumption made in this example is the aggregate has single size with a uniformly cubical shape (i.e., 0 % of Flakiness Index).

For Indiana No. 12 aggregate which is graded size for the seal coat application, 60 % of the aggregate can be fully submerged in the fresh emulsion. This fully submerged aggregate in the fresh emulsion can be found in

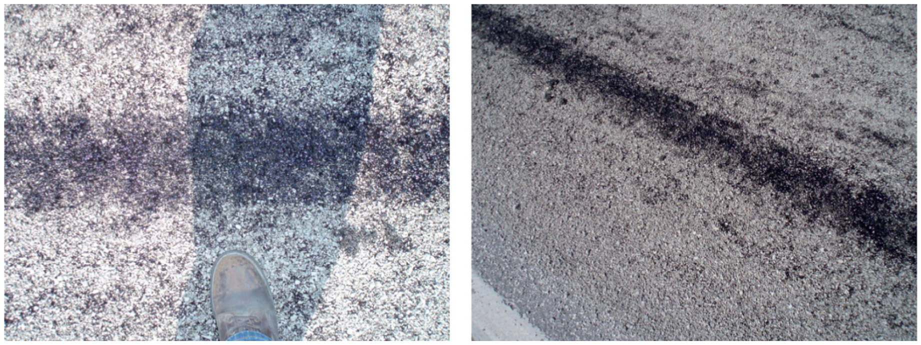


Figure 4.20 Immediate failure of seal coat

TABLE 4.14
Comparison between target and actual AAR

Test section Code	Aggregate Application Rate (lb/yd^2) Target	Actual (Measured)	Difference
14-20/0.25	20	25.3	5.3
14-20/0.31	20	19.2	-0.8
14-22/0.29	22	21.9	-0.1
14-17/0.26	17	18.1	1.1
110-18/0.27	18	15.7	-2.3
110-18/0.28	18	20.1	2.1
110-16/0.27	16	17.0	1.0
110-22/0.34	22	21.9	-0.1
110-22/0.27	22	21.9	-0.1
110-20/0.30	20	18.5	-1.5
110-20/0.30	20	21.1	1.1

TABLE 4.15
Emulsion application rate difference

Test section Code	Emulsion Application Rate (gal/yd^2) Target	Measured	Difference
14-20/0.25	0.25	0.25	0.00
14-20/0.31	0.30	0.31	0.01
14-22/0.29	0.30	0.29	-0.01
14-17/0.26	0.25	0.26	0.01
110-18/0.27	0.25	0.24	-0.01
110-18/0.28	0.28	0.28	0.00
110-16/0.27	0.25	0.27	0.02
110-22/0.34	0.33	0.35	0.02
110-22/0.27	0.30	0.30	0.00
110-20/0.30	0.30	0.30	0.00
110-20/0.30	0.28	0.29	0.01

the wheel path areas of an aggregate distributor if there are no excessive aggregates, as shown in Figure 4.20. The exposed emulsion easily coats the vehicle tires, which pick up adjacent aggregates. Aggregates in non-wheel path areas often float on the emulsion until they are compacted by rollers.

Fines content is another major factor affecting seal coat performance, since fines coat the emulsion and aggregate surfaces and prevent from proper bonding between them. The McLeod design method does not consider this factor, but generally, agency specifications limit fines content. INDOT specifies 2.0 % decant for the Indiana aggregate No. 12 aggregate used in this study. Even when qualified aggregates are used for a seal coat, it can experience short and long-term aggregate loss failure due to accumulated fines contents. A higher AAR can generate unacceptably accumulated fines contents between emulsion and coarse aggregate. During aggregate transportation from a stockpile to a construction site and aggregate distribution using a spreader, aggregates tend to be segregated and fine aggregate content often accumulates at the bottom of the seal coat aggregate layer. Greater accumulated fines contents cause aggregate loss failure.

In summary, the AAR should be high enough to protect the seal coat from immediate failure and low enough to avoid unacceptable levels of accumulated fines contents. These are important criteria for developing a new AAR correction factor for this study. The performance evaluation using friction and visual observation showed that all application rate combinations in SR-14 and SR-110 performed well. Accordingly, the minimum and maximum AARs in SR-14 and SR-110 were used for the optimum target range for AAR.

4.5.2 Equipment factor for aggregate distributor

Producing a seal coat quality as designed depends heavily on construction practice. Spraying and distributing the seal coat materials as designed is an important key for obtaining the expected quality of a seal coat. Accordingly, seal coat equipment should be calibrated prior to operation. However, discrepancies, occurring between designed rates and applied rates, are unavoidable, and this can sometimes significantly affect seal coat performance. For example, bleeding or even immediate failure will occur if fewer amounts of aggregates than designed are applied; on the other hand, short or long-term failure related to fines content will occur if larger amounts of aggregates than designed are used during the construction. Those differences can also occur only in localized areas from uneven distribution, under or over application. However, uneven distribution can influence an entire pavement's performance (e.g., chain-reaction failure). Nevertheless, a correction factor accounting for such discrepancies is not considered in current seal coat practice.

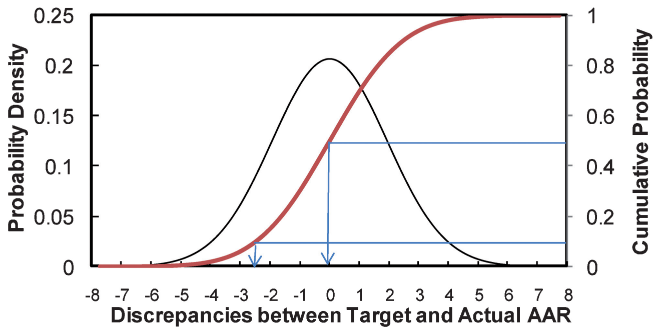


Figure 4.21 Selecting reliable target aggregate application rate

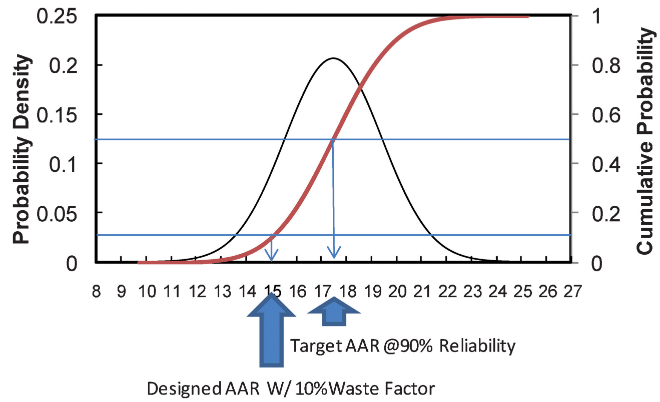


Figure 4.22 Selecting target aggregate application rate with designed rate

In order to address the discrepancy problem, an adjustment factor for AAR was developed to minimize the possibility of immediate failure. Thus, to avoid the chance of failure, the reliability of the target rate should be increased, resulting in an increased target rate. A probability distribution of rates made by an aggregate distributor can be used for the reliability adjustment. It should be noted that the adjustment factor developed in the study was based on data collected from test sections of SR-14 and SR-110, thus limited applications exits within. However, the emphasis lies on the developing process as well as the importance of the factor itself.

TABLE 4.14 presents aggregate application rate differences between targeted and measured, which were observed in test sections of SR-14 and SR-110. The difference varied from 5.3 lb/yd^2 to -2.3 lb/yd^2. The standard deviation is 1.93 lb/yd^2. Accordingly, the probability density curve and cumulative probability curve with a mean of 0 and a standard deviation of 1.93 are plotted, as shown in Figure 4.21.

To achieve reliability when an actual AAR greater than a target or design rate occurs, an AAR adjustment can be obtained from the rate difference corresponding between 0.5 cumulative probability and any cumulative probability smaller than 0.5. The adjustment (equipment) factor for the aggregate distributor used for this study was 2.5 lb/yd^2 for 90 % reliability. This gives a 10 % chance of obtaining values less than -2.5 lb/yd^2. To find the target AAR with the design AAR, an addition of 2.5 lb/yd^2 to the design AAR would be the target AAR, which ensures that the AAR will be larger than the target AAR 90 % of the time.

As an example, if the design or target AAR from the McLeod design method is 15 lb/yd^2, then overlap the rate to a rate corresponding to certain reliability (e.g., 90 % reliability, which is 0.1 cumulative probability) in Figure 4.21, as shown in Figure 4.22. The target rate should be 17.5 lb/yd^2 corresponding to 0.5 cumulative probability. This means that one out of 10 seal coats with 18 lb/yd^2 of AAR can be less than the designed AAR (15 lb/yd^2) and immediately fail during construction due to a lack of aggregate. It should be noted that a calculated AAR is practically rounded to its nearest integer (i.e., 18 lb/yd^2 for 17.5 lb/yd^2). To consider the performance related fines content, assuming that the 25.3 lb/yd^2 from 14-20/0.25 is the maximum AAR that generates a maximum allowable accumulated fines content, 18 lb/yd^2 of AAR has very little chance of causing failure due to fine content as shown in Figure 4.22.

4.5.3 Equipment factor for emulsion distributor

In general, the accuracy of an emulsion distributor is higher than that of the aggregate spreader since the distributor uses a computerized rate control system in current practice. Yet, the target emulsion application rate can also be corrected using the same approach used for AAR to account for any rate difference between the design and the results.

Test sections in SR-14 and SR-110 presented rate differences as shown in TABLE 4.15; the differences varied from 0.02 gal/yd^2 to -0.01 gal/yd2 with a standard deviation of 0.00987 gal/yd^2. The probability density and cumulative probability curves are shown in Figure 4.23. An EAR adjustment, used to achieve reliability when an EAR greater than a target or design rate occurs, can be obtained from a rate difference corresponding between 0.5 cumulative probability and

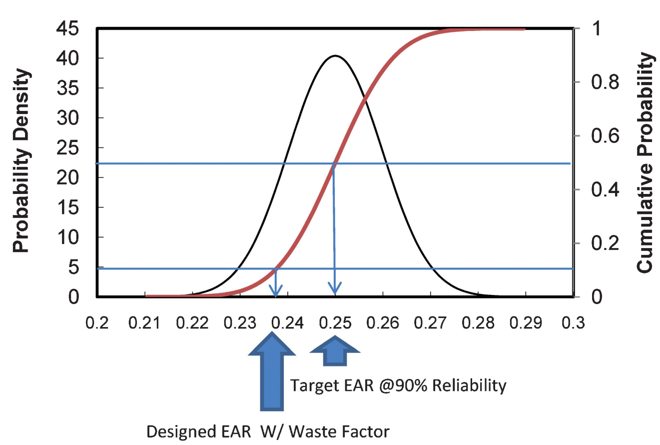


Figure 4.23 Selecting target emulsion application rate with designed rate

TABLE 4.16
Application rate comparison between design method for US-14 and SR-110

	US-14		SR-110	
	EAR (gal/yd^2)	AAR (lb/yd^2)	EAR (gal/yd^2)	AAR (lb/yd^2)
McLeod Design*	0.25	15	0.27	15
IINDOT Spec. 2010**	0.29 ~ 0.33	14 ~ 17	0.29 ~ 0.33	14 ~ 17
Suggested Rate***	0.25	18	0.27	18

*A wastage factor of 1.1 is applied

**INDOT specification is based on use of 2P emulsion and size 12 aggregate on a single application (3)

***Suggested rate assumes a bulk specific gravity of 2.41; a water content of 4.0 %; 90 % reliability; and a distributor's standard deviation of 1.93 lb/yd^2

any cumulative probability smaller than 0.5. The adjustment (equipment) factor for the emulsion distributor used for this study was 0.015 gal/yd^2 for 90 % reliability.

According to McLeod, the correct amount of emulsion should embed each aggregate particle in the residue of the emulsion to a certain percentage of the seal coat depth. Aggregate particles embedded less than 50 % into the residue of the emulsion are likely to be dislodged by traffic. An adjustment with 0.015 gal/yd^2 for 90 % reliability at the McLeod design rate (0.25 gal/yd^2) for SR-14 and SR-110 results in 0.235–0.265 gal/yd^2. This is higher than a 50 % embedment depth (i.e., an equivalent EAR for the 50 % embedment depth is 0.2 gal/yd^2) and less than 0.33 gal/yd^2 which performed well in the experimental program. It should be noted that embedment depth equals traffic factor in the McLeod design as explained in an earlier chapter. This study suggests that an EAR calculated using the McLeod design method does not need to be corrected for the emulsion distributor used in this study since the EAR errors are ignorable using a computerized rate control system. In conclusion, the designed EAR and AAR corrected for are summarized in TABLE 4.16. The INDOT seal coat application rate is much higher than the suggested EAR and slightly lower than the suggested AAR determined from this study.

4.6 Indot seal coat design software (iSeal)

The current INDOT seal coat design in the specification is not performance-related, thus the design cannot incorporate various factors, including traffic, existing pavement condition, and material type and properties. In addition, it only provides a range of values for both aggregate and emulsion application rates, which could potentially lead to an improper combination of aggregate and emulsion application rates in a seal coat application. For example, if the maximum emulsion application rate within the specified range is combined with the minimum aggregate application rate within the specified range, bleeding might occur. Another problem could arise when a seal coat is applied to a pavement with an exceptionally high traffic volume or severely damaged surface condition.

Design software, "INDOT SEAL COAT DESIGN (iSeal)", was developed in part of the study to aid seal coat design process and incorporates with INDOT seal coat practice. The software is largely based on the McLeod design method which includes factors introduced in section 2.2.3. Furthermore, an additional equipment factor was implemented into the design process to resolve issues due to discrepancies between the designed rate and the applied rate.

iSeal software consists of four input tabs, including general, AAR, EAR, and attachments. Although the attachment tab is not directly related to the design process, it provides a convenient feature: users can upload any form of documents into the software for reference purposes. Outputs are AAR and EAR with an option to print a detailed report. TABLE 4.17 summarizes all of the inputs used in the seal coat design.

During development, engineers emphasized intuitiveness in using the software, thus providing more user-friendly software. In addition, the software provides various options when inputting values, namely user defined, typical, and measured. "User Defined" allows a user to manually input desired values while "Typical" provides selection of generally accepted values for the factor. "Measured" accepts experiment data and then converts them into a corresponding value. Details about the inputs and the options as well as a tutorial are available in the separate document, "INDOT Seal Coat Design Software Manual."

4.6.1 General

The "General" tab, as shown in Figure 4.24, is the default screen when the software is launched. This allows a user to input general information regarding specific seal coat design, including designer information and location along with existing pavement condition and material type and source. The District and Sub-district features are Indiana's, and existing pavement type selections are constructed based on the Indiana Design Manual Chapter 52 (INDOT 2010).

4.6.2 AAR

The "AAR" tab, as shown in Figure 4.25, allows a user to input values required to calculate aggregate application rate, including Median Particle Size, Flakiness Index, Loose Unit Weight, Dry Bulk Specific

TABLE 4.17
Inputs in tabs

General	AAR	EAR
• Design Date / Designer	• Median Particle Size	• Traffic Factor
• DES Number	• Flakiness Index	• Surface Condition Factor
• District/Sub-district Name	• Loose Unit Weight	• Absorption
• Road Name	• Dry Bulk Specific Gravity	• Asphalt Content of Emulsion
• Location of Road with R. P.	• Wastage Factor	
• Lane-miles	• Equipment Correction Factor	
• Average Daily Traffic		
• Existing Pavement Condition with type and Date		
• Presence of Surface Condition Evaluation and Crack Sealing/Filling on Existing Pavement		
• Material Type and Provider		
• Note		

Gravity, Wastage Factor, and Equipment Correction Factor. "Typical" input option under the median particle size box allows a user to select among widely used sizes of aggregates, such as Indiana aggregate No. 11, No. 12 and SC-16. Upon selection, the software inputs median particle size accordingly and the values are based on INDOT Specification (3). Values for the Flakiness Index generally range from 10 to 25 % and for Loose Unit Weight and Dry Bulk Specific Gravity should be obtained under AASHTO T 19 (35) and T 85

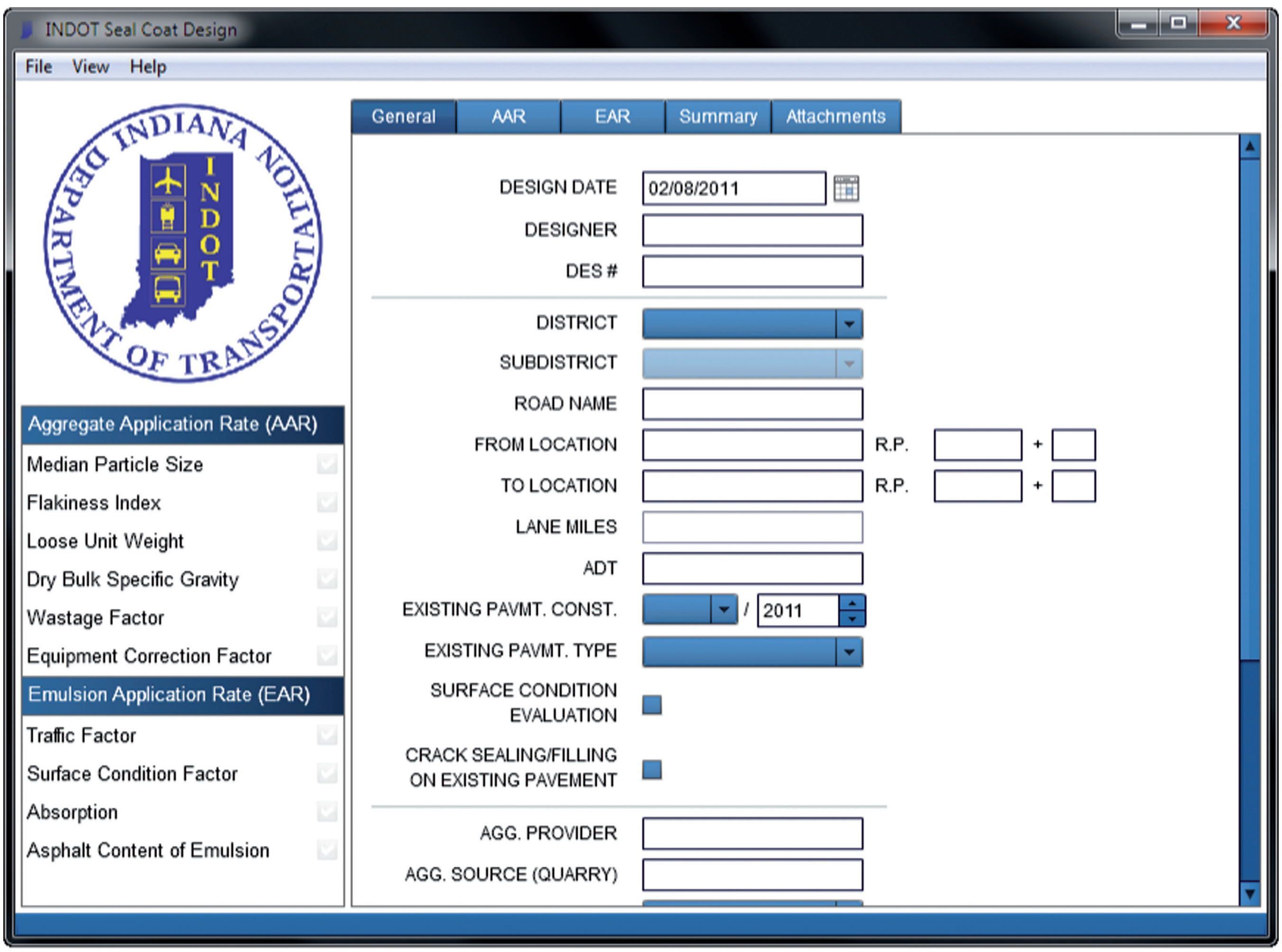


Figure 4.24 General tab of iSeal

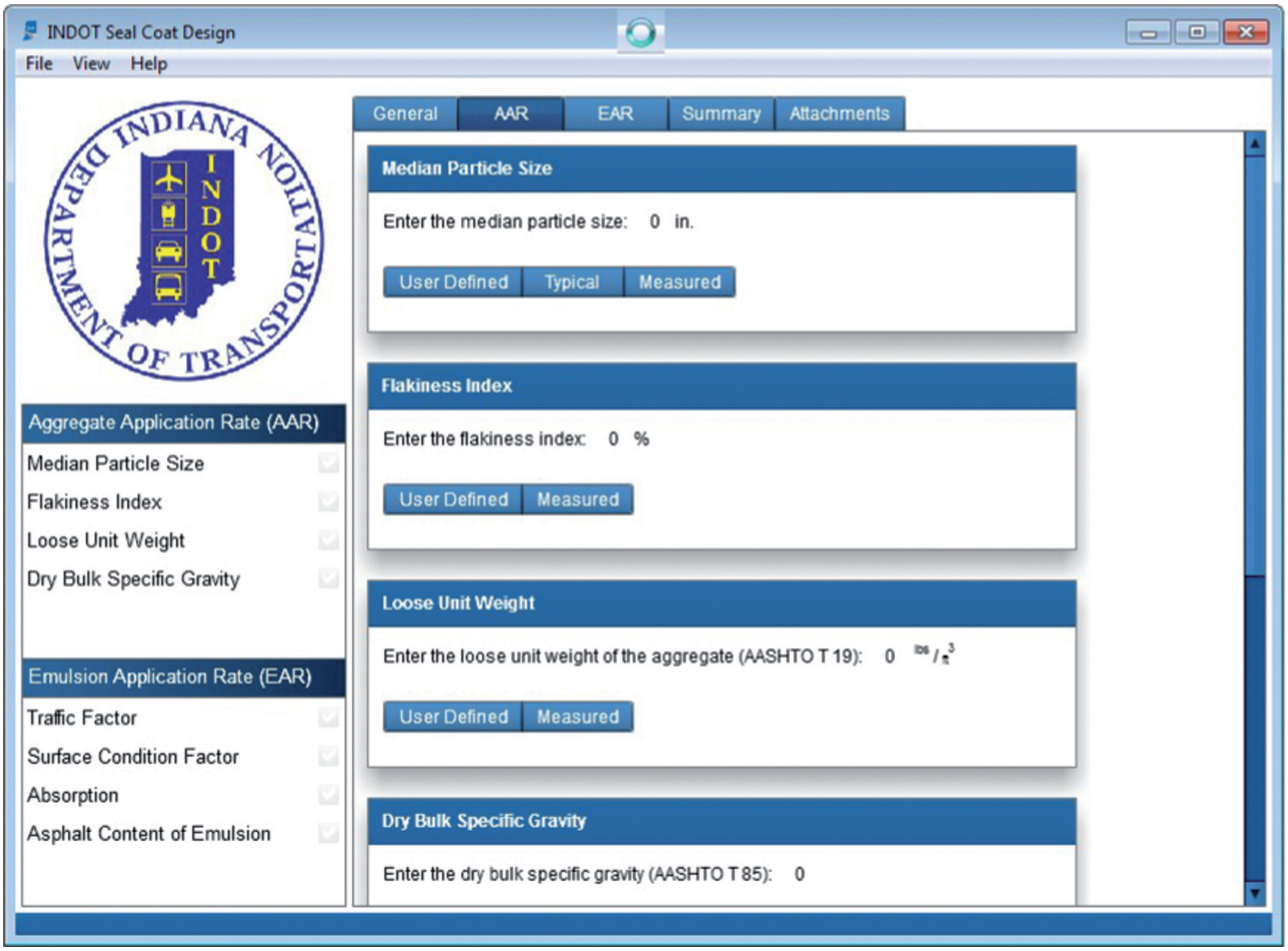


Figure 4.25 AAR tab of iSeal

(36), respectively. Although the last two factors have an option not to use them, it is strongly advised for the user to apply those factors.

4.6.3 EAR

The "EAR" tab, as shown in Figure 4.26, allows a user to input values required to calculate emulsion application rate, including Traffic Factor, Surface Condition Factor, Absorption, and Asphalt Content of Emulsion. Traffic Factor is calculated based on average daily traffic on the road. Traffic Factor contributes significantly in designing EAR since it determines average embedment depth which ranges from 60 to 85 % of the average least dimension of aggregates. Surface Condition Factor features five pictures to help a user to determine the existing pavement condition and improve objectivity in selecting categories. The input value for Absorption is the water absorption of aggregates, although aggregate is mixed with emulsion in a seal coat application. It is mainly due to lack of testing methods which can measure actual amount of emulsion absorption by aggregates. The "Typical" input option again is available under the Asphalt Content of Emulsion box, which allows a user to select among widely used types of emulsion, namely RS-2, RS-2P, AE-90S and HFRS-2. Upon selection, the software inputs asphalt content of emulsion accordingly and the values are based on INDOT Specification (3).

4.6.4 Summary

The "Summary" tab, as shown in Figure 4.27, presents a user all input values as a summary and it is instantly updated as a change in value occurs. A small box featured on the right side of each line displays which type of values are used for each type of factor. AAR and EAR are also automatically calculated and displayed once the required data are defined in the software and changed once any change in values of each factor is detected. The "Summary" tab also features a print report option button at the left lower corner of the window, which provides a user to print a detailed report if desired. Detailed report shows every

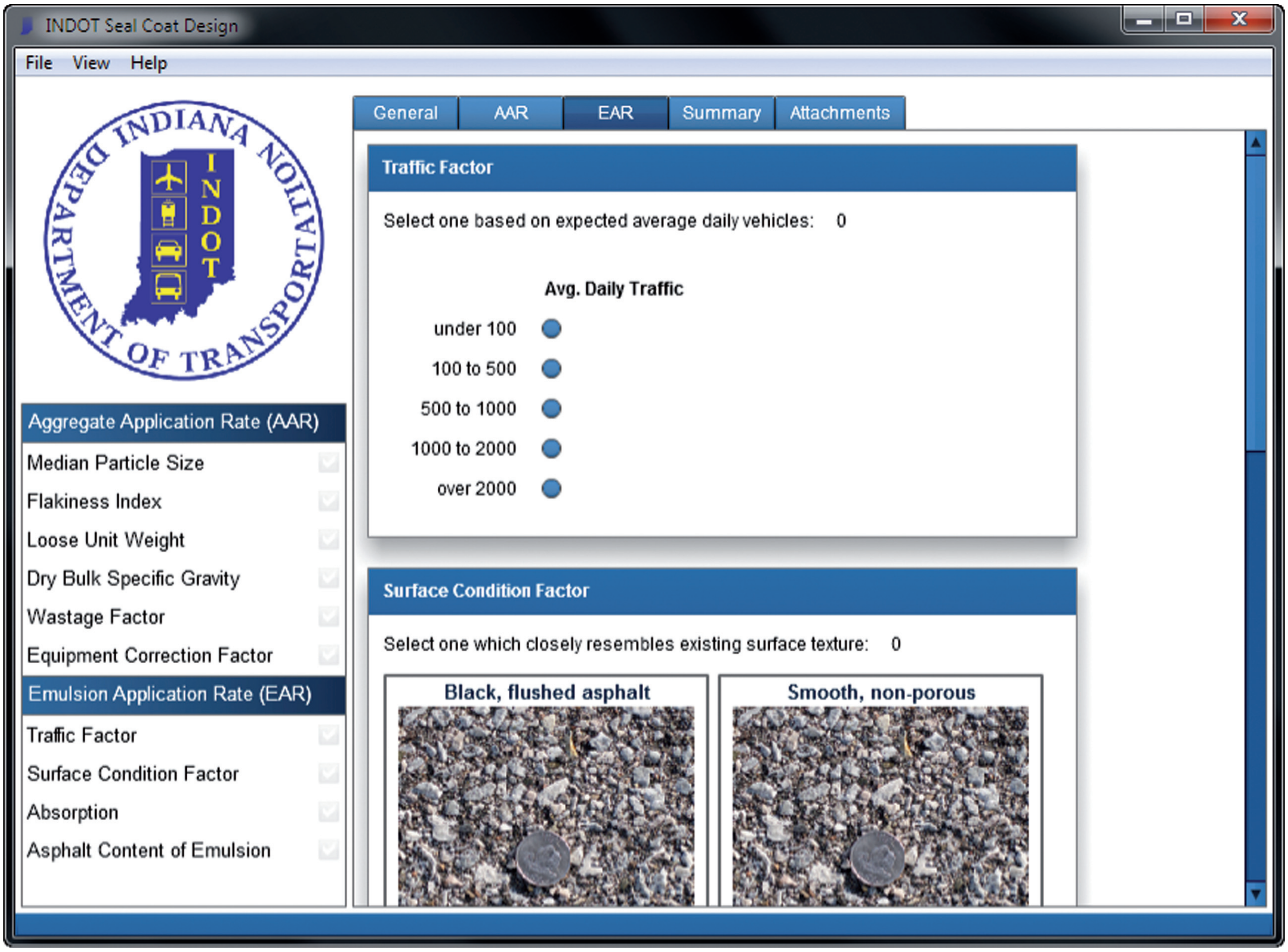


Figure 4.26 EAR tab of iSeal

value input by the user and step-by-step calculation of AAR and EAR in pdf format.

4.6.5 Attachments

The "Attachments" tab, as shown in Figure 4.28, displays a user a list of attached files. This feature essentially works the same way as attaching a file to an email. Furthermore, it provides a drag and drop function, which allows a user to simply drag any file to a software window and automatically the file in that location. This feature also provides options to manage multiple files at once by selecting the check box located in the lower left corner of the window.

4.6.6 Additional features

Status indicator

The status indicator is located in the lower left corner of the window and provides an overview of required inputs. Figure 4.29 illustrates how the status indicator displays once any change in the values of each required input is detected.

Multiple sheets

iSeal allows a user work with a number of sheets (up to five). And a user can easily switch between sheets in iSeal using either their keyboard shortcut (CTRL + Tab) or mouse by clicking on an individual sheet.

Figure 4.30 illustrates how multiple sheets are shown in iSeal along with their file name. The current sheet is indicated by darker color.

