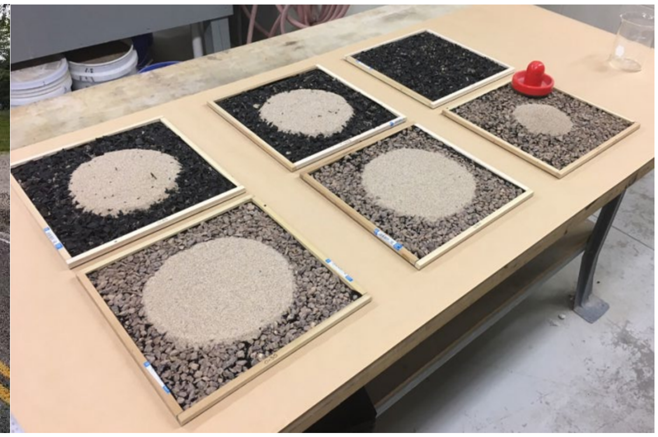
FIELD IMPLEMENTATION OF RUBBERIZED CHIP SEAL



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16. Abstract

Chip seals have been widely used as a pavement maintenance surface treatment due to its competitive cost and construction time. Recently, the research team developed a rubberized chip seal where natural aggregate is replaced with crumb rubber obtained from recycled tires. During this study, a total of 108 laboratory specimens and a field chip seal section with different crumb rubber replacement ratios were investigated. Aggregate macrostructure, retention, and skid resistance were measured. The crumb rubber showed a remarkable performance in aggregate retention measured using the Vialit and Pennsylvania tests. The values of the mean texture depth of rubberized chip seal specimens were significantly higher than those of the conventional chip seal. Finally, while a reduction in the British Pendulum Number (BPN) was recorded with an increase in the crumb rubber replacement ratio immediately after construction, after a period of more than a year of service life in the experimental section road, the rubberized chip seal segments recorded a much higher BPN compared to that of the conventional chip seal segment. Furthermore, it is recommended also to increase the curing time for chip seal, regardless of aggregate type, to at least six hours to improve the performance of the chip seal.

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FINAL REPORT

Field Implementation of Rubberized Chip Seal

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EXECUTIVE SUMMARY

Chip seals have been widely used as a pavement maintenance surface treatment due to its competitive cost and construction time. Recently, the research team developed a rubberized chip seal where natural aggregate is replaced with crumb rubber obtained from recycled tires. During this study, laboratory chip seal specimens and a field chip seal section with different crumb rubber replacement ratios were prepared. A total of 108 chip seal laboratory specimens were prepared to investigate aggregate retention using six tests: the standard sweep test, modified sweep test, Vialit test, modified Vialit test, Pennsylvania test, and modified Pennsylvania test. The crumb rubber showed a remarkable performance in aggregate retention measured using the Vialit and Pennsylvania tests.

The macrotexture of the laboratory specimens was investigated using the sand patch and image processing methods and how that reflects on the skid resistance. The values of the mean texture depth (MTD), which is a measure for pavement macrotexture of rubberized chip seal specimens, were significantly higher than that of the conventional chip seal. However, a reduction in the British Pendulum Number (BPN) was recorded with an increase in the crumb rubber replacement ratio. However, after a period of more than a year of service life in an experimental section road, the chip seal segments with 25% and 50% crumb rubber replacement ratios recorded much higher BPN compared to that of the conventional chip seal segment. A rubberized chip seal section, having up to a 50% crumb rubber replacement ratio by volume, was constructed successfully using standard procedures and equipment. However, it was necessary to use a steel roller compactor instead of a rubber tire compactor to compact the chip seal. This section was monitored for its texture, skid resistance, and aggregate dislodge over a period of one year. The MTD increased significantly with an increase in the rubber content where the MTD of rubberized chip seal with 50% replacement ratio was increased by 77% compared to the conventional chip seal. Raveling distress was also observed due to snowplowing actions. No damage or any sort of distress was observed in the wheel paths due to traffic loads. Therefore, this study concluded that crumb rubber can be used in the chip seal as a partial replacement of mineral aggregates up to 50%. It is recommended also to increase the curing time for chip seal, regardless of aggregate type, to at least six hours to improve the performance of the chip seal.

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1. Task 1: Introduction and literature review

Chip seals have been widely used as a pavement maintenance surface treatment. Chip seal is constructed by spreading binder on an existing pavement, followed by application of a one-size aggregate layer. Rollers are used after spreading the aggregate for compaction in order to achieve the required embedment depth of the aggregates into the binder layer. Chip seal surfacing is usually used on roads with traffic volumes in a range of 500 to 2400 vehicles per day. With certain techniques, such as increasing the embedment depth, traffic control at an early age using a pilot vehicle, and/or using a push or vacuum sweeper instead of traditional sweep methods, the chip seal can be used as a protecting layer and crack sealant for conventional pavements with traffic volumes higher than 7,500 vehicles per day per lane (Shuler 1998, Kim and Adams 2011, Ozdemir et al. 2013, Adams 2014, Kutay et al. 2016).

The safety of vehicles traveling on chip seal pavement is connected to the temporal changes in friction and skid resistance, which depend on road geometry, traffic conditions (e.g. vehicles' speeds, traffic load factors), weather conditions (e.g. humidity, temperature, accumulation of rainfall, rainfall intensity, and rainfall duration), and the construction material and quality of the road (Yandell 1971, Moore 1972, Forster 1981, Yandell and Sawyer 1994, Do et al. 2000, Wallman and Åström 2001, Choubane et al. 2004, Wilson and Dunn 2005, Persson 2013).

An ongoing MoDNR-sponsored project (Gheni et al. 2018a) is investigating the effects of traffic (Fig.1) and weather (Fig.2) conditions on the performance of chip seal. Figure 3 summarizes the effects of construction material and quality on the texture of a road. As shown in the figure, the unevenness and mega-texture are affected by the construction quality while the macrotexture and microtexture are affected by the aggregate used. Mega-texture and unevenness do not have significant effect on the skid resistance of a road. However, macrotexture, which depends on aggregate gradation, size, and shape among other parameters controls the skid resistance for vehicles having higher speeds exceeding 25 mph (40 km/h) (Kotek and Kováč 2015). Macrotexture affects the hysteretic component of the skid resistance of vehicles, which is related to compression and decompression in vehicle tires (Henry 2000, Flintsch et al. 2003, Choubane et al. 2004). Macrotexture is quantified by measuring the mean texture depth (MTD) using the sand patch method (ASTM E965), or advanced laser technology methods. Finally, microtexture controls the skid resistance of low speed vehicles (Kotek and Kováč 2015). It has also a direct impact on the adhesion component of friction because it influences the tire-chip seal contact area. Microtexture describes the roughness of the aggregate particles and is affected by the type and manufacturing process of the aggregate. Microtexture can be measured using a laser-based analysis system and the standard test method for index of aggregate particle shape and texture (ASTM D3398).

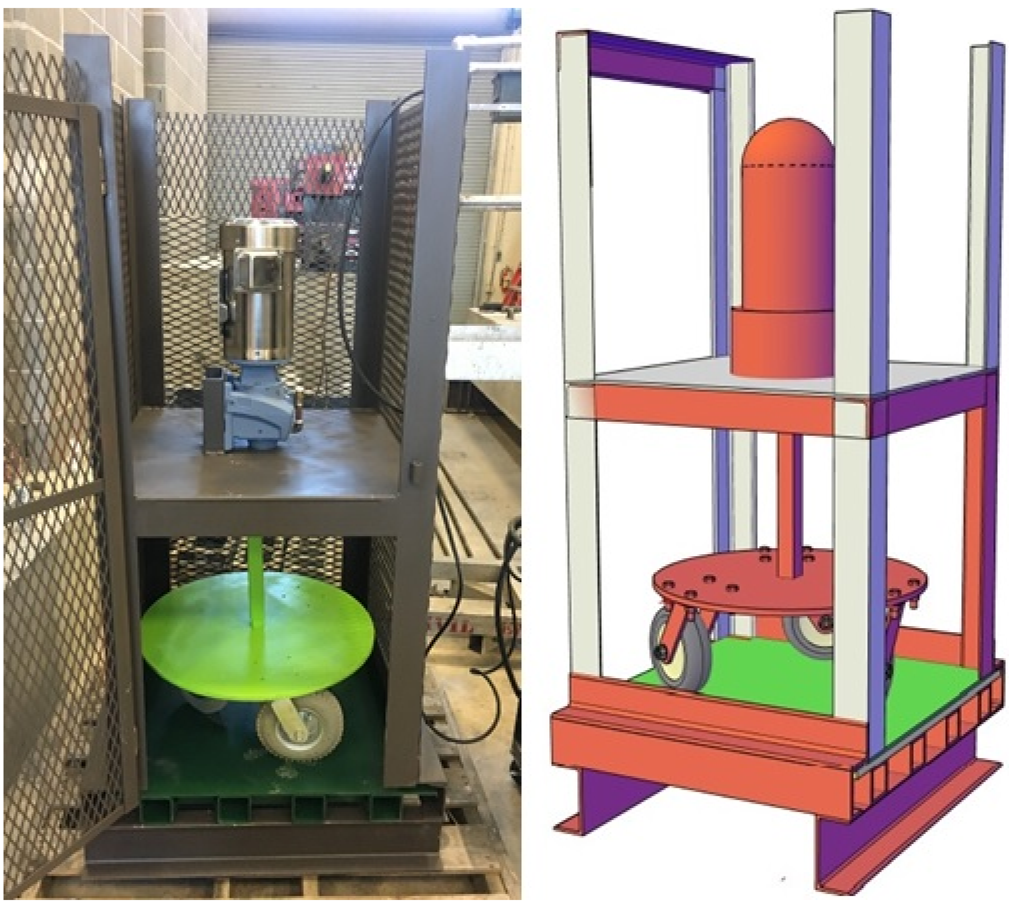


Figure 1: Pavement wear and polishing machine at Missouri S&T

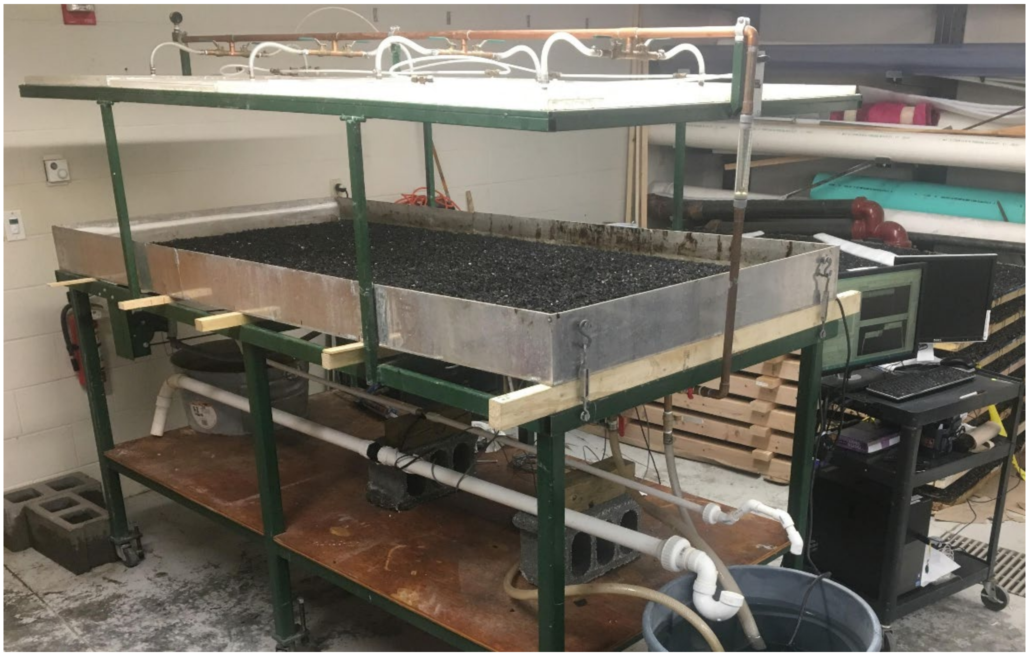


Figure 2: Testing a chip seal specimen in the rain simulator machine at Missouri S&T

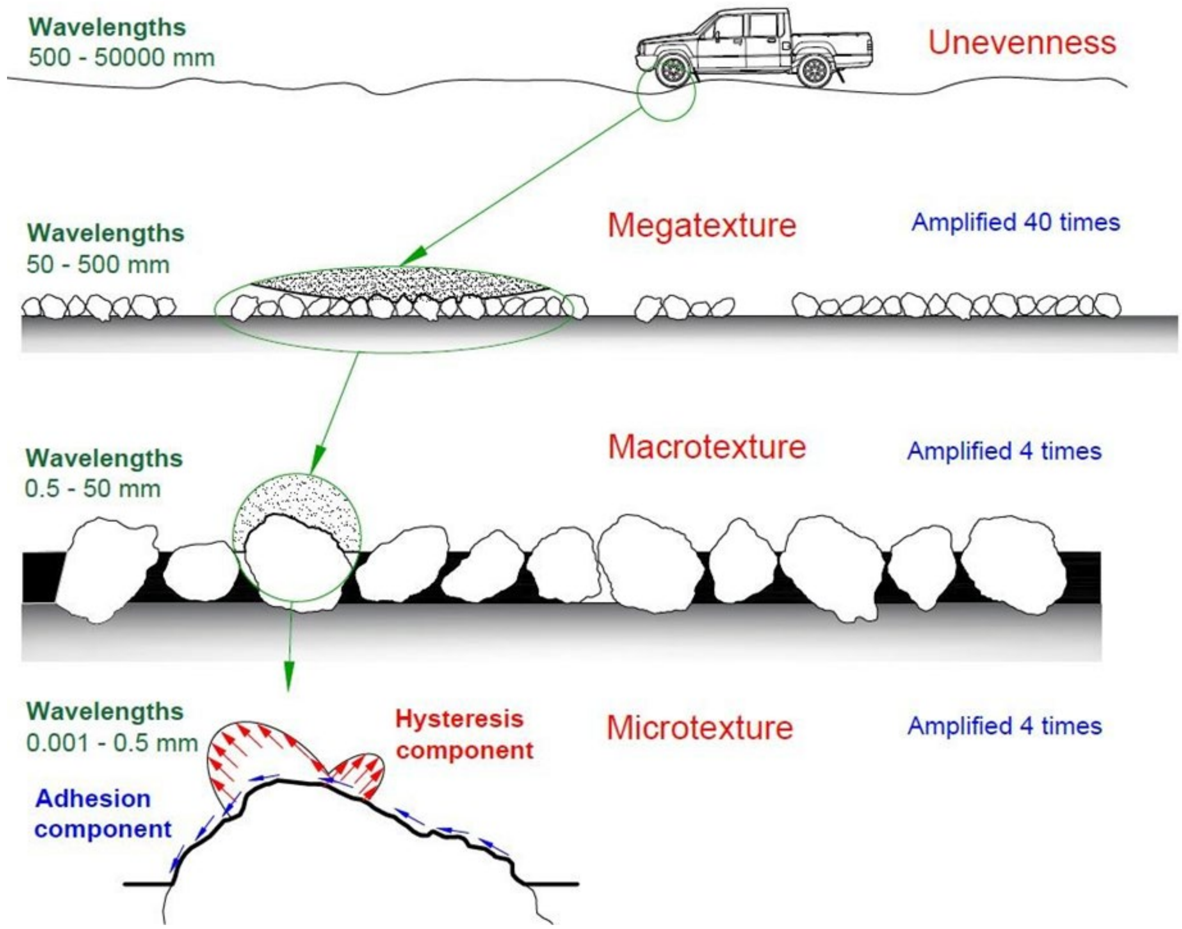


Figure 3: Schematic of pavement surface textures (Gheni et al. 2017)

Using mineral aggregates in chip seal has given rise to several issues. Dislodged aggregate may fly causing a serious safety issue for road users and passing vehicles. Driving on chip seal pavement is also commonly characterized by relatively high noise. Furthermore, it is common practice to hide the rocky color and display a darker color of chip seal by applying a layer of fog seal which increases the cost and reduces pavement friction. Replacing natural aggregate such as trap rock in chip seal construction with crumb rubber aggregate obtained from scrap tires will address these issues (Gheni; et al. 2017). Furthermore, the use of crumb rubber will allow the reuse of millions of tons of tires that otherwise would go to landfills.

As mentioned, several factors affect the performance of chip seal pavement. Comprehensive discussions of these parameters are presented by Gheni et al. (2017). Of particular importance for this project are the surface area of the aggregate used and the sweeping time. Gheni et al. (2017) investigated the microsurface of ambient and cryogenic crumb rubber as well as creek gravel and trap rock using a 3D digital microscope (Fig. 4). It was found that ambient shredded crumb rubber had the roughest surface among the four investigated types of aggregates (Fig. 4e).

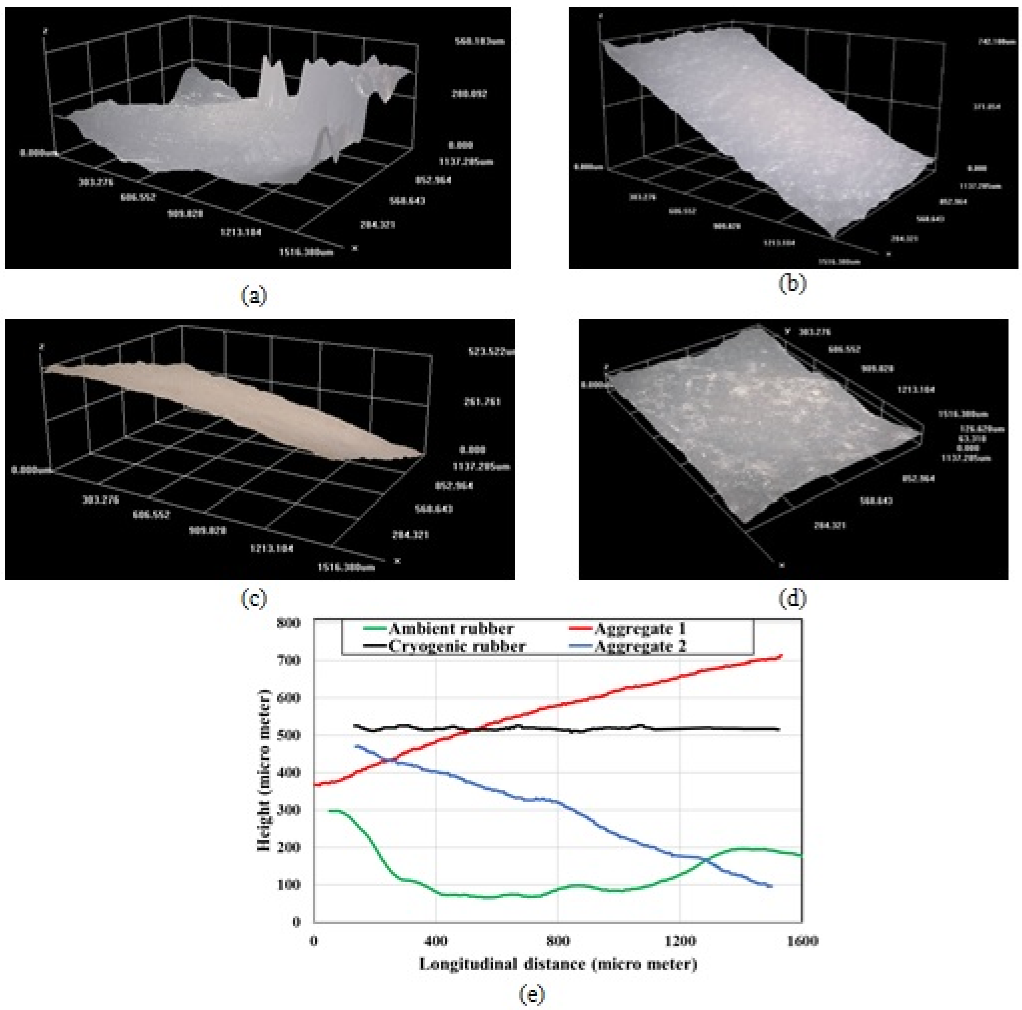


Figure 4: Microscope image of the aggregates' surface in the range of 250 µm for: (a) ambient crumb rubber, (b) cryogenic crumb rubber, (c) creek gravel, (d) trap rock, and (e) surfaces profiles of the different types of aggregates (Gheni et al. 2017)

Curing time, defined as the time between applying the chip seal and sweeping the road before opening for traffic, was found to be a very influential parameter on the performance of a chip seal (Gheni et al. 2017). Sweeping trap rock chip seal after one hour of placing the chip seal resulted in loss of 40% of the placed aggregates. This ratio increased to 60% in the case of 100% crumb rubber aggregate specimens. It was recommended to have a curing time of six hours to keep the dislodged aggregate below 20% of the placed aggregate.

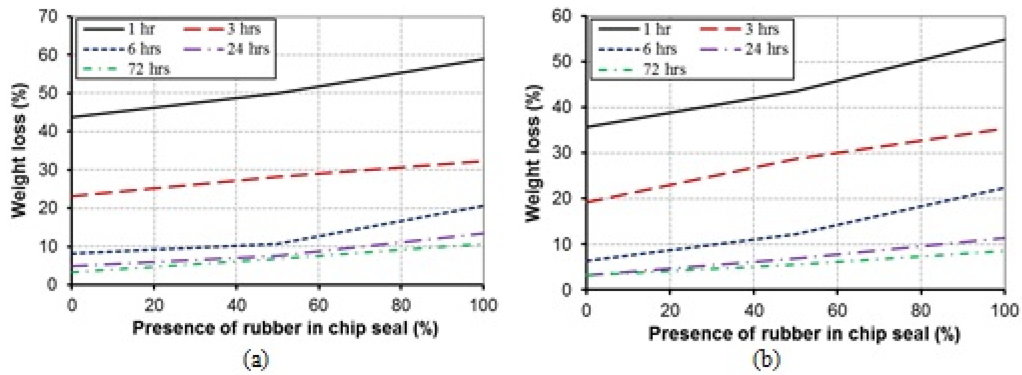


Figure 5: Crumb rubber weight loss after different curing times in chip seal specimens constructed using combinations of trap rock/crumb rubber and emulsion type: (a) CRS-2P, and (b) CHFRS-2P (Gheni et al. 2017)

Task 1.1: Long term monitoring of chip seal

The performance of chip seal pavement constructed using poorly graded aggregate was monitored over four years where longitudinal and transverse cracking and localized flushing were reported (Shuler 2013). The effect of construction parameters such as emulsion application rate, rolling patterns, and curing time on the aggregate retention was monitored over one year (Gürer et al. 2012). It was concluded that a minimum of a two-hour curing time is required before opening the chip seal road to traffic. In addition, the emulsion application rate was the most influential factor on the long-term performance of a chip seal where a higher emulsion application rate up to 0.41 gal/yd^2 was more appropriate (Roque et al. 1991). In the case of multilane roads, loss of aggregate on the passing lane (left lane) of the road was much higher than that on the right lane because of traffic speed, acceleration, and deceleration (Karasahin et al. 2014).

The temperature during the construction of a chip seal is important. It was found that a chip seal should not be constructed at ambient temperatures lower than 86˚ F or higher than 110˚ F to maintain adequate good long-term performance (Gürer et al. 2012). A comprehensive study was conducted to evaluate the performance of chip seals applied on Kansas highways from 1992 to 2006 and concluded that the average service life of chip seals in Kansas is about four years (Liu et al. 2010). Finally, a study concluded that the long-term performance of a chip seal is more dependent on the number of truck passes rather than the truck loading (Lukanen 1997).

Task 1.2: Report organization

This report is built upon the recently concluded project at Missouri S&T (Gheni et al. 2017) where the construction of a chip seal using rubber aggregate was investigated. This project focused on the field implementation of a rubberized chip seal in Rolla, Missouri with health monitoring of the road for approximately 13 months. This project includes twelve chapters summarizing the experimental work as well as the field implementation. Furthermore, three appendices are provided where detailed information about testing and raw data is summarized.

2. Task 2: Material characterization and properties

2.1. Asphalt emulsion

CRS-2P asphalt emulsion, which is a cationic rapid-setting and high-viscous type, was used during this study (Table 1). The CRS-2P includes 30% water content by weight of the total emulsion. The water breakout of the emulsion was examined by measuring the weight lost after exposing the emulsion to different temperatures over time (Fig. 6). Approximately 81% of the water breakout occurred after 6 hours at a temperature of 35^{o} C, beyond that there was approximately no evaporation after 24 hours of exposure.

