# INNOVATIVE EVALUATION OF RECYCLED ASPHALT PAVEMENT (RAP) USE IN SLURRY SEAL APPLICATIONS

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# ABSTRACT


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Slurry seal is a surface treatment used to extend the life of asphalt pavements. Sealing the surface from environmental effects (e.g., water penetration and ultraviolet light etc.), slurry seal retards aging (embrittlement) and prevents raveling. Slurry seal is a mixture of Aggregate/Reclaimed Asphalt Pavement (RAP), Asphalt Emulsion, and Mineral fillers. Multiple traditional tests, including Mix Time Test, Cohesion Test, Consistency Test, Wet Stripping Test, Wet Track Abrasion Test (WTAT), Sand Adhesion Test and Classification Compatibility Test, are used to assess the potential performance of slurry seals. These tests are typically performed to determine a slurry seal mixture formula (mixture design). In this study, a comprehensive experimental program was undertaken to compare the performances of slurry seal mixtures made with 100% RAP (Recycled Asphalt Pavement) and virgin (VG) aggregates. The tests included traditional tests such as residual binder content, mix time, cohesion, consistency, wet-abrasion, wet-stripping, integrity/compatibility tests. In addition, two new testing protocols were introduced to assess the abrasion, raveling and rutting resistance of the slurry seal mixtures using the Hamburg Wheel Tracking (HWT) device. It was observed that the slurry seals made with 100%RAP generally performed as good as or better than the slurry seals made with virgin aggregates.

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# 1 INTRODUCTION

Slurry seal and micro-surfacing treatments are two similar techniques that have been widely used in pavement preservation and rehabilitation. These treatments create a thin layer on an existing asphalt pavement surface and provide protection from moisture/air infiltration and reduce the rate of aging. These methods can also improve the skid resistance. This surface-coating method can improve a road condition by reducing the rate of deterioration caused by traffic and environmental effects.

Slurry seal is a cold mix product of aggregate, water, asphalt emulsion and mineral fillers. The cured slurry seal material can considerably improve the overall performance and preserve the pavement surface layer from being damaged by the water and UV lights and bringing a refreshing appearance on the old pavement after the application. Some states started using Reclaimed Asphalt Pavement (RAP) instead of virgin aggregates in slurry seal applications in recent years. The idea is that the additional binder in the RAP improves the slurry seal's stability and potentially reduces the amount of emulsion needed. The use of RAP instead of virgin aggregates also helps in reducing the environmental effects of extracting aggregates from the aggregate quarries and conserves natural resources.

The main objective of this study is to evaluate the use of RAP material in the slurry seal applications. The performances of the slurry seal mixture made with 100% RAP aggregate and the virgin aggregate (Type II) were tested using the traditional tests and the Hamburg wheel tracking (HWT) test.

# 2 LITERATURE REVIEW

## 2.1 Slurry seal application procedures

In recent years, slurry seal has been a more popular pavement preservation method. It restores the surface condition of an old pavement by providing a new asphalt surface layer and improving the pavement structure's resistance to various distresses. Slurry seal is a cold-pave material that is placed on the surface of an existing pavement. Because of its production method and the materials used, the slurry seal rehabilitation method is considered as a low-budget quick-cast method. A slurry seal mixture requires four basic composite elements mixed proportionally, which are aggregate, water, emulsion, and additives. Depending on the goal of the construction time, the emulsions have different setting times, e.g., CSS (Cationic Slow Setting), CQS (Cationic Quick Setting) and rejuvenating emulsion, etc. The proportion between each element affects the compatibility of the slurry seal material properties and influences the strength and durability of a designed slurry seal product.

The following fundamental aspects must be kept in mind when constructing a high-quality slurry seal layer:

- **Cleaning of the surface**: The surface of the pre-existing pavement should be cleaned and dried as much as possible before paving. The cluster of large amounts of dirt and water can reduce the area of the contact surface between the slurry seal layer and the top layer of the pre-existing pavement, which leads to the gaps between layers when an expansion or a contraction occurs due to temperature change. The gap between the layers can lead to moisture accumulation causing bleeding or peeling when the traffic passes the treated section.

- **Sealing of cracks**: To apply the slurry seal, it is a good practice to fill the cracks (e.g., using an overband crack fill) on the pre-existing road surface. A smoother road surface can give a better bond between slurry seal material and road surface, which results in a greater overall performance. Any crack that is larger than 6.4mm is considered to be a large crack and can lead to an uneven surface of a road if not sealed properly before applying a slurry seal layer. These ups and downs in pavement surface cause a weak point, and larger damage can happen to the after-paved road under the traffic load [4].
- **Weather Limitations**: To achieve a high-quality slurry seal mixture, construction should be avoided when there is a possibility of freezing temperatures in the 24 hours after the cast. If the surface of the pavement and the air have a temperature that is below 50°F (10°C) and can be potentially decreasing the process of application should be stopped and the slurry seal shall not be applied[11].
- **Application of Slurry Seal**: The application rate determines the thickness of the slurry seal layer and is related to the properties of component materials and the designed traffic. The application location and the targeting traffic influence the thickness since the thicker slurry seal layer can withstand more traffic. The size of aggregate being used in the slurry seal mixture is determined by the location(Table 1). [11]

The traditional tests are designed to evaluate the different properties of a slurry seal mixture. In this study, the traditional tests are categorized into two major groups: construction-related tests and performance-related tests (Table 2).

**Table 1. Rate of Application**

| Aggregate Type | Location | Suggested Application Rate |
|---|---|---|
| Type I | Parking Areas<br>Urban and Residential Streets<br>Airport Runways | 8 - 12 $lb/yd^2$<br>(4.3 – 6.5 $kg/m^2$) |
| Type II | Urban and Residential Streets<br>Airport Runways | 10 - 18 $lb/yd^2$<br>(5.4 – 9.8 $kg/m^2$) |
| Type III | Primary and Interstate Routes | 15 - 22 $lb/yd^2$<br>(8.1 – 12.0 $kg/m^2$) |

**Table 2. Traditional Tests Category**

| Construction Related Tests | Performance Related Tests |
|---|---|
| Mix Time Test | Wet-Stripping Test |
| Consistency Test | Wet-Track Abrasion Test |
| Cohesion Test | Sand Adhesion Test |
| | Classification Compatibility Test |

## 2.2 The construction-related tests

The construction-related tests are used to evaluate the basic characteristics to determine the appropriate proportions of each component of the slurry seal mixture to meet constructability requirements. These tests include the Mix-time Test, the Consistency Test, and the Cohesion Test.

### *2.2.1 Mix-Time Test*

Mix-Time Test, following the standard *ISSA TB113[16]*, is developed to estimate the mixing time of a combination of materials in a designed slurry seal mixture by using different mixing proportions between each material. In this test, the mixing time is evaluated so that the hardening of the slurry seal mixture can be prevented before construction. It ensures the mixing time is sufficient, and the slurry seal mixture is prepared in the ready-to-cast condition when constructing. Figure 1 shows the components of a typical slurry seal and Figure 2 shows the sample at the end of the mix time test.

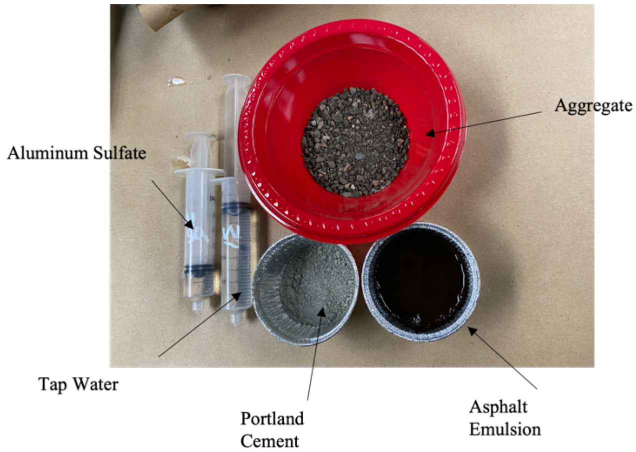



**Figure 1. Mix-Time Test Materials**

**Figure 2. Mix-time Test Sample Demonstration**

### *2.2.2 Consistency Test*

The consistency test is similar to the slump test that has been commonly used in concrete industry. Following the standard *ISSA TB 106 [14]*, the consistency test determines the percentage of water should be added during the mixing and provides a numerical measurement that indicates the flow characteristics of the designed slurry seal mixture. The proportion of water determines the viscosity of the slurry seal right after initial mixing. If excessive water is used, the consistency increases and the slurry seal mixture can behave as fluid in the field, which influences the slurry thickness. If the desired application thickness cannot be achieved, the slurry seal may not be able to withstand the target traffic load. Figure 3 shows the sample of a slurry seal material at the end of the consistency test.

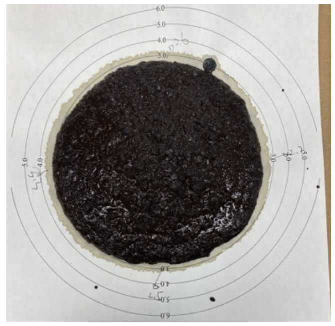


**Figure 3. Consistency Test Sample Result**

### *2.2.3 Cohesion Test*

Cohesion Test, following the standard *ISSA A 105[11] & A 139[18]*, is to determine the initial set time and cure development period by providing the torque-time relations function. The result of this test reveals the ability of the slurry seal to withstand the frictional forces due to the wheel of a vehicle after the pavement is opened to traffic. In the cohesion test, the value of the torque generated at the contact surface between the tested sample and the rubber head is measured by a torque meter (see Figure 4 and Figure 5). This torque is related to the maximum stress that the slurry seal materials can endure at the open traffic. The result from this test corresponding to the specification limits shows the mode of rupture at the time interval and forecast the actual resistance to the friction force induced by traffic loading at construction sections.

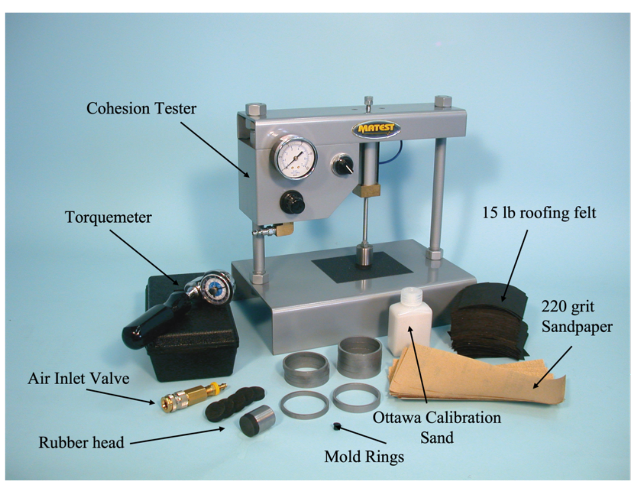


**Figure 4. Benedict Cohesion Tester**

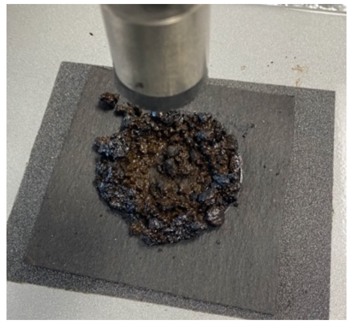


**Figure 5. Cohesion Sample Test Result**

## 2.3 Performance Tests

The performance tests focus on estimating the performance of the slurry seal mixture in the field. There are four tests under the performance tests group: Wet-Stripping Test, Wet-Track Abrasion Test, Sand Adhesion test and Classification Compatibility test. These four tests are going to ascertain the qualification of the mixture and based on the result, the relative component proportions should be slightly modified to reach the specification requirements.

### *2.3.1 Wet-Stripping Test*

The wet-stripping test, following the standard ISSA TB 114[17], can be considered as a torture test and is designed to evaluate the susceptibility of the mixture to stripping due to moisture. The stripping can lead to raveling, thus, the surface unevenness, which can lead to accidents. In this test, proportion of the aggregates coated with asphalt binder is visually quantified. The percentage of the aggregate with full asphalt coating is visually estimated and used to determine the acceptability of the mixture.

### *2.3.2 Wet-Track Abrasion Test*

The wet-track abrasion test, following the standard ISSA TB100[13], is used to measure the resistance to wearing of a slurry seal mixture under the wet conditions. Sufficient resistance to wearing caused by the frictional force between the vehicle tires and the road surface is crucial for the long-term performance of the slurry seal. This test quantifies the decrease in the frictional resistance and the potential aggregate loss under presence of moisture. The wet-track abrasion test is composed of two tests: the one-hour soaking test and the six-day soaking test. These two tests are different in the soaking period before the abrasion test. Figure 6 and Figure 7 show the wet track abrasion test setup and the condition of a sample at the end of the test, respectively.

**Figure 6. Benedict Wet Track Abrasion Tester (N-50)**

**Figure 7. WTAT Tested Sample Demonstration**

### 2.3.3 *Sand Adhesion Test*

Sand adhesion test, following the standard ISSA TB109[15], is used to determine the maximum amount of the asphalt in a slurry seal mixture to eliminate the possibility of flushing. Figure 8 shows the loaded wheel machine used in this test. The slurry seal sample is prepared at a temperature of 60°C (140°F) ± 3°C (5°F) and tested at 72 ± 5°F (22 ± 3°C). Total 1100 cycles of wheel passes are applied to the sample. The results from the sand adhesion test are noted and reported when the surface of the sample is visibly shining and a tackiness sound occurs. From the results of a sand adhesion test, the compaction rates and the plastic deformation are also recorded and used to predict the field performance when the road surface temperature is around 60°C.

The first part of the test includes the application of 1000 cycles to simulate the traffic load. After 1000 cycles, 200 grams of sand (preheated to 82.2°C(140°F) ± 3°C(5°F)) is uniformly spread on the surface and smoothened with a metal strip. Then, additional 100 cycles are applied to adhere the sand to the sample surface completely. It is noted in the standard that 300 grams of sand should be used if no metal strip is used. The result from the sand adhesion test is reported in the format as “The tack is reported as ___cycles of ___pound load at ___Temperature.” and the weight of the adhered sand per square foot.

**Figure 8. Benedict Loaded Wheel Tester**

### 2.3.4 *Classification Compatibility Test*

Classification Compatibility Test, following with the standard ISSA 144[19], is composite of two tests and includes four measurements to grade the level of compatibility between the aggregate fines and the emulsified asphalt residue in a slurry seal mixture. The results from this test represent the properties of the emulsified asphalt used in the mixture based on the absorption rate, the abrasion loss, the integrity, and the adhesion characteristic. These results can be used to predict the field performance of slurry seal layer.

In the test of compatibility, three tests are performed to obtain the results of absorption, abrasion, integrity, and adhesion. The test sample in the compatibility test is a 40-gram asphalt cylinder pill (see Figure 9) prepared by the pneumatic pill presser (see Figure 10) and soaked under water for 6 days at 25°C.

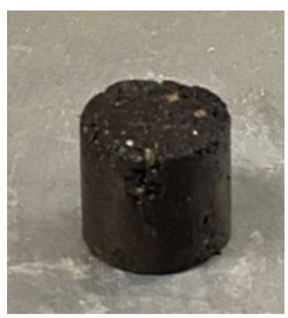


**Figure 9. Compatibility Test Sample**

**Figure 10. Benedict Slurry Pneumatic Pill Press**

- ***Absorption:*** The absorption value of the sample is measured after 6 days of water bath. This data estimates the air voids in the slurry seal pill samples, and the pill is compressed under a force of 1000 kg (2204 lb) $\pm$ 25 kg ( 55.1 lb) . The absorption value is the weight difference between the dry sample and the surface saturated dry (SSD) sample. This value indicates how much water can be potentially absorbed by the slurry seal in the field. The SSD weight from this test is used as a parameter in the following measurements.
- ***Abrasion:*** The abrasion test is performed by the Schulze-Breuer machine with water-filled shuttle cylinders (seeFigure 12) and uses the sample from Absorption test. At the abrasion test, the shuttle cylinders rotate at the rate of 20 RPM (rotations per minute) for 3600 rotations in total. As the shuttle cylinders rotate, the pill sample inside the cylinder moves in a falling motion from one end to another end. The water inside the shuttle provides a buffer to prevent the strong impact while the sample hits the cylinder end and provides a stable temperature distribution throughout the test. The sample weight change from SSD condition and after-test is recorded as the abrasion test value.

**Figure 11. Schulze-Breuer Machine**

**Figure 12. Demonstration of water-filled shuttle cylinder with sample**

- ***Integrity:*** The integrity test exams the sample pill in the saturated condition from abrasion test. In the integrity test, the sample is placed in a basket hung and immerged at least ¼ inch in an 800 ml beaker with boiling water. After being boiled for 30 minutes, the saturated surface dry (SSD) weight of the largest remaining part from the sample pill is measured. The value of the integrity is the percentage of the SSD weight of the largest remaining part after test to the SSD weight after abrasion test. This test measures the homogeneity of aggregate distribution inside the slurry seal mixture. The low integrity value indicates that the aggregates are not well distributed in the sample and the mixture blend can collapse in the field.

- ***Adhesion:*** The adhesion rate is measured after the integrity test. When finished with the integrity test, the sample is air-dried for 24 hours, and then the percentage of coating with the asphalt is visually estimated. This value is noted as the 'adhesion value'. The adhesion value of the sample represents the adhesion strength between asphalt particles and the aggregate when exposed to high temperatures under wet conditions.

#### *2.3.5 Modified Hamburg Wheel Tracking (HWT) device*

As part of a study funded by the Michigan Department of Transportation (MDOT), Boz et al. [3] developed practical laboratory tests to evaluate aggregate loss (abrasion resistance) and bleeding in chip seals. In these methods, a modified version of the Hamburg Wheel Tracking (HWT) device was used (see Figure 13a). The steel wheel in the HWT device was replaced with a rubber wheel, and the load level was reduced to 125 lb (same load level used for assessing bleeding of micro-surfacing mixtures, as described in ASTM D 6372). Details of the modified HWT testing configuration for pavement preservation treatments are shown in Table 3.

In the abrasion test (Test A), aggregate loss (Figure 13c) as well as friction loss (via British pendulum testing before and after the abrasion) were quantified. On the other hand, in bleeding testing (Test B), the percent bleeding area was determined via image analysis techniques (Figure 13b). Boz et al. [3] did extensive testing on chip seals with different emulsion and binder application rates, as well as aggregate and emulsion types to develop performance-based percent embedment limits for chip seals. The modified HWT is an excellent candidate to simulate the braking/acceleration effect (Test A) and assess the ability of slurry seal materials to withstand the surficial shear forces. The 'Test B' in Table 3 is an excellent candidate to assess the resistance of pavement surface to raveling (samples are saturated) as well as for rutting (test is at high temperature). The tests shown in Table 3 have been slightly revised in this study to better evaluate the performance of different slurry seals.