5 CONCLUSION AND RECOMMENDATION

5.1 Performacne evaluation of seal coat materials

To evaluate aggregate and emulsion types on aggregate loss performance of a seal coat, three emulsions and eight aggregates including CRS-2P, RS-2P, and AE-90S for emulsions and Trap Rock, Sandstone, Blast Furnace Slag, Steel Slag, Limestone, Dolomite, Crushed Gravel (one face), and Crushed Gravel (two faces) were tested utilizing the sweep test and Vialit test. In addition, to explore influence factors (i.e., electrical surface charge interaction, water evaporation change in emulsion, water affinity of aggregate, etc.), the Zeta

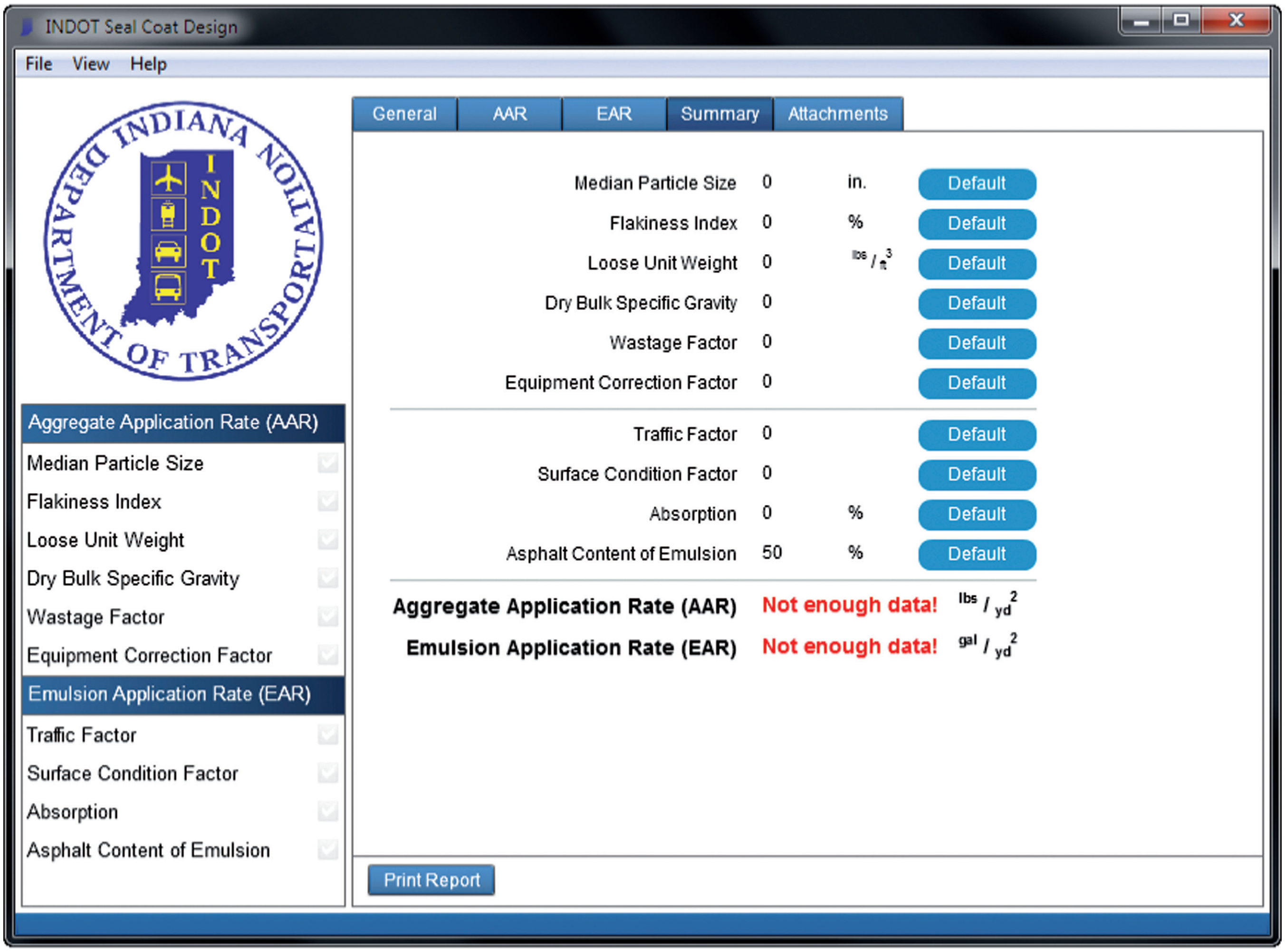


Figure 4.27 Summary tab of iSeal

potential, the water content, and the X-ray deflection test were conducted. The following conclusions can be made:

- The electrical surface charges of the aggregate and emulsion can be characterized and quantified by the Zeta potential. All aggregates and emulsions show positive Zeta potentials at low pH and negative Zeta potentials at high pH with the exception of Blast Furnace Slag, which exhibited negative Zeta potential values at all pH levels. This observation confirms that the Zeta potential varies with the pH of the solution. Conclusively, the electrical surface charge of an aggregate in emulsions varies with the type of emulsion (i.e., pH of emulsifier).
- Generally, the water evaporation process of an emulsion mainly depends on the emulsifier type and its concentration. According to the water content test, CRS-2P shows the fastest water evaporation among the three emulsions. Based on Schuler's critical moisture content, CRS-2P is the earliest emulsion to have enough bond strength among the emulsions for to retain aggregates in open traffic.
- Another observation made from the water content test is that aggregate can slow the water evaporation process of emulsions. Limestone aggregate can retard the water evaporation speed in CRS-2P. RS-2P and AE-90S show the similar retardations, but they are statistically insignificant. It should be noted that there was no electrostatic attraction among the emulsions and Limestone according to the Zeta potential test results. The electrostatic interaction between CRS-2P and Limestone has the smallest repulsion among Limestone with the emulsions. In other words, the more electrostatic repulsion between Limestone aggregate and emulsion, the less influence on the water evaporation in emulsions.
- X-ray deflection test: Among the many chemical characteristics of each mineral, the silica (SiO_2) contents are used as an index to determine aggregate characteristics, including acidity/basicity and water-affinity. The XRD results confirm that the percent ranges of SiO_2 contents for aggregates are within the typical range. Sandstone and Dolomite have the highest and smallest content of SiO_2, respectively among the eight aggregates. This means that Sandstone and Limestone have the highest and lowest water affinity (hydrophilic and hydrophobic), respectively. Conclusively, Sandstone is expected to have more of a chance to have water interface between the aggregate surface and the asphalt particles in emulsion. This interface can eventually interfere with the bonding between them.
- Sweep test: the sweep test with Limestone with varying curing time reveals that CRS-2P shows superior

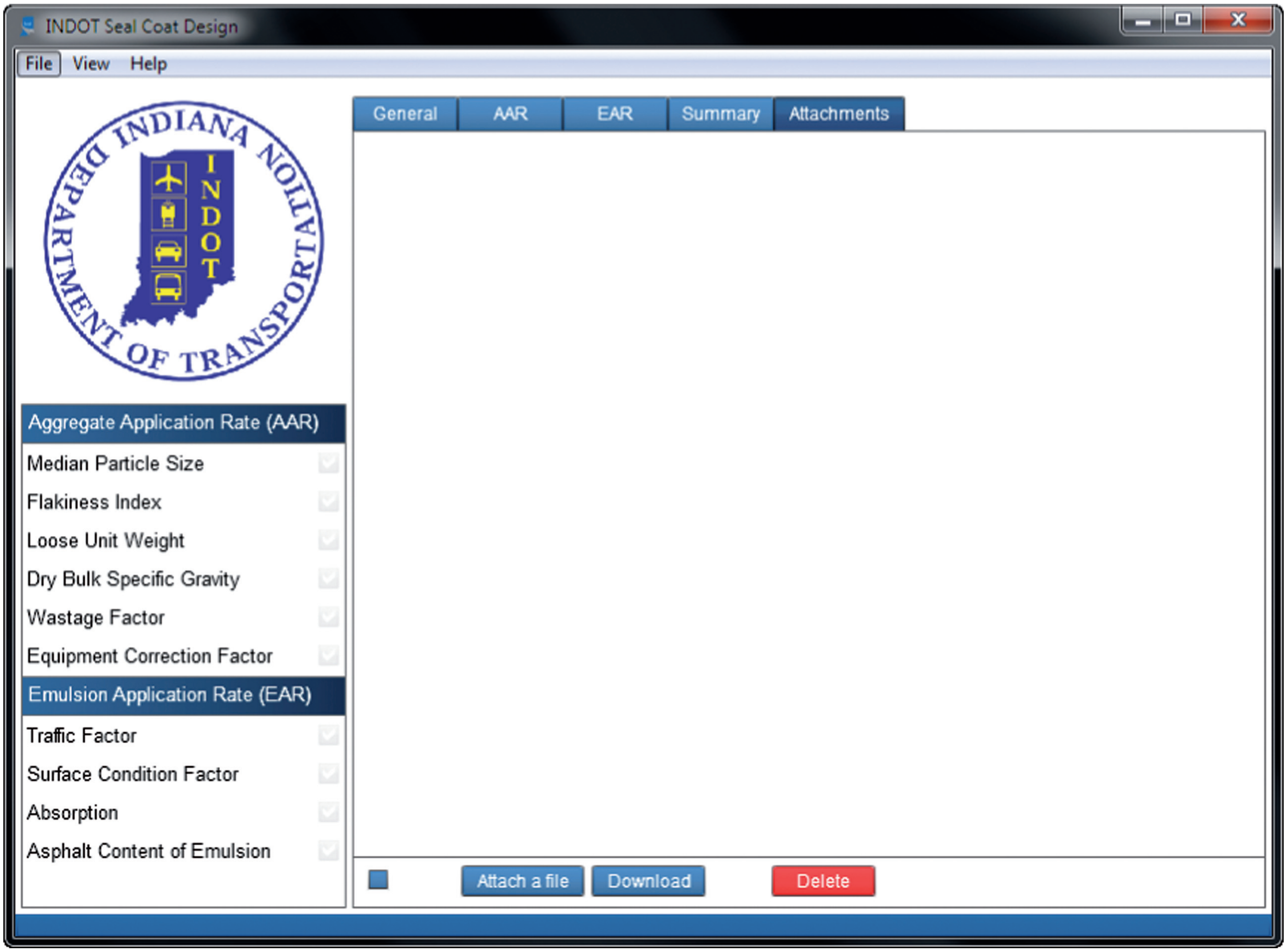


Figure 4.28 Attachment Tab of iSeal

aggregate loss performance among the emulsions. Comparing the sweep test results to the water contents of emulsions, faster water evaporation presents the better aggregate loss performance. This finding indicates that the bond strength of an emulsion to retain aggregate can be mainly a function of water evaporation in emulsion.

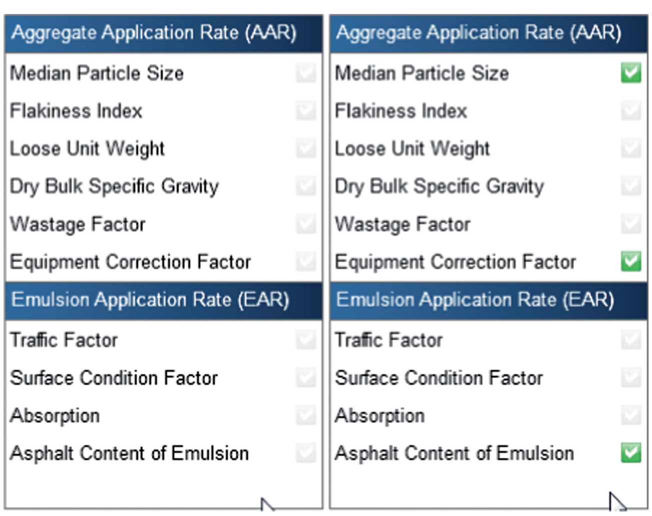


Figure 4.29 Status indicator of iSeal

- Based on the sweep test at 77 ˚F after 24 hours of curing with all 24 combinations of aggregates and emulsions, CRS-2P performs the best, regardless of the type of aggregates.
- Based on the Vialit test at temperatures from 35˚F to -22˚F after 24 hours of curing using all 24 combinations of aggregates and emulsions, the most aggregate loss occurs at lower testing temperatures. AE-90S has the strongest resistance to aggregate loss among the three emulsions at lower temperatures, which is an opposite trend compared to the sweep test results. Another finding was that the Crushed Gravel with two faces outperforms that with one face.
- According to statistical analysis results using the combined results of the sweep test and the Vialit test (i.e., aggregate loss performance with temperatures ranging from 77 ˚F to -22 ˚F), it is concluded that AE-90S and Crushed Gravel with two faces showed the best performance among emulsions and aggregates, respectively. In addition the best-performing aggregate-emulsion combinations are AE-90S with most of the aggregate except Steel Slag. Thus, the aggregate type in terms of mineral/chemical composition is not a major factor that affects the aggregate loss performance.

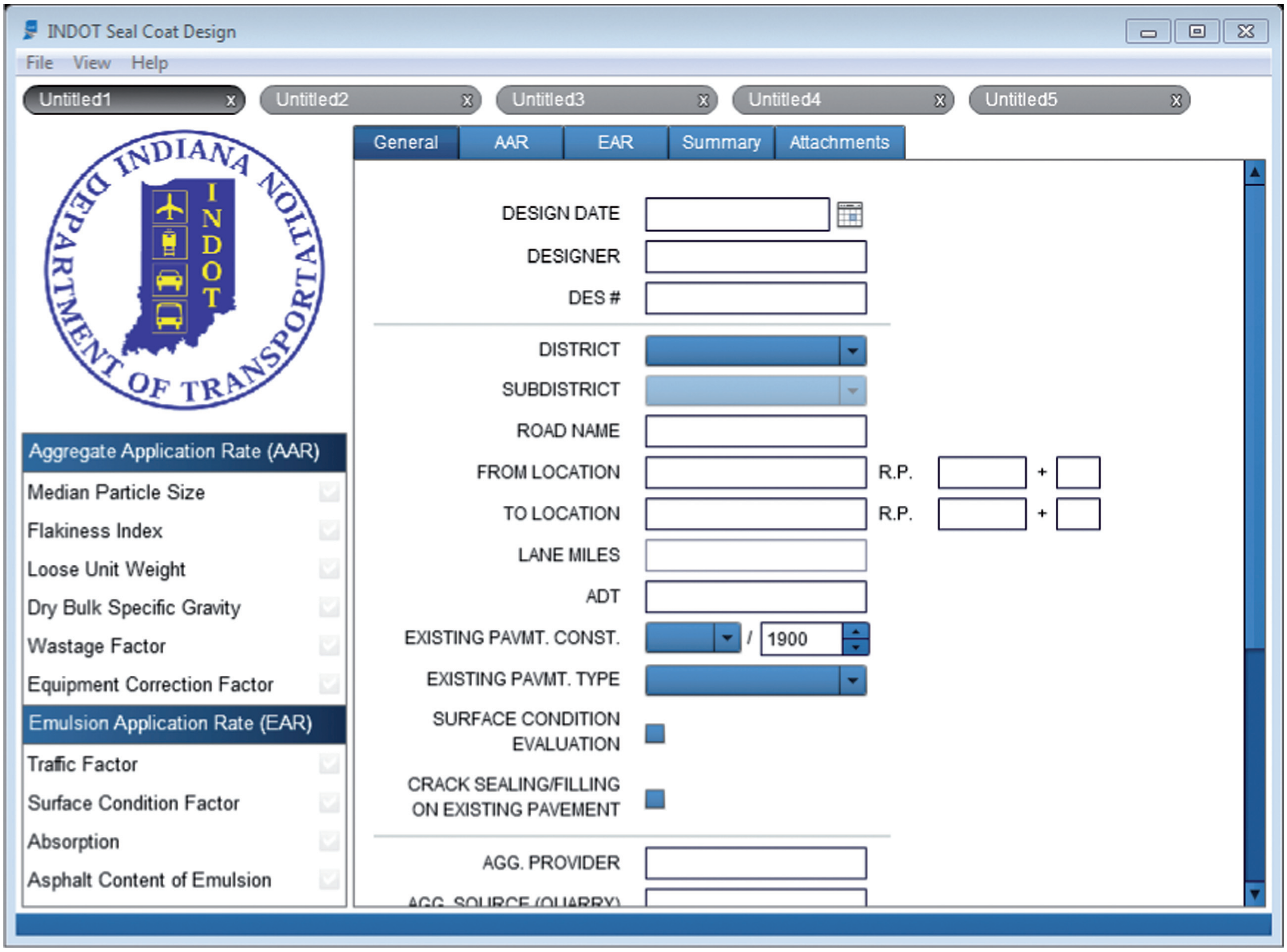


Figure 4.30 Multiple sheet features of iSeal

- It is noteworthy that there are other major factors from aggregate properties affecting seal coat performance, including fines content, shape, gradation, and size. These factors should be considered with the seal coat application rate design considering bleeding and aggregate loss performance. However, the sweep test and Vialit test have limitations to evaluate bleeding performance. An alternative way to evaluate the two performance modes should be considered as a future study.

5.2 Performance evaluation of seal coat design

Seal coat performance was evaluated for various emulsion and aggregate application rates by using three different evaluation methods: the IRI, friction, and visual inspection. Based on these performance tests, the following conclusions can be drawn:

- Immediate failure occurring locally during construction due to incorrect application rate (e.g., insufficient aggregate rate) can cause total failure of a seal coat road from a chain reaction. Employing a factor to compensate for AAR discrepancies between target and actual is critical for seal coat survival during construction.
- This study confirms the lack of relevance between seal coat application and IRI values due to the thin coat and the limitation of the IRI measurement (e.g., 250 mm moving average).
- The friction test results show an adequate skid resistance performance on all seal coat test sections. In addition, friction improvements due to seal coat applications were confirmed within a range of seal coat rates applied in this study.
- Overall, IRI, friction, and visual inspection do not show distinct differences in seal coat performance in terms of application rates.
- An equipment factor to correct for any difference between a target rate and a measured rate was developed considering reliability and a designed rate using the McLeod equation.
- The suggested aggregate rate for INDOT size 12 aggregate and emulsion for AE-90S based on this study are 18 lb/yd^2 and 0.25 gal/yd^2, which are higher and lower than INDOT specification, respectively.
- Design software “INDIANA SEAL COAT DESIGN (iSeal)” was developed based on the McLeod design equation and INDOT seal coat specification. Furthermore, an additional equipment factor was implemented into the design process to resolve issues due to discrepancies between the designed rate and applied rate.

6 APPENDIX

6.1 ZETA POTENTIAL TEST RESULT

6.1.1 EMULSION

CRS-2P

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Aug 27, 2010
Time: 00:14:14
Batch: 0

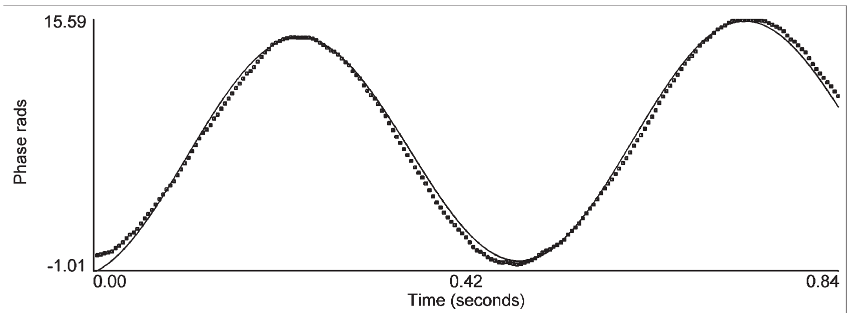
Sample ID **CRS pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= 73.72 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 5.76 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 6079 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 100.0 nm

Instrument Parameters:

Sample Count Rate	= 217 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 511 kcps	Electric Field	= 7.70 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 5e-02		



CRS pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	5.55	71.00	0.0437
2	6.02	77.04	0.0392
3	5.84	74.77	0.0473
4	6.05	77.47	0.0321
5	5.49	70.28	0.0439
6	6.07	77.75	0.0442
7	5.39	69.00	0.0454
8	5.93	75.85	0.0484
9	5.33	68.24	0.0479
10	5.92	75.77	0.0282
Mean	5.76	73.72	0.0420
Std. Error	0.09	1.17	0.0022
Combined	5.75	73.62	0.0262

RS-2P

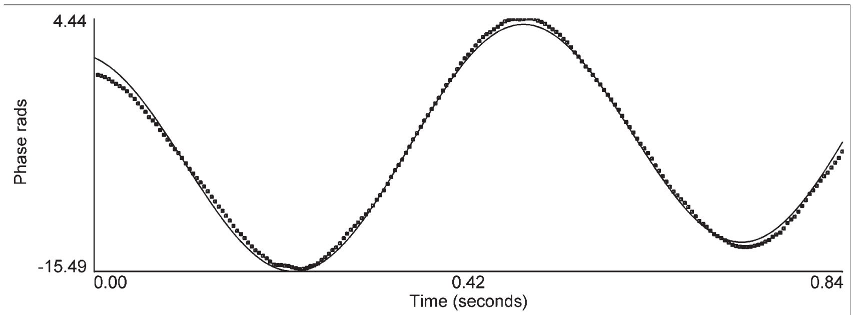
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Aug 27, 2010
Time: 00:00:20
Batch: 0

Sample ID **RS pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= -92.51 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -7.23 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 591 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 100.0 nm

Instrument Parameters:			
Sample Count Rate	= 199 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 496 kcps	Electric Field	= 7.33 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 5e-02		



RS pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-6.73	-86.16	0.0489
2	-7.28	-93.12	0.0484
3	-6.06	-77.50	0.0413
4	-8.17	-104.63	0.0342
5	-7.44	-95.19	0.0493
6	-7.70	-98.54	0.0352
7	-6.56	-84.01	0.0461
8	-8.05	-103.01	0.0407
9	-6.29	-80.56	0.0494
10	-8.00	-102.40	0.0431
Mean	-7.23	-92.51	0.0436
Std. Error	0.24	3.13	0.0018
Combined	-7.22	-92.46	0.0280

AE-90S

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Aug 26, 2010
Time: 23:13:48
Batch: 0

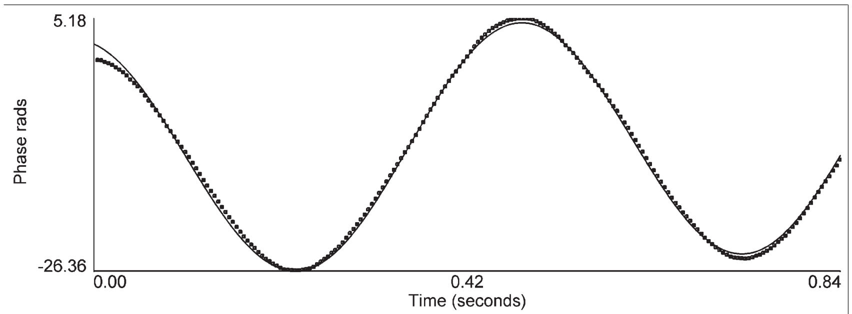
Sample ID **AE pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -145.92 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -11.40 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 621 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 100.0 nm

Instrument Parameters:

Sample Count Rate	= 301 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 696 kcps	Electric Field	= 7.59 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 5e-02		



AE pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-11.70	-149.80	0.0603
2	-11.55	-147.78	0.0499
3	-10.14	-129.76	0.0499
4	-12.84	-164.38	0.0676
5	-10.73	-137.38	0.0471
6	-11.74	-150.27	0.0430
7	-11.80	-151.02	0.0379
8	-12.20	-156.20	0.0447
9	-12.48	-159.66	0.0496
10	-8.82	-112.91	0.0495
Mean	-11.40	-145.92	0.0500
Std. Error	0.38	4.86	0.0027
Combined	-11.40	-145.87	0.0330

6.1.2 AGGREGATE

CRUSHED GRAVEL WITH TWO FACES

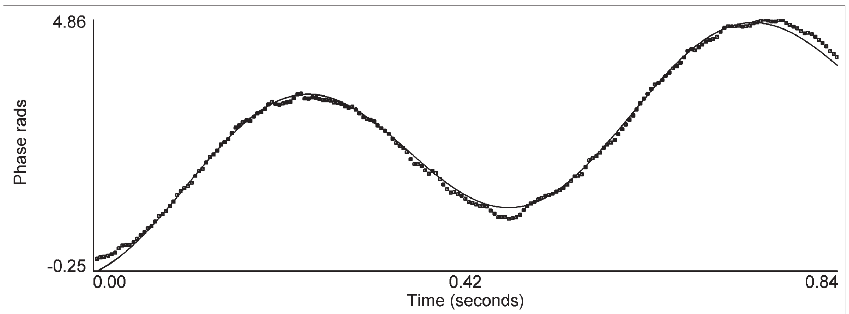
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 13:18:20
Batch: 0

Sample ID **#11 CG pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= 16.57 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 1.29 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 6644 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 135 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 549 kcps	Electric Field	= 6.73 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



#11 CG pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	1.32	16.85	0.0197
2	1.20	15.39	0.0194
3	1.30	16.67	0.0195
4	1.41	18.09	0.0180
5	1.56	19.91	0.0186
6	1.12	14.38	0.0154
7	1.10	14.06	0.0177
8	1.44	18.47	0.0200
9	1.25	16.05	0.0188
10	1.23	15.80	0.0185
Mean	1.29	16.57	0.0186
Std. Error	0.05	0.58	0.0004
Combined	1.29	16.45	0.0064

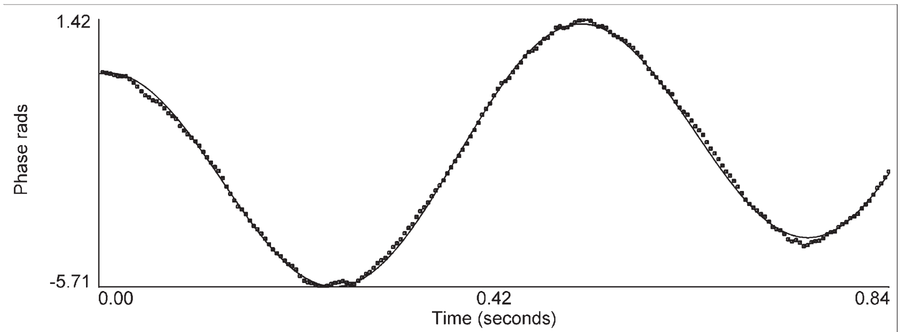
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 21, 2010
Time: 01:59:01
Batch: 0

Sample ID **#11 CG pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= -24.59 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.92 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 27 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 207 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 488 kcps	Electric Field	= 9.58 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



#11 CG pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.87	-23.98	0.0196
2	-2.19	-27.99	0.0198
3	-1.74	-22.32	0.0199
4	-1.84	-23.54	0.0179
5	-1.77	-22.68	0.0200
6	-2.00	-25.64	0.0197
7	-1.59	-20.32	0.0197
8	-2.31	-29.57	0.0195
9	-2.07	-26.55	0.0188
10	-1.82	-23.29	0.0194
Mean	-1.92	-24.59	0.0194
Std. Error	0.07	0.89	0.0002
Combined	-1.91	-24.47	0.0060

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Aug 1, 2010
Time: 03:28:27
Batch: 0

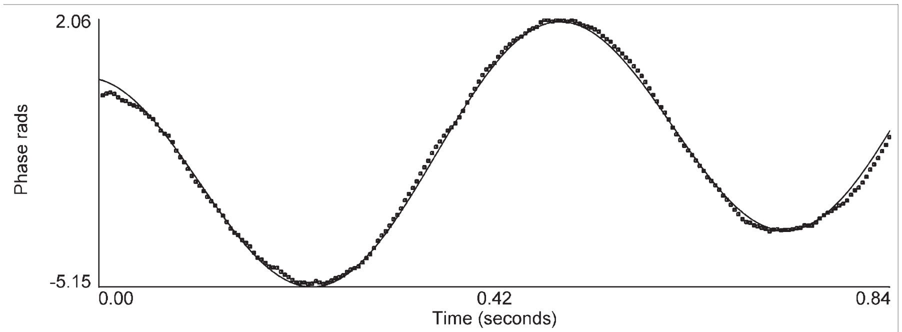
Sample ID **#11 CG pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -32.14 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.51 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 416 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 249 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 519 kcps	Electric Field	= 7.34 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



#11 CG pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-2.59	-33.16	0.0174
2	-2.60	-33.28	0.0198
3	-2.70	-34.56	0.0145
4	-2.68	-34.25	0.0181
5	-2.49	-31.89	0.0181
6	-2.47	-31.62	0.0179
7	-2.00	-25.56	0.0157
8	-2.60	-33.30	0.0198
9	-2.59	-33.20	0.0186
10	-2.39	-30.56	0.0180
Mean	-2.51	-32.14	0.0178
Std. Error	0.06	0.83	0.0005
Combined	-2.51	-32.08	0.0081

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 10:53:03
Batch: 0

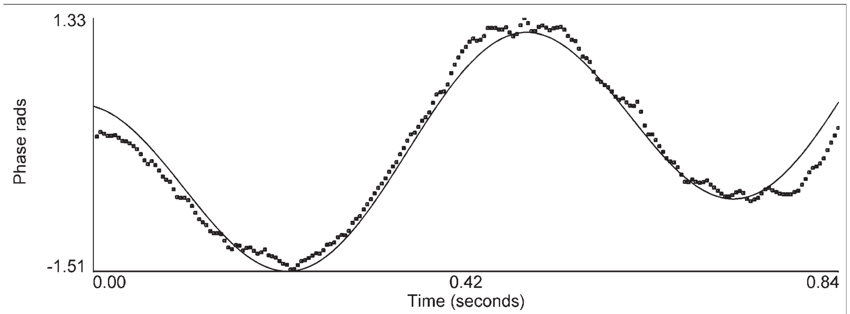
Sample ID **BF slag pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -12.87 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.01 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 4979 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 278 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 675 kcps	Electric Field	= 6.65 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



BF slag pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-0.94	-11.99	0.0199
2	-0.76	-9.69	0.0169
3	-0.94	-12.05	0.0199
4	-1.04	-13.37	0.0190
5	-1.25	-16.06	0.0165
6	-0.92	-11.83	0.0191
7	-1.00	-12.77	0.0195
8	-0.69	-8.78	0.0193
9	-1.13	-14.50	0.0185
10	-1.38	-17.67	0.0196
Mean	-1.01	-12.87	0.0188
Std. Error	0.07	0.85	0.0004
Combined	-0.98	-12.55	0.0104

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 21, 2010
Time: 00:38:29
Batch: 0

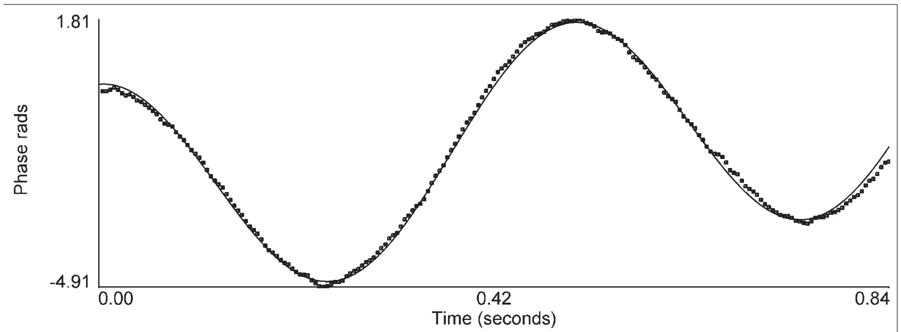
Sample ID **BF slag pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -21.46 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.68 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 21 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 223 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 473 kcps	Electric Field	= 9.86 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



BF slag pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.57	-20.06	0.0168
2	-1.92	-24.59	0.0190
3	-1.74	-22.27	0.0132
4	-1.86	-23.77	0.0195
5	-1.54	-19.67	0.0195
6	-1.56	-19.99	0.0199
7	-1.70	-21.81	0.0146
8	-1.29	-16.46	0.0192
9	-1.94	-24.79	0.0180
10	-1.66	-21.22	0.0173
Mean	-1.68	-21.46	0.0177
Std. Error	0.06	0.81	0.0007
Combined	-1.67	-21.43	0.0075

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 31, 2010
Time: 15:54:32
Batch: 0

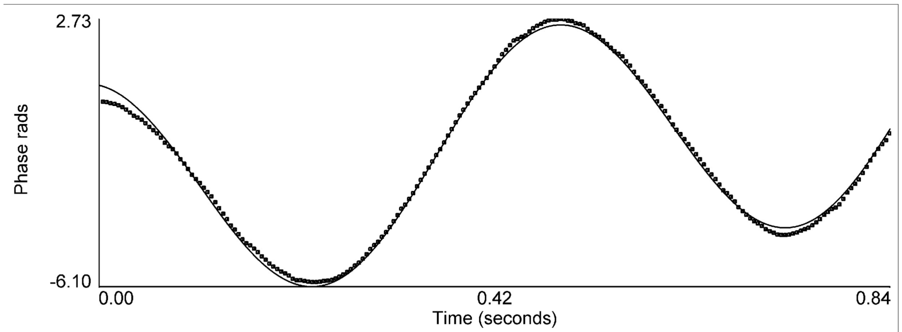
Sample ID **BF slag pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -37.99 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.97 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 421 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 254 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 552 kcps	Electric Field	= 7.45 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



BF slag pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-3.04	-38.87	0.0270
2	-2.34	-29.92	0.0175
3	-3.07	-39.35	0.0225
4	-3.14	-40.23	0.0200
5	-2.99	-38.30	0.0199
6	-3.07	-39.26	0.0177
7	-3.22	-41.16	0.0160
8	-3.15	-40.37	0.0190
9	-2.73	-34.99	0.0194
10	-2.93	-37.44	0.0194
Mean	-2.97	-37.99	0.0198
Std. Error	0.08	1.05	0.0010
Combined	-2.97	-37.96	0.0108