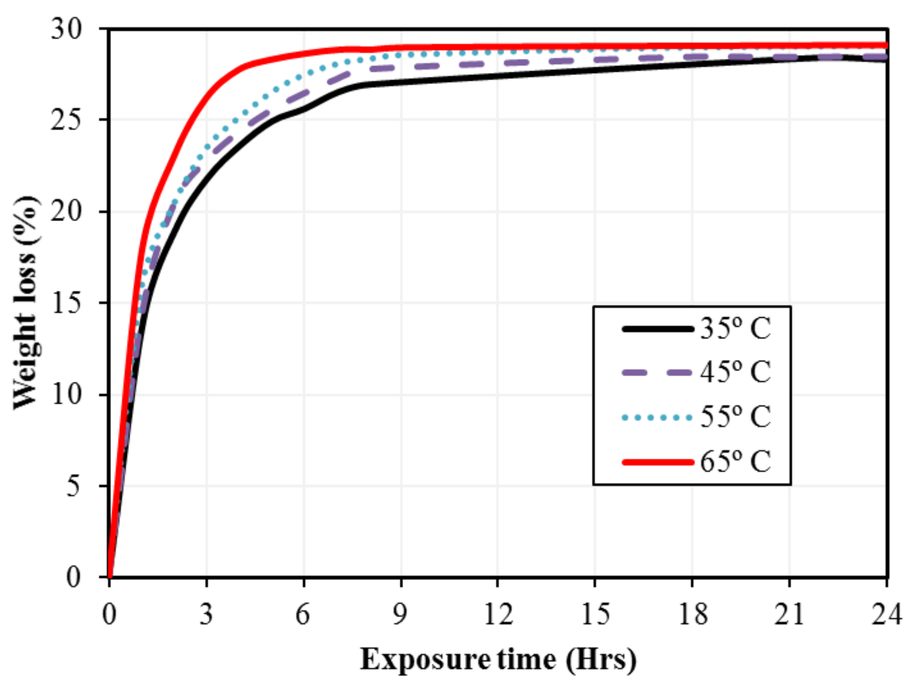


Figure 6: Emulsion weight loss due to water breakout

Table 1: Emulsion properties

Properties	Test Method	Min	Max
Viscosity, SFS @ 122°F	ASTM D-7496	100	300
Sieve test, %	ASTM D-6933		0.3
Demulsibility, % 35 mls 0.8% sodium dioctyl sulfosuccinate	ASTM D-6936	40	
Storage stability, 1 day, %	ASTM D-6930		1
Particle charge	ASTM D-7402	Positive	
Distillation Test: Residue by distillation, % by weight	ASTM D-244	65	
Distillation Test: Oil distillate, % by volume of emulsion	ASTM D-6997		3
Tests on Residue from Distillation: Polymer content, wt. % (solids basis)		3	
Tests on Residue from Distillation: Penetration, 77°F, 100g., 5 secs	ASTM D-5	100	150
Tests on Residue from Distillation: Viscosity, 140°F, poise	ASTM D-2171	NA	NA
Tests on Residue from Distillation: Solubility in TCE, %	ASTM D-2042	NA	NA
Tests on Residue from Distillation: Elastic recovery, 50°F., %	ASTM D-6084	60	
Tests on Residue from Distillation: Softening point, °C	ASTM D-36		
Tests on Residue from Distillation: Float test, 60°C, secs	ASTM D-139		
Tests on Residue from Distillation: Ductility, 39.2°F., 5 cm/min, cm	ASTM D-113	30	

2.2. Natural aggregate and crumb rubber

Trap rock and crumb rubber were used during this study as aggregates (Fig. 7). Figure 8 and Table 2 present the sieve analysis and properties of the aggregates used. As shown in Table 2, the natural aggregate had a median size of 0.271 inches with a maximum aggregate size of 0.374 inches while the crumb rubber aggregate had a median size of 0.312 inches with a maximum aggregate size of 0.5 inches. The crumb rubber had lower percentage of dust, materials passing through No. 200 sieve, where the crumb rubber had 0.20% and the natural aggregate had 0.52%.

The rubber aggregate had 0.40% and 0.37% Micro-Deval and Los Angeles abrasion resistance compared to 4.1% and 22.2%, respectively, for the trap rock aggregate (Table 2). The flakiness index, defined as the percentage by weight of the aggregates whose least dimension is less than three-fifths of its mean dimension, is another important factor in the design of the chip seal. The lower the flakiness, index is the better aggregate. The flakiness index of the natural aggregate was 42% while it was 31.3% for the crumb rubber. Another important parameter for a chip seal is the fractured face. One hundred percent of both types of aggregates had two or more fractured faces due to the fracturing and cutting process during the production.

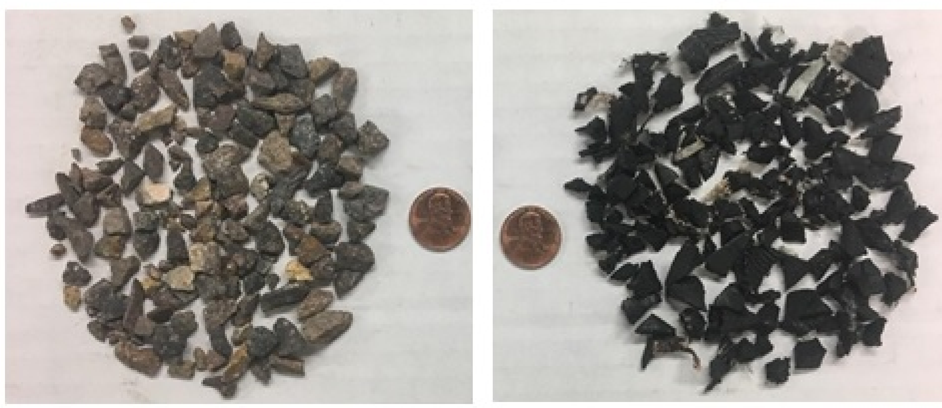


Figure 7: Aggregates used throughout this study: (a) trap rock, and (b) crumb rubber

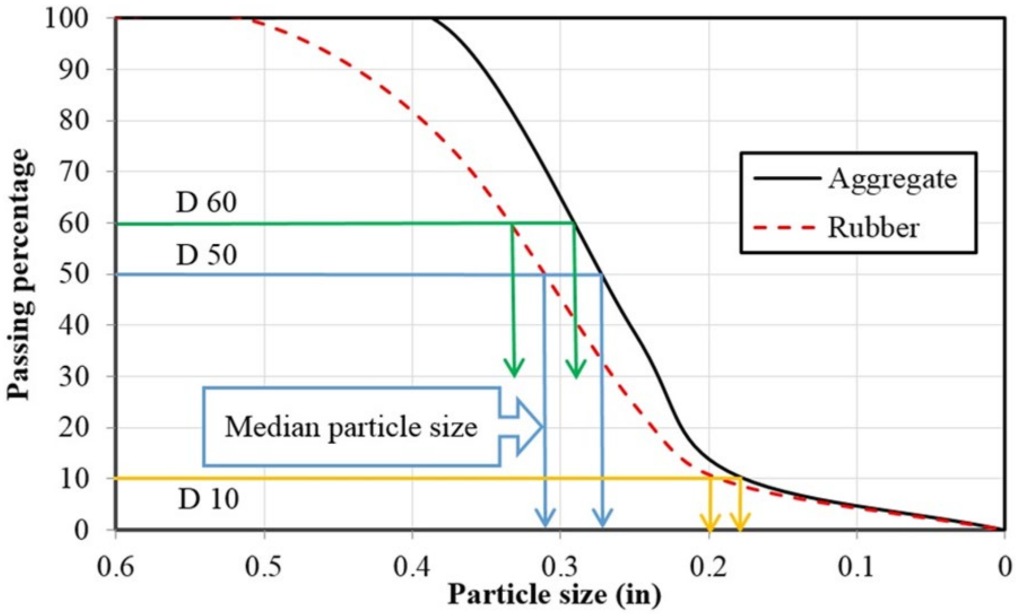


Figure 8: Sieve analyses of both crumb rubber and natural aggregate

The crumb rubber had a low bulk specific gravity of 0.87, which was approximately 33% of that of the natural aggregates. Furthermore, the crumb rubber had a dry unit weight of 26 lb/ft^3 that was approximately 34% of that of natural aggregates. The natural aggregate had water absorption of 2.27% compared to negligible water absorption for the crumb rubber. More detail about the aggregate can be found in Appendix A.

Table 2: Aggregate properties

Type of Aggregate	Crumb rubber	Trap rock
Bulk specific gravity	0.87	2.56
Absorption, %	0.00%	2.27%
Coefficient of uniformity	1.57	1.67
Fractured faces-Percent of non-fractured faces	0.00%	0.00%
Fractured faces-Percent of aggregates with one or more faces	100%	100%
Fractured faces-Percent of aggregates with two or more faces	100%	100%
Loose dry unit weight, lb/ft^3	26	78
Voids in loose aggregates, %	79.5	43.9

Type of Aggregate	Crumb rubber	Trap rock
Los Angeles loss by abrasion and impact, %	0.37%	22.2%
Micro-Deval weight loss, %	0.40%	4.1%
Dust (Materials passing No. 200 sieve), %	0.20%	0.52%
Median particle size, in.	0.31	0.27
Flakiness index, %	31.3%	42.0%

3. Task 3: Construction of chip seal laboratory specimens.

3.1. Design of chip seal specimens

There is no consensus in the U.S. on how to design a chip seal. A recent survey including 54 U.S. states and cities showed that only 18% of respondents use McLeod, Kearby, and modified Kearby methods to design a chip seal while 26% of the respondents do not use a formal design method. The remaining 56% of the respondents use their own local, empirical, or past experience design method (Gransberg and James 2005, Gheni; et al. 2017). For example, Minnesota Department of Transportation (MnDOT) adopted a software package to design a chip seal coating. This design software considers the condition of the road and traffic volume in addition to aggregate and binder properties. This software was used during the course of this study to design the chip seal specimens.

The design of a chip seal aims to determine the aggregate application rate required to form a blanket of one stone in depth and determine the corresponding asphalt binder application rate to satisfy a given aggregate embedment depth ranging from 50% to 80% of the median aggregate size depending on the design guidelines. Appendix B displays a step-by-step design of the test specimens following four different approaches: McLeod, Kearby, modified Kearby, and MnDOT. McLeod's method resulted in aggregate application rates of 19.15 and 7.86 lb/yd^2 for the natural aggregate and crumb rubber, respectively. There is no difference in determining the required aggregate per Kearby and modified Kearby methods. The board test (See Fig. B3, Appendix B) was used to determine the aggregate quantity in both the Kearby and modified Kearby methods. The test resulted in aggregate application rates of 14.1 and 5.0 lb/yd^2 for the natural aggregate and crumb rubber, respectively. The MnDOT method resulted in aggregate application rates of 23.7 and 9.25 lb/yd^2 for the natural aggregate and crumb rubber aggregate, respectively.

Determining the binder rate of application was more challenging, as there were more discrepancies between the results of the different design methods. The main reason behind this discrepancy was the time to achieve the required design aggregate embedment depth. For example, McLeod assumes that the design aggregate embedment depth will be satisfied after two years of service life, while the Kearby and modified Kearby methods assume that the design aggregate embedment depth will be satisfied immediately before opening the road for traffic. This will result in a smaller binder application rate following McLeod method compared to the Kearby and modified Kearby methods. Finally, MnDOT design software assumes the embedment depth will be satisfied immediately before opening the road for traffic. The McLeod, Kearby, modified Kearby, and MnDOT design methods resulted in emulsion application rates of 0.29, 0.36, 0.76, and 0.46 gal/yd^2, respectively, for natural aggregate and 0.34, 0.36, 0.83, and 0.48 gal/yd^2 respectively for crumb rubber assuming an embedment depth of 67% after two years of service for the McLeod's method, 50% for the Kearby and modified Kearby methods, and 70% for the MnDOT method as shown in the detailed calculations in Appendix B. To test the applicability of different binder application rates that were predicted by the above design methods, chip seal specimens were manufactured in the laboratory using the same binder, natural aggregate, and crumb rubber material that were used during the field implementation (Task 10 in this report). The specimens were manufactured using binder rates of 0.35, 0.425, and 0.50 gal/yd^2 with natural aggregate or crumb rubber (Fig. 9). These specimens were tested for their macrotexture using sand patch and image processing as explained in Tasks 4 and 5 in this report.

Table 3 summarizes the application rate following each design method in addition to the six laboratory specimens. As shown in Table 3, the natural aggregate rates varied between 15.0 and 23.7 lb/yd^2 while the emulsion rates were very diverse in a range of 0.29 to 0.83 gal/yd^2 based on the design method. As a result, the proposed laboratory specimens had ranges of emulsion and aggregate rates within the median of the different rates that were obtained from the design methods. In addition, the constructed laboratory specimens took into consideration common practice and application rates in the state of Missouri.

Table 3: Summary of chip seal design methods

Design Method	Trap Rock Emulsion (gal/yd^2)	Trap Rock Aggregate (lb/yd^2)	Rubber Emulsion (gal/yd^2)	Rubber Aggregate (lb/yd^2)
McLeod	0.29	19.2	0.34	7.86
Kearby	0.36	15.0	0.43	5.00
Modified Kearby	0.83	15.0	0.79	5.00
Minnesota DOT	0.46	23.7	0.49	9.25
Lab specimen 1	0.35	15.0	0.35	5.00
Lab specimen 2	0.43	15.0	0.43	5.00
Lab specimen 3	0.50	15.0	0.50	5.00

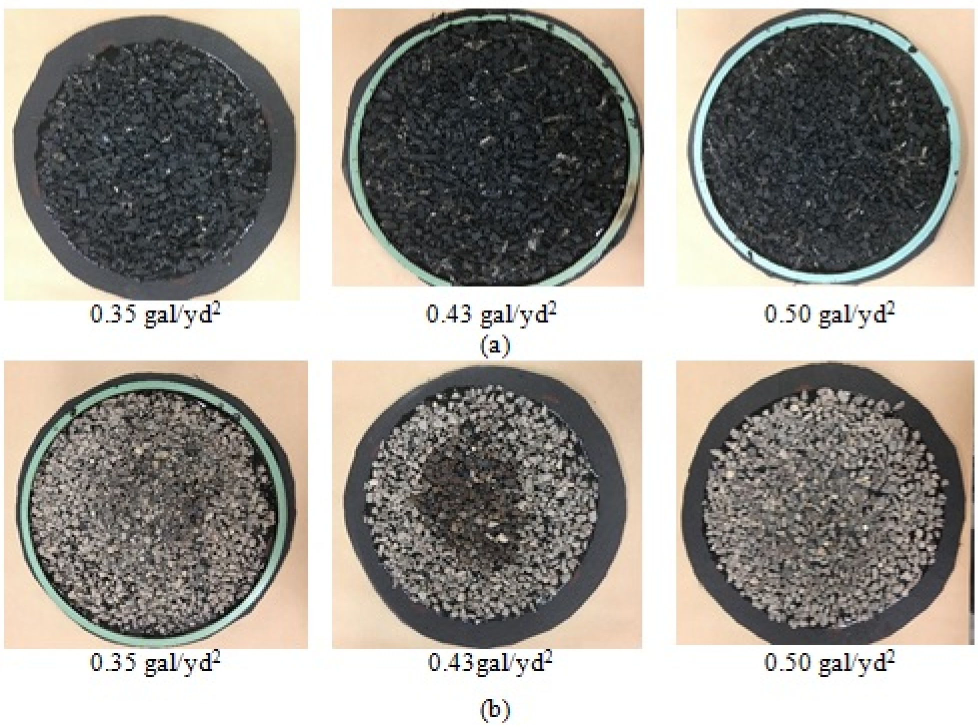


Figure 9: Chip seal specimens with different binder application rates and specimens with: (a) %100 crumb rubber, and (b) %100 trap rock

4. Task 4: Laboratory sand patch tests

During this task, the median texture depth (MTD) of each specimen constructed during Task 3 was measured using the sand patch method (ASTM E965). This procedure included preparing a volume of fine sand that, passes a No. 60 sieve and is retained on a No. 80 sieve. The sand was spread uniformly on the surface of each of the test specimens using an ice hockey puck with its bottom surface covered with a stiff rubber material. The diameter of the spreading sand on each investigated specimen was measured at least four times in different orientations. Appendix C demonstrates a step-by-step procedure for carrying out the sand patch testing. The average diameter, D, was determined and implemented in Equation 1 to determine the MTD which is an indication of the aggregate embedment depth (Fig. 10).

$$MTD= (4\,V)/(\pi\,D^{\wedge}2\,) \tag{1}$$

where V is the sand volume.

Figure 11 and Table 4 show the influence of having different rubber ratios and binder application rates on the MTD of chip seal specimens. As shown in Table 4 and Figure 11, the MTD of both conventional and rubberized chip seal specimens decreased with an increase in the binder application rate. The MTD values decreased from 0.187 and 0.242 inches to 0.131 and 0.172 inches for conventional and rubberized chip seal specimens having a binder application rate of 0.35 gal/ yd^2 and 0.50 gal/ yd^2, respectively. In addition, replacing trap rock with rubber aggregate linearly increased the MTD. For example, using a 100% rubber replacement ratio increased the MTD from 0.187, 0.160, and 0.131 inches to 0.242, 0.199, and 0.172 inches for chip seal specimens with binder application rates of 0.35, 0.43, and 0.50 gal/ yd^2 which represent increases of 30%, 24%, and 32%, respectively. This increase was due to the rough surface of rubber particles compared to trap rock aggregate (Gheni; et al. (2017). In addition, the rubber particles have a smaller flakiness index compared to trap rock aggregate (Table 2), i.e., the number of particles having a flat shape in rubber aggregate was about 27% less than that of the trap rock. Flat shaped aggregate particles tend to align their long dimensions perpendicular to the compaction force (Fig 12).

Table 4: MTD of chip seal specimens with different binder application rates

Binder application rate (gal/ yd^2)	MTD (inches) 0% Rubber (Conventional)	MTD (inches) 100% Rubber
0.35	0.1866	0.2421
0.43	0.1602	0.1988
0.50	0.1307	0.1724

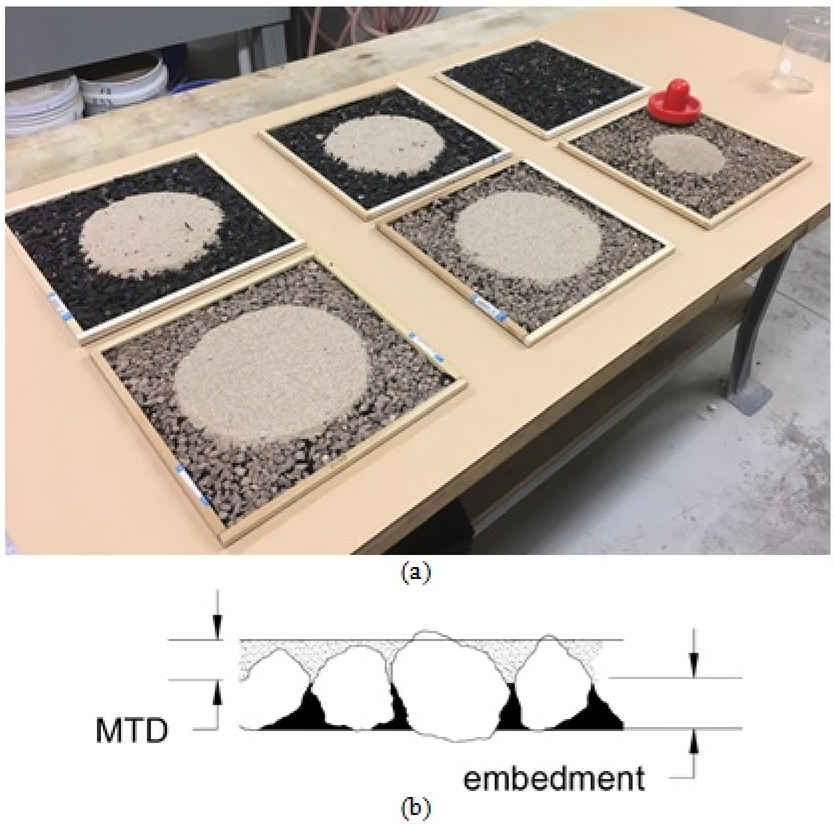


Figure 10: Sand patch: (a) test specimens, and (b) median texture depth (MTD)

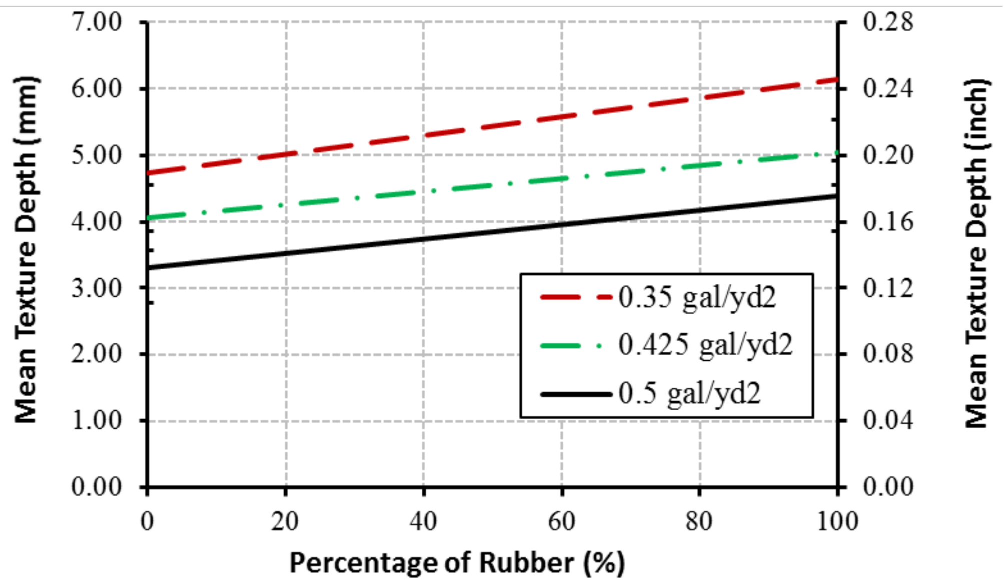


Figure 11: Sand patch test result

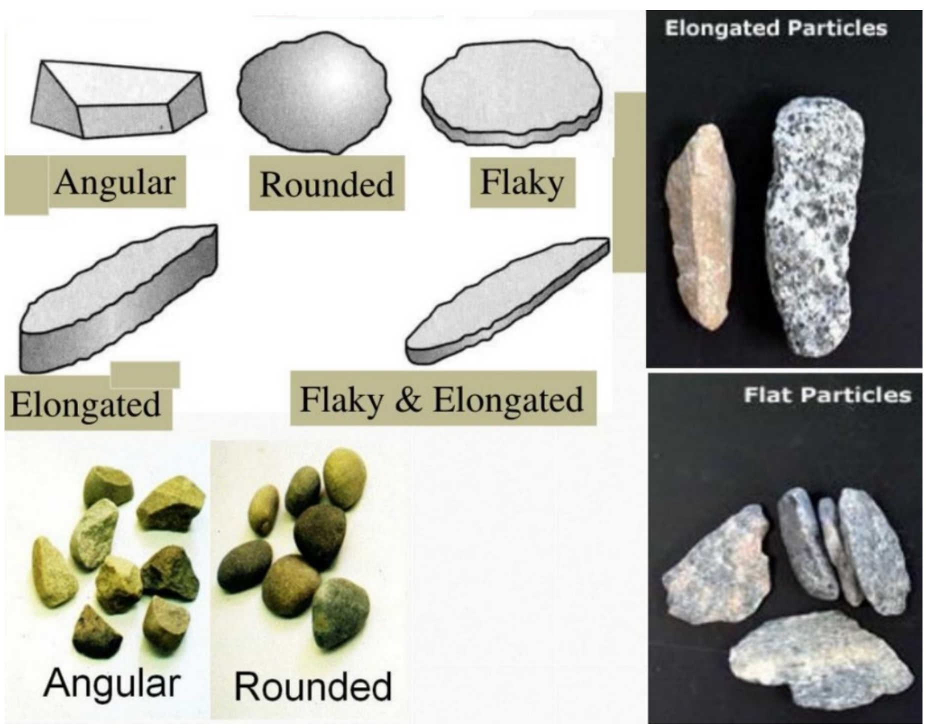


Figure 12: Aggregate particle's shapes

Based on the measured MTD values (Table 4) of the binder application rates, the embedment percentage of the trap rock and rubber particles can be calculated following equation 2 (Fig 10a). Using median particle sizes of 0.27 in. and 0.31 in. for trap rock and rubber aggregates, the average embedment values were 31%, 41%, and 52% of the median size of the used aggregate for trap rock chip seal specimens and 22%, 36%, and 45% of the median size of the used aggregate for chip seal specimens with 100% rubber replacement ratio, for chip seal specimens with emulsion application rate of 0.35, 0.43, and 0.5 gal/yd^2, respectively.

$$\text{Aggregate embedment } \% = \mathit{(Median\ particle\ size - MTD)/Median\ particle\ size} \qquad (2)$$

5. Task 5: Laboratory image processing analysis

The chip seal specimens that were prepared in the laboratory during Task 3 were tested for their MTDs using an image processing technique. The specimens were sectioned using a highly precise high-pressure water jet cutting machine (Figs. 13 and 14). The sections were scanned using a high-resolution scanner and then examined using the ImageJ™ image processing program to determine the MTD and aggregate embedment depth per binder application rate and aggregate replacement ratio. To determine the aggregate embedment depth, the area of the binder that was enclosed by the upper surface of the binder and the base of each specimen was measured using the software (Fig. 15). The calculated area was then divided by the length of the specimen to find the average depth of the binder and then the embedment ratio, which represents the depth of the binder divided by the median particle size. Once the aggregate embedment depth was determined, the MTD was calculated by subtracting the aggregate embedment depth from the total chip seal depth (Fig. 10a).

