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Developing Guidelines for Precoating of Aggregates Used in Seal Coats

Erica Lopez
Michael Rung
Dheeraj Adwani
Ahmad Masad
Darren Hazlett
Amit Bhasin

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16. Abstract

Seal coats in Texas are unique because most binder is hot applied, and aggregates are precoated. Precoating eliminates dust and improves adhesion between aggregate and binder. There currently exists no guidelines or specifications in place that can allow engineers to specify and accept the quality and extent of binder used to precoat aggregates. Precoating with certain binders can result in poor adhesion and premature failure of the seal coats. Inadequate precoating can result in dusty aggregate that impedes aggregate adhesion.

The objective of this study was to determine the amount of precoating that is optimal for seal coat aggregates. To address this objective, this study had three goals:

- Examine different factors of precoated aggregates that influence seal coat performance.
- Establish test methods and procedures to evaluate precoated aggregate adequacy.
- Establish requirements and acceptance criteria of precoating to ensure adequacy of the precoating.

The study used modifications of a sweep test and Vialit test for measuring seal coat aggregate adhesion and developed an image processing procedure to determine the percent area coverage of precoated seal coat aggregate. A laboratory testing program and field section evaluation were used to develop tentative limits for the percent of asphalt coverage for precoating and guidelines for implementation.

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Erica Lopez
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Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th floor
Austin, TX 78759

http://ctr.utexas.edu/

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Project Engineer: Amit Bhasin
Professional Engineer License State and Number: Texas No. 126265
P.E. Designation: Research Supervisor

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ABSTRACT

Seal coats in Texas are unique because most binder is hot applied, and aggregates are precoated. Precoating eliminates dust and improves adhesion between aggregate and binder. There currently exists no guidelines or specifications in place that can allow engineers to specify and accept the quality and extent of binder used to precoat aggregates. Precoating with certain binders can result in poor adhesion and premature failure of the seal coats. Inadequate precoating can result in dusty aggregate that impedes aggregate adhesion.

The objective of this study was to determine the amount of precoating that is optimal for seal coat aggregates. To address this objective, this study had three goals:

- Examine different factors of precoated aggregates that influence seal coat performance.
- Establish test methods and procedures to evaluate precoated aggregate adequacy.
- Establish requirements and acceptance criteria of precoating to ensure adequacy of the precoating.

The study used modifications of a sweep test and Vialit test for measuring seal coat aggregate adhesion and developed an image processing procedure to determine the percent area coverage of precoated seal coat aggregate.

A laboratory testing program and field section evaluation were used to develop tentative limits for the percent of asphalt coverage for precoating and guidelines for implementation.

EXECUTIVE SUMMARY

The purpose of using precoated aggregates in hot applied seal coats is to improve the aggregate-binder compatibility. Precoating also prevents dust particles from accumulating on the aggregate surface and inhibiting adhesion. Poor adhesion makes the aggregate particles prone to being dislodged and consequently susceptible to raveling.

Summary of Project Work

This study found that the use of hot applied binder and consequently use of precoated aggregates is not prevalent among many states, so the literature is not well developed. One roadblock to studying precoated aggregate is a lack of robust methods to evaluate the percent of area coated with asphalt. This study evaluated four methods:

- infrared imaging,
- microextraction,
- image analysis, and
- colorimeter.

To measure the area of precoating, image analysis provided the information needed, was easier to perform, and was the least expensive. The study produced an automated method using image analysis to determine percentage of area coated with binder.

A series of laboratory experiments were conducted to examine performance of manufactured seal coat specimens using a Sweep test and the Vialit test. Variations in the test matrix included: aggregate minerology (limestone, sandstone, rhyolite, and gravel), seal coat binder type (2 types of binders), precoat binder amount (5 different amounts of precoating).

Some of the findings from these laboratory tests are summarized here. The use of polymer modified binder resulted in lower aggregates loss in the performance tests than unmodified binder at all precoat levels. Overall, neither the Vialit test nor the Sweep test detected meaningful changes in adhesion as precoating increased, showing that a precoating area of 50% binder up to 100% precoat area performed similarly. The Sweep test detected a significant difference in bonding between uncoated and precoated aggregate samples, demonstrating the importance of precoating aggregate in a hot applied seal coat.

One rationale for precoating is to degrade the negative effect of dust on aggregate adhesion to the base binder in a seal coat. This study showed that this is true and significantly improves adhesion. Figure ES1 shows this significant improvement and the asymptotic relationship between loss and precoating, suggesting that there is a threshold area above which additional binder has no discernible effect. Based on the results gathered from this study, this threshold corresponds to approximately a precoating area of 50%.

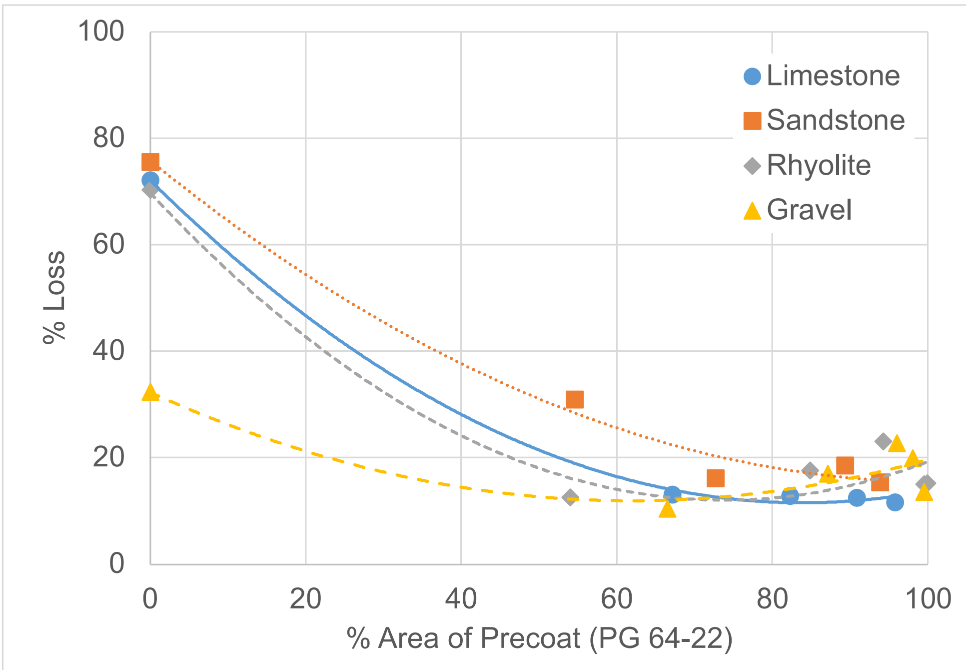

Figure ES1. Sweep test results including uncoated aggregate (AC-20-5TR base binder)

A precoating area of 50% translates to different amounts of precoat binder by weight of aggregate, depending on the aggregate. This depends on absorption, surface area (surface texture and aggregate size), dust content, and specific gravity. For all aggregate mineralogies used in this study, more than 85% precoated area leads to sticking and clumping of precoated aggregate.

Results from 34 field sections with known performance and retained original aggregate and binder were evaluated using the Sweep and Vialit tests and image analysis for area percent of precoat. Observation from the 34 field sections showed no significant aggregate loss due to adhesion. Both field and lab data confirm that a precoating area of 50% or higher is adequate to prevent excessive loss due to adhesion.

Conclusions

This study supports the following conclusions for seal coats using precoated aggregate with hot applied base asphalt.

- Precoating of aggregate increases aggregate adhesion according to the Sweep test.
- Image analysis can be used to quantitatively determine the precoat area.
- Aggregates with no precoat exhibit much more loss using the Sweep test. This means that precoating significantly increased aggregate retention, validating the use of precoated aggregate for hot applied seal coats.
- Aggregate precoat area above 50% has little effect on aggregate retention, but precoat area above 85% tends to produce clumping. Excess precoating may also exaggerate problems related with embedment and bleeding. Thus, the optimum precoat area is between about 50% and 85%.

Recommended Guidelines

Based on this study, it is recommended to:

- Use precoated aggregate for hot applied seal coats.
- Used precoat percentages by weight of aggregate that correspond to between 50% and 85% of aggregate area coated. This is aggregate specific as it depends on aggregate absorption and surface area.
- One mechanism of implementation can be to use project materials (aggregate and precoat binder) to precoat samples using different percentages by weight and measure the coated area of each sample. The percent by weight that corresponds to approximately 50% area coverage can be specified for use during construction.

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CHAPTER 1. INTRODUCTION

1.1 PROBLEM STATEMENT

Seal coats in Texas are unique because most binder is hot applied, and aggregates are precoated. Precoating eliminates dust and improves adhesion between aggregate and binder. There currently exists no guidelines or specifications in place that can allow engineers to specify and accept the quality and extent of binder used to precoat aggregates. Precoating with certain binders can result in poor adhesion and premature failure of the seal coats. Inadequate precoating can result in dusty aggregate that impedes aggregate adhesion.

1.2 STUDY OBJECTIVES

The objective of this study it to determine adequate precoating for seal coat aggregates. To address this objective, the study has three goals, to include:

- Examine different factors of precoated aggregates that influence seal coat performance.
- Establish test methods and procedures to evaluate precoated aggregate adequacy.
- Establish requirements and acceptance criteria of precoating to ensure adequacy of the precoating.

1.3 STRUCTURE OF THE REPORT

This report includes six chapters to address these goals. Chapter 1 provides the problem statement and objectives. Chapter 2 presents a literature review and results of a survey of TxDOT Districts and other state DOT personnel. Chapter 3 identifies and develops methods to evaluate the extent of precoating in aggregates. Chapter 4 uses these methods in a series of laboratory-based experiments to seal coat performance of precoated aggregates at various precoat levels to include aggregate mineralogy and absorption, binder grade, binder quantity and binder modifiers. Chapter 5 is an evaluation of the performance of field test sections according to a preliminary recommended protocol. Chapter 6 represents a summary of the work with proposed guidelines and acceptance criteria.

CHAPTER 2. LITERATURE REVIEW AND SURVEY

This chapter provides a summary of literature reviewed on the influence of precoating and performance of seal coats as well as potential methods that can be used to assess the extent of precoating. This literature review is accompanied by a summary and findings from a survey disseminated to TxDOT districts and other State DOTs. This survey was conducted to include current practice and concerns related to precoating of aggregates and to supplement the information gathered from the literature review.

2.1 BACKGROUND AND SIGNIFICANCE

The purpose of using precoated aggregates in hot applied seal coats is to improve the aggregate-binder compatibility. Precoating also prevents dust particles from accumulating on the aggregate surface and inhibiting adhesion. Poor adhesion makes the aggregate particles prone to being dislodged and consequently susceptible to raveling. Figure 2.1 shows excess fines or dust on aggregate particles on a seal coat prior to rolling. Note that this figure is for an emulsion-based seal coat and not a hot applied seal coat; in case of the latter, it is easy to visualize that such dust would create significant interference in bonding with the hot underlying binder surface.

Figure 2.1. Photograph showing excess fines / dust on aggregate particles on a seal coat (emulsion based before rolling)

Gallaway and William (1966) present one of the earliest efforts related to the use of precoated aggregates in Texas that involved gravel and crushed stone producers in 1958. At that time, they produced precoated aggregates for seal coats and surface treatments to reduce automobile damage due to flying stones (Gallaway and William, 1966).

Two important parameters for precoating are the extent of precoating and the binder used for precoating the aggregate particles. Currently, there are no guidelines or specifications in place that allow engineers to specify and accept the quality and extent of binder used to precoat aggregates. Precoating with potentially deleterious binders can result in poor adhesion and premature failure of the seal coats. This may be due to potential problems with the binder chemistry, which may result in a binder that otherwise meets all standard specifications. For example, the use of binders extended using higher percentages of re-refined engine oil bottoms have shown to result in poor adhesion and premature failure of seal coats (Karki et al., 2019). Inadequate precoating can result in dusty aggregate that impedes aggregate adhesion.

2.2 SUMMARY OF STATE DOTS STANDARD SPECIFICATIONS PERTAINING TO SEAL COATS

An extensive review of the state DOT specifications relevant to seal coats was carried out as a part of this study. Tables 2.1 and 2.2 summarize the material types used in seal coat construction according to the available state DOT Standard Specifications. This was extremely helpful in identifying the state DOTs that used precoated aggregates and made it possible to include them as a potential respondent to the survey. Findings and information from this summary were refined and fine-tuned by analyzing responses from the survey. It is important to note that the existence of a specification does not necessarily imply that it is practiced. For example, it is possible that there are specifications related to the use of cutbacks for seal coats, but other provisions or practices may prohibit the use of cutbacks.

Table 2.1. Commonly used binder types for seal coats in different states based on information available online

State	Emulsion	Polymer Modified Emulsion	AR Binder	Other Hot Binder	Cut Back	Info. not found	Precoated Aggregates	Reference
Alabama	X							2018 spec.
Arizona	X	X	X		X		Yes	2008 spec., Chip Seal Guide
Arkansas	X			X	X			2014 spec.
California	X	X	X				Yes	2018 spec.
Colorado	X							2012 Chip Seal Manual
Connecticut						X		2018 spec.
Delaware						X		2016 spec.
Florida						X		2020 spec.
Georgia				X				2013 spec
Hawaii	X							2005 spec.
Idaho	X			X				2018 spec.
Indiana	X							2020 spec.
Iowa	X				X			2012 spec.
Kansas	X			X	X			2015 spec.
Kentucky	X							2019 spec.
Louisiana	X			X			Yes	2016 spec.
Maine						X		2014 spec.
Maryland	X							2018 spec.
Massachusetts	X							2019 suppl. spec.
Michigan	X							2012 spec.
Minnesota	X							2018 spec
Mississippi	X			X	X			2017 spec.
Missouri	X							2018 spec.
Montana	X							2014 spec.
Nebraska	X							2017 spec.
Nevada	X							2014 spec.
New Hampshire						X		2016 spec.

Table 2.2. Commonly used binder types for seal coats in different states based on information available online (contd.)

State	Emulsion	Polymer Modified Emulsion	AR Binder	Other Hot Binder	Cut Back	Info. not found	Precoated Aggregates	Reference
New Hampshire						X		2016 spec.
New Jersey						X		2007 spec.
New Mexico						X		2019 spec.
New York	X							2016 spec.
North Dakota	X				X			2014 spec.
North Carolina	X							2018 NC spec.
Ohio		X						2016 spec.
Oklahoma	X			X			Yes	2009 spec.
Oregon	X			X			Yes	2016 Chip Seal Design and spec.
Pennsylvania	X			X	X			2020 spec.
South Carolina						X		2007 spec.
South Dakota		X						2015 spec.
Tennessee	X							2015 spec.
Texas	X	X	X	X			Yes	2017 Seal Coat Manual
Utah	X							2017 spec
Vermont						X		2018 spec.
Virginia						X		2016 spec.
Washington				X			Yes	2020 spec
West Virginia						X		2017 spec.
Wisconsin				X				2017 spec.
Wyoming								2010 spec.

2.3 FACTORS AFFECTING SEAL COATS

The main goal of this study is to develop guidelines pertaining to the quality of the precoating binder as well as the extent of precoating of aggregates that is required in seal coats with the intent to avoid premature failure. Although ensuring the quality of the precoating binder and extent of precoating are necessary, they are not sufficient to ensure adequate performance of seal coats. Since the field performance of seal coats serves as the benchmark for the findings from this study, it is important to recognize the different factors that influence the performance of seal coats. These factors can be grouped into three areas:

- material related factors including, binder quality (stiffness, viscoelastic properties, strength, and aging susceptibility), aggregate properties (absorption that affects amount of binder needed, angularity, texture, soundness), aggregate and binder compatibility (ability of the specific aggregate-binder pair to adhere to each other), and specifically for hot-applied seal coats the quality and extent of precoating binder used with the aggregate;
- design, i.e., factors related to the binder and aggregate application rates including aggregate embedment, traffic, voids in seal coats, and aggregate gradation; and
- construction related factors including extent of compaction, time, and allowable speed at which the roadway is opened to traffic, weather, existing pavement conditions, and nozzle orientation and pressure.

The focus of this project is on guidelines related to precoated aggregates. However, precoating is almost always used with hot applied binder. Based on a review and survey of state DOT specifications, hot applied binder and consequently the need for using precoated aggregates is limited to only a few states. Consequently, there is a very limited body of knowledge or research around this topic. Most of the practice in this regard is guided by past experiences that have been apparently codified to varying degrees. The following sections present findings from some of the research studies in this area and other areas that can be adapted for the purposes of this study.

2.4 PREVIOUS RESEARCH RELATED TO PRECOATED AGGREGATES

Research in this area has been concentrated on determining the detrimental effect of dust on aggregate retention and some work on determining the extent of coating.

2.4.1 Influence of precoating on durability of seal coat

The existence of dust on the surface of a seal coat aggregate is one of the most common causes of aggregate loss. Dust prevents the wetting of the aggregate particle surface by the binder and formation of a durable adhesive bond between the aggregate and the binder. The most common solution adopted to overcome this problem is the use of precoated aggregate.

Kandhal and Motter (1991) conducted a study on precoated aggregates for seal coats and surface treatments. They studied the effect of varying dust and precoating contents on uncoated and coated aggregates, respectively. For uncoated aggregates, they used five different aggregate types with varying dust contents (1,2,3,4 and 5% by weight) and the aggregate loss was measured using the Pennsylvania aggregate retention test. They found that after about 3% dust content (by weight), the aggregate loss increased significantly. For precoated aggregates, they used the same aggregate with the 3% dust content and precoated the aggregate with a cutback asphalt (MC-30) and varied the precoating content. They observed that increased precoating coverage decreased the initial aggregate retention loss, and that aggregate loss due to dust was significantly reduced by precoating to achieve at least 90% coverage of the aggregate surface area with the use of a precoating binder. Their results showed that with more than 90% precoating coverage, initial aggregate retention loss was reduced by as much as 80% when compared to non-precoated aggregates. Finally, they noted that the use of precoated aggregate with emulsified asphalt slowed the breaking time of emulsified asphalt so that the opening time to traffic was delayed. In fact, this is the main reason precoated aggregates are used mostly with hot applied seal coats.

Rahman et al. (2012) conducted a study to identify the aggregate-emulsion combinations that maximized aggregate retention in a seal coat. They investigated the effect of four different factors on aggregate retention. These factors included the type of aggregate, emulsion, and the type and amount of precoating binder. The effect of each factor was studied separately by observing the amount of aggregate retention in the sample. In addition, they statistically studied the effect of the interaction of these factors on aggregate retention by using Analysis of Variance (ANOVA). The aggregate retention was evaluated by using the ASTM sweep test and a modified version of this test.

Seven types of aggregates with different mineralogy were analyzed in their study. These included four types of light weight aggregates, gravel, limestone, and recycled aggregates from milling ultrathin bituminous pavement. They also included two polymer modified asphalt emulsions namely CRS-1HP and CRS-2P and a PG 64-22 for precoating. Only gravel and limestone were precoated and the amount of precoating was 1.5% and 2% each. Aggregate retention was evaluated before and after precoating. In general, limestone and lightweight aggregates performed better than gravel and recycled aggregates with both emulsion binders (except that one type of lightweight aggregate performed better than the limestone with CRS-2P). After precoating gravel and limestone with PG 64-22, they reported that only gravel with CRS-2P had improved performance compared to its performance before precoating. However, the effect of 1.5% and 2% precoating contents were the same. The ANOVA results concluded that the aggregate, emulsion, and their interaction are the most significant factors affect aggregate retention. However, it is important to note that Rahman et al. (2012) based their findings using the ASTM sweep test and the modified sweep test, and more importantly using precoated aggregates with emulsified binders and not hot applied binders.