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 02:04:35
Batch: 0

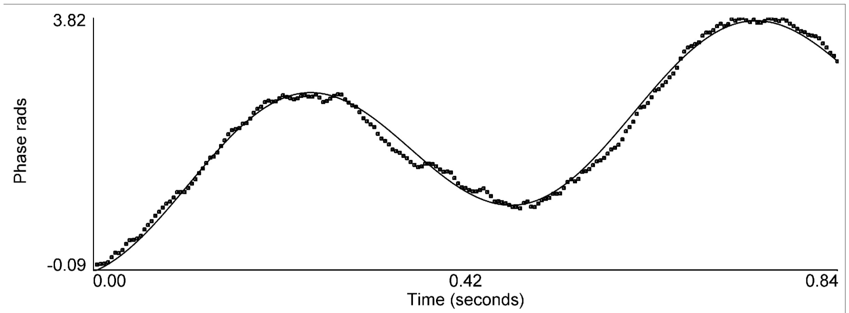
Sample ID **CA16 CG pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= 12.88 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 1.01 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 7663 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 208 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 483 kcps	Electric Field	= 6.63 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



CA16 CG pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	0.67	8.52	0.0190
2	1.02	13.00	0.0198
3	1.15	14.70	0.0183
4	1.30	16.60	0.0149
5	1.15	14.68	0.0180
6	0.80	10.24	0.0195
7	1.15	14.67	0.0183
8	1.02	13.09	0.0181
9	0.86	10.98	0.0179
10	0.96	12.32	0.0198
Mean	1.01	12.88	0.0184
Std. Error	0.06	0.77	0.0005
Combined	0.99	12.71	0.0064

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 21, 2010
Time: 02:41:18
Batch: 0

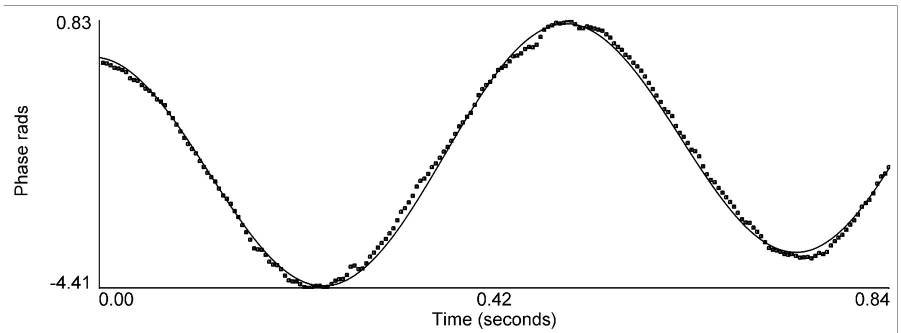
Sample ID **CA16 CG pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -19.32 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.51 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 40 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 193 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 520 kcps	Electric Field	= 9.24 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



CA16 CG pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.44	-18.48	0.0190
2	-1.86	-23.81	0.0199
3	-1.28	-16.45	0.0188
4	-1.39	-17.82	0.0176
5	-1.46	-18.62	0.0169
6	-1.64	-21.02	0.0181
7	-1.74	-22.31	0.0173
8	-1.36	-17.40	0.0198
9	-1.48	-18.91	0.0159
10	-1.44	-18.42	0.0199
Mean	-1.51	-19.32	0.0183
Std. Error	0.06	0.73	0.0004
Combined	-1.51	-19.26	0.0074

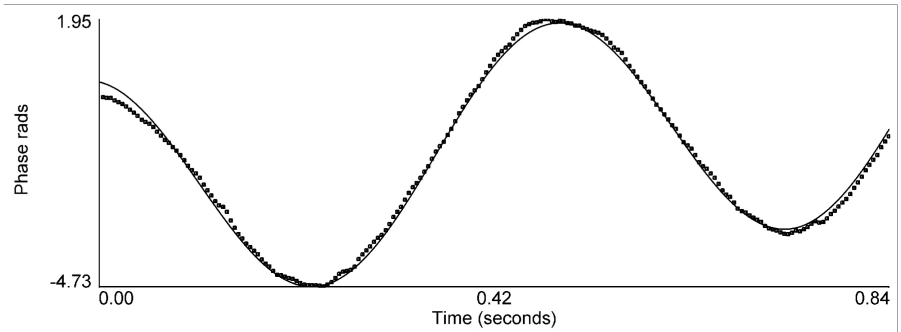
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Aug 2, 2010
Time: 01:47:39
Batch: 0

Sample ID **CA16 CG pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= -29.67 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.32 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 414 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 164 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 490 kcps	Electric Field	= 7.31 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



CA16 CG pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-2.18	-27.93	0.0193
2	-1.73	-22.15	0.0200
3	-2.37	-30.32	0.0192
4	-2.21	-28.22	0.0200
5	-2.37	-30.33	0.0193
6	-2.11	-26.95	0.0186
7	-2.68	-34.27	0.0189
8	-2.63	-33.63	0.0196
9	-2.65	-33.94	0.0198
10	-2.26	-28.92	0.0198
Mean	-2.32	-29.67	0.0194
Std. Error	0.09	1.18	0.0002
Combined	-2.31	-29.61	0.0088

DOLOMITE

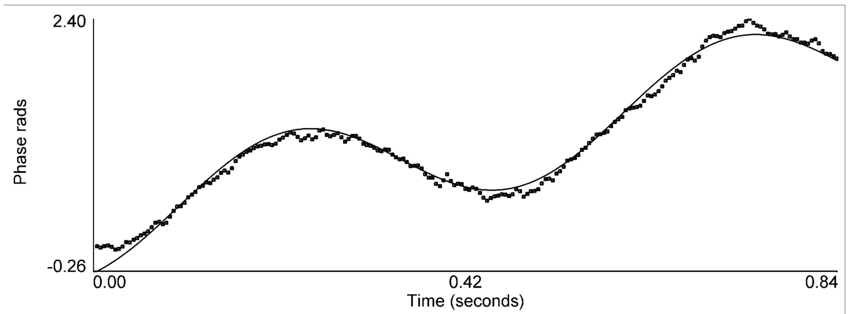
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 00:04:55
Batch: 0

Sample ID **Dolomite pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= 6.62 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 0.52 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 7176 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 87 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 545 kcps	Electric Field	= 6.69 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 1e-02		



Dolomite pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	0.54	6.95	0.0141
2	0.48	6.19	0.0149
3	0.56	7.15	0.0146
4	0.65	8.36	0.0138
5	0.36	4.66	0.0136
6	0.70	9.01	0.0149
7	0.75	9.55	0.0144
8	0.31	3.91	0.0123
9	0.60	7.66	0.0130
10	0.22	2.79	0.0148
Mean	0.52	6.62	0.0140
Std. Error	0.06	0.71	0.0003
Combined	0.48	6.09	0.0048

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 19, 2010
Time: 23:56:43
Batch: 0

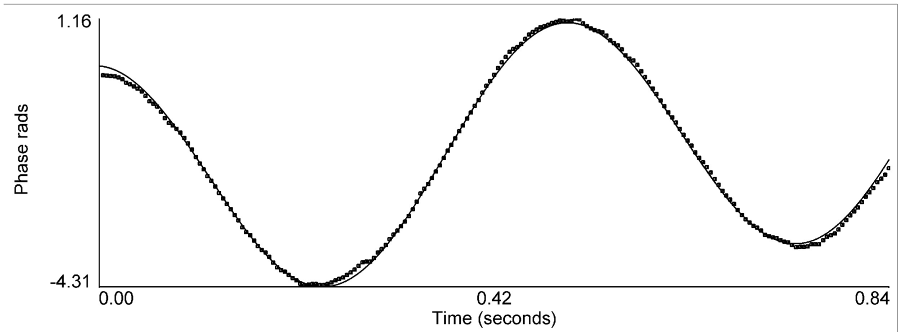
Sample ID **Dolomite pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -19.17 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.50 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 35 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 203 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 541 kcps	Electric Field	= 9.54 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Cycles Per Run	= 20		



Dolomite pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.35	-17.33	0.0077
2	-1.55	-19.83	0.0091
3	-1.54	-19.69	0.0152
4	-1.40	-17.91	0.0113
5	-1.46	-18.64	0.0091
6	-1.39	-17.78	0.0178
7	-1.66	-21.22	0.0120
8	-1.57	-20.06	0.0235
9	-1.47	-18.75	0.0132
10	-1.60	-20.51	0.0121
Mean	-1.50	-19.17	0.0131
Std. Error	0.03	0.41	0.0015
Combined	-1.50	-19.15	0.0046

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 31, 2010
Time: 16:55:27
Batch: 0

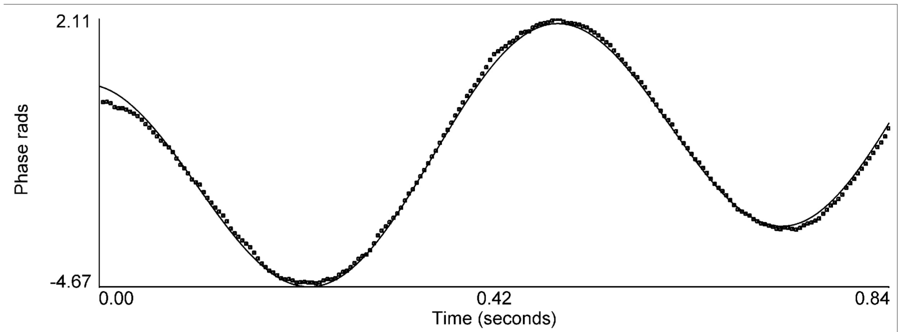
Sample ID **Dolomite pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -29.61 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.31 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 403 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 225 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 511 kcps	Electric Field	= 7.35 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Dolomite pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-2.45	-31.39	0.0196
2	-2.35	-30.10	0.0196
3	-2.32	-29.68	0.0192
4	-2.05	-26.27	0.0188
5	-2.35	-30.12	0.0158
6	-2.22	-28.39	0.0159
7	-2.48	-31.80	0.0189
8	-2.38	-30.42	0.0172
9	-2.37	-30.33	0.0197
10	-2.16	-27.59	0.0160
Mean	-2.31	-29.61	0.0181
Std. Error	0.04	0.54	0.0005
Combined	-2.31	-29.56	0.0075

LIMESTONE

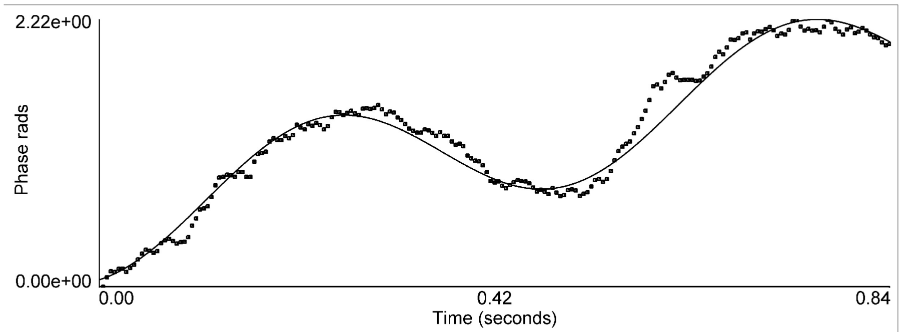
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 14:19:59
Batch: 0

Sample ID **Lime stone pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= 6.01 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 0.47 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 4389 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 48 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 456 kcps	Electric Field	= 6.70 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Lime stone pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	0.74	9.43	0.0182
2	0.35	4.54	0.0199
3	0.29	3.69	0.0187
4	0.71	9.06	0.0197
5	0.37	4.76	0.0194
6	0.46	5.91	0.0187
7	0.45	5.73	0.0182
8	0.49	6.31	0.0179
9	0.52	6.66	0.0197
10	0.32	4.06	0.0185
Mean	0.47	6.01	0.0189
Std. Error	0.05	0.62	0.0002
Combined	0.42	5.42	0.0068

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 20, 2010
Time: 01:33:11
Batch: 0

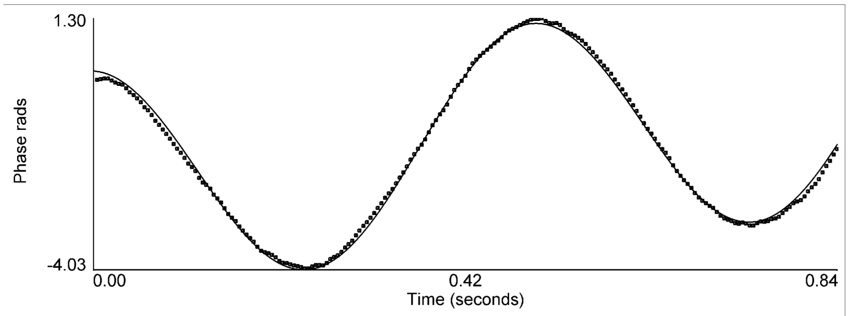
Sample ID **Lime Stone pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -19.71 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.54 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 74 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 196 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 519 kcps	Electric Field	= 8.86 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Cycles Per Run	= 20		



Lime Stone pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.51	-19.27	0.0104
2	-1.69	-21.68	0.0089
3	-1.50	-19.23	0.0169
4	-1.52	-19.45	0.0097
5	-1.57	-20.13	0.0137
6	-1.46	-18.75	0.0083
7	-1.58	-20.26	0.0189
8	-1.48	-18.93	0.0122
9	-1.59	-20.30	0.0105
10	-1.50	-19.14	0.0168
Mean	-1.54	-19.71	0.0126
Std. Error	0.02	0.28	0.0012
Combined	-1.54	-19.67	0.0056

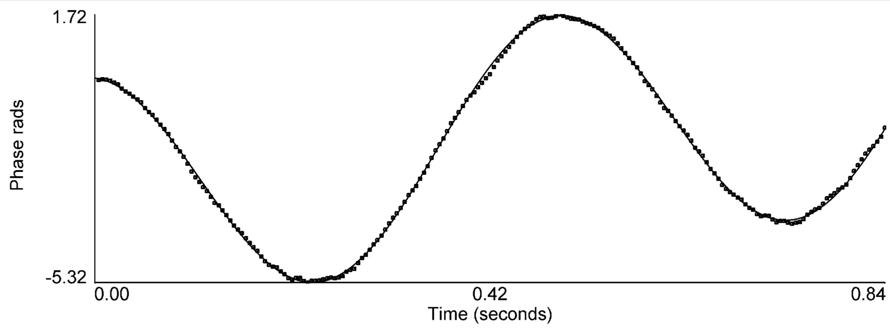
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 27, 2010
Time: 02:23:04
Batch: 0

Sample ID **Lime Stone pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= -30.63 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.39 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 370 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 219 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 548 kcps	Electric Field	= 7.46 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Lime Stone pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-2.12	-27.14	0.0191
2	-2.48	-31.68	0.0187
3	-2.23	-28.52	0.0190
4	-2.52	-32.26	0.0183
5	-2.67	-34.17	0.0192
6	-2.42	-30.92	0.0196
7	-2.48	-31.80	0.0182
8	-2.42	-31.01	0.0190
9	-2.64	-33.77	0.0193
10	-1.95	-25.01	0.0196
Mean	-2.39	-30.63	0.0190
Std. Error	0.07	0.92	0.0002
Combined	-2.39	-30.60	0.0039

SANDSTONE

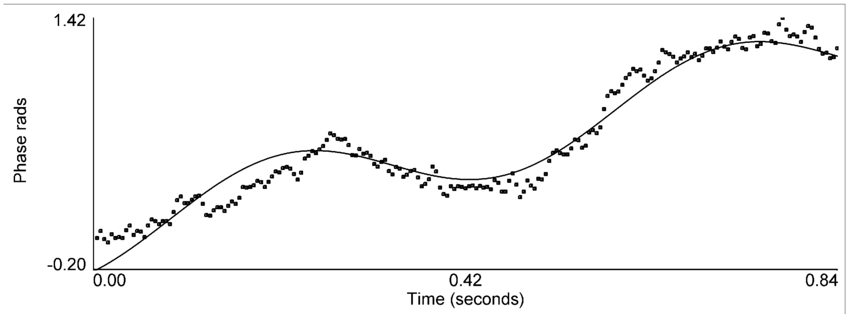
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 13:49:05
Batch: 0

Sample ID **Sand stone pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= 2.91 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 0.23 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 7597 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 198 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 495 kcps	Electric Field	= 6.67 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Sand stone pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	4.52e-01	5.78e+00	0.0197
2	6.06e-01	7.75e+00	0.0146
3	4.37e-01	5.59e+00	0.0184
4	-6.98e-01	-8.94e+00	0.0189
5	-1.44e-01	-1.85e+00	0.0195
6	4.13e-01	5.29e+00	0.0180
7	3.63e-01	4.64e+00	0.0187
8	-9.53e-02	-1.22e+00	0.0183
9	4.68e-01	5.99e+00	0.0197
10	4.76e-01	6.09e+00	0.0197
Mean	2.28e-01	2.91e+00	0.0186
Std. Error	1.29e-01	1.66e+00	0.0005
Combined	2.10e-01	2.69e+00	0.0064

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 20, 2010
Time: 23:22:20
Batch: 0

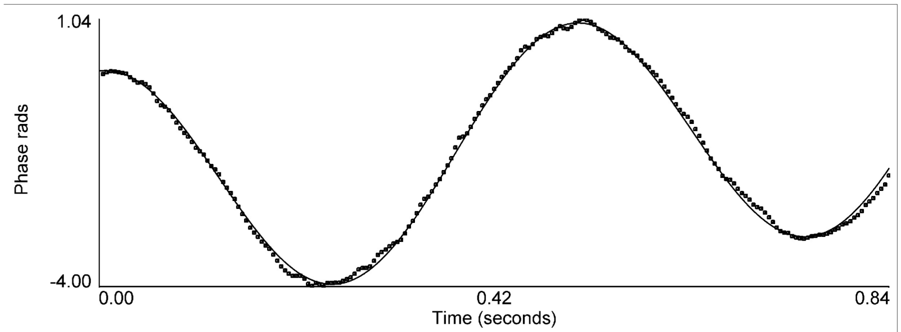
Sample ID **Sand Stone pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -16.73 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.31 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 20 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 279 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 694 kcps	Electric Field	= 9.92 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Sand Stone pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.37	-17.48	0.0181
2	-1.23	-15.79	0.0174
3	-1.39	-17.78	0.0199
4	-1.17	-14.97	0.0182
5	-1.20	-15.37	0.0194
6	-1.29	-16.50	0.0157
7	-1.40	-17.97	0.0193
8	-1.38	-17.64	0.0167
9	-1.30	-16.61	0.0191
10	-1.34	-17.14	0.0181
Mean	-1.31	-16.73	0.0182
Std. Error	0.03	0.34	0.0004
Combined	-1.30	-16.67	0.0053

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 31, 2010
Time: 02:56:47
Batch: 0

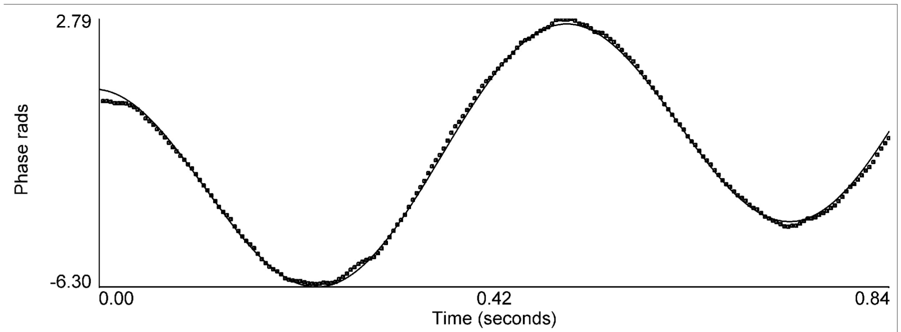
Sample ID **Sand Stone pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -37.94 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.96 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 376 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 163 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 472 kcps	Electric Field	= 7.61 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Sand Stone pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-3.42	-43.82	0.0194
2	-2.84	-36.36	0.0185
3	-3.16	-40.49	0.0319
4	-3.08	-39.45	0.0196
5	-2.83	-36.28	0.0173
6	-2.69	-34.41	0.0186
7	-2.65	-33.91	0.0195
8	-2.96	-37.88	0.0179
9	-3.15	-40.35	0.0173
10	-2.85	-36.47	0.0191
Mean	-2.96	-37.94	0.0199
Std. Error	0.08	0.97	0.0014
Combined	-2.96	-37.86	0.0077

STEEL SLAG

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 15:35:04
Batch: 0

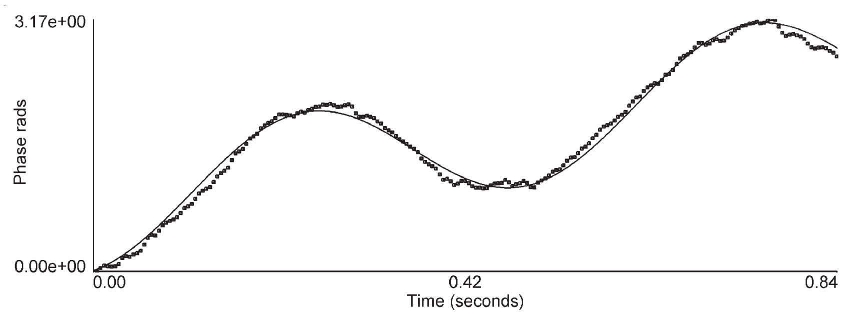
Sample ID **Steel slag pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= 7.87 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 0.62 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 6783 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 87 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 425 kcps	Electric Field	= 7.02 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 1e-02		



Steel slag pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	0.39	5.03	0.0149
2	0.77	9.88	0.0143
3	0.50	6.40	0.0143
4	0.52	6.71	0.0146
5	0.65	8.31	0.0149
6	0.68	8.71	0.0148
7	0.52	6.69	0.0139
8	0.84	10.76	0.0142
9	0.58	7.38	0.0149
10	0.69	8.83	0.0103
Mean	0.62	7.87	0.0141
Std. Error	0.04	0.55	0.0004
Combined	0.61	7.79	0.0053

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 21, 2010
Time: 00:10:32
Batch: 0

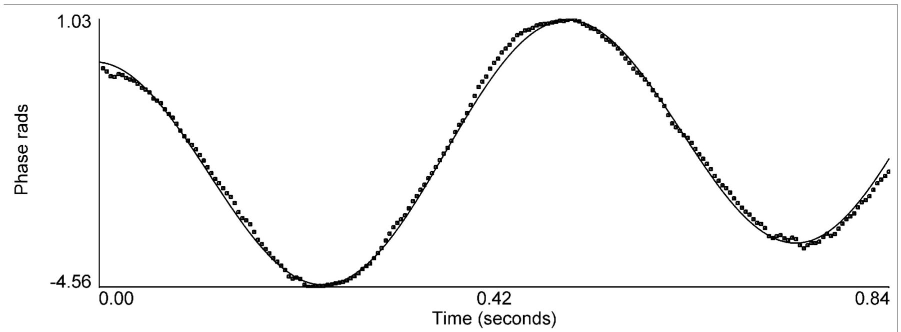
Sample ID **Steel slag pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -21.21 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.66 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 61 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 192 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 518 kcps	Electric Field	= 8.89 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Steel slag pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.57	-20.16	0.0163
2	-1.56	-19.94	0.0189
3	-1.87	-23.99	0.0177
4	-1.75	-22.44	0.0160
5	-1.79	-22.92	0.0179
6	-1.66	-21.28	0.0193
7	-1.72	-21.95	0.0182
8	-1.43	-18.29	0.0194
9	-1.56	-19.91	0.0193
10	-1.66	-21.21	0.0172
Mean	-1.66	-21.21	0.0180
Std. Error	0.04	0.53	0.0004
Combined	-1.65	-21.15	0.0074

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 27, 2010
Time: 03:24:28
Batch: 0

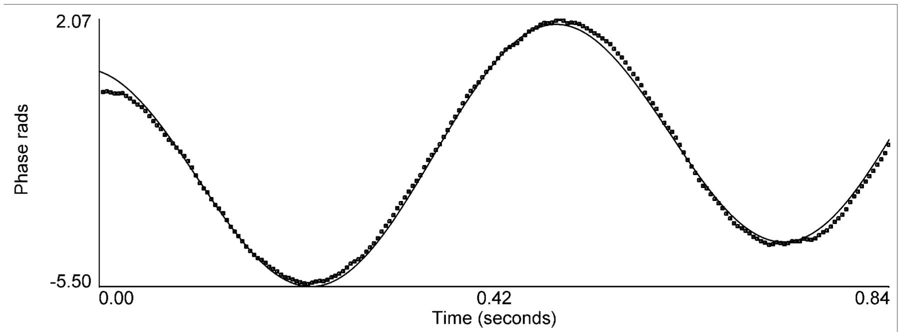
Sample ID **Steel Slag pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -33.50 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -2.62 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 546 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 198 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 540 kcps	Electric Field	= 7.50 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Steel Slag pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-2.49	-31.81	0.0179
2	-2.35	-30.03	0.0156
3	-2.26	-28.92	0.0189
4	-2.62	-33.50	0.0188
5	-2.91	-37.31	0.0180
6	-2.81	-35.95	0.0127
7	-2.66	-34.08	0.0177
8	-2.85	-36.45	0.0185
9	-2.48	-31.68	0.0198
10	-2.75	-35.24	0.0194
Mean	-2.62	-33.50	0.0177
Std. Error	0.07	0.89	0.0007
Combined	-2.62	-33.48	0.0098

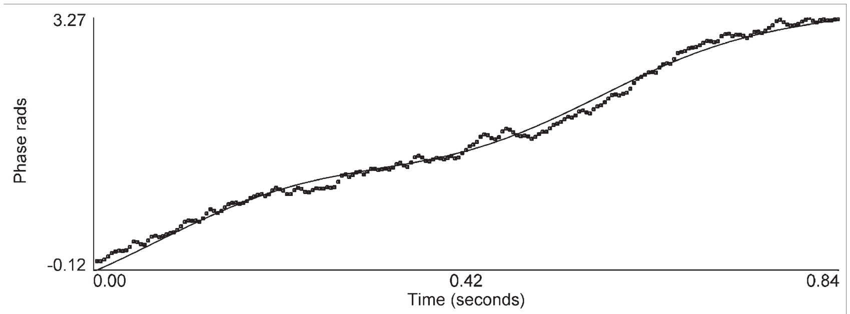
Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 23, 2010
Time: 15:14:58
Batch: 0

Sample ID **Trap rock pH2 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:			
Mean Zeta Potential	= 2.01 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= 0.16 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 2.00	Refractive Index	= 1.330
Conductance	= 8458 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:			
Sample Count Rate	= 169 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 491 kcps	Electric Field	= 6.73 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 1e-02		



Trap rock pH2 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	3.11e-01	3.98e+00	0.0135
2	3.01e-01	3.85e+00	0.0138
3	-1.20e-01	-1.54e+00	0.0149
4	4.28e-01	5.48e+00	0.0147
5	-2.98e-01	-3.81e+00	0.0139
6	-6.75e-02	-8.64e-01	0.0134
7	1.51e-01	1.93e+00	0.0148
8	5.70e-01	7.30e+00	0.0138
9	2.19e-01	2.81e+00	0.0141
10	7.93e-02	1.01e+00	0.0131
Mean	1.57e-01	2.01e+00	0.0140
Std. Error	8.38e-02	1.07e+00	0.0002
Combined	1.35e-01	1.73e+00	0.0053

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 20, 2010
Time: 23:42:15
Batch: 0

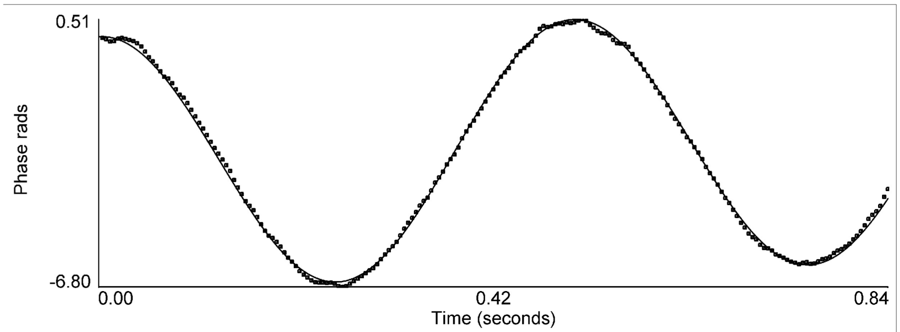
Sample ID **Trap Rock pH 7 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -24.67 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -1.93 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 7.00	Refractive Index	= 1.330
Conductance	= 7 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 219 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 604 kcps	Electric Field	= 10.43 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		



Trap Rock pH 7 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-1.85	-23.72	0.0190
2	-1.96	-25.09	0.0177
3	-1.97	-25.22	0.0164
4	-1.87	-23.95	0.0183
5	-2.10	-26.82	0.0194
6	-1.77	-22.69	0.0198
7	-1.77	-22.66	0.0170
8	-1.96	-25.11	0.0179
9	-2.14	-27.43	0.0183
10	-1.88	-24.03	0.0198
Mean	-1.93	-24.67	0.0184
Std. Error	0.04	0.50	0.0004
Combined	-1.92	-24.61	0.0060

Brookhaven Instruments Corp.
PALS Zeta Potential Analyzer Ver. 3.29

Date: Jul 31, 2010
Time: 01:46:54
Batch: 0

Sample ID **Trap Rock pH11 (Combined)**
Operator ID **Daehwan**
Notes

Measurement Parameters:

Mean Zeta Potential	= -56.03 mv	Liquid	= Aqueous
Zeta Potential Model	= Smoluchowski	Temperature	= 25.0 °C
Mean Mobility	= -4.38 (μ/s) / (V/cm)	Viscosity	= 0.890 cP
pH	= 11.00	Refractive Index	= 1.330
Conductance	= 359 μS	Dielectric Constant	= 78.54
Concentration	= 0.10 mg/mL	Particle Size	= 1000.0 nm

Instrument Parameters:

Sample Count Rate	= 257 kcps	Voltage	= 4.00 volts
Ref. Count Rate	= 530 kcps	Electric Field	= 7.69 V/cm
Wavelength	= 659.0 nm	User1	= 0.00
Field Frequency	= 2.00 Hz	User2	= 0.00
Target Residual	= 2e-02		

Trap Rock pH11 (Combined)

Run	Mobility	Zeta Potential (mV)	Rel. Residual
1	-4.10	-52.44	0.0192
2	-4.49	-57.47	0.0179
3	-4.55	-58.20	0.0183
4	-4.37	-55.93	0.0188
5	-4.23	-54.15	0.0156
6	-4.26	-54.55	0.0200
7	-4.12	-52.71	0.0200
8	-4.71	-60.33	0.0187
9	-4.31	-55.22	0.0194
10	-4.63	-59.27	0.0187
Mean	-4.38	-56.03	0.0187
Std. Error	0.07	0.86	0.0004
Combined	-4.37	-55.99	0.0076

6.2 EMULSION LAB TEST RESULTS

6.2.1 CRS-2P

TD-465

EMULSIFIED ASPHALTS

year: 10 | field/lab: | submitter: | sequence: CRS 2P

material: | spec.: | partial or complete: C | INFO

Test	Code							
Furol Visc., 25°C SFS	04	X	X	X	X			
Furol Visc., 25°C Exceeds 50 SFS	52	X	X	X	X			
Furol Visc., 50°C SFS 0.984 x 68.2 = ✕	05	X	X	X	X		6	7
Residue From Distillation % by Weight ✓	18	X	X		6	9	.	8
Stone Coating, Pass = 1 Fail = 2	71	X	X	X	X	X	X	
Oil Portion, ml/100g Emul. ✓	19	X	X		0	.	5	0
Demuls., 35ml. 0.02N $CaCl_2$, % dioctyl Sodium Sulfosuccinate	22	X	X	X	X		2	8
Demuls., 50ml. 0.1N $CaCl_2$, %	23	X	X	X	X			
Float Test @ 50°C Sec.	24	X	X	X				
Float Test @ 50°C less than 200 Sec.	54	X	X	X				
Float Test @ 60°C Sec.	25	X	X	X				
Float Test @ 60°C exceeds 1200 Sec.	55	X	X	X				
Penetration of Residue by Distillation								
25°C, 100g., 5 Sec. 106 106 106 ✓	20	X	X	X	X	1	0	6
25°C, 100g., 5 Sec., exceeds	53	X	X	X	X			
25°C, 50g., 5 Sec.	44	X	X	X	X			
25°C, 50g., 5 Sec., exceeds	45	X	X	X	X			
Solubility in Organic Solvents, % 17.5525 [( ) – (17.5506) 100%] 0.002 ; 115.9994 [( ) – (113.9473) 100%] 2.052	26	X		9	9	.	9	2
Duct., 25°C Cm.	28	X	X	X	X			
Duct., 25°C exceeds Cm. ✓	56	X	X	X	X	4	0	0
Storage Stability, 24 hr., % Difference	42	X	X	X			.	
Settlement, 5 Day, % Difference	27	X	X	X			.	
Sieve Test, % Retained ✓	43	X	X		0	.	8	8
Sand Penetration Time, Sec.	46	X	X	X	X			
Sand Penetration Time, exceeds Sec.	47	X	X	X	X			
Sand Penetration Depth, (× 1/16″)	48	X	X	X	X	X		
Weight/Gallon 25°C lbs.	60	X	X	X		.		