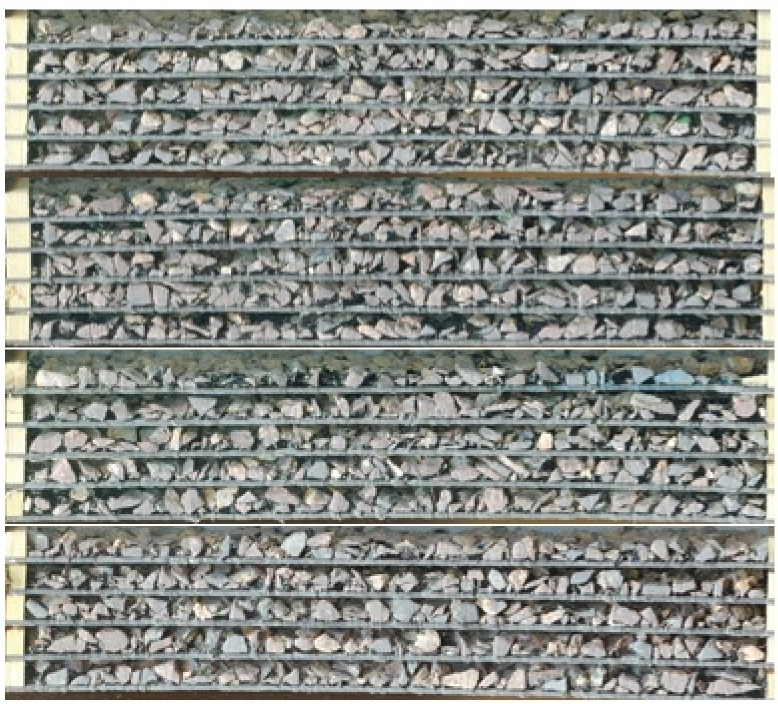


Figure 13: Chip seal sections for image processing for specimens with 100% trap rock aggregate

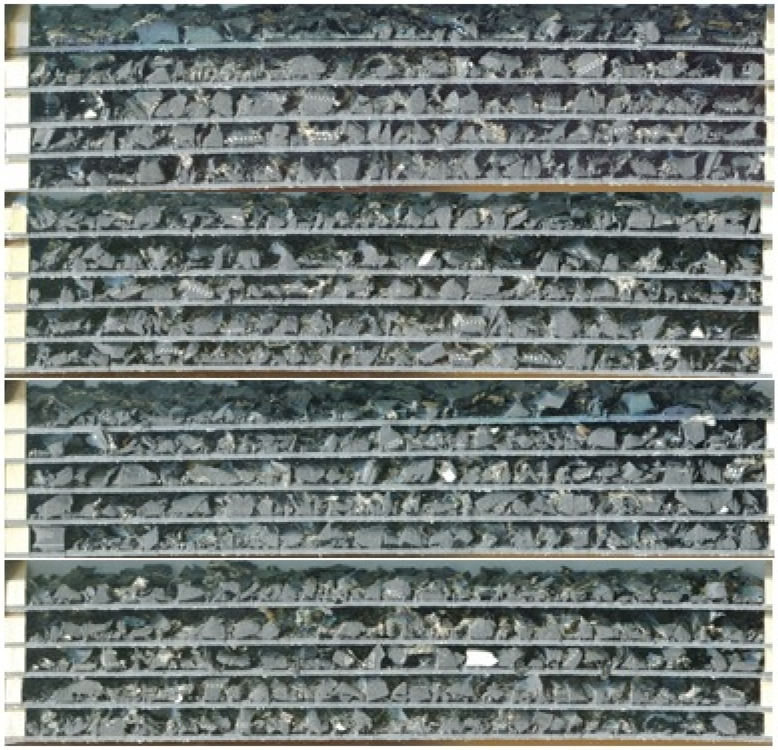


Figure 14: Chip seal sections for image processing for specimens with 100% rubber aggregate

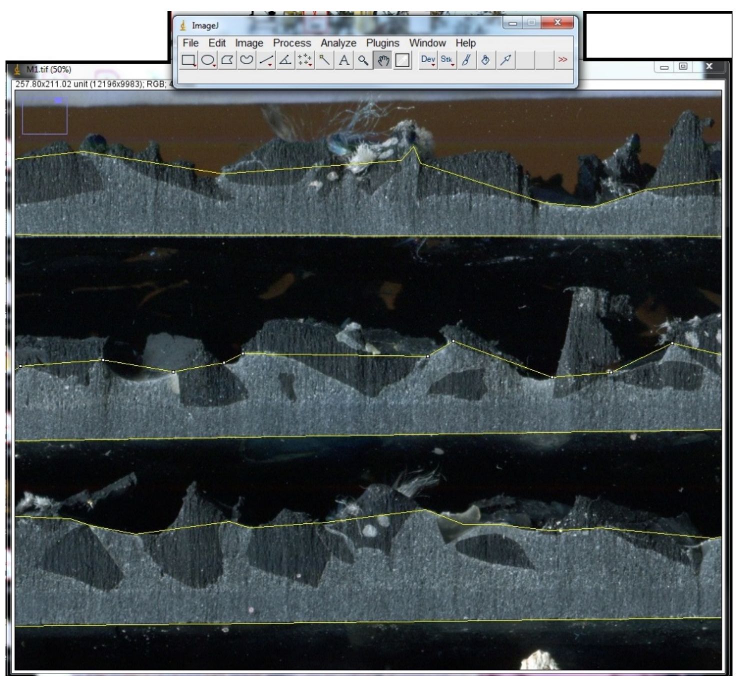


Figure 15: Finding the MTD using the image processing software ImageJ™

The binder application rate versus the MTD curves was then obtained (Fig. 16a). Similar to the findings of the sand patch test, for the same binder application rate, the crumb rubber specimens had larger values of MTD compared to those of the trap rock aggregate specimens. The increase in MTD was approximately 0.041 inches which is equivalent to an increase from 25% to 35% based on the binder application rate. Taking into account that the crumb rubber had a 0.031 inch larger median aggregate size than that of the trap rock, the increase in the MTD values of the crumb rubber specimens was due not only due to this small difference in particle size but also mainly due to the rough surface of crumb rubber particle as shown by the microtexture measurements (Gheni et al. 2017).

Figure 16b shows the relationship between the MTD measured using the sand patch test and those measured using the image processing technique. As shown in the figure, the sand patch method resulted in higher MTD since when the sand layer is applied during sand patching, it is recommended to cover all aggregate particles within this spot and hence sand patch deals with maximum aggregate size rather than the median particle size, which is the case with image processing method.

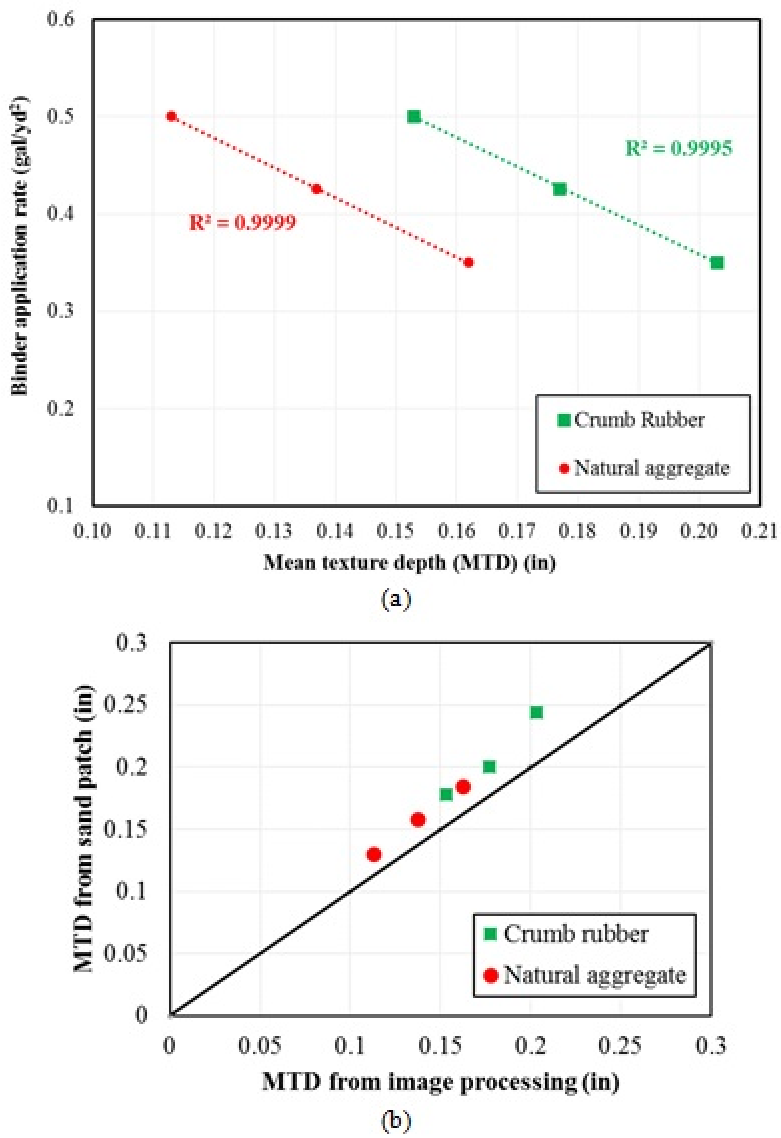


Figure 16: Effect of binder application rate on MTD: (a) MTD from image processing method, and (b) MTD from image processing method versus MTD from sand patch method

6. Task 6: Laboratory sweep tests

The effects of using different sizes of crumb rubber in chip seals on aggregate retention were evaluated during this task using sweep tests per ASTM D7000-11 (ASTM 2011). The standard test requires a binder application rate of 0.183 lb for an 11-inch diameter specimen. This amount of binder is equal to a binder application rate of 0.32 gal/yd^2. To investigate the impact of the binder application rate, a second set of specimens was prepared with 0.366 lb of binder, i.e., equivalent to a binder application rate of 0.64 gal/yd^2. Sixteen specimens with a 50% crumb rubber replacement ratio were prepared with four sets of crumb rubber aggregate particles where the sets had particle sizes ranging from 0.094 to 0.500 inches and two different binder application rates of 0.32 gal/yd^2 and 0.64 gal/yd^2. The trap rock in all specimens had the same size ranging from 1/4 to 3/8 inches (Fig A-1). For each binder rate and rubber aggregate particle size, six specimens were prepared. Three specimens were tested after two hours of curing, and the other three after 24 hours of curing.

The test consisted of running a brush (designed to closely replicate the sweeping action of a broom) across the aggregate used on surface treatments. An emulsion is applied to an asphalt felt disk. Aggregate is applied and embedded into the bituminous emulsion. The sample is then conditioned at 90 ˚F for a prescribed time period before testing. A mixer abrades the surface of the sample using a nylon brush. After one minute of abrasion, the test is stopped, any loose aggregate is removed, and the percent of mass loss is calculated. More details about the test steps can be found in Appendix C. After each test, the mass loss due to the sweeping was calculated. The dislodged rubber and natural aggregate particles were collected separately, and their masses and volumes were calculated (Figs. 17 and 18).

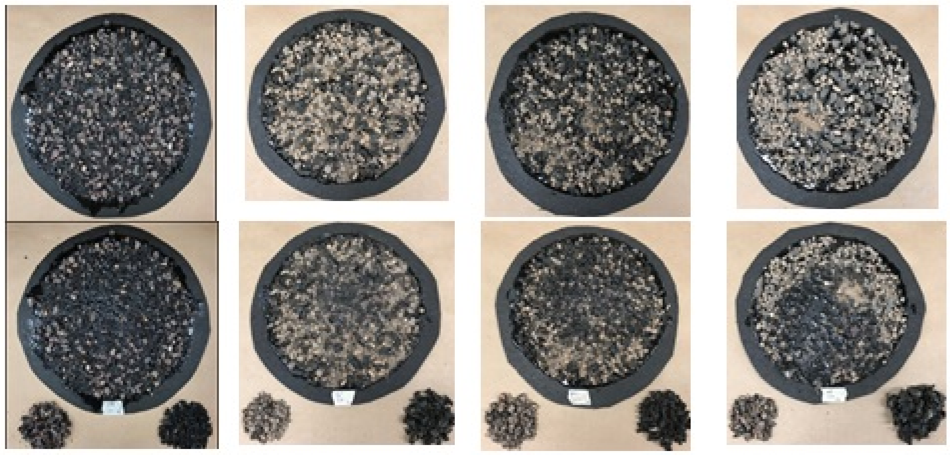


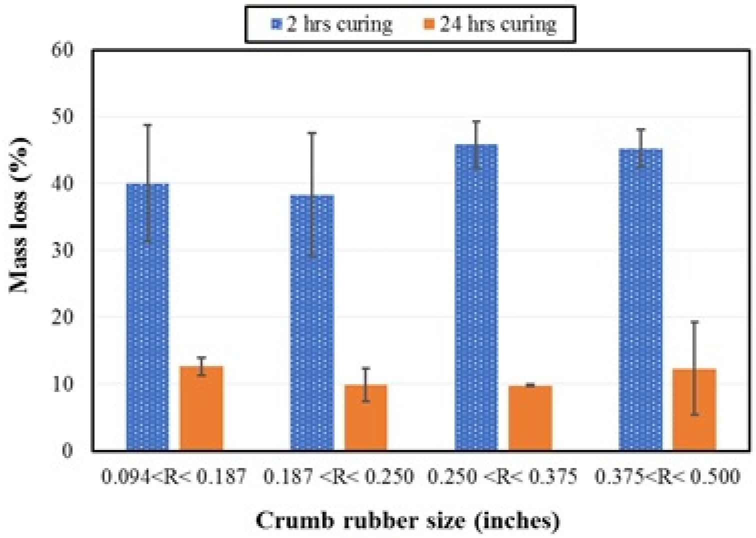
Figure 17: Laboratory sweep tests for specimens with different crumb rubber sizes before and after 2 hours of curing

Figure 18: Laboratory sweep tests for specimens with different crumb rubber sizes before and after 24 hours of curing

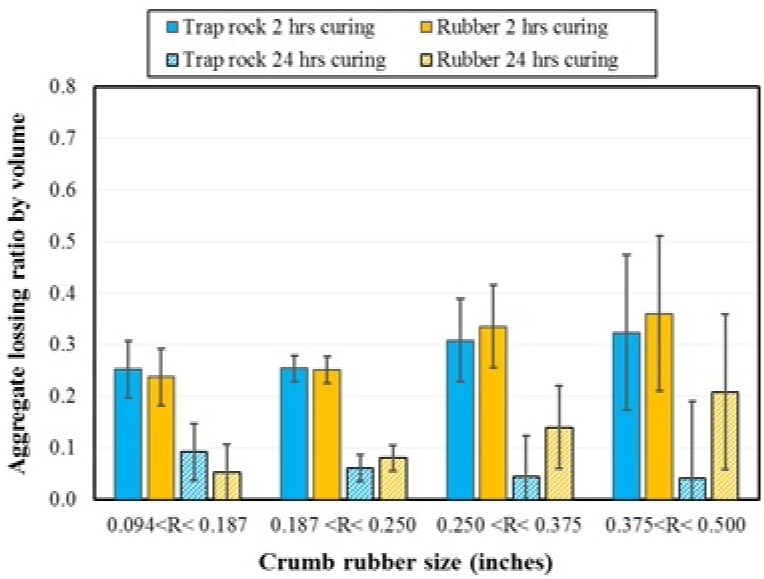
Figure 19 represents the sweep test results for specimens with 0.183 lb of binder cured for 2 and 24 hours. Figure 20 represents the sweep test results for specimens with 0.366 lb of binder cured for 2 and 24 hours. In each figure, Figure (a) represents the percent of total aggregate (trap rock and rubber) mass loss per ASTM D7000-11 to the total applied aggregate mass. Figure (b) represents the percent of the volume of dislodged aggregate for each of the trap rock and crumb rubber compared to the original applied volume of that type of aggregate.

As shown in Figures 19, and 20, after two hours of curing, increasing the size of rubber while keeping the trap rock size constant increased the total mass loss and the ratio of the amount of dislodged crumb rubber particle to that of the trap rock aggregate for specimens with both

0.183 lb and 0.366 lb of the binder. For example, increasing the rubber maximum particle size from 0.187 to 0.500 inches increased the mass of dislodged aggregate from 40% to 45% and from 37% to 49% for binder applications of 0.183 lb and 0.366 lb, respectively. Furthermore, increasing the maximum rubber particle size from 0.187 to 0.500 inches increased the ratio of dislodged crumb rubber from 0.24 to 0.36 and from 0.25 to 0.48 for binder applications of 0.183 lb and 0.366 lb, respectively. Increasing the rubber aggregate size in a test specimen made the rubber aggregate more exposed compared to the trap rock and hence increased the potential for dislodging.



(a)



(b)

Figure 19: Effect of crumb rubber particle size on aggregate loss after laboratory sweep tests for specimens with emulsion rate of 0.183 lb, after 2 and 24 hours of curing: (a) absolute mass, and (b) the percent of the volume of dislodged aggregate for both trap rock and crumb rubber for the same specimen.

After 24 hours of curing (Figs. 19 and 20), the total mass loss was approximately similar for all specimens regardless of the rubber aggregate size. The mass loss of the aggregate ranged from 10% to 12% and from 8% to 10% for binder application rates of 0.183 lb and 0.366 lb, respectively. Furthermore, the amount of dislodged crumb rubber particles increased with increasing the crumb rubber particle size compared to the dislodged trap rock aggregate for specimens with both binder rates. For example, increasing the crumb rubber particle size from 0.187 to 0.500 increased the ratio of dislodged crumb rubber from 0.05 to 0.20 and from 0.05 to 0.18 for binder application rates of 0.183 lb and 0.366 lb, respectively. However, this decrease was measured in volume not weight and as the crumb rubber particle size was increased, the volume of the particles increased significantly in a way that the dislodging of one particle made a significant difference.

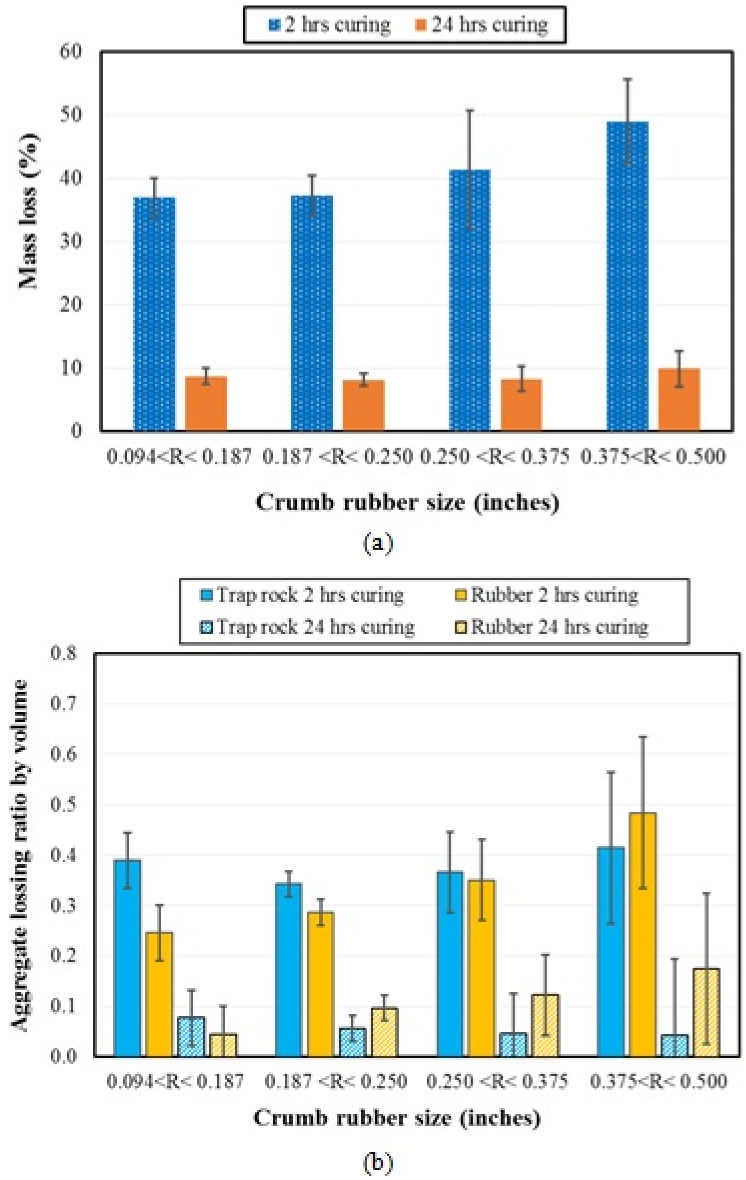


Figure 20: Effect of crumb rubber particle size on aggregate loss after laboratory sweep tests for specimens with emulsion rate of 0.366 lb, after 2 and 24 hours of curing: (a) absolute mass, and (b) the percent of the volume of dislodged aggregate for both trap rock and crumb rubber for the same specimen.

As shown in Figures 21, for chip seal specimens with different crumb rubber sizes, increasing the curing time decreased the mass loss for both binder application rates. For example, for chip seal specimens with maximum particle's size of 3/8 inches, increasing the curing time from 2 hours to 24 hours decreased the mass loss from 46% to 10% and from 42% to 8% for binder applications of 0.183 lb and 0.366 lb, respectively.

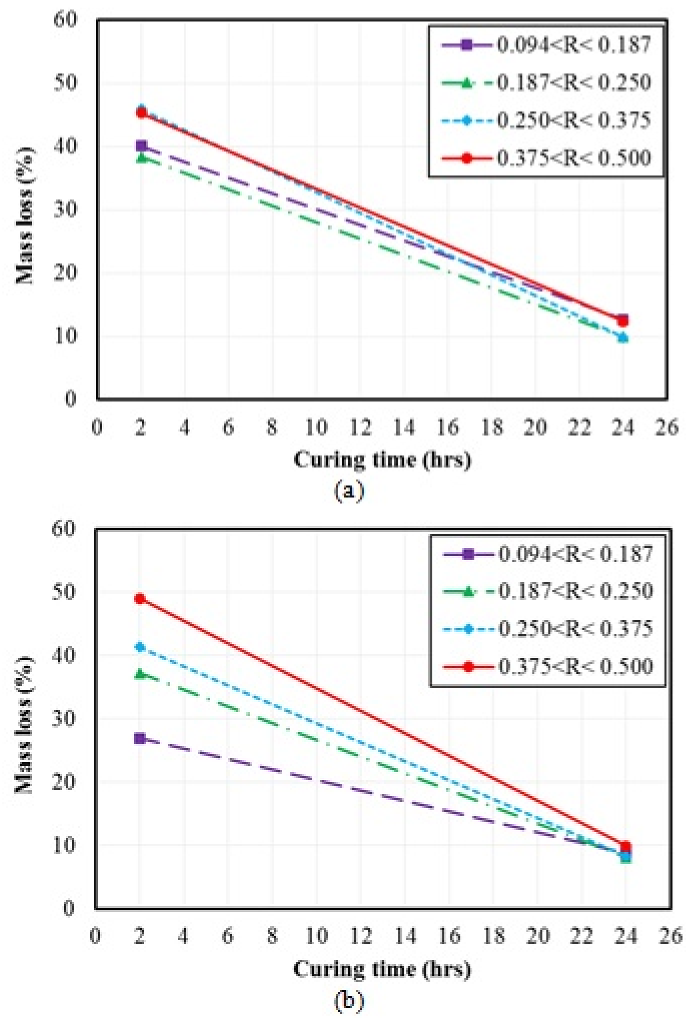


Figure 21: Effect of curing time on the sweep test mass loss for chip seal specimens with different crumb rubber particle sizes and emulsion rates of: (a) 0.183 lb, and (b) 0.366 lb

7. Task 7: Laboratory Vialit tests

This test was conducted, per the British Standard 12272–3 (EN 2003), to investigate the rubber aggregate and trap rock retention in emulsion pavement under impact loads (Fig. 22). As shown in the figure, the standard Vialit test involves a standard ball falling from 19.7 inches on a 7.8 inch x 7.8 inch cured and frozen specimen. The test is repeated three times and the numbers of dislodged and retained aggregate particles are determined. A detailed description of the Vialit test procedure can be found in Appendix C. More details about general preparation of test specimens for the Vialit test can be found in Gheni et al. (2017). Gheni et al. (2017) also introduced a modified Vialit test where 10, 20, and 30 ball-drops were used to investigate the retention of chip seal aggregate. Gheni et al. (2017) investigated the different parameters that affect the performance of trap rock and rubber aggregate during a Vialit test. The crumb rubber showed a superior performance of 100% retained aggregate due to the compatibility between the rubber and the asphalt emulsion as both the rubber and asphalt emulsions are made with a hydrocarbon organic base, especially at high temperature when partial melting of the surface of the crumb rubber particles occurred at the embedment depth, which creates a stronger bond with the surrounding binder.

