DEVELOPMENT OF AN EVALUATION SYSTEM FOR ASPHALT PAVEMENT SEALERS

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Roger W. Meier, Ph.D.
Paras Panadi
Department of Civil Engineering
The University of Memphis
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16. Abstract

The objective of this research was to develop testing protocols to evaluate and rank asphalt pavement sealers to produce a qualified product list. Two parameters, wet track abrasion resistance and permeability, were used to evaluate the sealers in the laboratory. The wet track abrasion resistance of aged specimens was used to determine the potential longevity of the sealers. Sealers with higher resistance should stand up to more prolonged wear from traffic loads. The permeability was used to determine the potential sealing performance of the sealers. Sealers with greater reduction in permeability should better inhibit pavement damage from the intrusion of air, water, or liquids. Test specimens were prepared, aged, and tested for each of several sealers using the test protocols developed. The results fell into distinct groups, allowing the sealers to be ranked to produce a qualified product list. Future research is needed to validate the laboratory results in the field.

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Chapter 1
Introduction

Asphalt pavement gets weathered when it is exposed to environmental agents such as ultraviolet radiation, oxygen, moisture, and freezing temperatures. These degrade the asphalt cement in the pavement, resulting in cracking, raveling, and stripping. Maintaining the integrity of the pavement's surface is necessary to keep the pavement in full service, at minimum expense, and with the least inconvenience to the public.

Surface sealers, also called fog seals, are a low-cost preventive maintenance treatment to protect and prolong the life of asphalt pavements. The Asphalt Emulsion Manufacturers Association (AEMA) defines a fog seal as "a light spray application of dilute asphalt emulsion used primarily to seal an existing asphalt surface to reduce raveling and enrich dry and weathered surfaces" (Kim and Im 2012). Fog seals are referred to as enrichment treatments since fresh asphalt is added to an aged surface to lengthen the pavement surface life.

Sealers extend pavement life in two way. First, they seep into the pavement and fill up narrow cracks and interconnected void spaces. This seals off and waterproofs the surface and reduces the pavement's susceptibility to aging by lowering its permeability to air and water. The seal coat limits water, oil, gas, or any other petroleum liquids from infiltrating through the pavement into the underlying base material and protects the asphalt pavement from the harmful effects of these chemicals (Yamada 1999).

Sealers also add a protective layer to the pavement surface that helps to reduce the impacts of oxidation and ultraviolet (UV) radiation. Oxygen flows through the interconnected air voids into the pavement causing changes in the asphalt cement physical properties, making it hard, brittle, and more viscous. The photo-oxidative effects of UV radiation further escalate these changes. A sealer applied to the pavement provides a barrier to oxygen and UV radiation, thereby slowing their effects (Shoenberger 2003).

The use of asphalt pavement sealers by the Tennessee Department of Transportation (TDOT) is presently hampered by the proprietary nature of many of the products available. Because there are no applicable material specifications for these products, there is no way to differentiate them or approve them for use. This robs TDOT of the potential to use sealers that may perform better, last longer, and do less damage to the environment than non-proprietary products for which material specifications do exist, such as the generic asphalt emulsions currently used.

The objective of this research is to develop laboratory test methods to evaluate and rank sealers in order to generate a qualified product list (QPL). There are no material specifications for sealer products, thus the necessity of this research. The research emphasis is on performance, longevity, and durability tests that will simulate field conditions as much as possible to determine how the sealers will perform over time. The better the sealer product, the longer it lasts and the better it performs to seal off the pavement.

In order to assess performance over time, the goal is to artificially age the sealers in the laboratory then determine how well they seal the pavement surface and stand up to prolonged wear from traffic. The next chapter investigates methods for aging asphalt-based materials and testing their permeability and resistance to tire wear.

Chapter 2
Literature Review

This chapter details relevant literature reviewed for this study to gain an understanding of laboratory aging and the measurement of air void content, permeability, and abrasion resistance of compacted asphalt specimens.

2.1 Laboratory Aging of Hot Mix Asphalt

Aging in an asphalt pavement represents the changes in the asphalt's physical properties produced by the effects of traffic loading and environmental conditions such as ultraviolet radiation, moisture, oxygen, and temperature (Bell et al. 1994). These cause volatilization, oxidation, and steric hardening of the asphalt cement that results in premature failure or poor performance of the asphalt pavement. The simulation of aging in the laboratory is considered important for the development of the sealer evaluation system.

Short-term aging simulates the volatilization that occurs at elevated temperatures during the production, storage, transport and laying of the asphalt. This volatilization results in a loss of asphalt weight due to evaporation and a concomitant reduction in the asphalt flow properties.

Long-term aging simulates the progressive damage suffered by the compacted mixture in the field due to oxidation and steric hardening. Oxidation refers to chemical reactions that occur when the organic compounds in asphalt cement react with atmospheric oxygen and ultraviolet radiation. Oxidation makes asphalt cement harder and more brittle, which makes the pavement more susceptible to cracking as the result of traffic loading or rapid changes in temperature.

Steric hardening refers to physical hardening over time that reduces the flexibility of an asphalt pavement. Steric hardening is mostly attributed to wax crystallization, referring to the crystallization of linear alkanes present in aspartame fractions that involve molecular reorganization (Fernández-Gómez et al. 2013). Steric hardening causes an increase in asphalt cement viscosity and a slight volume contraction.

Oxidation aging is due to pavement's exposure to atmospheric oxygen that causes an increase in dynamic viscosity and other rheological properties of the asphalt cement in the asphalt pavement. The oxidative aging of pavements begins at the time of construction and continues throughout the pavement's life. The oxidation aging rate is influenced by temperature, ultraviolet radiation, and intrinsic characteristics of the materials (Fernández-Gómez et al. 2013). The oxygen accessibility into the pavement forms sulfoxide and carbonyl groups, which causes asphalt pavement to become stiffer and more brittle, leading to higher stresses under a given deformation and thus reduces the performance life of the asphalt pavement. The oxidative behavior degrades polymers in asphalts into smaller molecules, hardens the base asphalt, and contributes to the hardening, embrittlement and loss of cohesion and adhesion of the asphalt cement in the asphalt pavement (Ruan et al. 2003). The process is relentless and thus, over time, can destroy the pavement.

Ultraviolet (UV) radiation has a significant influence on the level of photo-oxidation of the asphalt and is responsible for almost all photo-degradation of durable materials exposed outdoors. Carbonyl compounds form during the asphalt aging process and these compounds increase gradually with an increase in the UV radiation intensity (da Mota Lopes et al. 2012). UV light with a combination of moisture and temperature can accelerate oxidation and deterioration of the asphalt cement allowing the top fines to come loose thus exposing the course aggregate. UV is a major cause of aging, although the resultant effect occurs in the top quarter to half inch of the pavement and decreases with depth.

To simulate field aging on laboratory compacted asphalt specimens, the specimens are exposed to the dominant aging factors described above. The aging effects can be achieved by exposing the specimen to severe environmental conditions (UV radiation, temperature, and moisture) in the laboratory to accelerate the aging. These aging effects can be simulated in an accelerated weathering tester in the laboratory. The accelerated weathering testers can expose the HMA specimens to temperature, UV radiation or moisture conditions that exceed ambient levels. It is also believed that aging of HMA specimen at a higher temperature may be fundamentally different and cause more degradation than aging at a lower temperature. The chemical reaction increase and cause more damage to the HMA specimens with an increase in temperature (Grzybowski et al. 2012). Various methods that may be applicable to age the HMA specimens are described below.

UV aging involves aging the test specimens using an accelerated weathering machine that simulates natural exposure by creating severe environmental conditions. Accelerated weathering testers use a fluorescent UV or Xenon light and water spray to reproduce the aging effects that occur when materials are exposed to sunlight and moisture as rain or dew in actual usage. The test specimens are exposed to a cycle comprising a UV light at a controlled elevated temperature and an intermittent water spray. The florescent UV and Xenon lamps most commonly used in accelerated weathering testers produce different spectra of radiation. Xenon lamps reproduce the entire spectrum of sunlight, including ultraviolet (UV), visible light, and infrared (IR). The accelerated weathering testers using UV fluorescent lamps, on the other hand, do not attempt to reproduce sunlight, just the damaging effects of sunlight that occur at wavelengths from 300 nm to 400 nm. This wavelength range simulates the critical short-wave UV that produces the most physical property damage caused by sunlight.

Fluorescent UV lamps are usually classified as UVA and UVB lamps based on their wavelength spectra. The UVA lamps produce the most realistic simulation of sunlight in the critical short wavelength portion of the spectrum. The spectral power distribution of the UVA lamps matches sunlight very closely from the solar cutoff to about 360 nm and depends upon the irradiance intensity of the lamps. UVB lamps include the shortest wavelength found on the earth's surface and emits an unnatural light source, but degrades material faster than UVA lamps (Airey 2003). UVA-340 lamps provide better correlation with actual outdoor weathering compared to UVB and Xenon lamps.

Oven aging involves aging the compacted asphalt specimens at elevated temperatures in an oven. Hot air is blown across the compacted asphalt specimens and simulates field aging that takes place during pavement service life. One common long-term aging procedure involves placing the compacted asphalt specimens in the oven at 185^{o}C for 120 hours, after which the specimens are removed from the oven and allowed to slowly cool to room temperature (AASHTO 1990).

Environmental Room aging exposes test specimens to natural environmental weather conditions comprising 60^{o}C and 50% relative humidity under a pressure of 1 atm. One month of aging of the asphalt specimen under these conditions was found approximately equal to 15 months in the field in Texas

(Davidson and Glover 2007). The actual aging time can vary in different places depending upon such things as the number of hours per day of sunlight and the angle of the sun.

2.2 Laboratory Study of Wet Track Abrasion

The wet track abrasion (WTA) test is a simulated field performance test that has been correlated to the measurement of the wearing qualities of slurry seals under wet abrasion conditions. Slurry seals are a mixture of asphalt emulsion and fine aggregate that are used to refurbish the travel lanes of asphalt pavements, whereas fog seals are typically used for untraveled surfaces such as shoulders and lightly traveled surfaces such as parking lots. Under the ISSA TB 100 test specification, the slurry seal mixture is prepared by adding proper amounts of asphalt emulsion, portland cement, hydrated lime or other additives, and water to fine-graded aggregate. The mixture is then spread over a 279-mm-diameter roofing felt disk to a uniform thickness and then left in an oven at 60^{o}C for 15 hours. After curing, the specimen is immersed in a 25^{o}C water bath for 1 hour. The abrasion test is then performed using a modified Hobart tester (N-50) as shown in Figure 1.

Figure 1. Wet track abrasion tester – Hobart N-50 (Mastard Limited).

The specimen is clamped to the pan and the mounting plate by tightening the quick clamps, then covered with a quarter inch of water. Then, the specimen is mechanically abraded with a rubber hose attached to the motor driven shaft of the Hobart mixer for a specified time of 5 minutes and 15 seconds. After each test the hose is rotated to a fresh side. After completing the abrasion cycle, the specimen is removed from the pan, washed free of debris, dried in an oven at 140°F, and weighed. The difference in weight before placing the specimen in the water bath and after drying it in the oven gives the wear value or material loss of the slurry seal. The test is repeated with different amounts of asphalt emulsion to determine the optimum mix proportions.

The wet track abrasion test can be used to test the durability and longevity of fog seals (asphalt sealers) by replacing the slurry seal specimen with a fog-sealed asphalt concrete specimen. In this way, we can test both the abrasion resistance of the fog seal itself and its ability to bind to the pavement surface. A foam brush can be used to spread sealer uniformly over the surface of the asphalt substrate. Before testing, the fog-sealed specimens will be allowed to cure in the laboratory environment, then placed in an aging apparatus to artificially age the sealer before performing the abrasion test. Some minor modifications have to be made to the Hobart tester (N-50) in order to use an asphalt disk substrate, but other than that, the apparatus and test procedure will be same as in ISSA TB 100. This modified WTA test will help to find the wear value of sealer products such that good quality fog seals exhibit better resistance to abrasion.