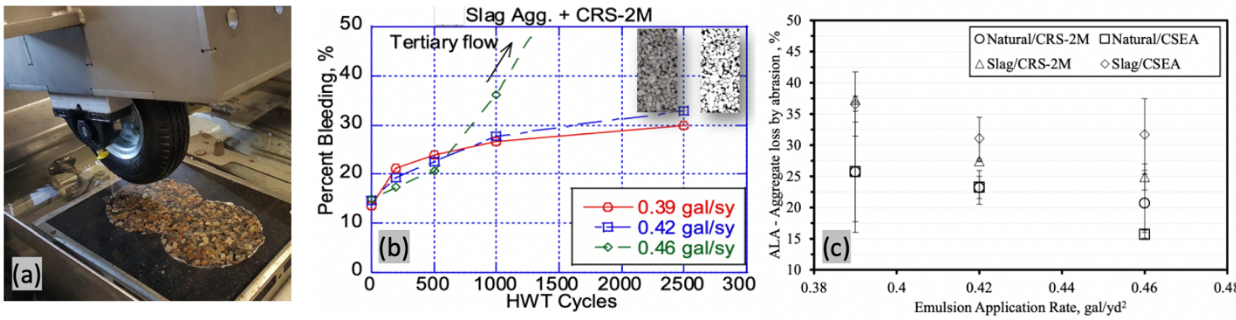



**Figure 13. (a) A picture of the modified HWT device for chip seal abrasion and bleeding testing, (b) an example bleeding data and (c) abrasion (aggregate loss) data.**

**Table 3: Modified Hamburg Wheel Tracking (HWT) test configuration for pavement preservation treatments**

| Test | Purpose of assessment | Tire pressure | Tire Load | Test Temp. | Water | Wheel Config. | Number of HWT Cycles |
|---|---|---|---|---|---|---|---|
| A | Abrasion resistance (Aggregate loss for chip seals) | 34 psi | 125 lbs | 19°C | Dry | Locked (slipping) | 10 (20 passes) |
| B | Bleeding (for chip seals), raveling/rutting (all others) | 34 psi | 125 lbs | 54°C | Wet (saturated) | Rolling | 2500 (5000 passes) |

## 2.4 Use of Recycled Asphalt Pavement (RAP) in Slurry Seals and Micro-surfacing

Several researchers investigated the use of RAP in slurry seals (Poursoltani and Hesami, 2018a; ROBATI et al., 2013a; Saghafi et al., 2019a). Saghafi et al. [29] evaluated the performance of the slurry seal mixtures with cement and hydrated lime as fillers. In the research, they tested two types of slurry seal made with virgin aggregate and RAP respectively by using wet track abrasion test and loaded wheel test. They also conducted wet cohesion as well as wet friction tests (sand patch and British pendulum tests on WTAT samples) and observed that RAP can successfully be used in slurry seals for the materials they considered in their studies. They also showed that the use of RAP decreased the slurry seal material cost by about 14% and has a better overall performance. Robati et al. [27] tested slurry seal mixtures made with RAP as well as Recycled Asphalt Shingles (RAS) by using cohesion, wet track abrasion, and loaded wheel displacement tests and concluded that it is possible to prepare micro-surfacing with 100% RAP, whereas a limit of 17% was suggested for the use of RAS with virgin aggregates and 10% RAS was suggested if mixed with 90% RAP in micro-surfacing. Wang et al. [1] performed a study to develop a modified mix design methodology for micro-surfacing made with 0%, 20%, 40%, 60% and 80% of RAP. They suggested several performance tests such as mixing conditioning, moisture susceptibility, shear resistance and skid resistance tests. They showed that the optimum asphalt binder content decreases when the amount of RAP increases in use. They also indicated the possibility of using 100% RAP in micro-surfacing. Garfa et al. [6] evaluated fine grained and coarse-grained micro-surfacing mixtures made with 100% RAP using loaded wheel test, modified cohesion test and wet track abrasion test. They found that all mixtures they tested required more time than what is specified in the ISSA specifications to reach to a good internal cohesion. Poursoltani and Hasemi [25] tested three different RAP contents in micro-surfacing, namely 100%, 69% and 43%. They showed that all these mixtures met the ISSA guidelines. They also showed that the mixtures with RAP needed about 1% more binder to obtain sufficient cohesion, whereas they needed lower amounts of additives (to increase mixing time and workability), and the application of RAP-containing micro-surfacing mixture can reduce the overall material cost. The research also concluded that the RAP-containing mixtures have a higher resistance to flushing distress and the micro-surfacing mixtures with 69% RAP have the best performance.

## 2.5 Synthesis of the Previous Work Motivations of the current study

The literature review indicated that use of recycled asphalt pavements is quite possible in micro surfacing applications. However, there is limited studies on slurry seals and most of the past studies used traditional ISSA tests to evaluate the materials. One of the major drawbacks of the traditional ISSA tests is that they are quite empirical in nature and there are many questions about how well they represent the field conditions under realistic tire loading. There is a need for developing more realistic testing methods to evaluate the field performance of slurry seals more thoroughly. While this is an important need, the cost of new testing methods should also be considered. The Hamburg wheel tracking (HWT) device has traditionally been used to evaluate hot mix asphalt pavements with respect to rutting and moisture damage (raveling). Modified versions of HWT were also used in the literature to evaluate pavement preservation methods such as the chip seals. Given the abundance of HWT device in many academic institutions, industry labs and state DOT labs, the use of realistic loading offered by the HWT device is a promising alternative to evaluate the slurry seals.

# 3 OBJECTIVES AND RESEARCH PLAN

The objectives of this study are summarized below:

1. Investigate the feasibility of integrating 100% RAP amount into slurry seals as direct replacement to Type II natural aggregate
2. Compare the performance of slurry seals containing RAP with that of Type II natural aggregate
3. Develop recommendations for RAP contents suitable for incorporation into slurry seals.
4. Evaluate the effects of emulsion type on the performance of the slurry seals

To meet the objectives listed above, a comprehensive experimental program was undertaken to assess the performances of several kinds of slurry seal samples. The testing program included the traditional slurry seal tests and the more advanced evaluation methods using the Hamburg Wheel Tracking (HWT) device. The experimental program of this study can be grouped into the following three categories:

1) Traditional ISSA tests
2) Evaluation of abrasion resistance using Hamburg Rolling Wheel (HRW) test.
3) Evaluation of raveling and rutting resistance using Hamburg Locked Wheel (HLW) test.

Figure 14, Figure 15 and Figure 16 show the detailed testing plans for each of the groups above

**Traditional ISSA Tests**

- **Construction-related Tests**
  - **Mix-Time test**
    - **2 samples at each aggregate type**
  - **Consistency test**
    - **2 samples at each aggregate type**
  - **Cohesion test**
    - **2 samples at each aggregate at 15, 30, 60, 90, 120 and 240 minutes curing time**
    - **Additional test with modified mix formula**
- **Performance Tests**
  - **Wet-Stripping Test**
    - **3 samples at each aggregate type**
  - **Wet-Track Abrasion Test**
    - **2 samples at each aggregate type with two soaking period**
  - **Classification Compatibility Test**
    - **4 samples at each aggregate type**
- **Test Material**
  - **Type II virgin aggregate**
  - **RAP aggregate meet Type II gradation**
- **Additional Measurements**
  - **RAP aggregate binder content**
  - **Gradation of RAP aggregate with and without binder**
  - **Gradation of virgin aggregate**

**Figure 14 Test plan for the traditional ISSA tests**

**Hamburg Rolling Wheel Tracking (HRWT) Test**

- **Characteristics**
  - Slurry seal loss under load
  - Application force produced by rubber tire
  - Two samples to minimize variability
- **Test Layout**
  - Rubber Tire with pressure at 35psi
  - Test at high temperature (54℃)
  - Constant force loaded on tire = 125 lbs (ASTM D6372)
  - Test under wet (saturated) and dry condition
  - Total at 2500 HWT cycles with stops at 200, 300, 500 and 1000 cycles
- **Test Matrix**
  - Application rate
    - 10 lb/yd2 (58mm 5E3 AC base)
    - 18 lb/yd2 (55mm 5E3 AC base)
  - Emulsion
    - LM-CQS in all test samples
  - Two replicates respect to each application rate and aggregate material
  - Aggregate Materials
    - Type II virgin aggregate
    - Recycled Asphalt Pavement (RAP) satisfied with type II gradation specification
- **Test Output**
  - Slurry seal material loss (g/ft2)
  - Visual results to percentage asphalt coating(%)
  - Rutting depth (mm)

**Figure 15. Hamburg rolling wheel (HRW) test plan**

**Hamburg Locked Wheel Tracking (HLWT) Test**

- **Characteristics**
  - Aggregate loss under abrasion
  - Friction force from rubber tire tread
  - Two samples to minimize variability
- **Test Layout**
  - Rubber Tire with pressure at 35psi
  - Test at laboratory temperature (23℃)
  - Constant force loaded on tire = 125 lbs (ASTM D6372)
  - Test under dry condition (no moisture encounter)
  - Total at 55 HWT cycles
- **Test Matrix**
  - Application rate
    - 10 lb/yd2 (58mm 5E3 AC base)
    - 18 lb/yd2 (55mm 5E3 AC base)
  - Emulsion
    - LM-CQS in all test samples
  - Two replicates respect to each application rate and aggregate material
  - Aggregate Materials
    - Type II virgin aggregate
    - Recycled Asphalt Pavement (RAP) satisfied with type II gradation specification
- **Test Output**
  - Slurry seal abrasion loss (g/ft2)
  - Percentage loss by abrasion (%)

**Figure 16. Hamburg locked wheel (HLW) test plan**

# 4 MATERIALS AND METHODS

## 4.1 Aggregates

Aggregate properties (e.g., the morphology, reactivity, cleanliness, and soundness) can significantly affect the performance of slurry seals [8]. The unwanted moisture and deficient aggregate gradation can be detrimental to the stability of the mixture in the field [4]. Type II aggregate gradation limits based on ISSA guidelines are illustrated in Table 4. In this study, two different types of aggregates were used: (i) virgin aggregates and (ii) 100% recycled asphalt pavement (RAP) aggregates. The gradation of the aggregates in RAP was determined via direct sieving (as received from the stockpile) and sieving after burning out all the binder using the NCAT ignition oven test (Figure 17). The gradations of the RAP aggregate with/without binder and the Virgin Aggregate are shown in Table 5 as well as in Figure 18, Figure 19 and Figure 20. It is noted that the asphalt binder content of the RAP was 5.76% by weight of the dry aggregates and the RAP aggregate has a gradation close to the lower limit of ISSA guidelines.

**Figure 17 NCAT ignition oven**

**Table 4 Type II ISSA aggregate gradation limits for micro-surfacing and slurry seals**

| Sieve Size | | Proportion Passing (% by mass) | | Stockpile Tolerance, % |
|---|---|---|---|---|
| | | Type II | | |
| In | mm | Lower Limit | Upper Limit | |
| **3/8** | 9.500 | 100 | 100 | +/-5 |
| **No.4** | 4.750 | 90 | 100 | +/-5 |
| **No.5** | 2.360 | 65 | 90 | +/-5 |
| **No.6** | 1.180 | 45 | 70 | +/-5 |
| **No.7** | 0.600 | 30 | 50 | +/-5 |
| **No.8** | 0.300 | 18 | 30 | +/-5 |
| **No.9** | 0.150 | 10 | 21 | +/-5 |
| **No.10** | 0.075 | 5 | 15 | +/-5 |

**Table 5 Gradation of RAP, RAP_No Binder Virgin Aggregate**

| Sieve Size | Type II Percent Passing | RAP_1 | RAP_2 | RAP_No Binder | Virgin Aggregate |
|---|---|---|---|---|---|
| **3/8** | 100 | 100 | 100 | 100 | 100 |
| **#4** | 90-100 | 93 | 92 | 93 | 99 |
| **#8** | 65-90 | 66 | 57 | 65 | 74 |
| **#16** | 45-70 | 46 | 36 | 47 | 54 |
| **#30** | 30-50 | 31 | 21 | 34 | 39 |
| **#50** | 18-30 | 15 | 9 | 21 | 21 |
| **#100** | 10-21 | 7 | 3 | 11 | 11 |
| **#200** | 5-15 | 3 | 1 | 6 | 6 |

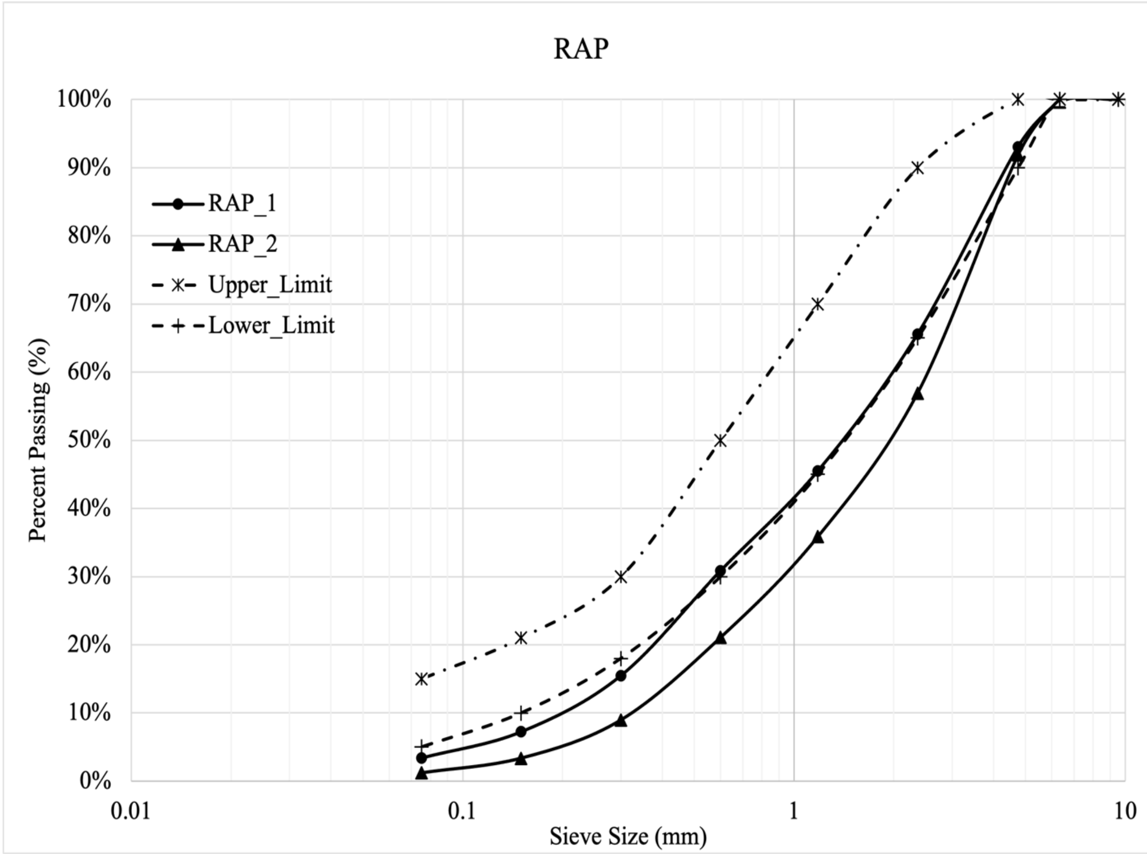



**Figure 18 Gradation of RAP aggregate (covered with binder – as it was received from the RAP stockpile)**

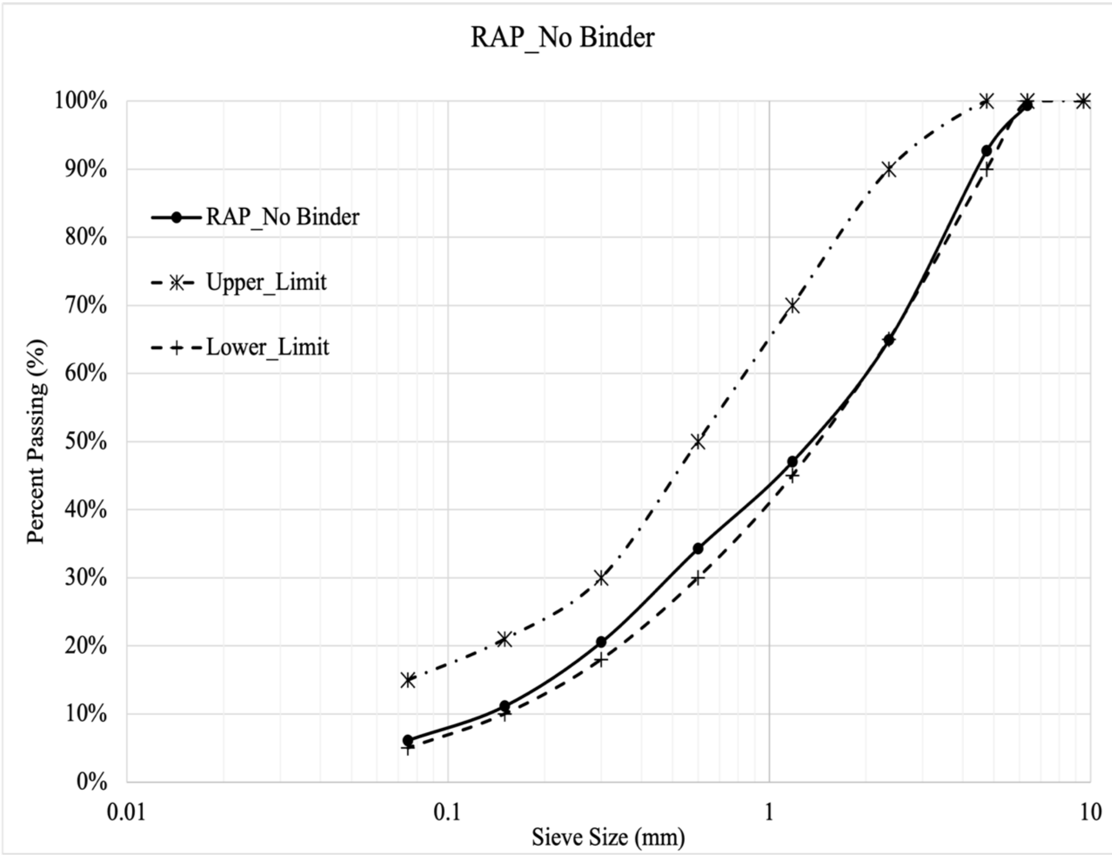



**Figure 19 Gradation of RAP aggregate without binder (after burning out the binder from the surface of the RAP aggregates)**

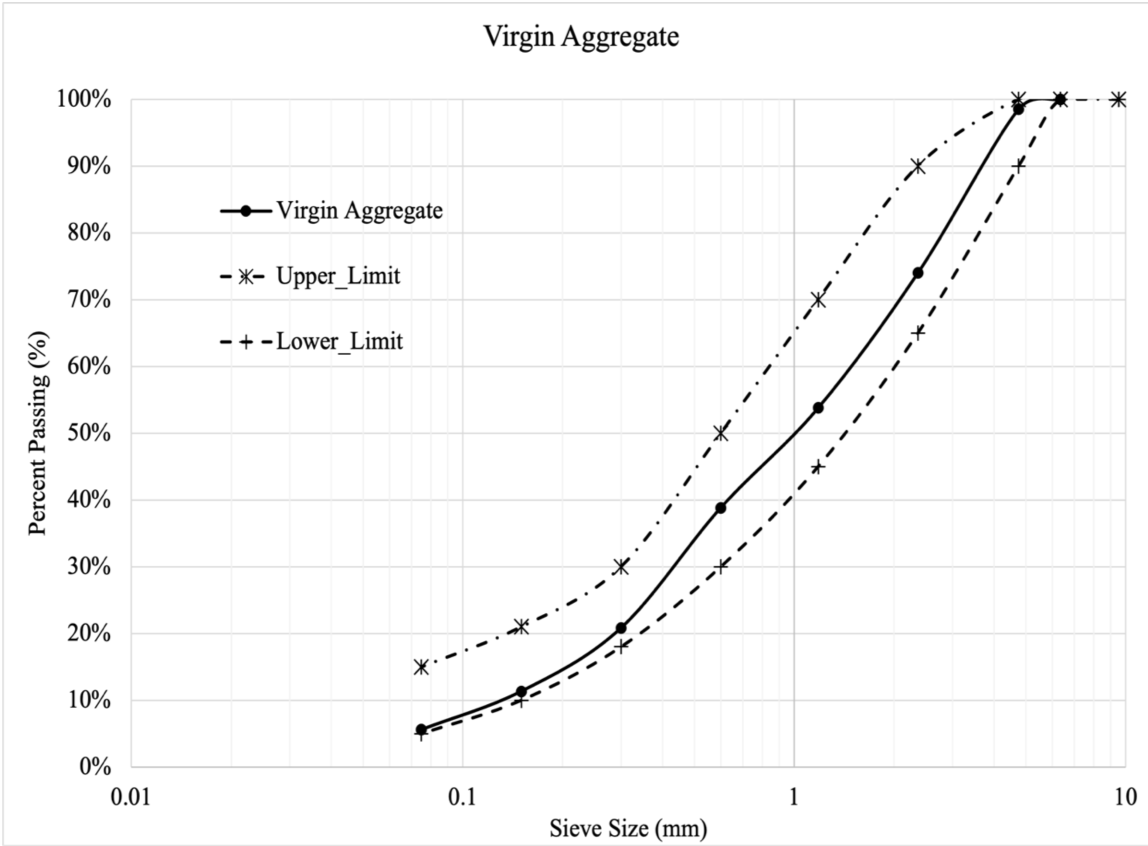



**Figure 20 Gradation of Virgin aggregate without binder**

## 4.2 Asphalt Emulsion

Asphalt emulsion is the mixture of water and asphalt binder and is essential to have a certain level of stability and viscosity [9]. Based on the emulsion characteristics, it can be categorized into anionic, cationic, amphoteric and nonionic. The primary ingredients used while manufacturing the asphalt emulsion are water, asphalt binder, diluents, fluxes, surfactants, reactants and additives [2].