Akbulut et al. (2014) focused on evaluating the impact of dust on aggregate surfaces on the performance and specifically the aggregate-binder adhesion in hot mix asphalt. They used two different limestone aggregates with different dust contents. Although this is not directly relevant to seal coats, the findings can be useful in interpreting potential impact of precoating and preventing dust on the durability of the aggregate-binder bond in a seal coat. The dust content on the aggregate surface was synthesized artificially using a rolling drum to allow the aggregate to degrade and deposit in the form of dust on the surface. This process was used to simulate the dust formation during typical material handling and construction processes that are carried out in the field. The dust content was determined by trial and error and weighing the aggregate before and after rolling in drums. The aggregate properties were determined using different tests such as bulk specific gravity, water absorption, and Los Angeles

Abrasion. In one case, the aggregate was more porous and resulted in a higher dust content. However, when the aggregate samples were evaluated for adhesion using the Vialit test, the more porous aggregate sample resulted in less raveling. Although this result was counter intuitive, it is possible that aggregate porosity provided better bonding through mechanical interlock which more than offset loss of bond due to dust. The study also investigated the influence of dust content on the HMA using the Marshall test and reported a decrease in the voids in mineral aggregate (VMA). Based on these results, they concluded that dust could affect HMA in two ways, it could act as a filler or act as dust that prevents adhesion.

Wasiuddin et al. (2013) used the sweep test to evaluate both cold and hot-applied seal coats. Their study utilized 15 different seal coat sections. These sections included two emulsion-based seal coats and two hot applied seal coats. These sections also included several different types of aggregates including a precoated expanded shale lightweight aggregate and five different types of uncoated aggregates. Overall, they reported that precoated aggregates performed better than uncoated aggregates in terms of aggregate loss. While this study did not specifically look at the quality of precoating, their results do support the importance of adequate precoating to ensure performance of the seal coat.

2.4.2 Image analysis to quantify extent of precoating

Digital images of aggregate particles can be used to quantify the extent of precoating on aggregate particles. Several image analysis algorithms are available that can be refined or modified as necessary to compute percent area of covered by the binder. In fact, such tests are often used in conjunction with the boil test to evaluate stripping resistance of asphalt binder-aggregate pairs. One limitation of this approach is that for dark colored aggregates (e.g., rhyolite and basalt) the contrast difference is generally very small to accurately distinguish between the binder and the aggregate surface. One way to alleviate this weakness is to use IR images with spectral sensors in the 1 to 3 micrometer wavelength range. The methylene- and ethylene- bonds abundantly found in asphalt binders absorb specific wavelengths of IR light within this window whereas the inorganic aggregate surface does not readily absorb these wavelengths. This creates a contrast that can be used to assess the extent of precoating more accurately. Based on a review of the literature, two other potentially viable candidates have emerged. These have been summarized in the paragraphs below.

Mulsow (2012) used an approach to determine the percentage of precoating binder on the aggregate particle that involved the use of colored light. The author used a multi-directional reflectance measurement, which is sensitive to the surface characteristics of the aggregate and binder. The roughness of the aggregate is significantly higher than the binder. Therefore, if a laser is aimed towards a precoated aggregate, it will scatter because of its roughness. Interestingly, the binder will act as a mirror-like reflecting surface (at least locally) because of the mechanical stress and smoothing of the rough aggregate texture after the mixing process with aggregate. Figure 2.2 shows the image under regular light and after scatter under laser. This figure clearly shows the difference between binder and aggregate is not noticeable under ambient light, but this difference can clearly be seen in high contrast when examining under a laser source.

Figure 2.2. Aggregate surface before and after being examined for scatter under laser (Mulsow, 2012)

Lantieri et al. (2017) proposed a 2D image analysis method to replace the visual inspection analysis of aggregate and binder after the rolling bottle test for aggregate adhesion. The rolling bottle test was used to quantify the affinity between aggregate and binder. The visual inspection of aggregate surface and loss of binder coating is performed by two operators and is highly subjective. Although the scope of their work was not aimed at measuring precoating, the end goal of measuring the extent of coating (or lack thereof) is the same. Their study included both light and dark colored aggregates and used these aggregates with wax modified binder (70/100 pen bitumen). The image analysis method was used to objectively quantify the binder coverage on the surface of the aggregate particle after mixing. This task is particularly challenging considering the dark color of the basalt aggregate. For this purpose, the sample was laid on a green background and irradiated with two lamps as shown in Figure 2.3. The image analysis is based on pixel classification of binder and aggregates. This is done by selecting a color space and then assigning one color to pixels that represent the binder and a different color to pixels that represent the uncoated aggregate surface. The color space that was selected is the YUV which separates the image into luminance and chrominance information. Once the images are uploaded to the computer-aided software, the background is eliminated by assigning initial values for YUV.

Figure 2.3. Photograph showing imaging of the aggregate surface using a con trasting background to assess extent of aggregate coating (Lantieri et al., 2017).

The three aforementioned approaches, i.e., use of IR camera, use of laser scattering, and use of high contrast imaging in different color spaces were used as preliminary methods to assess the extent of precoating in this study.

2.4.2.1 Ignition oven test

Based on a review of the specifications and also based on responses received from different states and districts within TxDOT, an ignition oven is sometimes used to assess the binder content from a sample of precoated aggregate. The use of an ignition oven to estimate binder content for hot mix asphalt is a well-established procedure within TxDOT (Tex-236-F). The procedure basically involves the use of an ignition oven to burn the asphalt binder coating the aggregate. By weighing the mass of the aggregate before and after, and applying appropriate correction factors, it is possible to quantitatively determine the quantity of binder coating the aggregates.

2.5 SUMMARY

A literature review was conducted with focus on the main goals of this study, i.e., to develop guidelines and a process to evaluate the extent of precoating for seal coat aggregates. Based on a survey of the literature and state DOTs, it appears that hot applied binder and consequently use of precoated aggregates is not prevalent among many states. This is expected because hot applied seal coats are more suitable for warmer climates such as Texas. Consequently, the body of knowledge in this area is limited. However, based on a review of the literature on topics related to quantification of precoating for the purposes of evaluating moisture damage resistance in hot mix asphalt, researchers were able to identify at least three different candidate methods that can be further evaluated for routine use as a part of this study.

CHAPTER 3. METHOD DEVELOPMENT AND ESTABLISHMENT OF TEST PROTOCOLS

3.1 OVERVIEW

The main goal of this study was to examine the factors related to precoating of aggregates and their influence on the performance of hot applied seal coats. However, a first step to achieve this goal is to quantify the extent of precoating on an aggregate particle. The main goal of this part of the study was to develop a test method and protocol that can be used to quantify the amount of precoating on aggregate particles. This chapter documents the methods explored to achieve this goal.

3.2 CANDIDATE TEST METHODS

A review of the literature revealed that there is very limited development in the area of methods to evaluate extent of precoating of aggregate particles that are specifically intended for seal coat application. Therefore, this study examined potential methods based on other similar applications to develop a tool that can easily be used to evaluate the extent of precoating on aggregate particles. Specifically, three methods were explored in this study:

- Infrared imaging to detect asphalt and differentiate it from inorganic aggregate substrate
- Image analysis
- Colorimeter with dissolved binder

The following sections describe the findings from this part of the study.

3.3 MATERIALS

Material selection for the current and future tasks was based on results from surveys prepared in Task 1. The materials used for this part of the study included one binder (PG 64-22) for precoating and aggregates representing three different mineralogy (limestone, sandstone, and rhyolite). The survey identified the most common types of materials used in hot applied seal coat construction in Texas. In addition, the percentages of precoating binders were varied with respect to aggregate mineralogy to evaluate the optimum amount of binder precoating.

Table 3.1 presents the initial set of material combinations that were evaluated. Additional material combinations were prepared and used with the specific methods at later stages as the need arose to evaluate the sensitivity of the test method. The aggregates were precoated by heating the aggregate particles and the binder (pre-weighed based on target percentage) and mixing the two in a silicone container.

Two important notes from this exercise were as follows. First, in addition to mineralogy, the aggregates were also selected based on their color. Specifically, for image analysis techniques, the color of the aggregate can have a significant influence on the outcome. Therefore, it was important to select aggregates that represented a gamut of colors. The limestone was a light-colored aggregate and the rhyolite was a dark colored aggregate and possibly the darkest in the state of Texas. The sandstone was somewhere in between with a slightly brown tint.

Second, the extent of precoating was aggregate dependent. For example, for limestone and sandstone 1.5% appeared to be the maximum the aggregate could handle before the aggregates become overcoated and started sticking with each other. Interestingly, for the rhyolite aggregate this limit was reached at 1.0% by weight of the aggregate. Note that these percentages are not necessarily the target or optimum for precoating, rather these are just the maximum limits that should not be exceeded during precoating to avoid agglomeration of particles in a stockpile. Figures 3.1 through 3.3 show typical samples of uncoated and coated aggregates that were used as the basis of the different techniques evaluated in this study.

Table 3.1. Material combinations used to evaluate different test methods

	Limestone	Sandstone	Rhyolite
Precoating percentage	0.5%	0.5%	0.5%
	1.0%	1.0%	1.0%
	1.5%	1.5%	–
	2.0%	2.0%	–

Figure 3.1. Limestone aggregates coated with controlled amount of binder (left to right: 0.5%, 1.0%, 1.5%)

Figure 3.2. Sandstone aggregates coated with controlled amount of binder (left to right: 0.5%, 1.0%, 1.5%)

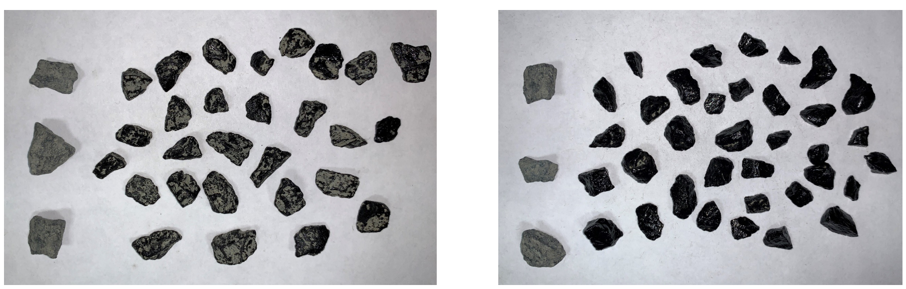


Figure 3.3. Rhyolite aggregates coated with controlled amount of binder (left to right: 0.5%, 1.0%)

3.4 METHOD 1: IR IMAGING

The rationale to use infrared or IR images was that asphalt binder is primarily a hydrocarbon that coats an aggregate particle, which is an inorganic material. Consequently, it was hypothesized that an IR image, particularly with wave numbers in the range of 2750 to 3150 cm^{-1} would be very sensitive to the organic coating from the binder, whereas the aggregate surface would not register in this range. This was also considered advantageous because the method would be largely independent of the color of the underlying aggregate. Figure 3.4 shows a typical IR spectrum for an asphalt binder with wave numbers ranging from 400 to 3600 cm^{-1}. The wave numbers in the range of 2750 to 3150 cm^{-1} are dominant because they represent the methyl- and ethyl-functional groups in a hydrocarbon.

To explore this technique, an IR camera was used to image the surface of a sample of precoated aggregates. Figure 3.5 shows an image of the setup used to acquire IR images of the aggregate surface and a sample of precoated aggregate that was analyzed using an IR camera. However, based on preliminary testing and analysis this approach was not pursued any further for two reasons.

First, the IR image was extremely sensitive to thermal changes and fluctuations even in the small region surrounding the sample. However, researchers believe that this shortcoming can be overcome with appropriate image acquisition procedures and analysis. Second, and perhaps the more critical reason for not pursuing this approach, was that the camera that could provide sufficient resolution and IR wavelength range required for this application had a very high capital cost that was deemed not viable for the scope of this project as well as the intended application. However, researchers believe that with continual development of semi-conductor technologies, it may be viable to use IR cameras for this and other applications in the near future. Therefore, it is recommended that this technology be revisited again in the near future for this and other similar applications.

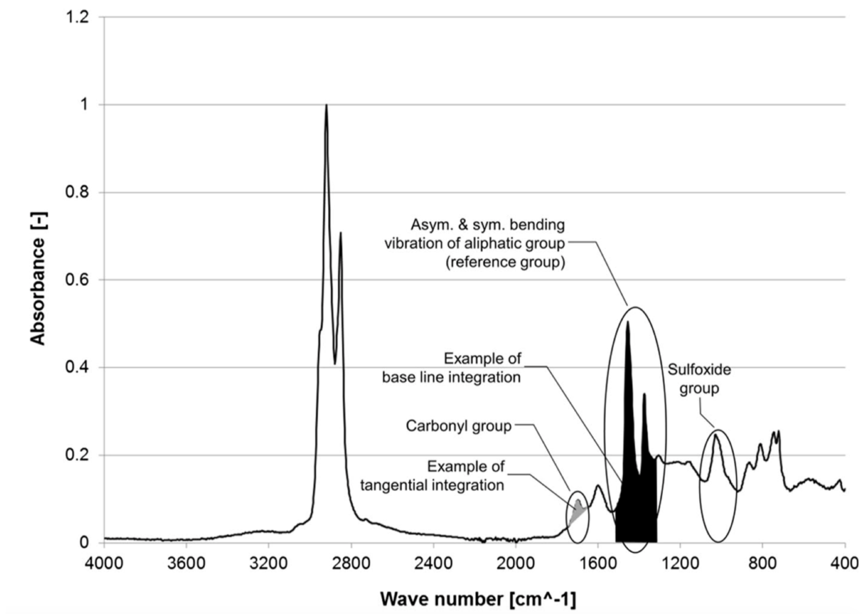


Figure 3.4. FTIR spectra of asphalt binders (Hofko, B et.al,2018)

Figure 3.5. Example of IR imaging

3.5 METHOD 2: USE OF MICROEXTRACTION TO ESTIMATE BINDER CONTENT

After precoating it was also important to verify that the percentage of binder by weight of aggregate was achieved uniformly and without any losses in the container used for mixing. To this end, a sample of the precoated aggregate particles was weighed, mixed in toluene, and stirred overnight in an air-tight jar to fully dissolve and remove the coated asphalt binder. The aggregate particles were decanted from the toluene-binder solution, then the aggregate particles were dried and weighed to determine the percentage of binder that was coating the particles. This exercise was carried out for the limestone aggregates with the target binder coating amounts of 0.5%, 1.0%, and 1.5%. The actual binder contents were determined to be 0.48%, 0.93%, and 1.51% respectively.

However, when repeating the above process for the precoated sandstone aggregate, the measured binder coating amounts were much larger than the target amounts. This meant that either excessive binder was being added during the precoating process, or aggregate particles or fines were being poured out with the toluene-binder solution, leading to an overestimation of the binder coating amount. Given the precautions that were taken during weighing and mixing, it was determined that it was unlikely that excessive binder was used during mixing. Therefore, the second possibility, i.e., loss of fines during the decanting process, was the likely reason for the bias. To mitigate this, the process was revised as described below.

The above microextraction process calculated binder content indirectly by measuring the mass of a precoated aggregate sample before and after dissolution of the binder. To reduce experimental error, a more direct method of microextraction was adopted in which the binder would be separated from the aggregate and measured in lieu of measuring the weight of the residual aggregate. To this end, a sample of precoated aggregate particles was weighed and mixed with toluene in an air-tight jar. Enough toluene was added so that the aggregate particles were fully submerged. The particles were mixed in the toluene overnight using a magnetic stirrer. The toluene-binder solution was extracted from the jar using a syringe fitted with an 18-gauge needle and filtered through 1.0 μm filters using a vacuum desiccator. The filtered toluene-binder solution was set aside, and the same sample of precoated particles was submerged a second time in toluene and stirred overnight. The extraction and filtration steps were repeated, and the extracted solution was mixed with the filtered solution collected on the previous day.

The toluene-binder solution was transferred to small, lightweight, oven-safe containers, whose weights had been previously measured. The containers with solution were then placed in a vacuum oven. The vacuum was set to 400 mmHg and the temperature of the oven was slowly increased over the course of 2.5 hours to a final temperature of 165°C, to fully evaporate the toluene without the solution boiling over (Table 3.2).

Table 3.2. Vacuum oven temperatures for microextraction

Global Time (min)	Vacuum Oven Temperature (°C)	Vacuum Oven Temperature (°F)
0	40	104
15	60	140
30	80	176
45	120	248
60	165	329
120	165	329

Once the solvent was evaporated using the vacuum oven, the containers were removed, allowed to cool to room temperature, and the mass of the residual binder was determined using the final and initial masses of the containers. The mass of the binder residue was divided by the mass of the original precoating sample to calculate the percentage of binder by weight of aggregate in the initial precoating sample.

This microextraction process was performed on the four different mineral aggregates: limestone, sandstone, rhyolite, and gravel-precoated at 0.2%, 0.4%, 0.6%, and 0.8% by weight. Table 3.3 shows a comparison between the target and actual percentage binder weights, which are also compared in Figure 3.6.

Overall, it was found that the percentage of binder determined using this method was very close to the target percentage of binder used to prepare the samples. Most of the precoating samples had actual weights that were very slightly below the target binder weights, which can be due to the small amount of binder that is lost to adhesion

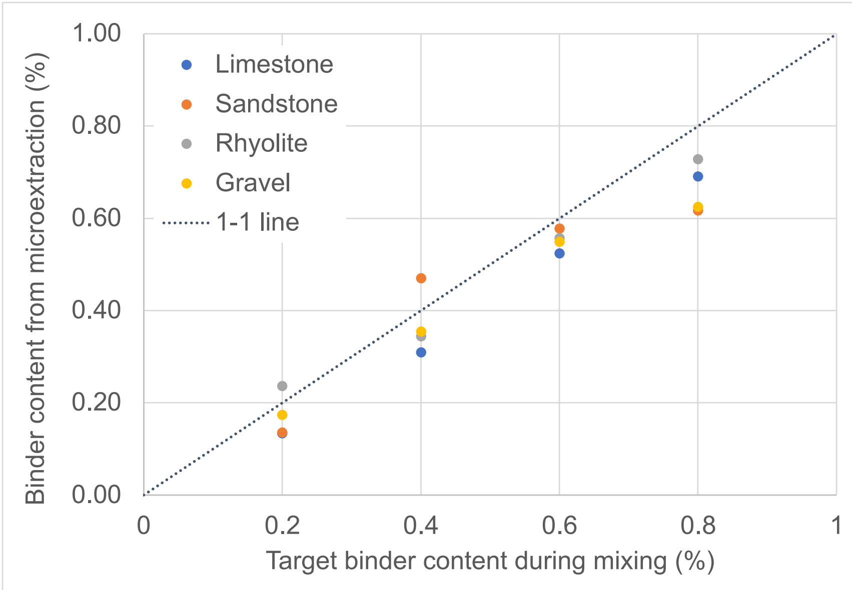


Figure 3.6. Comparison of binder content from the microextraction method to binder content used to precoat the aggregates.

with mixing tools and sides of the containers during the mixing process. Great care was taken to minimize these losses, and as a result there were only minimal differences in actual and target weights.

Although this microextraction process was originally explored as a method of verifying the accuracy of the precoating process, it is also an effective and precise method of estimating the amount of binder in a precoating aggregate sample. Precoated aggregate can be collected in the field and tested in the lab using this microextraction process in order to estimate the amount of precoating binder. This method works best if time is not a constraint and measurement precision is needed.

3.6 METHOD 3: IMAGE ANALYSIS TO ESTIMATE PRECOATING BINDER CONTENT

Table 3.1 shows the baseline materials that were used to develop a procedure to estimate the binder content using image analysis. The first step for any image analysis method is to acquire a well-controlled image of the aggregate particles. In order to avoid variability from cameras and lighting, the first attempt to acquire consistent images was using a typical desktop office scanner. Several coated aggregate parti-

Table 3.3. Binder contents determined using the microextraction method

Aggregate	Binder content based on microextraction (%)	Binder content used during mixing (%)
Limestone	0.2	0.13
	0.4	0.31
	0.6	0.52
	0.8	0.69
Sandstone	0.2	0.14
	0.4	0.47
	0.6	0.58
	0.8	0.62
Rhyolite	0.2	0.24
	0.4	0.34
	0.6	0.56
	0.8	0.73
Gravel	0.2	0.17
	0.4	0.35
	0.6	0.55
	0.8	0.63

cles were placed on the bed of the scanner and an image was acquired as shown in Figure 3.7. However, an examination and analysis of the image revealed that the asphalt binder created high reflection spots on the aggregate surface that were often misinterpreted during the subsequent image analysis steps.