2.3 Permeability of Hot Mix Asphalt

The presence of air voids characterizes the internal structure of asphalt mixtures and affects rutting, fatigue cracking, low temperature cracking, stripping, and changes in the permeability characteristics of the asphalt pavement. Air filtration into a permeable pavement accelerates the aging of the asphalt pavement through oxidation. The penetration of excessive amounts of air and water into the pavement structure may induce stripping of the asphalt cement from the aggregate surface, leading to potential pavement distresses (Choubane et al. 1998). The presence of water for extended periods in the pavement is directly linked to early deterioration and poor performance of the pavement.

For the sealers to work well, they have to fill up the interconnected air void space and seal off the pavement so that oxygen and liquids such as water and chemicals will be blocked from penetrating the surface. Sealer applied on the surface penetrates into the pavement to fill tiny small cracks and help to reduce the binder oxidation flow by passing into the air voids of the pavement. It is important to characterize the internal structure of the compacted asphalt specimen by determining the air voids content and permeability characteristics. This is done using a water permeability test or flow test. For our research the sealer quality can be analyzed by studying the change in permeability of compacted asphalt specimens before and after sealing.

The laboratory and field permeability of the compacted asphalt mix can be determined by passing the water through the compacted HMA specimen under gravity. The test method uses a Darcy's Law falling head approach. The coefficient of water permeability, k, is determined using the following equation (Cooley Jr. 1999).

$$k = \frac{aL}{A\Delta t}\ln\left(\frac{h_1}{h_2}\right)t_c$$

where: k = coefficient of permeability, cm/s
a = inside cross-sectional area of the standpipe, cm^2
L = average thickness of the test specimen, cm
A = average cross-sectional area of the test specimen, cm^2
h_1 = initial head across the test specimen, cm
h_2 = final head across the test specimen, cm
Δt = elapsed time between h_1 and h_2, s
t_c = temperature correction for the viscosity of water to 20°C

Traditionally, the permeability of compacted asphalt specimens was measured in the laboratory by using a permeameter device developed by the Florida Department of Transportation (FDOT) as shown in Figure 2. The permeameter consists of a graduated burette suspended from a cast iron tripod and attached to a specimen holder by a plastic hose. The specimen holder is formed by two PVC plates, one above the specimen and one below, with O-rings between the PVC plates and the test specimen and an epoxy sealing ring around the sides of the test specimen to prevent water from bypassing the specimen. The standpipe is filled with water and allowed to flow through an opening in the PVC plate where the surface area of the water expands to the specimen cross-sectional area. The time needed for the water level to drop from some initial head value to the final head value is recorded for use in determining the permeability.

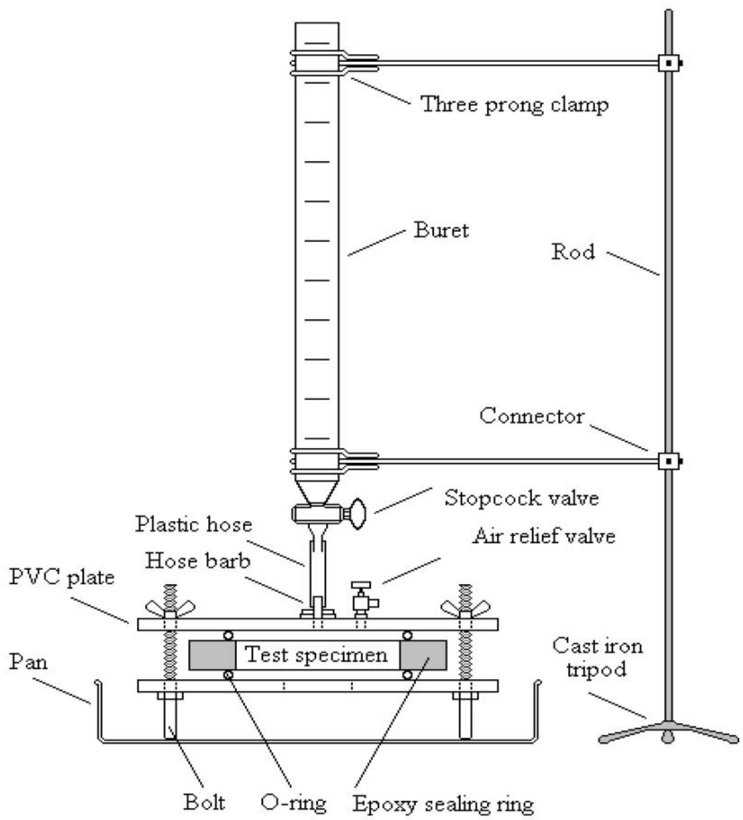

Figure 2. Schematic of FDOT standpipe permeameter (Choubane et al. 1998).

Presently, FDOT uses a different permeameter as shown in Figure 3. Models are available to test either 4-inch-diameter Marshall or 6-inch-diameter gyratory specimens. Florida DOT standard FM 5-565 and ASTM PS 129-01 specify the test procedures.

An asphalt specimen is placed inside a metal cylinder and water is allowed to flow through the saturated asphalt specimen under gravity. To prevent water from flowing around the specimen or out the sides of the specimen, a rubber or latex membrane inside the specimen chamber is pressurized against the sides of the specimen. The permeameter device contains a hand pump that provides a vacuum to hold the membrane flat against the sides of the chamber during assembly as well as the confining pressure to push the membrane against the specimen during testing. The surface texture along the sides of gyratory compacted specimens is not smooth, leading to potential water loss down the sides despite the membrane. To prevent water loss, an additional thin layer of petroleum jelly is applied to the sides of the specimen to achieve a satisfactory seal between the membrane and the gyratory specimen. For field HMA cores, petroleum jelly is not required because of their smooth surface texture.

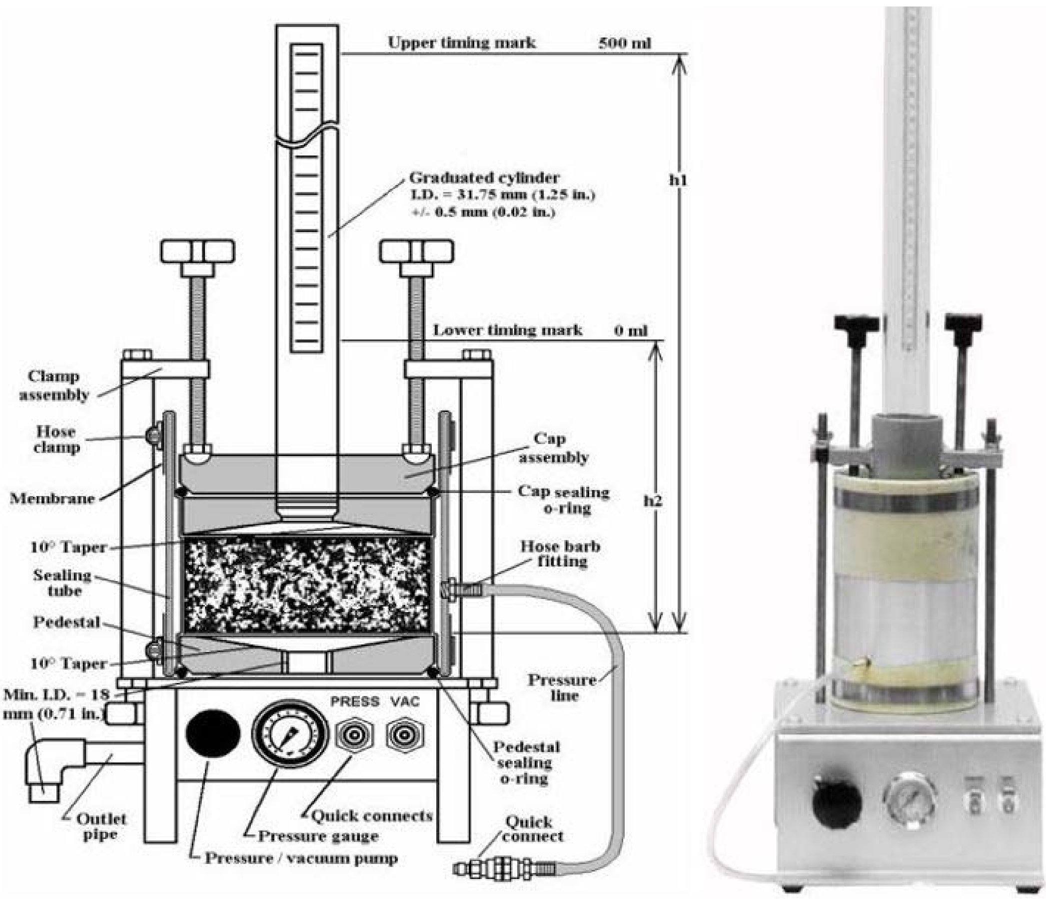

Figure 3. Schematic (left) and photograph (right) of permeameter (FDOT 2014; Gilson).

Several others devices have been developed by the National Center for Asphalt Technology (NCAT), the Virginia Department of Transportation (VDOT), and other agencies to measure HMA permeability in the laboratory, but all of them are similar to the FDOT device and FM 5-565 test procedures.

Complete saturation of the HMA specimen is the main issue in accurately determining permeability because a partially saturated specimen has a lower permeability than a fully saturated specimen. Saturation can be achieved by infiltrating 500 ml of water through the specimen. The test is run three times without allowing the remaining water in the graduated cylinder to run out, as this would allow air to reenter the specimen. A specimen is considered saturated if the first and third readings are within 4% of each other (Harris 2007). One technique that aids in achieving saturation is to nearly fill the graduated cylinder with water and adjust the water inflow so that it equals the outflow. The water is allowed to run for five or ten minutes and then timed testing begins.

Meanwhile, the bulk specific gravity of asphalt core specimens can be simply measured using standard laboratory techniques in accordance with AASHTO T 209 (or ASTM D 2726) to determine percent air voids. The air void content determination of the laboratory prepared specimens may help to determine the correlation between air voids and permeability and may provide further explanation of the performance of the sealer product in filling the air voids in the specimens. The air void content is computed from the specimen bulk specific gravity and theoretical maximum specific gravity by the following formula (Maupin Jr. 2000):

$$G_{mb} = \frac{W_a}{W_w - W_{SSD}}$$

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right) 100$$

where: VTM = Voids in total mix (air void content), %
G_{mb} = Bulk specific gravity of compacted specimen
G_{mm} = Maximum theoretical specific gravity of mixture
W_a = Weight of specimen in air, grams
W_w = Weight of specimen suspended in water, grams
W_{SSD} = Weight of specimen in saturated surface dry condition, grams

Chapter 3
Research Methodology and Results

As initially proposed, the wet track abrasion test used for the design of slurry seals (ISSA TB 100) was to be modified to test asphalt sealer longevity. The literature review revealed that asphaltic materials are degraded over time by UV radiation, so one component of the longevity testing is UV weathering of the asphalt sealers prior to testing. Since one of the primary purposes of asphalt sealers is to reduce the infiltration of water into the pavement, permeability testing of sealed asphalt specimens was also proposed as a way to classify sealers.

3.1 Wet Track Abrasion Test

The proposed research approach for longevity testing is to perform wet track abrasion tests on artificially weathered sealer specimens to assess their field performance over time. Because a major factor in the weathering of asphalt sealers is UV degradation, we chose a UV-based accelerated weathering device, the Q-lab QUV/Spray, that meets the ASTM G154 specification to simulate environmental weathering conditions. The QUV/Spray can apply as much as one year of UV exposure in 1000 hours because the UV lighting remains on nearly 24 hours per day.

As a result of the long weathering times, we needed to test as many sealer specimens at a time as possible. We therefore chose to use 150-mm-diameter asphalt disks cut from gyratory specimens as the sealer substrate. This allowed us to age 24 specimens at a time in the QUV/Spray. In the wet track abrasion device, the maximum distance from the bottom of the abrasion hose to the floor of the pan holding the specimen is ¾ inch. This limits the thickness of the asphalt disk specimens that can be used in the device without substantial modifications. The design of the QUV/Spray further limited the specimen thickness; therefore, we settled on ½-inch asphalt disks as our substrate. The asphalt disks will be cut from each end of a standard gyratory pat.