(a) (b)

Figure 22: Vialit test: (a) test setup, and (b) a frozen specimen before test

This Task focused on assessment of the effect of aggregate size on retention of aggregate in emulsion under impact load. Vialit test specimens with 100% crumb rubber or 100% trap rock were prepared with four different aggregate particle sizes ranging from 0.094 to 0.500 inches (Fig. 23).

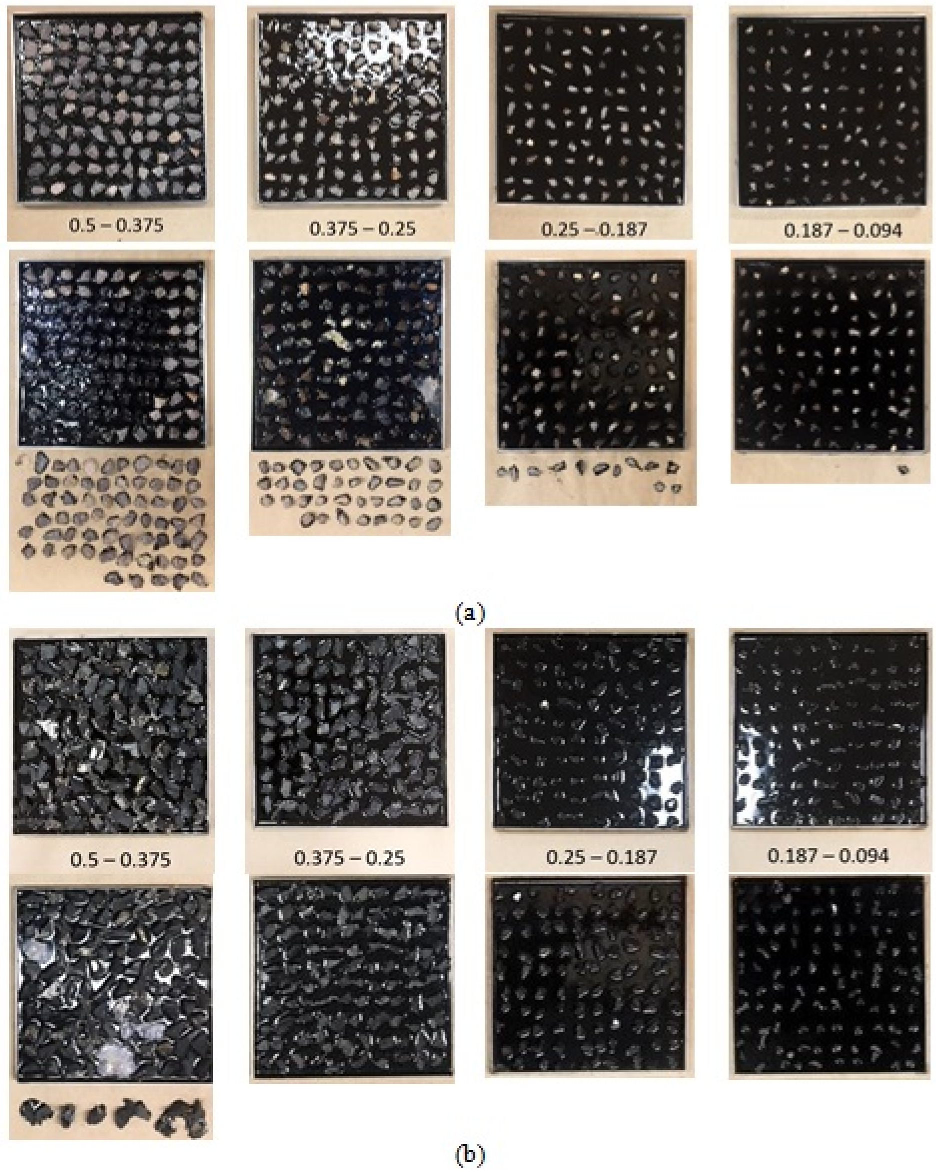


Figure 23: Vialit test specimens having different aggregate sizes before and after testing: (a) trap rock specimens, and (b) crumb rubber specimens

Figure 24 shows the number of drops versus the number of retained aggregate particles during the modified Vialit test for specimens prepared using trap rock or crumb rubber. As shown in the figure, the crumb rubber significantly outperformed the trap rock for all sizes except specimens having particles smaller than 0.187 inches where both types of aggregate behaved very similar.

Under the standard Vialit test, the emulsion retained 100% of the crumb rubber aggregate, having different sizes. Furthermore, increasing the number of drops by ten times, i.e., reaching 30 drops, the emulsion retained 100% of the crumb rubber aggregate except for specimens with crumb rubber particles between 0.375 and 0.500, inches where the retention was 90%.

Specimens with trap rock aggregate, having particles smaller than 0.250 inches, had a 100% retention rate under the standard Vialit test. However, under the modified Vialit test, larger aggregate sizes lost up to 65% of the aggregate after 30 drops. Increasing the number of drops increased the number of dislodged aggregate particles. At 30 drops, the aggregate retention rates were 99%, 87%, 62%, and 35% for specimens with aggregate particles smaller than 0.187, 0.250, 0.375, and 0.500 inches, respectively.

In addition to the compatibility between the rubber and asphalt emulsion materials, the rubber density is approximately 1/3 that of trap rock. Under dynamic impact load a rubber aggregate particle would be subjected to 1/3 the force demand compared to a trap rock particle having the same mass. Gheni; et al. (2017) also found that rubber particles have about 30% more surface area compared to trap rock particles. Therefore, the larger surface area increased the cohesion with asphalt emulsion compared to trap rock.

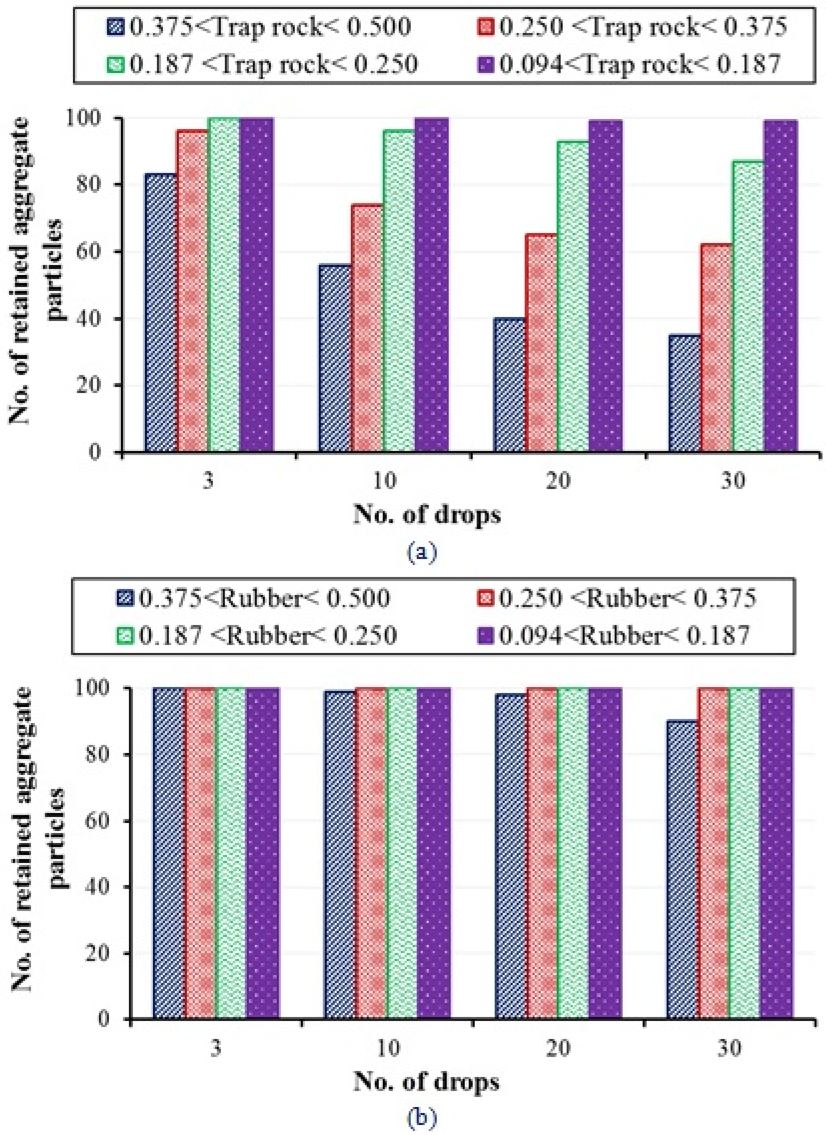


Figure 24: Number of retained aggregates particles versus no. of drops for specimens made of: (a) trap rock, and (b) crumb rubber

8. Task 8: Laboratory Pennsylvania test

This test was conducted to investigate the rubber aggregate and trap rock retention in emulsion pavement under dynamic loads (Fig. 25). As shown in the figure the test involves preparing a column consisting of six sieves each with an eight-inch diameter and a pan located at the bottom of the column. The whole assembly was inserted into an inclined sieve shaker. During the test, the required amount of aggregate was dropped through the sieves into the pan which included the required emulsion amount. The specimen collected in the pan was taken off and compacted using standard pressure. The specimen was left to cure; then, the whole assembly was placed upside down into the sieve shaker which was rotated for 5 minutes. The weight of the knocked-off aggregate particles in the bottom was collected and measured. A detailed description of the Pennsylvania test procedure can be found in Appendix C. More details about the preparation of test specimens for the Pennsylvania test can be found in Gheni et al. (2017).

(a) (b)

Figure 25: Pennsylvania test: (a) complete assembly for applying aggregate, and (b) Knock-off test assembly

While the Pennsylvania test is not a standard test, it has been used by several researchers in the literature as a tool to compare the retention performance of different chip seal constituents, i.e., aggregate types and/or emulsion types (Kandhal and Motter 1991). Gheni et al. (2017) investigated the different parameters that affect the performance of trap rock and rubber aggregate during a Pennsylvania test. Crumb rubber showed distinguished performance with knock-off loss of about 1%. This behavior was due to the low unit weight and the high, rough surface of the crumb rubber.

This Task focused on assessment of the effect of aggregate size on retention of aggregate in emulsion pavement using the Pennsylvania test. Pennsylvania test specimens with 100% crumb rubber or 100% natural aggregate were prepared with four different maximum crumb rubber particle sizes ranging from 0.187 to 0.500 inches (Fig. 26). The test specimens were tested as explained earlier and the knock-off aggregate was collected and weighted (Fig. 27). As shown in the figure, the crumb rubber significantly outperformed the trap rock for all sizes with knock-off loss of 1.0%, 0.8%, 0.3%, and 0.0% for specimens with crumb rubber compared with 1.8%, 2.6%, 3.4%, and 1.1% for specimens with trap rock while the total mass loss was 2.5%, 1.3%, 0.7%, and 0.0% for specimens with crumb rubber compared with 34.8%, 19.2%, 7.2%, and 1.1% for specimens with trap rock for a maximum particles size of 0.187, 0.250, 0.375, and 0.500 inches, respectively. It is worth noting that the Pennsylvania test examines the aggregate retention based mainly on the aggregate self-weight, surface area, and cohesion as each specimen is subjected to high compression forces, i.e., 40 psi to achieve good embedment depth before starting the test. The superior performance of the crumb rubber can be interpreted as explained earlier due to the low unit weight as well as high and rough surface area of the crumb rubber and compatibility between rubber and pavement.

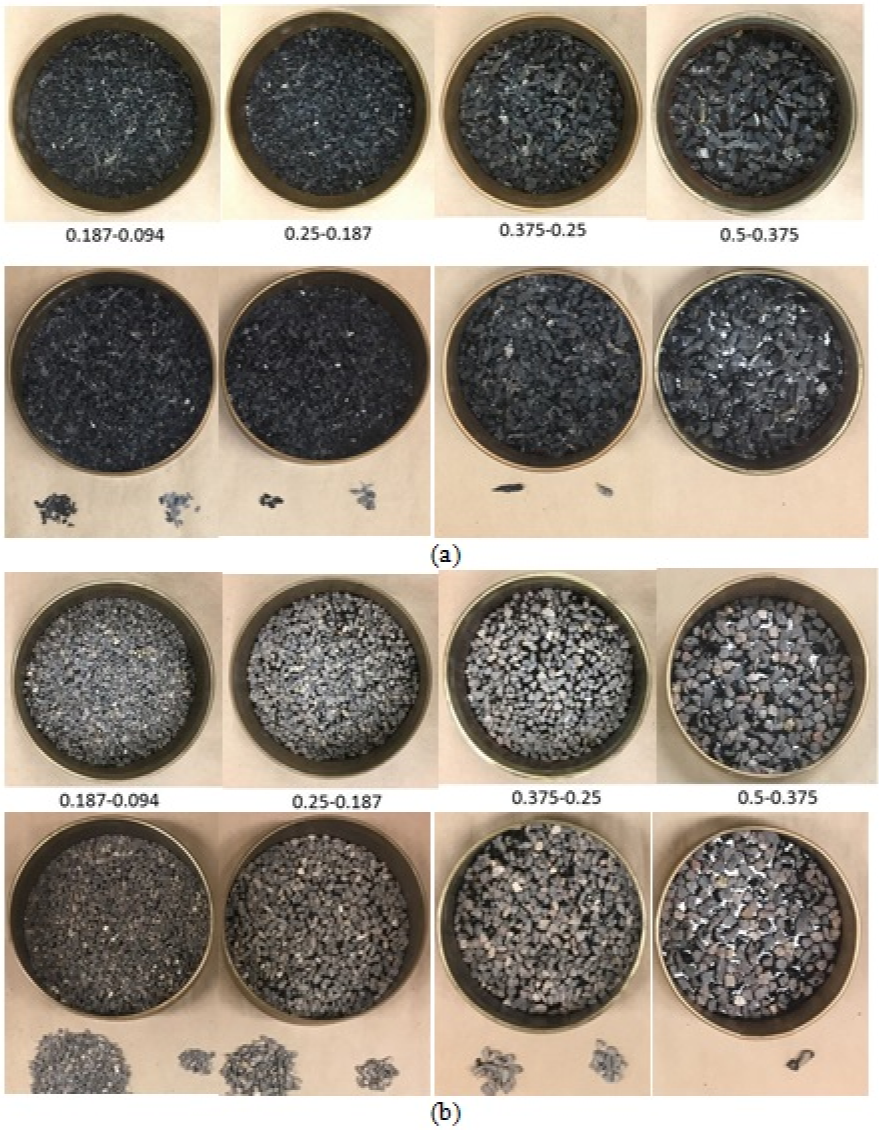


Figure 26: Pennsylvania test specimens with different trap rock aggregate and crumb rubber sizes: (a) crumb rubber specimens, and (b) trap rock specimens

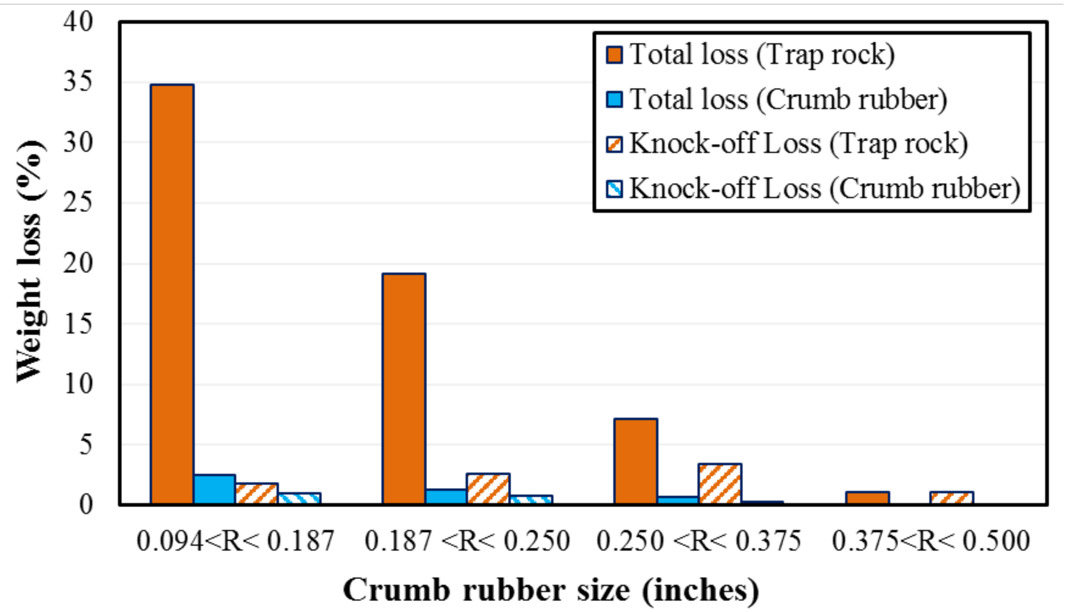
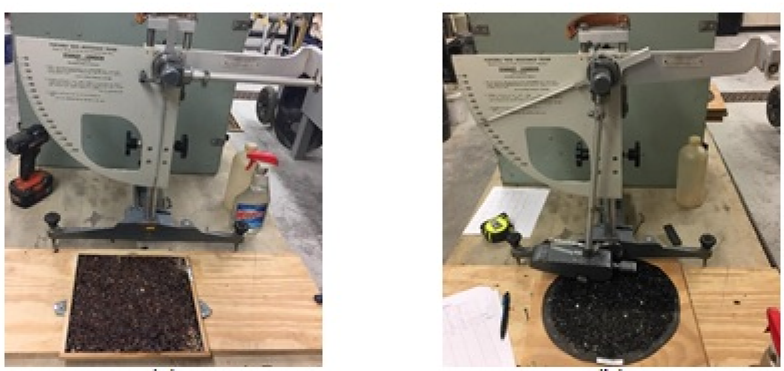


Figure 27: Total and knock-off weight loss for chip seal specimens having trap rock aggregate or crumb rubbe

9. Task 9: Laboratory skid friction resistance tests

This test was conducted, per ASTM E303-93, to investigate the skid friction of chip seal specimens having rubber aggregate and trap rock. The specimens manufactured during Task 3 of this report using binder rates of 0.35, 0.425, and 0.5 gal/yd^2 with natural aggregate or crumb rubber (Fig. 9) were tested for their skid friction (Fig. 28). As shown in the figure, the British Pendulum Test (BPT) was used to measure the skid friction and the test involved adjusting the pendulum vertically in order to achieve a slider contact path on the chip seal surface of 5 ± 1/16 inches. Water was sprinkled on the specimen surface before running the test. After releasing the pendulum, the British Pendulum Number (BPN) was recorded and used to represent the friction resistance of the specimen. The test was repeated four times after one trial test to get the average BPN for each specimen. Detailed description of the BPT procedure can be found in Appendix C. Gheni et al. (2017) investigated the different parameters that affect the skid resistance performance of chip seal specimens having trap rock and rubber aggregates. While both micro and macrotexture showed significant improvements when crumb rubber was used as an aggregate, a reduction ranging from 1.5% to 20% in the BPN for specimens with crumb rubber replacement ratios ranging from 25% to 100% were recorded. It should be noted that the BPN is not reliable for rough surface such as chip seal. Hence, more advanced techniques are required to measure the skid resistance of crumb rubber chip seal. Furthermore, under high temperatures, crumb rubber chip seal specimens outperformed those of trap rock chip seal specimens.



(a) (b)

Figure 28: Laboratory skid test for specimens with 100%: (a) trap rock, and (b) crumb rubber

Figure 29 shows the measured BPN versus binder application rate for test specimens. As shown in the figure, increasing the binder application rate decreased the friction measured in the form of BPN. Fig. 32 shows the reduction in the BPN due to increasing the binder application rate beyond 0.35 gal/yd^2. As shown in Fig. 30, the reduction in BPN is approximately linear regardless of the aggregate type. The reduction in BPN occurred since increasing the binder application rate increased the aggregate embedment depth, which decreased the MTD.

While the sand patch and image processing indicated that the micro and macrotexture of the crumb rubber were better than those of the trap rock, the skid friction tests showed that the BPNs decreased when the trap rock was replaced by crumb rubber. A decrease in the BPNs ranging from 26% to 30% (Fig. 29) was measured for specimens having rubber content ratios of 100%, based on the binder application rate, compared to that of the specimens having trap rock. The contradiction between the skid resistance test results and the texture characterization results using image analysis and sand patch is attributed to three reasons. First, the adhesion component which is part of the skid friction resistance cannot be fully captured by the British pendulum tester (BPT) as the contact area between the BPT slider and specimen is infinitesimal. Mataei et al. (2016) reported that BPT displayed unreliable behavior when used on coarse-textured pavement such as chip seal, due to the infinitesimal contact area. Second, the BPT measures the friction at low speed where microstructure of the pavement is controlling the behavior. Third, the hysteresis component of the friction is related to the energy loss that occurs as the rubber layer in the pendulum is alternately compressed when it comes into contact with a rigid aggregate and decompressed when it separates from the aggregate; since crumb rubber aggregate is less rigid than trap rock, the hysteretic component should be less in the case of rubberized chip seal. Therefore, despite the fact that the BPN for specimens having trap rock was in average 28% higher than that of specimens having crumb rubber, this should not be a serious concern due to the singularities in the BPN measurements as well as the fact that BPN represents the micro-texture of the chip seal (versus sand patch which represents the macro-texture) which controls the friction at speeds lower than 25 mph.

It is worth noting that Gheni et al. (2017) found that under higher temperatures such as those that pavement experiences during summer seasons, chip seal specimens constructed using trap rock lost up to 9% of their measured BPN. Using rubber significantly reduced such losses (Fig.31).

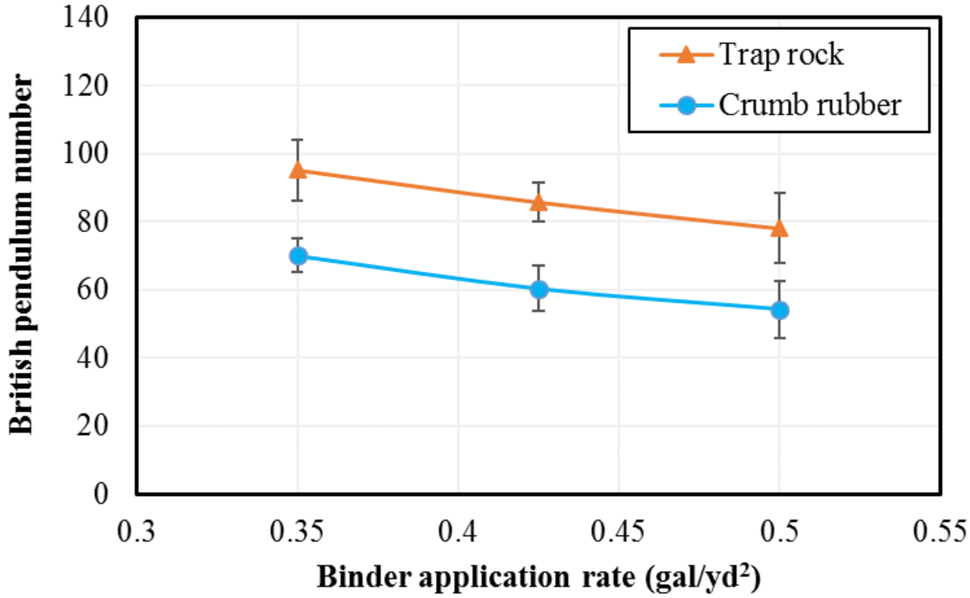


Figure 29: Measured BPN versus binder application rate

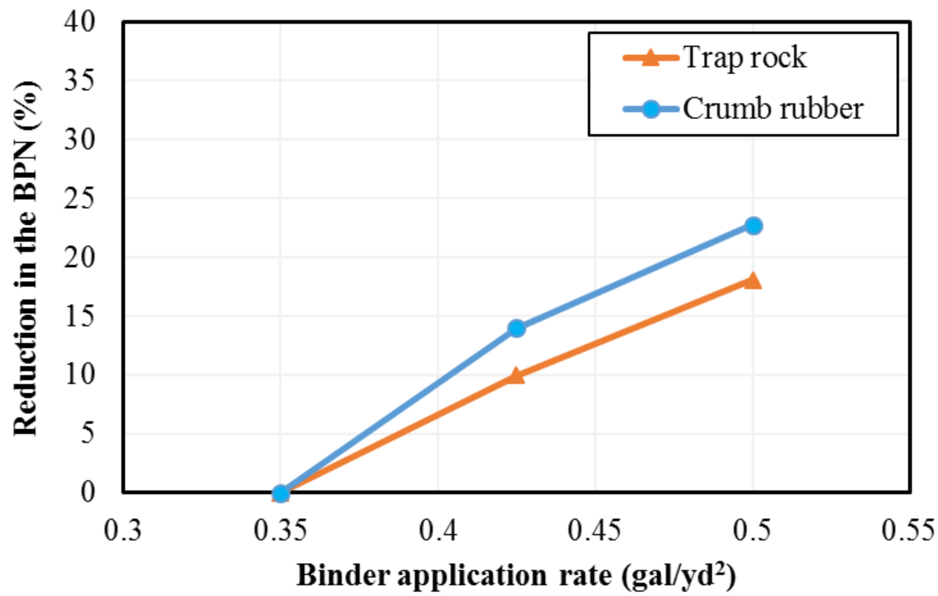


Figure 30: The reduction in the BPN as a function of the binder application rate

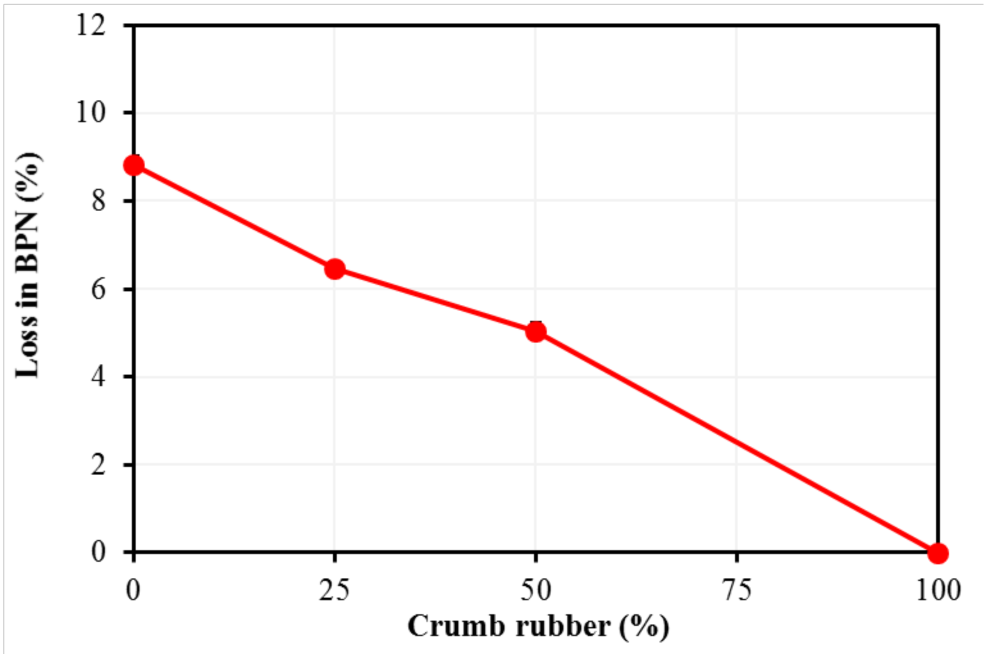


Figure 31: Losses in the BPN for chip seal specimens constructed using combinations of crumb rubber/trap rock aggregates during a summer season

10. Task 10: Construction of a field test section

A 2000 ft two-lane test section was constructed in Route CC, Rolla, Missouri (Fig. 32). The section was divided into five segments constructed using 0%, 25%, 50%, 75%, and 100% of crumb rubber replacing natural aggregate. The average daily traffic on this road according to the last MoDOT three-year cycle traffic volume map is 958 vehicle/day (Fig. 33). The effect of traffic was not taken into consideration when comparing the chip seal test segments since all the test segments would have the same traffic loads.