The next attempt to acquire consistent images of the aggregate particles was using a cell phone camera with the flash on. The intent of the flash was to avoid shadows and unwanted artifacts in the image. A few aggregate particles were placed on a white sheet of paper (typical printer paper) and photographed using a cell phone camera with the flash enabled. In another iteration of this process a transparent film was placed in front of the flash to diffuse the light and mitigate any specular reflection. However, this was not effective. After multiple trials, it was determined that a regular image with flash or without flash under well lighted conditions was the simplest and also most effective method of acquiring images that could be processed to estimate the percentage of coating on the aggregate surface. The acquired images were processed

Figure 3.7. Image of precoated aggregate on the bed of a scanner

using an open-source image processing software, "Image-J", to develop a standardized method of analysis that could potentially be used or implemented via the web. The image processing steps involved multiple trials and errors to match the results from the processed images with the ground truth, i.e., the applied binder content for the three different types of aggregates. The steps from image acquisition to analysis that could potentially be used on a routine basis are described below.

1. Approximately 10 to 12 precoated aggregate particles were selected and placed without touching each other on a typical white printer paper.
2. A cell phone camera was used to take an image of these precoated particles by pointing the camera from right above the particles to avoid harsh shadows. It is possible to take similar images in well-lit conditions without a flash, as long as there are no harsh shadows. Figure 3.8 shows a typical image.

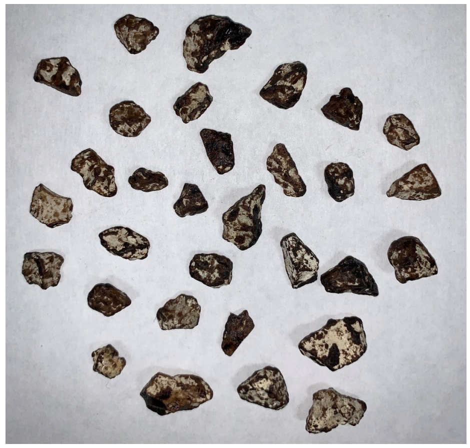


Figure 3.8. Typical image of precoated aggregate particles that can be used for image analysis

The next steps involve image processing of this image. Although these steps were carried out using an open-source image analysis software, these steps are standard image analysis processes and could potentially be replicated on any platform.

3. Digital noise in the acquired image was removed by applying a median filter. In this case a median filter with a 5-pixel radius was used. In addition to digital noise, this also removes most of the highlighted spots from specular reflection. Figure 3.9 shows the image after applying median filter.

Figure 3.9. Image from Figure 3.8 shown after applying a median filter

4. The filtered image was then duplicated. One image was used to calculate the

total area of the aggregate and the other was used to calculate the total area of the asphalt binder.

5. To facilitate thresholding of the image, the image was split into three channels, red, green, and blue.

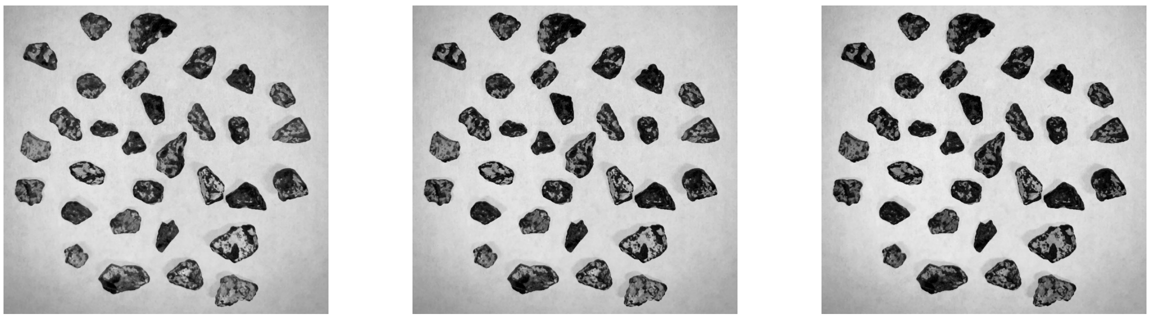


Figure 3.10. Image from Figure 3.9 split into three channels, left to right: red, green, and blue channel

6. The image from each channel was then converted to a binary image using a thresholding algorithm. Typically, a distribution of the pixel intensities will yield two distinct peaks for the aggregate and background and one for the binder. The thresholding limits can be carried out manually or automated based on the distribution. Figure 3.11 shows the images converted to a binary format after thresholding.

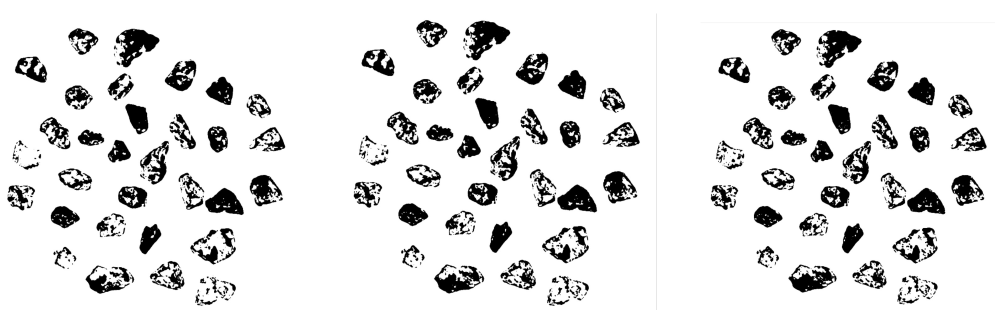


Figure 3.11. Image from Figure 3.10 after thresholding and converting to a binary image

7. The images from the previous step were merged into a single image. The merged image was then inverted, flattened, and converted to a gray scale image. Figure 3.12 shows the results from performing the aforementioned steps.

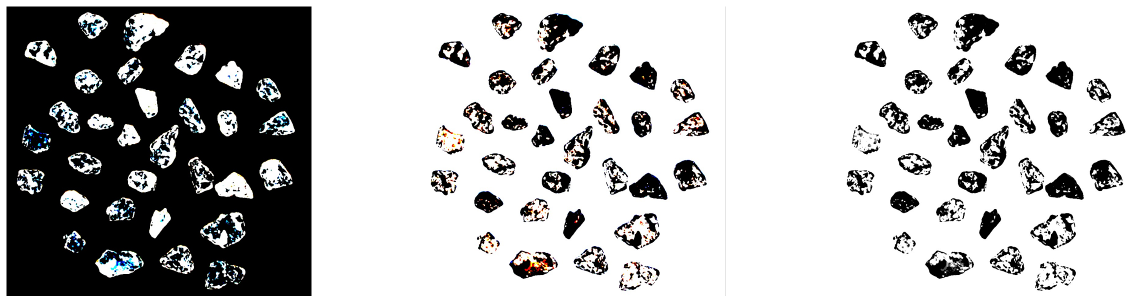


Figure 3.12. Image from Figure 3.11 after inverting, flattening and converting to a gray scale (from left to right, respectively)

8. The last step was to count the number of black pixels, which correspond to the portion of the image coated by the asphalt binder. However, the total area of the aggregate particles is also required to compute the percentage of area coated. This is achieved in the following steps.
9. The second image (duplicate from the first step) was first converted to an 8-bit gray scale image. An edge detection algorithm is then used to trace the outline of the aggregate particles.

Figure 3.13. Duplicate image showing outline detection

10. The gray scale image is then converted to a binary image with a dark background (inverted). All holes in the image are filled and the image is eroded a couple of times. The inversion now causes all aggregate particles to be in black color and therefore a count of the number of black pixels gives the total area of the aggregate particles in the image.

Figure 3.14. Image from Figure 3.13 after converting to gray scale, inverting, and filling holes

11. The ratio of the total number of binder pixels to the total number of aggregate pixels gives the percentage of aggregate area that is coated by the binder.

The aforementioned process was used with all the different precoated aggregates described earlier. Figure 3.15 and Table 3.4 present the results from these analyses. A few pertinent observations from these results are summarized below.

- The ImageJ image analysis algorithm generates consistent measurements for each sample (e.g. sandstone 0.5%), with an average precoating percentage standard deviation of ±3%.
- The algorithm struggles with heavily coated samples because of the high reflectivity of the binder. It is possible to get accurate results but requires more manual adjustments. However, this exercise may be unnecessary or moot since aggregates are rarely over coated and even if they are they would immediately present a problem in stockpiling before they present a problem in seal coat adhesion.
- The relationship between the mass of the binder and the area it covers is not linear. This is somewhat expected because at some point (approximately 1.0% by weight of the aggregate) any additional mass of binder shifts from contributing to the area of coverage to contributing to the thickness.
- The percentage of binder from microextraction was very close to the intended binder content. The fractions of a gram discrepancy is probably attributed to a small amount of binder being stuck to the silicone bowl and the fact that only a sample representative sample was tested.

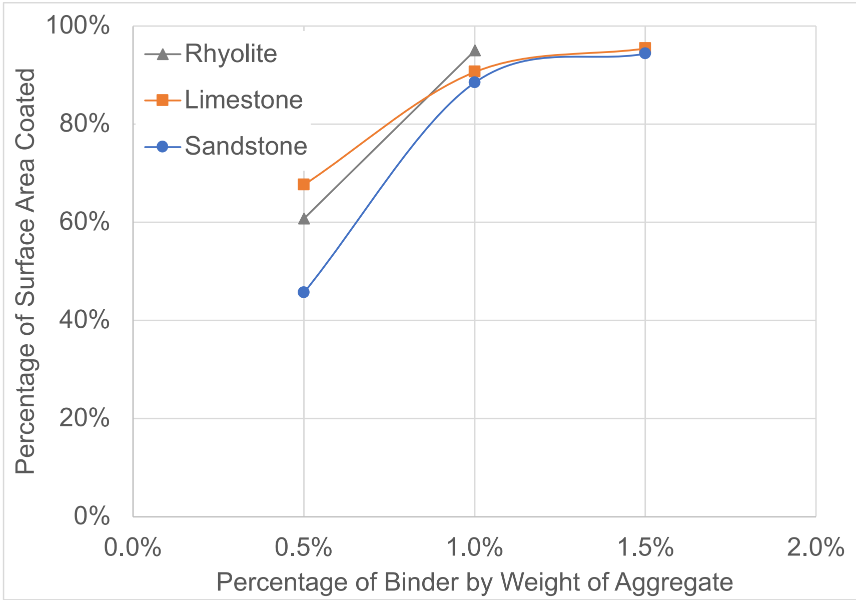


Figure 3.15. Percentage of precoating on aggregates based on image analysis

Table 3.4. Results from image analysis

Aggregate	% Binder (by weight of aggregate)	% Precoated area
Sandstone	0.5 1.0 1.5	46 88 94
Limestone	0.5 1.0 1.5	68 91 95
Rhyolite	0.5 1.0	61 95

3.7 METHOD 3B: AUTOMATING THE IMAGE ANALYSIS PROCESS

The image analysis technique was initially developed to quantify the percentage of aggregate surface area covered by the binder with the intent to determine the optimum coverage for adhesion in a seal coat system and to recommend a limit or range for aggregates from different sources. Based on this rationale, the technique was used with some of the most common types of aggregates. However, the simplicity and speed of the image analysis process makes it a good candidate for routine use. In order to achieve this, the method had to be further developed to accommodate a few adjustments that could be automated through a user-friendly interface.

A user interface provides a way for users to upload images of precoated aggregate and receive back a percentage value that represents the relative amount of binder coating the surface of the aggregate particles. One option considered was to create and host a website that ran a full-stack web application. An image analysis script would be run on the uploaded image, and the results would be displayed to the user on the website. However, such a setup would require significant maintenance that may not be sustainable over the years. Instead, an email application method was chosen instead, to bypass the need for developing an entire website. This approach requires relatively lower maintenance and was used in this study as a proof-of-concept for potential future implementation.

A script was written in Google Apps and was programmed to run every few minutes to search the inbox of a designated email address for new emails with attachments. When a new email is found, the script grabs the images and sends a confirmation email to the user. The script then posts the images, as well as pertinent information in the email, to a Google Drive folder, where a process checks for new images and launches ImageJ. ImageJ is an open-source application that was originally developed through funding from the National Institutes of Health (NIH). The ImageJ program runs an image analysis macro, which processes the image and calculates the precoating binder percentage. The result is collected and emailed back to the user.

From a user perspective, this method is simple: the user needs to take a picture of precoated aggregate using a cell phone in well-lit conditions, email the image to a specified email address, and receive a reply minutes later with the estimated percentage of binder precoating. One of the advantages of an email application is that all smartphones have email integrated in their camera app, and people can email photos easier than navigating and uploading an image to a website. Ideally, engineers and contractors in the field would be able to determine the precoating percentage of a chip seal they are analyzing within minutes, and technicians in the lab can determine the precoating percentage of a sample without needing to operate a program themselves.

3.8 METHOD 4: COLORIMETER TO ESTIMATE PRECOATING BINDER CONTENT

One of the central tenants of this research project is to develop practical and user-friendly approaches that are not only accurate but are also easy to implement in the field and district laboratories. To this end, another approach that was considered to estimate binder content was the use of a colorimeter to measure the color of a solvent that has binder dissolved in it. The premise for this approach was as follows: a small sample of the precoated aggregates could be selected and thoroughly mixed in a solvent that is easy to obtain in the field or a district laboratory followed by a measurement of the change in color as a quantitative indicator of the percentage of binder on the aggregate particles. In this case it was hypothesized that diesel or kerosene, which are often also used to dissolve and clean asphalt binder, could be used to extract the binder. The color measurements could be made using a simple handheld colorimeter that is available commercially. The basic operations of a colorimeter and the work done to explore the feasibility of this approach is described in this section.

Colorimeter is a measuring device that is used to determine the color of an object by shining a controlled light towards an object and quantifying the reflection through three different color filters (red, green, and blue). The color of an object can be quantified using several different industry standards that are interchangeable. The approach used in this study is based on the LAB standard, i.e., measurement of three parameters namely "L" which is the degree of lightness/darkness, "a" which represents the degree of redness/greenness and "b" which represents the degree of yellowness/blueness.

The following is a summary of the work done to develop and examine the feasibility of the aforementioned approach to quantify the extent of precoating of aggregate particles. The first trial was to test the feasibility of the method by trying to detect the color of diesel using a commercial handheld colorimeter. Note that the diesel used in this case was automobile fuel and has a slight yellow tint to it, typically added for regulatory purposes. Researchers considered that this could be an issue but considered evaluating it along with other options such as kerosene (which is colorless). This trial was done by pouring a small amount diesel in a glass jar as shown in Figure 3.16. In this first trial, the color measurements were not close to the color of the sample (yellow in this case). Several other variations or adjustments were attempted, such as by pointing the colorimeter downward into the liquid and using a white sheet of paper at the bottom, but these did not change the outcome significantly. It was believed that this false color reading was on account of the fact that the light being transmitted from the spectrum was not being correctly reflected back to the sensor and was largely being transmitted through the glass and liquid sample. It must be noted that the colorimeter used in this case is typically intended for use on solid opaque surfaces.

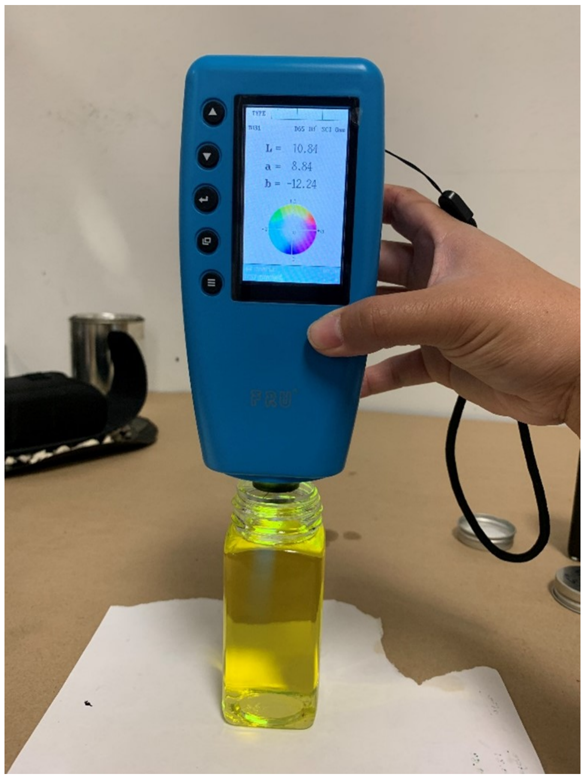


Figure 3.16. Image of a colorimeter pointed towards a diesel sample to measure color measurements

In an effort to improve the color readings to be more realistic and allow better reflection of light from the sample, additional trials were conducted using cuvettes instead of glass jars. Figure 3.17 shows an image where a solution was added into the cuvette and the colorimeter was held on the side of the cuvette and a thick sheet of white paper was held on the opposite side to prevent light from escaping and creating reflection back into the sensor.

The use of the cuvette worked well to get colorimeter readings. The frosted glass

Figure 3.17. PG 64-22 mixed with diesel in cuvette; the colorimeter is used from the side and a white sheet of paper was used to reflect light back into the colorimeter sensor.

kept light contained in the cuvette very well, and the white paper (thicker than the one shown in Figure 3.17) also reflected light back into the cuvette well. The color measurements were consistent, with little variation, for each sample. The L, a, and b values all remained within the same 0.3-point range when taking multiple readings for the same sample. Typically, three readings were taken for each sample and averaged for the final value.

Once the method to measure color was established, experiments were conducted to evaluate the changes in color of the solvent (diesel in this case) with a change in the concentration of the binder. To this end, samples were prepared first by dissolving small amounts of the binder directly in diesel. This was considered as a more controlled means of evaluating the feasibility of this method before attempting to dissolve binder from precoated aggregates. In this step, small samples of the binder were obtained from a container with a target weight and dissolved in the binder. Specifically, binder samples weighing 0.15, 0.30, and 0.45 grams were weighed and then dissolved in 100 ml of diesel to prepare three different solutions. After that, the binder and diesel were mixed by shaking the glass jars and the solution was allowed to sit until all the binder dissolved. In this trial, binder was suspended and took about 24-48 hours to dissolve completely (Figure 3.19). Once dissolved, it was observed that the three binder solutions were too dark to obtain meaningful color measurements. Thus, it was decided to dilute these three solutions, referred to as stock solutions, with more diesel to improve sensitivity to detect the color contrast.

Figure 3.18. Difference in color between samples contain different percentages of binder dissolved in diesel

To this end, for each stock solution, three different solutions were prepared by further diluting volumes from the previous stock solution with diesel.

- Solution A: 5 ml of stock solution + 95 ml of diesel
- Solution B: 10 ml of stock solution + 90 ml of diesel
- Solution C: 20 ml of stock solution + 80 ml of diesel

A total of 24 solutions of varying concentration of binder were prepared, colorimeter measurements were taken, and a preliminary calibration curve was prepared shown in Figure 3.20. It can be seen from the graph that the lightness values, generally follow a linear trend for concentrations less that 0.0004 (g/ml) and becomes asymptotic when the concentration exceeds 0.004 (g/ml). It is important to note that just one of the three LAB parameters was being used in this curve; an asymptotic value in the L value does not imply a lack of change in color since other dimensions of color continue to

Figure 3.19. Solution A, B and C from left to right

change. However, in this initial exercise the goal was to try and create a calibration curve that would work with a single dimension of color, if possible. Additional samples were prepared specifically to cover the range from 0.0004 g/ml to 0.001 g/ml.

After establishing the calibration curve for diesel, it was decided to test the sensitivity of color measurements with respect to a different solvent. In this case, 18 samples were prepared by mixing binder in Kerosene and the same method of colorimeter measurements of solution inside the cuvette were recorded. Figure 3.20 presents the calibration curves for diesel and kerosene. It can be seen that the L values for binder dissolved in Kerosene followed the same trend as diesel except slightly lower lightness values. This was expected because the diesel had a slight yellow tint to begin with.