REMARKS:	LINE	RMK 1	RMK 2	RMK 3	AUTHORITY	ARD
	5				CMP/	

Research study for Chip Seal
Lee/Jusang

DATE RECEIVED	CKD. BY	DATE REPORTED BY LAB
9-14-10		9-16-10

State Form 37870 (R3/1-89)

6.2.2 RS-2P

TD-465 **EMULSIFIED ASPHALTS**

year: 10 | field/lab: | submitter: | sequence: RS 2P

material: | spec.: | partial or complete: C INFO

Test	Code								
Furol Visc., 25°C SFS	04	X	X	X	X				
Furol Visc., 25°C Exceeds 50 SFS	52	X	X	X	X				
Furol Visc., 50°C SFS 0.999X55.7= ✓	05	X	X	X	X		5	6	
Residue From Distillation % by Weight ✓	18	X	X		6	8	.	8	
Stone Coating, Pass = 1 Fail = 2	71	X	X	X	X	X	X		
Oil Portion, ml/100g Emul. ✓	19	X	X		0	.	5	0	
Demuls., 35ml. 0.02N $CaCl_2$, % ✓	22	X	X	X	X		2	8	
Demuls., 50ml. 0.1N $CaCl_2$, %	23	X	X	X	X				
Float Test @ 50°C Sec.	24	X	X	X					
Float Test @ 50°C less than 200 Sec.	54	X	X	X					
Float Test @ 60°C Sec.	25	X	X	X					
Float Test @ 60°C exceeds 1200 Sec.	55	X	X	X					
Penetration of Residue by Distillation									
25°C, 100g., 5 Sec. 107 106 104 ✓	20	X	X	X	X	1	0	6	
25°C, 100g., 5 Sec., exceeds	53	X	X	X	X				
25°C, 50g., 5 Sec.	44	X	X	X	X				
25°C, 50g., 5 Sec., exceeds	45	X	X	X	X				
Solubility in Organic Solvents, % 17.0637 [100% − (17.0617) ×100%] 0.002 / 122.7000 (120.6339) 2.065	26	X		9	9	.	8	9	
Duct., 25°C Cm. ✓	28	X	X	X	X				
Duct., 25°C exceeds Cm. ✓	56	X	X	X	X	4	0	0	
Storage Stability, 24 hr., % Difference	42	X	X	X			.		
Settlement, 5 Day, % Difference	27	X	X	X			.		
Sieve Test, % Retained ✓	43	X	X		0	.	0	7	
Sand Penetration Time, Sec.	46	X	X	X	X				
Sand Penetration Time, exceeds Sec.	47	X	X	X	X				
Sand Penetration Depth, (× 1/16″)	48	X	X	X	X	X			
Weight/Gallon 25°C lbs.	60	X	X	X		.			

REMARKS:	LINE	RMK 1	RMK 2	RMK 3	AUTHORITY	ARD
	5				CMP/	

Research study for Chip seal
Lee Jusang

DATE RECEIVED	CKD. BY	DATE REPORTED BY LAB
9-14-10		9-16-10

State Form 37870 (R3/1-89)

6.2.3 AE-90S

TD-465 **EMULSIFIED ASPHALTS**

10 — year | field/lab | submitter | CRS 2P — sequence

material | spec. | C — partial or complete | INFO

Test	Code							
Furol Visc., 25°C SFS	04	X	X	X	X			
Furol Visc., 25°C Exceeds 50 SFS	52	X	X	X	X			
Furol Visc., 50°C SFS 0.984×68.2= ×	05	X	X	X	X		6	7
Residue From Distillation % by Weight ✓	18	X	X		6	9	.	8
Stone Coating, Pass = 1 Fail = 2	71	X	X	X	X	X	X	
Oil Portion, ml/100g Emul.	19	X	X		0	.	5	0
Demuls., 35ml. 0.02N $CaCl_2$, % dioctyl Sodium Sulfosuccinate	22	X	X	X	X		2	8
Demuls., 50ml. 0.1N $CaCl_2$, %	23	X	X	X	X			
Float Test @ 50°C Sec.	24	X	X	X				
Float Test @ 50°C less than 200 Sec.	54	X	X	X				
Float Test @ 60°C Sec.	25	X	X	X				
Float Test @ 60°C exceeds 1200 Sec.	55	X	X	X				
Penetration of Residue by Distillation								
25°C, 100g., 5 Sec. 106 106 106 ✓	20	X	X	X	X	1	0	6
25°C, 100g., 5 Sec., exceeds	53	X	X	X	X			
25°C, 50g., 5 Sec.	44	X	X	X	X			
25°C, 50g., 5 Sec., exceeds	45	X	X	X	X			
Solubility in Organic Solvents, % 17.5522 [( ) − (17.5506) 0.002] / 115.9994 [( ) − (113.9473) 2.052] × 100%	26	X		9	9	.	9	2
Duct., 25°C Cm.	28	X	X	X	X			
Duct., 25°C exceeds Cm. ✓	56	X	X	X	X	4	0	0
Storage Stability, 24 hr., % Difference	42	X	X	X			.	
Settlement, 5 Day, % Difference	27	X	X	X			.	
Sieve Test, % Retained ✓	43	X	X		0	.	8	8
Sand Penetration Time, Sec.	46	X	X	X	X			
Sand Penetration Time, exceeds Sec.	47	X	X	X	X			
Sand Penetration Depth, (× 1/16″)	48	X	X	X	X	X		
Weight/Gallon 25°C lbs.	60	X	X	X		.		

REMARKS:	LINE	RMK 1	RMK 2	RMK 3	AUTHORITY	ARD
	5				CMP/	

Research study for Chip Seal

Lee/Jusang

DATE RECEIVED	CKD. BY	DATE REPORTED BY LAB
9-14-10		9-16-10

State Form 37870 (R3/1-89)

6.3 AGGREGATE LAB TEST RESULT

6.3.1 US-421

US-421

R084441904900

LOGANSPORT AREA LAB

Form 358

FIELD WORK SHEET

AGGREGATE INSPECTORS TEST LOG

REPORT NO. | SAMPLE NO. | CONTRACT NO.

SOURCE: 2412918 — NAME OF PLANT: Vulcan - Monon — LOCATION

MATERIAL: 12 CS

SPECIFICATION: 85 — 1965; 88 — 1988; SP — SPEC. PROV.

SAMPLE DATE: Mo. 06 Day 03 19 08

PURPOSE: R; 73 — JOB CONTROL; 75 — INFORMATION

SAMPLE FROM: Medaryville Plant — PLANT LOCATION

X X X X X X — Z

1. Stock/Stockpile
2. Bin or Tank
3. Processing Equip.
4. Truck, Barg. or Car
5. Inplace, Jobsite
6. Ledge or Pit
9. None of the above

REMARKS: 2644.4 - Wet; 2596.9; 2570.8

TEST NO. — R — LEDGES

INSPECTION CARD DATE: Mo. Day 19

TOTAL WEIGHT — GRAMS — LBS.

SIEVE SIZE	LONG GRAD. WEIGHT RET.	WEIGHT RETAINED	WEIGHT PASSING	PERCENT PASSING	PERCENT REQUIRED	Producer	Differce	C.S
2½"								
2								
1½								
1								
1/2		0	2596.9	100				
3/8		3.5	2593.4	99.9				
1/4		134.6	2458.8	94.7				
No. 4		378.4	2080.4	80.1				
6								
8		1424.4	656.0	25.3				
16		458.6	197.4	7.6				
30		102.1	95.3	3.7				
50		23.8	71.5	2.8				
100		12.7	58.8	2.3				
200		12.9	45.9	1.8				
PAN		19.2	26.7	1.0				

DECANT	ORIGINAL	FINAL	GRAMS LOSS	% LOSS	% REC.
	2596.9	2570.8	26.1	1.0	

NON-DURABLE	SAMPLE WT. 3/8" UP	WT. OF NON-DUR.	% NON-DUR.	LONG GRADED MATERIAL	TOTAL WT. PASS. No. 4	SAMPLE SIZE	PROPORT. FACTORS
					GM	GM	

TOTAL CHERT	SAMPLE WT. 3/8" UP	WT. OF TOT. CHERT	% TOTAL CHERT	TOTAL CHERT	SAMPLE WT. No. 4 UP	WT. OF TOT. CHERT	% TOTAL CHERT
AGG. SIZE 5, 8, 57, 53, 73				AGG. SIZE 9, 11			

MECH. CRUSHED	SAMPLE WT. No. 4 UP	WT. OF MECH. CRUSHED PT.	% MECH. CRUSHED	TOTAL CRUSHED	SAMPLE WT. No. 4 UP	WT. TOTAL CRUSHED	% TOTAL CRUSHED

DELETERIOUS TESTS PERFORMED: YES — 3; NO — 4 — MOISTURE (CAS) (CBI) %

K2 — X3 — K7 — LS

Pan
L-14

Specific Gravity & Absorption

Material Size:	12CS
Source of Mat'l:	Vulcan Monon
Sample Marking:	R08444419 04900

T 85 Procedure 8.1

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100 (85.9)	3.629		
Bulk Sp. Gr. = DRY / (WET - WATER) (944.5)	2.506		
Apparent Sp. Gr. = DRY / (DRY - WATER) (858.6)	2.757		
Bulk Sp. Gr. (SSD) = WET / (WET - WATER) (944.5)	2.597		

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.
2366.8	2452.7	1508.2	

T 85 Procedure 8.2

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100			
Bulk Sp. Gr. = DRY / (WET - WATER)			
Apparent Sp. Gr. = DRY / (DRY - WATER)			
Bulk Sp. Gr. (SSD) = WET / (WET - WATER)			

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.

* Equations above for Course Agg. ONLY
** Fine Agg. Data is the same for 8.1 and 8.2

SR-14

R 08444190 4898

LOGANSPORT AREA LAB

Form 358

FIELD WORK SHEET

AGGREGATE INSPECTORS TEST LOG

REPORT NO.

SAMPLE NO.

CONTRACT NO.

SOURCE 214213 Ens. Agg. Plant #1

NAME OF PLANT

LOCATION

MATERIAL 12 CS

SPECIFICATION 85 — 1545 84 — 1586 SP — SPEC. PROV.

SAMPLE DATE Mo. 08 Day 30 19 98

PURPOSE (R) 73 — JOB CONTROL 75 — INFORMATION

SAMPLE FROM X X X X X X Z Wabash Sub PLANT LOCATION

1. Stock/Stockpile
2. Bin or Tank
3. Processing Equip.
4. Truck, Barg, or Car
5. Inplace, Jobsite
6. Ledge or Pit
9. None of the above

REMARKS

2470.4

2394.5

2349.9

TEST NO. (R) LEDGES

INSPECTION CARD DATE Mo. Day 19

TOTAL WEIGHT GRAMS LBS.

SIEVE SIZE	LONG GRAD. WEIGHT RET.	WEIGHT RETAINED	WEIGHT PASSING	PERCENT PASSING	PERCENT REQUIRED	Producer	Differce	C.S
2½"								
2								
1½								
1								
½		0	2394.5	100				
3/8		0	2394.5	100				
¼	P/F	217.9	2176.6	90.9				
No. 4		587.5	1589.1	66.4				
6								
8		1399.0	190.1	7.9				
16		107.4	82.7	3.5				
30		11.4	71.3	3.0				
50		5.5	65.8	2.7				
100		4.1	61.7	2.6				
200		4.0	57.7	2.4				
PAN		7.9	49.8	2.1				

DECANT	ORIGINAL	FINAL	GRAMS LOSS	% LOSS	% REQ.
	2394.5	2349.9	44.6	1.8	

NON-DURABLE	SAMPLE WT. 3/8" UP	WT. OF NON-DUR.	% NON-DUR.	LONG GRADED MATERIAL	TOTAL WT. PASS. No. 4	SAMPLE SIZE	PROPORT. FACTORS
					GM	GM	
TOTAL CHERT	SAMPLE WT. 3/8" UP	WT. OF TOT. CHERT	% TOTAL CHERT	TOTAL CHERT	SAMPLE WT. No. 4 UP	WT. OF TOT. CHERT	% TOTAL CHERT
AGG. SIZE 5, 8, 5?, 53, 73				AGG. SIZE 9, 11			
MECH. CRUSHED	SAMPLE WT. No. 3 UP	WT. OF MECH. CRUSHED PT.	% MECH. CRUSHED	TOTAL CRUSHED	SAMPLE WT. No. 4 UP	WT. TOTAL CRUSHED	% TOTAL CRUSHED
DELETERIOUS TESTS PERFORMED	YES — 3	NO — 4		MOISTURE (CA5) (CA31)	%		

K? X5 K7 L1

Specific Gravity & Absorption

Pan A-4

Material Size:	12cs
Source of Mat'l:	Eng Agg 1
Sample Marking:	R08444190489 8

T 85 Procedure 8.1

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100	4.711		
Bulk Sp. Gr. = DRY / (WET - WATER) 899.6	2.421		
Apparent Sp. Gr. = DRY / (DRY - WATER) 797	2.732		
Bulk Sp. Gr. (SSD) = WET / (WET - WATER) 899.6	2.535		

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.
2177.7	2280.3	1380.7	

T 85 Procedure 8.2

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100			
Bulk Sp. Gr. = DRY / (WET - WATER)			
Apparent Sp. Gr. = DRY / (DRY - WATER)			
Bulk Sp. Gr. (SSD) = WET / (WET - WATER)			

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.

* Equations above for Course Agg. ONLY

** Fine Agg. Data is the same for 8.1 and 8.2

SR-110

R08441904897

#1

LOGANSPORT AREA LAB

Form 358

FIELD WORK SHEET

AGGREGATE INSPECTORS TEST LOG

REPORT NO. | SAMPLE NO. | CONTRACT NO.

SOURCE: 212514 | NAME OF PLANT: Rock Ind. | LOCATION: Peru

		REMARKS
MATERIAL	12's	2268.2 - wet wt.
SPECIFICATION	85 — 1985, 88 — 1988, SP — SPEC. PROV.	2225.5 -
SAMPLE DATE	Mo. 05 Day 30 19 08	2159.9 ·
PURPOSE ®	73 — JOB CONTROL, 75 — INFORMATION	
SAMPLE FROM	PLANT: Rochester Unit; LOCATION	
XXXXXX Z		
TEST NO. ®	LEDGES	
INSPECTION CARD DATE	Mo. Day 19	
TOTAL WEIGHT	GRAMS LBS.	

1. Stock/Stockpile
2. Bin or Tank
3. Processing Equip.
4. Truck, Barg, or Car
5. Inplace, Jobsite
6. Ledge or Pit
9. None of the above

SIEVE SIZE	LONG GRAD. WEIGHT RET.	WEIGHT RETAINED	WEIGHT PASSING	PERCENT PASSING	PERCENT REQUIRED	Producer	Difference	C.S
2½"								
2								
1½								
1								
½		0	2225.5	100				
3/8		0	2225.5	100				
¼		244.9	1980.6	89.0				
No. 4		665.2	1315.4	59.1				
6								
8		1978.2	337.2	15.2				
16		208.6	136.6	6.1				
30		36.3	100.3	4.5				
50		9.8	90.5	4.1				
100		3.2	87.3	3.9				
200		3.9	83.4	3.7				
PAN		11.3	72.1	3.2				

Fail ⇒

DECANT	ORIGINAL	FINAL	GRAMS LOSS	% LOSS	% REQ.
	2225.5	2159.9	65.6	2.9	

NON-DURABLE	SAMPLE WT. 3/8" UP	WT. OF NON-DUR.	% NON-DUR.	LONG GRADED MATERIAL	TOTAL WT. PASS. No. 4	SAMPLE SIZE	PROPORT. FACTORS
					GM	GM	
TOTAL CHERT	SAMPLE WT. 3/8" UP	WT. OF TOT. CHERT	% TOTAL CHERT	TOTAL CHERT	SAMPLE WT. No. 4 UP	WT. OF TOT. CHERT	% TOTAL CHERT
AGG. SIZE 5, 8, 57, 53, 73				AGG. SIZE 9, 11			
MECH. CRUSHED	SAMPLE WT. No. 4 UP	WT. OF MECH. CRUSHED PT.	% MECH. CRUSHED	TOTAL CRUSHED	SAMPLE WT. No. 4 UP	WT. TOTAL CRUSHED	% TOTAL CRUSHED
DELETERIOUS TESTS PERFORMED	YES — 3	NO — 4		MOISTURE (CAS) (CA3) %			

K2 K3 K7 L1

Specific Gravity & Absorption

12cs

Pan B.1

Material Size:	Rock Ind 12cs
Source of Mat'l:	
Sample Marking:	R084441904997

T 85 Procedure 8.1

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100	3.986		
Bulk Sp. Gr. = DRY / (WET - WATER)	2.469		
Apparent Sp. Gr. = DRY / (DRY - WATER)	2.739		
Bulk Sp. Gr. (SSD) = WET / (WET - WATER)	2.568		

851.4

767.6

851.4

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.
2102.3	2186.1	1334.7	

T 85 Procedure 8.2

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100			
Bulk Sp. Gr. = DRY / (WET - WATER)			
Apparent Sp. Gr. = DRY / (DRY - WATER)			
Bulk Sp. Gr. (SSD) = WET / (WET - WATER)			

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.

* Equations above for Course Agg. ONLY

** Fine Agg. Data is the same for 8.1 and 8.2

SR-110

Sample #2 Different stockpiles

K084 44904901

LOGANSPORT AREA LAB

Form 358

FIELD WORK SHEET

AGGREGATE INSPECTORS TEST LOG

REPORT NO. SAMPLE NO. CONTRACT NO.

SOURCE 2034 — NAME OF PLANT: Rock IND — LOCATION: Peru

MATERIAL: 12 CS

SPECIFICATION: 85 — 1985, 88 — 1988, SP — SPEC. PROV.

SAMPLE DATE: Mo. 06 Day 04 19 08

PURPOSE: 73 — JOB CONTROL, 75 — INFORMATION

SAMPLE FROM: 1. Stock/Stockpile 2. Bin or Tank 3. Processing Equip. 4. Truck, Barg, or Car 5. Inplace, Jobsite 6. Ledge or Pit 9. None of the above

PLANT / LOCATION: XXXXXX Z

TEST NO. ® LEDGES

INSPECTION CARD DATE: Mo. 06 Day 04 19 08

TOTAL WEIGHT — GRAMS — LBS.

REMARKS: 2468.7 - Wet; 2391.0; 2323.2

SIEVE SIZE	LONG GRAD. WEIGHT RET.	WEIGHT RETAINED	WEIGHT PASSING	PERCENT PASSING	PERCENT REQUIRED	Producer	Difference	C.S
2½"								
2								
1½								
1								
1/2		0	2391.0	100	100			
3/8		0	2391.0	100	95-100			
1/4	1/4	241.3	2149.7	89.9				
No. 4		641.9	1507.8	63.1	50-80			
6								
8		1133.0	348.0	14.6	0-35			
16		238.4	136.4	5.7				
30		36.8	99.6	4.2	0-4			
50		9.5	90.1	3.8				
100		4.3	85.8	3.6				
200		3.9	81.9	3.4				
PAN		7.3	74.6	3.1				

DECANT	ORIGINAL	FINAL	GRAMS LOSS	% LOSS	% REQ.
Fail ⇒	2391.0	2323.2	67.8	2.8	0-2.0

NON-DURABLE	SAMPLE WT. 3/8" UP	WT. OF NON-DUR.	% NON-DUR.	LONG GRADED MATERIAL	TOTAL WT. PASS. No. 4	SAMPLE SIZE	PROPORT. FACTORS
					GM	GM	
TOTAL CHERT	SAMPLE WT. 3/8" UP	WT. OF TOT. CHERT	% TOTAL CHERT	TOTAL CHERT	SAMPLE WT. No. 4 UP	WT. OF TOT. CHERT	% TOTAL CHERT
AGG. SIZE 5, 8, 57, 53, 73				AGG. SIZE 9, 11			
MECH. CRUSHED	SAMPLE WT. No. 4 UP	WT. OF MECH. CRUSHED PT.	% MECH. CRUSHED	TOTAL CRUSHED	SAMPLE WT. No. 4 UP	WT. TOTAL CRUSHED	% TOTAL CRUSHED
DELETERIOUS TESTS PERFORMED	YES — 3	NO — 4		MOISTURE (C45) (C33) %	K2	K5	K7 L1

Specific Gravity & Absorption

Pan F

Material Size:	Rock 12cs
Source of Mat'l:	
Sample Marking:	R08444190490l

T 85 Procedure 8.1

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100	3.683		
Bulk Sp. Gr. = DRY / (WET - WATER)	2.485		
Apparent Sp. Gr. = DRY / (DRY - WATER)	2.735		
Bulk Sp. Gr. (SSD) = WET / (WET - WATER)	2.836		

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.
2153.2	2232.5	1366.0	

T 85 Procedure 8.2

	Coarse	Fine	Wt. Average
Absorption = (DRY - WET) / DRY * 100			
Bulk Sp. Gr. = DRY / (WET - WATER)			
Apparent Sp. Gr. = DRY / (DRY - WATER)			
Bulk Sp. Gr. (SSD) = WET / (WET - WATER)			

IN AIR - DRY	IN AIR - WET	IN WATER	Fine AGG. Wt.

* Equations above for Course Agg. ONLY
** Fine Agg. Data is the same for 8.1 and 8.2

6.4 FIELD TEST METHOD FOR MEASURING SEAL COAT AGGREGATE AND EMULSION APPLICATION RATES

EQUIPMENT

Field Balance
32 Gallon Trash Bin
5-gallon Bucket
1 SYD carpet, burlap, or canvas, cut into square
Long-handled Tongs/Hooks/Pliers
Garbage Bags
Marker
Rubber Gloves
Rolled Paper (for walk path)

EMULSION MEASUREMENT METHOD

1. Label each carpet square.
2. Place a clean trash bag in the garbage container.
3. Weigh and record weights of each carpet square and the garbage container/bag.
4. Record location of test.
5. Lay 1 SYD carpet squares in line with distributor – 2 squares, roughly in the wheel paths.
6. Run distributor at application speed and emulsion rate over squares.
7. Place the ground paper on sprayed emulsion to approach the carpets.
8. Immediately pick up carpet square, garbage container, and weigh.
9. Record total weight.
10. Calculate and report application rate.
11. Reseal the area covered the carpets.

AGGREGATE MEASUREMENT METHOD

1. Weigh and record weight of 5-gallon bucket.
2. Record location of test.
3. Lay 1 SYD burlap or canvas in line with aggregate spreader.
4. Run aggregate spreader at application speed and application rate over burlap.
5. Pick up burlap square, and deposit aggregate into 5-gallon bucket.
6. Weigh 5-gallon bucket and aggregate.
7. Record total weight.
8. Calculate and report application rate.
9. Sweep/reseal the area covered by the burlap square.

Figure 6.1 Emulsion application rate measurement procedure at the project site

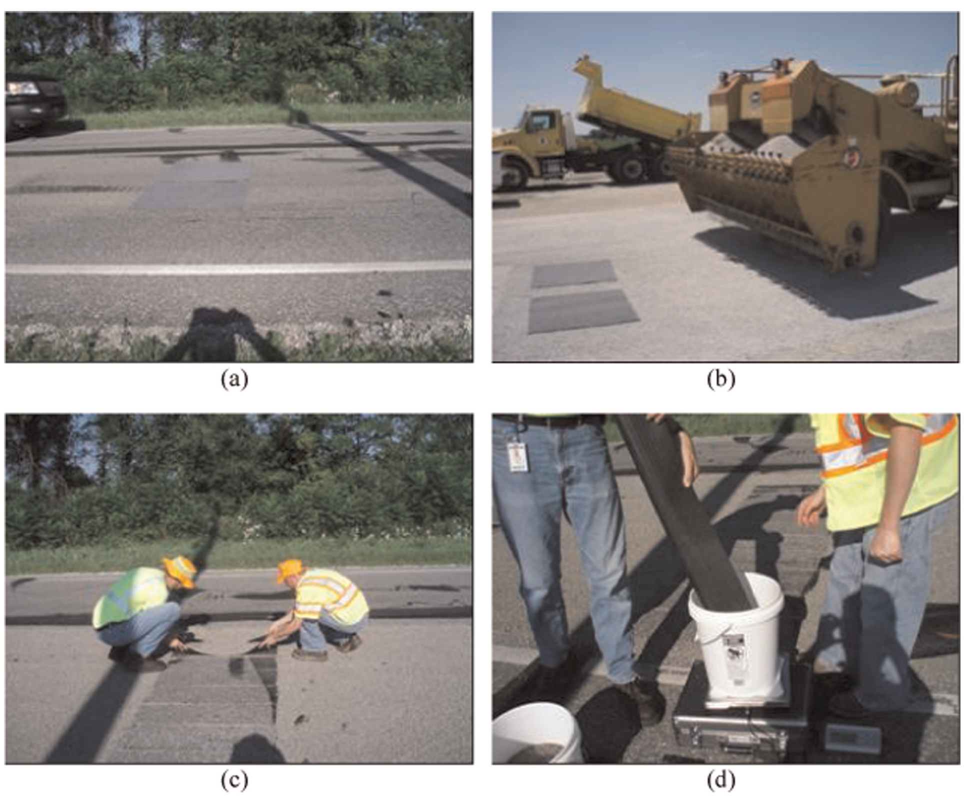


Figure 6.2 Aggregate application rate measurement procedure at the project site

Worksheet for Field Determination of Emulsion Application Rate

Date: ______________ Location: ______________ Emulsion Type: ______________

Emulsion Density = 235 Gal/ton
Emulsion Density = 8.51 lb/gal

		A	B	C	D=C-(A+B)	D/8.51
Location	**Carpet Label**	**Carpet Weight (lbs)**	**Garage Bin + Bag (lbs)**	**Total Weight with Emulsion (lbs)**	**Weight of Emulsion (lbs)**	**Application Rate (gal/SYD)**

Revised 1/1/08

Worksheet for
Field Determination of Aggregate Application Rate

Date: ______________ Location: ____________

Aggregate Type: ____________

	A	B	C=B-A	C
Location	**5 Gallon Bucket Weight (lbs)**	**Total Weight with Aggregate (lbs)**	**Weight of Aggregate (lbs)**	**Application Rate (lb/SYD)**

6.5 INDIANA DEPARTMENT OF TRANSPORTATION OFFICE OF MATERIALS MANAGEMENT QUANTITY DETERMINATION OF ASPHALT MATERIALS AND AGGREGATES FOR SEAL COATS, ITM NO. 579-08P

1.0 SCOPE.

1.1 This method covers the procedure for determination of the quantity of asphalt materials and aggregates in seal coat applications.
1.2 The values stated in either acceptable English or SI metric units are to be regarded separately as standard, as appropriate for a specification with which this ITM is used. Within the text, SI metric units are shown in parentheses. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other, without combining values in any way.
1.3 This ITM may involve hazardous materials, operations, and equipment and may not address all of the safety problems associated with the use of the test method. The user of the ITM is responsible for establishing appropriate safety and health practices and determining the applicability of regulatory limitations prior to use.

2.0 TERMINOLOGY. Definitions for terms and abbreviations shall be in accordance with the Department's Standard Specifications, Section 101.

3.0 SIGNIFICANCE AND USE. This ITM shall be used to determine the quantity of asphalt materials and aggregates required for a seal coat application.

4.0 APPARATUS.

4.1 Traffic control equipment and personnel to be furnished by the District
4.2 Pneumatic tire roller or vehicle
4.3 Yield test scales
4.4 Buckets as needed
4.5 5-gallon can with pour spout
4.6 Stove
4.7 0.5 yd2 template consisting of a 30 x 48 in. metal plate with an 18 x 36 in. opening, ITM 579-08P, Revised 1/1/08
4.8 Aggregate shaker box approximately 18 in. square and 3 in. deep with a 1-in. open slot in the bottom along one side. A piece of 1/2-in. opening screen cloth shall extend under this open slot.
4.9 Squeegee and brushes as needed
4.10 Thermometer, range 50 to 300°F

5.0 MATERIALS.

5.1 A minimum of 5 gallon of the asphalt material that is to be used on the project.
5.2 A minimum of 75 lb. of the aggregate that is to be used on the project.

6.0 PROCEDURE.

6.1 Select a location typical of the project. Sites shall be selected to prevent tracking of asphalt from one test area to another. On the mainline, select a wheel path.
6.2 Set up traffic control.
6.3 Heat the asphalt material according to the following:
6.4 Clean and prepare surface as necessary.
6.5 Place the template on the selected site.
6.6 Weigh the aggregate. The quantity shall be within the values listed in TABLE 1.

Asphalt	Temperature
AE-90, AE-150	140 – 160°F
RS-2	120 – 140°F
RC-800	230 – 250°F
RC-3000	250 – 275°F

6.7 Weigh the heated bituminous material. The quantity shall be within the values listed in TABLE 1.
6.8 Apply the liquid asphalt uniformly on the test area by pouring and using the squeegee, and brush to distribute.
6.9 Place the aggregate uniformly on the test area with the shaker box.
6.10 Remove the template.
6.11 Roll the test area with the pneumatic tire roller or the vehicle tire.
6.12 Repeat the above procedure by varying the quantities of asphalt material and aggregates until the desired result is obtained.
6.13 Remove traffic control. If test areas are on the mainline, removal of traffic control shall be delayed until the asphalt material has cured sufficiently to hold the aggregate without displacement.

Rate of Application per Square Yard		
Aggregate Size No.	Cover Aggregate, lb	Asphalt Material gal at 60°F
23, 24	12 – 15	0.12 – 0.16
12	14 – 17	0.29 – 0.33
11	16 – 20	0.36 – 0.40
9	28 – 32	0.63 – 0.68

6.14 Return to location the next day, broom off and weigh the excess aggregate for shoulder locations. This procedure is not required for mainline locations.

6.15 Make a visual inspection of the test areas for asphalt content and aggregate retention. Further visual inspection shall be made until the seal coat operation starts. The test area shall appear to be one aggregate particle in depth, and the particle shall be embedded in the asphalt material 50-70%.

7.0 REPORT.

7.1 The quantity of asphalt material and aggregate for the seal coat shall be reported on the appropriate form for use on the proposed project. If there are different pavement sections on the project, several test sections may be necessary.