The proposed test procedure involves applying sealer products over the asphalt disks at a rate specified by the manufacturer, then curing the sealer in a normal laboratory environment for approximately four days. Next, the sealed specimens will be placed inside the QUV/Spray to age them per

ASTM G154. In the QUV/Spray, the specimens are exposed to an alternating cycle of 8 hours of UV radiation from a UVA-340 light source in a 60°C temperature-controlled environment, followed by a water spray for 15 minutes. The cycles repeat to a total time of 1000 hours. The aged specimens will then be removed from the QUV/Spray, cooled to room temperature, saturated in a water bath for 1 hour and placed in the wet track abrasion tester for testing per ISSA TB 100. The abrasion loss of the various sealers will be measured and compared to one another to evaluate relative sealer longevity. The lower the abrasion mass loss, the higher the presumed longevity of the sealer in the field.

The gyratory pats are to be made in the laboratory from reheated plant mixed asphalt concrete compacted to a target air void content using a Brovold Superpave gyratory compactor (Pine Test Company AFGB1). The target void content can be achieved by compacting a specified mass of asphalt mix to a specified height. Then ½-inch disks can be cut from both ends.

We initially attempted to cut the ½-inch disks using a band saw fitted with a carbide cutting blade. This produced disks with a uniform sample thickness and flat faces but the work was inordinately slow (approximately 30 minutes per disk). After exploring several alternatives, we settled on an industrial radial-arm saw fitted with a 14-inch diamond blade designed for cutting joints in green concrete. We modified the saw to allow the blade to cut through the full 150-mm width of the gyratory pats in a single pass and built a jig to align the pats and hold them in place for accurate and repeatable cutting. This process was significantly faster (approximately 2 minutes per disk) and allowed us to produce a large number of disks relatively quickly.

To hold the ½-inch-thick asphalt disks in the QUV/Spray, we designed and fabricated aluminum specimen holders (shown in Figure 4 and Figure 5) to replace the specimen mounts that come with the QUV/Spray. Each specimen holder has two 5½-inch-diameter holes for exposing the asphalt disks to the UV light and three small pegs to support the disks in the nearly-vertical holders. The QUV/Spray has four compartments and each compartment can hold up to three specimen holders, for a total of 24 disks.

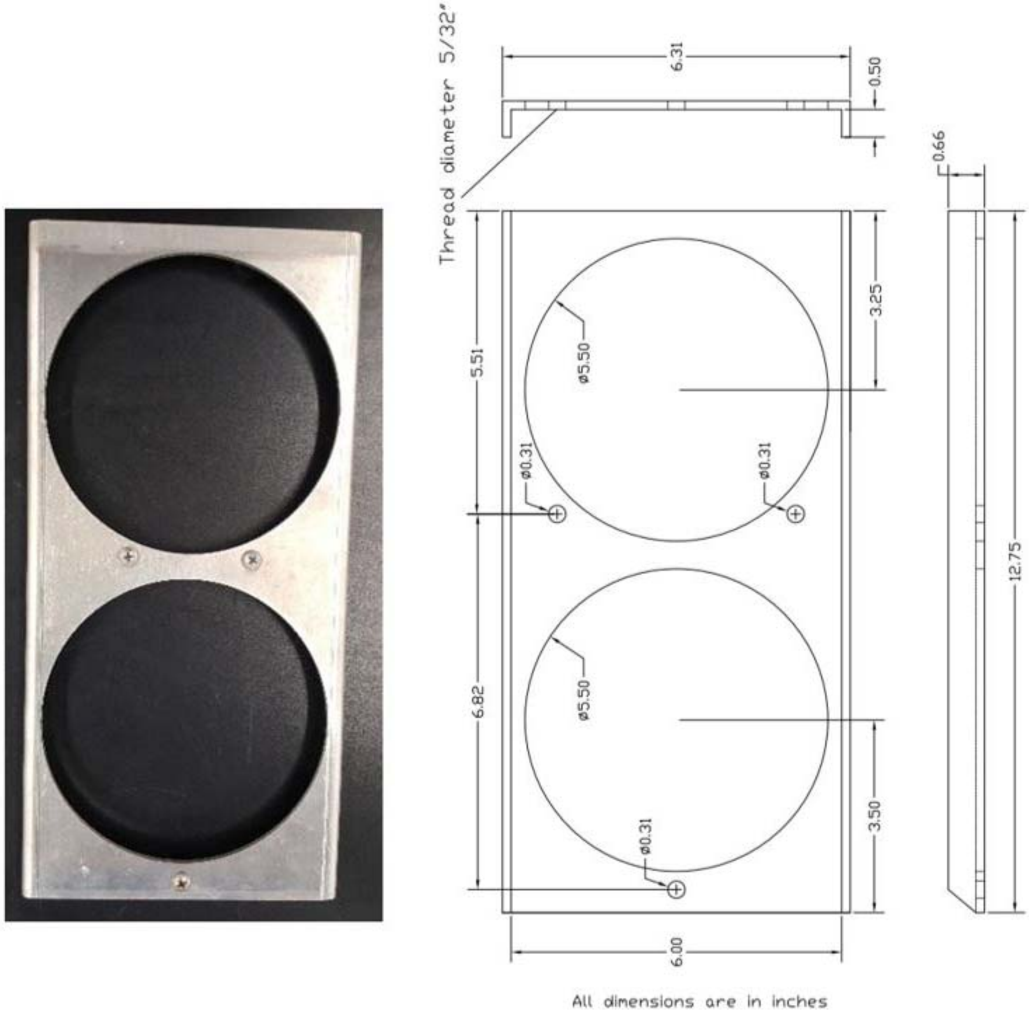

Figure 4. Photograph (left) and schematic (right) of disk specimen holder.

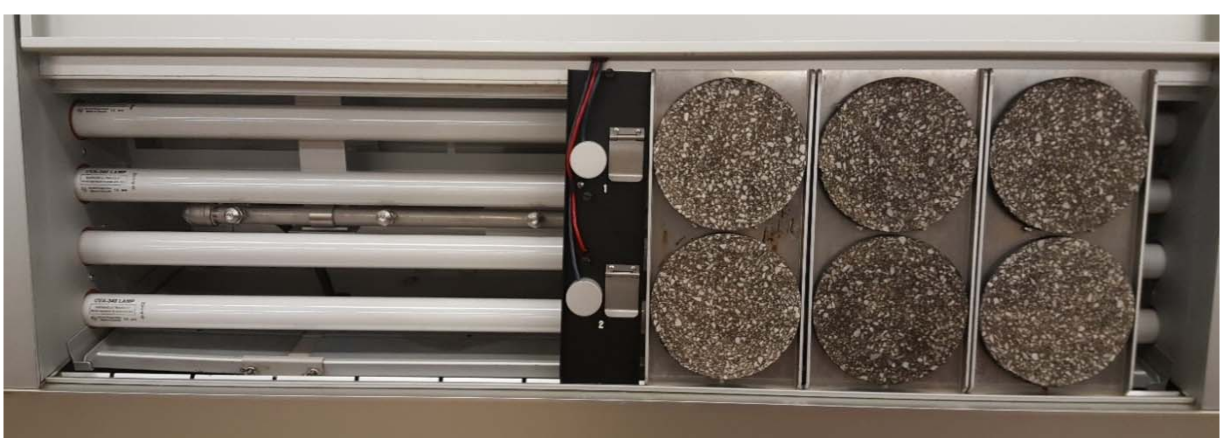

Figure 5. Specimen holders with asphalt disks inside QUV/Spray.

We also designed a rubber specimen holder, shown in Figure 6, to secure the ½-inch-thick disks in the wet track abrasion device. The specimen holder is an 8-mm-thick rubber sheet that is cut to make a 150-mm-diameter hole to hold the asphalt disk in place. The hole is located off-center so the disk is centered beneath the loading head. We also shortened the PVC hose on the loading head to a length of 85 mm to match the abraded area to the 150-mm-diameter sealed surface area of the disks. We added ½-inch metal spacers at both sides of the hose to match the original hose length for which the loading head was designed.

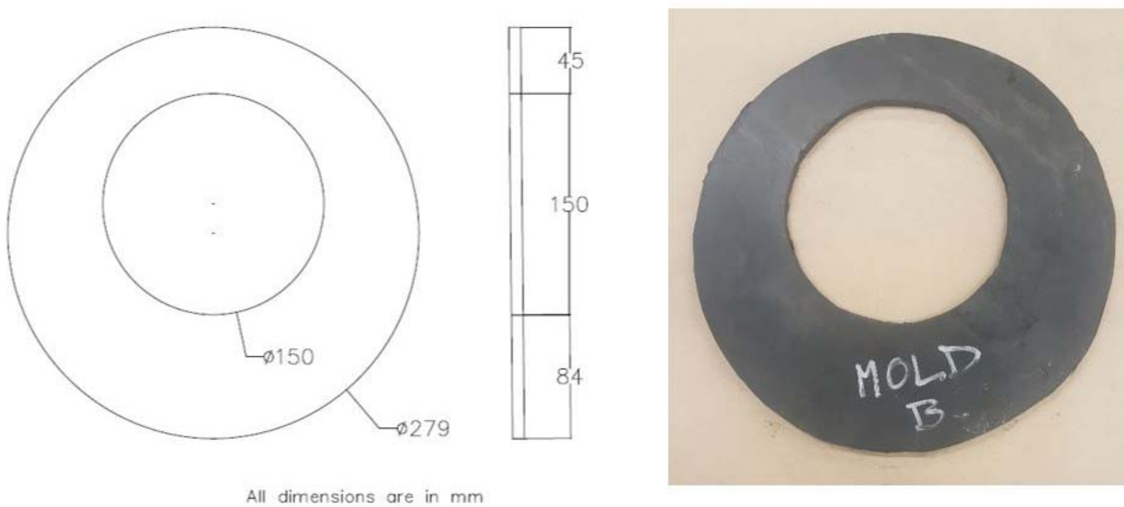

Figure 6. Schematic (left) and photograph (right) for Hobart N-50 disk specimen holder.

To make the gyratory pats from which the ½-inch disks would be cut, we initially selected a shoulder lane asphalt mix (TDOT 411-E mix) because asphalt sealers are often applied to these lanes. We compacted the 411-E mix to TDOT's 4% design air void content. When CSS-1h sealer was applied over the surface of those asphalt disks, we encountered an unanticipated problem wherein much of the sealer drained through the disks. This was attributed to interconnected void spaces within the disks that allowed the sealer to drain through rather than stay on the surface.

To correct this problem, we tried using disks made from over-compacted gyratory pats. The gyratory pats were compacted to three different air void contents—2.5%, 3%, and 3.5%—lower than the previous 4% air voids, but sealer drained through those disks, too. Test results obtained per ASTM D3203 showed that the ½-inch-thick disks have a much higher air void content than the gyratory specimen as a whole. Tests on the disks cut from both sides of the gyratory specimen and on the remainder of the specimen produced the air voids shown in Table 1 below.

Table 1. Percent air voids for 411-E specimens

Specimen Type	Percentage Air Voids				
	Target	Overall	End	Middle	End
411-E	2.50%	3.05%	5.93%	2.08%	5.09%
	3.00%	3.38%	6.39%	2.37%	5.13%
	3.50%	3.80%	6.37%	3.01%	5.64%

A review of the literature suggests that this is endemic to field and laboratory compaction specimens. The top and bottom regions have higher air voids than the middle portion. As an extreme example, for 164-mm-high gyratory specimens compacted at a target 7% air void content, the air void content in the top and bottom 20-mm regions was found to be 25% (Tashman et al. 2002; Yener and Hinislioglu 2014). This happens due to the restrained mobility of aggregate near the platens of the gyratory compactor, which results in inadequate compaction. Coarse-graded mixes exhibit greater susceptibility to this problem than fine-graded mixes. The lesser compaction may also occur in the field at the top and bottom of compacted lifts due to the constraint of the steel roller and the underlying pavement. Our test results and the literature review suggest that the sealer drained through the ½-inch-thick disks due to the thin size of the disks and the insufficient compaction of the asphalt in that region. Further exacerbating the problem, the maximum particle size of the mix is equal to the thickness of the disks, so interfaces between the undercompacted large aggregate particles within the disks can create a passage for the sealer to drain through the full thickness of the disks.