- ***Asphalt binder:*** Asphalt binder is the component that forms 50-70 percent of an emulsion product.

- ***Diluents and Fluxes:*** Diluents and fluxes are solutes used to improve the properties of the neat asphalt in emulsification procedures. It can help the asphalt colloids to be homogeneously distributed within the emulsion.
- ***Water:*** Water in the asphalt emulsion acts as a solvent to provide an environment where all ingredients interact and mix. Water quality can affect the performance of slurry seal mixture and may cause premature braking in asphalt emulsion. It is noted that the magnesium and calcium ions can react with some types of emulsifiers and form compounds with no emulsifying properties.
- ***Surfactants:*** Surfactant, also known as surface active agent or emulsifier, lowers the interfacial or surface tension and generates a stable surface for the mixture.
- ***Reactants:*** The function of reactant in an emulsion is to provide the solubility to the emulsion and give it a hydrophilic property. A reactant is regulated by generating a desired final emulsion pH. If the asphalt emulsifier is cationic, typically hydrochloric acid is used. On the other hand, if the asphalt emulsifier is anionic, a Sodium hydroxide or Potassium hydroxide is generally used.

The type of emulsion that was used in this study was LM-CQS. The name of the emulsion represents its basic behavioral properties. LM-CQS represents that the emulsion being used in this study is a latex-modified cationic quick-set asphalt emulsion [30].

## 4.3 Slurry seal application rates

The slurry seal is applied as a single layer on a roadway surface. The performance of the slurry seal layer is highly associated with the thickness of the layer, which is influenced by the NMAS (Nominal Maximum Aggregate Size) of the aggregate used in the mixture. Table 6 shows the typical application rates used in the slurry seal applications, which were also evaluated in this study. In a designed application rate, the aggregates in a slurry seal mixture should be uniformly mixed with asphalt emulsion during preparation and construction. It is not qualified when having aggregates directly exposed from the slurry seal mixture with no binder covering the surface.

**Table 6 Application rates used in this study**

| Material | Application Rates (lb/yd2) | | |
|---|---|---|---|
| | Rate 1 | Rate 2 | Rate 3 |
| 100% RAP | 10 | 15 | 18 |
| Type II aggregate | 10 | 15 | 18 |

## 4.4 Traditional ISSA tests

The following traditional tests were performed in this study to obtain the basic characteristics of the slurry seal samples tested: residual binder content, mix time, cohesion, consistency, wet-abrasion, wet-stripping, integrity/compatibility. The mixing time, cohesion and consistency tests provide information about the constructability of the slurry seal mixture. On the other hand, wet track abrasion, wet stripping and integrity of the slurry seal are thought to relate to the field performance under the traffic load after construction.

### *4.4.1 Residual binder content test by using ignition oven*

The residual binder content in the reclaimed asphalt pavement (RAP) is used in adjusting the proportion of emulsified asphalt. The lower and upper limits of the asphalt content in a slurry seal mixture are suggested by ISSA A105[11] and shown in Table 8. The steps of the ignition oven test are presented below:

- Step-1: Prepare 3000 to 5000 grams of reclaimed asphalt pavement (RAP)

- Step-2: Measure the exact weight of the RAP sample before the test and then put it in the ignition oven tray.
- Step-3: Gently spread the material and be sure to have 1 inch distance from the edge of the tray.
- Step-4: Place the container in the ignition oven and start the operation.
- Step-5: When the test is done, remove the sample from ignition oven (be very careful while handling the tray since it is extremely hot).
- Step-6: Record the weight of the material after the test and use the equation below to calculate the percentage of asphalt binder.

$$Binder\ Content(\%) = \frac{Wt.Before\ Test - Wt.After\ Test}{Wt.After\ Test} \times 100 \qquad \textbf{Equation 1}$$

**Table 7. Ignition Test Data**

| Weight Before Test (gram) | Weight After Test (gram) | Percentage of Binder Content (%) |
|---|---|---|
| 2266 | 2142.5 | 5.76 |

**Table 8. Component Material Suggested Limits**

| Component Materials | Suggested Limits |
|---|---|
| Residual Asphalt | Type I: 10 - 16%<br>Type II: 7.5 – 13.5 %<br>Type II: 6.5 – 12 %<br>(Based on dry weight of aggregate) |
| Mineral Filler | 0.0 – 3.0%<br>(Based on dry weight of aggregate) |
| Additives | As needed |
| Water | As required to produce proper mix consistency |

### 4.4.2 *Mix Time of Slurry Seal*

Mix time of a slurry seal material shows how fast the material is going to harden under the room temperature (25°C or 77°F). This test relates to the workability of the slurry seal during construction. As the mixing time increases, the mixture workability increases. The mix time test was performed in accordance with the ISSA TB 113 test method, by stirring the freshly mixed slurry seal sample continuously for 5 mins. The minimum hardening time based on the ISSA A105 specification is 180 seconds. In this test, the dry weight of the aggregate in a sample should be between 100 and 400 grams to minimize the aggregate segregation. Figure 21 shows the components of the slurry seal mixing time test. Three samples of each material were performed under this test, which is six in total (three samples for RAP aggregate, three samples for Type II virgin aggregate). The steps of the mix time test are illustrated in Figure 22 and listed as follows:

- Step-1: Measure 100 to 400 grams of dry aggregate.
- Step-2: Mix the aggregates with Portland cement and stir until the distribution is uniform.
- Step-3: Add the desired amount of water and Aluminum Sulfate.
- Step-4: Mix the sample at a rate of 60-70 rpm in circular motion for 20 seconds before adding the asphalt emulsion.
- Step-5: Mix with asphalt emulsion at 60-70 rpm in circular motion for 30 seconds immediately after mixing with the water.
- Step-6: After 30 seconds of mixing with asphalt emulsion, pour half of the mix onto the paper, aluminum foil, or roofing felt and continue mixing the rest material in the container until it stiffens and “breaks”, or 5 minutes in maximum.

- Step-7: The time when the material stiffens is recorded as the test result.

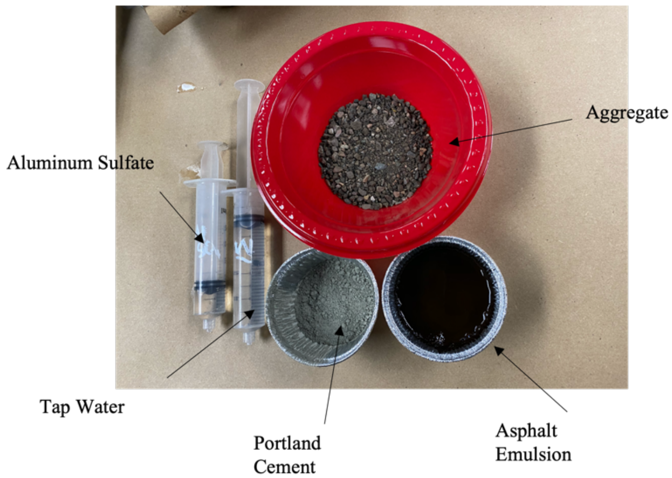



**Figure 21. Components of the slurry seal mix time (ISSA TB 113) test**

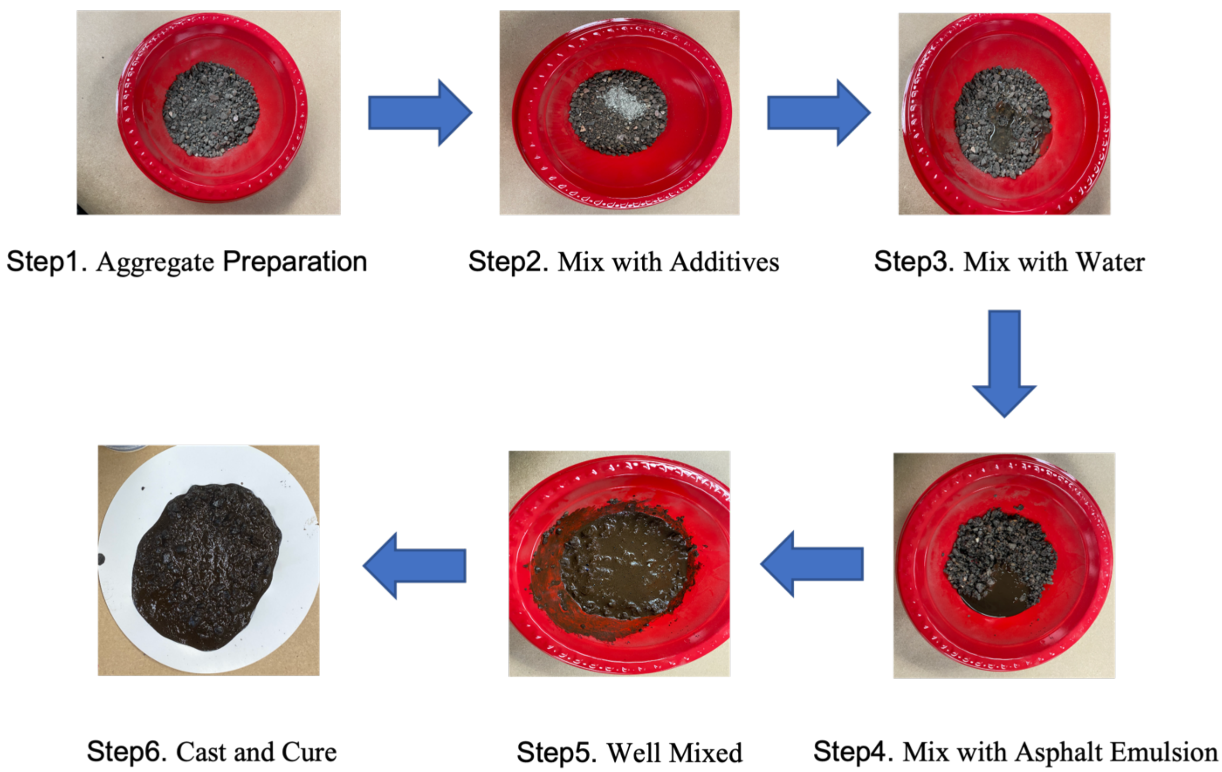



**Figure 22. Mix-time test procedures**

### *4.4.3 Consistency Test*

The consistency test (ISSA TB106) is conducted to quantify the flow characteristics of a slurry seal mixture. As the slurry seal is a cream-like fluid material, the consistency of a slurry seal determines the stability when casting on the pavement. The large consistency number indicates that the slurry seal flows too fast and is not sticky enough to hold the aggregates together. In such a case, it can easily flow and cause significant thickness reduction after the cast. The same sand cone in ASTM C 128 or AASHTO T 84 is used (see Figure 23) in the test. This study tested two replicates of each aggregate materials (RAP and Type II virgin aggregate) to evaluate the slurry seal mixture consistency. The steps of this test are summarized as follows:

- Step-1: Prepare a slurry seal mixture with proportions determined based on the results of the mixing time test (ISSA TB113). The amount of the slurry seal mixture should be based on 400 grams of dry aggregate weight.
- Step-2: Place the large side of the cone at the center of the flow scale (see Figure 23).
- Step-3: Pour the slurry seal mixture into the cone through the small opening immediately after 30 seconds of mixing until the cone is topped off.
- Step-4: Lift the cone smoothly in the vertical direction to avoid any disturbance.
- Step-5: After sample spreads on the consistency template paper, record the diameter of the slurry seal at four points with 90 degrees apart (see Figure 24). The average value is calculated and recorded as the designed slurry seal consistency result.

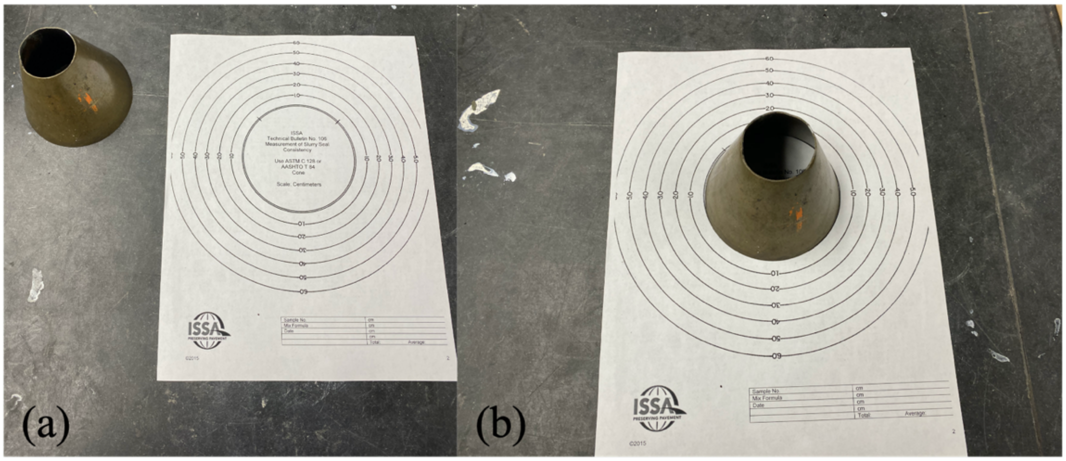



**Figure 23. Consistency test set-up**

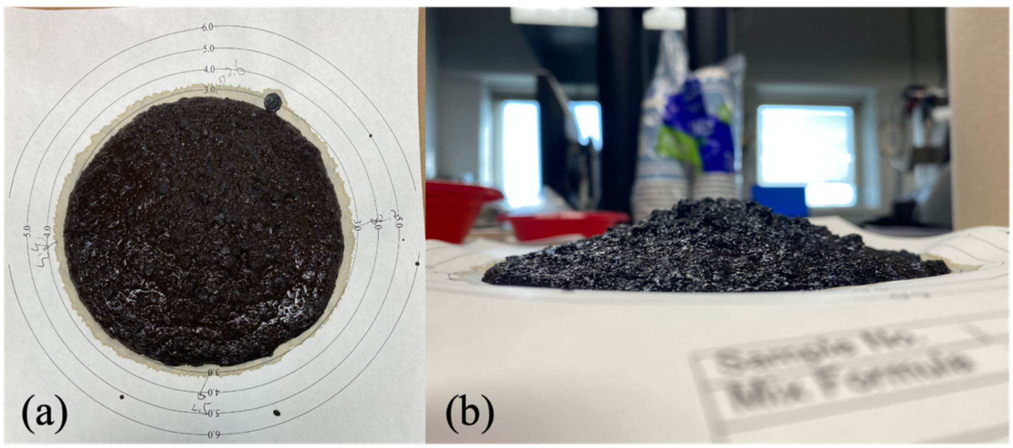



**Figure 24. (a) Illustration of spreading of the slurry seal sample and (b) side-view of the slurry seal 'clump'**

### *4.4.4 Cohesion Test*

The cohesion test (ISSA TB139) allows the determination of the development of the initial set-time and the cure condition in a slurry seal layer system. In the cohesion test, the cohesion tester machine (shown in Figure 25) was used with 100 psi (700 kPa) air supply to achieve sufficient load (1000 kg or 2204 lbs) on the slurry seal material. A torque meter shown in Figure 4 is used to measure the torque applied to the sample. When the neoprene foot is lowered on to the slurry seal sample surface under 200 kPa air pressure, the torque meter is manually rotated at a horizontal direction to generate load. To determine the set time and the cure condition of a slurry seal, the test is performed at a list of curing time: 15mins, 30mins, 60mins, 90mins, 120mins and 240 mins. At each time, the torque resistance is measured by the torque meter. The 6mm thick ring mold was used since the material gradation follows Type II aggregate distribution.  The tests were done by two times at each period for each aggregate material (RAP and Type II virgin aggregate). The overall steps of the cohesion test are shown as below:

- Step-1: Prepare an appropriate amount of slurry seal material with the mixture formula determined based on the mixing time and consistency tests.
- Step-2: Cast the material into the mold after 30 seconds of mixing. The surface of the cast should be smoothened by a spatula within 75 seconds from the time of mixing started (see Figure 26).
- Step-3: Remove the ring mold when the mixture is firm enough.
- Step-4: Prepare the tester and set the air pressure to 200kPa (29psi) (see Figure 27).
- Step-5: Lower the foot of the cohesion tester and after 5-6 seconds of contact, apply the torque by torquemeter manually at a rate of 90 to 120 degree arc within 0.5 to 0.7 seconds.
- Step-6: Read the torque meter and record the mode of rupture in accordance with the standard illustrated in Figure 28.