General Information

Name of Recorder		*Time/Date*	
Road	US 421/SR14/SR110		-
Temperature			

Performance Scores

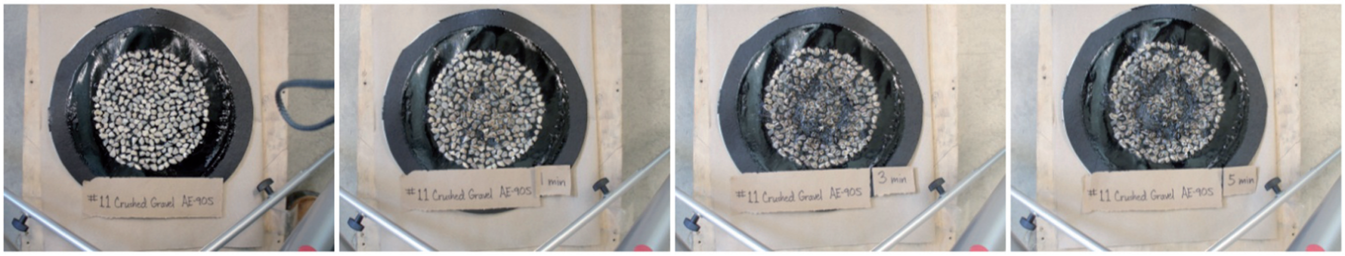
Number	Distress	Sections												
		421NB-204-205	421NB-205-206	14EB-39-40	14EB-40-41	14EB-41-42	14EB-42-43	110WB-3-4	110WB-4-5	110WB-5-6	110WB-6-7	110EB-3-4	110EB-4-5	110EB-5-6
1	Aggregate Loss													
2	Bleeding /Flushing													
3	Excessive Aggregate													
4	Delamination													
5	Streaking													
6	Reflected Bleeding from Crack Seal													
7	Polishing													

Note: 0 being excellent to 10 being unacceptable

6.7 SWEEP TEST RESULT

6.7.1 AE-90S

CRUSHED GRAVEL WITH TWO FACES



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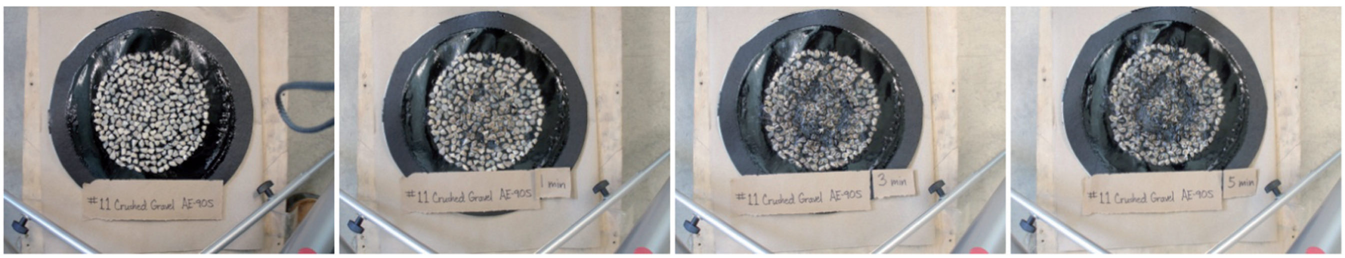
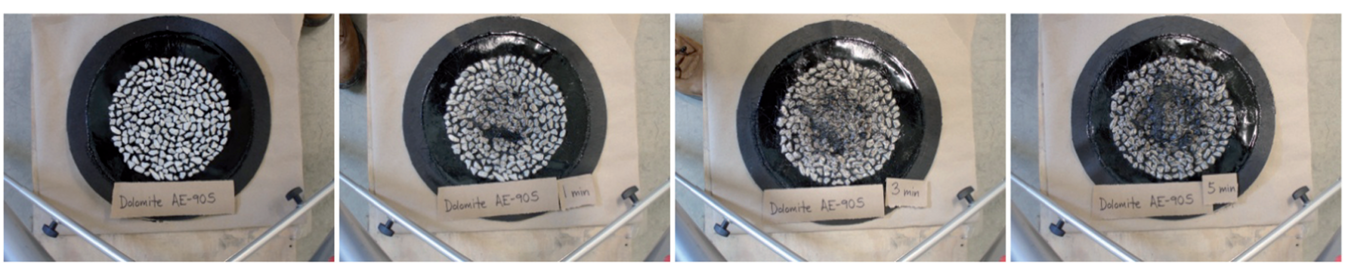


CRUSHED GRAVEL WITH ONE FACE

DOLOMITE



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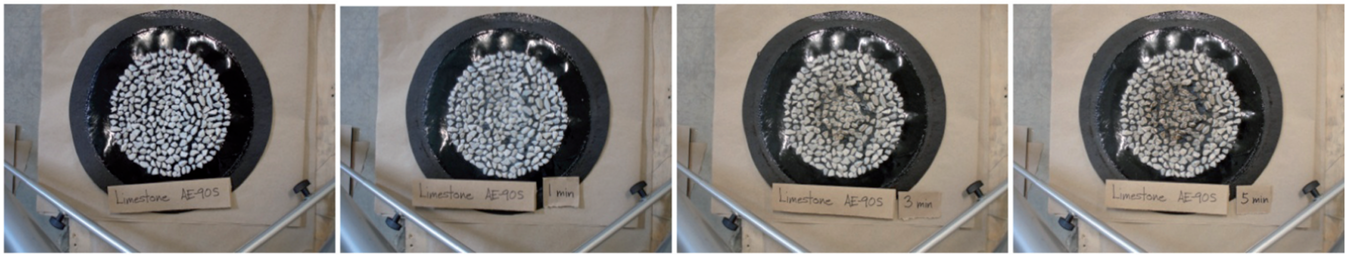
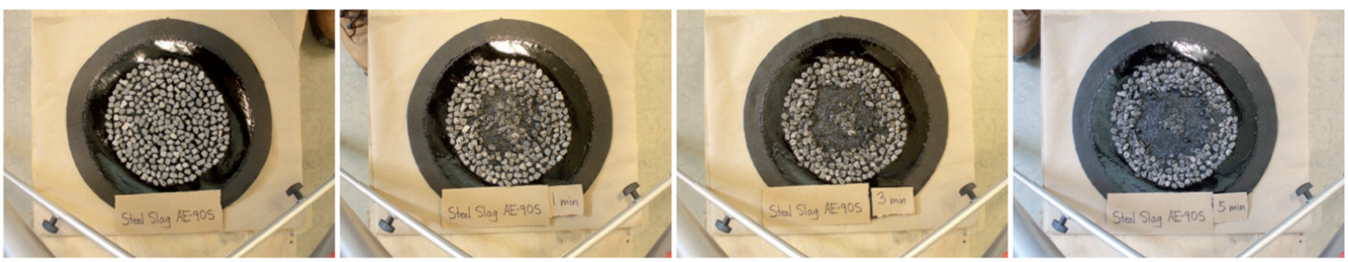


SANDSTONE

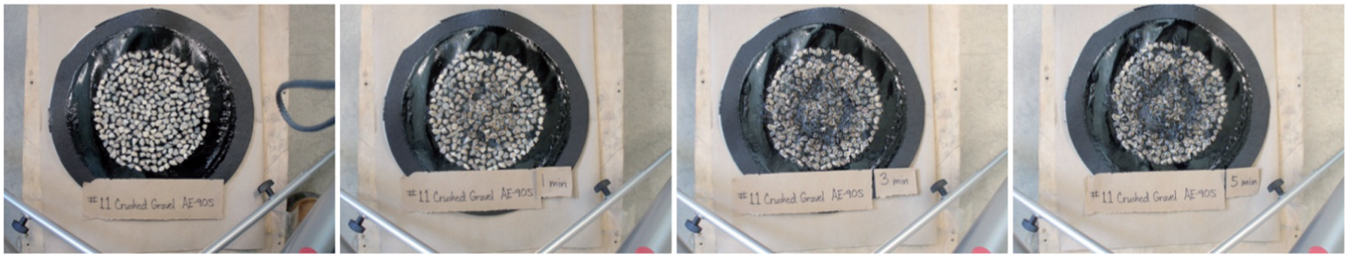
STEEL SLAG



TRAP ROCK

6.7.2 CRS-2P

CRUSHED GRAVEL WITH TWO FACES



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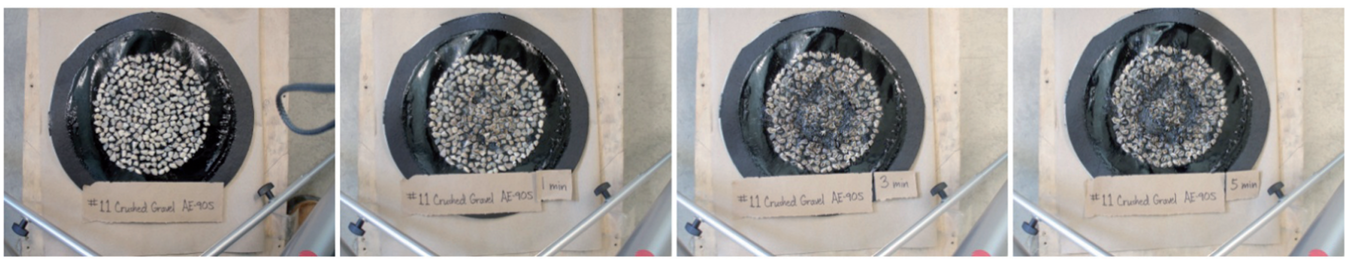

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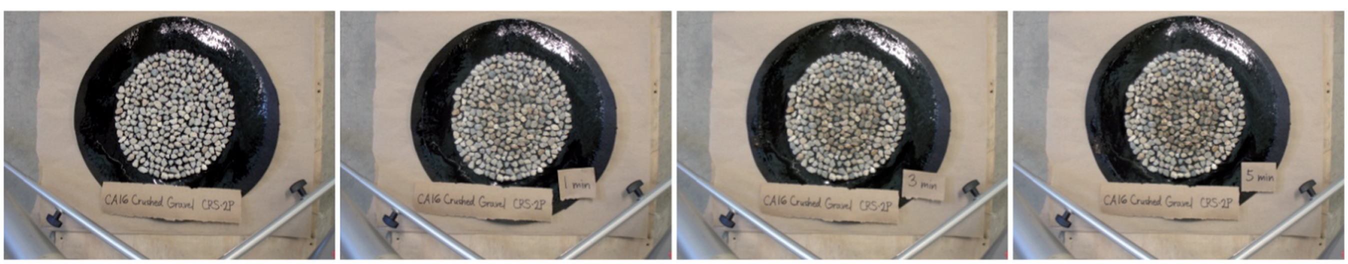

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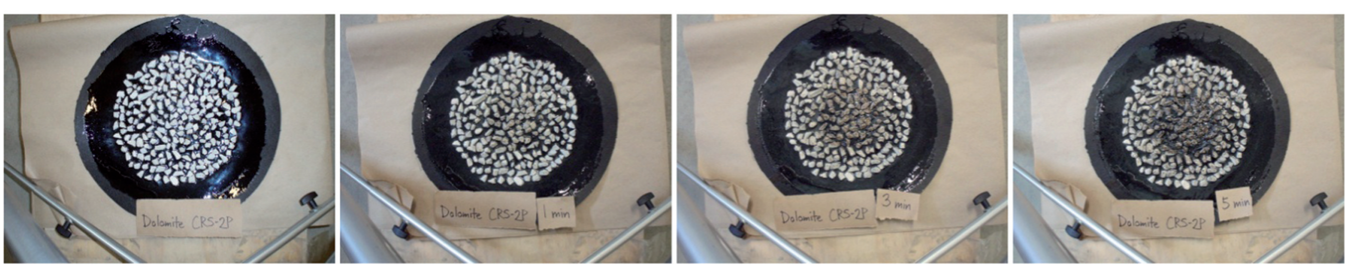

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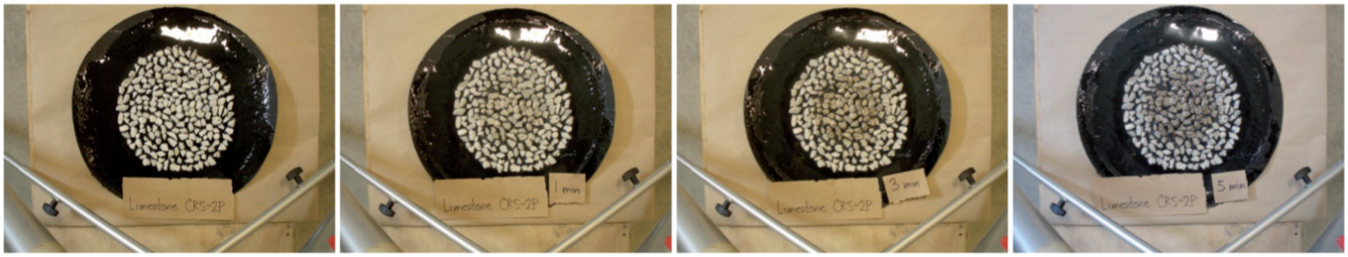

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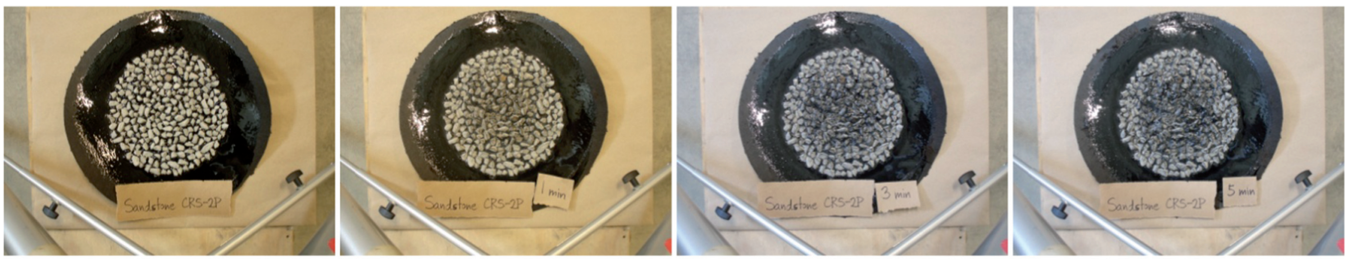

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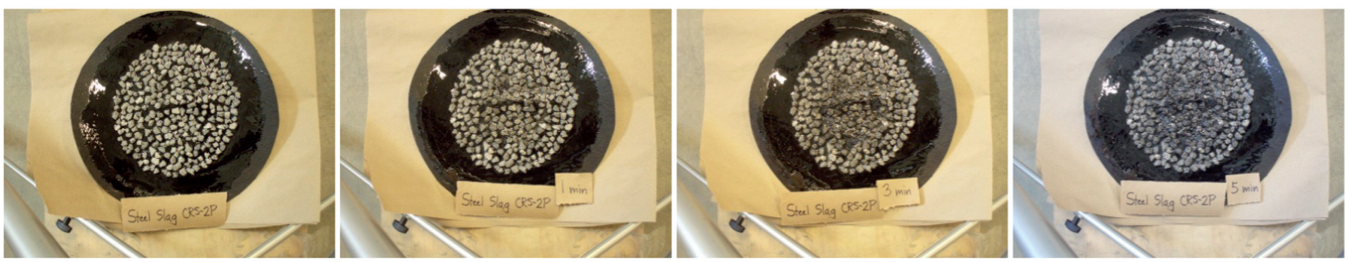

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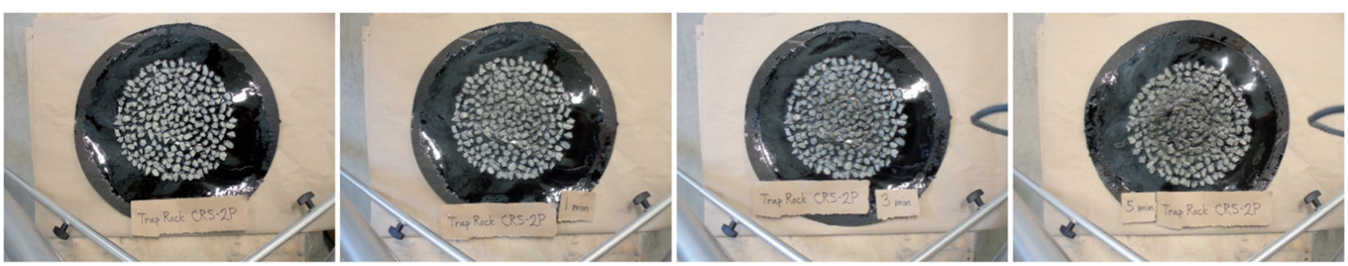

6.7.3 RS-2P

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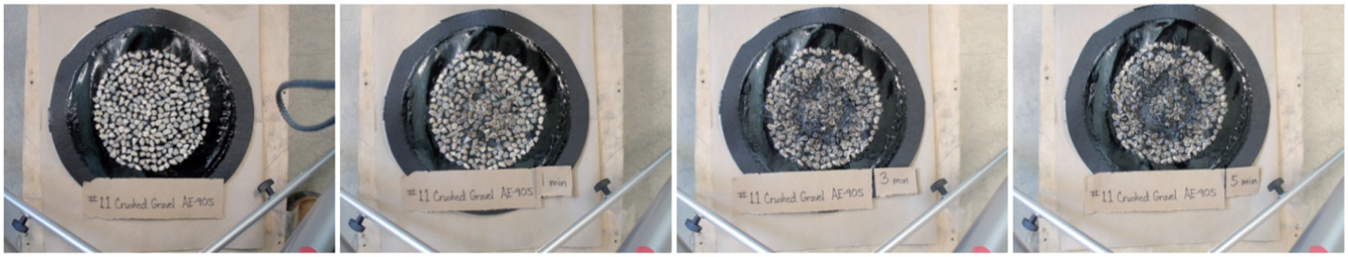

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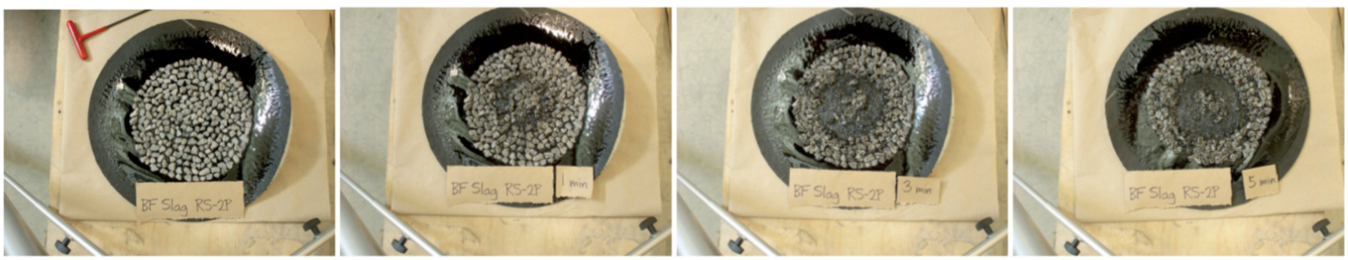

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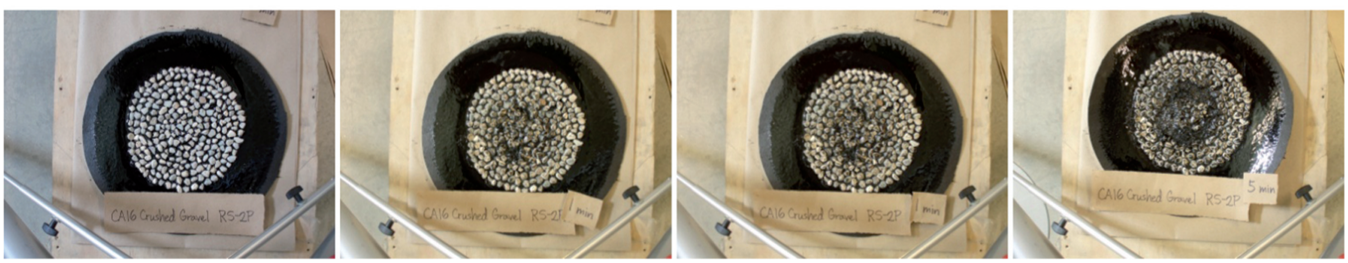
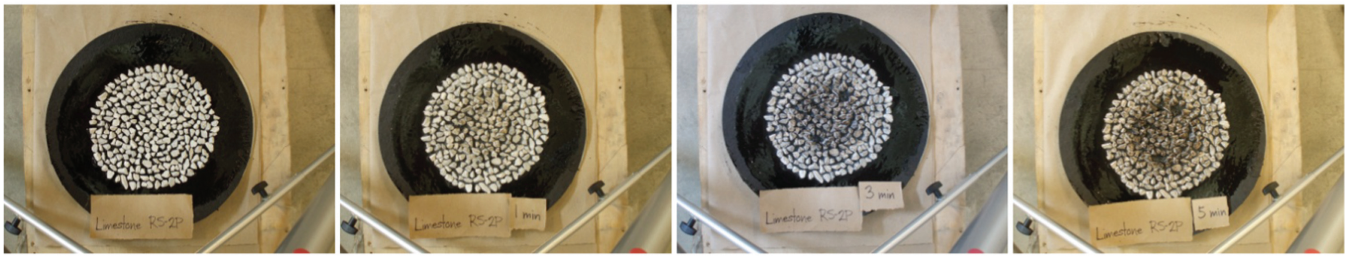


DOLOMITE

LIMESTONE



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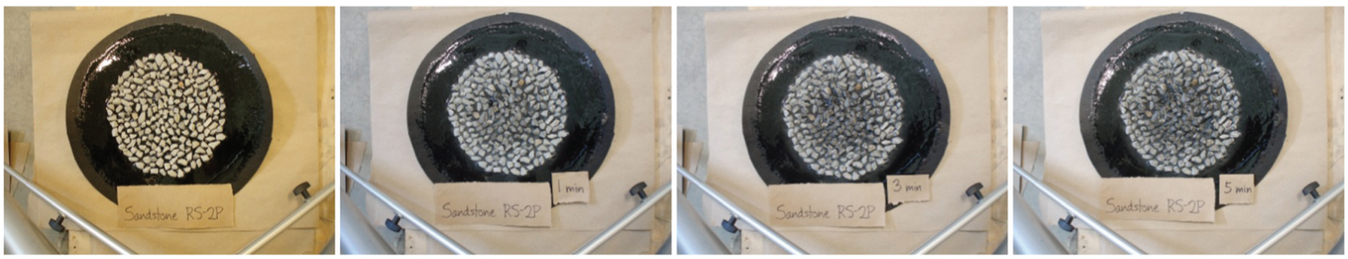
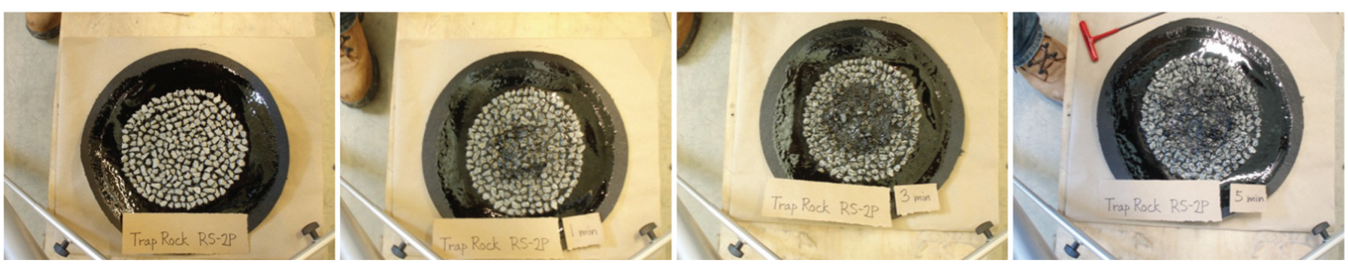


STEEL SLAG

TRAP ROCK

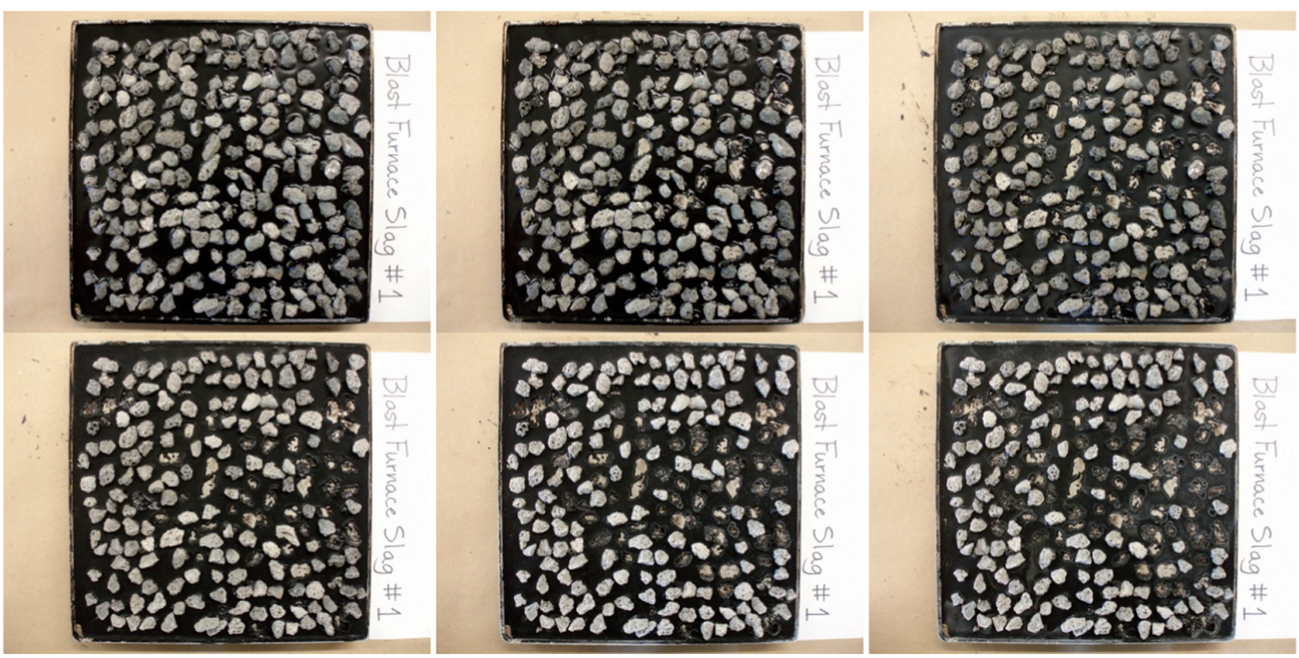


6.8 VIALIT TEST RESULT

6.8.1 AE-90S

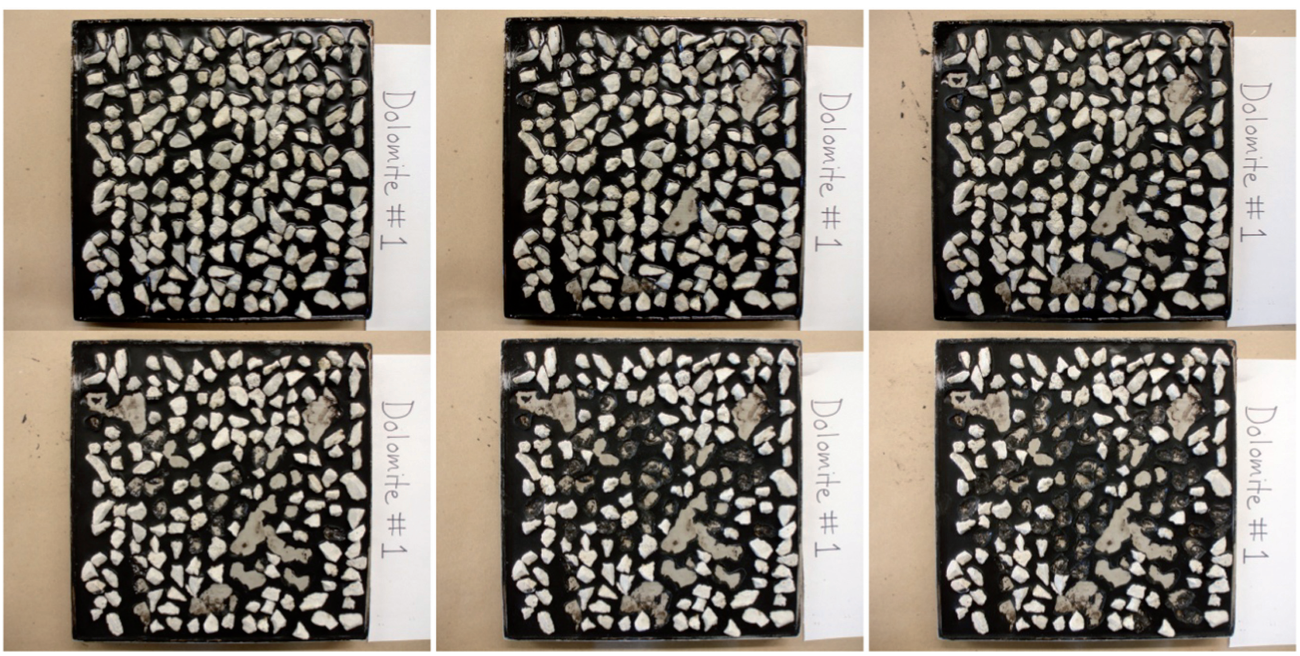
CRUSHED GRAVEL WITH TWO FACES

BLAST FURNACE



CRUSHED GRAVEL WITH ONE FACE

DOLOMITE



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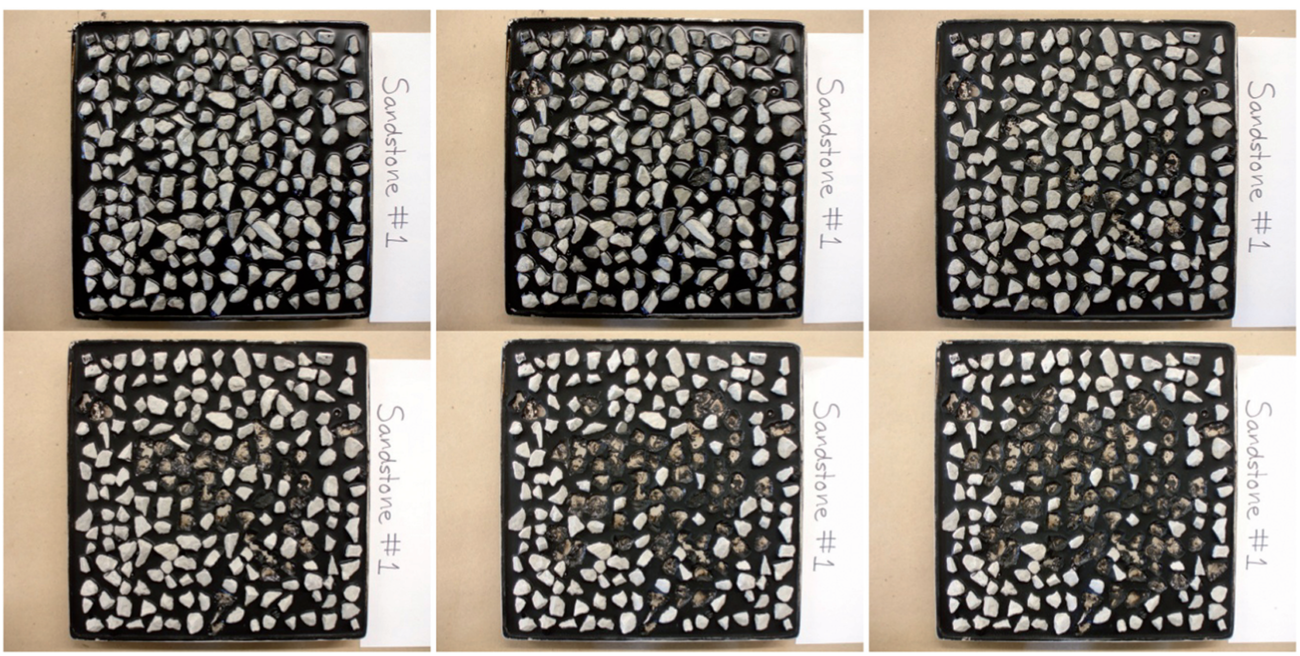
SANDSTONE