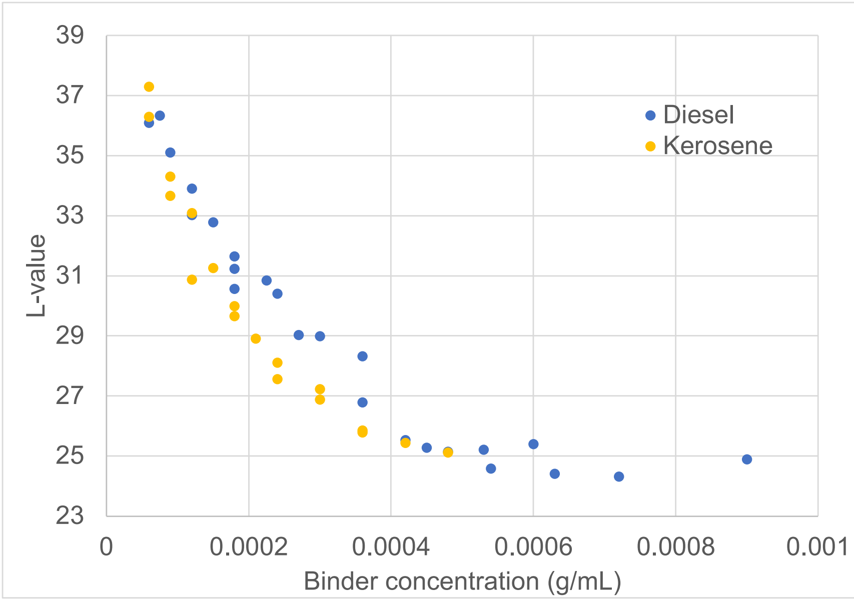


Figure 3.20. Preliminary calibration curves for binder dissolved directly in diesel and kerosene.

As mentioned earlier, the previous steps involved dissolving binder directly into solvent (Diesel or Kerosene) to investigate the feasibility of using a colorimeter to detect differences in color contrast in solvents containing different percentages of binder. The next step was to dissolve the precoated aggregates in the solvent and compare the color measurements between binder dissolved from the aggregate into solvent to the calibration curves obtained from the direct dissolution of the binder.

To achieve this, 25 g of precoated limestone were dissolved in 100 ml of diesel and color measurements were recorded. Figure 3.21 shows the lightness values versus two binder concentrations; the first binder concentration was obtained by dissolving the binder directly in the solvent as discussed earlier and the second concentration was obtained by dissolving precoated aggregates with known amount of binder coating. As it is shown from the graph, colorimeter measurements using both methods (direct dissolution of the binder and dissolution of the binder from precoated aggregates) are almost identical although there was a slight vertical shift in the data between the two sets. This is very likely because the binder from the aggregate surface was not completely dissolved in diesel (Figure 3.22). A similar exercise was carried out using kerosene as the solvent (Figure 3.23 with similar results. In fact, in the case of kerosene, it appears that the bias in the data was slightly larger on account of kerosene being potentially a weaker solvent compared to diesel.

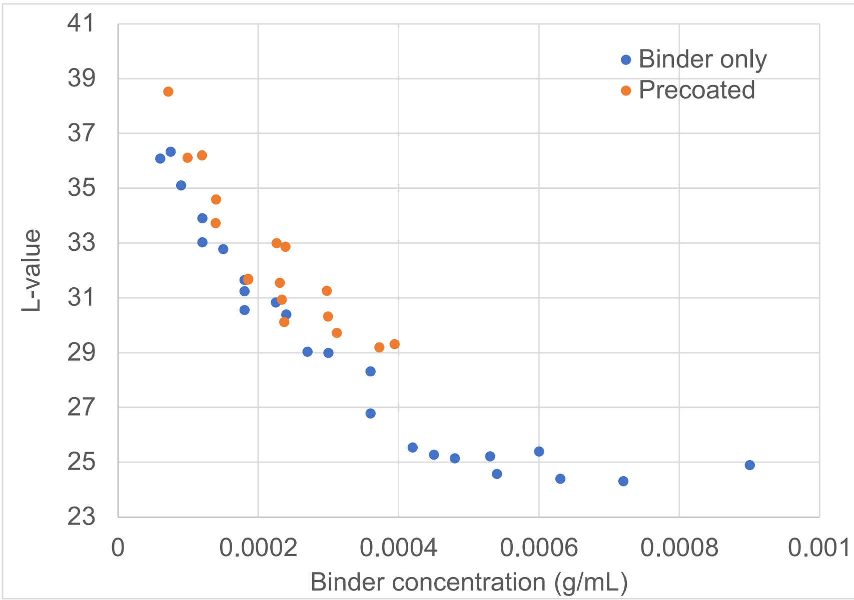


Figure 3.21. Difference in lightness values of PG 64-22 dissolved directly in Diesel and dissolved off of aggregate in diesel.

In summary, the use of a colorimeter appears to be a simple and promising approach to assess the percentage of binder coating the surface of an aggregate, particularly with diesel fuel. Although results showed a small bias, this could be corrected by using a correction in the calibration and/or allowing additional time to dissolve the binder from the precoated aggregate. The biggest advantage of this approach is that it does not use any equipment beyond a low cost handheld colorimeter, a cuvette, and a mass balance to assess the amount of binder used to coat the aggregate particles.

Figure 3.22. Precoated aggregates after dissolving in solvent (Diesel/Kerosene); notice that a small amount of binder did not completely dissolve.

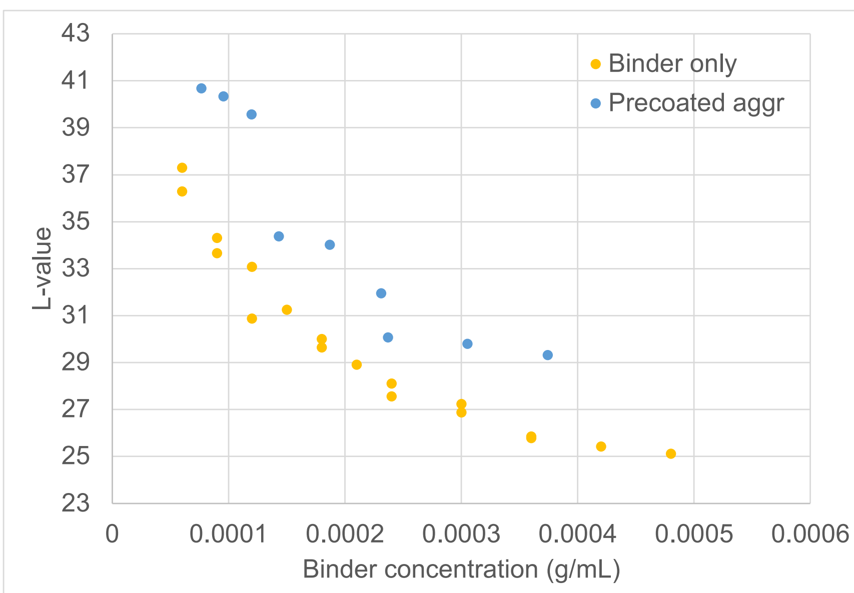


Figure 3.23. Difference in lightness values of PG 64-22 dissolved directly in Kerosene and dissolved off of aggregate surface in kerosene.

3.9 DUST CONTENT

While precoating the aggregates in this project, it was observed that different quantities of binder adhered to the surface of different aggregates at the same binder precoating percentage. For instance, at a target binder percentage of 0.4%, the limestone aggregate was speckled with binder while the rhyolite aggregate was nearly fully covered with binder, as shown in Figures 3.24 and 3.25. These varied precoating results could be dependent on a few factors related to the material properties of the aggregate, including but not limited to the absorption capacity, specific gravity, angularity, and dust content. To better understand the relationship between these material properties and the precoating binder, the dust contents of the aggregate stockpiles were measured. It was hypothesized that aggregates with higher dust content on the surface would adsorb or require higher mass percentage of binder to achieve a similar level of surface coverage. The following exercise was carried out to evaluate this hypothesis.

Figure 3.24. Limestone aggregate precoated in 0.4% binder by weight.

A sample of approximately 1 kg of aggregate was taken from the center of each stockpile. The aggregates were placed in an oven overnight at 150°C to bring the aggregates to an oven dry state and eliminate the influence of any absorbed moisture. The oven dry aggregates were weighed and then rinsed thoroughly in water to wash out all the dust in the sample. This washed sample was dried in an oven overnight

Figure 3.25. Rhyolite aggregate precoated in 0.4% binder by weight.

and its oven dry weight was measured. The dust content was determined using the mass difference between the washed and unwashed oven dry aggregate samples. It was found that the aggregates used in this project had a broad range of dust contents from 0.09% to 0.55%. The dust contents were then compared to the binder coverage area at a 0.4% precoating percentage. The binder coverage areas were measured using image analysis through ImageJ.

Based on Table 3.1, gravel has the lowest dust content, at 0.09%, and also has the greatest binder coverage, at 96.0%. Sandstone possesses both the highest dust content and smallest binder coverage, at 0.55% and 72.7% respectively. The results from these comparisons suggest a relationship between the dust content and the ability of binder to coat an aggregate surface.

The inverse relationship between the dust content and binder coverage area can be attributed to the dust absorbing some of the binder, leaving less available for precoating. Therefore, the more dust on the aggregate, the more binder may be required to precoat the aggregate to achieve a target surface area coverage. The existence of dust on aggregate to be used for precoating is not a concern because the purpose of precoating is to counteract the deleterious effect of dust on adhesion, but more binder will be needed in order to compensate for the dust. Therefore, the amount of dust (up to a certain extent) should be considered when selecting the desired amount of binder by weight to precoat the aggregate.

Table 3.5. Dust content measurements of aggregate stockpiles and the percentage surface area coverage from image analysis at 0.4% binder content by mass

Aggregate	Dust content (%)	Binder surface area at 0.4% binder (%)
Sandstone	0.55	72.7
Limestone	0.28	82.3
Rhyolite	0.21	94.2
Gravel	0.09	96.0

3.10 SUMMARY

The main goal of this part of the study was to examine potential methods that can be used to quickly and easily assess the extent of precoating of aggregate particles used in hot applied seal coats. This information can then be used with findings from later parts of this study, i.e., to provide guidelines on the required optimal amount of binder that can be used for precoating. Specifically, three methods were explored in this part of the study. A summary of these three methods is provided below.

1. **Infrared imaging**
    - Overview: This method uses an infrared imaging camera to estimate the amount of binder on the surface of an aggregate particle.
    - Advantages: The method, when fully developed, is highly reliable particularly because it is independent of the color of the aggregate and can be used in this and other applications with asphaltic materials.
    - Limitations: At the time of this study, the capital cost of the hardware with adequate resolution in terms of the wavelength of interest and image quality was extremely high.
    - Summary: This approach was not pursued any further due to the high capital cost of the equipment. However, it is recommended that this technique be considered for future applications related to asphalt materials, particularly as the cost of the technology reduces.
2. **Microextraction**

- Overview: This method measures the weight of precoating binder on an aggregate sample by separating the binder from the aggregate using toluene dissolution.
- Advantages: Since the binder is being extracted and directly weighed, the results of this procedure provide a clear gravimetric benchmark. Another advantage of this method is that it requires very little capital equipment and very small amounts of solvent to carry out the measurements.
- Limitations: The microextraction procedure can take more than a couple of days to complete due to the steps taken to ensure that all the binder has dissolved from the aggregate sample (although the actual man hours involved are not extensive). The sample is soaked in toluene overnight, and often a second time, and the filtration and vacuum desiccation are done slowly to ensure that no binder is lost. Due to time constraints, it is not practical to use this for high volume testing.
- Summary: The method is a reliable option to measure the amount of precoating binder if precision is a concern and there are no time constraints. This method can also be used as a quality assurance tool to verify the results of quicker, less precise methods.

3. **Image analysis**
   - Overview: This method uses images from a typical digital camera (e.g., from a smart phone) to analyze the percentage of surface area of aggregate particles that are precoated with the binder.
   - Advantages: The method, has shown consistent results with aggregates of different colors. The only hardware required is a typical smart phone camera. Further, this method utilizes an open-source analysis tool developed by National Institutes of Health (NIH) for image analysis that is freely available on the internet. The specific steps used for image analysis for this application can be packaged and made available to field engineers as a macro that will allow them to easily obtain the desired measurement when using in the field.
   - Limitations: There are very few limitations to this approach. The engineer interested in using this technique will have to install a small package (open source and freely available) to run on their computer. Researchers are

exploring the possibility of making this analysis available via the cloud to make it even easier for field engineers to use.

- Summary: This approach appears to be the most promising and reasonable method to assess the extent of precoating in the field and will be used in the remainder of this project.

4. **Colorimeter**
   - Overview: This method is based on measuring the color of the binder that is dissolved from precoated aggregates using diesel.
   - Advantages: The method has shown consistent results with different levels of precoating. A cuvette and a colorimeter are required pieces of hardware in addition to a mass balance. The cuvette and a colorimeter are readily available commercially and cost only a few hundred dollars.
   - Limitations: The method relies on a calibration curve, which is a onetime exercise and can be shared by all users once it is developed. The method also requires some time to allow the diesel to dissolve all the precoating binder. However, this method measures the mass of the binder, which is slightly different from the percentage of area of aggregate particles coated by the binder (although these two parameters may be related when the coating is less than 100%).
   - Summary: This is a very promising method and may be developed to some extent as a part of this study as a secondary technique. More importantly, this technique can be an extremely useful tool beyond a means to measure precoating of the asphalt binder. For example, this technique can be refined to measure binder content for QC/QA in hot mix asphalt samples or binder content in a sample from a RAP stockpile.

CHAPTER 4. LABORATORY TESTING TO ESTIMATE OPTIMAL LEVELS OF PRECOATING

4.1 MATERIALS USED FOR LABORATORY EVALUATION

4.1.1 Aggregates and binders

Material selection was based on results from surveys prepared in Task 1. The materials selected included one binder (PG 64-22) for precoating, two base binders (AC-10, AC-20-5TR), and aggregates representing four different mineralogy (limestone, sandstone, gravel, and rhyolite). The survey identified the most common types of materials used in hot applied seal coat construction in Texas. In addition, the percentage of precoating binder was varied with respect to aggregate mineralogy to evaluate the optimum amount of binder precoating.

The materials identified above were obtained from different producers who supply seal coat materials to the state of Texas. The total number of producers was seven; three producers supplied binders (precoating and base binders) and four producers supplied seal coat aggregates. For the latter, it was important to reach out to producers from different parts of the state of Texas to ensure a diversity of aggregate mineralogy.

4.1.2 Summary of materials

In summary, the materials selected for laboratory evaluation included a variety of combinations and scenarios. Table 4.1 below presents the experimental program that was carried out during this project.

4.2 LABORATORY TESTS AND RESULTS

The aggregate-binder adhesion for the material combinations in Table 4.1 were evaluated using two test methods: the Vialit test and the Sweep test. These test procedures were chosen and further developed after examining several different candidate methods to evaluate the quality of adhesion in seal coat materials. These two methods can be used to evaluate the adhesion quality based on aggregate loss, or raveling,

Table 4.1. Aggregate and binder combinations for laboratory evaluation

Aggregate	Precoating binder (percentage)	Base Binder
Limestone	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-20-5TR
Limestone	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-10
Sandstone	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-20-5TR
Sandstone	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-10
Gravel	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-20-5TR
Gravel	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-10
Rhyolite	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-20-5TR
Rhyolite	PG 64-22 (0.2, 0.4, 0.6, 0.8 %)	AC-10

which is one of the most common forms of failure in a chip seal. To be compatible with the chip seal materials used in this study, existing methods for these tests were reviewed, modified, and used for the remainder of this study. Details pertaining to the development of these methods are covered in another accompanying report.

Each of the aggregate and binder combinations shown in Table 4.1 were tested using both the Vialit test and the Sweep test, and the resultant aggregate loss from these tests were analyzed to determine the compatibility between materials for the four precoating binder levels of 0.2%, 0.4%, 0.6%, and 0.8% by weight.

4.2.1 Test procedures

The Sweep test in its original protocol (ASTM D7000) is designed to evaluate emulsified, or cold applied, seal coats to determine the length of time needed for a seal coat to cure before being opened to traffic. This method was modified to serve as an adhesion test in another accompanying study. A more detailed description of this procedure can be found in the companion project report (Project 0-7058). The following is a brief description of the method that was used in this study. The base binder was applied to a circular metal pan and a pre-specified amount of the aggregate was spread over the binder. A roller compactor was then used to compact and embed the aggregate into the binder. The sample was allowed to cool to room temperature as measured with an infrared (IR) gun. The sample was then placed in the Sweep test machine, in which it was abraded with a rubber hose for one minute. The percentage of aggregate loss was calculated by comparing the weight of the specimen before abrasion to the weight of the specimen after abrasion. Although this test method is generally intended for determining the curing performance of cold applied seal coats, it is hypothesized that this test can be extended to evaluate the aggregate-binder adhesion between aggregate and hot applied binders.

The Vialit test, according to the European test standard (EN 12272-3), is designed to be used on binder at low temperatures since aggregate loss or raveling is more critical at low temperatures. In this study, the following procedure was used to prepare the Vialit test specimens. A more detailed description of this procedure can be found in the companion project report (Project 0-7058). The Vialit sample was created by heating and applying the base binder to a square metal tray. The aggregates were placed onto the binder and compacted using a roller compactor. The tray of binder and aggregate was placed in a refrigerator at 5°C for one hour to bring it to test temperature. Once the sample was temperature conditioned, it was removed from the refrigerator and placed upside down on metal supports. A 510 g steel ball was dropped three times on the back of the plate from a height of 50 cm. The percentage of aggregate loss was calculated by comparing the before and after weights of the specimen. Since the Vialit test, unlike the Sweep test, is conducted at a low temperature, the Vialit results may be able to lend insight into the low-temperature adhesion behavior of chip seals.

4.2.2 Comparing results by percent area of precoating

Aggregate particles are precoated prior to use in hot applied chip seals to counteract the deleterious effect of dust on stockpile aggregate and promote bonding with the underlying binder. The relative surface area of an aggregate that is precoated with the binder is hypothesized to be the main factor when it comes to improvement of adhesion - the more surface area coated with binder, the less dust is available to interfere, and the better the adhesion of the aggregate to the base binder. When aggregates are precoated for use in the field, the amount of precoating binder is typically specified on a mass basis, such as 0.2% binder by weight of aggregate. For a given weight percentage of the binder, the surface area of the aggregate particles that is precoated depends on the aggregate's properties such as specific gravity, absorption capacity, shape, dust content, and texture. For example, 1 kg of a dense, high specific gravity aggregate would have fewer aggregate particles, and therefore a lower total surface area, than 1 kg of a light, low specific gravity aggregate with a similar gradation. If both aggregates were mixed with 0.2% binder by weight, or 2 g in this example, the dense aggregate would have a higher precoating area percentage compared to the light aggregate due to the difference in surface area. This difference in effective area covered by the same mass percentage of the binder was demonstrated in the previous chapter of this report.

In this study, the aggregate was precoated by mass at four different precoating levels. The precoat by mass was then converted to approximate surface area coverage, using the data gathered through image analysis, and the relationships between aggregate loss and precoat area for both the Vialit and Sweep tests were explored. The goal of this analysis was to determine a relationship between aggregate loss and precoat area in order to select an optimal precoating level for the development of future specifications. All data presented in the remainder of this section is based on the average of at least two replicates (typically three) for each test condition.

4.2.3 Precoated limestone

Some of the key observations based on Figures 4.1 and 4.2 are as follows.

1. In terms of the precoating area, a 0.2% to 0.8% by mass of precoating binder translated into 67% to 96% by area of surface coverage.
2. In general, the AC-10 binder showed more aggregate loss compared to the AC-20-5TR binder for both test results under all precoating conditions (note that all binders were precoated using the same PG 64-22 binder). This is expected because AC-10 is typically a softer binder and not typically recommended for use in chip seal applications, but it was included here to amplify the effects of adhesion or lack thereof.
3. For the Vialit test, the sample with the largest amount of precoating exhibited the largest amount of loss, which is the opposite of the expected behavior. This could, at least partially, be due to expected variability in the test results. However, since this slight increase is observed for both the AC-10 and AC-20-5TR binders, it is possible that excessive precoating could create weak cohesive links that cause bonding failure, especially when evaluated at low temperatures, as in the case of the Vialit test.
4. In the case of the Sweep test, for the AC-10 base binder, the loss percentage decreased with increasing precoating, and for AC-20-5TR, the loss percentage

remained constant as precoating changed. This suggests that while precoating may have a positive effect on aggregate paired with AC-10 binder, beyond a certain point it may not add to the bonding of the aggregate in chip seals with binders such as AC-20-5TR.