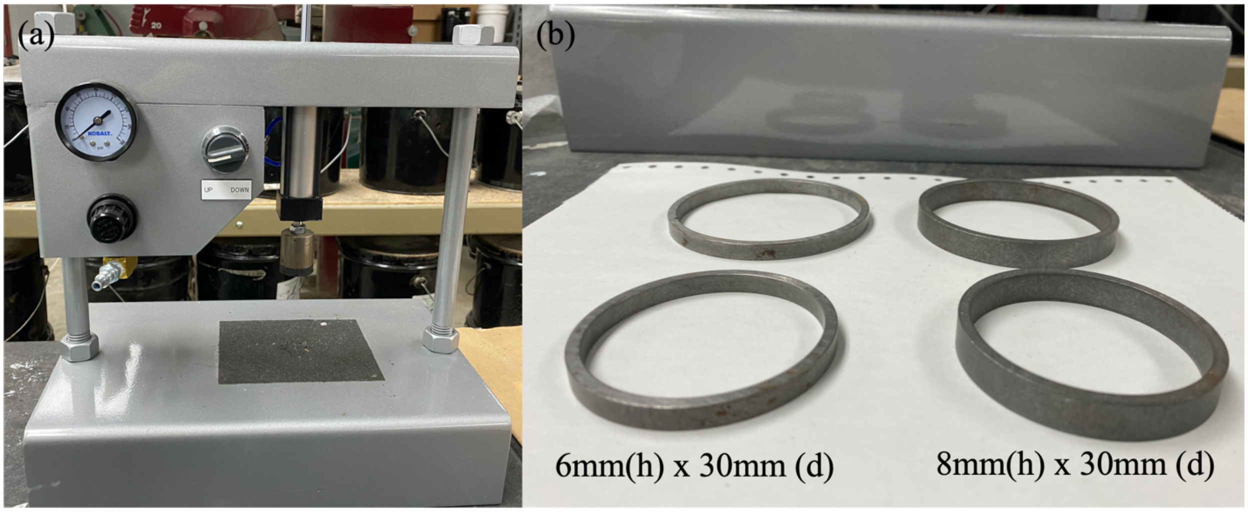
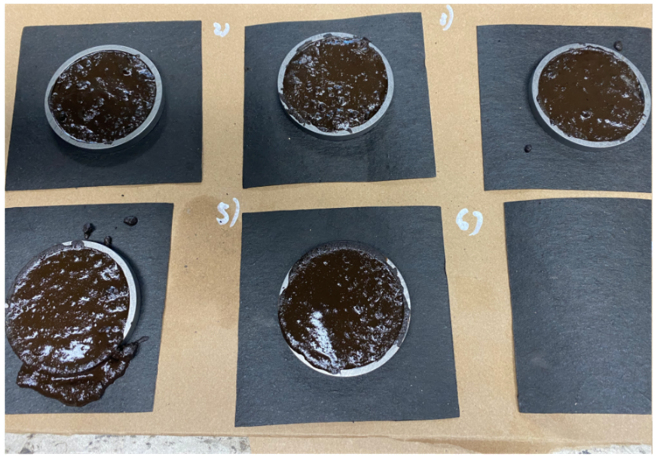
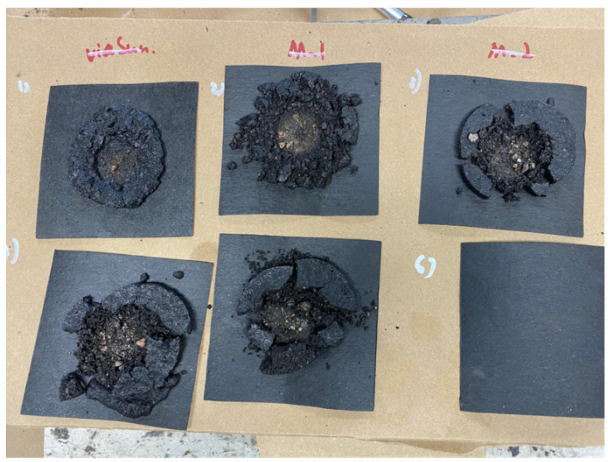


**Figure 25. (a) Cohesion tester and (b) mold rings**



(a)



(b)

**Figure 26. Slurry seal samples (a) before and (b) after the cohesion test.**


**Figure 27. Gauge pressure set-up**

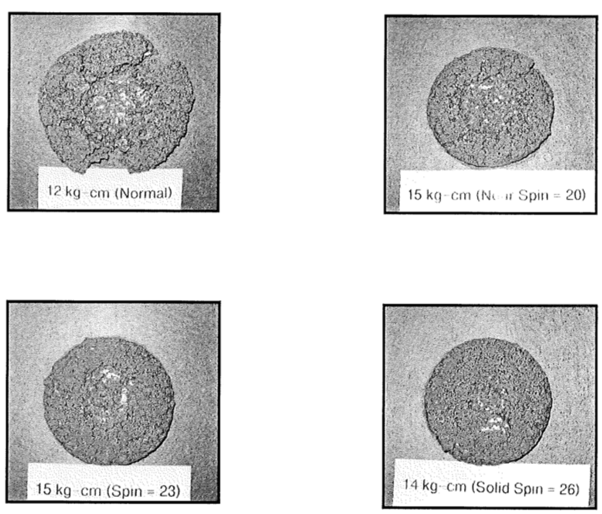



**Figure 28. Cohesion test standard modes of rupture**

### 4.4.5 *Wet Track Abrasion Test*

The wet track abrasion test measures the resistance of abrasion under wet condition. To obtain the analytical results, the test was performed by an N-50 WTAT tester as shown in Figure 6. Four tests were done in the study with two times on each material at two different soaking periods. It is noted that the asphalt emulsion used in this study is a quick-set emulsion and the sample should only be mixed for 30 seconds before casting while three minutes maximum for other types of emulsions. The steps of the wet track abrasion test are listed below:

- Step-1: Prepare the slurry seal material based on at least 600 grams of dry aggregate weight.
- Step-2: Pour the mixture into the mold within 30 seconds from the start of the mixing and smoothen the surface by using a spoon or spatula (see Figure 29).
- Step-3: Remove the mold when the mixture is stiff enough to be handled. Within three hours of casting, place the sample in the oven at 60°C (140°F) $\pm$ 3°C (5.4°F) and dry for a minimum of 15 hours but no longer than 30 hours.
- Step-4: Remove the sample from the oven after drying and allow it to cool to room temperature. Record the dry sample weight.
- Step-5: Place the sample in 25°C (77°F) $\pm$ 3°C (5.4°F) water bath for test preparation. When performing the one-hour test, the sample is soaked for 60 to 75 minutes and, in the six-day test, the sample is submerged under water for six days and the test should be performed at the 2 hours of the end of the six-day soaking period.
- Step-6: Place the prepared sample in the abrasion tester and clamp the sample to the pan and mounting plate tight (see Figure 30).

- Step-7: Lock the rubber hose and lower the hose to contact the sample. Set the speed to the lowest setting of the abrasion test machine.
- Step-8: After the test, place the sample into 60℃ (140℉) ± 3℃ (5.4℉) oven for drying. Weight and record the weight remained. The abrasion loss value is the weight difference before and after the test.

Mixture Preparation

Sample cast and smoothening

Oven dry at 60 ℃
for 15-30hours

**Figure 29. Sample preparation steps for the WTAT**

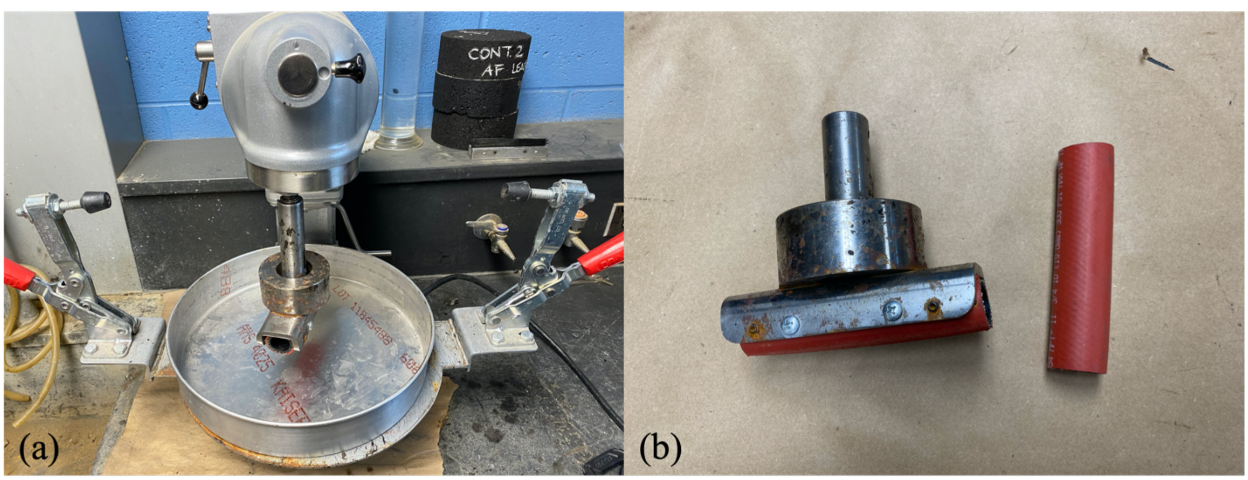



**Figure 30. (a) WTAT device N-50 Hobart model and (b) rubber hose used to abrade the surface**

### 4.4.6 *Wet-Stripping Test*

The wet-stripping test (ISSA TB 114) is a boiling test that measures the strength of adhesion between the asphalt binder and the aggregates and determines the resistance of the cured slurry seal sample to the test condition. The listed steps are followed to run the wet-stripping test:

- Step-1: Prepare 10 ± 1 grams of cured (hardened) slurry seal mixture (after minimum 24 hours of curing at room temperature).
- Step-2: Place the slurry seal sample into a beaker filled with demineralized or distilled water.
- Step-3: Heat the water in the beaker till it starts boiling vigorously.
- Step-4: Place the prepared slurry seal sample directly into the boiling water.
- Step-5: After 3 minutes of boiling, remove the beaker from the heat source and allow to stand for 1-2 minutes.
- Step-6: Gently flow cold tap into the beaker till the free parts are washed off.
- Step-7: Remove the sample from water and measure the weight after air drying for 24 hours.

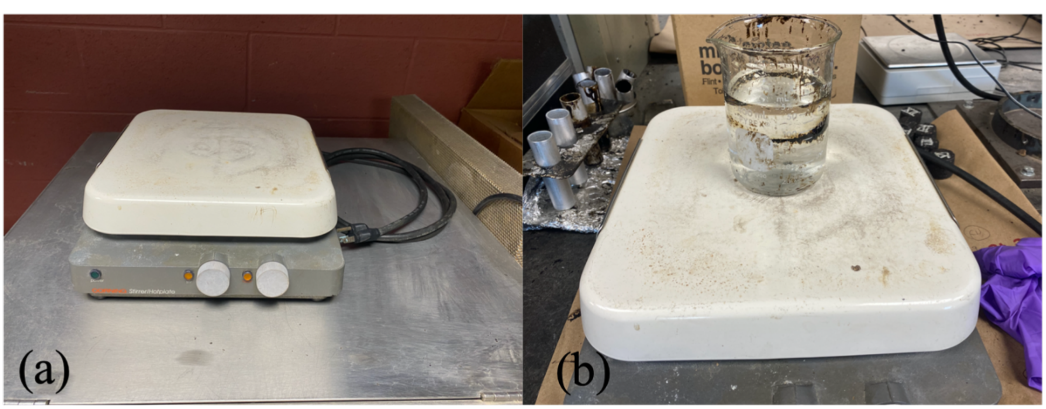



**Figure 31. Heating device(a) and test set-up(b)**

### 4.4.7 *Compatibility Test*

The compatibility test (ISSA TB 144) determines the compatibility between aggregate fines and the asphalt residue. The sample of the compatibility test is prepared by the pill compressor machine (Figure 33) and the entire test is composed of four sub-tests (absorption, abrasion, integrity and adhesion) that are explained in ISSA TB144 standard [19] and Ch 2.3.4. The sample preparation and the test procedures are described below.

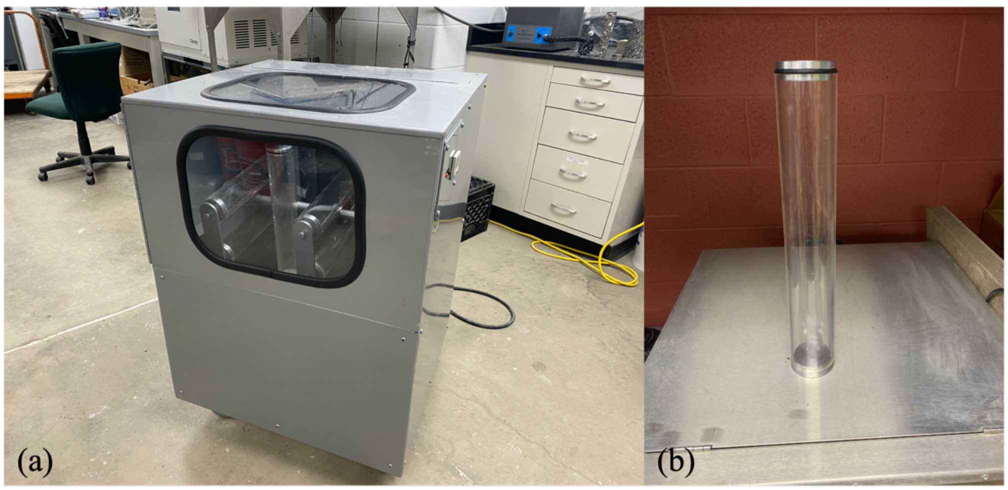



**Figure 32. Schulze-Breuer device(a) and test tube(b)**

- Sample preparation:
    - Step-1: Prepare slurry seal mixture using 200 grams of dry aggregate and break the cured sample on an aluminum foiled pan.
    - Step-2: Air dry the material for one hour and place the sample in oven with 60 ℃ (140°F) till it dries to constant weight.
    - Step-3: Separate the samples into small parts with 40 $\pm$ 1 grams each and place them into oven at 60 ℃ (140°F). Place the compaction molds in the oven to ensure their temperatures are also 60 ℃ (140°F).

- Step-4: Place the separated sample into the mold and compress the sample by using the pill compressor. Then wait till the pill cools to laboratory temperature.

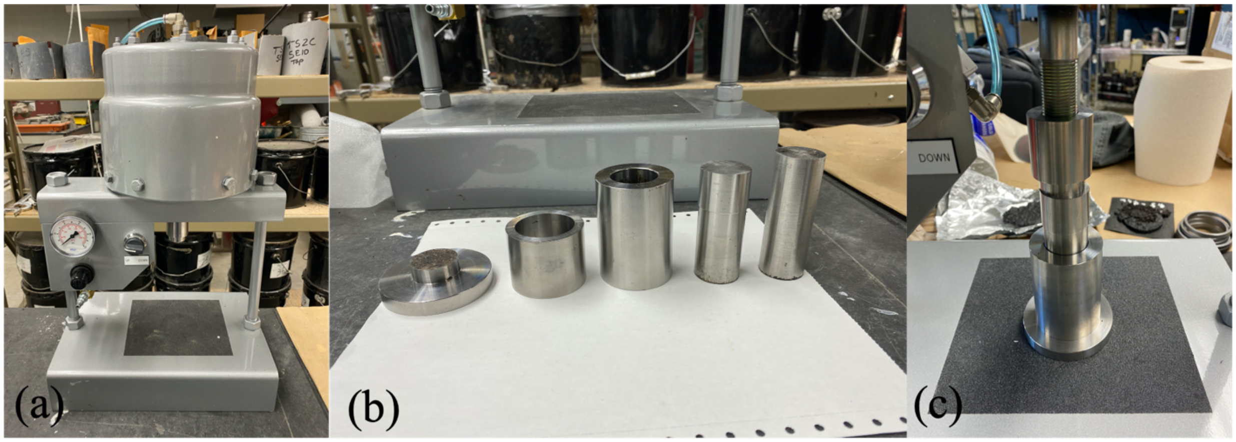



**Figure 33. (a) Pill compressor, (b) compaction molds and (c) pill preparation**

- Absorption test

The absorption test measures the air voids in a sample pill and the absorption rate in a cured slurry seal sample when exposed to moisture. The test steps are summarized below:

- Step-1: Clean the sample pill and remove the loose particles on its surface before submerging the sample. The sample is soaked in water for 6 days at 25°C by using the water conditioner as shown in Figure 34.
- Step-2: After six days of soaking period, use paper towel to gently surface dry the sample pill and measure the saturated weight.

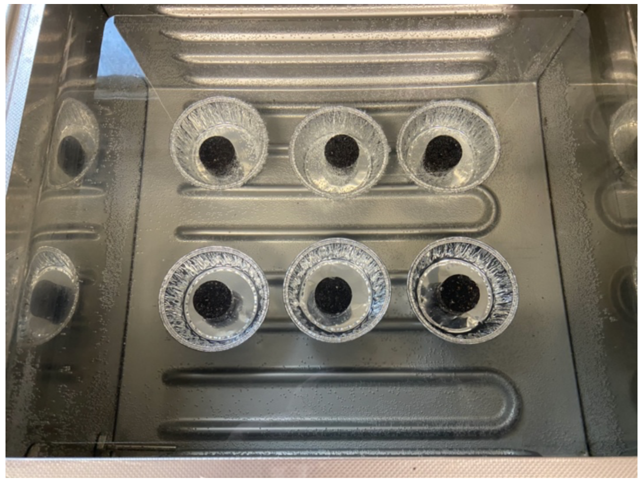


**Figure 34. Compatibility Test 6-Day Soaking**

- Abrasion test

The abrasion test evaluates the cohesion strength between aggregate and asphalt content when subject to collide impact. It is noted that the abrasion from compatibility test differs from the abrasion from WTAT test based on the mechanism of loaded force. The test steps are shown under:

  - Step-1: Fill the shuttle cylinder in the Schulze-Breuer machine (see Figure 35) with 750ml $\pm$ 25ml of water. The volume of the water is estimated by using the density (1g/ml) and measured the weight of the water filled in the shuttle cylinder.
  - Step-2: Place the sample pill from the previous test (Absorption test) and operate the machine at the rate of 20RPM for 3600 cycles.
  - Step-3: Remove the pill from the cylinder after the test is completed and use paper towel to surface-dry the pill.
  - Step-4: The weight difference before and after the abrasion test is used to calculate the abrasion loss of the slurry seal sample.

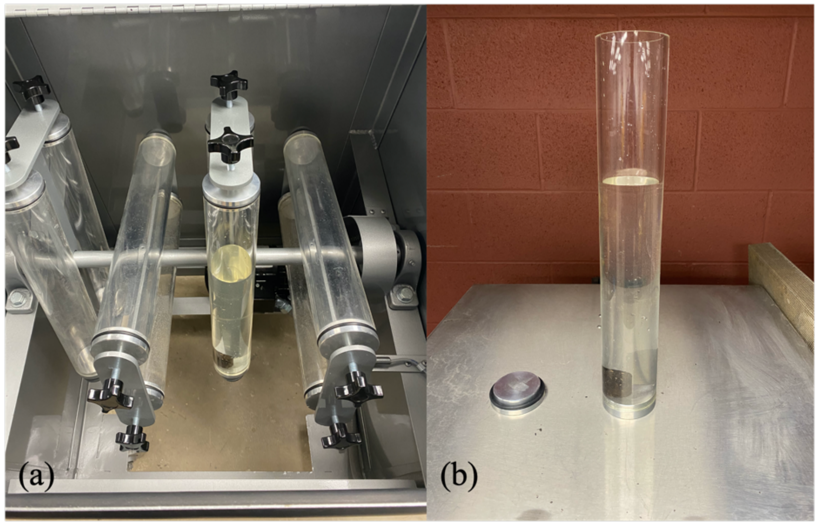


**Figure 35. Compatibility Test Abrasion Test Setup**

- Integrity test

The integrity test was performed by exposing the pill to boiling water for 30 minutes. The experimental setup is illustrated in Figure 36. The metal container directly contacts with the boiling device and the beaker functions as a barrier that holds the aluminum foil cup, at which the pill is placed. Several holes were drilled at the bottom of the foil cup to let the air bobbles move through and generate an effect similar to the suspended basket. General steps are as follows:

- Step-1: Place the sample pill from the previous test (saturated and abraded pill) in the equipment set shown in Figure 36 to boil the sample for 30 minutes.
- Step-2: Place the boiled pill on a paper towel and weigh the largest part remained after the boiling test.
- Step-3: Calculate the integrity by using the saturated surface dry weight recorded in the absorption test and the largest part remained after boiling.

**Figure 36. Compatibility Test Integrity Test Setup**

- Adhesion test

In the adhesion sub-test, the sample piece from the previous test is air dried and the percent aggregate coated with asphalt is estimated.

**Figure 37. Sample after test (left) and before test (right)**

## 4.5 Hamburg Wheel Tracking Tests

Although traditional tests were developed based on experience and meet their purpose for mix design, there have always been concerns over these tests as to how well they represent the field conditions. The Hamburg wheel tracking (HWT) device has been used by the academia, industry, and state DOTs to assess the susceptibility of asphalt mixtures to moisture damage and rutting. In this study an innovative approach was used to test the slurry seal samples using the HWT device. The goal was to use the HWT device to assess the properties of slurry seal mixture in terms of raveling (moisture damage), rutting and surface abrasion.