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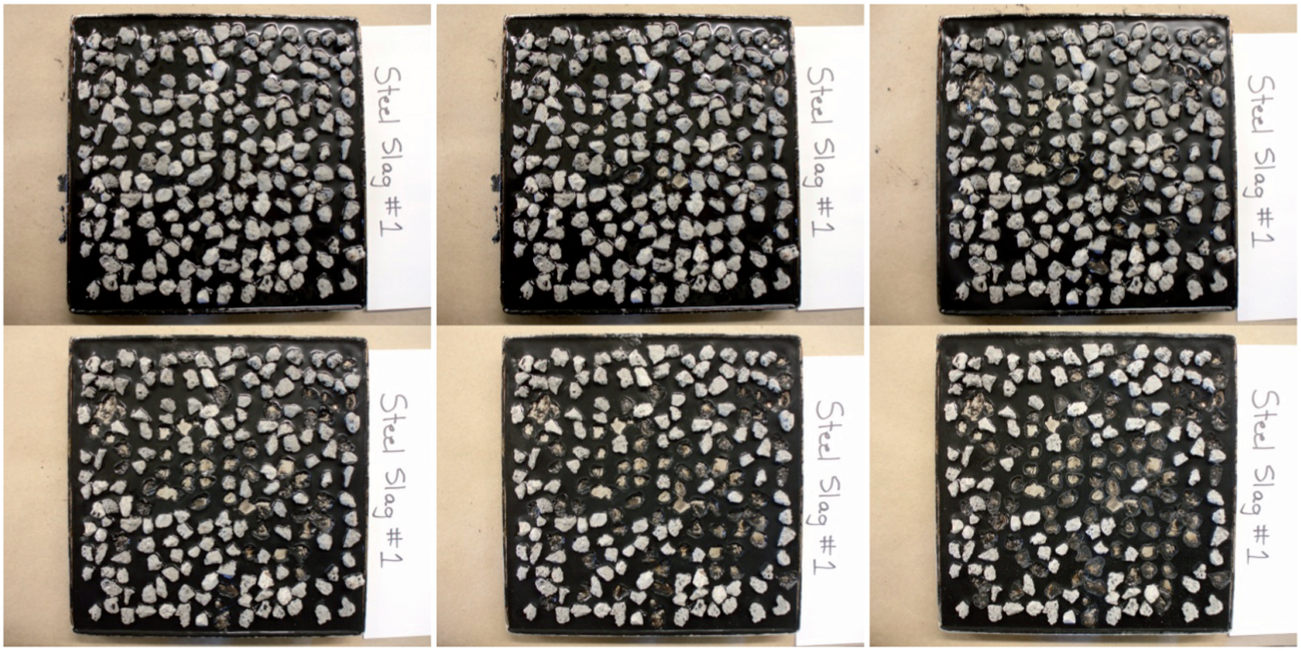

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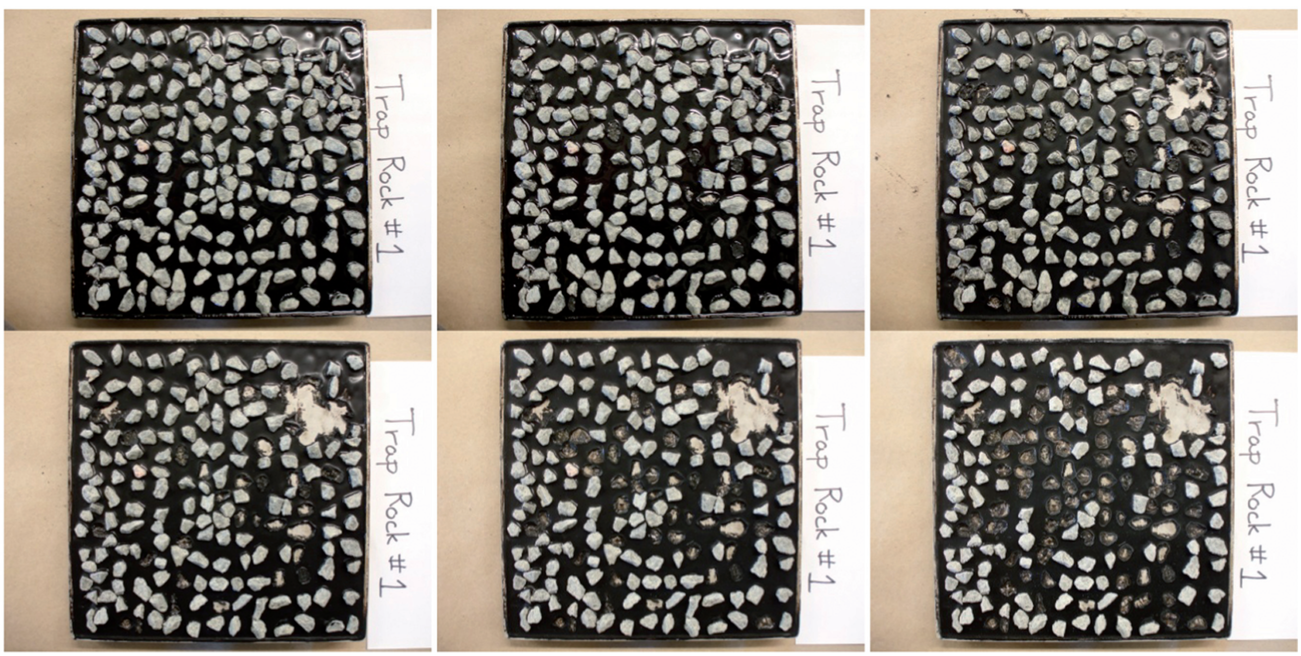

6.8.2 CRS-2P

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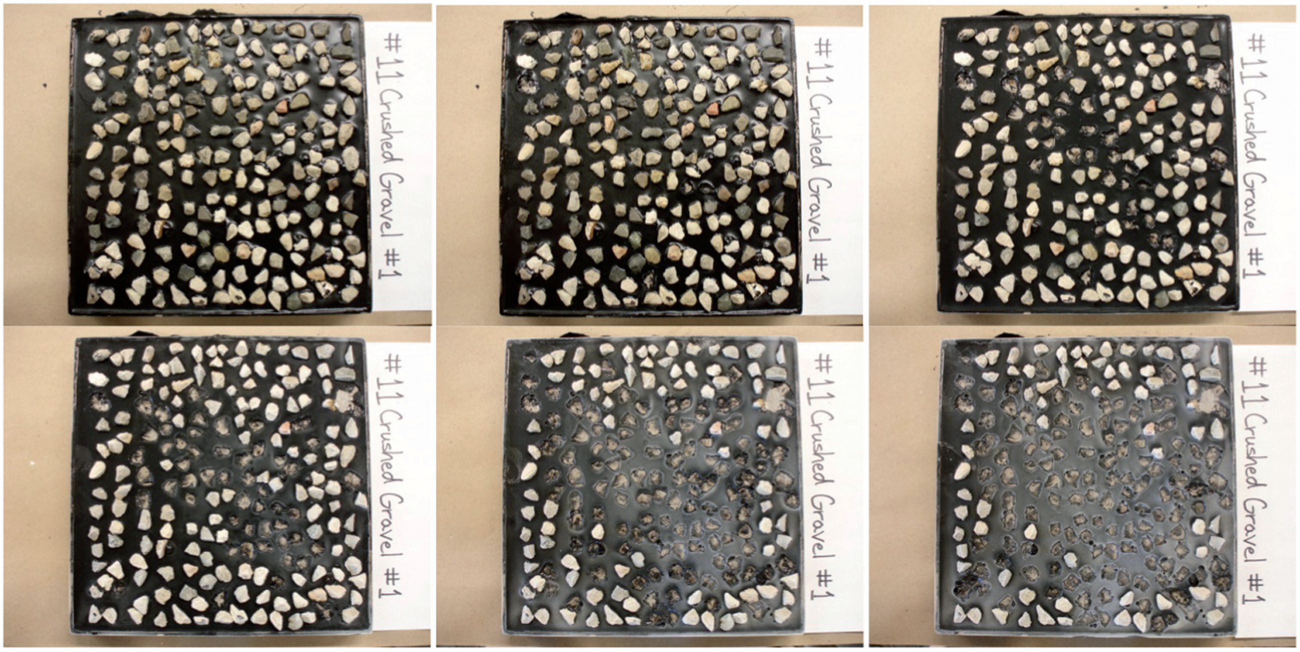

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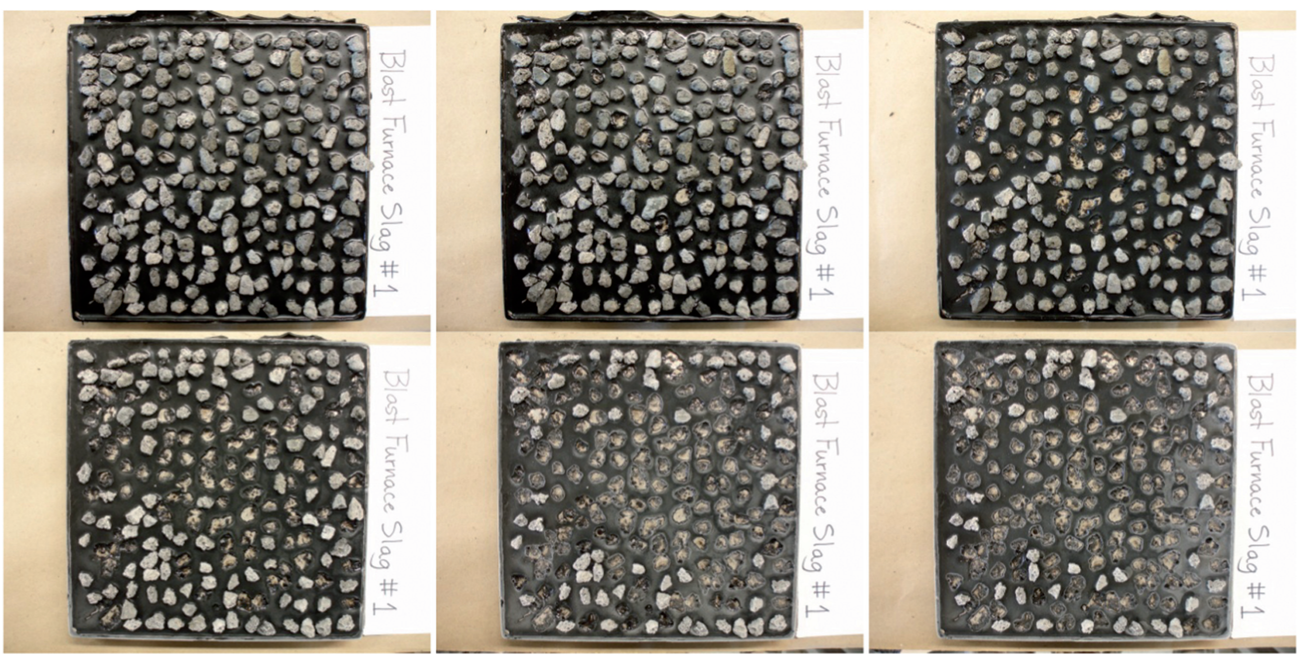
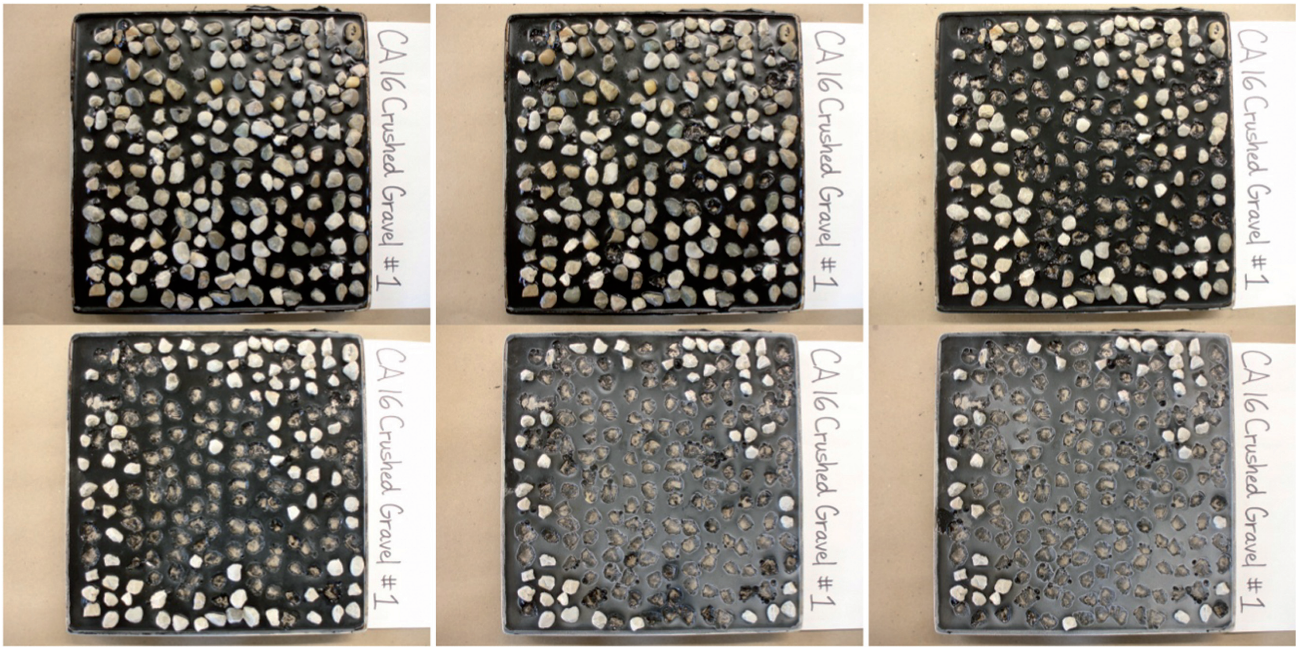


CRUSHED GRAVEL WITH ONE FACE



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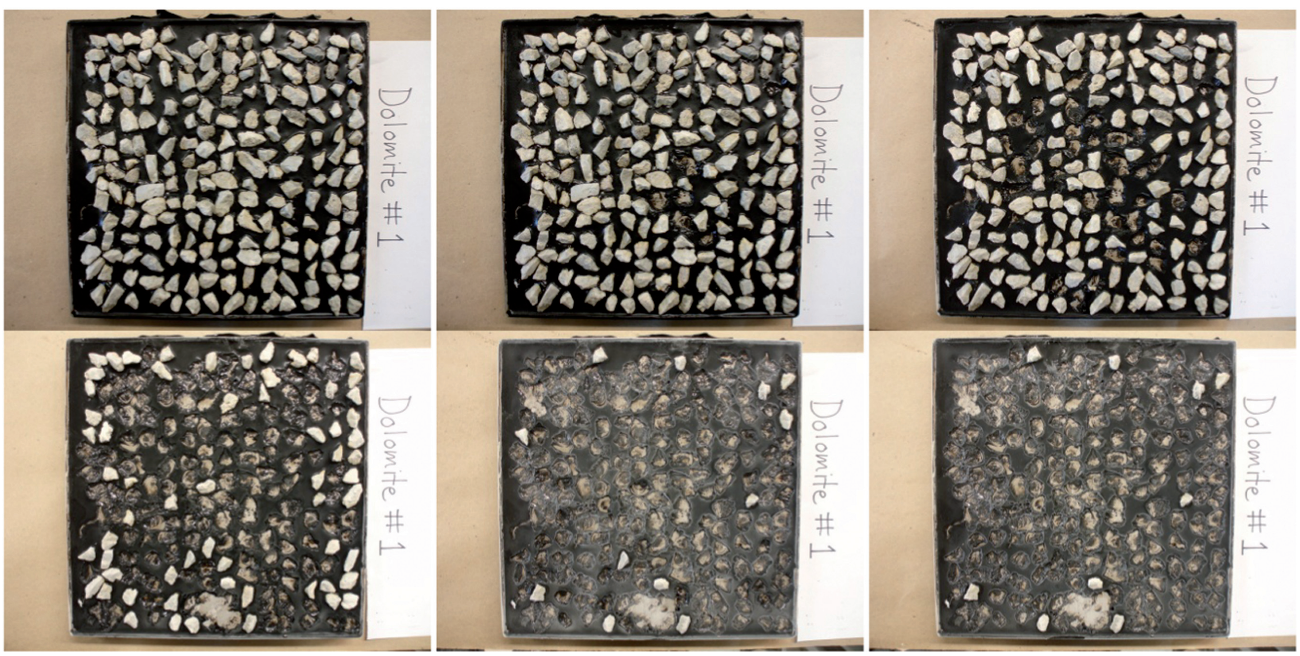
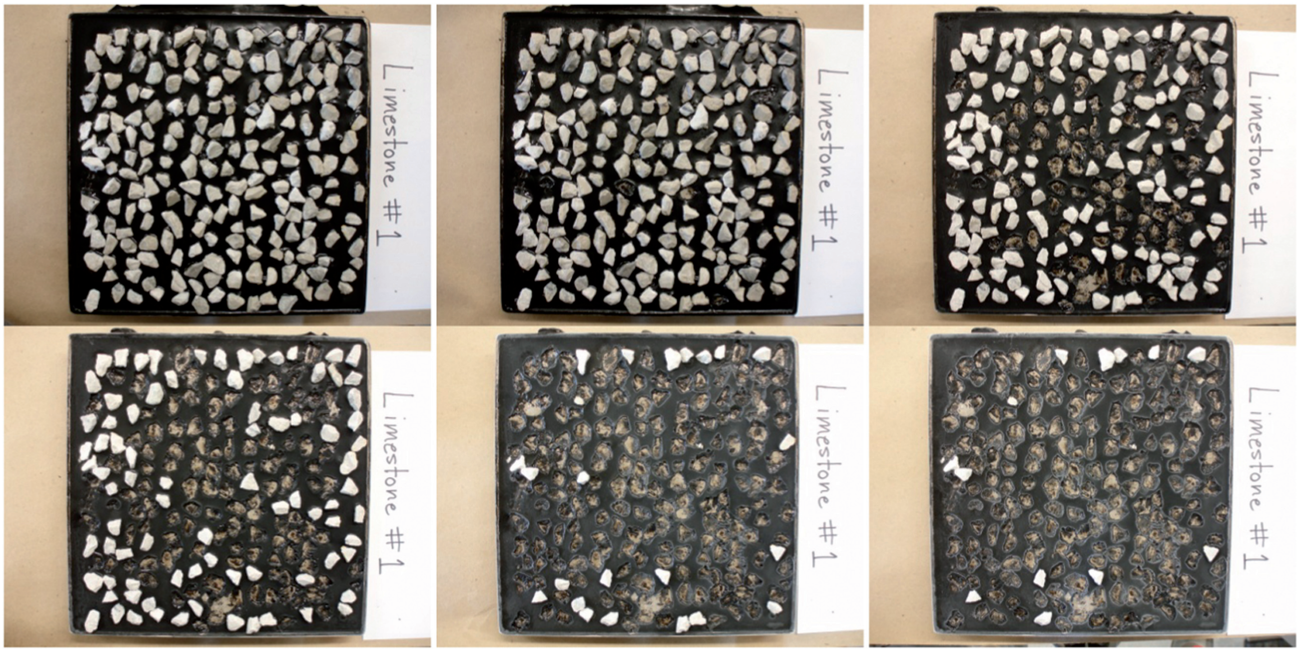
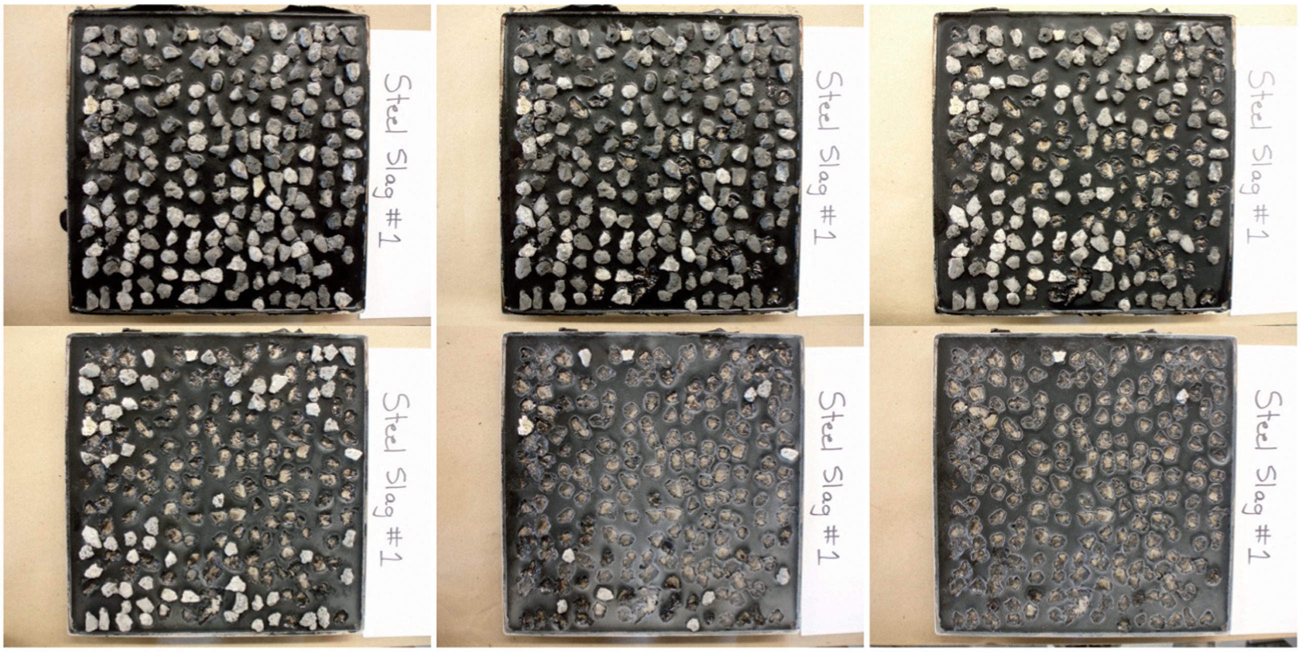


LIMESTONE



SANDSTONE

STEEL SLAG



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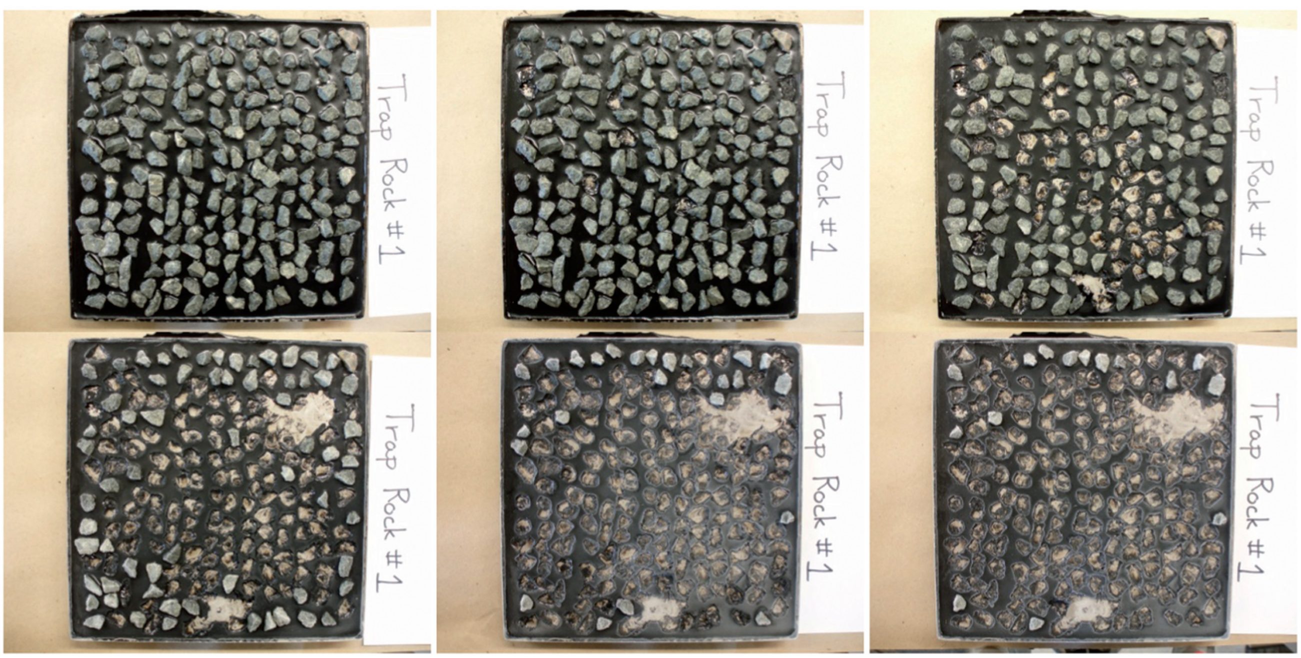
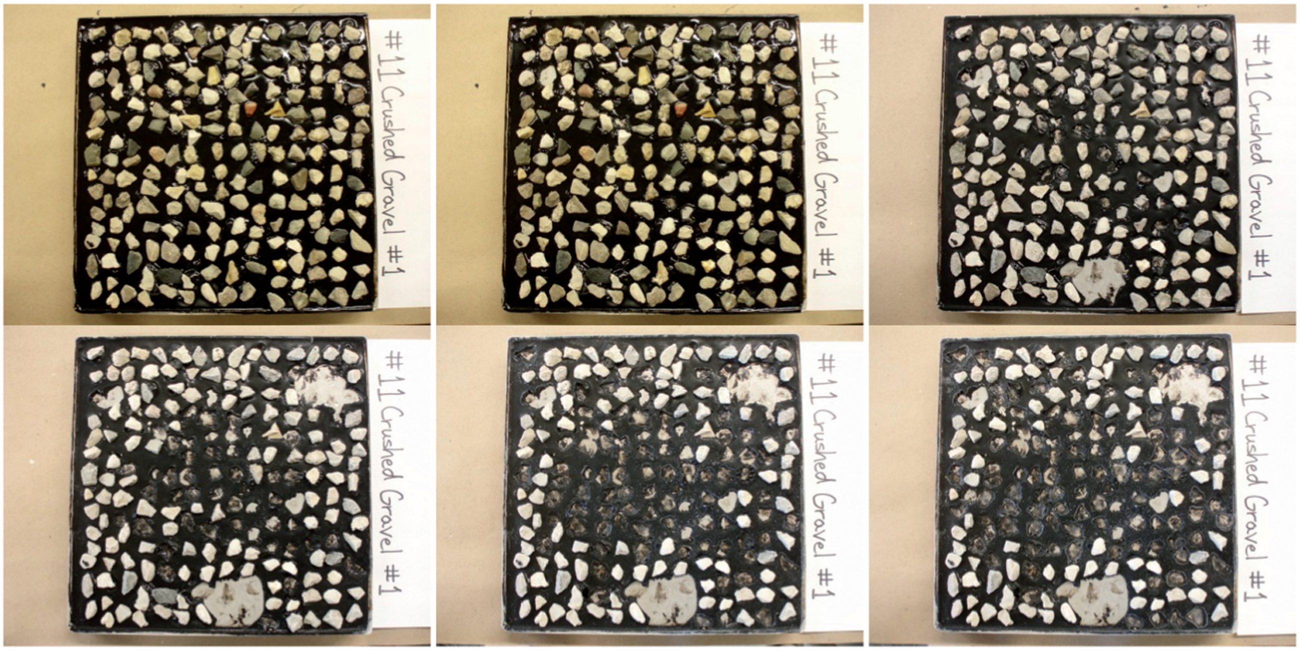


6.8.3 RS-2P

CRUSHED GRAVEL WITH TWO FACES



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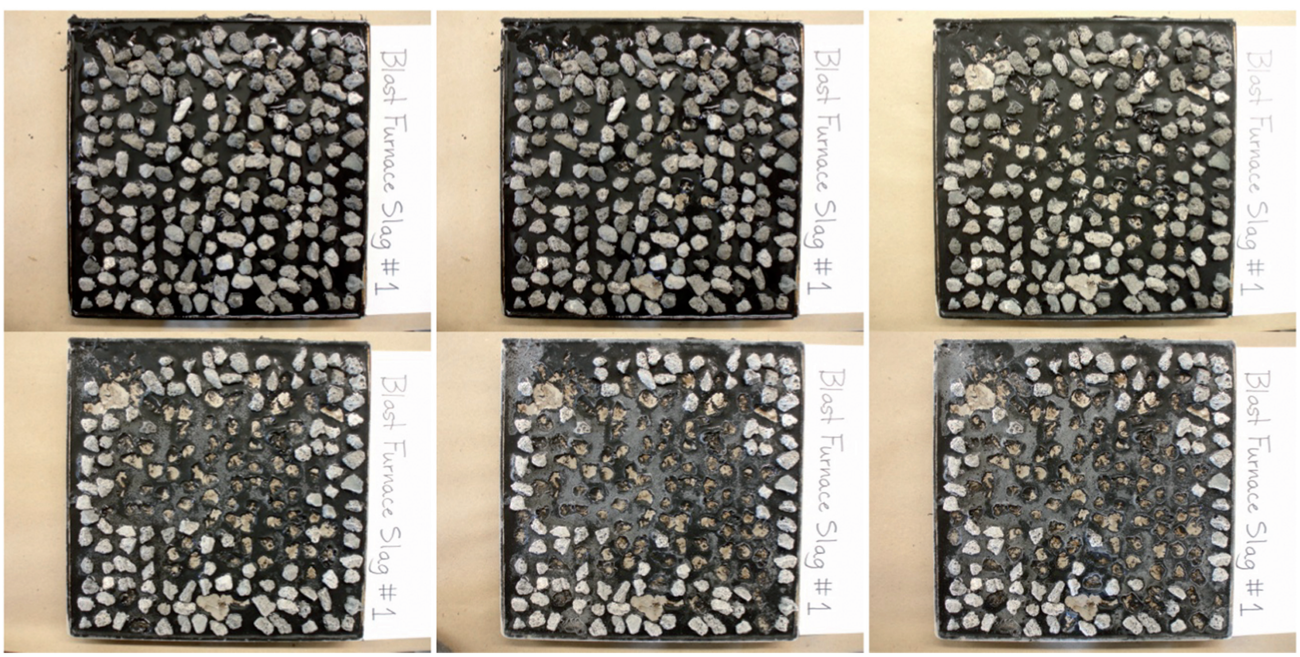
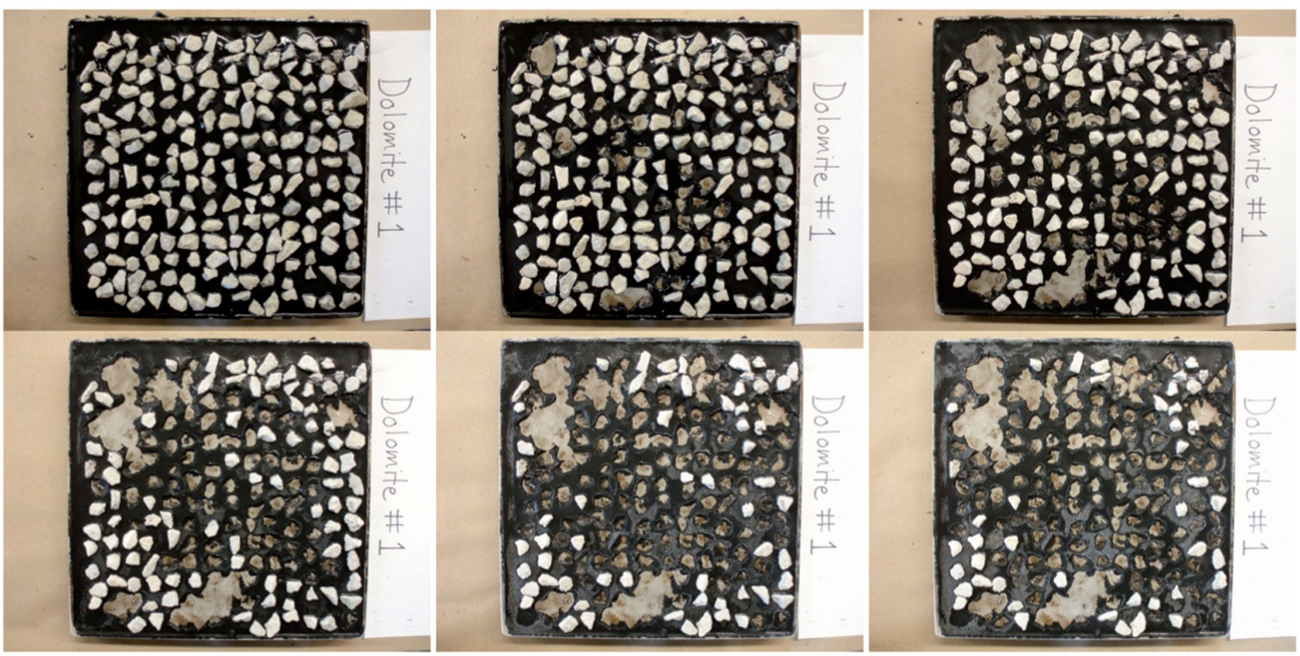