We explored several solutions for the sealer drain-through problem. One approach was to apply polyurethane sealant at the cut surface of the ½-inch-thick disk to prevent sealer draining from the bottom, but sealer still finds a way to flow from the disk edges. Another approach was to use an asphalt concrete mix with a much smaller nominal maximum aggregate size, such as a fine-graded 411-CS mix or 411-TL mix. 411-CS and 411-TL mixes have a 5/16-inch maximum aggregate size, which is much smaller than the ½-inch maximum aggregate size of the 411-E mix. We found that asphalt disks made from 411-CS or 411-TL asphalt mix compacted to TDOT's 4% design air void specification have a much lower permeability such that sealer did not drain through to the bottom and out the sides. We therefore settled on fine-graded 411-CS or 411-TL disks rather than coarser-graded 411-E mix because the smaller aggregate size helps to eliminate direct flow paths connecting the top to the bottom of the disks.

The making of asphalt disks in the laboratory is time-consuming and requires considerable effort. First, a suitable asphalt mix must be procured from the asphalt plant. Then it must be heated to proper compaction temperatures and compacted to TDOT's design specification. Lastly, the ½-inch-thick disks must be cut from the gyratory specimens. This process takes several days. Therefore, we sought an alternative asphalt substrate that has a surface texture similar to 411-TL or 411-CS asphalt disks. We explored mineral-surfaced roll roofing as a surrogate.

Mineral-surfaced roll roofing is made of a woven fiberglass base mat covered with a waterproof asphalt coating and topped with ceramic granules that provide some surface texture and protect the asphalt. If the tenacity of the pavement sealers has more to do with the physical integrity of the sealer layer than the adhesion between the sealer and the pavement, the shingles should provide the same results as the asphalt concrete disks with much less specimen preparation time and effort. The roll roofing has significant advantages over the asphalt concrete disks: it is inexpensive; it can be easily obtained from hardware and home improvement stores; and, most importantly, it eliminates the need to procure asphalt, make gyratory specimens and cut the disks.

The roll roofing was cut into 6-inch squares (which we will refer to as "asphalt shingles" hereafter) to occupy the same space in the QUV/Spray as the asphalt disks. To test the asphalt shingles in the wet track abrasion device, we fabricated a ½-inch-thick circular plastic holder (shown in Figure 7) on which the shingle is fixed by screwing at the four corners. The holes are slightly offset so the shingles are centered beneath the loading head during the test.

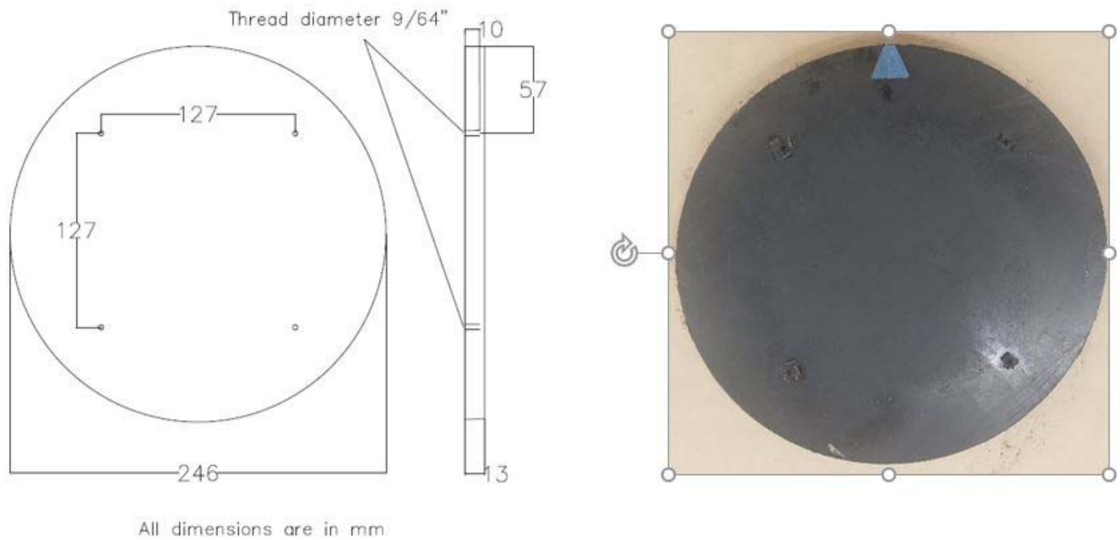

Figure 7. Schematic (left) and photograph (right) for Hobart N-50 shingle specimen holder.

Next, we applied CSS-1h sealer over the asphalt shingles and aged them inside the QUV/Spray. The CSS-1h sealer was applied at the typical 0.15 gal/S.Y. rate specified by TDOT over a circular area 5.5 inches in diameter (the same area covered in the sealed asphalt disks). The sealers were then weathered for 666 hours and 1000 hours under UV light and tested in the wet track abrasion device. A set of sealed but unweathered asphalt shingles were also tested in the abrasion device for comparison. Typical results are shown in Table 2 below.

Table 2. WTA results for CSS-1h sealer

Specimen ID	Shingle Specimen Mass Loss (g)		
	Unweathered	Weathered for 666 hours	Weathered for 1000 hours
1	2.18	2.15	2.10
2	5.99	2.97	2.77
Average	4.09	2.56	2.44

An unexpected result of this testing was that unweathered specimens suffered significantly more mass loss during the WTA test than UV-weathered specimens. It was suspected that the heat in the QUV/Spray was hardening the sealers more than they were degraded by the UV light. To investigate this further, we applied CSS-1h sealer to 12 shingles and placed 1/3 of them in the UV-weathering device, 1/3 of them in a 140°F oven (the same temperature as in the weathering device) and 1/3 of them in a dark drawer at room temperature. After 1000 hours, they were tested in the wet-track abrasion device. The results are shown in Table 3.

Table 3. WTA results for CSS-1h sealed shingles under different aging conditions

Specimen ID	Shingle Specimen Mass Loss (g)		
	QUV/Spray	Oven	Drawer
1	2.15	1.60	3.08
2	2.97	1.34	2.90
3	2.10	0.87	2.50
4	2.77	2.01	2.34
Average	2.50	1.46	2.71

This time, there was no statistically significant difference (t-Test: two-sample assuming unequal variance, p-two-tail value = 0.48) between the UV-weathered specimens and those stored in a dark drawer at room temperature, but oven-cured specimens suffered much less mass loss. Upon closer inspection, we noticed the removal of mineral granules from the unsealed portion of the shingles just outside the sealed area due to imperfect alignment of the shingles beneath the abrasion head. To prevent loss of granules, which could be misinterpreted as sealer loss, we applied sealer to the entire surface of the 6-inch squares of the mineral-surface roofing and repeated the previous experiment.

We applied 0.15 gal/S.Y. of non-diluted CSS-1h sealer to 36 mineral-surfaced roll roofing specimens and placed 12 each in (a) the QUV/Spray, (b) a 140^{o}F oven, and (c) a dark drawer at room temperature. We aged 1/3 of the specimens for 1000 hours, 1/3 for 2000 hours, and the rest for 3000 hours. All of the specimens were sealed at the same time to ensure consistency. Table 4 below shows the wet track abrasion results after the first 1000 hours of weathering. The results show no statistically significant difference (t-Test: two-sample assuming unequal variance, p-two-tail value = 0.19) in mass loss between the UV-weathered (QUV/Spray) specimens and those cured in the oven. There is a statistically significant difference in mass loss between the QUV/Spray and drawer (t-Test: two-sample assuming unequal variance, p-two-tail value = 0.07) and also for the oven and the drawer (t-Test: two-sample assuming unequal variance, p-two-tail value = 0.09) The specimens stored in a dark drawer at room temperature suffered more than twice the mass loss, supporting the hypothesis that the temperature inside the QUV/Spray and the oven hasten volatilization of the lighter hydrocarbons in the sealers, making them harder and stiffer.

Table 4. WTA results for CSS-1h sealed shingles under different aging conditions

Shingle Specimen Mass Loss (g)					
QUV/Spray		Oven		Drawer	
ID	Loss	ID	Loss	ID	Loss
9	0.15	10	0.18	3	0.71
17	0.13	14	0.17	15	0.75
33	0.12	34	0.20	31	0.31
41	0.17	38	0.13	47	0.24
Average	0.14	Average	0.17	Average	0.50

We aged the remaining asphalt shingles to even longer times, 2000 hours and 3000 hours, to determine if additional UV weathering begins to degrade the sealers more than curing improved them. The summarized wet track abrasion results are shown in Table 5 below. Each value is the mean of four replicates.

Table 5. WTA results for CSS-1h sealed shingles after different aging times

Aging Condition	Shingle Mean Mass Loss (g)		
	1000 hours	2000 hours	3000 hours
QUV/Spray	0.14	0.11	0.08
Oven	0.17	0.15	0.07
Drawer	0.50	0.70	0.51

The results for the specimens stored in the drawer exhibited significant scatter, making it much more difficult to discern a consistent trend for those specimens over time, but the weathered specimens showed similar rates of change of mass loss over time, suggesting that the oven and the QUV/Spray hardened the sealers at similar rates. This further suggests that UV exposure is not having the intended effect of aging the sealers or the hardening of the sealers at elevated temperatures is masking the effect. Therefore, aging in an oven might be an alternative to the QUV/Spray weathering equipment. In fact, prolonged aging might not even be needed since it seems to improve the results. The conclusion was made that the UV exposure had no appreciable effect on the sealers.

All of the previous wet track abrasion results are from unaged asphalt substrates. Since sealers are often applied to damaged pavements to preserve their life, we next wanted to determine whether aged substrates produced different results. We sealed 12 asphalt concrete disks with CSS-1h sealer and weathered them for up to 2000 hours in the QUV/Spray before testing them in the WTA device. Eight of the asphalt disks were themselves UV-weathered for 1000 hours before being sealed; the remaining four were unweathered before sealing. The WTA mass loss results are shown in Table 6 below.

Table 6. WTA results for aged and unaged disks

Disk Specimen Mass Loss (g)			
Time after sealing (hours)	1000	1000	2000
Weathered before sealing	No	Yes	Yes
Specimen (1)	0.12	0.05	0.02
Specimen (2)	0.16	0.06	0.01
Specimen (3)	0.12	0.12	0.02
Specimen (4)	0.34	0.06	0.04
Average	0.19	0.07	0.02

The results show that the WTA mass loss for the sealers applied to unweathered asphalt disks is more than twice that of the sealers applied to weathered asphalt disks. In addition, the specimens weathered for 2000 hours after sealing suffered much less mass loss than those weathered for just 1000 hours, further suggesting prolonged exposure to the elevated temperatures of the UV-weathering device improves the abrasion resistance of the sealers more than the UV light degrades them. The same is true for weathering of the substrates prior to sealing.

Many of our preliminary experiments were conducted using asphalt shingles due to the ease of specimen preparation. Table 7 compares the WTA results obtained using sealed shingles (Table 4) and sealed disks (Table 6) after 1000 hours of weathering in the QUV/Spray.

Table 7. WTA mass loss for CSS-1h sealed shingles and disks

QUV/Spray Specimen ID	Specimen Mass Loss (g)	
	Disk	Shingle
1	0.12	0.15
2	0.16	0.13
3	0.12	0.12
4	0.34	0.17
Average	0.19	0.14

We found that the disk and shingle substrates produce approximately the same mass loss. One of the disk specimens lost more than double the amount of the others, perhaps due to the loss of a couple of sand grains during handling, but the others showed mass loss nearly identical to the asphalt shingles. The results support the hypothesis that asphalt shingles (roll roofing) are a suitable substitute in the WTA test.

Our preliminary testing revealed that the QUV/Spray was not aging the specimens enough to embrittle the sealer and produced wet track abrasion results similar to oven-aged specimens. At the same time, unaged specimens produced highly variable results that were not conducive to comparing sealers. Therefore, we abandoned the QUV/Spray and settled on oven aging the specimens. To reduce the time needed to age the specimens, we adopted the AASHTO R 30 specification (AASHTO 1990), which specifies 5 days in a forced air draft oven at 185°F for long term aging of asphalt concrete. Since most sealers are asphalt emulsions, AASHTO R 30 should provide the same aging for the sealers as it does for asphalt concrete.

Table 8 shows the sealer mass remaining after 4 days curing in the air and before oven aging for both shingle and disk substrates. The CSS-1h, CQS-h, and CHPF sealers were diluted 1:1 with water prior to application. The applied sealer masses for the shingles are higher than for the disks because the applied area of the shingles (6-in by 6-in) is higher than for the disks (150-mm-diameter). The relative masses of the cured sealers differ slightly because of the loss of some sealer attached to the cellophane tape used to prevent sealer from draining off the disk surface during application. This tape was removed from the disks after 4 days of sealer curing in the air.