The HWT device was retrofitted with a rubber tire with 35 psi pressure and two different tests were performed:

- Hamburg Rolling Wheel (HRW) test at high temperature to assess the potential for raveling (moisture damage) and rutting
- Hamburg Locked Wheel (HLW) test at intermediate temperature to assess the abrasion resistance

### *4.5.1 Sample preparation*

In this study, both HRW test and HLW test use the substrate produced by the 5E3 loose mixture and the amount of slurry seal mixture is applied on the top of the substrate based on the application rate. The substrate of the Hamburg test is compacted to a height based on the desired slurry seal thickness. The total height of the base and the coated slurry seal layer should be within the range of 60mm $\pm$ 2mm, which is the height of the mold in the Hamburg wheel tracking device. It is noted that the 5E3 loose mixture was aged at 135 °C for 4 hours and compacted at 148 °C. The base height was calculated to be 55 mm and 58 mm for the slurry seal application rates of 18 $lb/yd^2$ and 10 $lb/yd^2$, respectively.

The sample preparation includes two major components: (i) preparation of substrate and (ii) preparation of slurry seal. The main steps of each component are given below:

- Preparation of substrate (see Figure 38):
    - Step-1: Sample a certain amount of 5E3 loose mixture based on the desired height of the substrate.
    - Step-2: Place the material and compaction mold into the oven for 4 hours at 148°C.
    - Step-3: Set the aged loose mixture in the compaction mold.
    - Step-4: Compact the 5E3 loose mixture to the desired substrate height.
    - Step-5: Place the compacted base at the laboratory temperature for 24 hours for curing.
    - Step-6: Cut the sample to the shape matching the mold of Hamburg wheel tracking tester

Step1: Prepare desired amount of HMA loose mixture

Step2: Place material and compaction molds in oven at compaction temperature

Step2: Place HMA material in compaction molds


Step3: Compact the HMA mixture in desired height

Step4: Air-cool 24 hours for hardening

Step5: Cut the base to match the Hamburg wheel tracking tester mold

**Figure 38. Illustration of HWT substrate preparation steps**

- Preparation of slurry seal sample:
  - Step-1: Gently surround the top side of the HMA base with aluminum foil tape as the fence to guard the slurry seal mixture and hold the mixture while pouring (see Figure 39).
  - Step-2: Prepare the amount of slurry seal mixture based on application rate.
  - Step-3: Cast the slurry seal mixture on the HMA base and gently smoothen the material with spatula and minimize the unevenness (see Figure 40).
  - Step-4: Wait 15 minutes in laboratory temperature for the casted specimen to settle down and place the specimen in the 60°C (140°F) $\pm$ 3°C (5.4°F) for 24 hours to dry to the constant weight.
  - Step-5: Remove the specimen from the oven and cool it to laboratory temperature (see Figure 41).

**Figure 39. Illustration of the wrapping of the circumference of the sample with an aluminum tape.**

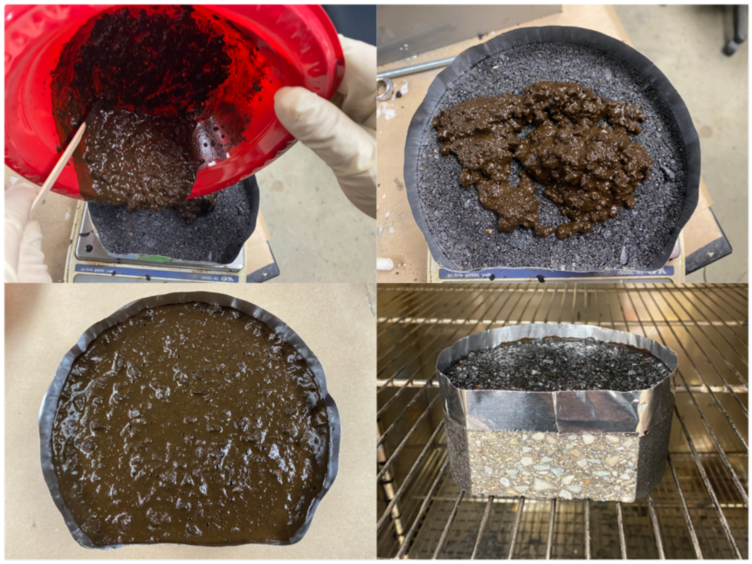


**Figure 40. Illustration of casting of the slurry seal sample and oven-drying**


**Figure 41. Prepared HWT specimen**

The amount of the slurry seal to be applied on the base depends on the application rates required. In this study, three application rates were used, which are 10 $lb/yd^2$, 15 $lb/yd^2$ and 18 $lb/yd^2$. Figure 42 is a prepared substrate ready for casting, Figure 43 shows a fresh cast HWT slurry seal sample and Figure 44 shows the slurry seal sample after curing. The 24-hour air-dry procedure was performed to simulate the field condition after the slurry seal construction, while the overnight 60°C oven-dry procedure is used to simulate the condition where the sun heats up the surface of the pavement on a sunny summer day.

**Figure 42. Compacted asphalt mixture substrate used in the Hamburg tests**

**Figure 43. Asphalt substrate with wet slurry seal layer**

**Figure 44. Asphalt substrate with cured slurry seal layer**

### 4.5.2 *Hamburg Rolling Wheel (HRW) test for Moisture Damage/Rutting Potential*

The HRW test was performed under wet (saturated) and dry conditions at a high temperature (54℃). Figure 45 and Figure 46 show the HRW test in wet and dry conditions, respectively. In both wet and dry testing conditions, the slurry seal mixture and the substrate were produced separately. The substrate shown in Figure 42 is a cylindrical hot mix asphalt compacted samples with dimensions of 55mm (2.2in) to 58mm (2.3in) in thickness and 150mm (6in) in diameter. This substrate functions as the existing asphalt pavement. The slurry seal mixture is prepared and cast on the top of the base within 30 seconds after mixing (Figure 43).

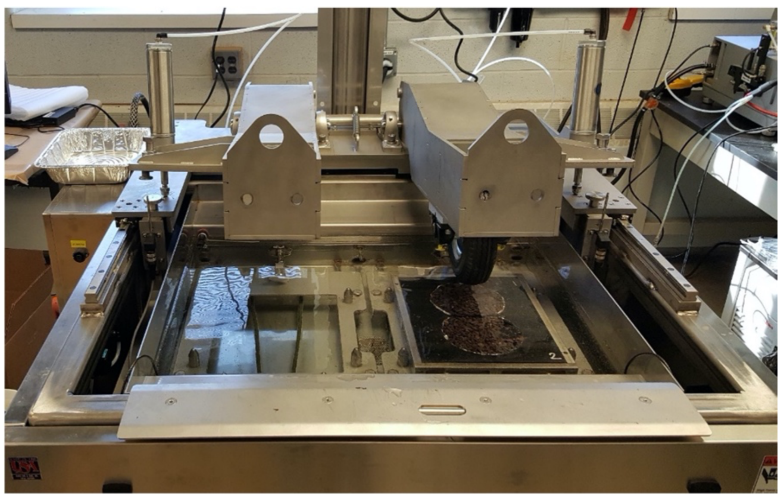


**Figure 45. Hamburg wheel tracking tester set up with water bath**

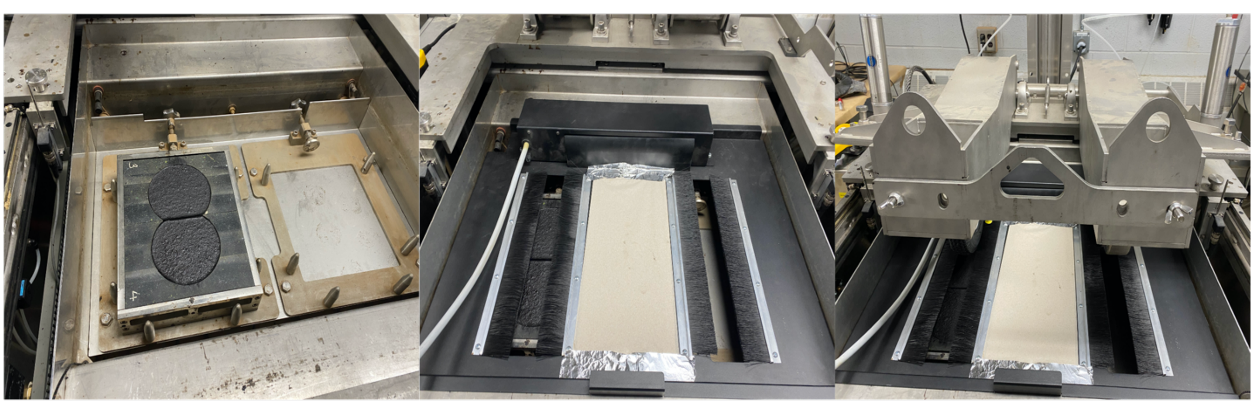


**Figure 46. Hamburg wheel tracking tester (dry set up)**

In the HRW test, a rubber tire with 35psi pressure was used and total of 2500 cycles were applied. Before starting each test, the samples were placed in the conditioning chamber for 4 hours at the test temperature and the sample is placed in the tester for minimum of 15 minutes underwater conditioning.


**Figure 47. HWT test sample pre-conditioning in the environmental chamber**

The HRW water bath test is designed to simulate the behavior of slurry seal under a high-temperature and high-moist conditions such as a quick rain in the summer. The results from this test can be compared with the stripping results from the wet-stripping test and the abrasion results from wet-track abrasion test. Both wet-stripping test and wet-track abrasion test are under wet condition; hence, the combination of these two tests can be compared with the water bath test. The HRW water bath test is conducted under a high-temperature condition to act as a torture test, which is similar to a high-temperature wet abrasion test. From the simple method described by Solaimanian and Kennedy [21], the maximum pavement temperature profile is related to the maximum air temperature and hourly solar radiation. Therefore, at the low latitude region or certain urban areas (e.g., Arizona, Texas, southern California etc.), the pavement surface temperature can easily reach 54 °C and above, which is the chosen test temperature for the HWT water bath test. The total number of cycles applied in the HRW test was 2500, which was the same number of cycles used in the Chip Seal Bleeding tests [10]. At each cycle, the rubber tire goes back and forth over the sample; hence, the 2500 cycles in the Hamburg machine correspond to 5000 passes of the tire on the surface. It is noted that during the HWT water bath test at 54°C, the asphalt binder often became soft and sticky, and adhere to the rubber tire. In order to prevent the potential effect of the accumulated asphalt binder on the test results, the test was periodically paused at 200, 300, 500, and 1500 cycles and the tire was cleaned at each pause.

- Loading:
    - Step-1: Prepare two samples and place them in the mold
    - Step-2: Fasten the mold to ensure no loose movement of the sample mold in the metal frame.
    - Step-3: Condition the device to the test temperature (if in wet test, the distilled water is filled before conditioning)
    - Step-4: Lower the arm and start the software to initiate the calibration.
    - Step-5: Lift-up the arm and place the sample in the test position.
    - Step-6: Set the test to 2500 cycles in total and start the test.

#### *4.5.2.1 Raveling Loss*

The raveling loss is calculated by the change in weight before and after the test by using Equation 2.

$$Raveling\ loss = \frac{Wt.Before - Wt.After}{Wt.Before} * 100 \qquad \textbf{Equation 2}$$

where $Wt.Before$ is the weight of the slurry seal portion of the sample before the test and the $Wt.After$ weight of the slurry seal portion of the sample after the test.

Raveling loss indicates the integrity of a paved slurry seal surface when exposed to the traffic load under saturated condition. Since the slurry seal material is a cold mix of asphalt emulsion, water, aggregate and additives, it can be regarded as an inexpensive asphalt layer added to the pavement. Moisture susceptibility is a common cause of distresses in asphalt pavement, when, especially, the water penetrates the surface and goes into the interface between binder and aggregates. Hence, under the wet condition, the moisture in the slurry seal can quickly weaken the bond between asphalt binder to the aggregate inside the slurry seal layer and causes break-off.

In the WTAT test (Wet Track Abrasion Test), a 12” x 12” 30lb roofing felt is taken as the base. 30lb roofing felt means that one square yard roofing felt weights 30lb so that, on average, the weight of the roofing felt is calculated by $\frac{12\ in\ x\ 12\ in}{144in^2/1ft^2} \times \frac{30\ lb}{100ft^2} \times \frac{453.592\ gram}{1\ lb} \cong 136\ gram.$

The asphalt substrate in the Hamburg wheel test is assumed to have a unit weight of 4000 lb/yd$^3$ (148 lb/ft$^3$) and the asphalt base was cut in the size of 55mm height with a segmented circle shown in Figure 38. The base weight is calculated by the method below and is 2385 grams in assumption.

$$4000\frac{lb}{yard^3} \times \left(0.0218yard^2\ \times\ 55\ mm \times \frac{1\ yard}{914.4\ mm}\right) \times \frac{1\ gram}{0.0022lb} \cong 2384\ gram \qquad \textbf{Equation 3}$$

#### *4.5.2.2 Stripping Rate*

The definition of the stripping is “The breaking of the adhesive bond between the aggregate surface and the asphalt cement content” [22]. As the excessive moisture in the slurry seal materials break the bond between the asphalt binder molecules and the aggregate surface, the tensile stresses that the slurry seal mixture can take decreases remarkably. In the wet stripping test, the observed coating area percentage after 30 mins boiling in hot water is estimated visually. However in the wet stripping test, the slurry seal material is only exposed to boiling temperatures with no application of tire force, which is unrealistic. In the HWT test, the slurry seal material is soaked under a 54$^{o}$C water. An inflated rubber wheel with 35psi pressure and 125lbs of load is applied to simulate the more realistic loading and environmental conditions. At the end of the HWT test, the wet-stripping percentage is estimated via visual observation of aggregates.

#### *4.5.2.3 Rutting*

The rutting occurs as a surface depression on an asphalt pavement surface. It is typically located at the wheel path due to the traffic load or the damages from studded snow tires[31]. The asphalt pavements are visco-elasto-plastic materials that continuously deform (with limited recovery) when exposed to repeated traffic loading at high temperatures. The accumulations of the uncovered deformation in the wheel path forms rutting on an asphalt pavement. As the temperature increases, the adhesive bond between asphalt molecules and aggregates becomes weak. Most of the accumulation of rutting occurs during the summer months when the pavement has a high temperature. In this study, the rutting results are measured in HRWT test and used to determine the performance of the test slurry seal material. In the HRWT test, the rutting is measured by the LVDT (Linear Variable Displacement Transducer) at two-decimal precisions in millimeters.

### *4.5.3 Hamburg Locked Wheel (HLW) test for Abrasion Potential*

In the traditional WTAT (Wet Track Abrasion Test), the resistance to abrasion is evaluated under the wet (saturated) condition where the friction force is generated from a rubber hose using 75-85 smooth° shore A hardness rubber shown in Figure 30. The HLW test was developed in this study to quantify the abrasion loss in a slurry seal sample at the intermediate temperature. The HLW test was performed at the laboratory (room) temperature (23℃) and the vertical load applied on the wheel is 125 lbs. In the HLW test, the HWT test device and the samples are prepared following the dry-condition HRW test. The difference between HLW test and HRW test is that in HLW test the rubber tire is firmly fixed to prevent it from rotating. Figure 48 shows the setup of HLW test and Figure 49 shows the locked wheel. The idea of HLW test is to simulate the frictional force caused by traffic stop-and-start.

The specification of HLW test is based on the WTAT test standard (ISSA TB100). In the ISSA TB100, the maximum aggregate abrasion loss of the WTAT test is 75 $g/ft^2$, which is the upper limit proposed in the HLW test. In the initial trials with 20 and 40 HLW cycles, the test conditions were too light to evaluate the performance of the slurry seal mixtures and did not produce significant damage. At 60 HWT cycles, the results were marginal and were no more aggregate dislodged at the last few cycles. Therefore, 55 HWT cycles were chosen as the HLW test cycles. In addition, the abrasion value from the HLW test is obtained from the maximum abrasion aggregate loss value of two sides in the HLW sample model. This minimizes the variation of the load distribution by the HWT wheel track position and the possible impact force differential from wheel traveling on the uneven sample surface. It is noted that at each HWT cycle, the rubber tire moves once in forward direction and once in backward direction which provides two passes in total.

The sample preparation of HLW test is similar to the HRW test shown in section 4.5.1. A summary of the HLW test procedures is provided below:

- Step-1: Place the samples in the mold and tie it up by using the screws on the sides.
- Step-2: Lower the arm and start the software to initiate the calibration.
- Step-3: Fix the wheel with steel rod.
- Step-4: Lift the arm and set the sample in the test position.
- Step-5: Set the test to 55 cycles and start the test.

**Table 9 HLW test trial data**

| HWT Cycles | Application Rate | Aggregate Material | Average Aggregate Loss (g/ft2) | Specification Limitation (g/ft2) |
|---|---|---|---|---|
| 20 | 10 | RAP | 20.92 | 75 |
| | | VG | 5.94 | |
| | 18 | RAP | 22.33 | |
| | | VG | 14.13 | |
| 40 | 10 | RAP | 57.4 | |
| | | VG | 32.2 | |
| | 18 | RAP | 20.92 | |
| | | VG | 17.52 | |
| 55 | 10 | RAP | 88.75 | |
| | | VG | 80.94 | |
| | 18 | RAP | 63.31 | |
| | | VG | 57.66 | |
| 60 | 10 | RAP | 94.97 | |
| | | VG | 81.40 | |
| | 18 | RAP | 71.23 | |
| | | VG | 62.47 | |

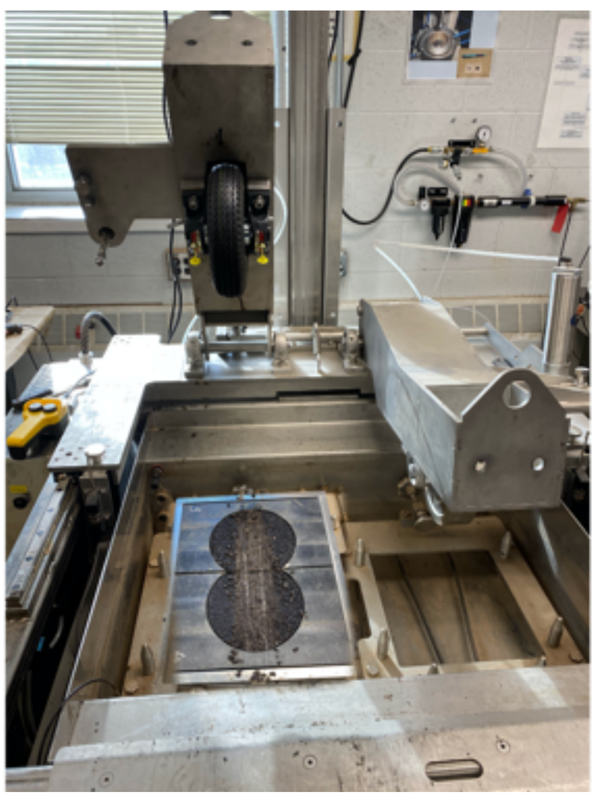


**Figure 48. HLW test setup with slurry seal (after the abrasion test)**


**Figure 49 Illustration of how the wheel was locked by a steel rod in HLW test**

# 5 RESULTS AND DISCUSSION

## 5.1 Mix-time and cure-time tests

The mix-time results of slurry seal design in both aggregates used (RAP and Virgin aggregate) are shown in Table 10. All samples met the mix time requirements within 5 minutes. After 15 minutes of the setting, the specimen was dry on the surface but could not resist any load. It was observed that the actual time for the samples to completely cure varied between RAP and virgin aggregate, where it took about 8 hours for the slurry seal with RAP to cure and it took about 10 hours for the slurry seal with virgin aggregate to cure. The possible reasons for this may be due to the amount of dry and fine soil particles (dusts) in Type II virgin aggregate. In the RAP aggregate, the small fine particles are already coated with the existing asphalt binder. Hence, after the mixing with asphalt emulsion, it absorbs less amount of water and takes less time to stiffen.