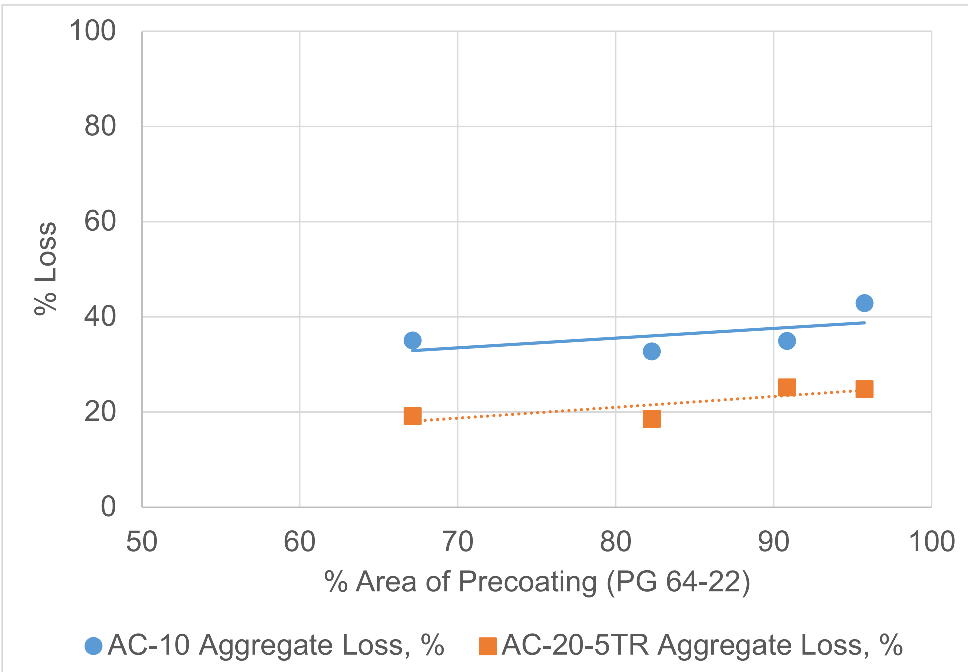


Figure 4.1. Vialit results by percent precoat area for limestone

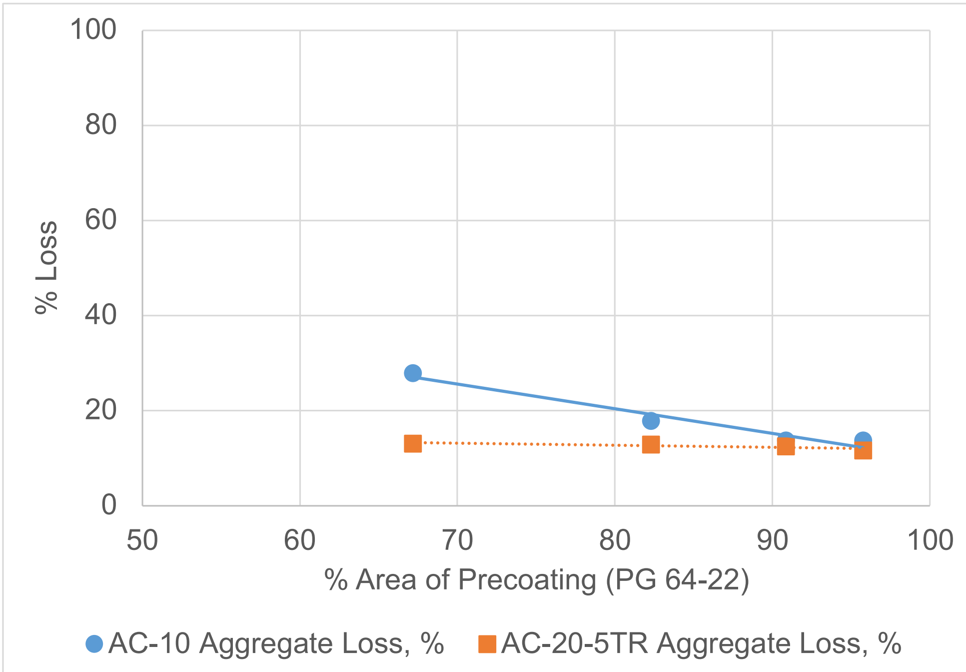


Figure 4.2. Sweep test results by percent precoat area for limestone

4.2.4 Precoated sandstone

Some of the key observations based on Figures 4.3 and 4.4 are as follows.

1. In terms of the precoating area, a 0.2% to 0.8% by mass of precoating binder translated into 55% to 94% by area of surface coverage.
2. The percent loss in both the AC-10 and AC-20-5TR binder samples remained within the typical variation of loss measurements across all four precoating levels. This suggests that an increase in precoating area, from 55% to 94%, has little to no effect on the binder-aggregate bonding in the Vialit test.
3. The percent loss behavior observed in the Sweep test was similar to that observed in the Vialit test. The loss percentage slightly decreased with increased precoating, but the range of losses measured was within expected variability. Therefore, in the Sweep test, increased precoating area leads to a minor, if not negligible, improvement in bonding (for the range of values covered in these tests).

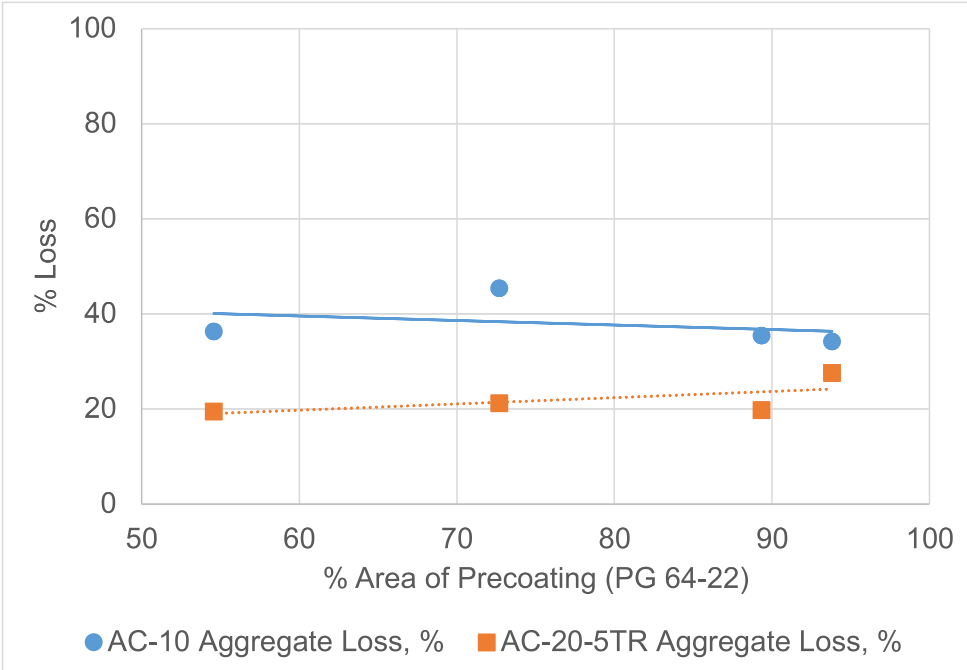


Figure 4.3. Vialit results by percent precoat area for sandstone

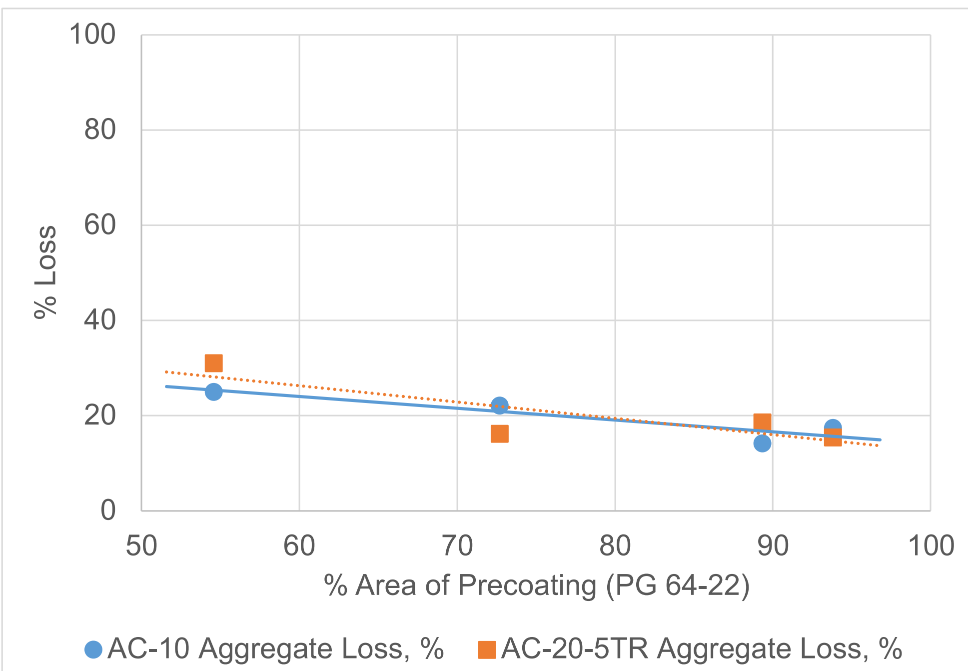


Figure 4.4. Sweep test results by percent precoat area for sandstone

4.2.5 Precoated gravel

Some of the key observations based on Figures 4.5 and 4.6 are as follows.

1. In terms of the precoating area, a 0.2% to 0.8% by mass of precoating binder translated into 87% to 100% by area of surface coverage. This narrow range of precoat area is due to gravel having a significantly higher specific gravity, lower specific surface area, and lower binder absorption capacity than limestone and sandstone, which had precoat areas ranging from 55% to 95% - a 40-point range compared to gravel's 13%.
2. For the AC-10 binder in the Vialit test, the loss steeply decreased with increased precoating area, while the AC-20-5TR binder experienced no change in aggregate loss.
3. The AC-10 binder at 87% precoating area experienced a loss percentage of nearly 100%. Considering that the loss percentages at the three other precoating levels were similar to each other and significantly less than the first loss percentage, and considering that no other samples, across all aggregate and binder types, experienced nearly as high of a loss as this one sample, it is possible that this point may be an anomaly and that AC-10 exhibited no change in aggregate loss, similar to AC-20-5TR. Regardless, it is important to point out that the purpose of using AC-10 in these measurements was to amplify the results from the test since this binder is not a typical binder used in seal coats.
4. Since the precoating areas of gravel at 0.2%-0.8% binder by mass are so high and the range so narrow, it is possible that the effects of excess precoating (i.e., the precoating negatively impacting the binder-aggregate adhesion) counteracted any improvements in adhesion to be gained by increasing precoating area, leading to the constant loss seen across all precoating areas.
5. In the Sweep test, both the AC-10 and AC-20-5TR binders experienced no change in aggregate loss at different precoating areas. Since the range of gravel precoat areas was so narrow, the Sweep test results in this narrow range may not be sensitive to the changes in adhesion between precoat areas. Another contribution to these results may also be the high levels of precoating and variability due to excessive precoating binder.

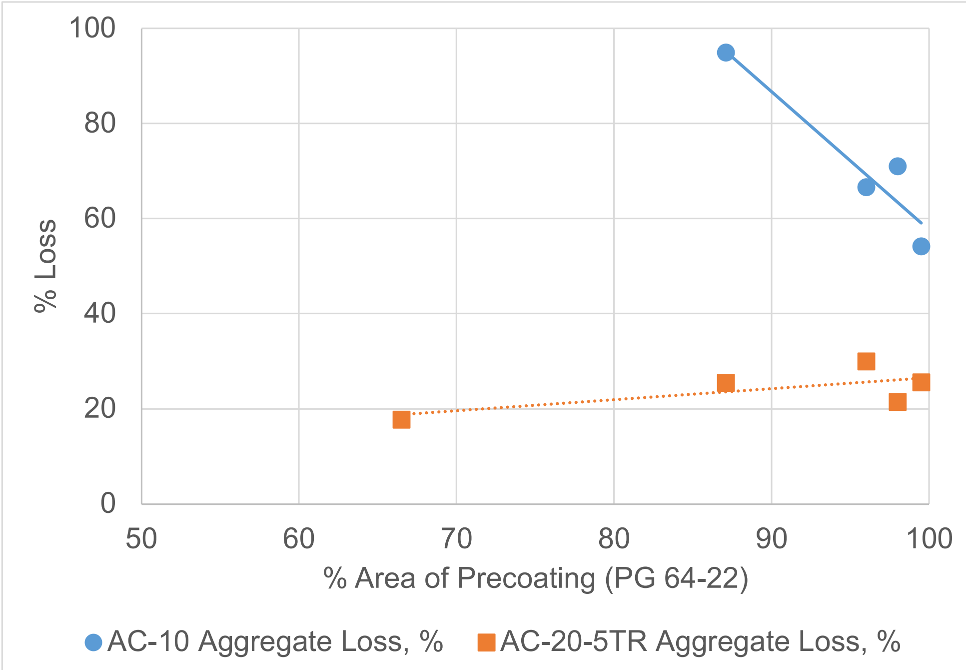


Figure 4.5. Vialit results by percent precoat area for gravel

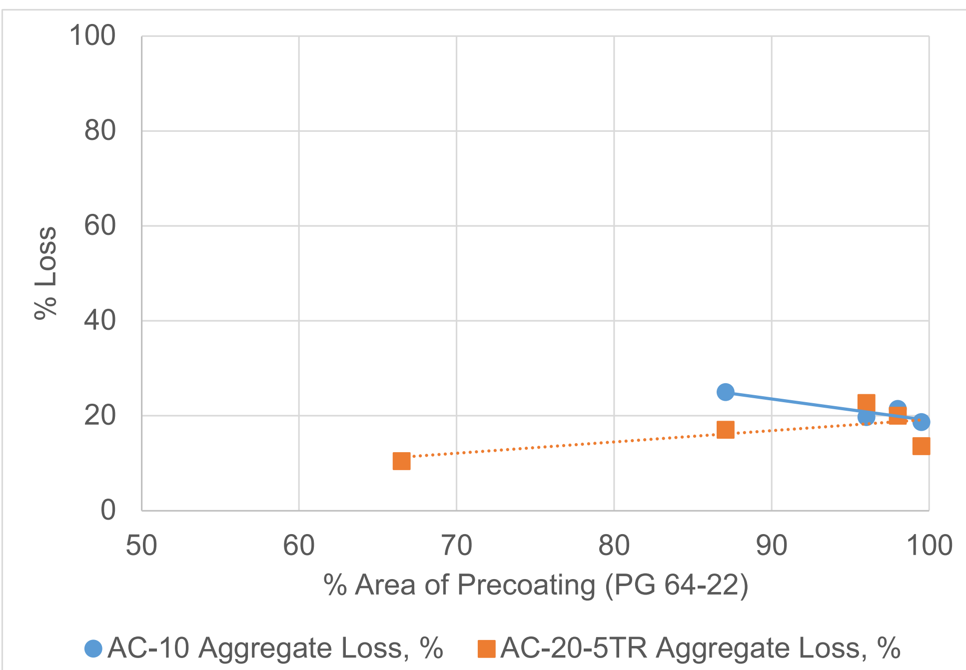


Figure 4.6. Sweep test results by percent precoat area for gravel

4.2.6 Precoated rhyolite

Some of the key observations based on Figures 4.7 and 4.8 are as follows.

1. In terms of the precoating area, a 0.2% to 0.8% by mass of precoating binder translated into 85% to 100% by area of surface coverage.
2. Similar to gravel, the precoating areas of rhyolite fell into a narrow, high range, due to rhyolite's high specific gravity, low specific surface area, and low absorption capacity.
3. For the Vialit test, AC-10 experienced a slight increase in aggregate loss with increasing precoating. AC-20-5TR on the other hand, did not exhibit any relationship between aggregate loss and precoating area. It must be emphasized that this is likely due to the narrow range in the precoating area that resulted for these two aggregates despite the fact that the percentage of binder used for precoating had a much broader range.
4. For the Sweep test, neither binder experienced a change in aggregate loss with increasing precoating area.

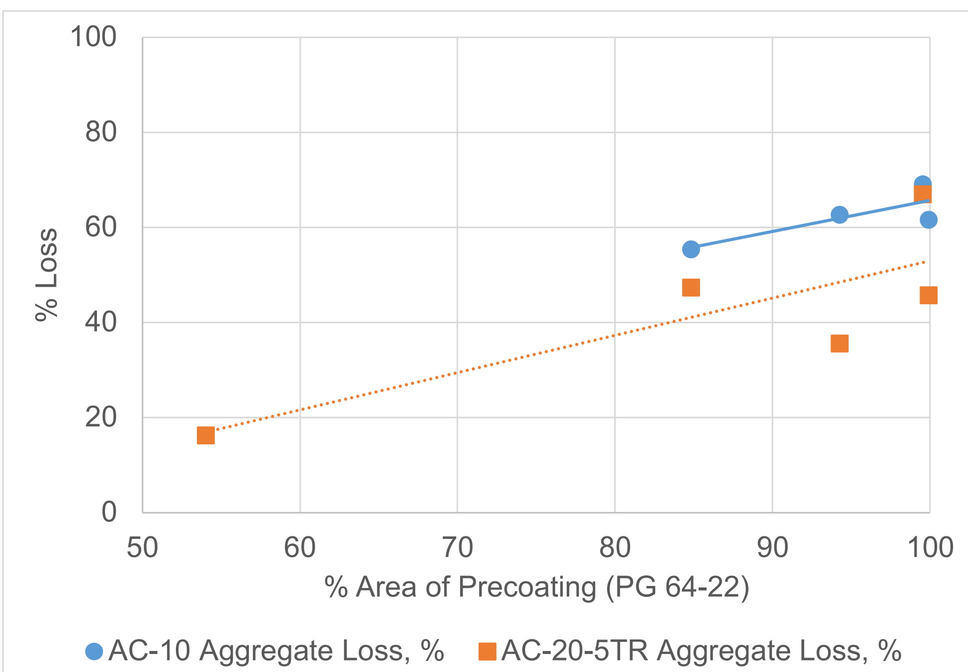


Figure 4.7. Vialit results by percent precoat area for rhyolite

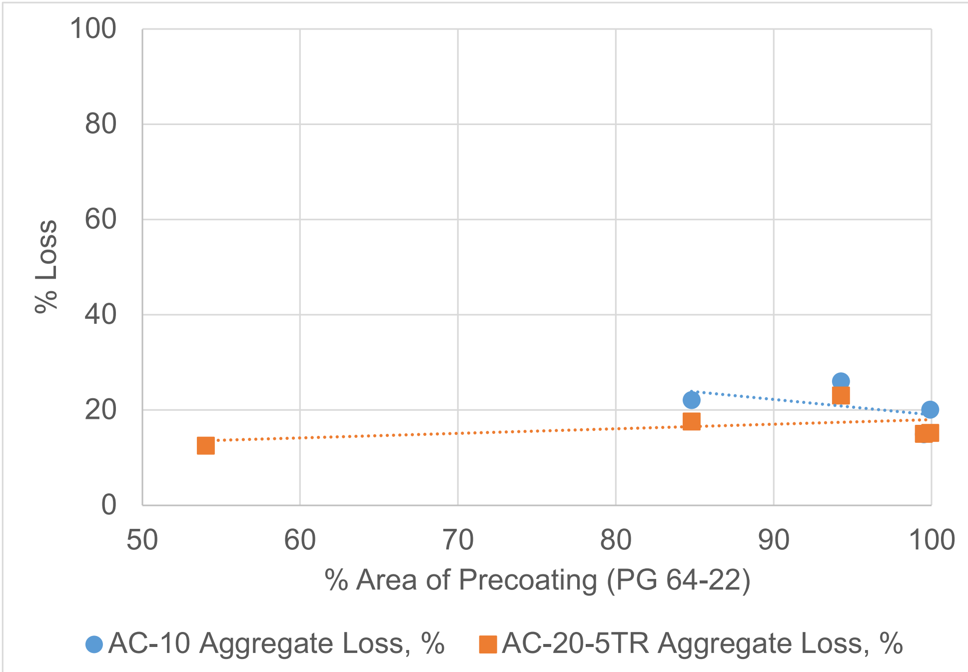


Figure 4.8. Sweep test results by percent precoat area for rhyolite

4.2.7 Impact of precoating based on the Vialit test for all aggregate types

Figures 4.9 and 4.10 show the relationship between loss and precoat area for the four aggregates in both base binders in the Vialit test. Linear trendlines were used to approximate the loss versus precoating relationship. For the AC-10 binder (it must be noted that this is an atypical binder for such applications), the limestone, sandstone, and to some extent rhyolite showed no change in aggregate loss with increase in the amount of precoating beyond approximately 50%. With one exception, this was also true for the gravel aggregate.