Table 8. Sealer application rates and the residual mass left after curing in the air

Sealer Type	Specific Gravity (G_s)	Application Rate (gal/S.Y.)	Sealer Mass Applied (g)		Cured Sealer Mass Left (g)	
			Disk	Shingle	Disk	Shingle
TRMSS	1.05	0.14	11.75	15.44	3.74	6.25
LD-7	1.10	0.10	8.80	11.57	2.91	4.48
CQS-1h	1.00	0.15	12.00	15.77	3.78	5.02
PMM	1.15	0.10	9.20	12.09	3.51	5.90
CSS-1h	1.00	0.15	12.00	15.77	3.64	5.10
CHPF	1.00	0.15	8.00	10.51	2.64	3.49

The results show that the cured sealer mass is similar for all of the sealers, regardless of the application rate of the uncured sealer. This suggests that the thickness of the cured sealer layer is also similar for all of the sealers prior to the wet track abrasion test. The notable exception is the CHPF sealer, which had approximately 2/3 of the sealer mass of the others.

The end result of this investigation was a procedure for testing the longevity of asphalt sealers using both asphalt concrete disks and shingles as the substrate. These procedures are outlined in Appendix A and Appendix B, respectively. Using these test procedures, and the modified wet track abrasion device, we performed a final round of wet track abrasion tests on a variety of sealers. The wet track abrasion test results are shown in Table 9 and Table 10 beginning on the next page. The mean results are illustrated in the box-and-whisker plots in Figure 8 and Figure 9.

The results show that the CSS-1h and CHPF sealers had the lowest mass loss and the LD-7 had the highest mass loss among all sealers in both substrates. To corroborate the wet track abrasion results, we saved the contents of the specimen pan from each test into a metal bowl and placed it in the oven to dry. The residual left in the metal bowls is shown in Figure 10. The LD-7 lost considerable sealer mass and therefore the residue looks black, whereas the CSS-1h lost little mass and the residue looks red. The red color is not from the sealer but is due to the abrasion of the red hose used in the wet track abrasion test.

Table 9. WTA results for different sealers using shingles

Sealer Type	Specimen ID	Shingle Mass Loss (g)	
		Specimen	Mean
TRMSS	1	0.31	0.28
	2	0.32	
	3	0.29	
	4	0.19	
	5	0.29	
	6	0.27	
LD-7	1	0.47	0.45
	2	0.44	
	3	0.29	
	4	0.51	
	5	0.40	
	6	0.58	
CQS-1h	1	0.18	0.17
	2	0.18	
	3	0.16	
	4	0.19	
	5	0.14	
	6	0.19	
PMM	1	0.15	0.17
	2	0.20	
	3	0.19	
	4	0.16	
	5	0.17	
	6	0.17	
CSS-1h	1	0.07	0.07
	2	0.07	
	3	0.07	
	4	0.09	
	5	0.06	
	6	0.07	
CHPF	1	0.10	0.08
	2	0.10	
	3	0.07	
	4	0.08	
	5	0.07	
	6	0.07	

Table 10. WTA results for different sealers using disks

Sealer Type	Specimen ID	Disk Mass Loss (g)	
		Specimen	Mean
TRMSS	22A	0.36	0.37
	24A	0.38	
	36A	0.31	
	38B	0.24	
	39B	0.48	
	43A	0.48	
LD-7	23A	0.48	0.49
	27A	0.51	
	31B	0.45	
	34A	0.52	
	42A	0.54	
	43B	0.42	
CQS-1h	22B	0.21	0.24
	32B	0.26	
	33B	0.19	
	36B	0.29	
	38A	0.25	
	42B	0.22	
PMM	4A	0.15	0.18
	8B	0.20	
	13B	0.18	
	23A	0.17	
	25A	0.17	
	27A	0.19	
CSS-1h	4B	0.11	0.12
	18A	0.16	
	18B	0.15	
	28A	0.10	
	28B	0.09	
	41B	0.14	
CHPF	2B	0.19	0.13
	5A	0.10	
	13A	0.12	
	25B	0.11	
	37A	0.11	
	41A	0.16	

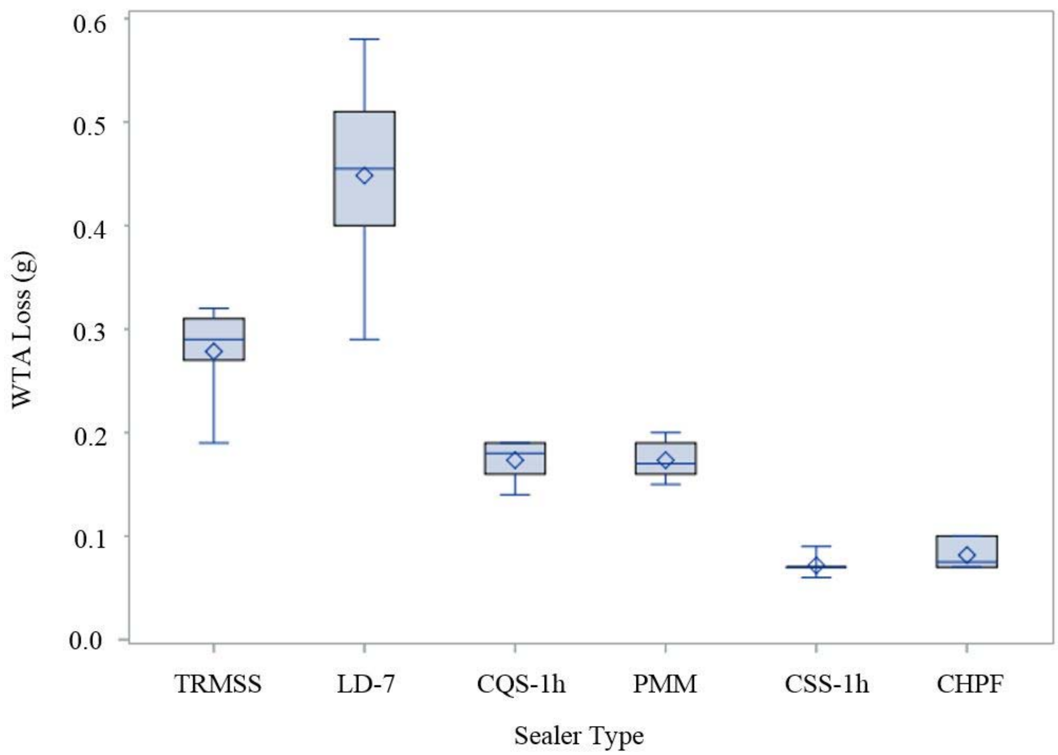

Figure 8. WTA mass loss for different sealers using shingles.

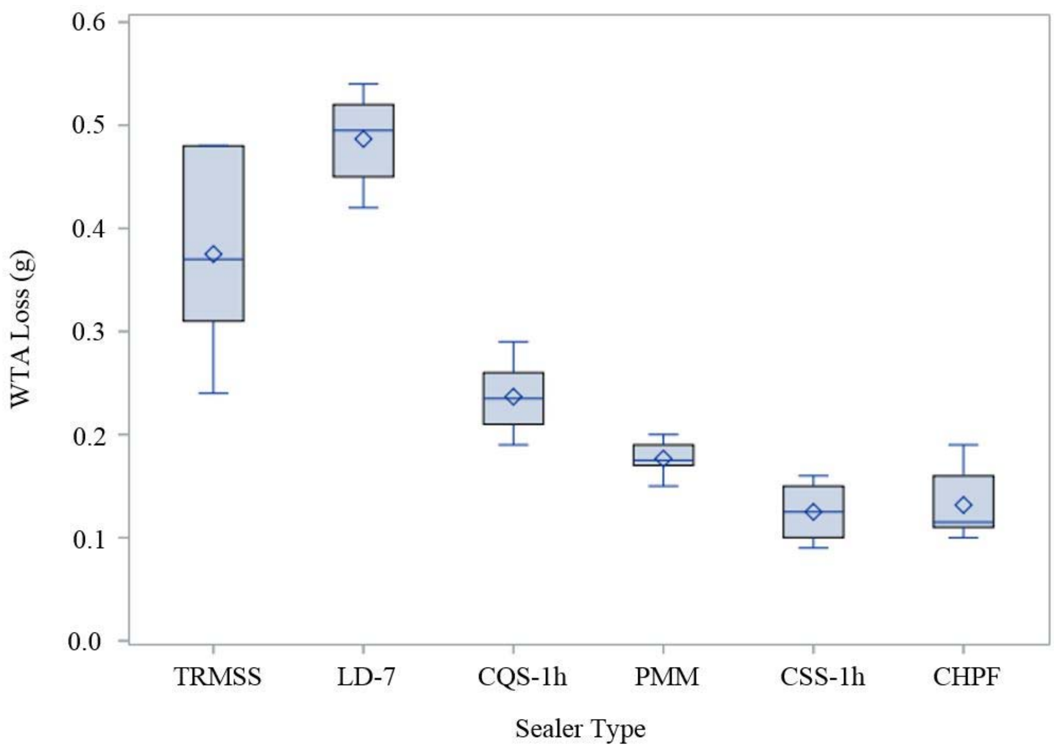

Figure 9. WTA mass loss for different sealers using disks.

Figure 10. Photograph of WTA residue for CSS-1h (left) and LD-7 (right) specimens.

The box-and-whisker results also show that the CSS-1h and CHPF mass losses were indistinguishable, and the LD-7 and TRMSS mass losses were higher and more variable. The CQS-1h and PMM mass losses were similar to each other, but slightly higher than the CSS-1h and CHPF mass losses. The standard deviations of the mass losses are shown in Table 11 below.

Table 11. Standard deviation of WTA results

Sealer Type	Standard Deviation	
	Shingle	Disk
TRMSS	0.047	0.095
LD-7	0.099	0.045
CQS-1h	0.020	0.037
PMM	0.019	0.018
CSS-1h	0.010	0.029
CHPF	0.015	0.035

For the shingle specimens, the standard deviations of the mass losses are close to the 0.01-g accuracy of the electronic balance used to measure the mass of the specimens, suggesting excellent repeatability. The TRMSS and LD-7 sealers showed the greatest scatter among the results, but all of the standard deviations are within one order of magnitude of the measurement accuracy. From this we conclude that six specimens from each sealer are sufficient to compare the sealers.

The comparison of the wet track abrasion results for the shingles and the disks is shown in Figure 11. The results show that the disk substrates exhibited more sealer mass loss than the shingle substrates for all sealers. This is likely because of the slight difference in surface texture between the disk and shingle substrates. Shingles have more surface texture due to the uniform height of the mineral granules. Sealer settles in between the mineral granules, so less sealer is exposed to the abrasion hose. Despite that, the ranking of the sealers did not change no matter the substrate. This also suggests that shingles are a suitable alternative to the asphalt disks for evaluating sealer mass loss.

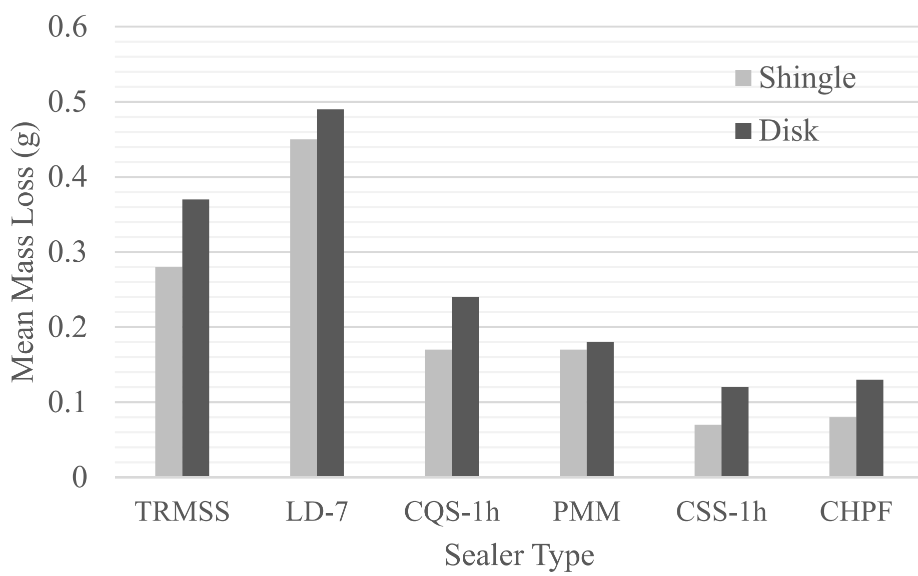

Figure 11. WTA results for shingles and disks.