**Table 10. Mix-time test results**

| Test | Aggregate | Results | Pass/Fail | Specification Limits |
|---|---|---|---|---|
| Mix Time, 70-85°F, sec (ISSA TB-113) | RAP | >300 seconds | Pass | 180 seconds minimum |
| Mix Time, 70-85°F, sec (ISSA TB-113) | Type II Virgin Aggregate | >300 seconds | Pass | 180 seconds minimum |
| Slurry Seal Mixing Test, 70-85°F, (ISSA TB-102), 30 minutes cure | RAP | No Staining | Pass | No more than slight discoloration |
| Slurry Seal Mixing Test, 70-85°F, (ISSA TB-102), 30 minutes cure | Type II Virgin Aggregate | No Staining | Pass | No more than slight discoloration |
| Slurry Seal Mixing Test, 70-85°F, (ISSA TB-102), 1 hour cure | RAP | No Staining | Pass | No Brown Staining |
| Slurry Seal Mixing Test, 70-85°F, (ISSA TB-102), 1 hour cure | Type II Virgin Aggregate | No Staining | Pass | No Brown Staining |

## 5.2 Consistency test results

The results of consistency of the slurry seal mixtures of both RAP and Type II virgin aggregate are shown in Table 11. This table shows that the mixtures by using Type II virgin aggregate exhibited a higher flow potential as compared to the mixtures with RAP aggregate. It should be recalled that high flow potential is not desirable because of the possibility of not having sufficient thickness of the slurry seal in the field. Although results were close, it appears the slurry seal with RAP aggregates performed better than the slurry seal with virgin aggregates in this test. This may be attributed to the finer particles in the virgin aggregate and the stronger adhesive bond of total asphalt content in RAP aggregate.

**Table 11. Consistency test results**

| Material | Point 1 (cm) | Point 2 (cm) | Point 3 (cm) | Point 4 (cm) | Average (cm) | Specification (cm) |
|---|---|---|---|---|---|---|
| RAP | 2.5 | 3.3 | 2.2 | 2.6 | 2.65 | 2-3 |
| RAP | 2.7 | 3.1 | 2.4 | 2.5 | 2.68 | 2-3 |
| Type II VG | 3.1 | 2.8 | 2.5 | 2.9 | 2.83 | 2-3 |
| Type II VG | 3.3 | 2.2 | 2.9 | 2.8 | 2.80 | 2-3 |

## 5.3 Cohesion test results

The cohesion test is an important test being used to determine when the slurry seal mixture is stiff enough to handle normal and shear forces caused by the traffic. In this study, the samples were tested at different time periods after cast: 15 minutes, 30 minutes, 60 minutes, 120 minutes and 240 minutes. Table 12 and Figure 50 show the cohesion test results obtained in this study. The abbreviation RAP represents the slurry seal with 100% RAP and VG represents the slurry seal with virgin aggregates. It was observed that neither of the slurry seal mixtures tested in this study met the requirements of 12 kg-cm at the end of 30 minutes and 20 kg-cm at the end of 60 minutes. Figure 51 shows the pictures of the samples at the end of 30 minutes, where both samples were appeared to be still quite soft. Two mix design documents were shared with the team at the beginning of this study. One of them was developed by Wood Environment & Infrastructure Solutions, Inc. (Wood) for the mixture with 100% virgin aggregates and the ViaSun corporation developed the other one for the mixture with the 100% RAP. Figure 52 shows a snapshot of the results provided by Wood (Figure 52) where the Type II virgin aggregate mixture meets the desired amount of torque (12 kg-cm) at 30 minutes after cast. In the results provided by ViaSun shown in Figure 53, the RAP aggregate mixture meets the desired amount of torque (12kg-cm) at 30 minutes after cast. These results contradict the results obtained in this study. As shown in Table 12, the torque resistance of the slurry seal with RAP samples ranges from 7 to 11, which are below the minimum requirement from the ISSA A105 standard. The mode of rupture (see Figure 51) is determined to be as 'Normal' according to standard ISSA TB139 shown in Figure 28 [18]. In the Type II virgin aggregate mixture, the torque resistance was also insufficient at the end of 30 and 60 minutes, but this mixture reached 12 kg-cm at 120 minutes and 20 kg-cm at 240 minutes.

**Table 12. Cohesion data based on the original mixture design formula**

| | **RAP** | | **VG** | | **Specification** |
|---|---|---|---|---|---|
| Time(min) | Torque (lb-in) | Torque (kg-cm) | Torque (lb-in) | Torque (kg-cm) | Torque (kg-cm) |
| 15 | 7 | 8 | 6 | 7 | - |
| 30 | 11 | 13 | 9 | 10 | 12 min. |
| 60 | 9 | 10 | 9 | 10 | 20 min. |
| 90 | 10 | 12 | 9 | 10 | - |
| 120 | 10 | 12 | 11 | 13 | - |
| 240 | 7 | 8 | 17 | 20 | - |

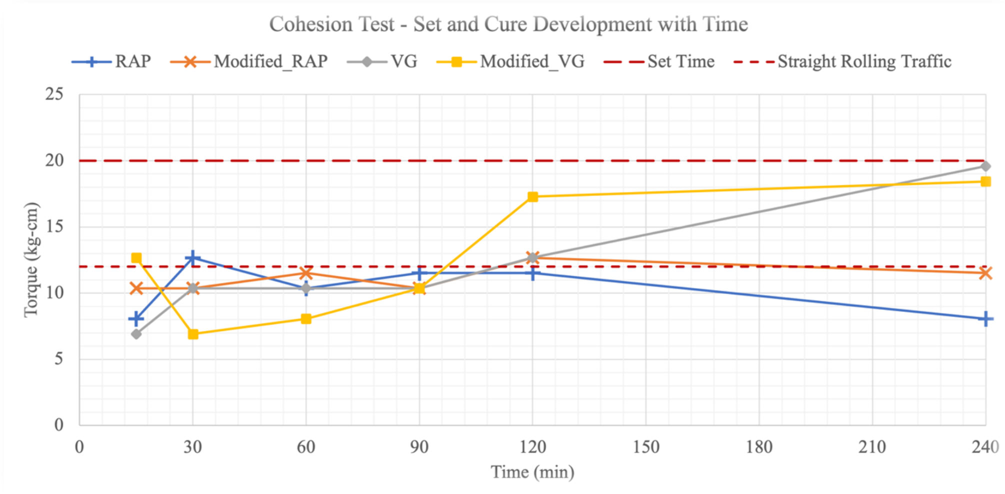



Figure 50. Cohesion test results from this study

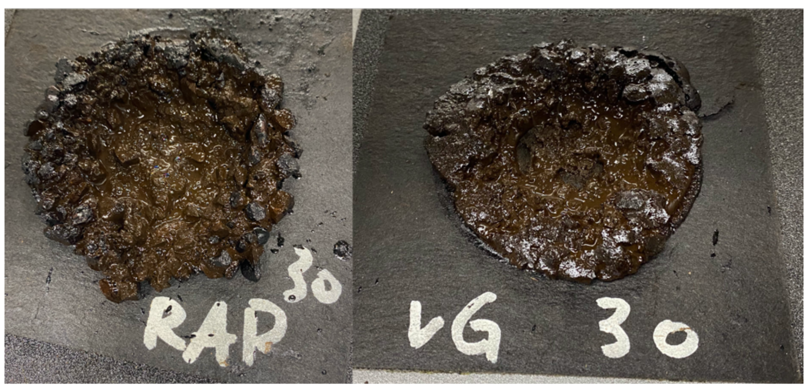



Figure 51. The modes of rupture for RAP and VG aggregates tested at 30 minutes

Cohesion Data

| Time (min) | Torque (kg-cm) | Specification, min. (kg-cm) | Mode of Rupture |
|---|---|---|---|
| 15 | 11.0 | -- | Near Spin |
| 30 | 13.0 | 12 | Near Spin |
| 60 | 20.0 | 20 | Near Spin |
| 90 | 21.0 | -- | Spin |
| 120 | 22.0 | -- | Solid Spin |
| 240 | 23.0 | -- | Solid Spin |

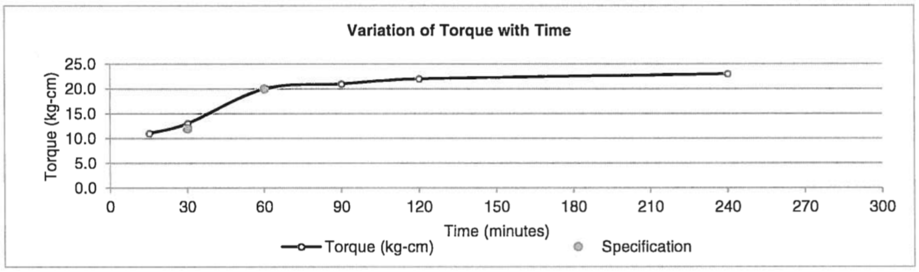



**Figure 52. Cohesion data from the Wood**

Cohesion (TB-139)

| Time (min) | Torque (kg-cm) | Specification (kg-cm) | Mode of Rupture |
|---|---|---|---|
| 15 | 8 | - | Normal |
| 30 | 12 | 12 minimum | Near Spin |
| 60 | 20 | 20 minimum | Spin |
| 90 | 23 | - | Spin |
| 120 | 24 | - | Solid Spin |
| 240 | 25 | - | Solid Spin |

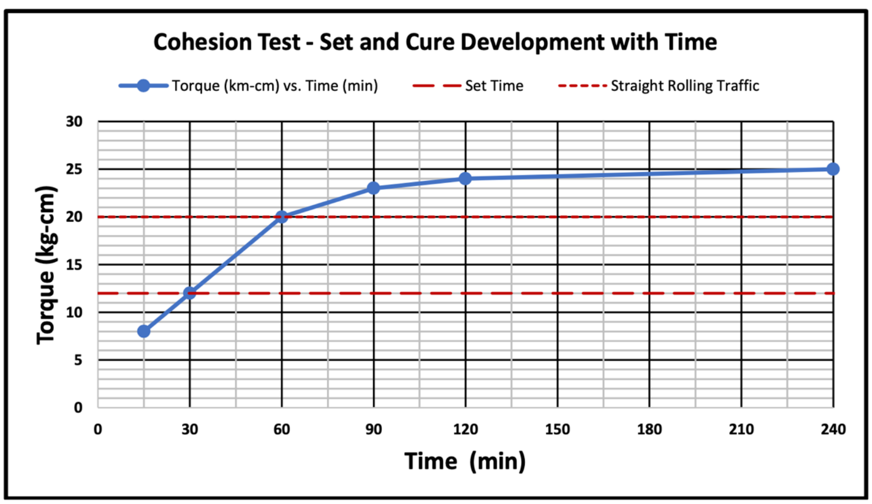



**Figure 53. Cohesion data provided by ViaSun Corporation**

In order to investigate the discrepancy between the mix design data and the results obtained in this study, the percentages of aluminum sulfate and water were modified (see Table

13). It was hypothesized that the samples with the original mix formula might have contained too much moisture when the samples were broken. Table 14 shows the results of the tests with the modified proportions of the constituents, where little to no difference was observed, as compared to the results shown in Table 12. It is noteworthy that the modified VG sample does not achieve the 20 kg-cm at the end of 240 minutes. Therefore, it was concluded that a small percentage change in aluminum sulfate and water does not significantly influence the results of the torque resistance measurements.

**Table 13. Slurry seal mixture formula**

| **Mixture** | **Emulsion** | **Portland Cement** | **Aluminum Sulfate** | **Water** |
|---|---|---|---|---|
| | % | % | % | % |
| RAP | 12.90 | 1.00 | 1.00 | 9.50 |
| Modified_RAP | 12.90 | 1.00 | 0.00 | 7.50 |
| Type II VG | 14.00 | 0.50 | 0.10 | 7.50 |
| Modified_Type II VG | 14.00 | 0.50 | 0.00 | 7.50 |

**Table 14. Cohesion data based on modified mixture formula**

| | **Modified_RAP** | | **Modified_VG** | | **Specification** |
|---|---|---|---|---|---|
| Time(min) | Torque (lb-in) | Torque (kg-cm) | Torque (lb-in) | Torque (kg-cm) | Torque (kg-cm) |
| 15 | 9 | 10 | 11 | 13 | - |
| 30 | 9 | 10 | 6 | 7 | 12 min. |
| 60 | 10 | 12 | 7 | 8 | 20 min. |
| 90 | 9 | 10 | 9 | 10 | - |
| 120 | 11 | 13 | 15 | 17 | - |
| 240 | 10 | 12 | 16 | 18 | - |

## 5.4 Wet-stripping test results

The wet-stripping test indicates the degree of coating of the aggregates with binder. This test is a visual determination test that has no actual numerical data to demonstrate. The results of this test are shown in Table 15. Figure 54 shows the test sample after the test where no uncoated area was observed.

Table 15. Wet-Stripping test results

| Aggregate Material | Results |
|---|---|
| RAP | No visually loose of asphalt binder, Greater than 90% retained coating |
| Type II virgin aggregate | No visually loose of asphalt binder, Greater than 90% retained coating |

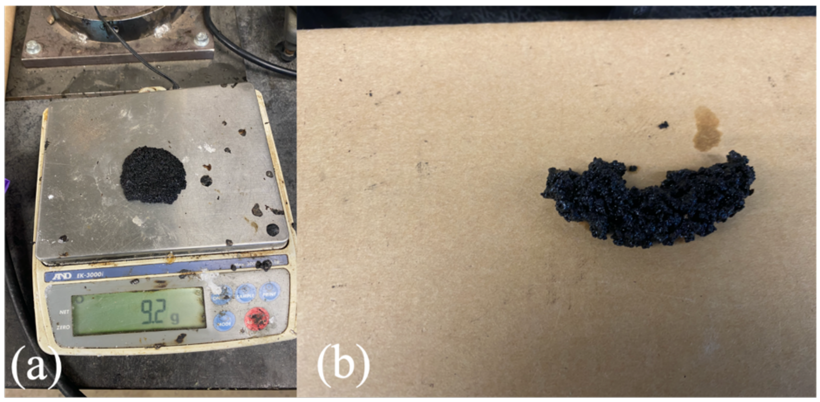



**Figure 54. Wet-stripping test sample (a) before and (b) after the test**

## 5.5 Wet-track abrasion test results

The wet-track abrasion test is designed to measure the resistance of the slurry seal to be shear stress due to traffic under wet condition. The test results are shown in Table 16 and Figure 55. As shown in Figure 55, the slurry seal samples using Type II virgin aggregate have a higher loss than using the RAP aggregate in 1-hour soaking period. However, the amount of loss in a 6-day soaking period was similar for RAP and VG materials. In both cases, the values were less than the upper limit of 75 g/ft$^2$, as specified in ISSA A105.

**Table 16. Wet-track abrasion test data**

| Sample No. | Material | Soaking Period | Weight Before Test (Felt Included) (g) | Weight After Test (Felt Included) (g) | Loss in grams | Loss in g/ft2 |
|---|---|---|---|---|---|---|
| 1 | RAP | 1 hour | 663.4 | 657.8 | 5.6 | 17.136 |
| 2 | VG | 1 hour | 707.1 | 696.9 | 10.2 | 31.212 |
| 3 | RAP | 1 hour | 601 | 587.3 | 13.7 | 41.922 |
| 4 | VG | 1 hour | 594.2 | 573 | 21.3 | 65.178 |
| 5 | RAP | 6 Days | 605.3 | 590.6 | 14.7 | 44.982 |
| 6 | VG | 6 Days | 708.1 | 690.6 | 17.5 | 53.55 |
| 7 | RAP | 6 Days | 621.7 | 603.3 | 18.4 | 56.304 |
| 8 | VG | 6 Days | 650.3 | 632.1 | 18.2 | 55.692 |

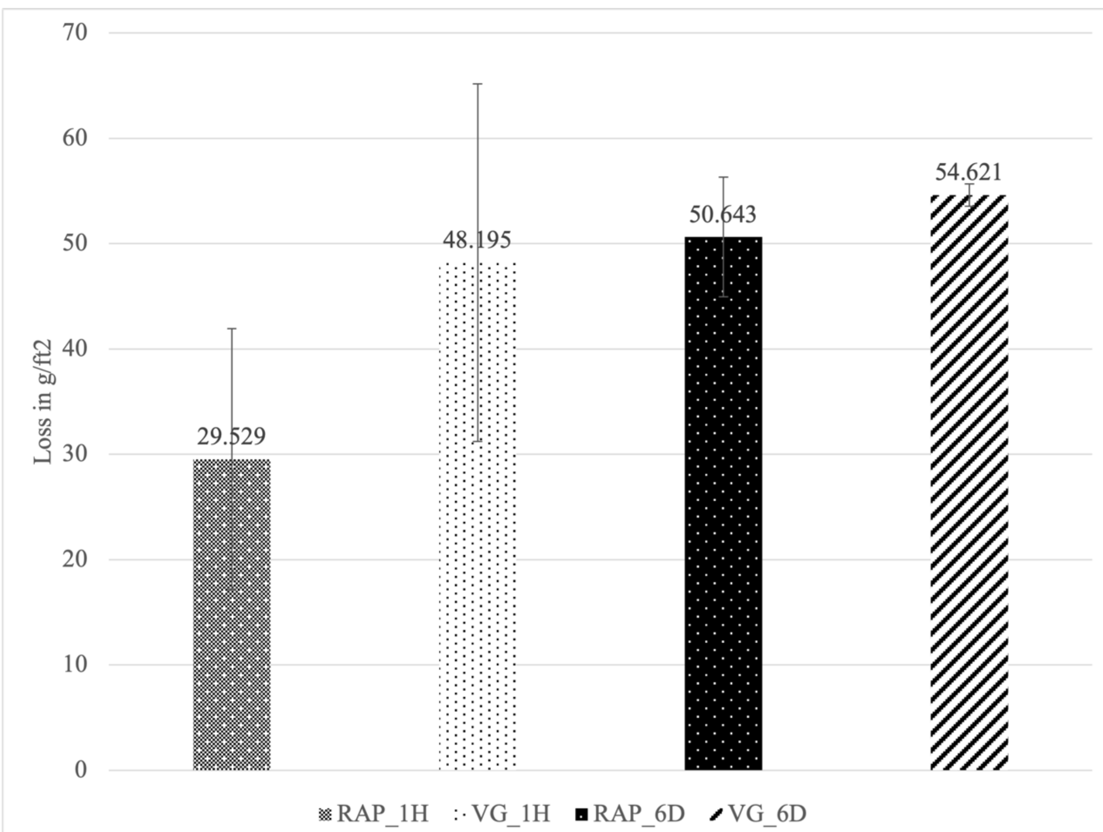



**Figure 55. WTAT Data**

## 5.6 Compatibility test results

The compatibility test contains four sub-tests to evaluate the absorption, abrasion resistance and integrity of the slurry seal mixture. The compatibility classification system based on the ISSA TB 144 is shown in Table 17. The results of each sub test are given in the following subsections.

**Table 17. Compatibility classification system (accoding to ISSA TB 144)**

| Grade Rating | Point Rating | Abrasion Loss, g | Integrity, % Retained | Adhesion, % Coated |
|---|---|---|---|---|
| A | 4 | 0-0.7 | 90-100 | 90-100 |
| B | 3 | 0.8-1.0 | 75-89 | 75-89 |
| C | 2 | 1.1-1.3 | 50-74 | 50-74 |
| D | 1 | 1.4-2.0 | 10-49 | 10-49 |
| 0 | 0 | 2.1+ | 0 | 0 |

### *5.6.1 Absorption test*

The absorption data of the tested samples is shown in **Table 18**. The following equation was used to compute the percent absorption:

$$P_{abs} = \frac{W_{SSD} - W_{dry}}{W_{dry}} * 100 \qquad \textbf{Equation 4}$$

where $P_{abs}$ = absorption percentage (%), $W_{SSD}$ = weight in saturated surface dry condition and $W_{dry}$ = weight in dry condition. It is noted that the ISSA TB 144 test standard does not include any guidance as to how much absorption is desirable/undesirable. The value is simply reported.