An ambient processed crumb rubber with a size and characterizations mentioned in section 2.1 in this report was used. The size of the crumb rubber was 15% larger than that of the natural aggregate used in the blend with the median particle size of 0.27 inches while that of the crumb rubber was 0.31 inches. Emulsion type CRS2P with a temperature at the application time of 130 °F was used at an air temperature of 70 °F in the construction location. Traditional chip seal procedures were used to apply the rubberized chip seal (Fig. 34). This included applying the emulsion at an application rate ranging from 0.25 to 0.40 gal/yd^2, applying the aggregate at an application rate ranging from 20 to 30 lb/yd^2 equivalent to a chip seal with 100% trap rock, and compacting the chip seal using a steel drum compactor. Finally, the road was swept using a sweeping truck and opened for traffic within one hour from the application of emulsion. This was not enough to evaporate the water in the used emulsion (Fig. 6). As shown in Fig. 6, it required six hours of curing time to evaporate 83% of the water at 35 °C and longer curing time at lower temperatures.

Figure 32: The location of the construction site

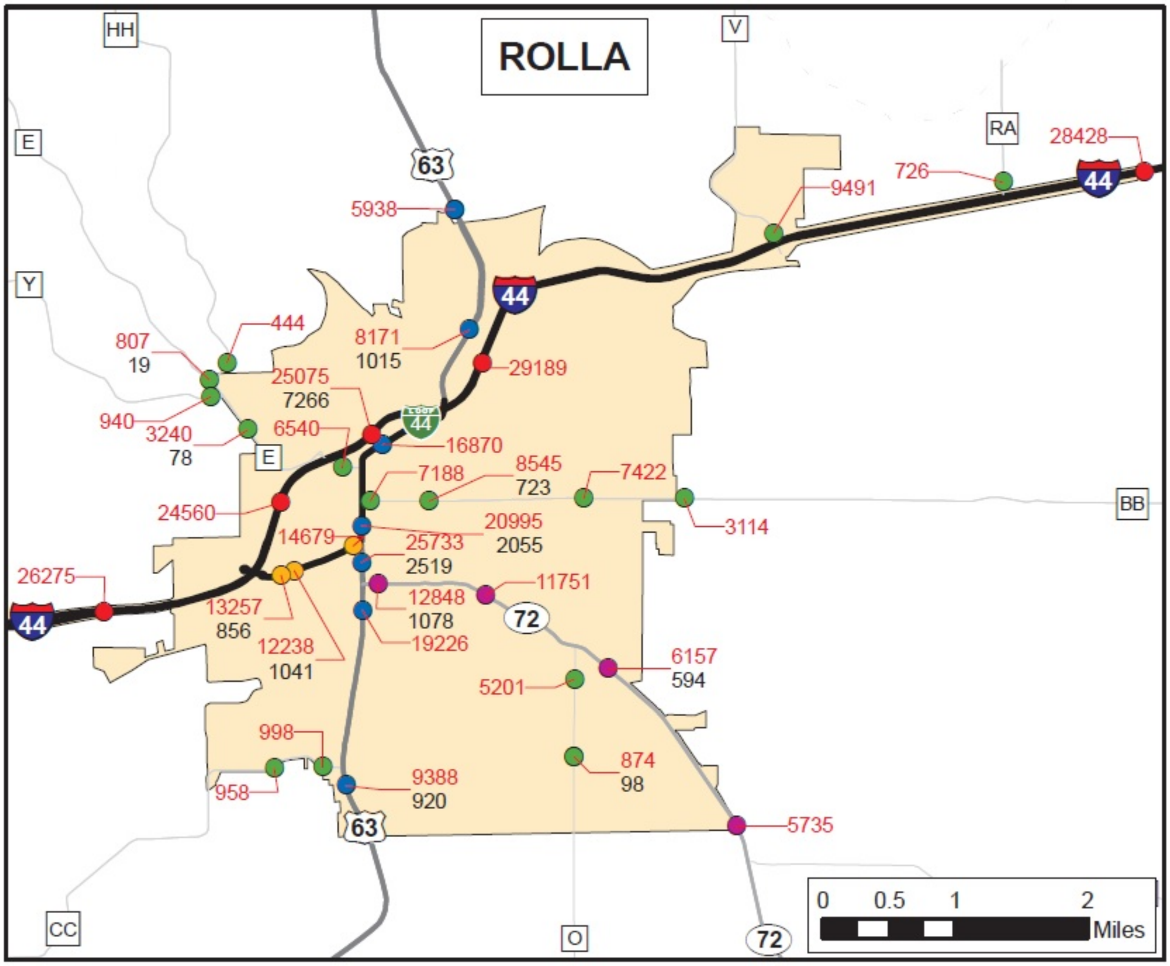


Figure 33: MoDOT three-year cycle traffic volume count map as of 2016

During spreading the aggregate and compaction process, it was noticed that rubber aggregate particles adhered to the wheels of the compactors and chipper because the flexibility of the rubber particles led the wheels to penetrate into and squeeze the crumb rubber layer and reached the emulsion film. As a result, the rubber tire compactors were replaced by steel roller compactors which compacted the material appropriately. It is worth noting in a more recent experimental section in Boonville, Missouri (Gheni et al. 2018b), using rubber tire compactor was successful with a rubberized chip seal having 25% crumb rubber due to selecting the right binder and aggregate rates which neither left extra aggregate to accumulate in front of the wheels nor leaving some road spots uncovered with aggregate which made them exposed and in direct contact with the wheels.

Figure 34: Construction steps of rubberized chip seal with different rubber replacement ratios

Chip seal application and compaction went smooth and normal up to 50% crumb rubber replacement ratios. In the cases of 75% and 100% crumb rubber replacement ratios, there was a problem with spreading the mixture of trap rock and crumb rubber because of the low unit weight of crumb rubber which made it hard to spread the crumb rubber by gravity. In addition, the low unit weight of crumb rubber made it easy to push the rubber particles in front of the chipper's wheels before the full curing of emulsion occurred. However, with 25% and 50% crumb rubber replacement ratios, the presence of trap rock, which has high unit weight, helped in pushing the crumb rubber particles through the chipper. For future applications and with gaining more application experience, the research team believes that replacing 100% of trap rock with crumb rubber is doable.

Samples were taken from the test section and were tested in the Material Testing Laboratory at Missouri S&T. It was crucial for the test specimens to be undisturbed as well as representative of the construction procedure and material used during the construction of the test section. The test specimens were collected cross the longitudinal direction of the road to avoid high sample-to-sample variability observed when transverse samples were collected (Kim and Lee 2009). The samples were collected by placing six pieces of asphalt felt (Fig. 35). To reduce the disturbance of the test specimens, the specimens were left to cure for 60 minutes which allowed the binder to have a good cohesion with the aggregate particles; then, the samples were removed from their locations and were placed on rigid plates to provide a rigid support.

Figure 35: Collecting chip seal samples from the construction site

11. Task 11: Field investigation

The research team visited the chip seal section six different times during 12 months of service life. The first visit occurred one day after the road was open to traffic. Table 5 summarizes the dates and special weather events that occurred before the visits. The test section was visually evaluated during each visit where both the right and left lanes were investigated; of particular interest was the driving path, which is at the left and right side of each lane, and snowplowing path which is at the middle crest of each lane. Furthermore, sand patch measurements were carried out during each visit to determine the MTD, which is an indication of the aggregate embedment depth. Also, BPT was carried out at the beginning and ending of the project.

Table 5: Summary of field investigation visits

Visit No.	Date	Weather	Tests
0	09/20/2017	Sunny day, an average temp of 75˚ F	Field implementation
1	09/22/2017	Sunny day, an average temp of 75˚ F	Visual inspection, Sand patch and skid test
2	12/18/2017	Partly cloudy, an average temp of 48˚ F	Visual inspection, Sand patch
3	01/25/2018	Clear day, an average temp of 46˚ F, this visit was after a snowstorm with a snowplowing of the road.	Visual inspection, Sand patch
4	05/09/2018	Cloudy day, an average temp of 75˚ F, this visit was after a heavy rain storm.	Visual inspection, Sand patch
5	06/28/2018	Sunny day, an average temp of 86˚ F, this visit was after a rain storm.	Visual inspection, Sand patch
6	10/15/2018	Mostly cloudy day, an average temp of 43˚ F	Visual inspection, Sand patch and skid test

In terms of the visual inspection, the major loss of chip seal was at the middle of each traffic lane, i.e., not in the wheel paths, which is the area with the highest elevation (Fig. 36).

This raveling type of distress was due to the snowplowing after the snow storms on December 23rd, 2017 and January 15th, 2018.

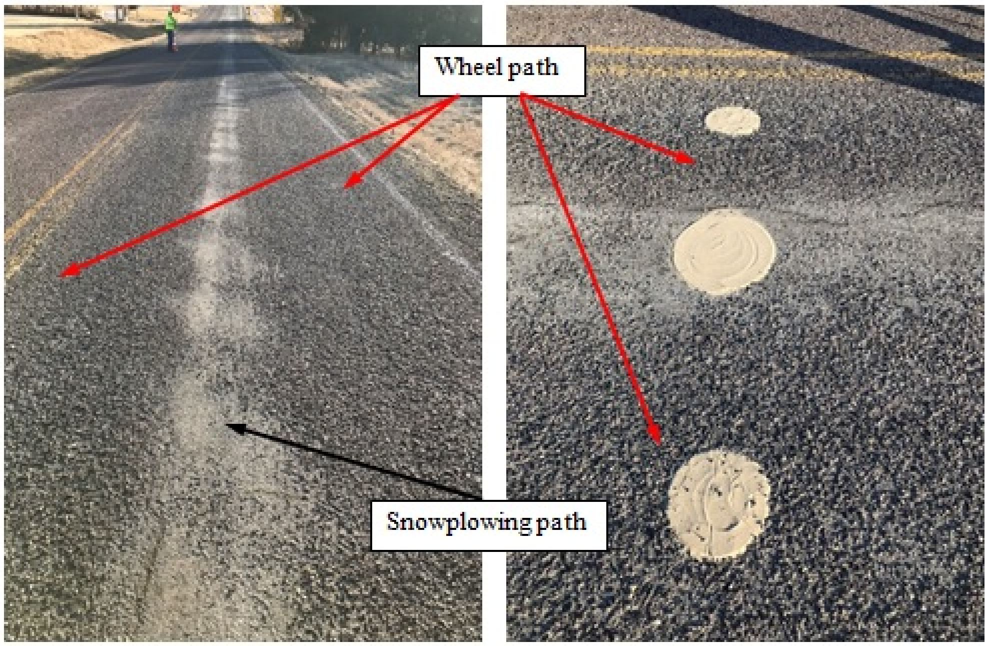


Figure 36: Raveling distress in the middle of the driving lane

11.1 Macrosurface measurement using sand patch method

The standard ASTM E965 sand patch method (ASTM 2015) was used to determine the MTD of the in-situ chip seal coating. Two volumes of sand namely 125 ml and 60 ml, passing a No. 60 sieve and retained on a No. 80 sieve were prepared in containers. Then, each volume of sand was independently spread uniformly on the surface of each of the investigated spots using an ice hockey puck with its bottom surface covered with a hard rubber material. Hence, for each spot two readings were obtained at each visit. Sand patch measurements were carried out at a total of 24 spots distributed on both lanes. In each lane, a tested transverse section was selected where the sand patch was performed on two spots in the wheel paths and one spot in the snowplow path at the center of the lane (Fig. 37). The diameter of the spreading sand on each investigated spot was measured at least four times in four different orientations (Fig. 37). The average diameter, D, at each spot was determined using the measurements from the two sand volumes and four diameter measurements which was then implemented in equation 3, repeated here for convenience, to determine MTD.

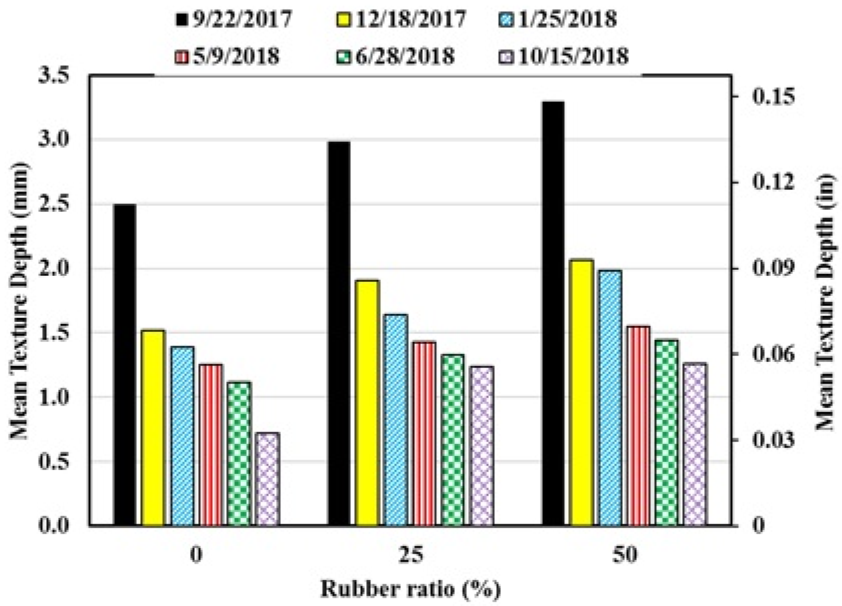
$$MTD = (4V)/(\pi D^2) \quad (3)$$

where V is the sand volume.

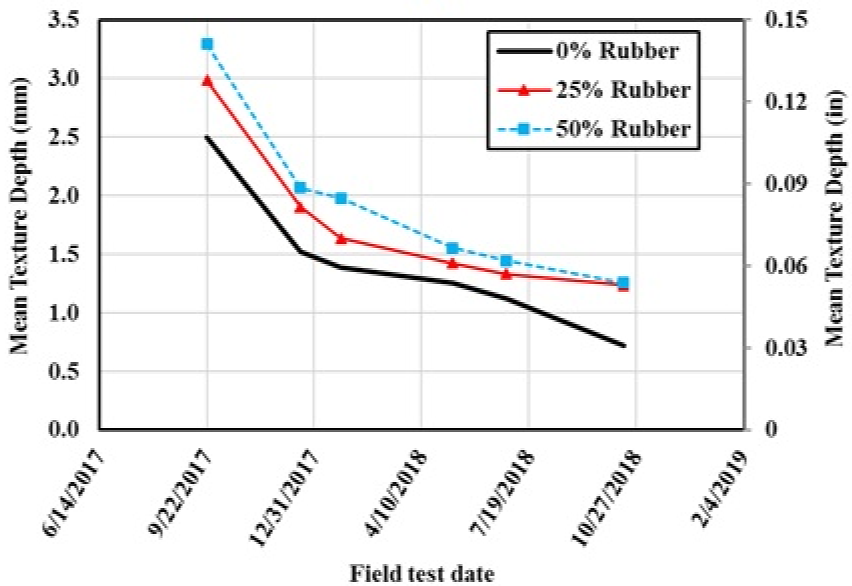
The detailed results of the MTD at the different spots are summarized in Appendix B. The results of the sand patch test during each visit at different locations and spots are shown in Figures 38a and 39a for the wheel path and snowplowing path, respectively. The MTD versus service life age is also shown in Figures 38b and 39b for the wheel path and snowplowing path, respectively. As shown in the figures, the MTD significantly increased with an increase in rubber content. At the wheel path, the MTD increased from 0.098 inches for 0% rubber to 0.118 inches and 0.130 inches for 25% and 50%, respectively, representing 20.5% and 22.5% increases over that of the trap rock for the 25% and 50% crumb rubber replacements, respectively. Expectedly, the MTD of the chip seal decreased with an increase in its service life. However, this reduction was more pronounced for trap rock compared to crumb rubber segments. The MTD decreased to 0.028 inches, 0.049 inches, and 0.050 inches after 388 days of service life for sections with 0%, 25%, and 50% crumb rubber replacement, respectively. Therefore, the MTD of the rubberized chip seal represent 72% and 75% increases over that of the trap rock after a period of more than one year of service life. It is worth noting that the authors believe that the significant reduction in the MTD observed during the visit on December 18, 2017 for all types of aggregate was related to early opening of the road for traffic with a curing time of less than one hour.

It is worth noting that chip seal constructed using trap rock or rubber suffered from a significant loss in the MTD at the snowplowing path after two snow days on December 23rd, 2017 and January 15th, 2018. As shown in Figure 39b, the reductions in the MTD values were 47%, 51%, and 52% for 0%, 25%, and 50% crumb rubber respectively. Figure 40 shows the temporal development of the ratio between the MTD at the wheel path to that at the snowplowing path. As shown in this figure, the MTD values of both lanes immediately after construction were approximately the same. Beyond that, the MTD at the wheel path was smaller than that at snowplow path due to the daily traffic on the wheel path. However, after the snowplowing on December 23rd, 2017 and January 15th, 2018, the MTD at the wheel path was much higher than that of the snowplowing path due to the raveling distress in the middle of each lane as a result of snowplowing action.

Figure 37: Examples of the field investigation: (a) visit on 05/09/2018, and (b) visit on 06/28/2018



(a)



(b)

Figure 38: MTD monitoring at wheel path as a function of: (a) percentage of crumb rubber, and (b) date of the sand patch test

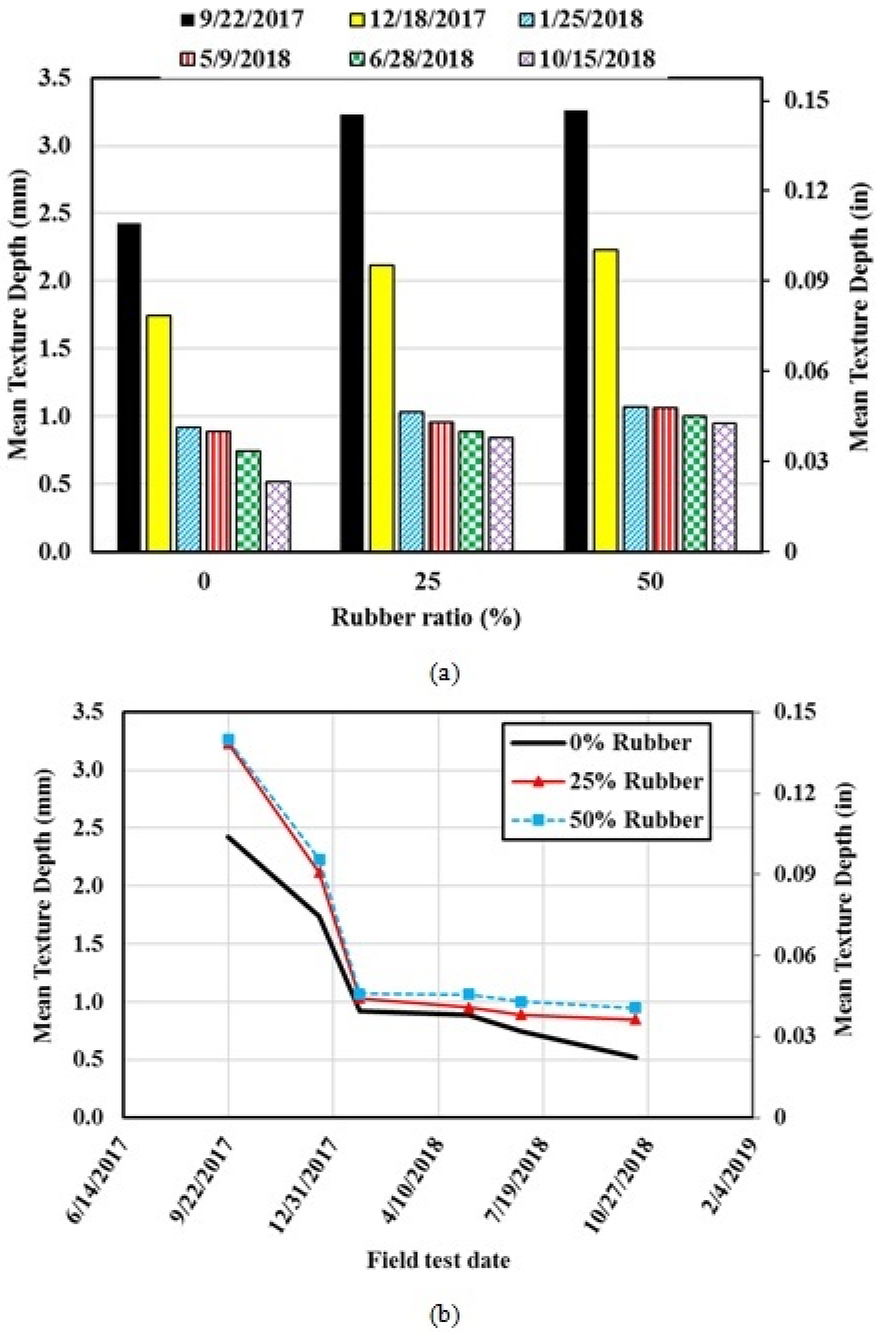


Figure 39: MTD monitoring at snowplowing path as a function of: (a) percentage of crumb rubber, and (b) date of the sand patch test

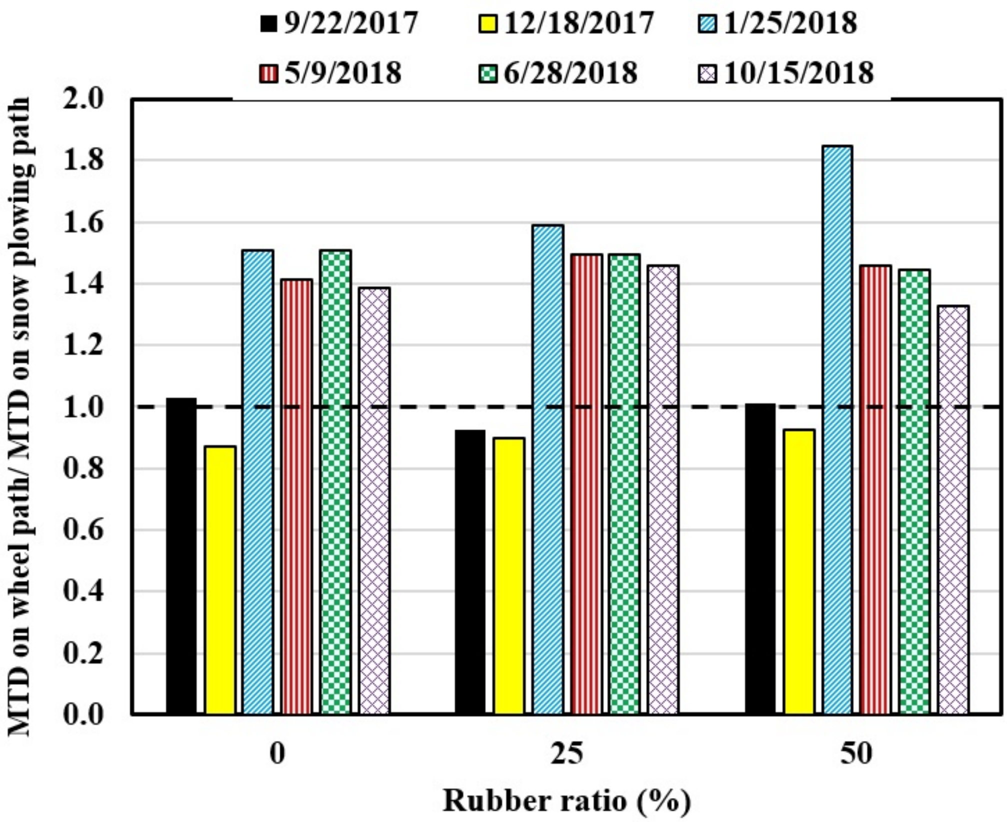


Figure 40: Effect of snowplowing on the ratio of the MTD on the wheel path to that on the snowplowing path

11.2 Skid measurement following ASTM E303

In addition to the sand patch, the BPN was also measured. The pendulum of the British Pendulum Tester (BPT) was vertically adjusted in order to achieve a slider contact path on the chip seal surface of 5 ± 1/16 inch. The distance between the center of gravity of the pendulum and the center of oscillation was 16.2 ± 0.2 inches. Water was sprinkled on the tested surface before running the test per ASTM E-303 (ASTM 1993) After releasing the pendulum, the BPN was recorded and used to present the friction resistance of the surface. The test was repeated four times after one trial test to get the average BPN for each area (Fig. 41). The detailed results are reported in Appendix B.