We ran subsequent tests on the previously tested specimens to determine if the sealer had been completely removed or if additional abrasion would change the results. We performed a 2nd and 3rd wet track abrasion test on those previously tested substrates. The summarized wet track abrasion results are shown in Table 12 and Table 13 below. This data is illustrated in Figure 12 and Figure 13, which show the mean mass loss from the first test and the mean total mass loss from all three tests.

Table 12. WTA mass loss for different sealers after different times using shingles

Sealer Type	Shingle Mean Mass Loss (g)			
	1st test	2nd test	3rd test	Total
TRMSS	0.28	0.08	0.05	0.41
LD-7	0.45	0.05	0.04	0.54
CQS-1h	0.17	0.02	0.02	0.21
PMM	0.17	0.04	0.05	0.26
CSS-1h	0.07	0.01	0.01	0.09
CHPF	0.08	0.04	0.02	0.14

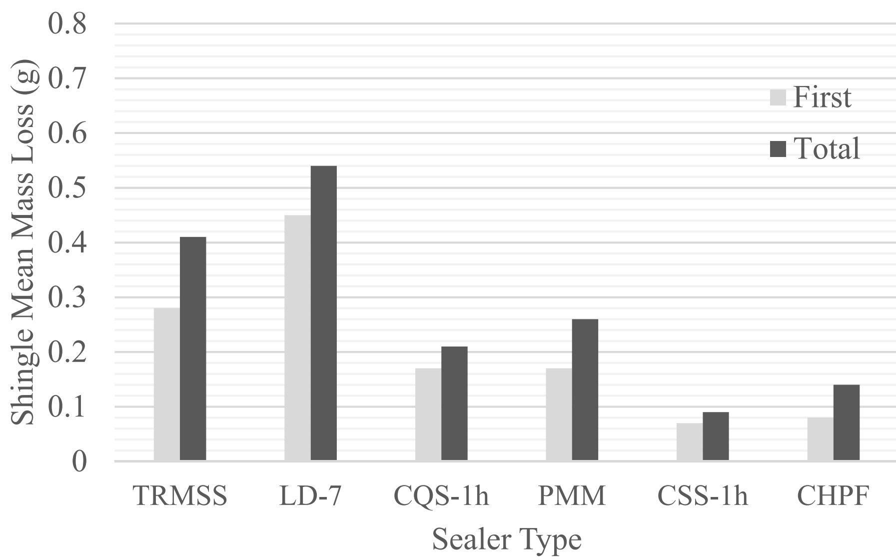

Figure 12. First and total mean mass losses for different sealers using shingles.

Table 13. WTA mass loss for different sealers after different times using disks

Sealer Type	Disk Mean Mass Loss (g)			
	1st test	2nd test	3rd test	Total
TRMSS	0.37	0.17	0.12	0.66
LD-7	0.49	0.10	0.10	0.68
CQS-1h	0.24	0.05	0.07	0.35
PMM	0.18	0.12	0.09	0.38
CSS-1h	0.12	0.06	0.05	0.24
CHPF	0.13	0.05	0.06	0.24

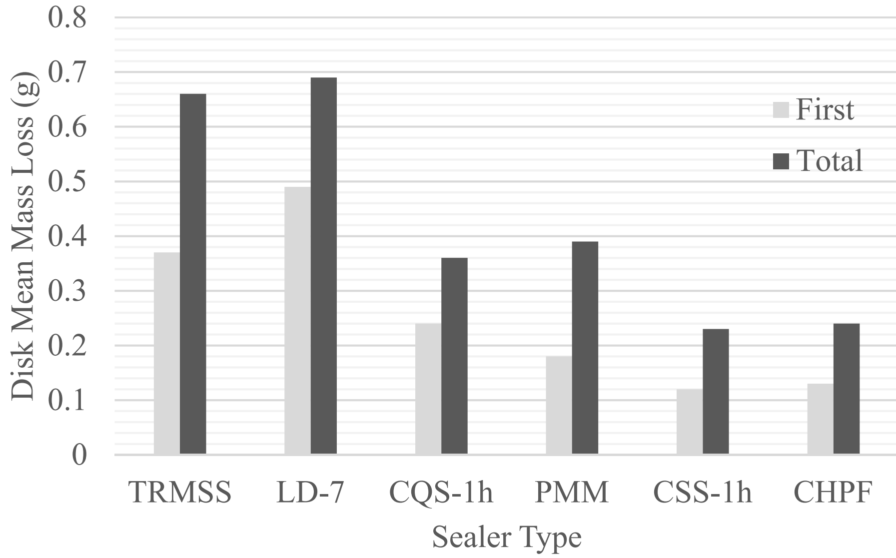

Figure 13. First and total mean mass losses for different sealers using disks.

For the shingles, the difference in sealer mass loss from the first test to the last is small for all sealers. This is because of the greater surface texture of the shingles. Most of the sealers were abraded from the surface of the mineral granules during the first abrasion test and there was no sealer left to lose after the first test. For the disks, there was a noticeable additional sealer mass loss after the 1st test. This is because more sealer remained on the top of the disks and exposed to the abrasion hose. The ratio of mean mass loss from the first test to the total from all three tests is consistent for all sealers. The mean mass loss ratio is 0.58 (standard deviation = 0.09).

For all sealers and both substrates, the majority of the mass loss occurred during the first test and the ranking of the sealers was the same using both total mass loss and mass loss during the first test. Therefore, we conclude that a single wet track abrasion test run for the specified time of 5 minutes and 15 seconds is sufficient to compare the sealers.

3.2 Permeability Test

Permeability testing of asphalt disks before and after sealing will be used to determine the performance of the sealer by analyzing the relative reduction in permeability. The methodology originally proposed was to use the same ½-inch disks for both wet track abrasion and permeability testing. The idea was to cut the disks, measure their permeability, seal them, age them, measure their permeability again, then test their wet track abrasion resistance. That way, a single disk could be used for both tests, cutting the number of samples in half.

We did initial permeability testing using a simple standpipe permeameter device made in the laboratory from a graduated cylinder as shown in Figure 14. The seal between the standpipe base and disk is provided by plumber's putty. A metal plate sitting on the base helps to provide stability.

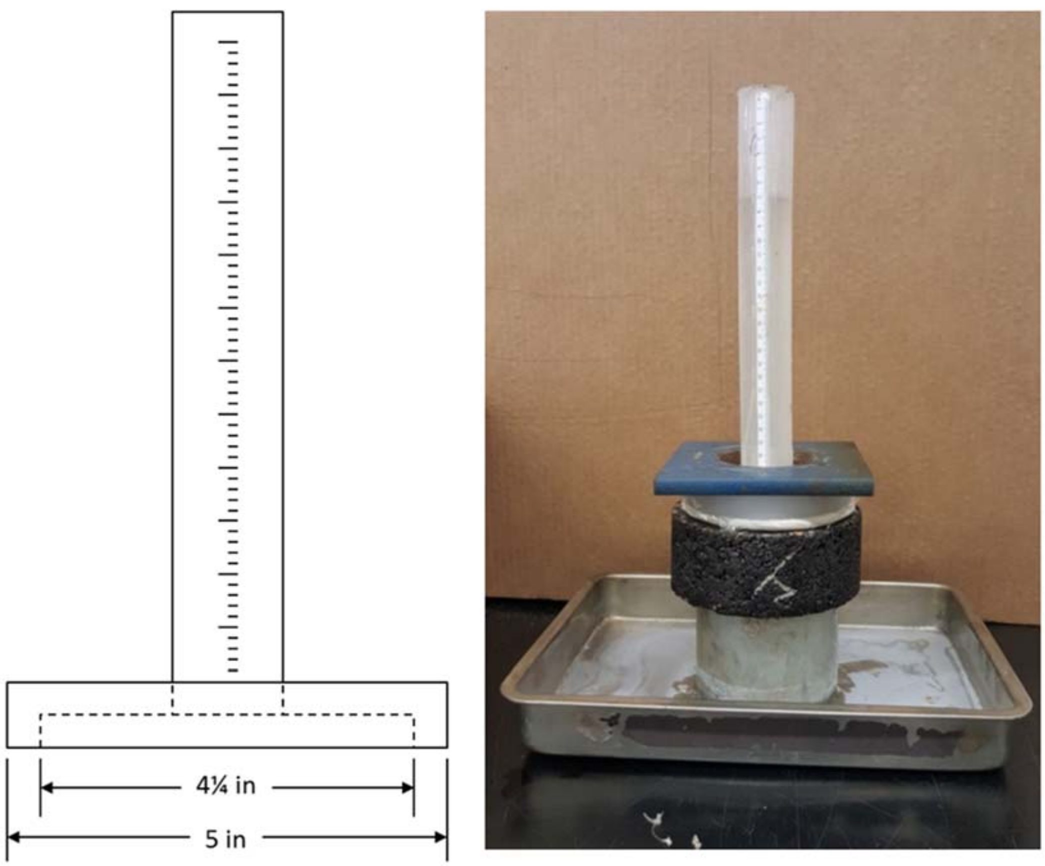

Figure 14. Schematic (left) and photograph (right) of laboratory permeameter.

We quickly discovered that the permeability of the 411-TL and 411-CS disks used for the wet track abrasion testing was too low to reliably discern a difference after sealing. This was a direct consequence of having switched to a fine-graded mix to prevent sealer drain-through. Therefore, we adopted a coarser-graded 411-TLD mix, which is used for thin overlays of the travel lanes on Tennessee highways. To maximize the unsealed permeability, we compacted the 411-TLD mix to a void content of 5.5%, which is the upper limit of production air void content in the TDOT specification.

Initial results varied over an unacceptably large range due, primarily, to the thinness of the asphalt disks. Because the nominal maximum aggregate size in the 411-TLD mix is equal to the ½-inch thickness of the disks, the permeability was determined in large part by the number of uninterrupted flow paths directly extending through the disk. In a full-height gyratory specimen, water takes a tortuous path through the disk that makes the total flow length much greater than the height of the disk. The thin disks reduce the tortuosity considerably, leading to much greater flow rates and higher measured permeabilities that vary considerably from disk to disk. It was also difficult to get a good seal between the standpipe permeameter and the asphalt, adding to the variability.

We abandoned the standpipe and obtained a Florida DOT-style permeameter (Gilson model AP-16), shown in Figure 15, that is specifically designed for gyratory specimens. The Gilson permeameter can accommodate full-thickness gyratory specimens, however we had previously determined that there were density variations through the thickness of the compacted specimens. The middle region is over-compacted and has low permeability, so the water flow would be interrupted in those regions, leading to very low permeabilities and making it difficult to discern the effect of the sealers. As a result, we could not use a full gyratory specimen nor even half of a gyratory specimen because it would contain some portion of the over-compacted middle region. To avoid the over-compacted central region, we chose to use disks made from only the end regions of the gyratory specimens. To determine the appropriate disk thickness, we made and tested disks having three different thicknesses: 1-inch, 1.25-inch, and 1.5-inch.

To use these disks in the permeameter, we fabricated hollow plastic spacers having a 150-mm outer diameter and a wall thickness of 5.5 mm to make up the difference in height between the disks and a full gyratory specimen. We made one spacer for each different disk size. We secured the plastic spacers to the specimen pedestal with duct tape to make a watertight seal. We also extended the outlet pipe upward such that the pipe outlet elevation and the top of the spacer (bottom of the disk) are at the same elevation in order to maintain the continuity of water flow from the bottom of the disk to the outlet. The extension was sized for a minimum 1-inch disk thickness, which will work for all three disk thicknesses because the bottom elevation of the disk is always below the pipe outlet elevation as shown in Figure 15 and Figure 16.