CRUSHED GRAVEL WITH ONE FACE

DOLOMITE



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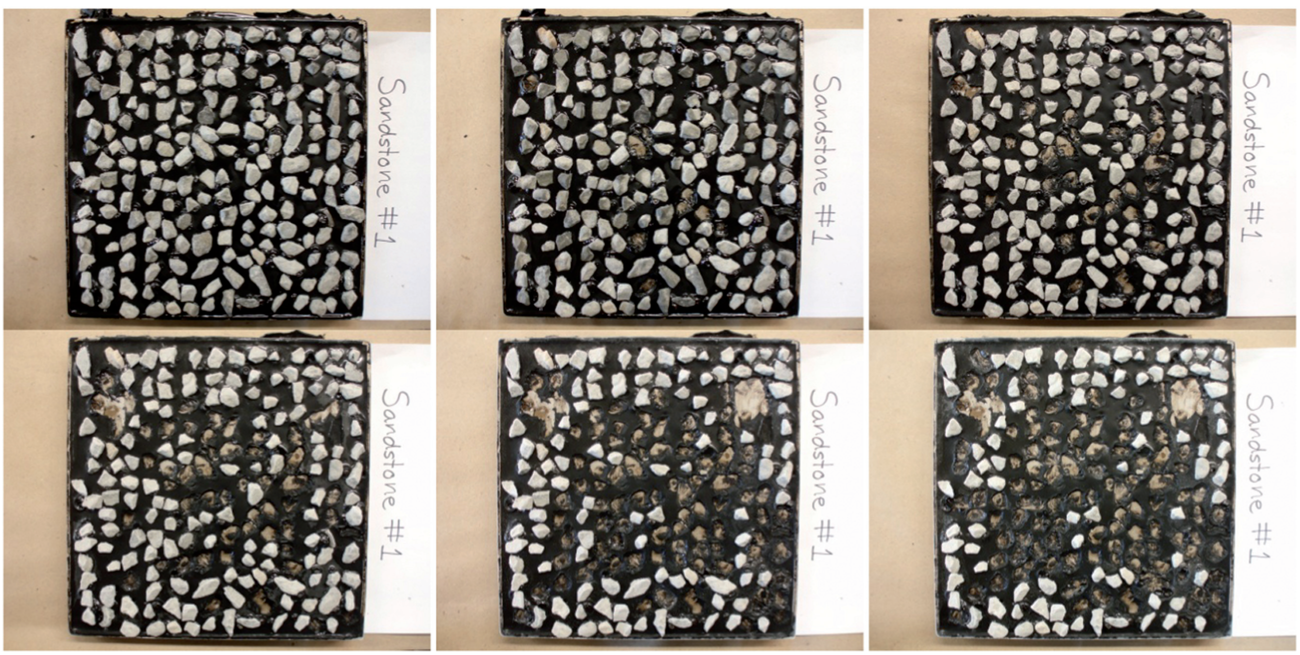
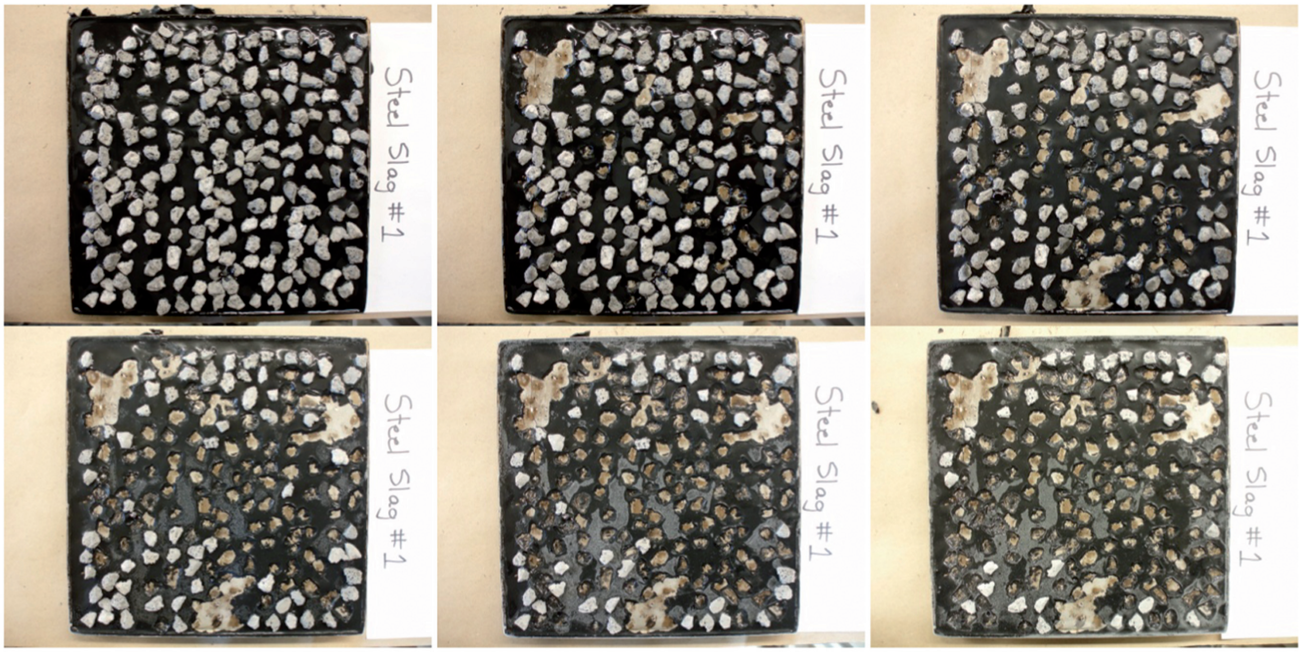
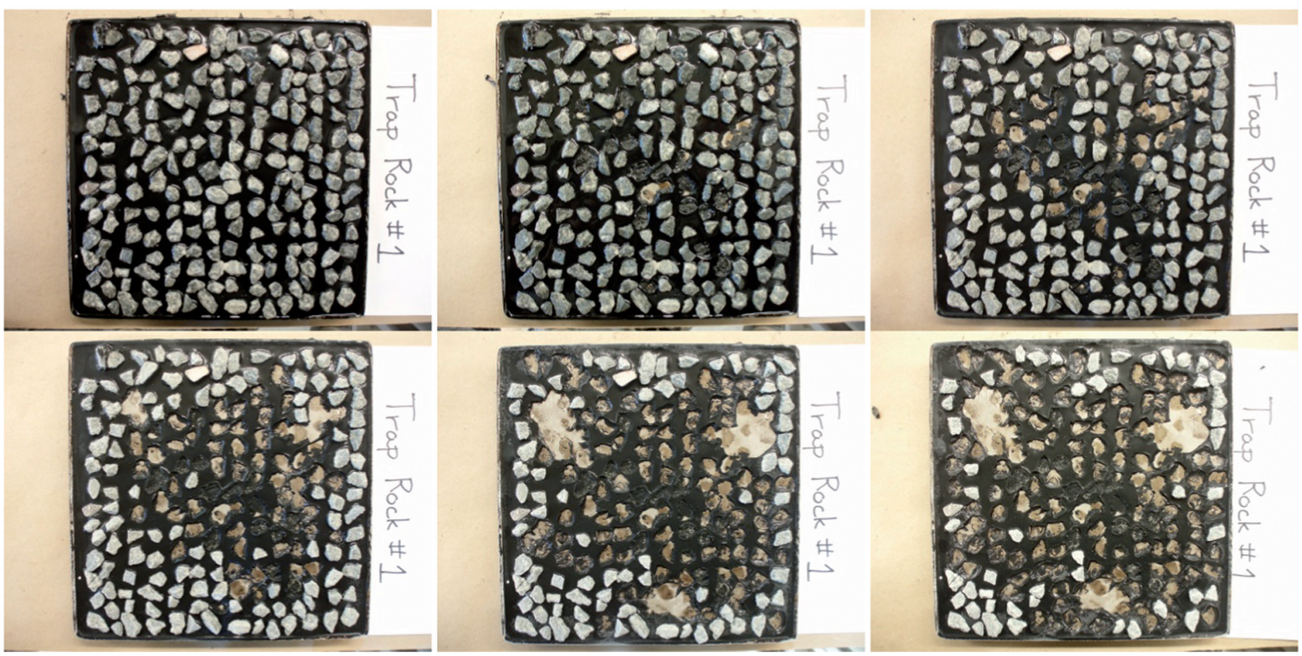
SANDSTONE



STEEL SLAG



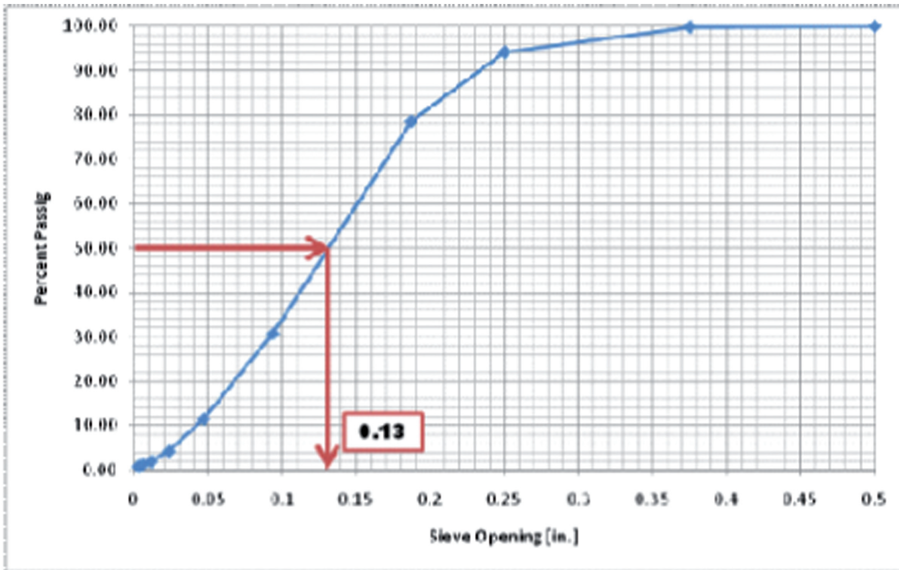
TRAP ROCK



6.9 MCLOED DESIGN CALCULATION

6.9.1 US-421

1. Median Particle Size



$$M \ := \ 0.13 \text{ in}$$

2. Flakiness Index

$$FI := 18.35\%$$

3. Average Least Dimension (H)

$$H : \frac{M}{1.139285 + (0.011506)FI} = 0.114 \cdot \text{in} \quad H = 0.114 \cdot \text{in}$$

4. Loose Unit Weight (W)

$W_{agg} := 6.63$ kg   Weight of aggregates loosely filled in a metal cylinder with volume of 0.005 m^3

$$V_{cylinder} := 0.004729 \cdot m^3$$

$$W : \frac{W_{agg}}{V_{cylinder}} = 87.523 \frac{lb}{fl^3} \quad W = 87.523 \cdot \frac{lb}{ft^3}$$

5. Voids in the Loose Aggregate

$SG := 2.506$ Dry Bulk Specific Gravity

$\gamma_{water} = 62.4 \frac{lb}{ft^3}$ Density of water at 4°C

$$V := 1 - \frac{w}{\gamma_{water} \cdot SG} = 0.44 \quad V = 0.44$$

6. Cover Aggregate Application Rate (C)

$E_1 : 1 \quad E_2 := 1.1$ Wastage factors of 0% and 10% are assumed

$$C_1 = (1 - 0.4V) \cdot H \cdot SG \cdot \gamma_{water} \ E_1 = 11.005 \cdot \frac{lb}{yd^2}$$

$$C_2 = (1 - 0.4V) \cdot H \cdot SG \cdot \gamma_{water} \ E_2 = 12.106 \cdot \frac{lb}{yd^2}$$

$$C_1 = 11.005 \frac{lb}{yd^2} \quad \text{0\% wastage assumed} \quad C_2 = 12.106 \frac{lb}{yd^2} \quad \text{10\% wastage assumed}$$

7. Binder Application Rate

$T := 0.6$ ADT over 2000 has traffic factor of 0.6 (Minnesota Seal Coat Handbook 2006 Table 4.4)

$S : 0.03 \frac{gal}{yd^2}$ Surface Correction Factor of 0.03 used for slightly porous and oxidized road (Minnesota Seal Coat Handbook 2006 Table 4.6)

$A := 0.02 \frac{gal}{yd^2} 2.8 = 0.056 \frac{gal}{yd^2}$ Absorption of 3.6% falls in Class B resulting in correction factor of 2.8 (Minnesota Seal Coat Handbook 2006 Table 4.3)

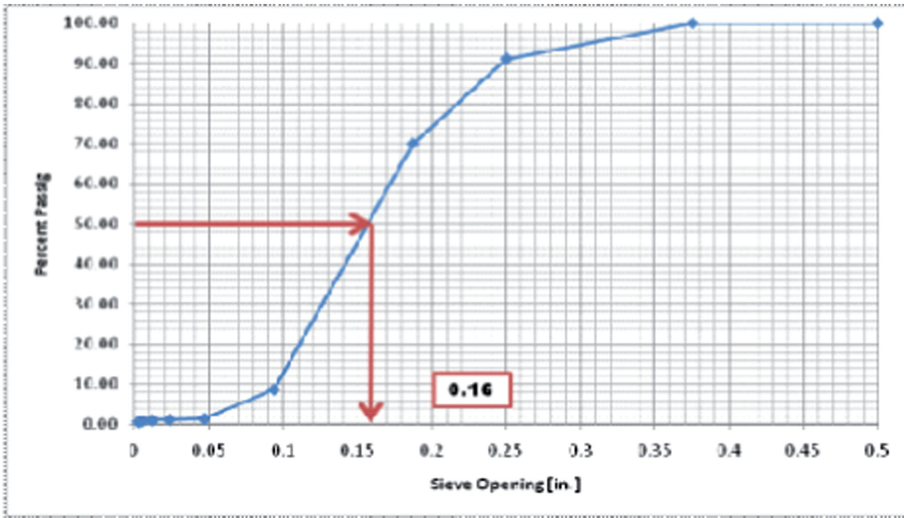
$R := 0.66$ Residual of AE-90S asphalt binder in decimal percent

$$B := \frac{0.4V\ H\ T + S + A}{R} = 0.233 \frac{gal}{yd^2}$$

$$B = 0.233 \frac{gal}{yd^2}$$

6.9.2 US-14

1. Median Particle Size



$$M := 0.16 \text{ in}$$

2. Flakiness Index

$$FI := 17.91\%$$

3. Average Least Dimension (H)

$$H : \frac{M}{1.139285 + (0.011506)FI} = 0.14 \text{ in} \quad H = 0.14 \text{ in}$$

4. Loose Unit Weight (W)

$W_{agg} := 6.73 \text{ kg}$ Weight of aggregates loosely filled in a metal cylinder with volume of 0.005m^3

$$V_{cylinder} := 0.004729 \text{ m}^3$$

$$W := \frac{W_{agg}}{V_{cylinder}} = 88.843 \frac{\text{lb}}{\text{ft}^3} \quad W = 88.843 \frac{\text{lb}}{\text{ft}^3}$$

5. Voids in the Loose Aggregate

$SG := 2.421$ Dry Bulk Specific Gravity

$\gamma_{water} := 62.4 \frac{\text{lb}}{\text{ft}^3}$ Density of water at 4°C

$$V : 1 - \frac{W}{\gamma_{water} SG} = 0.412 \quad V = 0.412$$

6. Cover Aggregate Application Rate (C)

$E_1 := 1 \quad E_2 := 1.1$ Wastage factors of 0% and 10% are assumed

$$C_1 := (1 - 0.4V) \cdot H \cdot SG \cdot \gamma_{water} \; E_1 = 13.266 \cdot \frac{\text{lb}}{\text{yd}^2}$$

$$C_2 := (1 - 0.4V) \cdot H \cdot SG \cdot \gamma_{water} \; E_2 = 14.593 \cdot \frac{\text{lb}}{\text{yd}^2}$$

$C_1 = 13.266 \cdot \frac{\text{lb}}{\text{yd}^2}$ 0% wastage assumed $\quad C_2 = 14.593 \cdot \frac{\text{lb}}{\text{yd}^2}$ 10% wastage assumed

7. Binder Application Rate

$T := 0.6$ — ADT over 2000 has traffic factor of 0.6 (Minnesota Seal Coat Handbook 2006 Table 4.4)

$S := 0.03 \frac{gal}{yd^2}$ — Surface Correction Factor of 0.03 used for slightly porous and oxidized road (Minnesota Seal Coat Handbook 2006 Table 4.6)

$A := 0.02 \frac{gal}{yd^2} 2.8 = 0.056 \frac{gal}{yd^2}$ — Absorption of 4.7% falls in Class B resulting in correction factor of 2.8 (Minnesota Seal Coat Handbook 2006 Table 4.3)

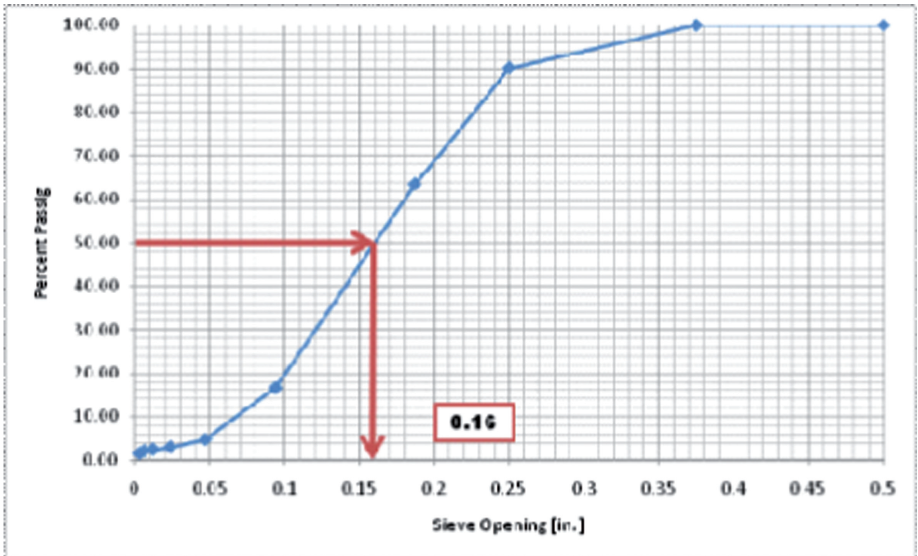
$R := 0.66$ — Residual of AE-90S asphalt binder in decimal percent

$$B := \frac{0.4V \cdot H \cdot T + S + A}{R} = 0.248 \cdot \frac{gal}{yd^2}$$

$$B = 0.248 \cdot \frac{gal}{yd^2}$$

6.9.3 SR-110

1. Median Particle Size



$$M := 0.16\ \text{in}$$

2. Flakiness Index

$$FI := 19.1\%$$

3. Average Least Dimension (H)

$$H := \frac{M}{1.139285 + (0.011506)FI} = 0.14 \cdot \text{in} \quad H = 0.14\ \text{in}$$

4. Loose Unit Weight (W)

$W_{agg} := 6.26\ \text{kg}$ Weight of aggregates loosely filled in a metal cylinder with volume of 0.005 m̂3

$$V_{cylinder} := 0.004729 \cdot m^3$$

$$W := \frac{W_{agg}}{V_{cylinder}} = 82.639 \frac{lb}{ft^3} \quad W = 82.639 \cdot \frac{lb}{ft^3}$$

5. Voids in the Loose Aggregate

$SG := 2.469$ Dry Bulk Specific Gravity

$\gamma_{water} := 62.4 \frac{lb}{ft^3}$ Density of water at 4℃

$$V : 1 - \frac{W}{\gamma_{water}\, SG} = 0.464 \quad V = 0.464$$

6. Cover Aggregate Application Rate (C)

$E_1 := 1 \quad E_2 := 1.1$ Wastage factors of 0% and 10% are assumed

$$C_1 = (1 - 0.4V)H\ SG\ \gamma_{water}\ E_1 = 13.193 \cdot \frac{lb}{yd^2}$$

$$C_2 = (1 - 0.4V)H\ SG\ \gamma_{water}\ E_2 = 14.512 \cdot \frac{lb}{yd^2}$$

$C_1 = 13.193 \cdot \frac{lb}{yd^2}$ 0% wastage assumed $C_2 = 14.512 \frac{lb}{yd^2}$ 10% wastage assumed

7. Binder Application Rate

$T := 0.65$ — ADT between 1000 and 2000 has traffic factor of 0.65 (Minnesota Seal Coat Handbook 2006 Table 4.4)

$S := 0.03\frac{gal}{yd^2}$ — Surface Correction Factor of 0.03 used for slightly porous and oxidized road (Minnesota Seal Coat Handbook 2006 Table 4.6)

$A := 0.02\frac{gal}{yd^2}2.8 = 0.056\frac{gal}{yd^2}$ — Absorption of 3.9% falls in Class B resulting in correction factor of 2.8 (Minnesota Seal Coat Handbook 2006 Table 4.3)

$R := 0.66$ — Residual of AE-90S asphalt binder in decimal percent

$$B := \frac{0.4V\ H\ T+S+A}{R} = 0.274\cdot\frac{gal}{yd^2}$$

$$B = 0.274\cdot\frac{gal}{yd^2}$$

6.10 MCLOED DESIGN FACTOR

6.10.1 AGGREGATE WASTAGE FACTOR, E

Percentage Waste* Allowed For	Wastage Factor, E
1	1.01
2	1.02
3	1.03
4	1.04
5	1.05
6	1.06
7	1.07
8	1.08
9	1.09
10	1.10
11	1.11
12	1.12
13	1.13
14	1.14
15	1.15

*Due to traffic whip-off and handling

6.10.2 TRAFFIC CORRECTION FACTOR, T

Traffic [Vehicles per day]	Traffic Factor
Under 100	0.85
100 to 500	0.75
500 to 1000	0.70
1000 to 2000	0.65
Over 2000	0.60

6.10.3 SURFACE CORRECTION FACTOR, S

Existing Pavement Texture	Correction, S [gal/yd^2]
Black, flushed asphalt	-0.01 to -0.06
Smooth, non-porous	0.00
Slightly porous and oxidized	+0.03
Slightly pocked, porous and oxidized	+0.06
Badly pocked, porous and oxidized	+0.09

6.10.4 AGGREGATE ABSORPTION

Aggregate Type		Class A			Class B		Class C
		Granite	Quartzite	Trap Rock	Limestone	Red Rock	Pea Rock
Percent Absorption	**Min.**	0.40	0.61	0.31	1.75	N/A	1.14
	Max.	0.92	0.72	0.59	5.44	N/A	2.32
	Avg.	**0.59**	**0.67**	**0.43**	**2.80**	N/A	**1.69**

6.11 CALIBRATION SETTING

Aggregate Spreader Calibration Table

Gate Opening (in)	Speed (ft/min)	Application Rate (lb/SYD)
0.75	340	10
0.75	350	10
0.75	320	10
1.00	350	13
1.00	340	14
1.00	320	15
1.25	350	16
1.25	320	17
1.25	340	18
1.50	350	20
1.50	340	22
1.75	340	24

Distributor Calibration Table

Distributor (Comm #)	Capacity (gal)	Pump Rate (gal/min)	Speed (ft/min)	Computer Setting (gal/SYD)	Application Rate (gal/SYD)
64462	2,500	120	300	N/A	0.38
64462	2,500	120	320	N/A	0.34
64462	2,500	120	340	N/A	0.31
64462	**2,500**	**120**	**350**	**N/A**	**0.30**
64185	2,500	90	300	N/A	0.24
64185	**2,500**	**95**	**300**	**N/A**	**0.25**
64666	3,500			0.40	0.41
64666	**3,500**			**0.35**	**0.35**

6.12 VISUAL OBSERVATION SHEET

General Information

Name of Recorder		Time/Date	
Road	US 421/SR14/SR110		-
Temperature			

Performance Scores

Number	Distress	Sections												
		421NB-204-205	421NB-205-206	14EB-39-40	14EB-40-41	14EB-41-42	14EB-42-43	110WB-3-4	110WB-4-5	110WB-5-6	110WB-6-7	110EB-3-4	110EB-4-5	110EB-5-6
1	Aggregate Loss													
2	Bleeding /Flushing													
3	Excessive Aggregate													
4	Delamination													
5	Streaking													
6	Reflected Bleeding from Crack Seal													
7	Polishing													

Note: 0 being excellent to 10 being unacceptable

6.13 FIELD TEST METHOD FOR MEASURING SEAL COAT AGGREGATE AND EMULSION APPLICATION RATES

Equipment:

Field Balance
32 Gallon Trash Bin
5-gallon Bucket
1 SYD carpet, burlap, or canvas, cut into square
Long-handled Tongs/Hooks/Pliers
Garbage Bags
Marker
Rubber Gloves
Rolled Paper (for walk path)

Emulsion Application Rate Measurement Method:

12. Label each carpet square.
13. Place a clean trash bag in the garbage container.
14. Weigh and record weights of each carpet square and the garbage container/bag.
15. Record location of test.
16. Lay 1 SYD carpet squares in line with distributor – 2 squares, roughly in the wheel paths.
17. Run distributor at application speed and emulsion rate over squares.
18. Place the ground paper on sprayed emulsion to approach the carpets.
19. Immediately pick up carpet square, garbage container, and weigh.
20. Record total weight.
21. Calculate and report application rate.
22. Reseal the area covered the carpets.

Aggregate Application Rate Measurement Method:

10. Weigh and record weight of 5-gallon bucket.
11. Record location of test.
12. Lay 1 SYD burlap or canvas in line with aggregate spreader.
13. Run aggregate spreader at application speed and application rate over burlap.
14. Pick up burlap square, and deposit aggregate into 5-gallon bucket.
15. Weigh 5-gallon bucket and aggregate.
16. Record total weight.
17. Calculate and report application rate.
18. Sweep/reseal the area covered by the burlap square.

(a) (b)

(c) (d)

Figure 6.3 Emulsion application rate measurement procedure

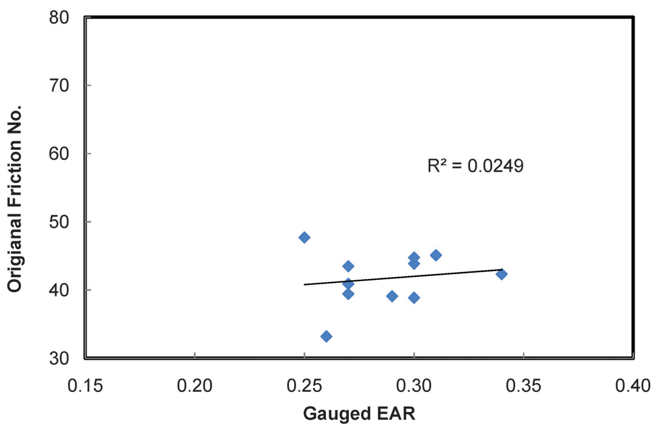
(a) (b)

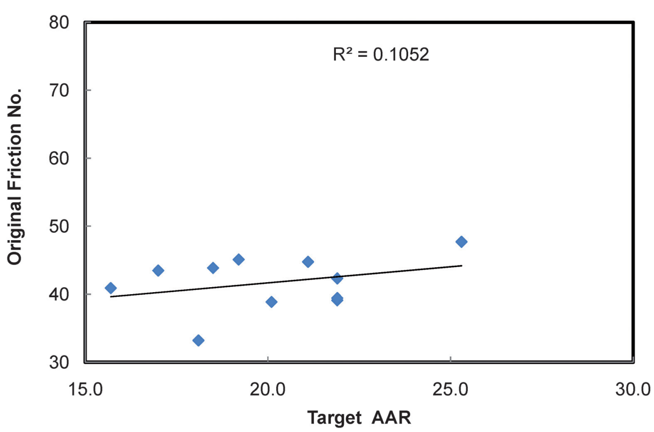
(c) (d)

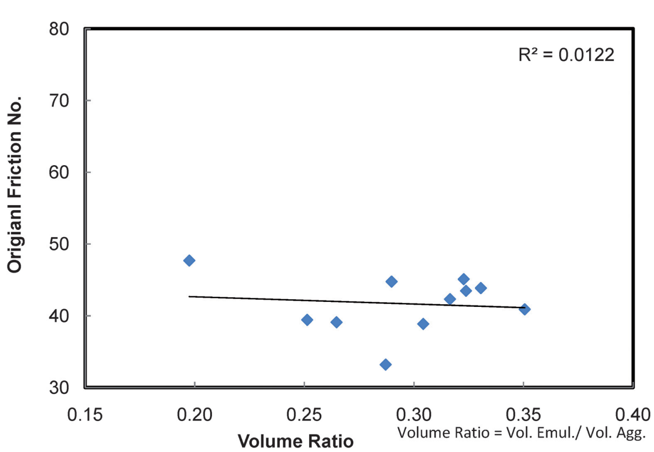
Figure 6.4 Aggregate application rate measurement procedure