For the AC-20-5TR binder, all four aggregates showed no substantial change with an increase in precoat area, when the precoat area increased from approximately 50% for limestone and sandstone and from approximately 85% for rhyolite and gravel aggregates.

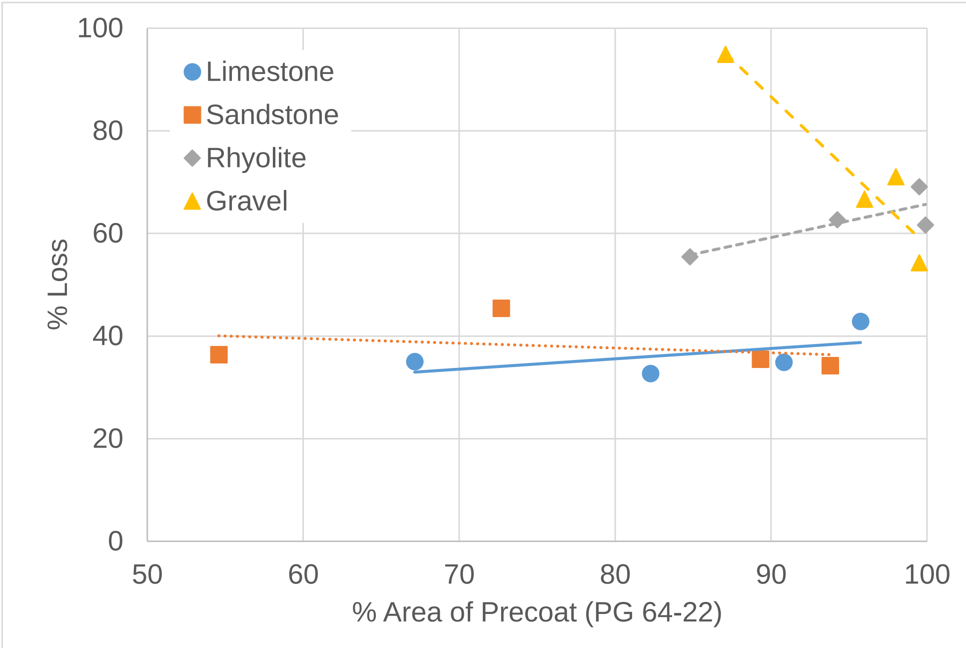


Figure 4.9. Vialit test results for AC-10 binder with all aggregate types

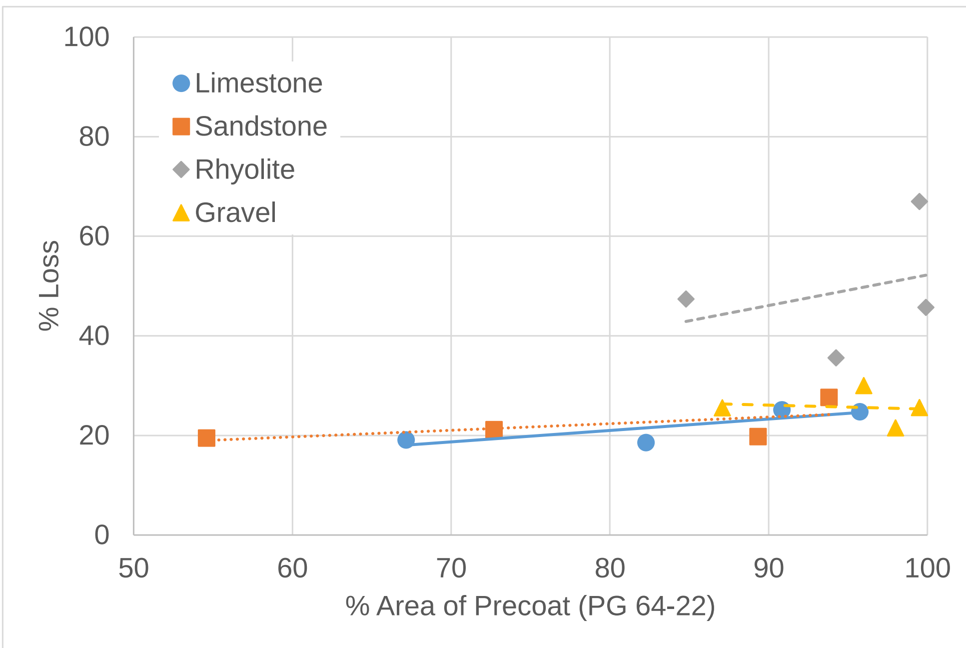


Figure 4.10. Vialit test results for AC-20-5TR binder with all aggregate types

4.2.8 Impact of precoating based on the Sweep test for all aggregate types

Figures 4.11 and 4.12 show the relationship between loss and precoat area for the four aggregates in both base binders using the Sweep test. Unlike the Vialit test, the Sweep test shows an improvement in adhesion as precoating increases, especially for the AC-10 binder. The limestone and sandstone show a consistent decrease over a wide range of precoating areas, and while the gravel and rhyolite data have high variation, they exhibit generally decreasing behavior. Based on these results, the Sweep test has a higher sensitivity to the changes in binder-aggregate adhesion performance over the range of precoating levels being tested, compared to the Vialit test. For precoating areas greater than approximately 80-90%, the losses recorded for each aggregate become more variable. This is especially evident in rhyolite and gravel, due to these two aggregates having such a narrow range of precoat areas.

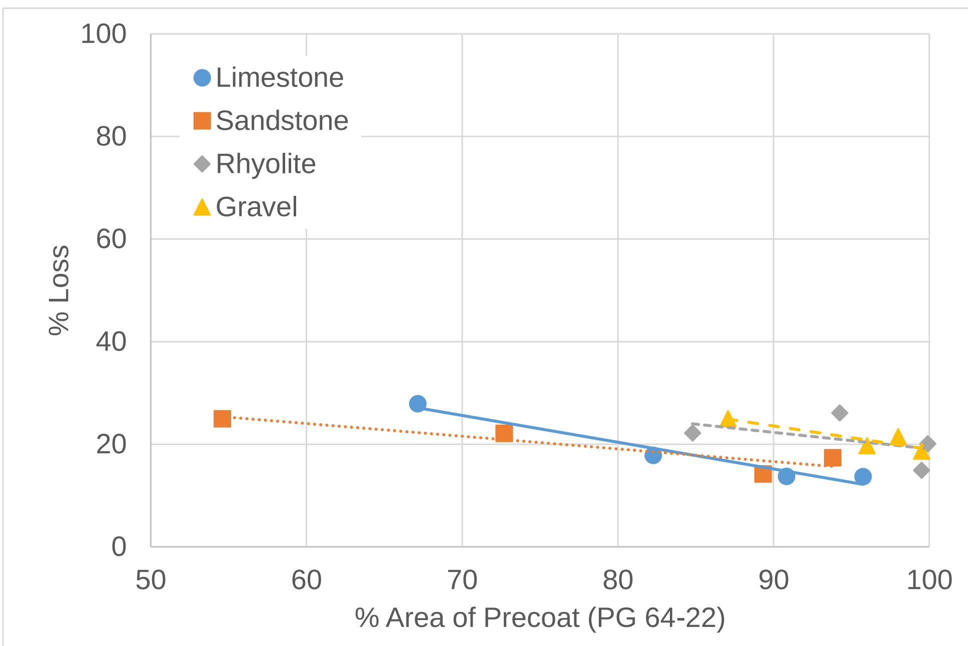


Figure 4.11. Sweep test results for AC-10 binder with all aggregate types

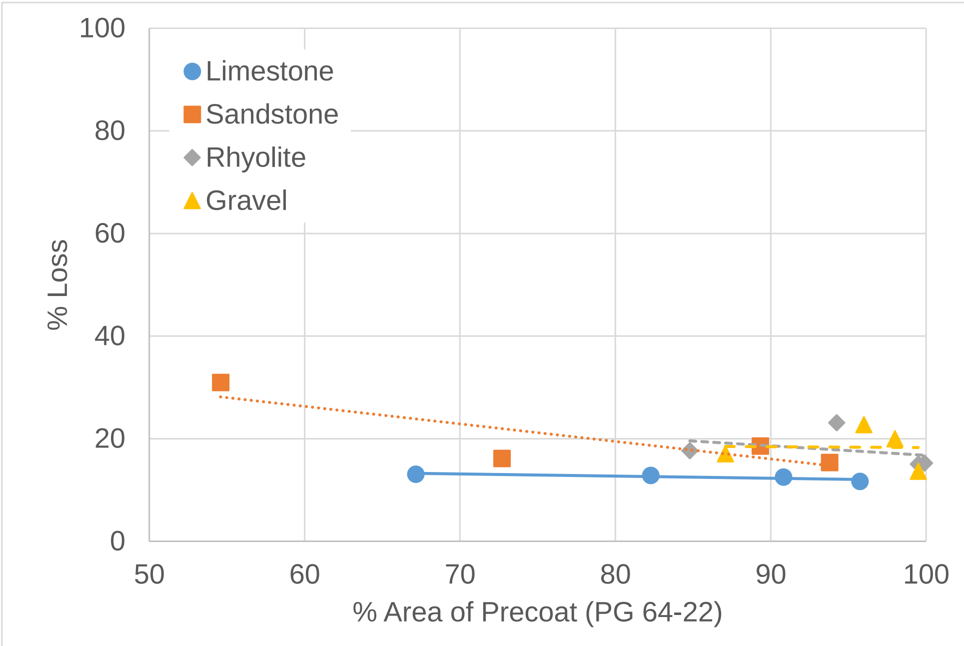


Figure 4.12. Sweep test results for AC-20-5TR binder with all aggregate types

4.3 COMPARISON OF PRECOATED AGGREGATE TO UNCOATED AGGREGATE

The data gathered from the Vialit and Sweep tests both largely showed no improvement in loss with an increase in precoating, particularly for AC-20-5TR. It was hypothesized that this behavior was due to the fact that there exists a certain threshold above which increasing precoating no longer improves adhesion, and the range of precoat areas tested in the section above lies at or above that threshold. For the range of precoating binder percentages selected, this threshold was not readily apparent. In order to verify that such a threshold exists and that there is a difference in aggregate loss between uncoated and precoated aggregate, samples of uncoated aggregate for the four mineralogies were prepared and tested in the Vialit and Sweep tests. Only AC-20-5TR was used as the base binder.

Figure 4.13 presents the results from the Vialit test for this scenario. The Vialit test was unable to detect a difference in aggregate loss between the uncoated and precoated aggregate. As precoating increased from 0% surface area to 100%, aggregate loss remained constant for three out of the four aggregates, and increased with rhyolite. The inability of the Vialit test to provide insight into the effects of precoating on adhesion may be a result of the testing conditions, as the Vialit test is conducted at a low temperature. This may suggest that this test is more suitable for predicting low temperature behavior of seal coat materials, e.g., distinguishing between an appropriate seal coat binder (AC-20-5TR) and a binder that is too soft (AC-10), but not suitable for evaluating initial adhesion.

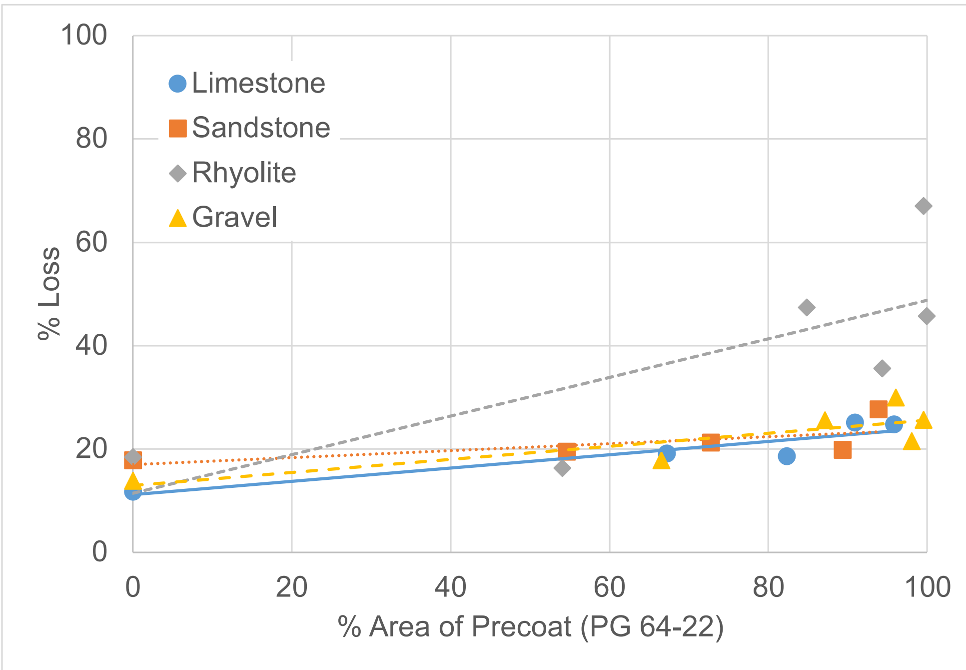


Figure 4.13. Vialit test results including uncoated aggregate (AC-20-5TR base binder)

However, the Sweep tests on the uncoated aggregate showed significantly more aggregate loss than the corresponding precoated aggregate (Figure 4.14). For limestone, sandstone, and rhyolite, the uncoated aggregate loss was approximately 75%, and the addition of precoating binder reduced loss to 15-20%. Uncoated gravel aggregate did not experience as much loss, at 30%, but the addition of precoating reduced loss to the 15-20% range as well. Note that the trendlines used to detail the relationships between precoating area and aggregate loss in the figure below are only approximations to show the general trend, given that extensive modeling of the relationships was not conducted.

The uncoated gravel aggregate experienced better binder-aggregate adhesion than the other aggregates because of its lower dust content. The dust content of the gravel was two times less than the limestone and rhyolite, and five times less than the sandstone, meaning that gravel's adhesion to the base binder was significantly less impacted by surface dust than the other aggregates. Sandstone's high dust content may impact the amount of precoat at which adhesion is maximized. Note that the aggregate loss of sandstone at roughly 55% precoat area is greater than the aggregates with lower dust contents because more binder is needed to absorb the dust. Regardless of the aggregate type, above some percent area of precoating, the aggregate loss measured by the Sweep test reduces to 15-20%.

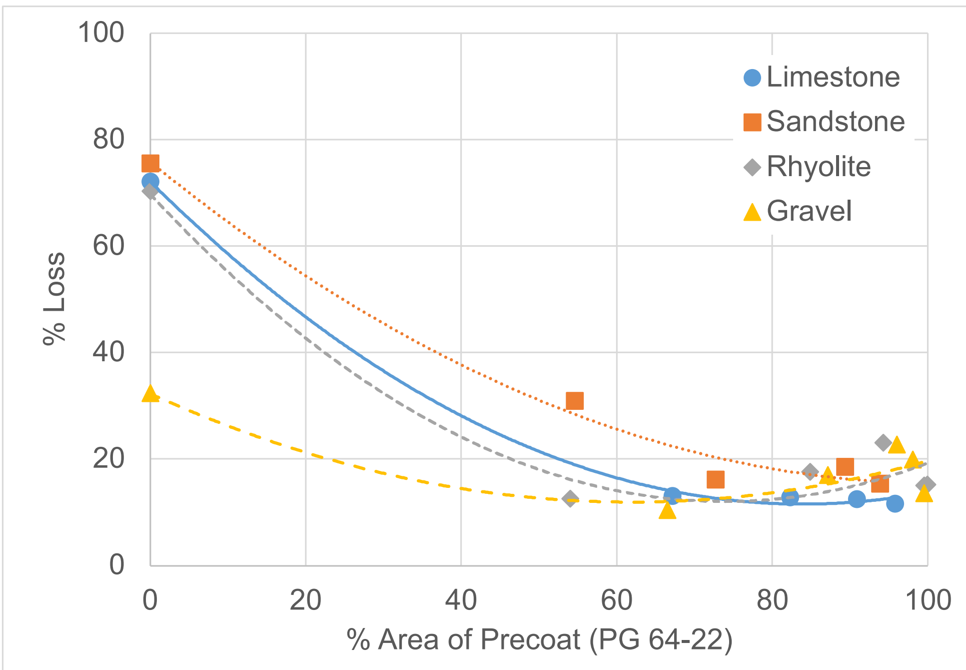


Figure 4.14. Sweep test results including uncoated aggregate (AC-20-5TR base binder)

4.4 SUMMARY OF LAB TEST RESULTS WITH DIFFERENT PRECOATING AREAS

Some of the key conclusions that can be drawn by examining all combinations of aggregate types, precoating amounts, and tests are as follows.

1. Across all aggregates, precoating levels, and tests, AC-20-5TR consistently ex-

hibited less aggregate loss than AC-10. This clear differentiation in performance confirms that these methods are sensitive enough to distinguish between adequate and poor base binders from a seal coat application point of view.

2. Considering only the results from the Vialit test, for the AC-10 binder, three of the aggregates showed slight to no improvement in bonding with an increase in precoating, whereas the final aggregate showed an improvement in bonding with an increase in precoating area. However, the improvement in bonding shown was likely due to experimental variability, rather than a true change in adhesion. For the AC-20-5TR binder, all four aggregates showed a slight deterioration in bonding with increasing precoat amount. Since the Vialit test is a low temperature test, these results show that there may be a slight detrimental effect on bonding when using excessive precoating in hot applied seal coats, in terms of low temperature raveling. This is something to be considered in specifying the precoating guidelines, although in practice it is unlikely that contractors will err on the side of higher precoating.
3. Considering only the results from the Sweep test, the bonding either remained constant or slightly improved with an increase in precoating area for all four aggregates and the two binders. The improvement of bonding was more pronounced for the AC-10 binder, which shows that precoating may have a greater benefit to adhesion with low quality binders compared to high quality binders.
4. Overall, neither the Vialit test nor the Sweep test detected meaningful changes in adhesion as precoating increased, showing that a precoating area of 50% binder with any of the four aggregates performed similarly to the same aggregate coated with 100% binder.
5. When taking into consideration the Vialit and Sweep test results for the uncoated aggregate samples, the Vialit test did not show a significant change in aggregate loss, while the Sweep test showed a drastic decrease in aggregate loss between the uncoated and precoated aggregate. The Vialit test's inability to distinguish between uncoated and precoated aggregate adhesion performance led it to become evident that it is not a sufficient test for evaluating the initial adhesion of a seal coat binder. It may, however, lend insight into other material properties, such as the performance of different binders at low temperatures, since it was capable of distinguishing between AC-10 and AC-20-5TR

base binder performances.

6. Conversely, the Sweep test detected a significant difference in bonding between the uncoated and precoated aggregate samples. The lack of agreement between these two tests can be attributed to their dissimilar temperature and mechanical conditions.
7. By comparing the uncoated aggregate to the precoated aggregate in the Sweep test, it was found that all four aggregates decrease to an aggregate loss of 15-20% with sufficient precoating. The aggregate loss of the uncoated aggregate is dependent on the amount of dust on the surface area of the aggregate, since dust is the main inhibitor of adhesion to the base binder in a seal coat. However, once this dust is absorbed by a certain amount of precoating binder, the loss approaches this asymptote of 15-20%.

4.5 DETERMINING THE OPTIMAL AMOUNT OF PRECOATING REQUIRED

The uncoated and precoated aggregate loss in the Sweep test confirm that binder-aggregate adhesion improves when precoating is used. There is, however, an asymptotic relationship between loss and precoating, suggesting some threshold area above which additional binder has no discernible effect. Based on the results gathered from this study, this threshold corresponds to approximately a precoating area of 50%. This threshold, however, is limited by the range of precoating areas tested. For some or all of the four aggregates, it may be possible to lower the precoating area below 50% and still obtain similar adhesion performance. However, for the sample sizes utilized in these tests, it was not practical to reduce the binder content due to lack of precision of the testing equipment.