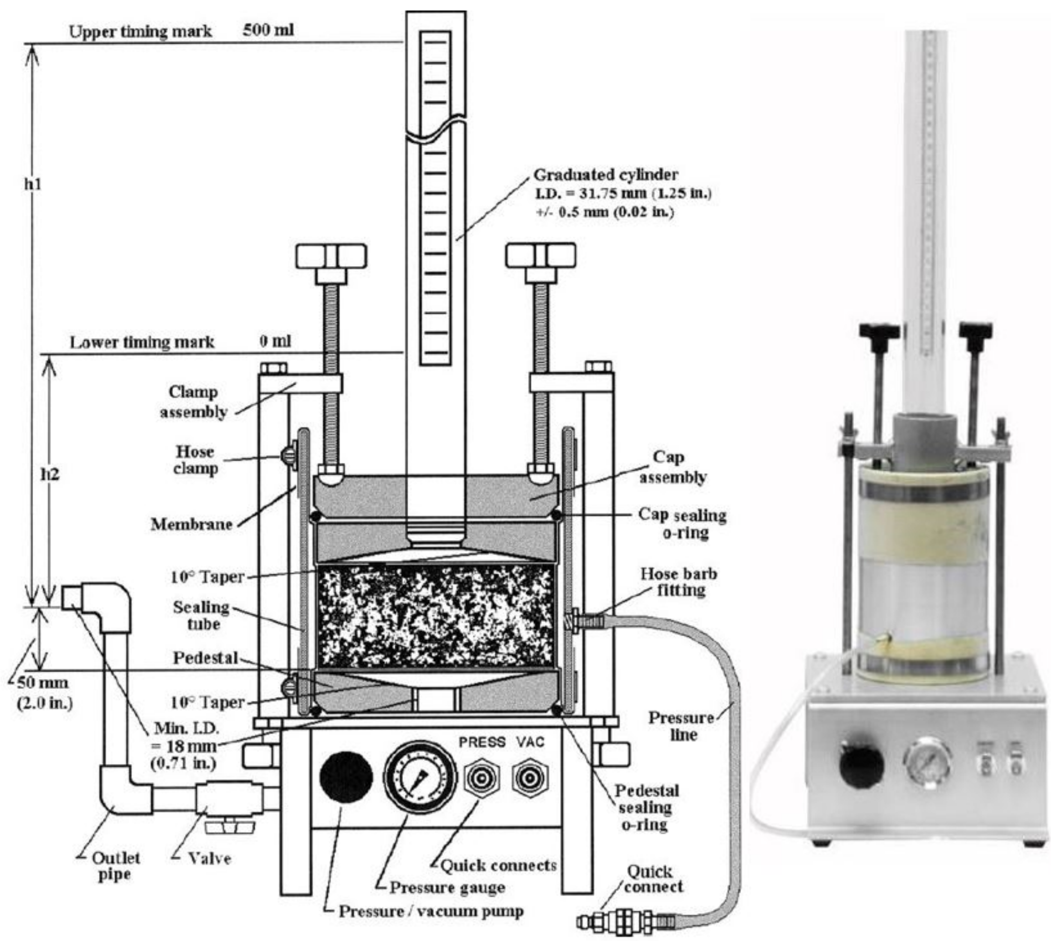

Figure 15. Schematic (left) and photograph (right) of Florida DOT-style permeameter.

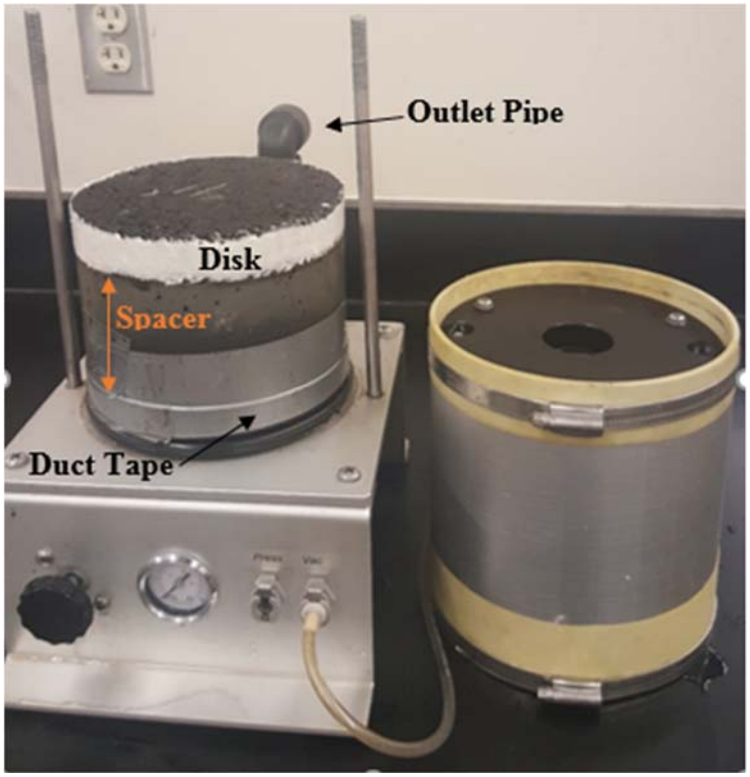

Figure 16. Photograph of Gilson permeameter with disk specimen spacer.

We measured the permeability of the various disks per FM-565, which is the Florida DOT test method for measurement of water permeability of compacted asphalt paving mixtures. The permeability results are shown in Table 14 and Figure 17 below.

Table 14. Permeability results of disks of different thickness

Thickness (inch)	Specimen ID	Permeability (cm/s)
1	A	2.27E-05
	B	5.25E-05
1.25	A	1.62E-05
1.5	A	1.05E-05
	B	9.89E-06

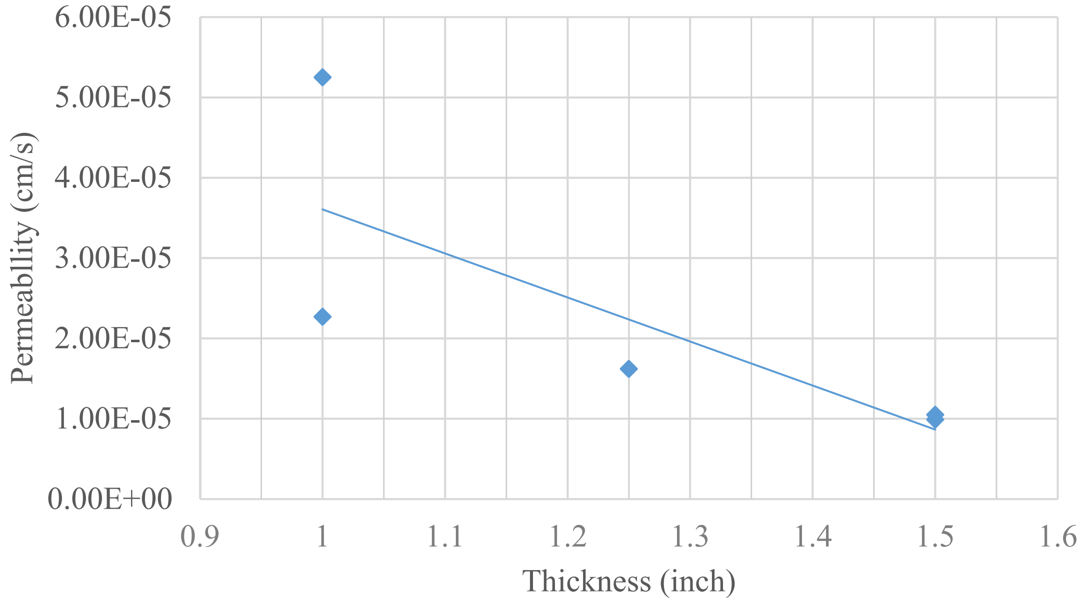

Figure 17. Permeability results with varying thickness.

The results show that the permeability values become lower with an increase in asphalt disk thickness. This is due to the thicker specimens having fewer water flow paths that extend directly through the specimens, giving more consistent results but a lower permeability. The lower permeability of the 1.25-inch and 1.5-inch disks will make it difficult to discern differences in permeability after sealing. So, we adopted a 1-inch asphalt disk thickness for subsequent tests.

Next, we performed permeability testing on unsealed 1-inch-thick asphalt disks. We then sealed those disks with a fresh batch of CSS-1h sealer, cured them in a normal laboratory environment for 4 days, then aged them in a forced air draft oven for 7 days at 140^{o}F (Braham et al. 2013). After aging, the permeability of these disks was measured again. The permeability results are shown in Table 15 below. The results show that the permeability of the asphalt disks decreases by 36% on average after sealing. The results confirmed that the 1-inch-thick disks produced discernable differences in permeability after sealing.

Table 15. Permeability results for CSS-1h sealer

Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)
	$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$
1A	7.71E-05	4.26E-05	0.45
1B	4.82E-05	3.43E-05	0.29
2A	7.02E-05	2.99E-05	0.57
2B	2.91E-05	2.56E-05	0.12
3A	5.86E-05	4.59E-05	0.22
3B	4.53E-05	2.11E-05	0.53
		Mean RF	0.36

Initially, the disks were aged for 7 days at 140°F (the temperature in the QUV/Spray) in a forced air draft oven. To reduce the time needed to age the specimens, we adopted AASHTO R 30 (AASHTO 1990), which specifies 5 days in a forced air draft oven at 185°F for long-term aging of asphalt concrete. This is the same aging method adopted for the wet track abrasion specimens. We performed permeability tests on a new batch of unsealed disks, sealed them using fresh batches of TRMSS and LD-7 sealers, aged them per AASHTO R-30, then performed a second permeability test. The results are shown in Table 16.

Table 16. Permeability results for different sealers

Sealer Type	Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)
		$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$
TRMSS	7B	9.67E-05	4.36E-05	0.55
	10A	6.85E-05	5.18E-05	0.24
	13B	1.02E-04	5.57E-05	0.45
	16B	8.99E-05	4.40E-05	0.51
	18B	2.81E-05	5.30E-05	-0.89
	19B	1.09E-04	4.00E-05	0.63
LD-7	8A	5.71E-05	3.48E-05	0.39
	8B	5.86E-05	6.68E-05	-0.14
	14A	3.35E-05	4.62E-05	-0.38
	15A	3.20E-05	3.88E-05	-0.21
	16A	4.25E-05	9.03E-05	-1.12
	20A	8.44E-05	8.79E-05	-0.04

An unexpected result of this testing was a higher permeability value for some sealed disks compared to the unsealed disks. We retested the disks and obtained similar results. The problem was attributed to the sealing agent (petroleum jelly) applied at the edge of the disks during the permeability test. Both the Florida FM 5-565 and ASTM PS 129-01 test methods use petroleum jelly to produce a watertight seal between the specimen and the flexible membrane of the permeameter. When the petroleum jelly is applied initially to the unsealed specimen, it will not damage the asphalt and gives accurate permeability values. But when those same disks are placed in the oven at 185°F for 5 days, the petroleum jelly softens the asphalt in the mix and slightly disintegrates the aggregate near the outer edges of the disks. This causes the water to bypass the specimen and increases the permeability value even after sealing.

We selected silicone gel as an alternative because it has the gel properties of petroleum jelly but with inert chemical properties. The specific product we used was white DAP® 100% Silicone Window, Door, & Siding Sealer.

We had already performed many permeability tests on unsealed disks using petroleum jelly. So as not to waste these disks, we removed the petroleum jelly and applied silicone gel as shown in Figure 18 before sealing the disks for the next set of tests. The silicone gel was allowed to cure for one day. We then sealed them with a fresh batch of TRMSS sealer and aged them per the AASHTO R 30 specification. We performed two sealed permeability tests of each disk and averaged the results to make them more reliable. The permeability results of the unsealed disks and the sealed disks after aging are shown in Table 17.

Figure 18. Silicone caulk (left) and silicone applied at the disk edges (right).

Table 17. Permeability results for TRMSS sealer

Sealer Type	Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)
		$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$
TRMSS	9B	1.00E-04	1.04E-04	-0.04
	21B	8.74E-05	6.75E-05	0.23
	22A	7.44E-05	4.68E-05	0.37
	26B	7.87E-05	1.73E-04	-1.20
	28A	6.84E-05	6.12E-05	0.11
	30A	9.97E-05	1.88E-04	-0.89

The results in Table 17 show that the permeability of TRMSS sealed disks after aging is still sometimes more than that of the unsealed disks. The poor result was due to the petroleum jelly used in the first unsealed permeability test that was not washed out completely. Therefore, we concluded not to use any of the remaining unsealed disks and repeated the sealed and unsealed tests with fresh asphalt disks. In addition, the silicone gel was not well cured in the previous tests, so we increased the curing time to 2 days for the next tests.