6.14 CORELATION CHART

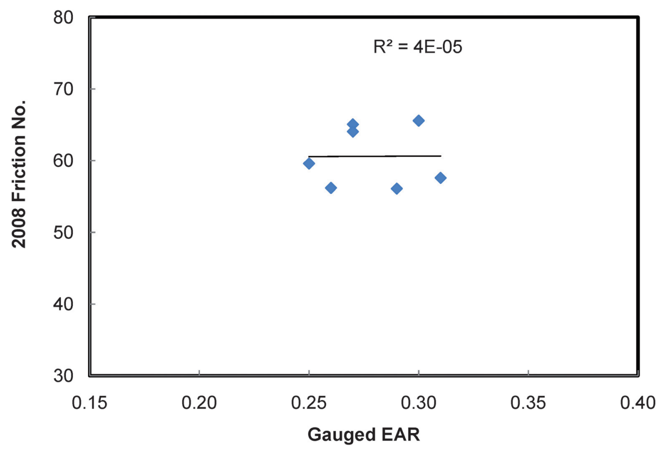
6.14.1 BEFORE SEAL COAT

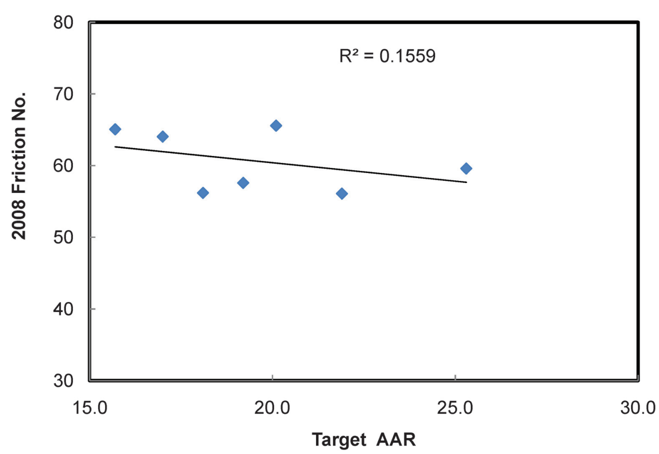


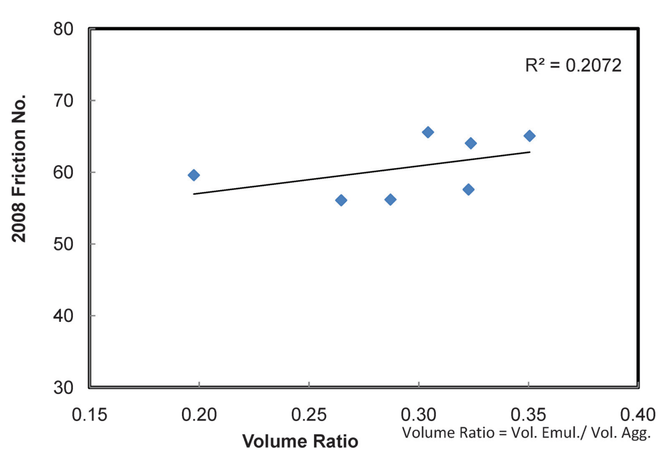




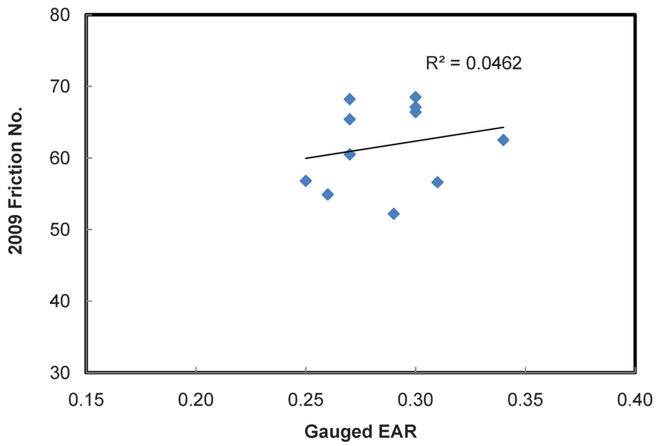
6.14.2 2008

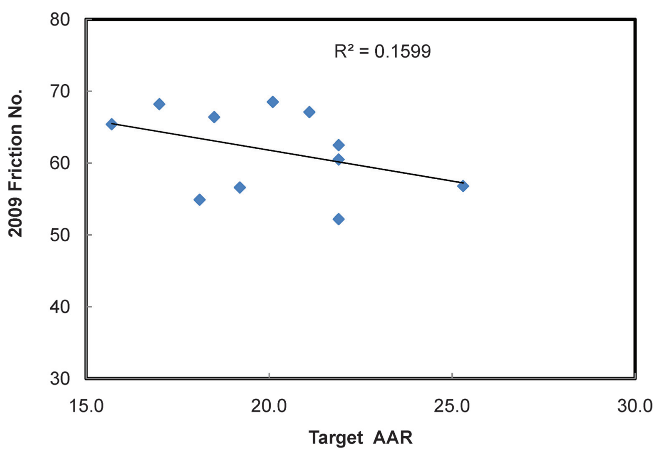


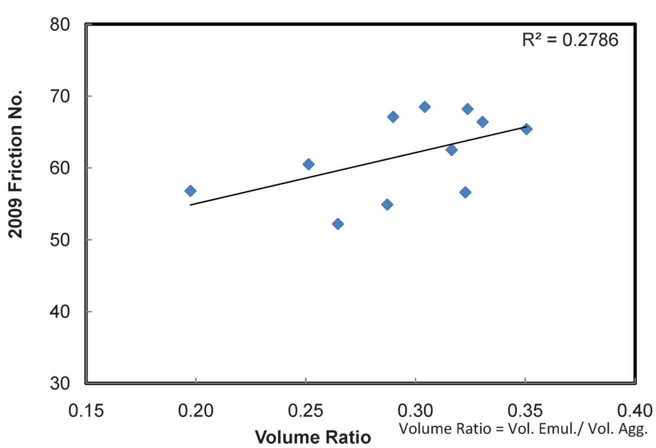




6.14.3 2009







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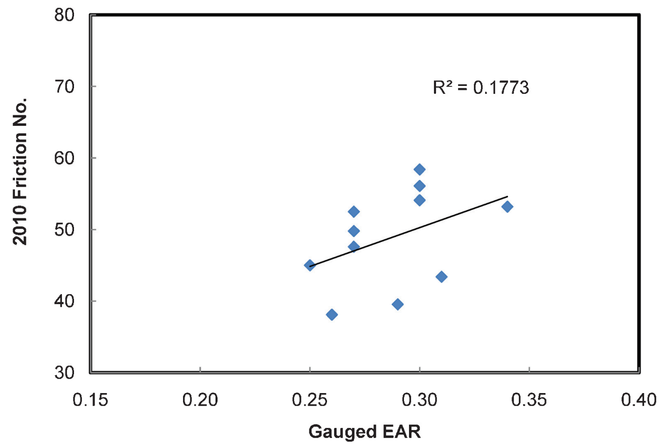
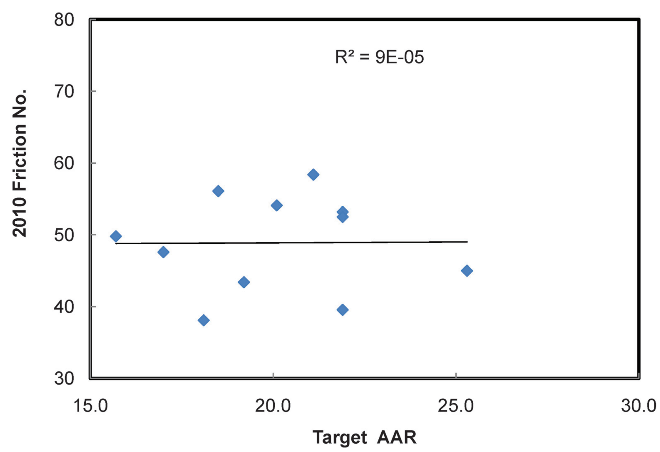
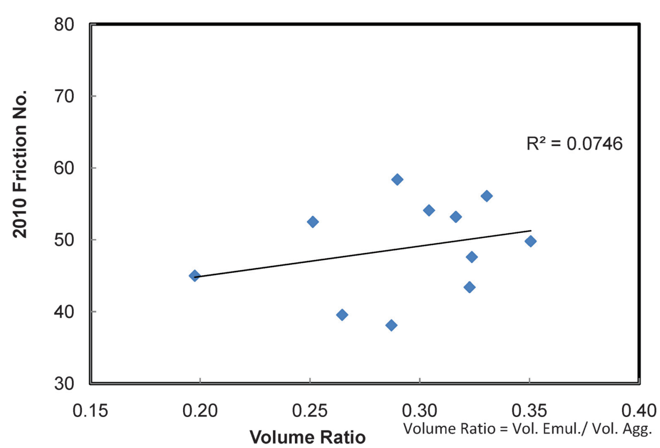
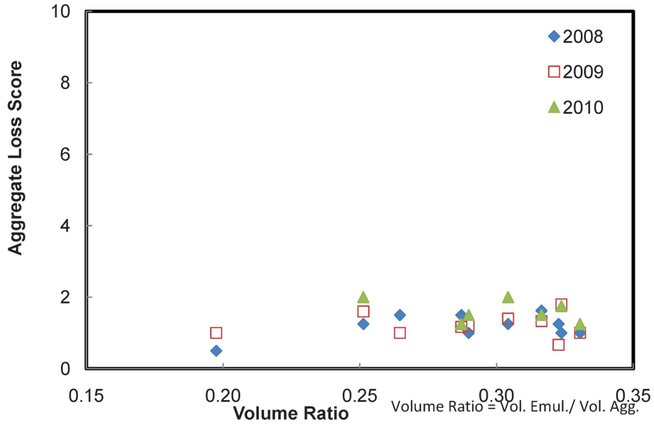
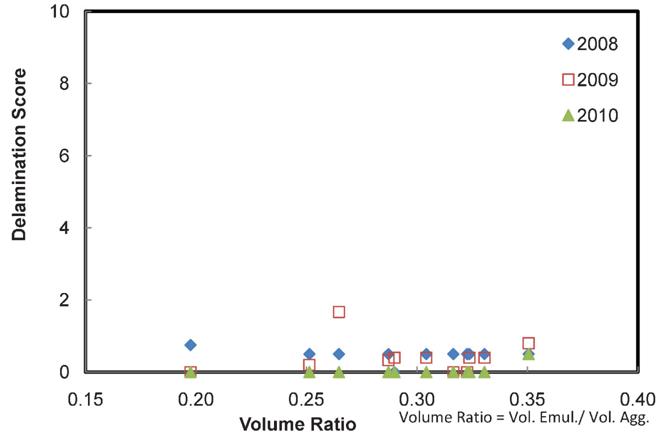


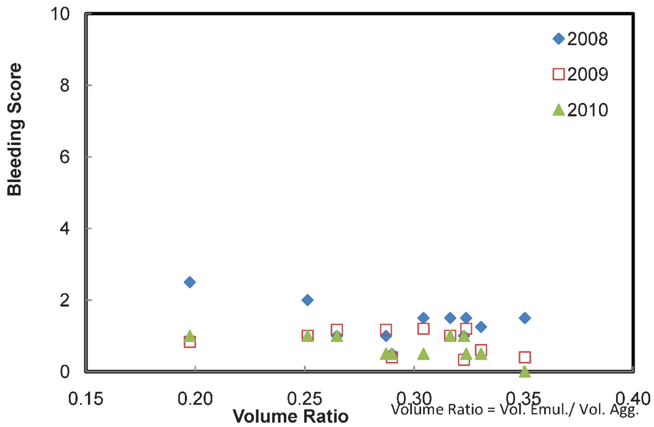


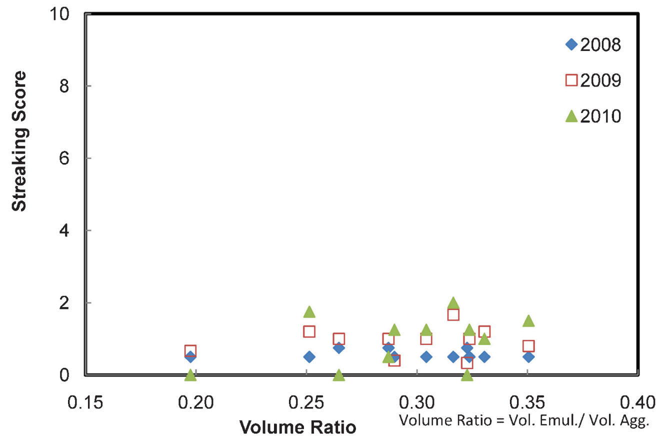


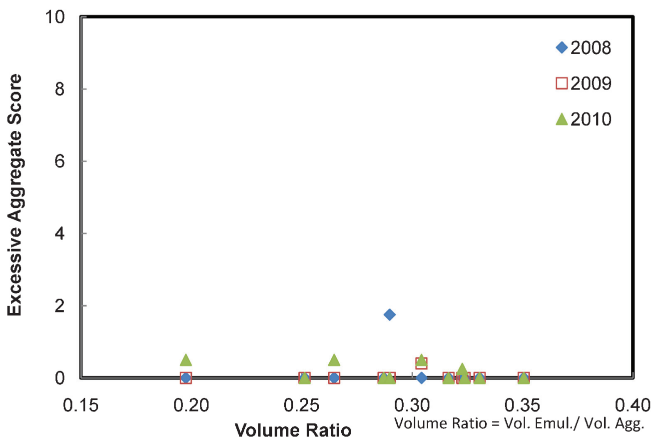
6.15 VISUAL OBSERVATION OVER VOLUME RATIO

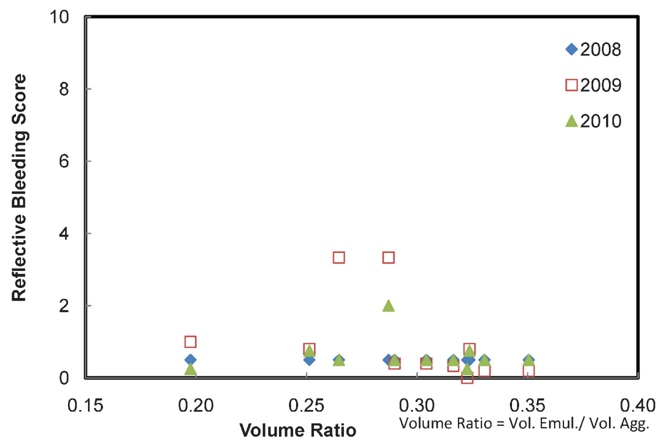


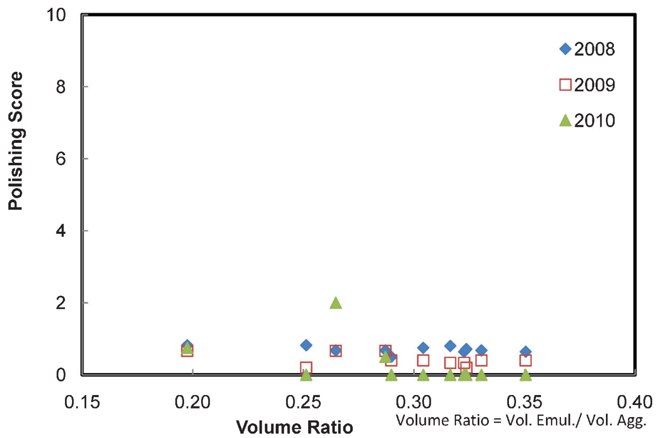


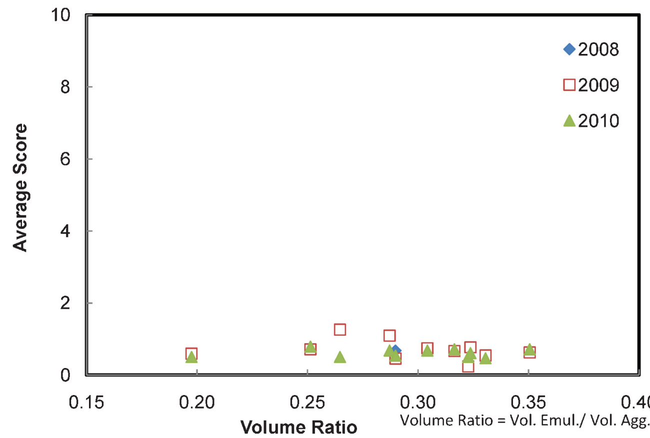









10
8
6
4
2
0
Polishing Score
2008
2009
2010
0.15
0.20
0.25
0.30
0.35
0.40
Volume Ratio
Volume Ratio = Vol. Emul./ Vol. Agg.


10
8
6
4
2
0
Average Score
2008
2009
2010
0.15
0.20
0.25
0.30
0.35
0.40
Volume Ratio
Volume Ratio = Vol. Emul./ Vol. Agg.

6.16 SURVEY QUESTIONNARIE

SURVEY OF SEAL COAT (CHIP SEAL) PRACTICE

6.16.1 RESPONDENT'S INFORMATION

Name of Person Compiling this Response: ____
Title: ____
Email/Phone: ____

6.16.2 OBJECTIVE

The purpose of this survey is to collect technical information of **full width seal coat** (hereinafter called **chip seal**) practices from District engineers. The results of this survey will help developing the Indiana chip seal best practice, updating the Indiana Standard Specification Section 404, developing a study program entitled *Performance Evaluation of Chip Seal Materials and Designs* sponsored by Joint Transportation Research Program.

If you have any question or comment, please contact followings

Jusang Lee
Materials Research Engineer
Office of Research and Development
Email: jlee@indot.in.gov
Office: (765) 463-1521 ext. 349

Todd Shields
Pavement Preservation Engineer
Division of Highway Operations
Email: tshields@indot.in.gov
Office: (317) 233-3345

6.16.3 GENERAL

1. How long have you worked for chip seal work in your District?
( ) years
2. Are you familiar with Indiana Standard Specification Section 404: Seal Coat?
☐ Yes, I am fully familiar with it.
☐ Yes, I am partially familiar with it.
☐ No, I am not familiar with it but I have read it.
☐ No, I haven't even heard about it.
3. What is the typical life of a chip seal in your District?
Approximately ( ) years
4. How do you rate your District's experience with the performance chip seals (aggregate loss, bleeding, etc.)? (Check one box only.)
☐ Excellent: very little difficulty
☐ Good: minor difficulties
☐ Fair: routine, manageable difficulties
☐ Poor: Serious difficulties
☐ Unacceptable difficulties
5. What are the major reasons for your District's decision to apply a chip seal to a given pavement? (check all that apply)
☐ Distress (cracking)
☐ Improve skid resistance
☐ Prevent water infiltration
☐ Provide a wearing surface
☐ Oxidation
☐ Raveling
☐ Eliminate surface rutting
☐ Improve night vision
☐ Improve contrast between stripes and road surface
☐ To meet annual work plan
☐ Other, please specify:
6. What is the "trigger point" in your chip seal decision-making process?
☐ Pavement condition rating or index
☐ Level/amount of cracking
☐ Skid number
☐ Amount of oxidation
☐ Age of the surface
☐ No trigger point
☐ Other reason, please specify:
7. How would you describe the level of distress (cracks or deformations) on roads that generally receive a chip seal?
☐ Severe ☐ Moderate ☐ Slight ☐ None
8. What is the major problem associated with chip seal work in your District? (Check one box only.)
☐ Early loss of aggregate
☐ Loss of aggregate due to cool evenings
☐ Premature flushing/bleeding
☐ Loss of aggregate over patches
☐ Flushing/bleeding over patches
☐ Flushing/bleeding at intersections and turning areas
☐ Other, please specify:

6.16.4 DESIGN

9. How do you determine the emulsion application rates?
☐ Compute using design procedure
☐ Based on past experience
☐ Based on INDOT standard specification
☐ Other, please specify:
10. How do you determine the aggregate application rates?
☐ Compute using design procedure
☐ Based on past experience
☐ Based on INDOT standard specification
☐ Other, please specify:
11. Do you apply different emulsion-aggregate application rate in different types of existing pavement condition?
☐ Yes ☐ No if No, please answer Question 10.
12. Please provide your typical chip seal application rate used for your District in 2007?
13. What is the maximum traffic volume on roads on which your District constructs chip seals?

Aggregate Size	Aggregate Application Rate (lb/yd^2)	Emulsion Application Rate (gal/yd^2)
11		
12		

☐ ADT < 500
☐ ADT < 1,000

☐ ADT < 2,000
☐ ADT < 5,000
☐ ADT < 20,000
☐ ADT > 20,000
Materials
14. What aggregates gradation or size do you use for your chip seal jobs? (Check all that apply.)
☐ 11
☐ 12
☐ Other, please specify:
15. What types of aggregate are used on your chip seal projects? (Check all that apply and indicate the single type of aggregate that is most typical.)

☐ Limestone	☐ most typical
☐ Quartzite	☐ most typical
☐ Granite	☐ most typical
☐ Dolomite	☐ most typical
☐ Trap rock	☐ most typical
☐ Sandstone	☐ most typical
☐ Natural gravels	☐ most typical
☐ Crushed gravels	☐ most typical
☐ Slag	☐ most typical
☐ Other, please specify.	☐ most typical

16. What are major aggregate providers (quarries) in your District?
Names of providers:
17. What is your major concern in aggregate for chip seal jobs?
☐ Cleanness
☐ Size and gradation
☐ Particle shape
☐ Source (ex. Limestone, Sandstone, etc)
☐ Other, please specify:
18. How do you select the emulsion type for chip seal jobs?
☐ Local climate
☐ Traffic level of road to be sealed
☐ Season in which seal will be applied
☐ Local availability
☐ Other, please specify:
19. What are the names of emulsions normally used for your chip seals?
(example: AE-90)

6.16.5 EQUIPMENT

20. Please provide your equipment information of chip seal job in the following table?
21. Do your emulsion distributors have computerized controls?

	Spreader	Distributor	Roller	Bloom
Number of equipment				
Company Name and Model you are using				
Please provide reason if you have any preference to specific model				

☐ Yes ☐ No
22. Is your emulsion distributor calibrated periodically?
☐ Yes ☐ No If Yes, how often? What procedure/method is used?
23. What is the allowable tolerance of emulsion application rate in your district? (example: the target rate: 0.2 gal/yd2, but it was found that your actual rate on chip seal job is 0.25 gal/yd2. This over application rate with +0.05 gal/yd2 can or cannot be acceptable in your District)
☐ ±( ) gal/yd^2
24. Do your aggregate spreaders have computerized gate controls?
☐ Yes ☐ No
25. Is your aggregate spreader calibrated periodically?
☐ Yes ☐ No If Yes, how often? What procedure/method is used?
26. What is the allowable tolerance of aggregate application rate in your district?
± ( ) lb/yd^2

6.16.6 CONSTRUCTION

27. What is your typical chip seal construction season? What were the dates you work in 2007?
From the month of to the month (From to)
Dates worked in 2007:
28. What are your temperature or weather limitations for chip seal job?
☐ Temperature: Upper limitation ( ) °F, Lower limitation ( ) °F,

☐ If you have any weather limitations, please describe it.

29. Do you broom prior to emulsion application?

☐ Yes ☐ No If Yes, how far in advance of the emulsion application? ( ) ft

30. How soon after the emulsion spray operation is aggregate spread?

( ) seconds or ( ) minutes or ( ) feet or ( ) miles

31. What is the typical time span between aggregate spread and initial rolling?

( ) seconds or ( ) minutes or ( ) feet or ( ) miles

32. Which of the following controls are in place for your roller operations?

☐ Number of passes
☐ Rolling patterns
☐ Speed limits
☐ Roller weight
☐ Other, please specify:

33. Which of the following rolling pattern is used for your chip seal jobs in your District?

34. What is the typical time span between final rolling and initial brooming?

( ) Hours or ( ) days

35. What is the typical speed of roller in your chip seal job?

( ) mph

36. What is the typical weight of roller in your chip seal job?

( ) lbs or ( ) tons

37. What is the typical number of broom passes?

☐ One
☐ Two
☐ Three
☐ Other, please specify:

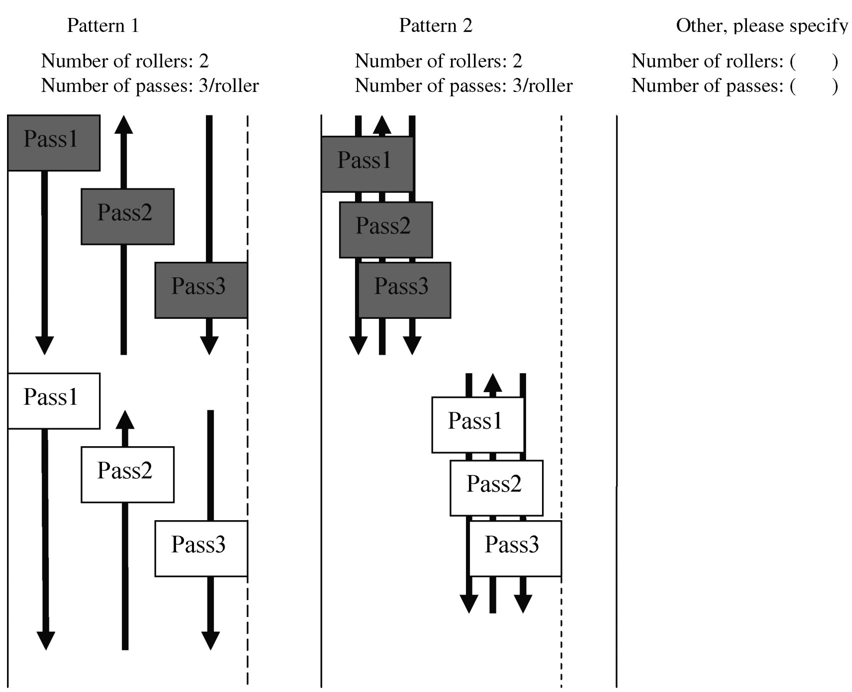
38. What traffic control measures are typically for you chip seal jobs? (Select all you use)

☐ Reduced speed
☐ Interim pavement markings and devices
☐ Pilot vehicles
☐ Flaggers
☐ Safety cones
☐ Other, please specify:

6.16.7 PERFORMANCE

39. What common distresses are observed in your chip seals? please indicate the top three distresses in order of occurrence.

☐ Potholes
☐ Raveling
☐ Bleeding
☐ Corrugation
☐ Crack reflection
☐ Streaking
☐ Transverse joints



☐ Longitudinal joints
☐ Other, please specify:
1.____________________ 2. ____________________ 3. ____________________

40. Which factor is most important in improving chip seal performance in your District? (Check one box only.)
☐ Construction procedure
☐ Design method
☐ Better emulsion
☐ Better aggregates
☐ Quality control
☐ Other, please specify:

41. What is the most common public-user complaint about a chip seal? (Check one box only.)
☐ Loose stone
☐ Road noise
☐ Vehicle ride
☐ Appearance
☐ Other, please specify:

42. How would you describe the pavement ride on roads that generally receive a chip seal?
☐ Excellent
☐ Good
☐ Fair
☐ Poor
☐ Very Poor

43. Of your District's chip seal failures, which of the following was a likely cause? Please indicate the top three causes in order of importance.
☐ Weather
☐ Insufficient rolling
☐ Improper emulsion application rate
☐ Improper aggregate rate
☐ Aggregate spread early
☐ Aggregate spread late
☐ Dirty or dusty aggregate
☐ Aggregate gradation
☐ Improper emulsion viscosity
☐ Improper emulsion temperature
☐ Other, please specify:
1.____________________ 2. ____________________ 3. ____________________

44. Which factors are most critical in determining the life of your chip seals?
☐ Original quality of pavement
☐ Traffic
☐ Underlying structure
☐ Maintenance spending
☐ Friction loss
☐ Materials of chip seal
☐ Cold climate considerations (freeze–thaw cycles, snowplowing, etc.)

45. Do you perform any field tests to monitor the quality of your chip seal?
☐ Yes ☐ No If Yes, what are they?

46. Do you have any maintenance method for your chip seals?
☐ Yes ☐ No If Yes, please specify:

47. Any comment about your chip seal practice? Thank you for your cooperation!

6.17 FLAKINESS INDEX ITM

INDIANA DEPARTMENT OF TRANSPORTATION

OFFICE OF MATERIALS MANAGEMENT
DETERMINING THE FLAKINESS INDEX
OF AGGREGATES
ITM NO. 2XX-07P

6.17.1 SCOPE

- This method describes a procedure to determine the Flakiness Index (FI) of aggregates. The sieve analysis shall be performed in accordance with AASHTO T 27. The (FI) will be determined in accordance with section 5.
- The values stated in either acceptable English or SI metric units are to be regarded separately as standard, as appropriate for the specification with which this ITM is used. Within the text, SI metric units are shown in parenthesis. The values stated in each system may not be exact equivalents: therefore each system shall be used independently of the other system, without combining values in any way.
- This ITM may involve hazardous materials, operation, and equipment. This ITM does not purport to address all of the safety problems associated with the ITM's use. The ITM user's responsibility is to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

6.17.2 SIGNIFICANCE AND USE

- This ITM provides guidance for determining the FI of aggregates.

6.17.3 APPARATUS

- An appropriate size scale or general purpose balance conforming to AASHTO M 231.
- A metal plate approximately 0.0625 inches thick with slotted openings conforming to the dimensions shown in Figure 1.
- Appropriate sieves conforming to AASHTO M 92

6.17.4 SIEVE ANALYSIS PROCEDURE

- Initial sample will be obtained in accordance with ITM 207
- The sample will be further reduce in accordance AASHTO T 248 to weight appropriate for the aggregate size being tested as indicated in the Inspection and Sampling Procedures for Fine and Coarse Aggregates.
- The percentage of materials finer than the #200 (75mm) sieve will be determined in accordance with AASHTO T 11.
- The particle distribution of the oven dried sample will be
- determined in accordance the AASHTO T 27.

6.17.5 FLAKINESS INDEX PROCEDURE

- Aggregates retained on each sieve (No. 4 and larger) which comprises at least 4 percent of the total sample shall be tested particle by particle for its ability to pass through the an appropriate slotted sieve or plate with elongated opening. The size of the slot for each size aggregate is given in table 1.
- For aggregates with a nominal maximum size of ½" or larger, where the FI is to be determined on material retained on the No. 4 (4.74mm)sieve, the test sample may be separated on 3/8" (9.5mm) sieve. The portion passing the 3/8" (9.5mm) sieve may then be further reduced, in accordance with ASTM Practice C 702 to a minimum of 0.5 lb (200 g). This will reduce the number of particles to be evaluated during the procedure. In this case, the percentage of particles found to be flakey is determined on each portion; and a weighted average percentage of flakey particles is calculated based on the mass of each of the portions to reflect the total percentage of flakey particles in the entire sample.
- Record the weights of the aggregates particles retained on each slot opening and the weight that passes each slot on the FI worksheet (form IT xxx). The total amount passing the appropriate slot opening shall be weighed to an accuracy of at least 0.1% of the mass of the test sample.
- Compute the FI using the worksheet in Figure 2. The FI is the total weight of the material passing the appropriate slot openings expressed as a percentage of the combined weight of the fractions tested on the slotted opening. Record the nearest whole percent.

$$\textbf{FlakinessIndex}^{(2)} = \frac{\text{Total of Column E}}{\text{Total of Column F}} = \underline{\hspace{4cm}}(100) = \boxed{}$$

TABLE 1
Slot Size for Each Aggregate Fraction

Range of Aggregate Size		
Material Passing	Material Retained	Width of Slotted Sieve Opening (inches)
1″	3/4″	0.525
3/4″	1/2″	0.375
1/2″	3/8″	0.263
3/8″	1/4″	0.183
1/4″	No. 4	0.131

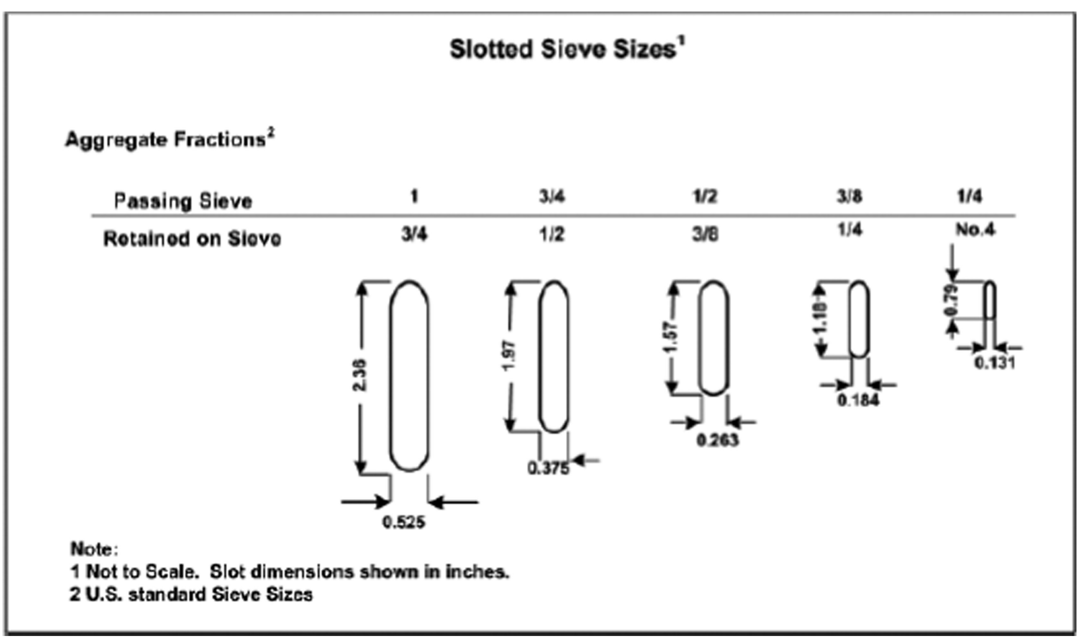


FIGURE 1 - SLOTTED SIEVE OPENINGS.

Project: ____ Source: ____

Where Sampled: _________________________ Quantity Represented: ___________________________________

Sample of: ______________________________ Lot No.: ____

Sampled By: ____________________________ Tested By:

Sieve Size (inches)	A Weight Retained (grams)	B Total Passing (grams)	C Flakiness Plate Slot Size Identification	D Weight Retained on Flakiness Plate (grams)	E Weight Passing Slot on Flakiness Plate (grams)	F Total Weight (grams) (D + E)
1			1 to ¾			
¾			¾ to ½			
½			½ to 3/8			
3/8			3/8 to ¼			
¼			¼ to No. 4			
No. 4						
			TOTAL			
Total						

Figure 2 - FLAKINESS INDEX WORKSHEET ITM XXX

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