Figure 41: Field skid resistance test for a segment

As shown in Figure 42, right after applying the chip seal, the BPN slightly decreased by increasing the rubber content. The BPN was 88, 83, and 77 for the trap rock, 25% crumb rubber, and 50% crumb rubber replacement which represent 5.70%, and 12.5% reduction in the BPN values, respectively. This is similar to the measured data in the laboratory; however, after more than a year of service life, the crumb rubber significantly outperformed the trap rock and the rubberized chip seal segments displaying higher BPN values of 67 and 65 with 25% and 50% crumb rubber replacement ratios, respectively, compared to 42 for the trap rock chip seal segment representing 60% and 55% increases in the BPN values, respectively.

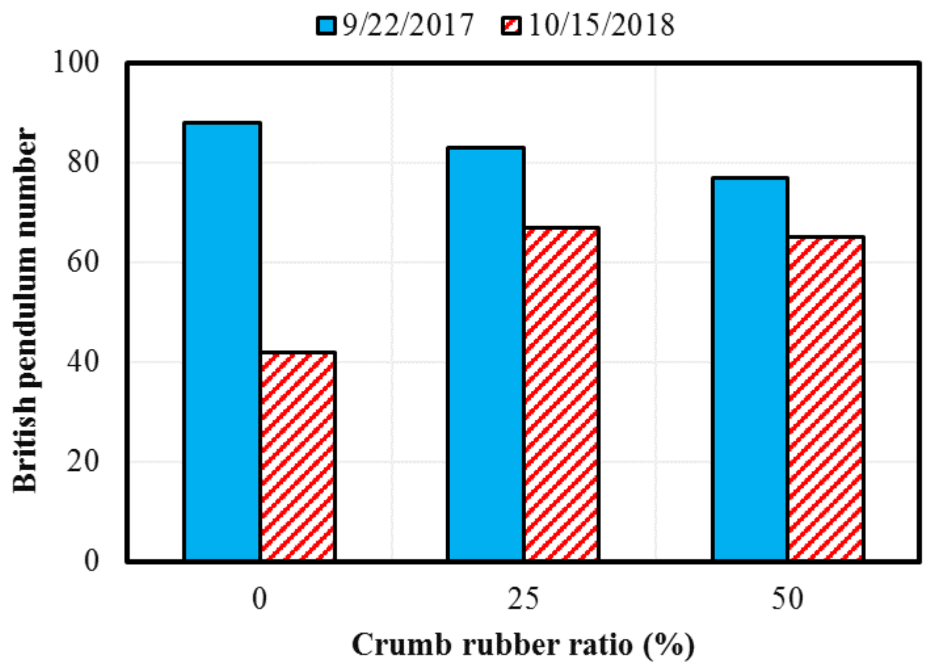


Figure 42: BPN versus percentage of rubber

11.3 Skid measurement following ASTM E274

In this task, the effects of speed on friction and skid resistance of rubberized chip seal were determined following ASTM E274 (ASTM 2015). MoDOT engineers utilized the locked wheel skid trailer (LWST) to determine the pavement friction in the east bound (EB) and west bound (WB) lanes. Note that ASTM E274 uses 40 mph as the standard testing speed. As shown in Figure 44, using a chip seal with trap rock or rubber increased the skid number (SN) by an average of 46% compared to segments where a chip seal was not used. Furthermore, similar to BPN, using rubber reduced the SN. Using 25%, and 50% rubber reduced the SN by 14%, and 12%, respectively. A repeat of the test is anticipated later next summer, and the results will be compared. The authors believe that the SN will follow the trend of the BPN and rubber would suffer less reduction in the SN compared to the trap rock section.

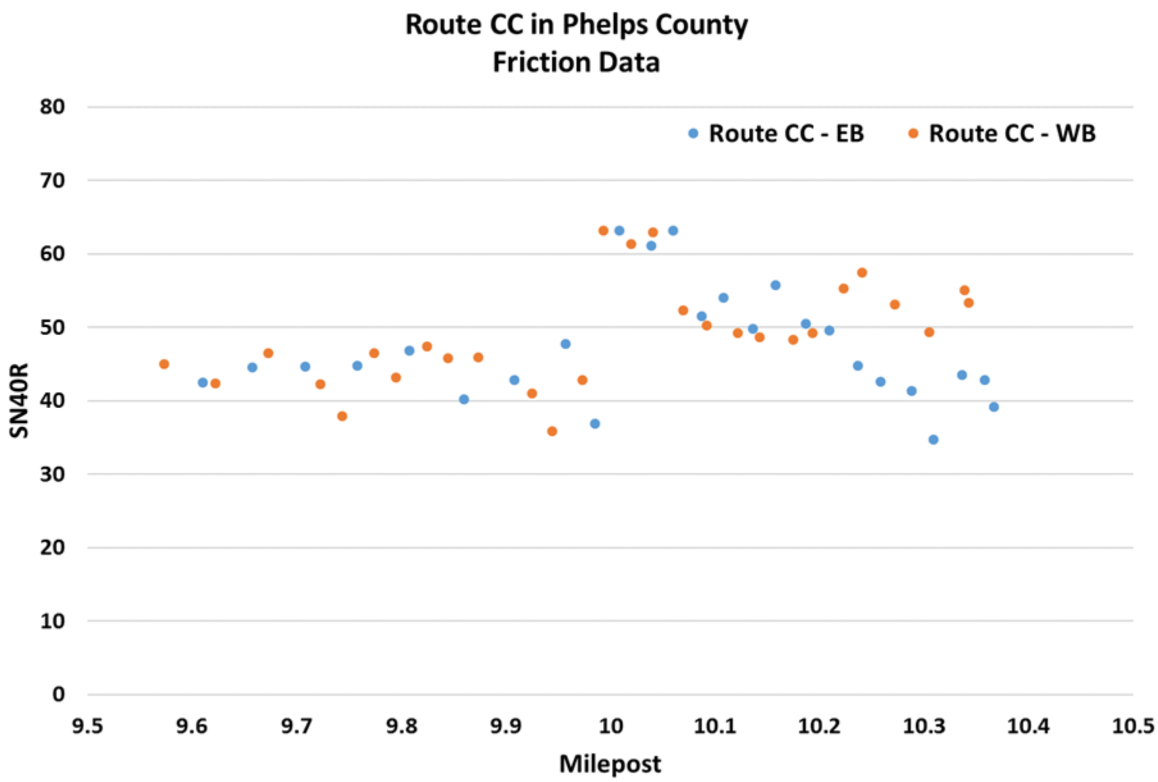


Figure 43: Locked wheel skid trailer (LWST) test results at different locations

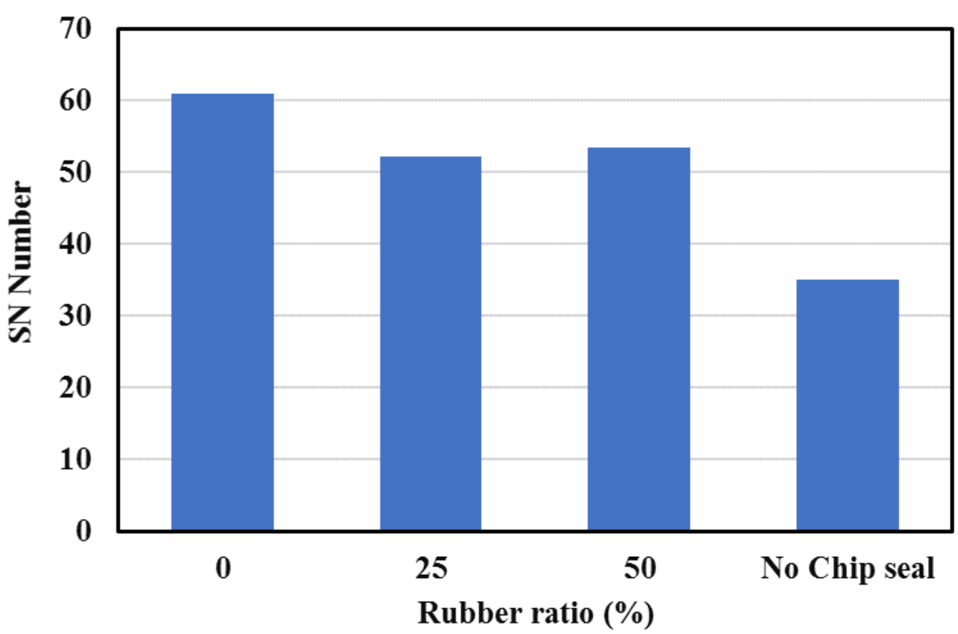


Figure 44: Locked wheel skid trailer (LWST) test results as a function of the rubber content

12. Findings, conclusions, and recommendations

Chip seals have been widely used as a pavement maintenance surface treatment due to its competitive cost and construction time. This project presents a study on chip seal pavement constructed using crumb rubber aggregate that was produced from scrap tires as an eco-friendly aggregate. Using recycled crumb rubber instead of mineral aggregate in two-lane chip seal roads consumes up to 4000 scrap tires per mile with 100% replacement ratio. It is worth noting that the State of Missouri produces 5 million scrap tires annually. Crumb rubber has a loose unit weight that is approximately 35% of that of the mineral aggregate. Hence, for a given aggregate volume, the freight cost should be much cheaper in the case of crumb rubber.

During this study, laboratory chip seal specimens and field chip seal sections with different crumb rubber ratios replacing natural aggregate were constructed. In the laboratory, standard and modified sweep tests, standard and modified Vialit tests, and standard and modified Pennsylvania tests were used to investigate the retention of the different sizes of crumb rubber in an emulsion binder of chip seal pavement. In addition, the macrotexture of the laboratory specimens in the form of mean texture depth (MTD) was investigated using the sand patch test and image processing methods. This investigation showed that the crumb rubber is an alternative for coarse aggregate in the construction of a chip seal. The crumb rubber outperformed the trap rock chip seal in all aspects investigated during this research including aggregate retention, macrotexture, skid, and friction performance. The following findings and conclusions can be drawn from the current study:

1. At the same binder application rate, the MTD values of rubberized chip seal specimens, which are a direct indication for the macrotexture, are higher than those of chip seal specimens constructed using trap rock. For a binder application rate of 0.35 gal/yd^2, chip seal specimens with 100% crumb rubber replacement ratio had a 29% increase in the MTD compared to that of the trap rock chip seal specimens.

2. Increasing the curing time significantly decreased the mass of the dislodged aggregate. For a chip seal specimen with trap rock particle size between 1/4 and 3/8 inches and crumb rubber replacement percentage of 50%, the mass of the dislodged aggregate after the standard sweep test decreased from 46% to 10% and from 42% to 8% for specimens

with a binder application rate of 0.32 and 0.64 gal/yd^2 respectively, when the curing time was increased from 2 to 24 hours.

3. The relative size of crumb rubber aggregate to trap rock is crucial for the performance of a chip seal. The amount of rubber particles dislodged during the standard sweep test, compared to that of the trap rock increased when increasing the size of the crumb rubber particles compared to the size of trap rock. For a chip seal specimen with a crumb rubber having maximum aggregate size of 0.187 inches and replacement ratio of 50%, the average mass of the dislodged total aggregate ranged from 9% to 38.5% depending on the binder application rate and curing time. However, this range increased from 11% to 47% for a chip seal specimen with crumb rubber having maximum aggregate size of 0.500 inches.

4. Chip seals with 100% crumb rubber passed the standard Vialit test and the modified Vialit test up to 30 drops with 100% of the rubber particles retained in the emulsion except for crumb rubber particles having sizes ranging from 3/8 to ½ inches. In that case, 10% of the rubber particles dislodged. However, with the same size, 65% of the trap rock aggregate was dislodged after 30 drops.

5. The Pennsylvania test showed that the crumb rubber had better retention than the trap rock. The knock-off weight loss was less than 1% for crumb rubber versus 3.4% for the trap rock chip seal specimens.

6. Using up to 50% crumb rubber as a partial replacement for trap rock was successfully implemented in Route CC in Rolla, Missouri using the procedures and equipment traditionally used for construction of chip seal pavement. However, it was required to use a steel roller compactor instead of a rubber tire compactor to compact the chip seal. It is worth noting that in another on-going test in Boonville, Missouri, rubberized chip seal with 25% crumb rubber was compacted successfully using a rubber tire compactor. This is due to the selecting of binder and aggregate rates which did not leave extra aggregate to accumulate in front of the rubber wheels of the chipper or compactor and also did not leave any road spots uncovered with aggregate and exposed to direct contact with the rubber wheels of the chipper and compactor.

7. The macro texture, measured in the form of MTD, of the crumb rubber chip seal segment in Route CC significantly outperformed the trap rock chip seal segment. Moreover, during its service life, the degradations in the crumb rubber chip seal segments were much slower than that of the trap rock chip seal segment. For example, the initial MTD increased significantly at higher rubber contents where the trap rock chip seal segment had an MTD of 0.0983 inches while the 50% crumb rubber rubberized chip seal segment had an MTD of 0.1296 inches representing an increase of 32%. Furthermore, after 13 months of service life, including snowplowing, the MTD of the trap rock chip seal decreased to 0.0283 inches compared with 0.0495 inches for the 50% crumb rubber chip seal representing a 75% improvement in the case of rubberized chip seal over the trap rock chip seal.
8. Measurements of the British Pendulum Number (BPN) immediately after construction of the field implementation section showed that the 50% crumb rubber chip seal segment displayed a reduction of approximately 12.5% in the BPN compared to that of the segment having 100% trap rock. However, after a service life of more than a year, chip seal road segments with 25% and 50% crumb rubber replacement ratios had BPN numbers of 67 and 65, respectively, compared to 42 for the trap rock chip seal segment.
9. With respect to the overall performance of the chip seal in the field, the major distress in the chip seal occurred at the middle of each lane, which is the area with the highest transverse elevation. This raveling type of distress was due to the snowplowing action rather than the traffic conditions.

Although this investigation shows the feasibility of utilizing crumb rubber as an aggregate in chip seal treatments, additional examinations are still required to evaluate the aggregate performance at the micro level and under different environmental conditions and driving speeds as well as the effect of snowplowing. These factors are under current investigation by the lead author of this report. In addition, it is recommended to measure the long-term aggregate retention with different types and rates of binders. Finally, the use of more precise equipment such as a laser scanner to monitor the temporal changes in the chip seal texture will be an interesting development for decision makers.

12.1 Recommendations

1. It is recommended to keep the crumb rubber replacement up to 50% of the natural aggregate until further research confirms the applicability of the 100% crumb rubber replacement.
2. The size of the crumb rubber particles should not exceed that of the natural aggregate. Using crumb rubber that has a median particle size larger than that of the natural aggregate exposes the crumb rubber particles and concentrates the traffic loads on the crumb rubber aggregate only.
3. Using flaky aggregate whether crumb rubber or natural aggregate is not recommended since flaky aggregate tends to lie on its flat side, reducing the skid and friction resistance of a chip seal.
4. Current and previous study by the authors (Gheni et al. 2017) concluded that sweeping the chip seal should be conducted at least 6 hours after the construction. Otherwise, significant aggregate dislodging occurs leading to a significantly shorter chip seal service life.
5. More studies are required to develop new techniques and equipment to snowplow on surfaces coated with chip seals. The current snowplow steel blades negatively affect the texture of a chip seal.
6. New texture measurement techniques that can cover larger chip seal areas instead of small spot measurements (such as sand patch) are required for better monitoring of the long-term performance and texture developments of a chip seal. The new laser scanning technique can perform a scan of large areas with high accuracy in a short time.

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Appendix A: Aggregate Properties

A.1. Detailed aggregate properties

Median particle size of rubber (D 50) = 0.312 in (7.93mm)

Median particle size of trap rock (D 50) = 0.271 in (6.88mm)

D60 (Trap rock) = 0.285 in (7.24mm) D60 (Rubber) = 0.333 in (8.46mm)

D10 (Trap rock) = 0.181 in (4.60mm) D10 (Rubber) = 0.200 in (5.08mm)

Coefficient of uniformity (Trap rock) = 1.57

Coefficient of uniformity (Rubber)= 1.67

Table A-1: Loose unit weight, specific gravity, and absorption of trap rock and crumb rubber

Test	Trap rock	Rubber
Bulk-density by rodding, kg/m3	1430.1	523.2
Voids in trap rock compacted by rodding, %	43.92	79.49
Loose dry density, kg/m3	1241	418
Bulk specific gravity	2.56	0.87
Bulk specific gravity (saturated surface-dry)	2.61	0.87
Absorption, %	2.27	0.0

Table A-2: Los Angeles abrasion of trap rock and crumb rubber

Test	Aggregate	Rubber
Dry mass of trap rock prior to Test, g	5001	1900
Nominal maximum size of trap rock, in	3/8	1/2
Grading used for test	C	C
Number of spheres used	8	8
Combined mass of spheres, g	3300	3300
Dry mass after test, gm	3903	1893
Loss by abrasion and impact, %	22.0%	0.37%

Table A-3: Micro-Deval test of reference aggregate (Brechin)

Reference aggregate Test No.	Reference aggregate Mass A	Reference aggregate Mass B	Reference aggregate % loss	Trap Rock Mass A	Trap Rock Mass B	Trap Rock % loss	Crumb Rubber Mass A	Crumb Rubber Mass B	Crumb Rubber % loss
1	1501	1257	16.26	1500	1439	4.07	500	498	0.4
2	1500	1269	15.4	1501	1446	3.66	500	497	0.6
3	1501	1265	15.72	1500	1442	3.87	500	500	0.0
4	1501	1248	16.86	1500	1439	4.07	500	499	0.2
5	1501	1246	16.99	1500	1444	3.73	500	496	0.8
6	1500	1245	17.00	1500	1437	4.20	500	496	0.8
7	1500	1240	17.33	1500	1431	4.60	500	500	0.0
8	1500	1244	17.07	1501	1435	4.40	500	499	0.2
9	1501	1253	16.52	1500	1437	4.20	500	498	0.4
10	1500	1260	16.00	1500	1435	4.33	500	497	0.6

Table A-4: Fractured faces of trap rock aggregate

Test	Sample 1	Sample 2	Sample 3
Dry mass before test	314.8	357.8	215.7
Dry mass after washing	310.5	356	214.3
Mass of non-fractured faces	0	0	0
Mass of faces with one or more fractures	310.5	356.0	214.3
Mass of faces with two or more fractures	310.5	356.0	214.3
Percent of non-fractured faces	0%	0%	0%
Percent of faces with one or more faces	100%	100%	100%
Percent of faces with two or more faces	100%	100%	100%

Table A-5: Aggregates properties

Type of aggregate	**Crumb rubber**	**Trap rock**
Bulk specific gravity	0.87	2.56
Absorption, %	0.0%	2.27%
Coefficient of uniformity	1.57	1.67
Fractured faces-Percent of non-fractured faces	0.0%	0.0%
Fractured faces-Percent of faces with one or more faces	100%	100%
Fractured faces-Percent of faces with two or more faces	100%	100%
Loose dry unit weight, kg/m^3	418	1241
Voids in loose aggregates, %	79.5	43.9
Los Angeles loss by abrasion and impact, %	0.37%	22.2%
Micro-Deval weight loss, %	0.4%	4.1%
Materials passing No. 200 sieve, %	0.20%	0.52%
Median particle size, mm	7.93	6.88
Flakiness index, %	31.3%	42.0%

Appendix B: Chip Seal Design Methods

B-1: Single application design with one-size aggregate (McLeod method)

$$C = 37.4HGE \qquad \text{(B-1)}$$

where

C = number of pounds of cover aggregate to be applied per square yard

H = Average Least Dimension of cover aggregate in inches (0.210 for rubber, 0.171 for trap rock)

G = ASTM bulk specific gravity of the cover aggregate (0.87 for rubber, 2.62 for trap rock)

E = wastage factor due to percent of cover aggregate lost due to whip-off by traffic and to unevenness of spread. In this research a waste of 15% was assumed resulting in E = 1.15

C= 37.4* 0.21*0.87*1.15= 7.857 lb/yd^2

C= 37.4* 0.17*2.62*1.15= 19.15 lb/yd^2

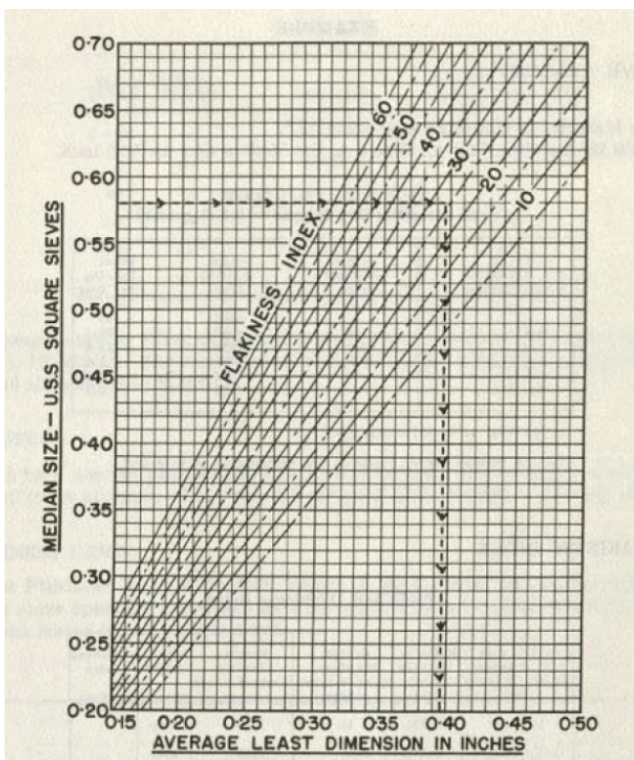


Fig. C. Determination of Average Least Dimension of Cover Aggregate.

Figure B-1: McLeod method

Quantity of asphalt binder to be applied per square yard

$$B=(1.122HT+S+A)/R \qquad \text{(B-2)}$$

Where:

B = total asphalt binder to be applied in US gallons per square yard

H = average least dimension of aggregate measured in inches

T = traffic factor, which depends upon the anticipated traffic volume. This study assumed a traffic volume in a range of 100 to 500 vehicles per day and hence T = 0.75

R = fraction of residual asphalt in the asphalt binder selected, this study assumed that the emulsion has 30% water based on its manufacture sheet and hence R = 0.70

S = surface texture correction in US gallons per square yard measured at 60 ^{o}F, resulting from expected gain or loss of asphalt binder due to the textural characteristics of the existing surface, this study assumed that the texture rating of existing surface is "Hungry 2h" which is the the fourth level of roughness out of five and hence S= www0.06

A= absorption correction in gallons per square yard measured at 60 ^{o}F due to loss of asphalt binder by absorption into the particles of the cover. This correction can be neglected for all but unusually absorptive aggregates. When necessary, the Country Roads Board makes an aggregate absorption correction factor of 0.03 US gallon per square yard,

$B=(1.122*0.21*0.75+0.06+0)/0.7$= 0.338 gal/ yd^2 (for rubber)

$B=(1.122*0.17*0.75+0.06+0)/0.7$= 0.290 gal/ yd^2 (for trap rock)

B-2: Kearby method

A binder rate = 0.25/0.7= 0.36 gal/ yd^2 was required for natural aggregate and 0.30/0.7= 0.43 gal/ yd^2 for crumb rubber assuming an aggregate embedment ratio of 50% which is the maximum embedment ratio that can be assumed based on this method.