**Table 18. Compatibility test absorption data**

| Test no. | Aggregate Material | Dry Weight (gram) | Saturated Surface Dry (gram) | Absorption Percentage |
|---|---|---|---|---|
| 1 | VG | 40.5 | 41.4 | 2.22% |
| 2 | VG | 40.2 | 41.0 | 1.99% |
| 3 | VG | 40.2 | 41.2 | 2.49% |
| 4 | VG | 40.1 | 41.1 | 2.49% |
| 5 | RAP | 39.9 | 40.4 | 1.25% |
| 6 | RAP | 40.2 | 40.8 | 1.49% |
| 7 | RAP | 40.5 | 41.0 | 1.23% |
| 8 | RAP | 40.4 | 40.9 | 1.24% |

As shown in **Table 18**, the average absorption percentage of VG mixture is 2.30% and the RAP mixture is 1.30%. From this data, it can be concluded that the VG slurry seal mixture has a higher potential to absorb moisture than the RAP slurry seal mixture.

### *5.6.2 Abrasion Test*

Table 19 shows the weight of each sample before and after the abrasion test. The VG slurry seal mixture exhibited slightly less loss than the RAP slurry seal mixture. The average aggregate loss in the virgin aggregate mixture was 0.4 gram and in the RAP aggregate mixture is 0.55 gram. In both cases, the samples were graded as Grade A, which is the best grade possible.

**Table 19. Compatibility test abrasion data**

| Test no. | Mixture material | Weight before test (gram) | Weight after test (gram) | Total weight loss (gram) | Grade rating (issa tb 144) |
|---|---|---|---|---|---|
| 1 | VG | 41.4 | 41.0 | 0.4 | A |
| 2 | VG | 41.0 | 40.7 | 0.3 | A |
| 3 | VG | 41.3 | 40.8 | 0.5 | A |
| 4 | VG | 41.0 | 40.6 | 0.4 | A |
| 5 | RAP | 40.8 | 40.2 | 0.6 | A |
| 6 | RAP | 40.4 | 39.9 | 0.5 | A |
| 7 | RAP | 41.0 | 40.4 | 0.6 | A |
| 8 | RAP | 40.8 | 40.3 | 0.5 | A |

The RAP aggregate has a less resistance to the abrasion in moisture condition in the compatibility test. However, in the WTAT (Wet tracking abrasion test), the RAP aggregate mixture performs better than the virgin aggregate mixture. The possible cause for this situation could be that in the WTAT test, the sample is exposed to a frictional shear force on the sample surface by a rubber hose while in the compatibility test, the sample is in a free dropping motion in the water when the Schulze-Breuer machine is running. In the compatibility abrasion sub-test, the sample experienced a force from the dropping. When the sample contacts with the tube wall, the force to the sample is similar to an impaction rather than horizontal friction force. Hence, in the compatibility abrasion test, the results showed that the corner of the RAP sample pill is less able to endure the impact and the bond between fines and asphalt content is not strong. From this point of view, the conclusion can be made that the RAP slurry seal mixture has a better adhesion percentage but the bond to connect the aggregate particles is not strong.

### *5.6.3 Integrity Test*

The integrity test in the compatibility test is similar to the wet-stripping test. The results from this test are analyzed numerically by using the weight obtained in the absorption test and the weight after the integrity test. The following equation was used to compute the integrity:

$$Intergrity = \frac{Weight\ after\ Integrity\ Test}{Saturated\ Surface\ Dry\ Weight} \times 100 \qquad \textbf{Equation 5}$$

Table 20 shows the integrity test results, where most of the samples were graded as A and one graded as B. It should be noted that in some samples, the weight after the test increased slightly, which was somewhat unexpected. The samples having a positive weight change are mostly expanded as shown in Figure 56 and consequently attributed to the additional moisture absorption by the samples.

**Table 20. Compatibility Integrity Test Data**

| Mixture Material | Weight in SSD (gram) | Weight after test (gram) | Integrity (%) | Grade Rating |
|---|---|---|---|---|
| VG | 41.4 | 35.7 | 86.23 | B |
| VG | 41.0 | 41.2 | 100.49 | A |
| VG | 41.3 | 41.3 | 100.00 | A |
| VG | 41.0 | 41.2 | 100.49 | A |
| RAP | 40.8 | 41.4 | 101.47 | A |
| RAP | 40.4 | 40.4 | 100.00 | A |
| RAP | 41.0 | 40.8 | 99.51 | A |
| RAP | 40.8 | 40.3 | 98.77 | A |

**Figure 56. Sample expansion after integrity test**

## 5.7 Hamburg rolling wheel (HRW) test results

### *5.7.1 Stripping Data*

The stripping was evaluated by determining the area of uncoated aggregates along the wheel path visually. Comparisons of pictures of the samples tested in wet and dry conditions are shown in Figure 57 and Figure 58 for RAP and VG mixtures, respectively. It was observed that there were more exposed (uncoated) aggregates in samples tested in wet condition as compared to those tested in dry condition. This was true for both RAP and VG aggregates, with VG aggregates exhibiting slightly more stripping (see Figure 59).

**Figure 57. HWT RAP Mixture Wet *(left)* and Dry *(right)* Comparison**

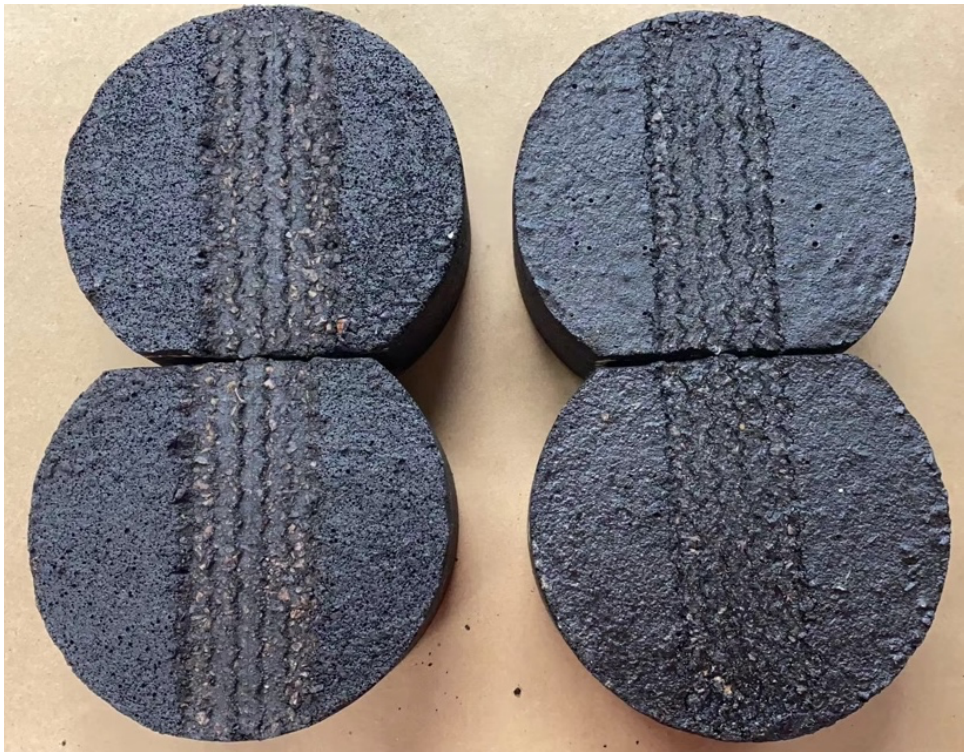


**Figure 58. HWT VG Mixture Wet *(left)* and Dry *(right)* Comparison**

**Figure 59. Samples tested in the wet condition: RAP(left) and VG(right) Comparison**

### 5.7.2 Raveling Loss

Table 21 and Table 22 show the reveling loss for RAP and VG mixtures, respectively, tested in both dry and wet conditions for all test replicates. Figure 60 shows a graph of the average (columns) and standard deviation (error bars) for each testing condition. As shown, RAP lost more material than VG sample in wet condition, whereas, in dry condition, both RAP and VG samples lost negligible amounts. This indicates that the slurry seal made with RAP may be more susceptible to moisture damage at high temperatures.

**Table 21. HWT Raveling Loss Results for RAP**

| Sample No. | Test Condition | Mixture Material | Weight Loss (gram) | Slurry Seal Applied (gram) | Raveling Loss (%) |
|---|---|---|---|---|---|
| **1** | Wet | RAP | 11.8 | 165.90 | 7.1 |
| **2** | Wet | RAP | 7 | 166.00 | 4.2 |
| **3** | Wet | RAP | 25.7 | 165.90 | 15.5 |
| **4** | Wet | RAP | 8.4 | 165.60 | 5.1 |
| **5** | Dry | RAP | 0.3 | 165.90 | 0.2 |
| **6** | Dry | RAP | 0.5 | 165.90 | 0.3 |
| **7** | Dry | RAP | 0.5 | 165.80 | 0.3 |
| **8** | Dry | RAP | 0.1 | 165.90 | 0.1 |
| | | **Average** | **6.8** | | **4.1** |

**Table 22. HWT Raveling Loss Results for VG**

| Sample No. | Test Condition | Mixture Material | Weight Loss (gram) | Slurry Seal Applied (gram) | Raveling Loss (%) |
|---|---|---|---|---|---|
| **1** | Wet | Type II VG | 1.5 | 165.90 | 0.9 |
| **2** | Wet | Type II VG | 1.2 | 166.10 | 0.7 |
| **3** | Wet | Type II VG | 4.5 | 166.00 | 2.7 |
| **4** | Wet | Type II VG | 2.6 | 166.00 | 1.6 |
| **5** | Dry | Type II VG | 0.2 | 165.90 | 0.1 |
| **6** | Dry | Type II VG | 1.1 | 165.90 | 0.7 |
| **7** | Dry | Type II VG | 0.2 | 166.00 | 0.1 |
| **8** | Dry | Type II VG | 0.1 | 166.10 | 0.1 |
| | | **Average** | **1.4** | | **0.9** |

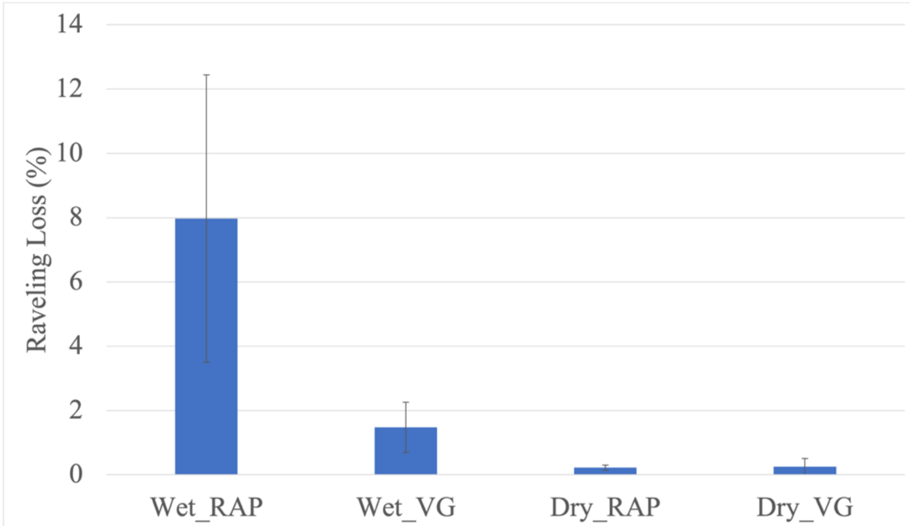



**Figure 60. HRW raveling loss values for both RAP and VG mixtures tested in dry and wet conditions.**

### *5.7.3 Rutting Data*

Figure 61 and Figure 62 show the progression of rutting in samples tested in wet and dry conditions, respectively. It appears that the RAP sample exhibited more rutting in both testing conditions. In the wet condition, the difference between the RAP and VG mixtures was more pronounced. It can be noticed from Figure 61 that the rutting data is not continuous in wet condition. This was since, as mentioned previously, the HRW test was stopped after 200, 500, and 1000 cycles to clean out the binder residue on the wheel. When tests were restarted at these cycles, there was an initially accelerated rutting, which slowed down and stabilized quickly. The tests with dry condition were not stopped at intermediate cycles because the problem of binder sticking to the tire was not observed in dry tests. Cross-sectional pictures of the slurry seal samples after the HRW tests are shown in Figure 63. As shown, the rutting in wet tests (whether the sample is RAP or VG) was quite significant. On the other hand, rutting doesn't seem to be an issue in dry tests. This clearly shows that the water at high temperatures causes significant damage to slurry seals.

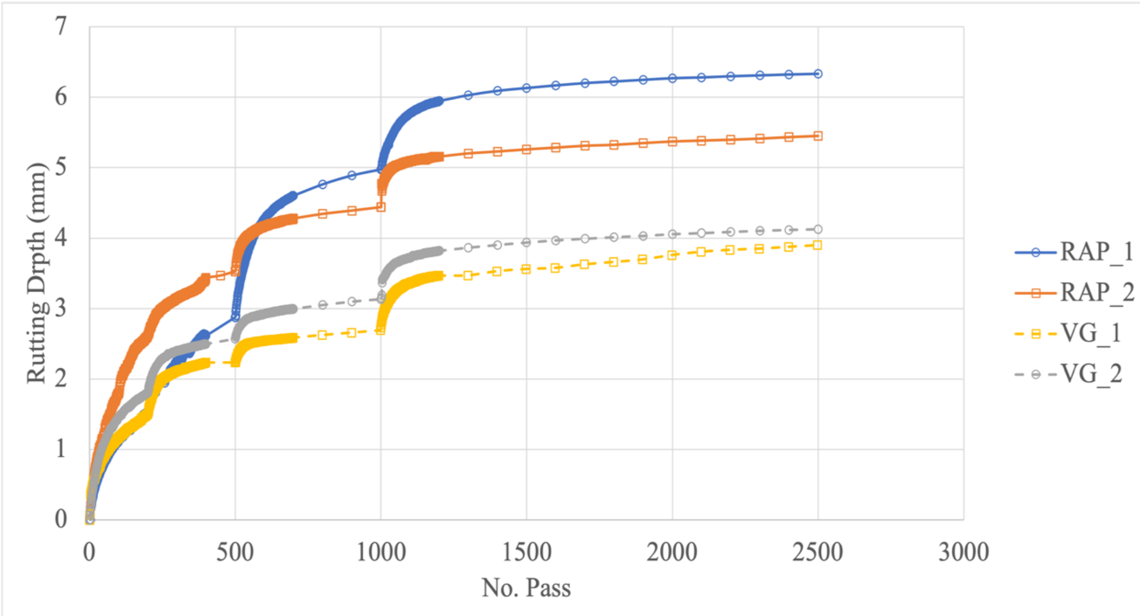



**Figure 61. HWT Rutting Plot Data at 54°C (wet)**

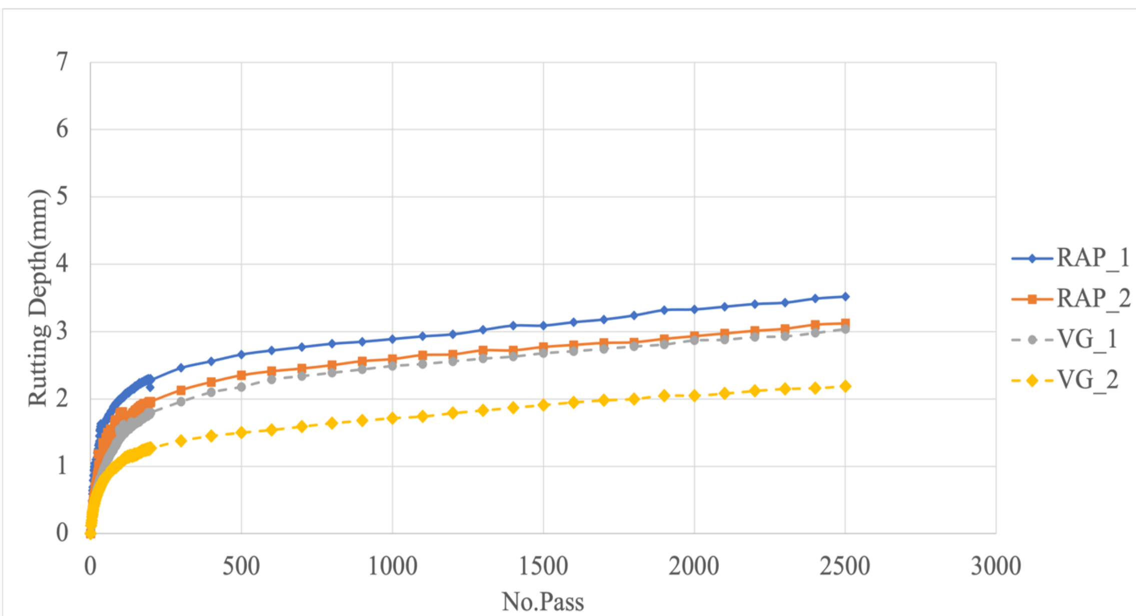
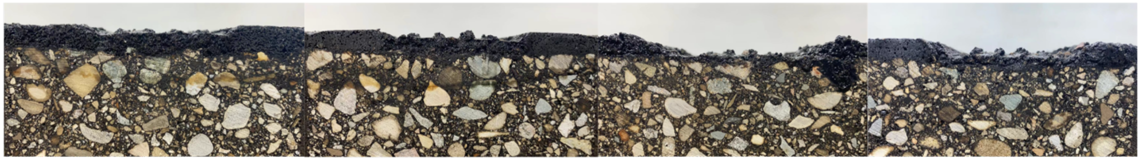



**Figure 62. HWT Rutting Plot Data at 54°C (dry)**



RAP (Dry test) VG (Dry test) RAP (Wet test) VG (Wet test)

**Figure 63. Cross sectional views of the slurry seal samples after the HRW tests**

Figure 64 and Figure 65 show the longitudinal rutting profiles for tests conducted in wet and dry conditions, respectively. As shown in Figure 64, the longitudinal profile of the samples tested in wet condition was quite rough and irregular, as opposed to those of the samples tested in dry condition (Figure 65).