A precoating area of 50% translates to different amounts of binder by weight, depending on the aggregate. Limestone and sandstone require more binder than rhyolite and gravel to reach this requirement, due to rhyolite and gravel having higher specific gravities and lower binder absorption capacities. Additionally, the dust contents of the rhyolite and gravel stockpiles were found to be lower than those of limestone and sandstone, meaning that there was less dust available to absorb the precoating binder. These three factors led to the rhyolite and gravel being much more heavily coated by binder than the other two aggregate types, despite all four aggregates being precoated at equivalent weight percentages. Based on the precoating by weight to precoating by area conversion, the recommended precoating binder by weight to obtain an approximate area of 50%, for limestone and sandstone, is 0.2%. For rhyolite and gravel, the recommended weight is 0.1%.

4.6 PHYSICAL CHARACTERISTICS OF PRECOATED AGGREGATES

The results from the Sweep test suggest that a precoating area of 50% is ideal for optimal binder-aggregate adhesion. However, while a high precoating level may yield the best test results, in practice high precoating levels generally lead to sticking and clumping in the stockpile of precoated aggregate. Clumping of aggregate inhibits the ability to properly mix and place the aggregate on a chip seal. It was observed in this study that both the precoated limestone and sandstone aggregate exhibited clumping after mixing and cooling at precoat levels of 0.6% and 0.8% by mass, while the limestone and sandstone at 0.2% and 0.4% did not. For these two mineralogies, a maximum of 85% precoat area is possible before the binder leads to clumping. The rhyolite and gravel both exhibited clumping at all precoat levels except for the lowest 0.2% by mass, or 85% and 87% by area. Therefore, the 85% maximum precoat area applies to all four aggregates in this study.

Image analysis was performed on samples of precoated aggregate of all four mineralogies and levels of binder by weight, and examples of each mineralogy with an approximate precoat area of 85% were selected for comparison. For the limestone and sandstone aggregate, the ideal 85% precoat area was found at a binder by weight of 0.6%. For rhyolite and gravel, a precoat area of 85% was found at a binder by weight of 0.2%. Figures 4.15 through 4.16 present a visual comparison of these aggregates.

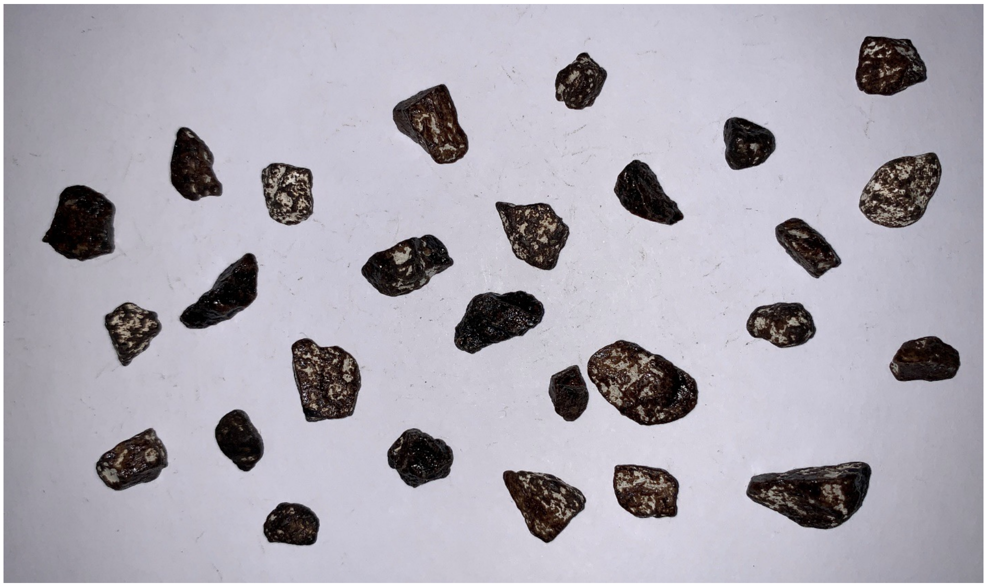


Figure 4.15. Limestone aggregate at 85.6% precoat (0.6% binder by weight)

Figure 4.16. Sandstone aggregate at 85.3% precoat (0.6% binder by weight)

Figure 4.17. Rhyolite aggregate at 85.5% precoat (0.2% binder by weight)

Figure 4.18. Gravel aggregate at 85.1% precoat (0.2% binder by weight)

4.7 FIELD EVALUATION

One of the main goals of this project is to validate and refine the selected test method using field materials. For this purpose, a multitude of field sections representing different geographical and climatic regions were identified. These sections were inspected and sampled across Texas. The sections are grouped as 2018, 2020A, and 2020B. A detailed discussion of results from these sections are presented in the following Chapter.

CHAPTER 5. RESULTS FROM FIELD SECTIONS

5.1 FIELD EVALUATION

One of the main goals of this task was to validate and refine the findings related to optimum amount of precoating required using field materials. To achieve this, a multitude of field sections representing different geographical and climatic regions were identified. These sections were inspected before and after construction. Figure 5.1 shows the location of these sections. The sections are grouped in this map based on the construction season and method of data collection (2018, 2020A, and 2020B). Note that the sections from 2018 construction season were from a different preceding study but the material samples and construction information were available for use to incorporate in this study. These sections were re-visited during the course of this study for performance evaluation. Details on material sampling and the protocol used for field inspection for these sections are described next. In summary, for the 2018 and 2020A sections a laser profiler was used to obtain a 3D point cloud of representative areas on the pavement before placement of the seal coat, immediately after placement of the seal coat, and after a period of performance. These data were used to obtain a quantitative assessment of texture change over time. Field assessment based on an on-site visit was conducted for all sections (2018, 2020A, and 2020B). Finally, the texture of the sections in the 2020B group was also obtained using 2D images collected by field engineers using photogrammetry. This was done primarily to explore the potential of using easy to access smartphone cameras to quantitatively assess surface texture.

Texture measurements were available for the 2018 and 2020A sections and were used to calculate the texture loss over the observation period. In addition, a qualitative assessment was made for all the 49 sections evaluated in this study. The qualitative assessment was based on a scale of 1 to 5 with 1 being the poorest performance and 5 being the best performance. Additional details on these sections and methods to compute texture loss are available in a companion report for this study for Project 0-7058.

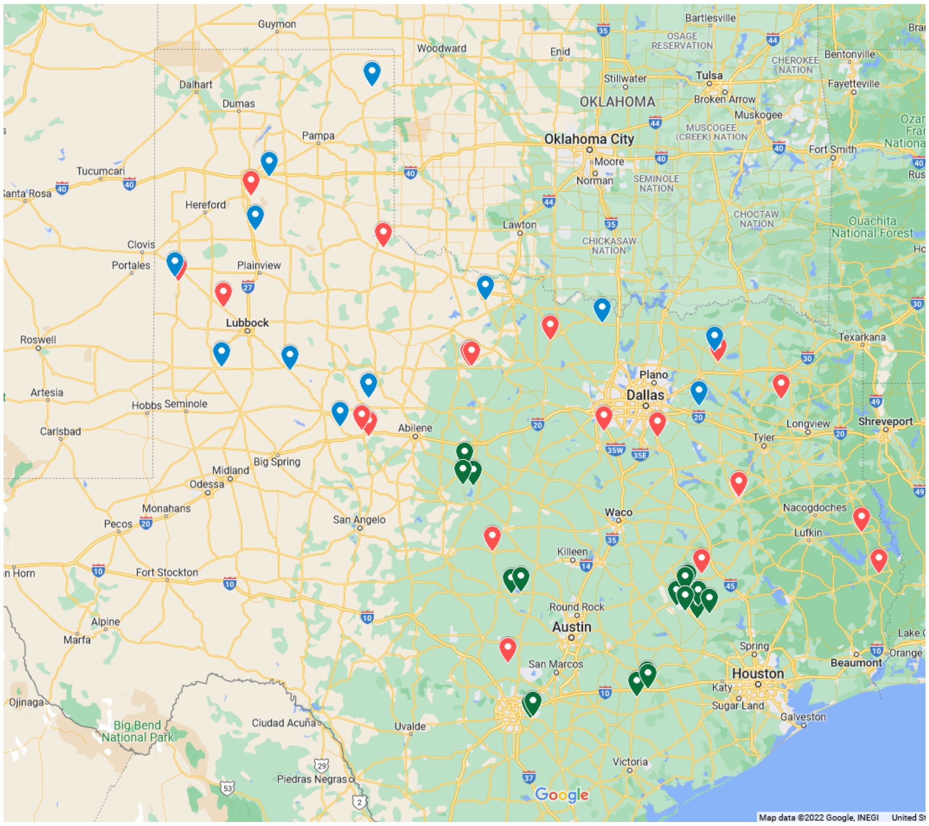


Figure 5.1. Seal coat sections monitored in this study; red pins indicate 2018 sections, green pins indicate 2020A sections, and blue pins indicate 2020B sec tions.

5.2 EVALUATION OF FIELD MATERIALS FOR PRECOATING

The image analysis technique, as described earlier in this report, was used to estimate the amount of binder precoating on aggregates. Note that this analysis provides the percentage of the area that is precoated and not the percentage of binder by mass of the aggregate. The significance of the former parameter has been discussed in the previous chapter.

Out of the total 49 field sections, precoated aggregates from 34 sections were available and all of these materials were analyzed for determination of percent binder precoating. For the image analysis, a small amount of the precoated aggregates for each section were placed on a white sheet (acting as a background). To acquire consistent images, the images were taken using a typical smartphone camera with flash. The intent of flash was to avoid shadows and unwanted artifacts in the image. Multiple images were taken for each sample of precoated aggregates and at least two images were used for analysis.

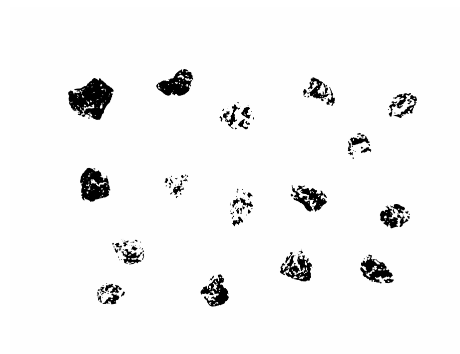
The images were then processed using an open-source image processing software, ImageJ. The standardized method adopted for this analysis can potentially be used as a tool to estimate binder coating using any similar image analysis program. The steps involved in the image acquisition and analysis are summarized below:

- Approximately 10 to 20 aggregate particles were selected randomly and placed on a white sheet. The aggregates were spaced apart to avoid individual particles coming into contact with each other.
- A cell phone camera was used to acquire the image of the precoated particles by pointing the camera from directly above the particles to avoid harsh shadows.
- The image from the camera was subjected to a median filter of 5-pixel radius to remove the digital noise. This step also removes most of the highlighted spots from specular reflection. Figures 5.2a and 5.3a show typical images acquired in this step for a dark and light-colored aggregate, respectively.
- The filtered image was then duplicated; one image was used to calculate the total area of the aggregate particles and the other was used to calculate the total area of the asphalt binder using the process described earlier in this report, i.e., by splitting the image into three channels, red, green, and blue, to facilitate thresholding of the image. The image from each channel was then converted to a binary image using a thresholding algorithm. Typically, a distribution of the pixel intensities will yield two distinct peaks: one for the aggregate and background, and one for the binder. The thresholding limits can be adjusted manually or automated based on the distribution.
- The three images from the previous step were merged into a single image. The merged image was then inverted, flattened, and converted to a grayscale image.
- The grayscale image obtained in previous step shows the binder coated area. The black pixels were counted which correspond to the asphalt binder area. Figures 5.2b and 5.3b show typical processed images with the binder highlighted in black pixels.
- For total aggregate area calculation, the other duplicated image was used. The image was first converted to an 8-bit grayscale image. An edge detection al-

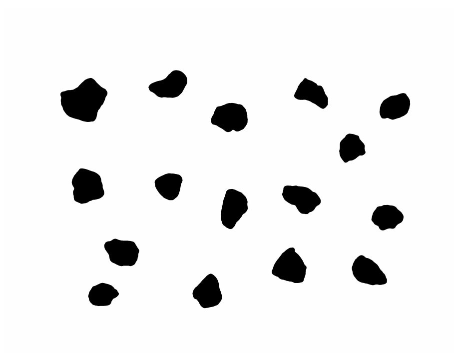
gorithm was then used to trace the outline of the aggregate particles. The grayscale image was then converted to a binary image with a dark background (inverted). All holes in the image were filled and the image was eroded a couple of times. The inversion caused all aggregate particles to be in black color and therefore a count of the number of black pixels represents the total projected area of the aggregate particles in the image. Figures 5.2 and 5.3c show typical processed images with the entire aggregate surface highlighted in black pixels.

- The ratio of the total number of binder pixels to the total number of aggregate pixels represents the percentage of aggregate area that is coated by the binder.

(a) Photograph of a sample of aggregates.



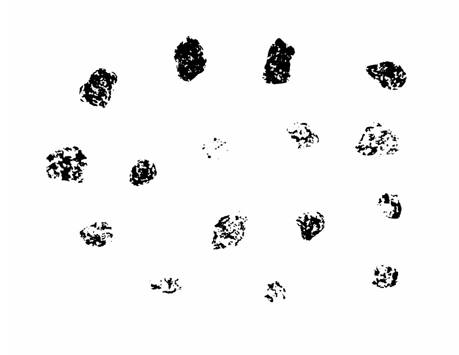
(b) Binder coating aggregate in black pixels.



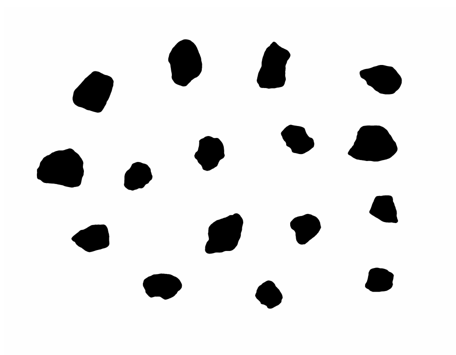
(c) Total aggregate surface area in black pixels.

Figure 5.2. Typical image and steps from image analysis to estimate amount of precoating for a dark-colored aggregate.

(a) Photograph of a sample of aggregates.



(b) Binder coating aggregate in black pixels.



(c) Total aggregate surface area in black pixels.

Figure 5.3. Typical image and steps from image analysis to estimate amount of precoating for a light-colored aggregate.

The aforementioned process was used with aggregates from the 34 field sections with aggregate samples and the percent precoating was determined. Table 5.1 presents the results from measurements of precoating along with the qualitative and quantitative ratings from the field sections. Figure 5.4 shows a distribution of the precoating values measured from these 34 sections.

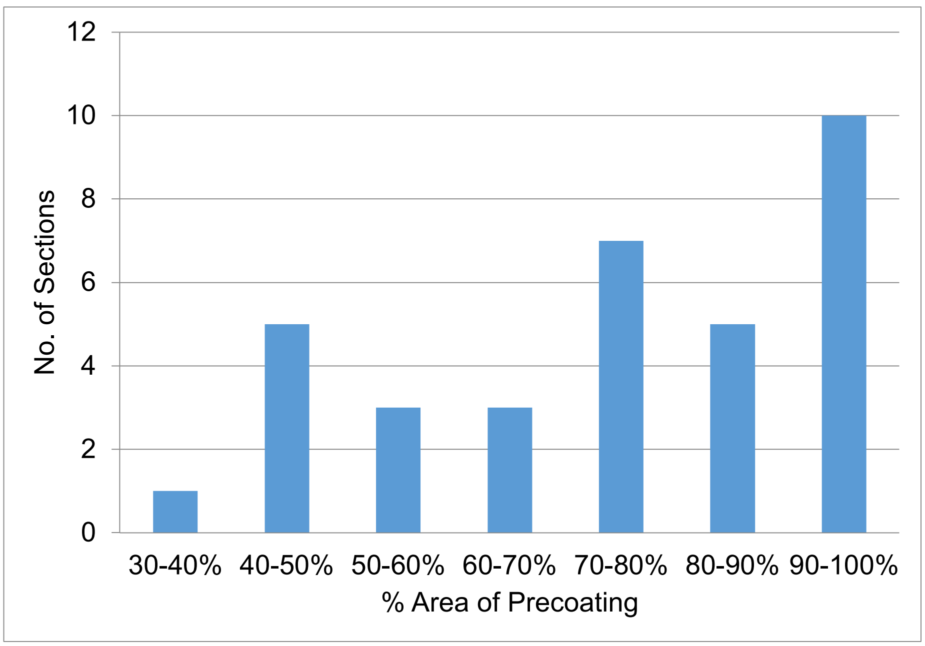


Figure 5.4. Distribution of surface areas of precoating from 34 field sections.

Table 5.1. Precoating with qualitative and quantitative rating of field sections.

Section No.	Qualitative Rating	Quantitative % Texture Loss	Aggregate Precoating (%)
1	4	56%	84.5%
2	4	68%	67.2%
3	3	56%	69.6%
4	2	83%	92.7%
7	3	42%	86.8%
8	2	82%	89.3%
11	3	52%	48.8%
12	3	69%	88.1%
13	3	84%	70.9%
14	4	54%	45.9%
15	3	66%	79.3%
17	3	72%	96.3%
18	1	85%	91.6%
22	4	40%	76.0%
24	2	59%	51.9%
25	4	45%	36.3%
26	3	62%	51.0%
28	3	63%	43.1%
29	2	68%	57.5%
30	2	82%	76.6%
31	4	50%	77.0%
32	2	78%	69.2%
33	4	63%	82.3%
34	3	62%	74.9%
35	3	60%	91.7%
36	4	65%	95.4%
37	3	62%	91.7%
40	4	N/A	94.6%
43	4	N/A	97.2%
45	2	N/A	92.1%
46	1	N/A	45.6%
47	1	N/A	46.4%
48	2	N/A	93.0%
49	3	N/A	72.1%

A subset of the materials acquired from 30 field sections were used with the Sweep and the Vialit tests to evaluate any impact of precoating on the adhesion between the aggregates and the binder. It is important to emphasize that none of the field sections showed any substantial amounts of aggregate loss due to adhesion. In almost all cases, texture or aggregate loss was driven by embedment of the aggregate particles in the substrate layers. Nevertheless, these materials were evaluated for comparison with results from materials used in the laboratory as well as to establish a threshold that is acceptable for materials intended to be used in the field.

Figures 5.5 and 5.6 compare the aggregate loss from the Sweep and the Vialit tests, respectively to the extent of precoating of aggregates. Figures 5.7 and 5.8 compare the aggregate loss measured in the field on a qualitative and quantitative basis, respectively to the extent of precoating of aggregates. In reviewing these figures, it must be emphasized that although the texture loss in the field is a reflection of multiple mechanisms, i.e., embedment and adhesion loss, of which the former is the dominant mechanism based on field observations, the aggregate loss measured in the laboratory tests is exclusively due to adhesion loss. However, another notable feature from Figure 5.8 is that the slight increase in texture loss due to embedment with an increase in precoating area. This increase may be due to the increased binder content from the aggregate surface contributing to the embedment or bleeding problem.

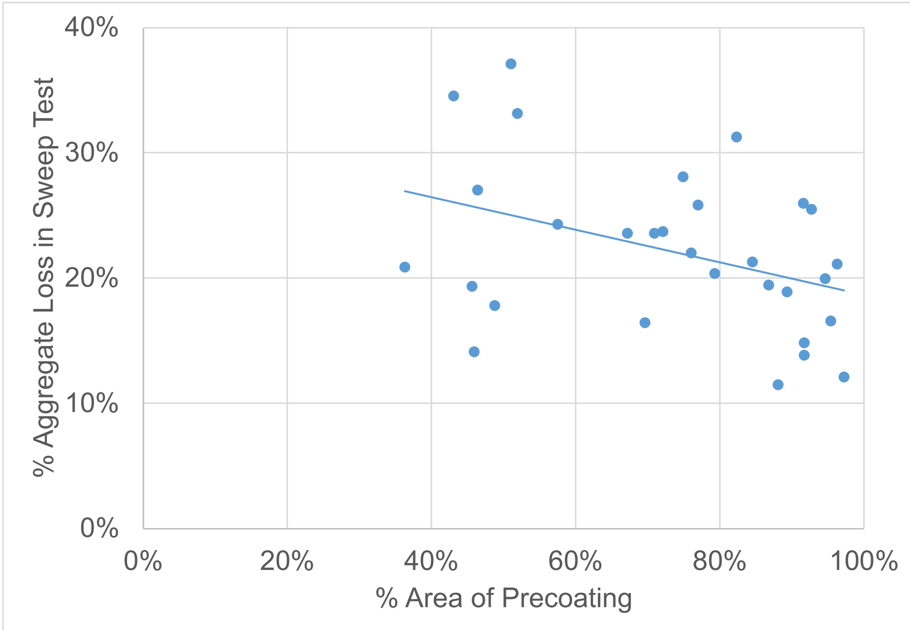


Figure 5.5. Comparison of amount of precoating with aggregate loss from the Sweep test.