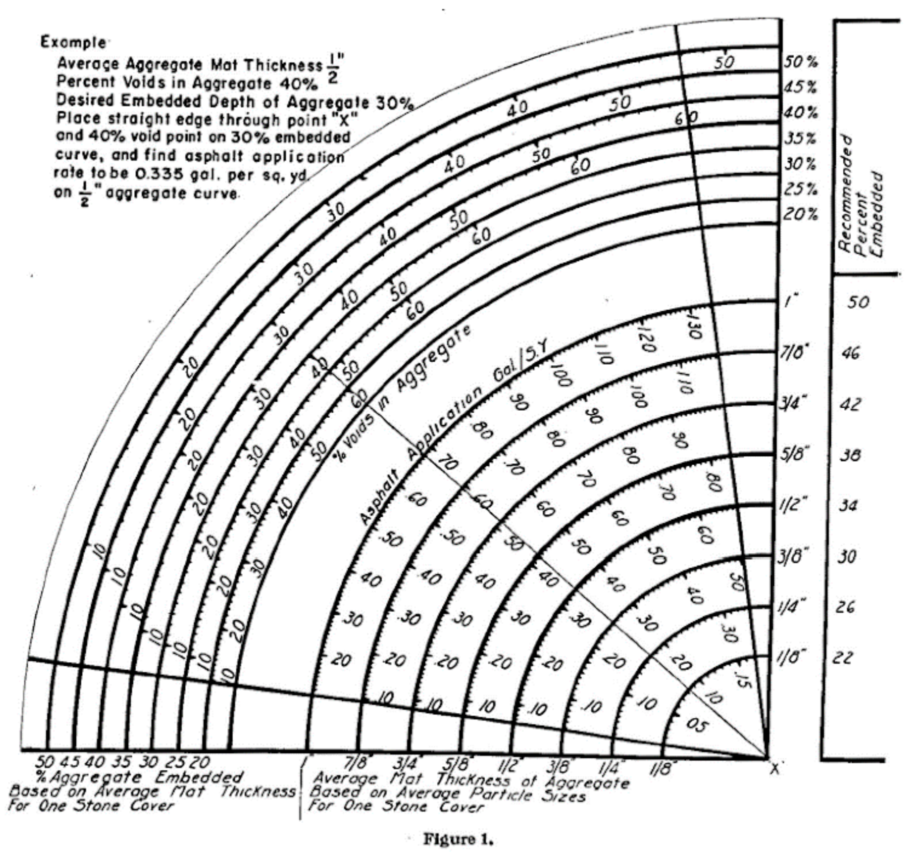


Figure B-2: Kearby method

B-3: Modified Kearby method

Following this method, a binder rate 0.826 gal/ yd^2 was required for natural aggregate and 0.79 gal/ yd^2 for crumb rubber assuming an aggregate embedment ratio of 50% which is the maximum embedment ratio that can be assumed based on this method.

The equation utilized to determine asphalt quantity by the existing Modified Kearby seal coat design method is shown below

$$A = 5.61E*(1-W/62.4G)*T+V \qquad \text{(B-3)}$$

where:

A = asphalt quantity, gallons/sq. yd.

W = dry loose unit weight, lbs. per cu. f t. (26 for rubber, 78 for trap rock)

Q = aggregate quantity determined from board test, lbs per sq. yd. (5 for rubber, 15 for trap rock)
E = embedment depth =e*d where e= 0.4 and d=1.33Q/W=(1.33*5)/27 = (0.246 for rubber, 0.256 for trap rock)
G = dry bulk specific gravity of aggregate (0.87 for rubber, 2.62 for trap rock)
T = this study assumed a traffic volume in a range of 250 to 500 vehicles per day and hence traffic correction factor =1.1
V = correction for surface condition (0)
Note: Asphalt quantities calculated by these methods are for asphalt cement. Appropriate corrections must be made where a cutback or an emulsion used.

$A= 5.61*0.246*(1-26/(62.4*0.87))*1.1+0$=0.790 gal/ yd^2

$A= 5.61*0.256*(1-78/(62.4*2.62))*1.1+0$=0.826 gal/ yd^2

B-4: Minnesota seal coat design

Minnesota Department of Transportation adopted software to design a chip seal coating. This design software considers the condition of the road and traffic volume in addition to aggregate and binder properties. This software was used during the course of this study to design a chip seal with 0, and 100% rubber as shown in Figs. B-3 and B-4. This design methods resulted in emulsion application rates between 0.35 and 0.57 gal/yd^2 based on the condition of the road and the traffic volume for chip seal with both natural aggregate and crumb rubber respectively. In addition, this method resulted in aggregate application rates 23.7 and 9.25 lb/yd^2 for natural aggregate and crumb rubber, respectively.

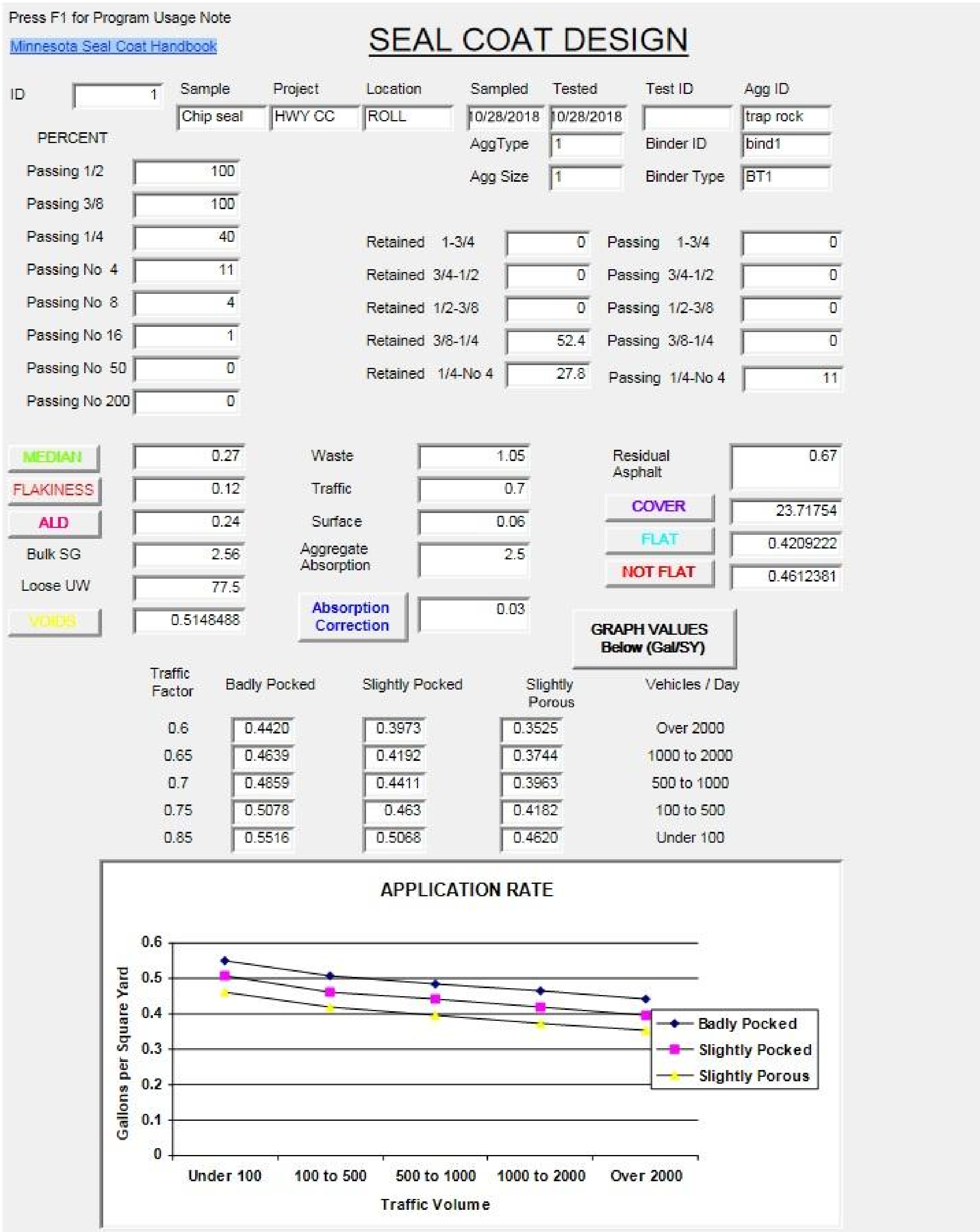


Figure B-3: Minnesota seal coat design software for chip seal with natural aggregate

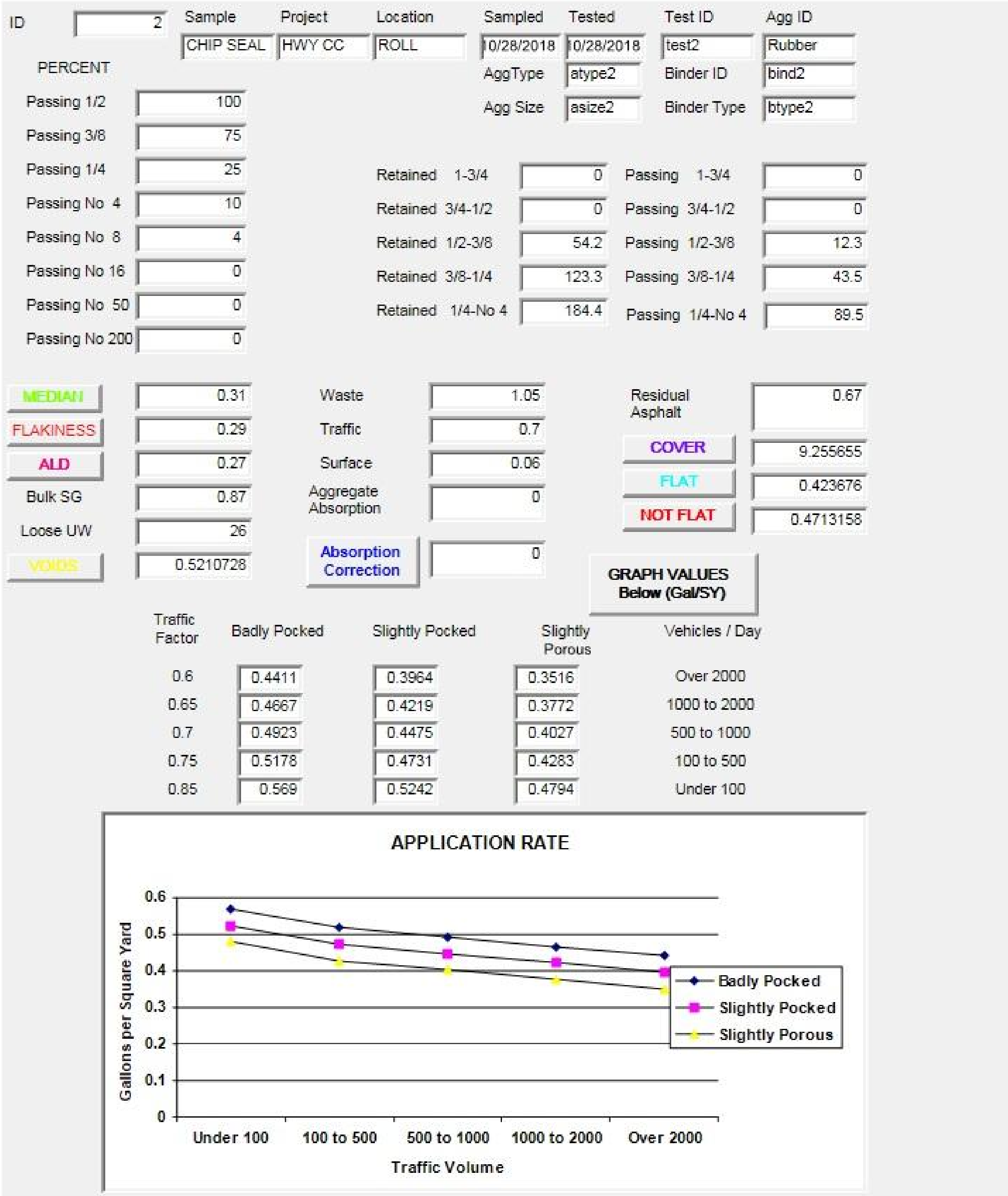


Figure B-4: Minnesota seal coat design software for chip seal with crumb rubber

Appendix C: Tests Procedures and Field Implementation

C-1: Construction of chip seal laboratory specimens.

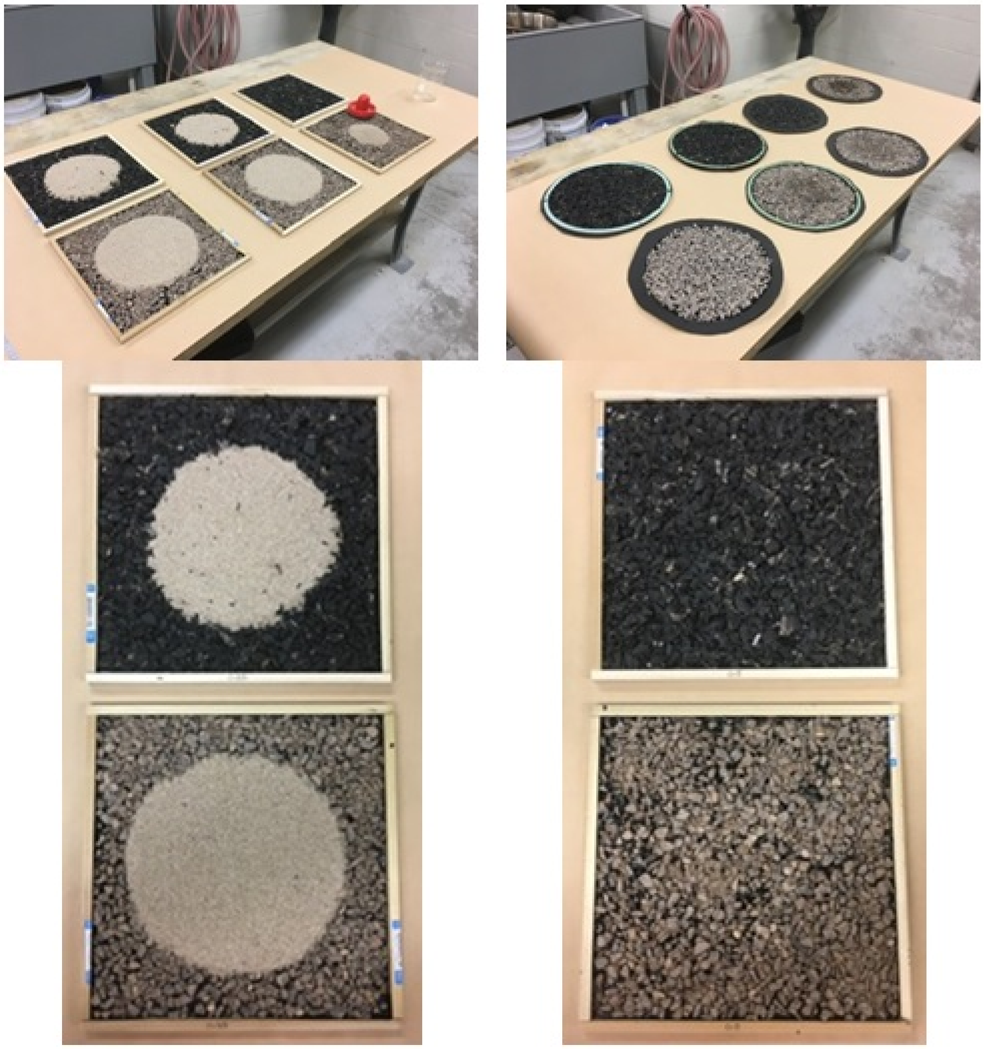


Figure C-1: Chip seal specimens with different binder application rate

C-2: Laboratory sweep tests

Figure C-2: Sweep test equipment (a) holding pan and brush holder, (b) specimen compactor (c) testing apparatus set-up, and (d) standard asphalt felt disks

Figure C-3: Sweep test procedure (a) pouring emulsion on the exposed felt disk, (b) excess emulsion was removed, (c) applying the pre-weighed aggregate, (d) compacting the aggregates, (e) conditioning specimens in the oven, (f) sweeping test, and (g) specimens after testing.

Table C-1: Sweep test of specimens with 50% rubber with size #8< R< #4

	Trial one	Trial two	Trial three
Emulsion type	1	1	1
Rubber ratio (%)	50	50	50
Asphalt felt (gm)	110.7	109.9	111.2
Trap rock (gm)	223	223	223
Rubber (gm)	70.5	70.5	70.5
Total (gm)	404.2	403.4	404.7
Emulsion (gm)	83 ±5	84 ±5	85 ±5
Sample weight (gm)	479.5	480.3	472.8
Initial specimen weight (gm)	388.6	376.6	361.1
Final specimen weight (gm)	319.2	274.9	292.9
Loose aggregate (gm)	49.5	73.7	45.7
Loose rubber (gm)	19.1	25.5	22.4
Time spent curing (hr)	2	2	2

Table C-2: Sweep test of specimens with 50% rubber with size #4< R< 0.25"

	Trial one	Trial two	Trial three
Emulsion type	1	1	1
Rubber ratio (%)	50	50	50
Asphalt felt (gm)	113.3	107.3	111.2
Aggregate (gm)	223	223	223
Rubber (gm)	70.5	70.5	70.5
Total (gm)	406.8	400.8	404.7
Emulsion (gm)	83 ±5	84 ±5	85 ±5
Sample weight (gm)	472.9	472.1	477.4
Initial specimen weight (gm)	403.3	400.1	400.1
Final specimen weight (gm)	306.8	301.8	343.2
Loose aggregate (gm)	65.1	64.9	40.1
Loose rubber (gm)	26.6	28.1	16.1

Table C-3: Sweep test of specimens with 50% rubber with size 0.25"< R< 0.375"

	Trial one	Trial two	Trial three
Emulsion type	1	1	1
Rubber ratio (%)	50	50	50
Asphalt felt (gm)	114	109.2	111.7
Aggregate (gm)	223	223	223
Rubber (gm)	70.5	70.5	70.5
Total (gm)	407.5	402.7	405.2
Emulsion (gm)	83 ±5	84 ±5	85 ±5
Sample weight (gm)	478.5	470.5	475.8
Initial specimen weight (gm)	433.9	386.1	415
Final specimen weight (gm)	332.8	284.1	308.5
Loose aggregate (gm)	65	65.4	75.9
Loose rubber (gm)	34.9	31.8	27.8
Time Spent Curing (hr)	2	2	2

Table C-4: Sweep test of specimens with 50% rubber with size 0.375"< R< 0.50"

	Trial one	Trial two	Trial three
Emulsion type	1	1	1
Rubber ratio (%)	50	50	50
Asphalt felt (gm)	111.2	111.4	113.6
Aggregate (gm)	223	223	223
Rubber (gm)	70.5	70.5	70.5
Total (gm)	404.7	404.9	407.1
Emulsion (gm)	83 ±5	84 ±5	85 ±5
Sample weight (gm)	480.9	479.1	481.9
Initial specimen weight (gm)	439.7	407.5	441
Final specimen weight (gm)	320.9	313.1	329.1
Loose aggregate (gm)	80.9	60.6	75
Loose rubber (gm)	36	30.8	34.8
Time Spent Curing (hr)	2	2	2

a

b

Figure C-4: Sweep test of specimens with 50% rubber: (a) 0.25"< R< 0.375", and (b) 0.375"< R< 0.50"

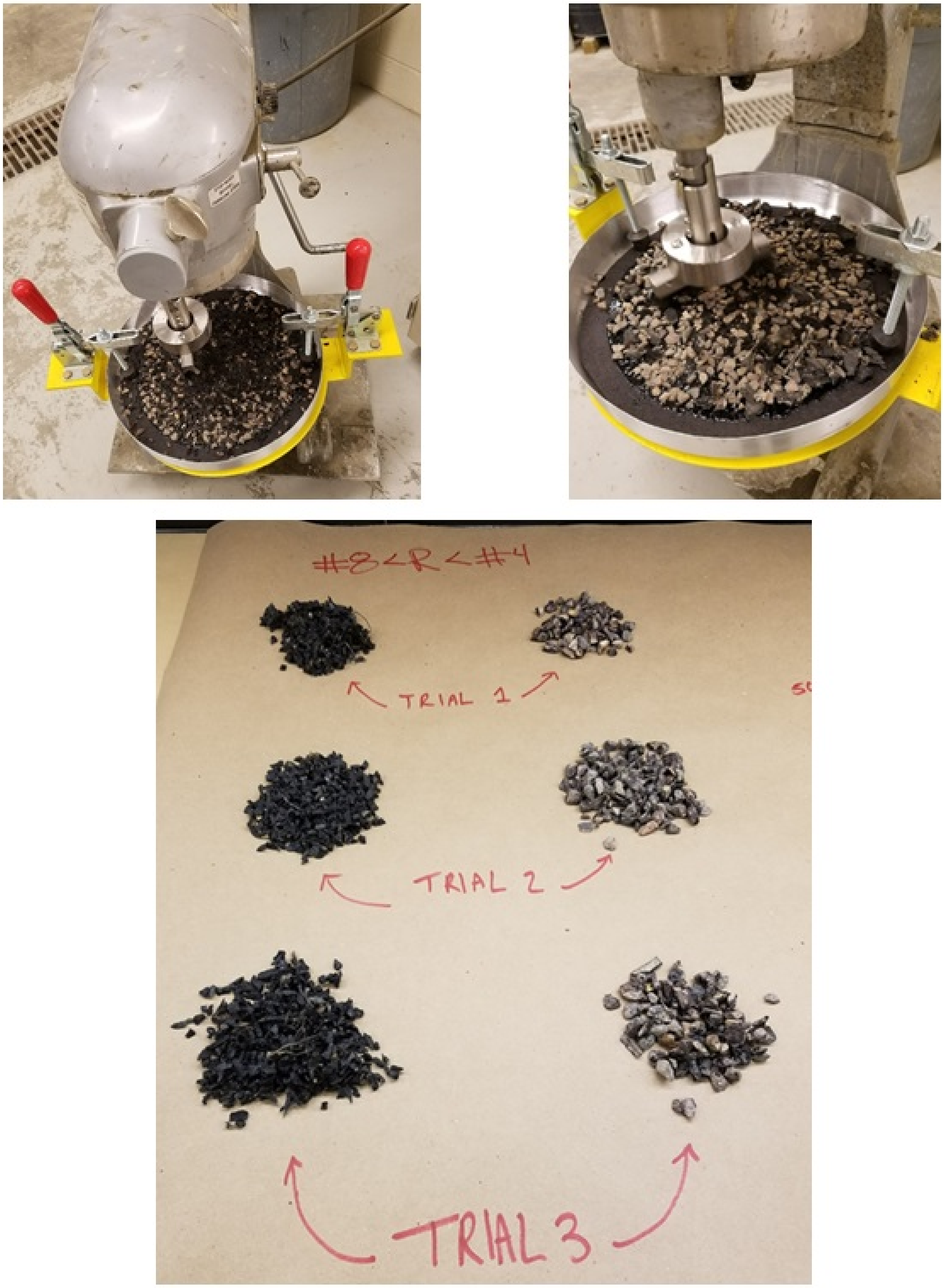


Figure C-5: Chip seal specimens with different rubber sizes during sweep test

Figure C-6: Chip seal specimens with different rubber sizes after sweep test

C-3: Laboratory Vialit tests

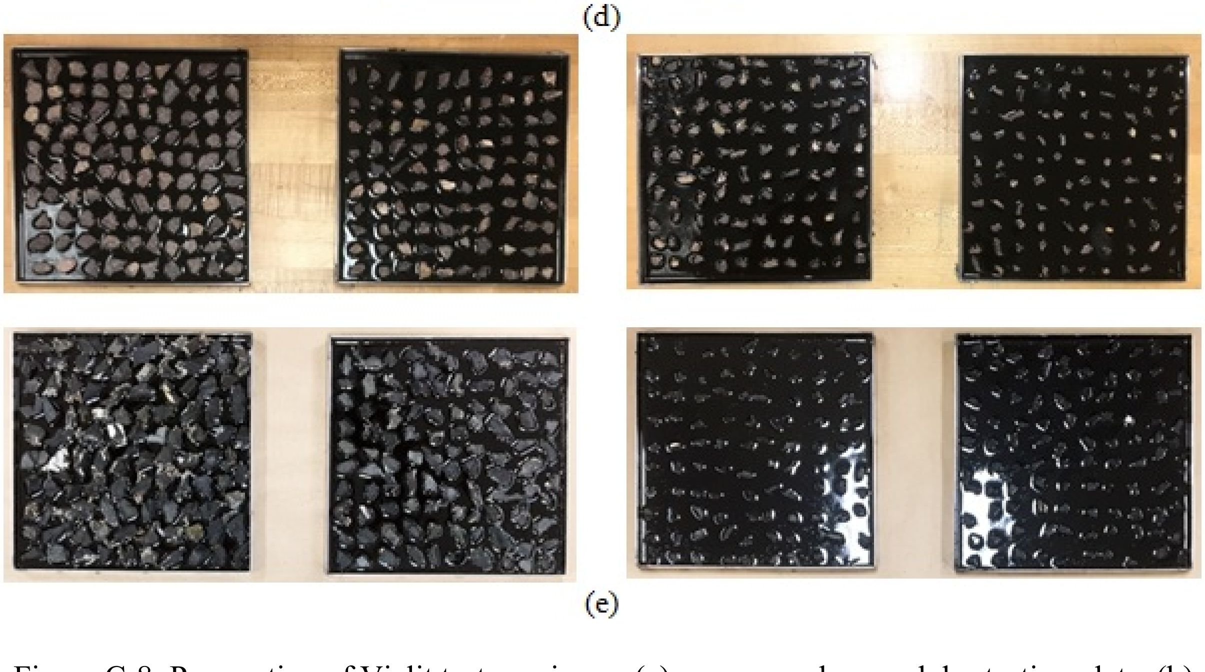
Figure C-7: Vialit test equipment

(a)

(b)

(c)

(d)



(e)

Figure C-8: Preparation of Vialit test specimens (a) prepare a clean and dry testing plate, (b) apply 79g asphalt cement emulsion, (c) emulsion after being tilted back and forth, (d) Placing aggregates uniformly using a 10x10 matrix, and (e) specimens with trap rock or crumb rubber

(a)

(b)

(c)

Figure C-9: Curing of Vialit test specimens (a) pans are placed in the oven for 48 hours at 60℃, (b) Pans are removed from the oven and allowed to cool in the ambient temperature for 30 minutes, and (c) pans are placed in the freezer for 30 minutes.