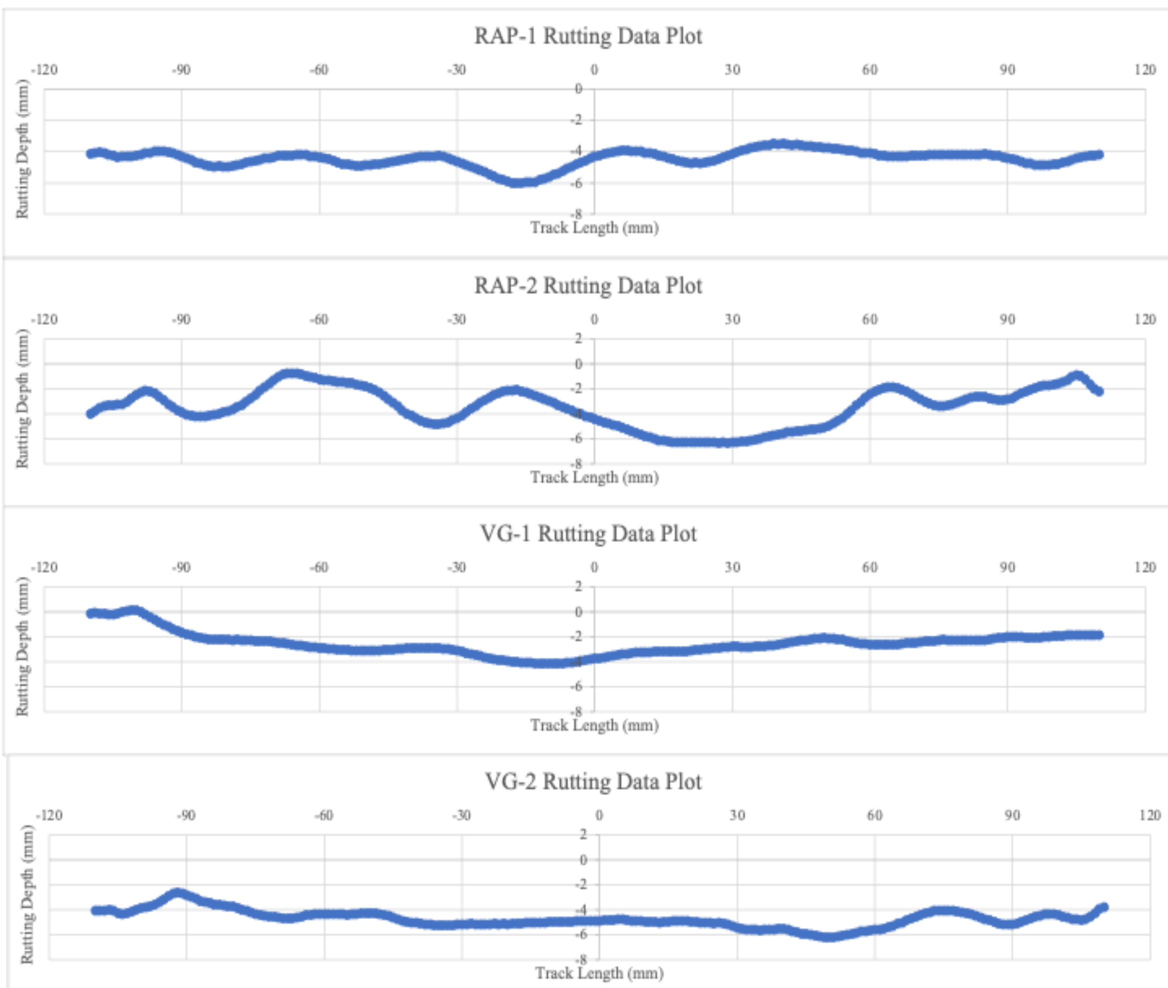



**Figure 64. Longitudinal rutting profiles of the samples tested in wet condition.**

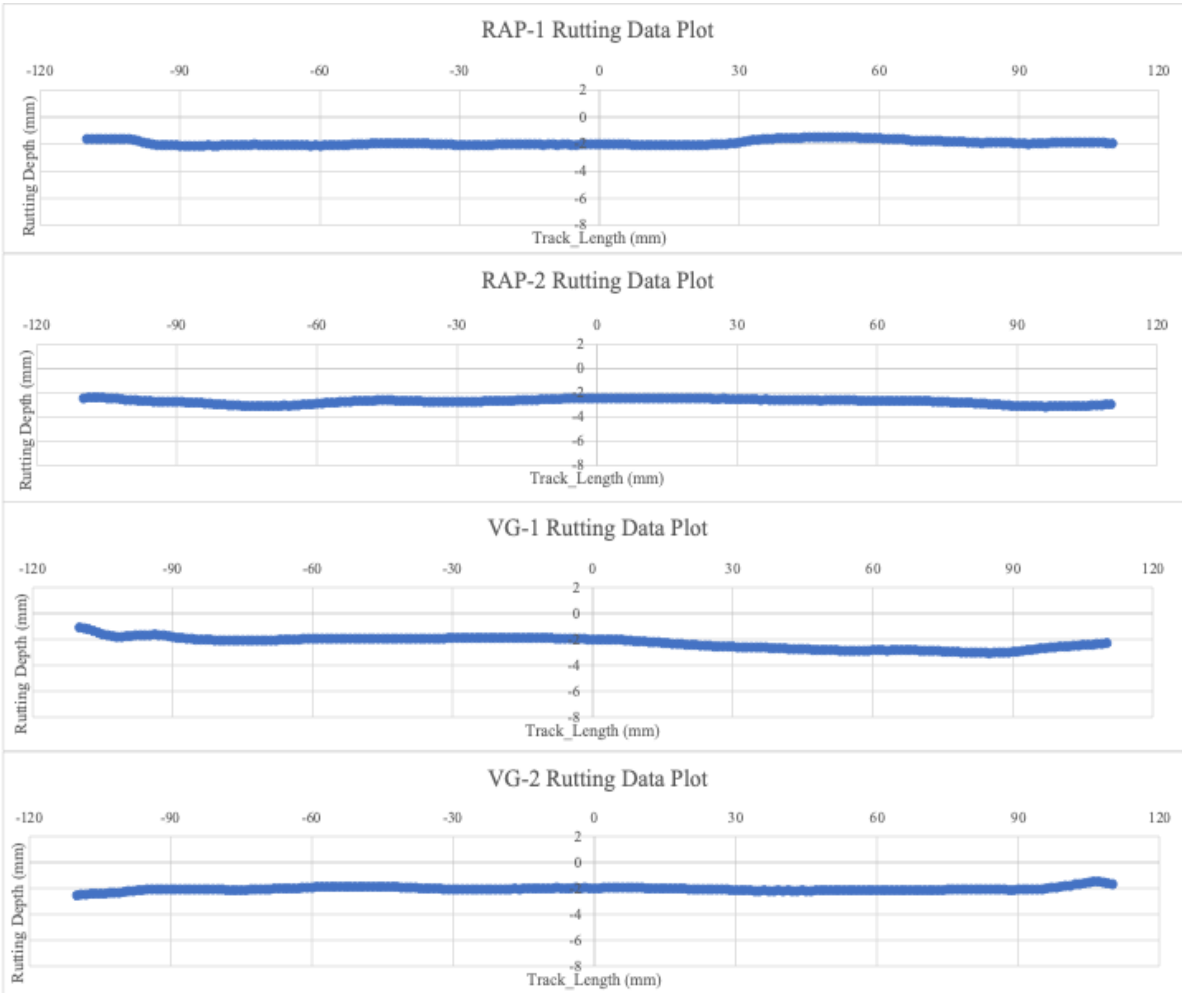



**Figure 65. Longitudinal rutting profiles of the samples tested in wet condition.**

## 5.8 Hamburg Locked Wheel (HLW) test results for abrasion

In the Hamburg locked wheel (HLW) test, the abrasion results for different application rates and aggregate types (100% RAP and virgin) were evaluated. Figure 66 and Figure 67 show both results for application rates of 10 $lb/yd^2$and 18 $lb/yd^2$, respectively. In both application rates, the slurry seal mixtures using RAP aggregate have a higher aggregate loss weight than VG slurry seal mixtures. This result contradicts with the results obtained in the WTAT test. The reason could be the peeling force applied by the tire tread in the HLW test compared with the smooth head used in the WTAT. These results are consistent with the raveling data from HRW test described in 5.7.2 . Even though the gradations of the aggregates are all with in the type II gradation range from ISSA standard, the RAP aggregate used in this study contains a less finer particles measured by the gradation test. The larger proportion of large aggregate particles gives a relatively shallower base of asphalt binder (shown in Figure 68 and Figure 69). At 20 and 40 HWT cycles, the aggregate loss is distinguishable between RAP and VG mixtures at lower application rate (10 $lb/yd^2$). It was observed from experiments that the low application rate leads to a shallow asphalt content base and a higher quantity of the aggregates exposed. This causes a large aggregate loss when exposed aggregates interact with rubber tire and the aggregates were removed from the sample by the tire tread curves. On the other hand, at the high application rate (18 $lb/yd^2$), the overall aggregate loss is less as compared to the low application rate (10 $lb/yd^2$). In addition, at the application rate 18 $lb/yd^2$, the difference between the aggregate losses of 100%RAP and VG samples are much less, primarily because of a smaller number of exposed aggregates in RAP. Therefore, it is recommended to use high enough application rates for the 100% RAP slurry seals to minimize the exposed aggregates. In both 100% RAP and VG samples, the aggregate loss was less than the upper limit of 75 $g/ft^2$.

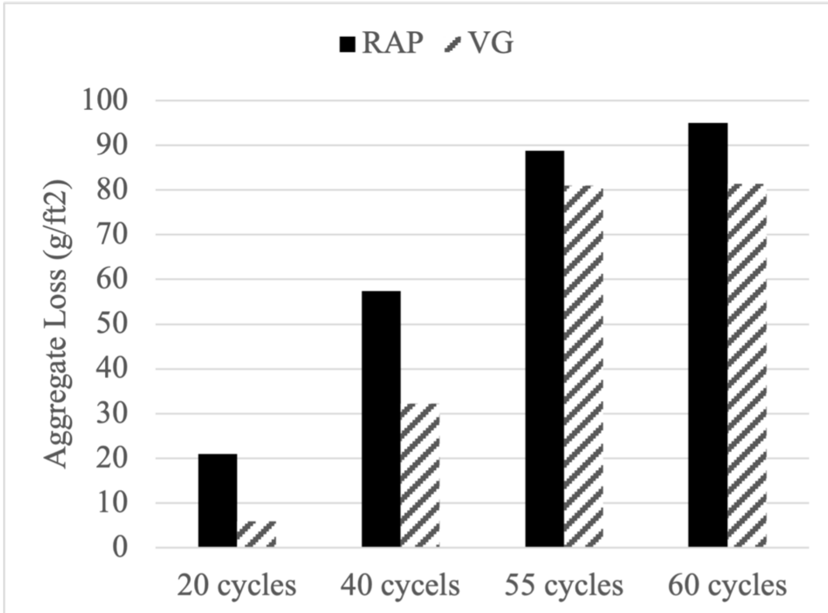


**Figure 66 HLW test abrasion loss with application rate at 10 lb/yd2**

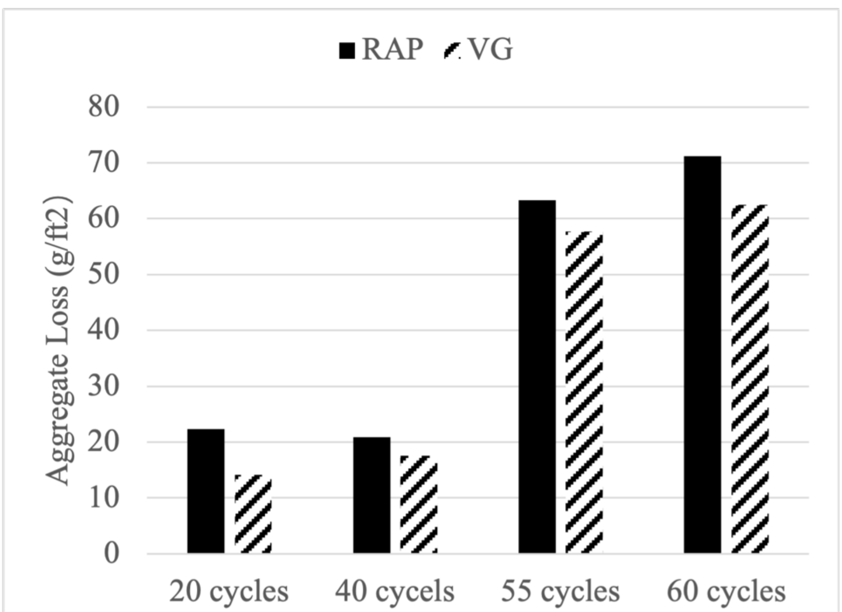


**Figure 67 HLW test abrasion loss with application rate at 18 lb/yd2**


**Figure 68 Conceptual drawing of exposed aggregates and asphalt binder base**

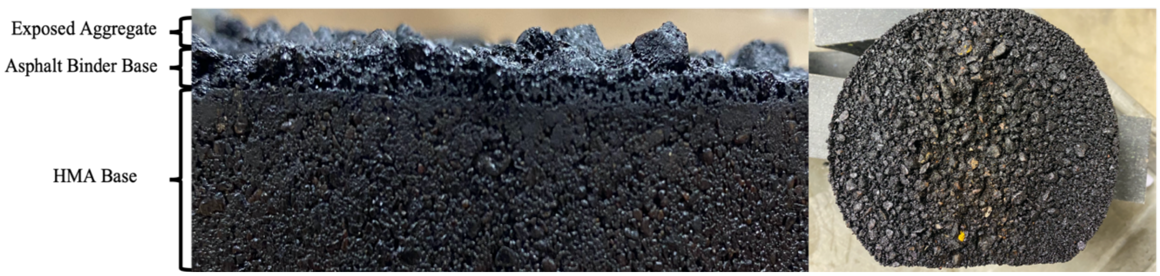



**Figure 69. Actual picture of slurry seal with RAP illustrating the exposed aggregates.**

Additionally, to fully understand the impact of asphalt binder content, the percentage of emulsified asphalt was reduced to 11% (from 12.9% originally). The modified tests were conducted at 10 $lb/yd^2$ and 18 $lb/yd^2$ application rates using RAP aggregate mixture and the results are shown in Figure 70. In the figure, the abrasion loss has a significant difference between 11% emulsion and 12% emulsion at the high application rate. However, at the low application rate, the modifications in emulsion content does not provide a distinguishable result. This can be because, at the lower application rate, the slurry seal layer is too thin; as a result, the abrasion loss is relatively high and the change in asphalt content does not benefit to the abrasion resistance.

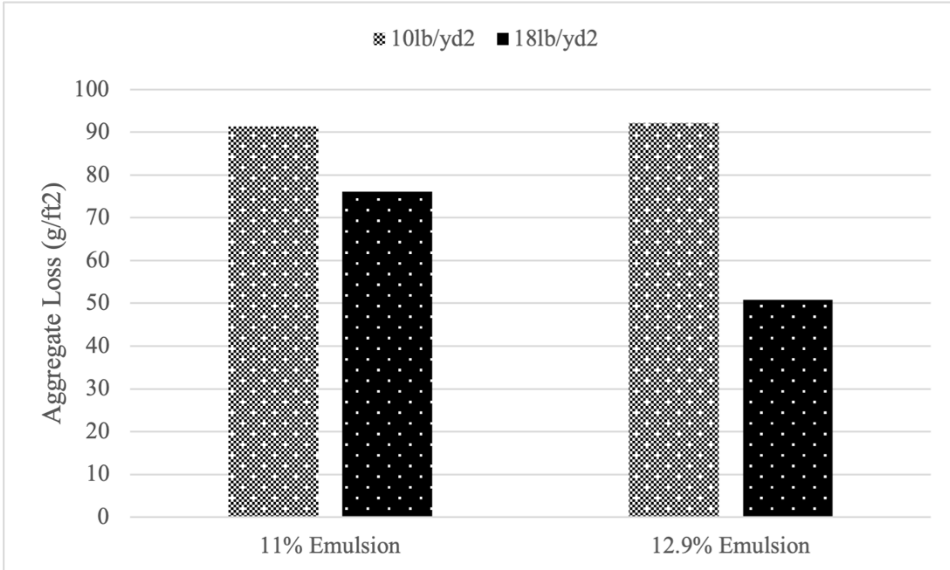



**Figure 70 Modified HLW test abrasion data using 100% RAP aggregates**

# 6 CONCLUSIONS

In this study, a comprehensive experimental program was undertaken to compare the performances of slurry seal mixtures made with 100% RAP and virgin (VG) aggregates. The tests included traditional tests such as residual binder content, mix time, cohesion, consistency, wet-abrasion, wet-stripping, integrity/compatibility tests. In addition, two new testing protocols were introduced to assess the abrasion, raveling and rutting resistance of the slurry seal mixtures.

The present research has studied the feasibility of 100% RAP slurry seal mixture. Both VG mixtures and RAP mixtures contain cement and aluminum sulfate additives. The mixtures with the most reasonable results were selected for traditional tests and HWT tests. The differences in performance between VG mixtures and RAP mixtures are acceptable and comparable. This report summarizes the laboratory study in which the performance of 100% RAP aggregate mixtures was investigated. Additionally, the advantages and the disadvantages related to each test are shown in Table 23.

The main findings of the present study can be summarized as follows:

- The performance of slurry seal made with 100% RAP is equivalent to slurry seal made with virgin aggregate, unless the application rate is too low to lead to exposed aggregates in the slurry seal.
- From the mix-time test, the cure time of both RAP and VG aggregates is larger than 5 minutes and the VG mixtures take longer time to fully stiffen.
- Although the cohesion test standard requires the sample to achieve a 12 kg-cm torque at 30 minutes and 20 kg-cm torque 60 minutes, both mixtures with RAP and VG aggregate did not meet the specification and they both need longer time to cure fully.

- The small change in Aluminum Sulfate content does not significantly affect the cohesion test results.
- From WTAT test, the mixtures made with RAP aggregate have a lower abrasion loss indicating a stronger resistance to horizontal abrasion force.
- In the compatibility test, both RAP mixtures and VG mixtures are graded as highest.
- In HRW (Hamburg Rolling Wheel) test, the slurry seals made with 100% RAP aggregate have a slightly higher raveling and rutting rate under moist condition at high temperature.
- In HLW (Hamburg Locked Wheel) test, the slurry seal made with 100% RAP aggregate has a slightly higher abrasion loss than VG mixtures.
- Although RAP mixtures have a higher total residual asphalt content, from the observation of both VG mixtures and RAP mixtures, the RAP mixtures have a higher aggregate exposure rate. It might be related to the lower percentage of emulsion and can be assumed that the emulsion content affects the asphalt base height.
- The main reason for the observed differences in abrasion loss between RAP mixtures and VG mixtures in WTAT test, compatibility test and HLW test can be the higher number of exposed aggregates in the RAP mix. With the higher exposure rate of aggregates, mixtures might have received a higher shear force at the contact between the tire and the aggregates.
- The Hamburg Wheel Tracking (HWT) test can be used in testing out the performance of a slurry seal mixture under a more detailed specification should be regulated.
- At the Hamburg rolling wheel test (HRWT), the wet (saturated) condition does a severe damage to the sample.

**Table 23. Summary of Advantages and Disadvantages from all tests in this study**

| Test Name | Test Measurements | Advantages | Disadvantages |
|---|---|---|---|
| Mix-time Test | Remain fluid for 300 seconds. | Help to determine the proportion of the components to control the moisture content in a sample. | Not clearly identified if it is the emulsion content or water content when the specification is not achieved. |
| | | | The time required might be too short while the quick-set emulsion used in this study can remain fluid for 300 seconds. |
| Consistency Test | Flow characteristic | Prevent a design from being too liquid | The paper used to print out the scale can potentially absorb the moisture in sample. |
| Cohesion Test | Initial set and cure development | Generate a torque-time function of slurry seal mixture | The test requirement does not corporate with different aggregate types. |
| Wet-Stripping Test | Sample remained coating at the test temperature and the potential to tripping | The sample is free to move at the process | The test condition is too harsh and can barely occur at field. |
| | | | No load applied to cause stripping. |
| Wet-Track Abrasion Test | Abrasion resistance under short-term and long-term moisture condition | Two soaking period | The sample is not thick enough to cause differences between two soaking period |
| | | | The rubber hose surface is too smooth. |
| | | Oven conditioned at 60°C | Load applied on the hose is not heavy to accommodate with real world. |
| Compatibility Test | Measures absorption, abrasion, integrity and adhesion of a slurry seal mixture | Four measurements on one sample | The sample is compacted at high force. |
| | | | At the abrasion test, the sample endures impact force rather than an abrasion force |
| | | | At the integrity test, the sample is restricted to move. |
| Hamburg Rolling Wheel Test | Measures stripping, raveling and rutting | Simulate the actual world slurry seal application | The test temperature at wet condition is too high and causes a severe damage to slurry seal mixture |
| | | | No damage to a sample at dry condition |
| Hamburg Locked Wheel Test | Measures abrasion | Simulate the actual world slurry seal application | The continuous 55 test cycles can generate heat accumulation and causes additional damage to the sample |

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