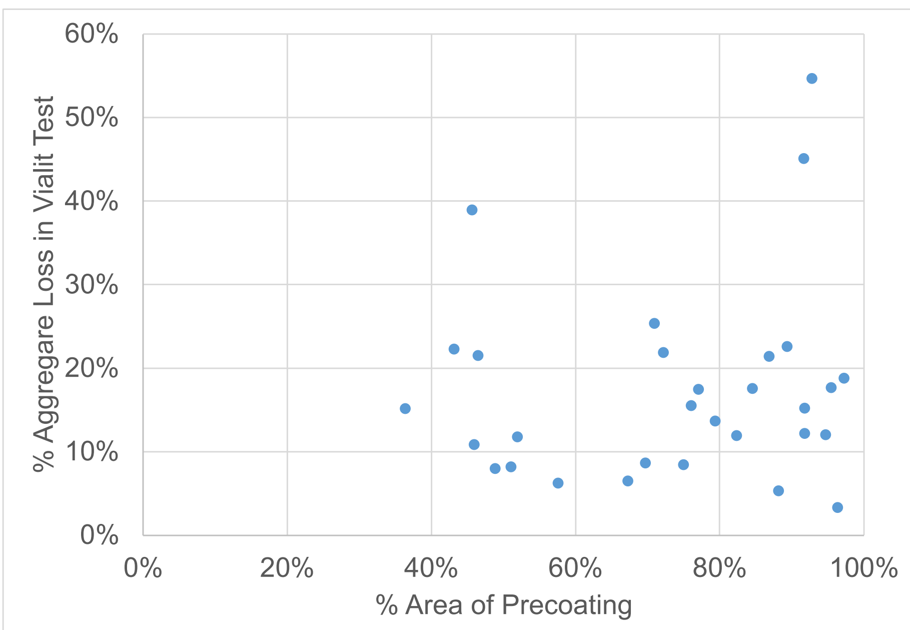


Figure 5.6. Comparison of amount of precoating with aggregate loss from the Vialit test.

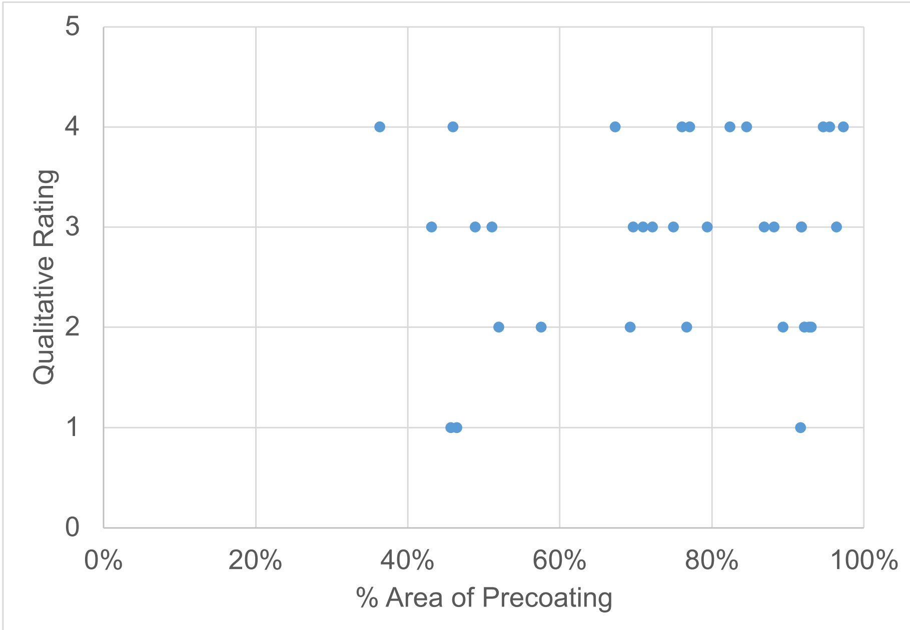


Figure 5.7. Comparison of amount of precoating with qualitative assessment of field sections.

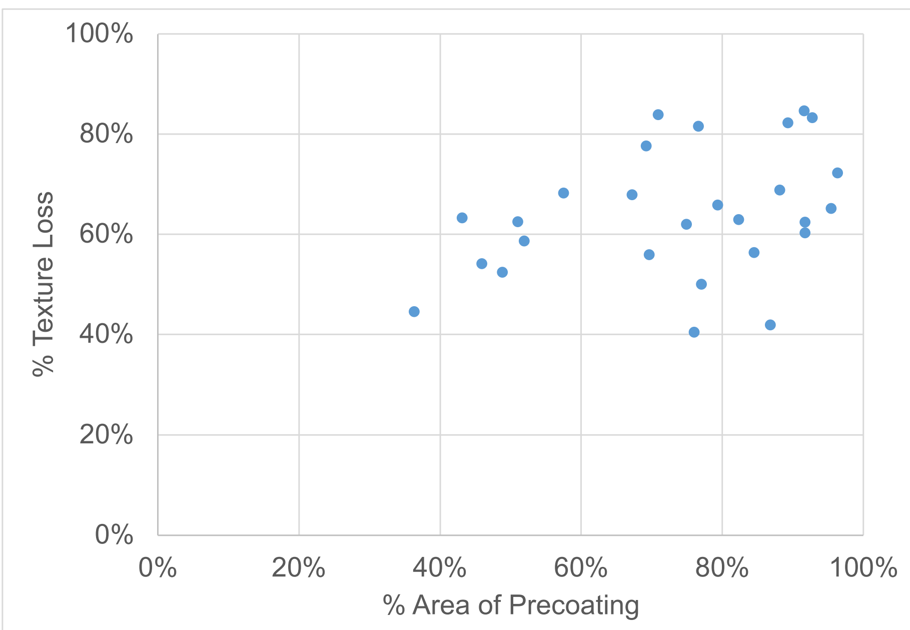


Figure 5.8. Comparison of amount of precoating with quantitative assessment of field sections.

5.3 CONCLUDING REMARKS

The following key conclusions can be made based on the observation of field performance and measurement of adhesion loss using field materials with the laboratory tests.

- The binder precoating from image analysis technique showed consistent results. The coefficient of variation in percent precoating for the two replicates for each material did not exceed 10%. Also, judging the percent precoating values with the visual inspection of the coated aggregates, the binder coating area estimations appeared to be consistent with visual observations.
- The distribution of percent precoating for the field sections revealed that most of the sections had aggregates with a precoating area of more than 50%. Only one section out of 34 had a precoating of less than 40% and five sections had precoating between 40-50%. Around two-third of the sections had a precoating of more than 70% showing good levels of precoating. Significant number of sections had almost total area precoated (90-100% range). This precoating level was also verified visually for aggregates from these sections.
- Higher levels of precoating were associated with higher texture loss due to embedment or bleeding. It is likely that the excess binder content from the surface contributed to this problem.
- Loss in Sweep and Vialit tests from all the test sections were comparable to the values from testing well controlled laboratory specimens and materials that are expected to perform well (e.g.AC-20-5TR). Tests results from laboratory materials also show that precoating area from approximately 50% or higher does not have a significant impact on the adhesion performance of the seal coat; although the sweep test results showed a slight trend that shows an improvement in aggregate retention with an increase in precoating. This is consistent with the observation from the 34 field sections that showed no significant aggregate loss due to adhesion. Both field and lab data confirm that a precoating area of 50% or higher is adequate to prevent excessive loss due to adhesion.

CHAPTER 6. SUMMARY, CONCLUSIONS AND RECOMMENDED GUIDELINES

The purpose of using precoated aggregates in hot applied seal coats is to improve the aggregate-binder compatibility. Precoating also prevents dust particles from accumulating on the aggregate surface and inhibiting adhesion. Poor adhesion makes the aggregate particles prone to being dislodged and consequently susceptible to raveling.

6.1 SUMMARY

A summary of the complete study is outlined by the following.

6.1.1 Literature Review and Survey

- The use of hot applied binder and consequently use of precoated aggregates is not prevalent among many states.
- Literature suggested some test methods used for seal coat evaluation, which included a Sweep test and the Vialit test. Variations of existing tests with procedures in the literature and were used to test seal coat materials for adhesion.
- Promising tests to evaluate amount of precoating binder include infrared imaging, image analysis, and colorimeter of dissolved binder.

6.1.2 Method Development and Establishment of Test Protocols

In addition to the three types of binder content analysis discussed in the literature review, a micro-extraction procedure was also investigated, resulting in four techniques that were evaluated in this study. The following are some of the findings from these evaluations.

1. Infrared imaging

   This method uses an infrared imaging camera to estimate the amount of binder on the surface of an aggregate particle. At the time of this study, the capital cost of the hardware with adequate resolution in terms of the wavelength of interest and image quality was extremely high. This approach was not pursued any further due to the high capital cost of the equipment. However, it is recommended that this technique be considered for future applications related to asphalt materials, particularly as the cost of the technology reduces.

2. Micro-extraction

   This method measures the weight of precoating binder on an aggregate sample by separating the binder from the aggregate using toluene dissolution. The micro-extraction procedure can take more than a couple of days to complete due to the steps taken to ensure that all the binder has dissolved from the aggregate sample. Due to time constraints, it is not practical to use this for high volume testing. The method is a reliable option to measure the amount of precoating binder if precision is a concern and there are no time constraints. This method can also be used as a quality assurance tool to verify the results of quicker, less precise methods.

3. Image analysis

   This method uses images from a typical digital camera (e.g., from a smart phone) to analyze the percentage of surface area of aggregate particles that are precoated with the binder. This approach appears to be the most promising and reasonable method to assess the extent of precoating in the field and will be used in the remainder of this project.

4. Colorimeter

   This method is based on measuring the color of the binder that is dissolved from precoated aggregates using diesel. The method relies on a calibration curve, which is a onetime exercise and can be shared by all users once it is developed. This method measures the mass of the binder, which is slightly different from the percentage of area of aggregate particles coated by the binder.

To measure the extent to area of precoating, the image analysis provided the information needed and was easier to perform. All precoat area determinations used in this study were based on this technique. The study also produced an automated method of using image analysis to determine percentage of area coated with binder.

6.1.3 Laboratory Testing to Estimate Optimal Levels of Precoating

A series of laboratory experiments were conducted to examine performance manufactured seal coat specimens a sweep test and the Vialit test. Variations in the test matrix included: aggregate minerology (limestone, sandstone, rhyolite, and gravel), seal coat binder type (2 binder types), precoat binder amount (5 different amounts of precoating).

Some of the key conclusions that can be drawn by examining all combinations of aggregate types, precoating amounts, and tests are as follows.

1. Polymer modified binder exhibited less aggregates loss in the performance tests than unmodified binder at all precoat levels.
2. Overall, neither the Vialit test nor the Sweep test detected meaningful changes in adhesion as precoating increased from 50%, showing that a precoating area of 50% binder up to 100% precoat area performed similarly.
3. The Sweep test detected a significant difference in bonding between uncoated and precoated aggregate samples.
4. The aggregate loss of the uncoated aggregate is dependent on the amount of dust on the surface area of the aggregate, since dust is the main inhibitor of adhesion to the base binder in a seal coat. However, once this dust is absorbed by a certain amount of precoating binder, the loss approaches this asymptote of 15-20%.

The uncoated and precoated aggregate loss in the Sweep test confirm that binder aggregate adhesion improves when precoating is used. There is, however, an asymptotic relationship between loss and precoating, suggesting some threshold above which additional binder has no discernible effect. Based on the results gathered from this study, this threshold corresponds to approximately a precoating area of 50%. This is shown in Figure 4.14.

A precoating area of 50% translates to different amounts of precoat binder by weight of aggregate, depending on the aggregate. This depends on absorption, surface area (surface texture and aggregate size), dust content, and specific gravity. Based on the aggregates used in this study, the recommended precoating binder by weight to obtain an approximate area of 50%, for limestone and sandstone, is 0.2%. For rhyolite and gravel, the recommended weight is 0.1%. For all aggregate mineralogies used in this study, above 85% precoated area leads to sticking and clumping of precoated aggregate.

6.1.4 Results from Field Sections

Thirty-four field sections, with known performance and retained original aggregate and binder were evaluated for performance with sweep and Vialit tests and image analysis for area percent of precoat.

Most sections had aggregates with a precoated area of more than 50%. A significant number of sections had almost the total area precoated (90-100% range). This precoating level was also verified visually for aggregates from these sections.

Loss in Sweep and Vialit tests from all the test sections were comparable to the values from testing well controlled laboratory specimens and materials that are expected to perform well (e.g.AC-20-5TR).

Observation from the 34 field sections showed no significant aggregate loss due to adhesion. Both field and lab data confirm that a precoating area of 50% or higher is adequate to prevent excessive loss due to adhesion.

6.2 CONCLUSIONS

This study supports the following conclusions for seal coats using precoated aggregate with hot applied base asphalt.

- Aggregates with no precoat exhibit much more loss using the Sweep test. This means that precoating significantly increased aggregate retention, validating this use of precoated aggregate for hot applied seal coats.
- Precoating of aggregate increases aggregate adhesion according to Sweep testing and is validated by field test sections.
- Image analysis can be used to determine the precoat area.
- Aggregate precoat area above 50% has little effect on aggregate retention (based on Sweep test results), but precoat area above 85% tend to produce clumping. It is also possible that excess precoating can exaggerate the bleeding problem on the surface. Thus, the optimum precoat area is between about 50% and 85%.

6.3 RECOMMENDED GUIDELINES

Based on this study, it is recommended to:

- Use precoated aggregate for hot applied seal coats.
- Used precoat percentages by weight of aggregate that correspond to between

50% and 85% of aggregate area coated. This is aggregate specific as it depends on aggregate absorption and surface area.

- One mechanism of implementation can be to use project materials (aggregate and precoat binder) to precoat samples using different percentages by weight and measure the coated area of each sample. The percent by weight that corresponds to approximately 50% area coverage can be specified for use during construction.

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APPENDIX A. VALUE OF RESEARCH

PROJECT TITLE

Develop guidelines to precoat aggregates for seal coats.

PROJECT STATEMENT

Seal coats in Texas are unique because most binder is hot applied, and aggregates are precoated. Precoating eliminates dust and improves adhesion between aggregate and binder. There are currently no guidelines or specifications in place that can allow engineers to specify and accept the quality and extent of binder used to precoat aggregates. Precoating with certain binders can result in poor adhesion and premature failure of the seal coats. Inadequate precoating can result in dusty aggregate that impedes aggregate adhesion. This study examined the factors related to precoating of aggregates that influence the quality of seal coats, and used this information to provide guidelines for the Receiving Agency's Engineers. Table A.1 presents a summary of the functional areas and benefits from Project 7057.

Table A.1. Functional Areas for Project 0-7057

Benefit Area	Qual	Econ.	Both	Tx-DOT	State	Both
Level of knowledge				X		
Customer satisfaction	X			X		
					X	
Reduced Construction, Operations, and Maintenance Cost					X	
					X	

QUALITATIVE BENEFITS

Level of knowledge

This project conducted an extensive survey of TxDOT districts on their practices pertaining to seal coats. The results from this survey provide a comprehensive summary regarding the material specifications (e.g., binder grade, emulsion grade, precoating binder grade, precoating rate), practices (e.g., method used for design, percentage of seal coat carried out internally versus contracted outside), and experiences (e.g., failure types, failure rates) from different districts. This information is a valuable resource for TxDOT for understanding the breadth and depth of its seal coat program and to make any critical decisions in the future. In addition to a district survey, this study also reviewed specifications and practices from other states across the US and provided a comprehensive but relatively less granular summary.

Customer Satisfaction and Infrastructure Condition

Surface treated roads such as surfaces with seal coats comprise over 40% of the on-system roadways. Lack of precoating leads to loss of adhesion between the aggregate and the seal coat binder. This causes aggregate particles to break loose, which in turn not only reduces the quality of the pavement surface but it also causes windshield damage for any vehicle that may be following a vehicle that causes the aggregate particles to break loose. Improving precoating practices directly impacts the adhesive loss and accidents caused through such loss.

ECONOMIC BENEFITS

Increased service life and Reduced costs

This project started on January 1, 2020, and completed on August 31, 2022, with a duration of 2.67 years. The total budgeted cost for this project was $391,695. For the purposes of this analysis and considering full implementation of the recommendations, the following were considered:

- The TxDOT seal coat program costs approximately $280 million (based on estimate from 2022). Approximately, a conservative percentage of 85% of this can be attributed to hot applied seal coats that involve the use of precoated aggregates.

- Field examination of different sections show that more than 10% of pavement sections had lost significant texture within one to two years of placement instead of the expected five to seven years of service life.
- Further, as an extremely conservative estimate, premature failures due to poor precoating are estimated as 0.1% of the total seal coat placed in any given year. Considering the size of the seal coat program, this amounts to $238,000. This amount was used as the expected value per year.

The aforementioned parameters were used to obtain the NPV for this project as shown in Figures A.1 and A.2.

Texas Department of Transportation	**Project #**	0-7057			
	Project Name:	Develop guidelines to precoat aggregates for seal coats			
	Agency:	CTR	**Project Budget**	$	391,695
	Project Duration (Yrs)	2.7	**Exp. Value (per Yr)**	$	238,000
	Expected Value Duration (Yrs)	10	**Discount Rate**		0%
Economic Value					
Total Savings:	$	1,750,305	**Net Present Value (NPV):**	$	2,142,000
Payback Period (Yrs):		1.645777	**Cost Benefit Ratio (CBR, $1 : $___):**	$	5

Figure A.1. Parameters used for economic analysis for VOR.

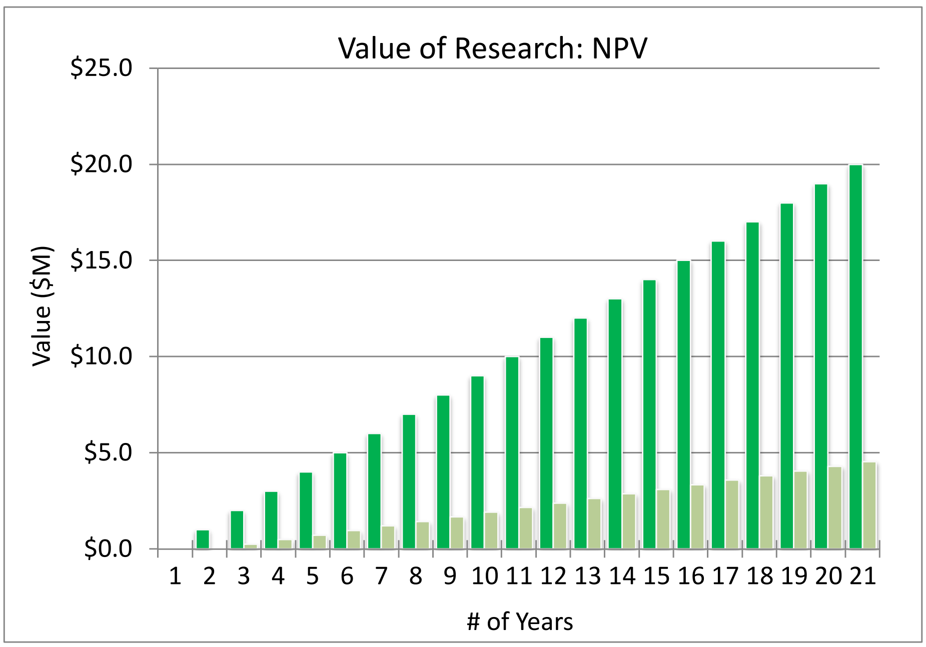

Figure A.2. Illustration of the NPV over a period of 20 years.