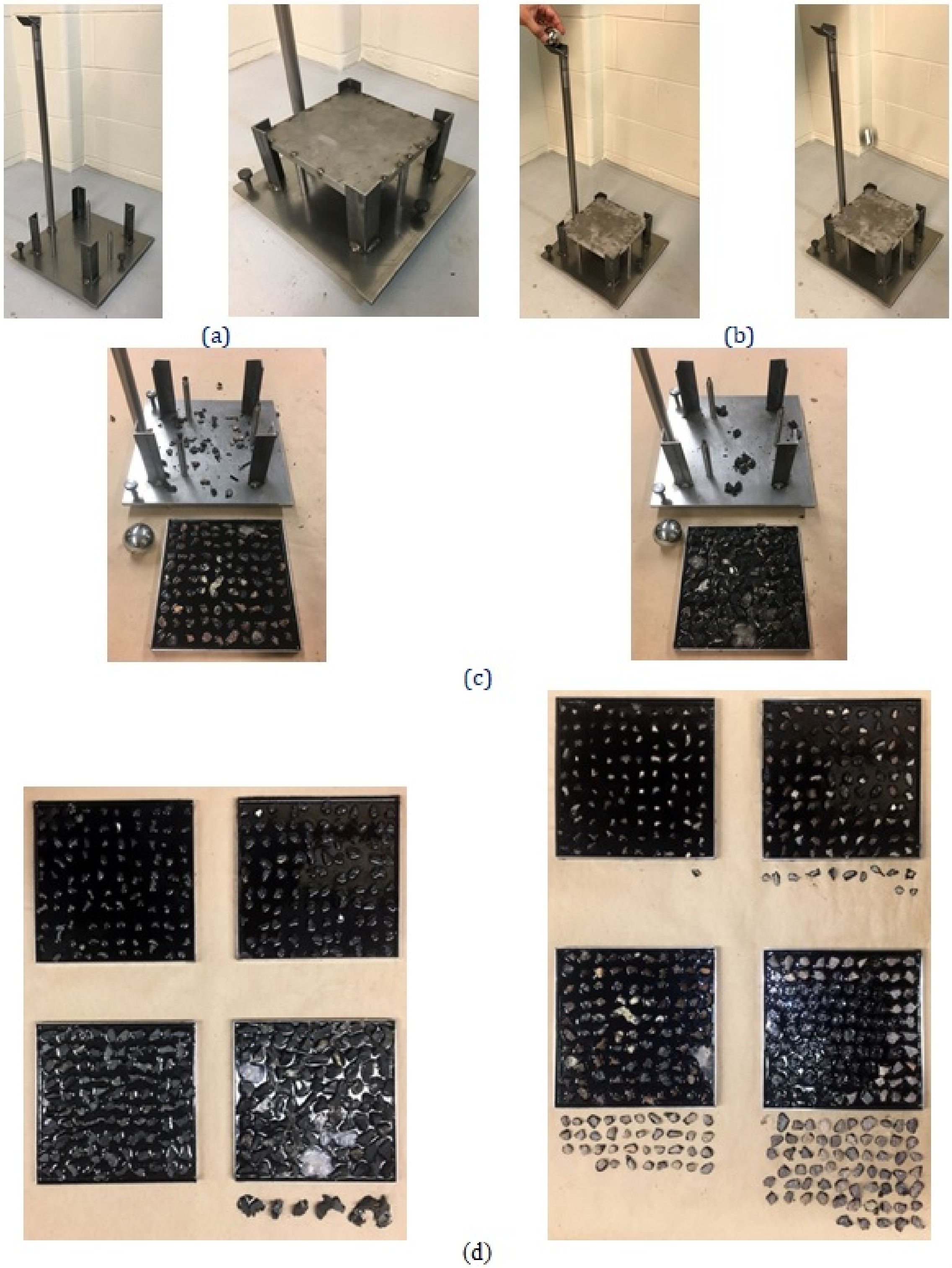


Figure C-10: Vialit test procedure (a) Pans were individually placed in an inverted position in the test apparatus, (b) ball was placed in the V-holder and fell freely, (c) the pan was flipped over and numbers of stones attached were counted after 3, 10, 20 and 30 drops of the ball, and (d) final result of the test

Table C-5: Results for percent aggregate retention for stone aggregates (first trial)

Specimen	Percent after	after 10 drops	after 20 drops	after 30 drops
1/2 – 3/8	NA	NA	NA	NA
3/8 – 1/4	96%	90%	77%	65%
1/4 – #4	100%	99%	95%	93%
#4 – #8	100%	100%	100%	100%

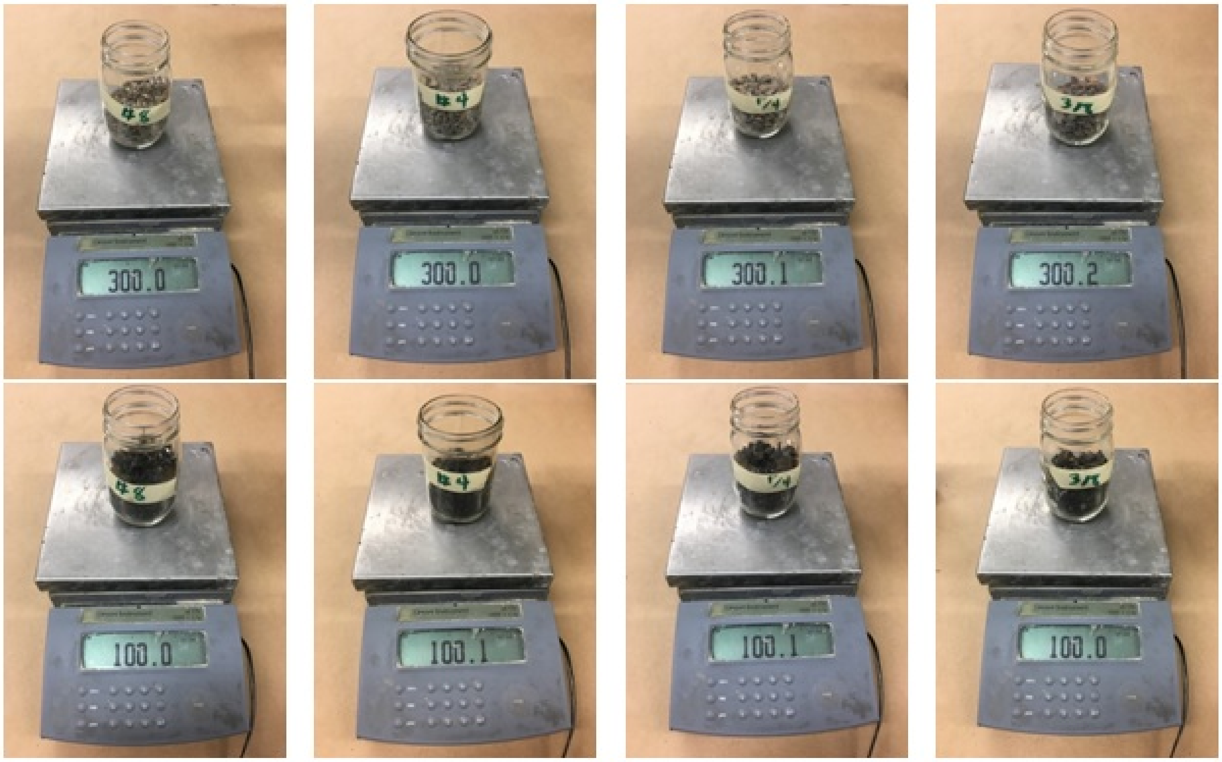
Table C-6: Results for percent aggregate retention for stone aggregates (second trial)

Specimen	after 3 drops	after 10 drops	after 20 drops	after 30 drops
1/2 – 3/8	83%	56%	40%	35%
3/8 – 1/4	96%	74%	65%	62%
1/4 – #4	100%	96%	93%	87%
#4 – #8	100%	100%	99%	99%

Table C-7: Results for percent aggregate retention for crumbed rubber

Specimen	after 3 drops	after 10 drops	after 20 drops	after 30 drops
1/2 – 3/8	100%	99%	98%	90%
3/8 – 1/4	100%	100%	100%	100%
1/4 – #4	100%	100%	100%	100%
#4 – #8	100%	100%	100%	100%

C-4: Pennsylvania aggregate retention test



(a)

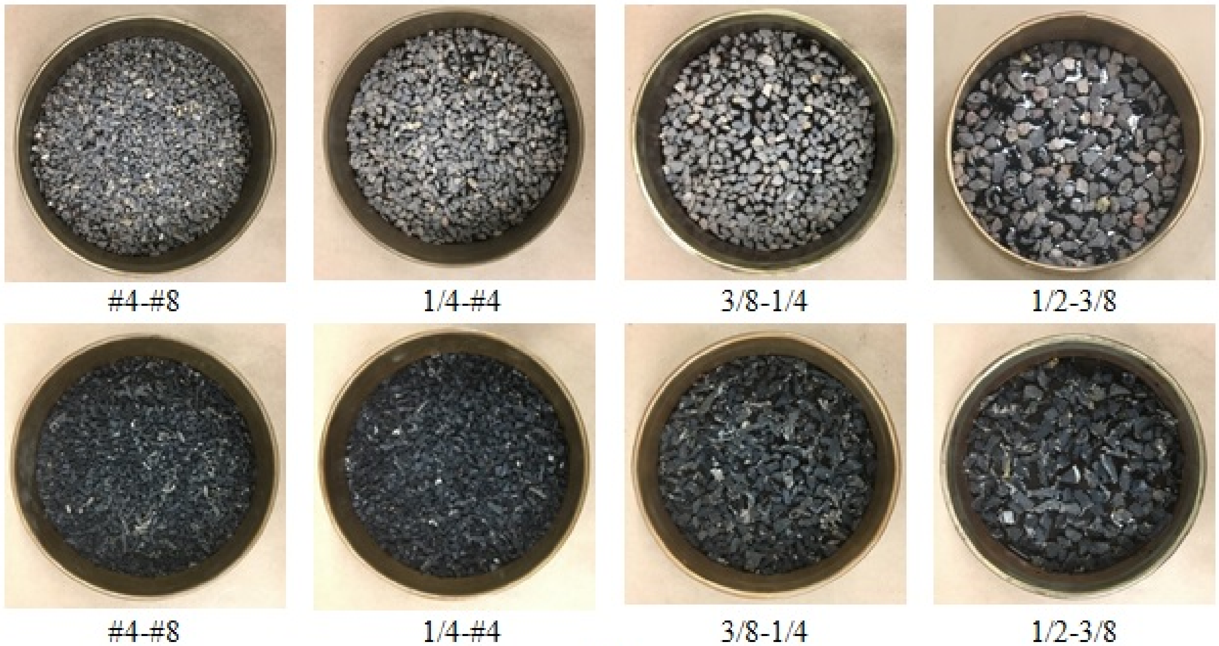
(b)

Figure C-11: Pennsylvania aggregate retention test: (a) preparing 300g of aggregate to obtain a single particle layer in 8” diameter pan and equivalent volume was used for the rubber that was 100 grams, and (b) 36.8 g of emulsified asphalt at 60℃ was applied inside an 8” diameter pan.

(a) (b)

(c) (d)

Figure C-12: Pennsylvania aggregate retention test: (a) the pan containing applied emulsion was placed at the bottom of five inverted 1/2" sieves, (b) the screen mesh in each 1/2" sieve was rotated 45˚from the adjacent top to bottom sieve so that two consecutive sieve meshes did not have the same orientation, (c) sieve shaker was inclined 45˚and the sieve assembly placed on the shaker, and (d) The prepared aggregate was poured into the sieve assembly from the top while the shaker was running for one minute.



(a)

(b)

Figure C-13: Pennsylvania aggregate retention test: (a) the pan containing emulsion and applied aggregate was removed and tapped to spread the aggregate evenly on the emulsion film, (b) the pan was covered with a 7-1/2” diameter x 3/4" thick neoprene bearing pad and then placed under a compression machine to apply a load of 2000lbs for 5 seconds.

(a)

(b)

Figure C-14: Pennsylvania aggregate retention test: (a) the pan containing emulsion and aggregate was cured at ambient temperature for 24 hours, and (b) the pan containing the seal coat was inverted to allow the loose aggregate particles to fall. These aggregate particles were weighed to determine the initial loss in grams.

Figure C-15: Pennsylvania aggregate retention test: (a) the pan containing applied emulsion was placed at the bottom of five inverted 1/2" sieves, (b) the screen mesh in each 1/2" sieve was rotated 45˚ from the adjacent top to bottom sieve so that two consecutive sieve meshes did not have the same orientation, (c) sieve shaker was inclined 45˚ and the sieve assembly placed on the shaker, and (d) The prepared aggregate was poured into the sieve assembly from the top while the shaker was running for one minute.

Table C-8: Results of trap rock

Specimen	Parameter A	Parameter B	Parameter C	Parameter D	Initial loss (%)	Knock-off loss (%)	Total loss (%)
1/2 – 3/8	300	0	3.2	3.2	0.0%	1.1%	1.1%
3/8 – 1/4	300	12	9.7	21.7	4.0%	3.4%	7.2%
1/4 – #4	300	51.2	6.4	57.6	17.1%	2.6%	19.2%
#4 – #8	300	100.9	3.6	104.5	33.6%	1.8%	34.8%

Table C-9: Results of crumb rubber

Specimen	Parameter A	Parameter B	Parameter C	Parameter D	Initial loss (%)	Knock-off loss (%)	Total loss (%)
1/2 – 3/8	100	0	0	0	0.0%	0.0%	0.0%
3/8 – 1/4	100	0.4	0.3	0.7	0.4%	0.3%	0.7%
1/4 – #4	100	0.5	0.8	1.3	0.5%	0.8%	1.3%
#4 – #8	100	1.5	1	2.5	1.5%	1.0%	2.5%

A= Weight of total aggregate
B= Initial loss in grams
C= Knock-off loss in grams
D= Total loss (B+C) in grams
Percent Initial loss = (B/A)*100
Percent knock-off loss = (C/ (A-B))*100
Percent total loss = (D/A)*100

C-5: Skid resistance test

Figure C-16: Skid resistance test

Table C-10: Results of skid resistance test British Pendulum Friction Test

Specimen ID	Run 1	Run 2	Run 3	Run 4	Run 5	Mean	Standard Deviation
Specimen Tire S1		64	63	62	61	63	1.3
Specimen Tire S1	-	53	53	51	51	52	1.2
Specimen Tire S1	-	49	45	45	45	46	2.0
Specimen Tire S1	-	51	50	50	49	50	0.8
Specimen Tire S2	-	61	61	56	55	58	3.2
Specimen Tire S2		59	57	55	54	56	2.2
Specimen 0.425 Tire		57	53	55	54	55	1.7
Specimen 0.425 Tire		55	64	65	64	62	4.7
Specimen 0.425 Tire		65	62	66	62	64	2.1
Specimen 0.425 Tire		69	66	66	65	67	1.7
Specimen 0.425 Tire S2		68	67	66	66	67	1.0
Specimen 0.425 Tire S2		55	53	54	52	54	1.3
Specimen 0.425 Tire S2		61	59	56	55	58	2.8
Specimen 0.425 Tire S2		55	57	59	58	57	1.7
Specimen 0.425 Coarse		95	94	94	89	93	2.7
Specimen 0.425 Coarse		89	85	90	91	89	2.6
Specimen 0.425 Coarse		85	81	79	80	81	2.6
Specimen 0.425 Coarse		86	85	85	85	85	0.5
Specimen 0.425 Coarse S2		85	85	87	86	86	1.0
Specimen 0.425 Coarse S2		86	86	81	83	84	2.4
Specimen 0.425 Coarse S2		80	81	82	82	81	1.0
Specimen 0.425 Coarse S2		89	86	80	91	87	4.8
Specimen 0.5 Coarse		63	63	63	64	63	0.5
Specimen 0.5 Coarse		77	75	75	75	76	1.0
Specimen 0.5 Coarse		56	53	56	53	55	1.7
Specimen 0.5 Coarse		59	56	31	32	45	15.1
Specimen 0.5 Coarse S2		80	81	79	81	80	1.0
Specimen 0.5 Coarse S2		96	95	95	94	95	0.8
Specimen 0.5 Coarse S2		105	103	108	102	105	2.6
Specimen 0.5 Coarse S2		115	118	105	88	107	13.5
100% EM2		85	85	82	86	85	1.7
100% EM2		72	74	69	70	71	2.2

Specimen ID	Run 1	Run 2	Run 3	Run 4	Run 5	Mean	Standard Deviation
100% EM2		90	90	82	83	86	4.3
100% EM2		95	95	95	95	95	0.0
100% EM2 S2		83	83	83	80	82	1.5
100% EM2 S2		86	90	89	91	89	2.2
100% EM2 S2		91	90	89	92	91	1.3
100% EM2 S2		91	90	91	100	93	4.7
100% EM2 S2		112	110	110	110	111	1.0
SP N2		61	61	63	60	61	1.3
SP N2		61	61	60	60	61	0.6
SP N2		65	69	65	65	66	2.0
SP N2		56	56	55	55	56	0.6
SP N2 S2		60	59	60	55	59	2.4
SP N2 S2		69	70	70	69	70	0.6
SP N2 S2		65	67	64	67	66	1.5
SP N2 S2		65	67	65	65	66	1.0
SP N3		71	70	74	69	71	2.2
SP N3		50	51	55	55	53	2.6
SP N3		80	79	79	80	80	0.6
SP N3		75	75	65	65	70	5.8
SP N4		62	59	59	57	59	2.1
SP N4		60	60	59	53	58	3.4
SP N4		60	59	58	55	58	2.2
SP N4		74	75	87	75	78	6.2
SP N4 S2		73	70	70	71	71	1.4
SP N4 S2		71	73	71	71	72	1.0
SP N4 S2		80	79	79	79	79	0.5
SP N4 S2		73	75	75	71	74	1.9
SP N5		69	69	70	69	69	0.5
SP N5		79	78	80	55	73	12.0
SP N5		50	60	60	70	60	8.2
SP N5		54	57	56	55	56	1.3
N11 S1		85	85	85	89	86	2.0
N11 S1		92	92	91	92	92	0.5
N11 S1		92	95	93	92	93	1.4
N11 S1		75	75	73	75	75	1.0
N11 S1 S2		75	77	79	79	78	1.9

Specimen ID	Run 1	Run 2	Run 3	Run 4	Run 5	Mean	Standard Deviation
N11 S1 S2		65	70	71	72	70	3.1
N11 S1 S2		77	75	73	73	75	1.9
N11 S1 S2		75	75	78	70	75	3.3
N12S1		79	74	74	71	75	3.3
N12S1		71	80	76	74	75	3.8
N12S1		74	73	73	74	74	0.6
N12S1		70	71	69	70	70	0.8
N12S1 S2		70	71	68	65	69	2.6
N12S1 S2		75	76	76	76	76	0.5
N12S1 S2		69	69	71	69	70	1.0
N12S1 S2		70	68	68	68	69	1.0
N13S1		83	90	88	86	87	3.0
N13S1		85	85	84	84	85	0.6
N13S1		89	85	85	87	87	1.9
N13S1		88	90	89	88	89	1.0
N13S1 S2		95	95	90	90	93	2.9
N13S1 S2		90	89	90	90	90	0.5
N13S1 S2		95	95	90	95	94	2.5
N13S1 S2		86	86	85	86	86	0.5
N5S1		91	102	85	93	93	7.0
N5S1		96	94	96	90	94	2.8
N5S1		84	84	84	85	84	0.5
N5S1		92	92	92	90	92	1.0
N5S1 S2		100	98	96	103	99	3.0
N5S1 S2		90	90	90	91	90	0.5
N5S1 S2		90	90	89	87	89	1.4
N5S1 S2		93	96	90	94	93	2.5
N17 S1		76	77	75	75	76	1.0
N17 S1		86	87	87	87	87	0.5
N17 S1		73	70	71	70	71	1.4
N17 S1		74	75	80	83	78	4.2
N17 S1 S2		120	110	90	101	105	12.8
N17 S1 S2		94	93	90	88	91	2.8
N17 S1 S2		100	90	84	88	91	6.8
N17 S1 S2		75	74	76	75	75	0.8
N18S1		90	91	86	87	89	2.4

Specimen ID	Run 1	Run 2	Run 3	Run 4	Run 5	Mean	Standard Deviation
N18S1		98	103	101	104	102	2.6
N18S1		79	81	94	99	88	9.8
N18S1		84	85	96	95	90	6.4
N18S1 S2		81	80	84	84	82	2.1
N18S1 S2		96	96	96	101	97	2.5
N18S1 S2		98	100	97	98	98	1.3
N18S1 S2		90	90	91	89	90	0.8
N14S1		83	80	80	80	81	1.5
N14S1		83	82	80	80	81	1.5
N14S1		85	88	87	79	85	4.0
N14S1		98	90	88	85	90	5.6
N14S1 S2		76	76	74	74	75	1.2
N14S1 S2		75	77	75	75	76	1.0
N14S1 S2		83	82	79	87	83	3.3

C-6: Construction of field test sections

Figure C-17: Construction of field test sections

Figure C-18: Construction of field test sections

C-7: Field investigation

Figure C-19: Field investigation visit on 09/22/2017

Figure C-20: Field investigation visit on 12/18/2017

Figure C-21: Field investigation visit on 12/18/2017

Figure C-22: Field investigation visit on 12/18/2017

Figure C-23: Field investigation visit on 01/25/2018

Figure C-24: Field investigation visit on 05/09/2018

Figure C-25: Field investigation visit on 06/28/2018

Figure C-26: Field investigation visit on 10/15/2018

Table C-11: Sand patch test results at the wheel path

9/22/2017

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000	250		253	252	2.496059
25	124	124000	229		231	230	2.984524
50	124	124000	223		215	219	3.291869

12/18/2017

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000	320		325	323	1.517999
25	125	124000	283		293	288	1.903469
50	124	124000	279		274	277	2.065097

1/25/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000	343		331	337	1.39018
25	125	124000	305		316	311	1.637599
50	124	124000	280		285	283	1.978308

5/9/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000	359		350	355	1.256314
25	125	124000	323		343	333	1.423778
50	124	124000	315		323	319	1.551492

6/28/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000	373		378	376	1.119724
25	125	124000	333		356	345	1.330308
50	124	124000	324		337	331	1.445399

10/15/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000	472		465	469	0.719303
25	125	124000	350		365	358	1.235318
50	124	124000	370		338.8	354	1.257023

Table C-12: Sand patch test results at the snowplowing path

9/22/2017

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000		255		255	2.42801
25	124	124000		221		221	3.232557
50	124	124000		220		220	3.262011

12/18/2017

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000		301		301	1.7426
25	125	124000		273		273	2.118388
50	124	124000		266		266	2.231349

1/25/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000		345		414	0.921149
25	125	124000		326		391	1.031652
50	124	124000		320		384	1.070701

5/9/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000		351		421	0.889926
25	125	124000		339		407	0.954045
50	124	124000		321		385	1.064041

6/28/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000		384		461	0.743543
25	125	124000		351		421	0.889926
50	124	124000		331		397	1.000719

10/15/2018

Rubber %	V (ml)	V (mm3)	C1	C2	C3	D Average (mm)	MTD
0	124	124000		460		552	0.518147
25	125	124000		360		432	0.845986
50	124	124000		340		408	0.948441