Prior to testing we applied silicone gel to the edges of the disks and left it to cure for 2 days in a laboratory environment. We then performed unsealed permeability tests of the disks. Then, the disks were dried in an oven and sealed with a fresh batch of CQS-1h and LD-7 sealers. We used a fresh batch of sealer every time because the sealer has a short life span. After 4 days of curing in the laboratory environment with silicone gel wrapped on the outer edges, the sealed disks were placed in the oven for 5 days at 185°F for aging and their permeability was measured again. The permeability results are shown in Table 18 below.

Table 18. Permeability results for different sealers

Sealer Type	Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)
		$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$
CQS-1h	24B	5.72E-05	3.25E-05	0.43
	25A	5.17E-05	1.62E-05	0.69
	25B	1.00E-04	3.49E-05	0.65
	27A	1.20E-04	4.00E-05	0.67
	28B	5.48E-05	4.03E-05	0.26
	30B	7.05E-05	2.88E-05	0.59
LD-7	12A	3.21E-05	4.05E-05	-0.26
	14B	7.41E-05	1.08E-04	-0.46
	18A	8.48E-05	5.14E-05	0.39
	20B	7.99E-05	1.09E-04	-0.36
	21A	7.46E-05	5.04E-05	0.32
	22B	3.83E-05	4.30E-05	-0.12

Table 18 shows that the results for the LD-7 specimens were incongruent for four of the disks because the sealed permeability is still greater than the unsealed permeability, but all of the results for CSS-1h were good. To investigate the cause for the higher permeability results even after sealing, we repeated the permeability testing of the TRMSS (from Table 17) and LD-7 (from Table 18) sealed disks that had a greater sealed permeability than the unsealed permeability. The new test results are shown in Table 19.

Table 19. Permeability results for different sealers

Sealer Type	Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)
		$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$
TRMSS	9B	1.00E-04	8.37E-05	0.16
	26B	7.87E-05	1.39E-04	-0.77
	30A	9.97E-05	2.14E-04	-1.15
LD-7	12A	3.21E-05	4.05E-05	-0.26
	14B	7.41E-05	1.08E-04	-0.46
	20B	7.99E-05	1.09E-04	-0.36
	22B	3.83E-05	4.30E-05	-0.12

The permeability results show that the problem persisted. We investigated and noticed cracks of a few millimeters in the disks wrapped with silicone gel. The cracks are located a few millimeters in from the outer edges. We concluded that the silicone gel shrinks in the oven and tightens around the asphalt disks, causing cracks to develop through the disks. To eliminate this problem, we decided to completely remove the silicone gel during the aging process. For all future tests, we applied the silicone gel to the outer edge of the asphalt disks and cured it for 2 days and then tested the unsealed permeability. The silicone gel was then removed right after testing. The asphalt disks were then dried, sealed, aged in the oven for 5 days, and the silicone gel was then reapplied and left to cure for another 2 days. We also tried using another type of silicone gel (Transparent DAP® 100% Silicone Window, Door, & Siding Sealer), but the bond between the silicone gel and the outer edge of the disks was poor. We settled on White DAP® 100% Silicone Window, Door, & Siding Sealer brand only.

Next, we turned our attention to whether aging of the unsealed specimens will change their permeability even without sealers. We measured the unsealed permeability of several disks, aged them in the oven for 5 days at 185°F, and measured their unsealed permeability again. The permeability results are shown in Table 20 below. A paired t-test showed no statistically significant difference (p-two-tail value = 0.08) in permeability between the aged and unaged results. Therefore, we settled on using unaged asphalt disks for the rest of the permeability tests.

Table 20. Permeability results for unsealed disks with and without aging

Sealer Type	Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)
		$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$
TRMSS	23A	9.96E-05	1.21E-04	-0.21
	23B	1.27E-04	1.96E-04	-0.54
	29A	1.28E-04	1.37E-04	-0.07
	29B	2.24E-04	2.55E-04	-0.14
	24A	1.12E-04	1.05E-04	0.06
	36A	9.44E-05	1.09E-04	-0.15

In preparation for the final round of permeability testing, we determined the unsealed permeabilities of all 102 disks that we had made using 411-TLD mix. The data ($k_{unsealed}$) formed a lognormal distribution as shown in Figure 19. In order not to disadvantage any particular sealer, it was important to assign disks to each sealer so as to cover the entire range of permeabilities. To that end, we eliminated the disks in the bins furthest from the mean, then selected six specimens from the remaining bins for each sealer such that all sealers had a similar factor-of-three range of unsealed permeabilities. This range can be seen by comparing the unsealed permeabilities in Figures 22 to 27 in Appendix D.

Table 21. Distribution of unsealed permeability results

Bin	log ($k_{unsealed}$)	Count
1	-4.60 – -4.48	2
2	-4.48 – -4.36	2
3	-4.36 – -4.24	6
4	-4.24 – -4.12	15
5	-4.12 – -4.00	26
6	-4.00 – -3.88	23
7	-3.88 – -3.76	18
8	-3.76 – -3.64	5
9	-3.64 – -3.52	4
10	-3.52 – -3.40	1
		102

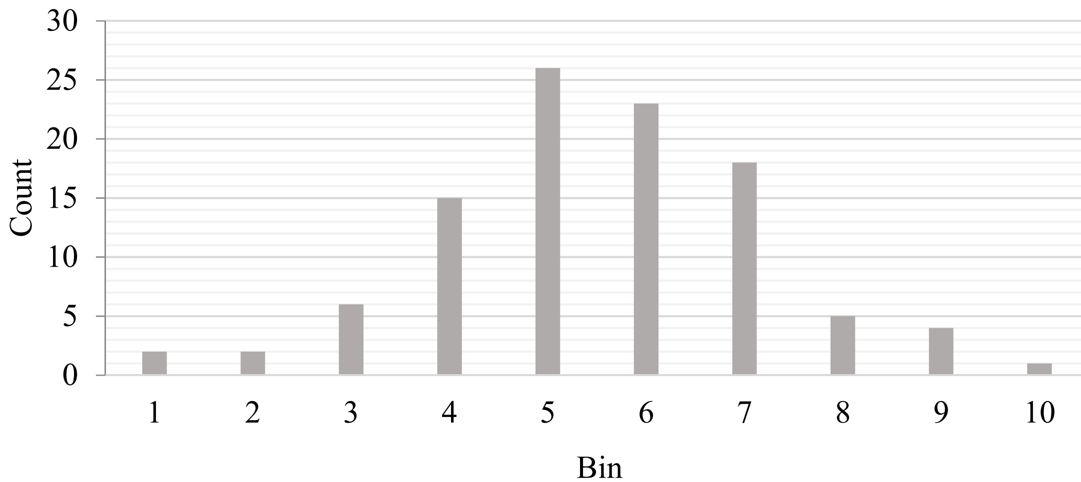

Figure 19. Lognormal distribution of unsealed permeabilities.

Using the test procedures we developed (as outlined in Appendix D), we performed a final round of permeability tests on a variety of sealers. We analyzed the permeability results by averaging the reduction factors for each sealer. The reduction factor is equal to one minus the ratio of the sealed permeability to the unsealed permeability. The permeability results are shown in Table 22 on the next page. The mean reduction factors results in Table 22 are illustrated in Figure 20 below.

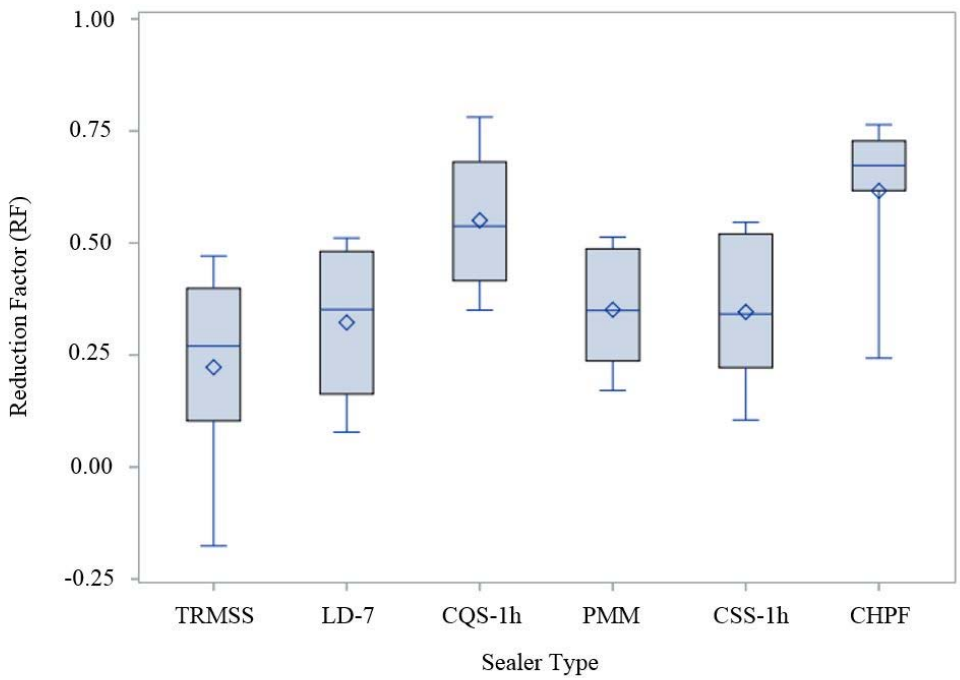

Figure 20. Permeability reduction for different sealers.

The box-and-whisker plot shows a small and fairly consistent variability in reduction factors for all sealers. One of the TRMSS specimens showed a small negative reduction factor. This was attributed to random measurement errors in the permeability test. From this we conclude that six specimens from each sealer are sufficient to compare the sealers based on mean reduction factor results.

Table 22. Permeability results for different sealers

Sealer Type	Specimen ID	Permeability (k), cm/s		Reduction Factor (RF)	Mean RF
		$k_{unsealed}$	k_{sealed}	$RF = 1 - \frac{k_{sealed}}{k_{unsealed}}$	
TRMSS	57A	1.03E-04	6.19E-05	0.40	0.22
	58A	1.27E-04	8.30E-05	0.35	
	59B	8.11E-05	6.54E-05	0.19	
	62A	8.01E-05	4.24E-05	0.47	
	64A	4.99E-05	5.87E-05	-0.18	
	70A	1.74E-04	1.56E-04	0.10	
LD-7	31B	6.09E-05	4.69E-05	0.23	0.32
	49A	1.05E-04	5.45E-05	0.48	
	50A	9.27E-05	7.76E-05	0.16	
	51B	1.38E-04	7.27E-05	0.47	
	67B	1.62E-04	7.92E-05	0.51	
	71A	8.46E-05	7.80E-05	0.08	
CQS-1h	43A	3.60E-05	2.03E-05	0.44	0.55
	48B	1.61E-04	5.82E-05	0.64	
	51A	9.57E-05	5.59E-05	0.42	
	56B	1.05E-04	3.35E-05	0.68	
	62B	1.54E-04	3.37E-05	0.78	
	64B	7.26E-05	4.72E-05	0.35	
PMM	45B	9.00E-05	5.21E-05	0.42	0.35
	48A	1.58E-04	1.14E-04	0.28	
	57B	1.03E-04	5.28E-05	0.49	
	65A	8.92E-05	6.81E-05	0.24	
	66B	1.44E-04	7.02E-05	0.51	
	70B	1.18E-04	9.78E-05	0.17	
CSS-1h	32A	4.84E-05	4.33E-05	0.11	0.35
	49B	9.70E-05	4.66E-05	0.52	
	53A	7.33E-05	5.70E-05	0.22	
	54A	1.47E-04	6.67E-05	0.55	
	60B	6.90E-05	4.64E-05	0.33	
	68B	1.36E-04	8.77E-05	0.36	
CHPF	35A	1.34E-04	4.31E-05	0.68	0.62
	46A	9.97E-05	3.82E-05	0.62	
	52A	8.05E-05	1.90E-05	0.76	
	65B	9.00E-05	6.81E-05	0.24	
	66A	1.63E-04	4.44E-05	0.73	
	69A	5.94E-05	1.97E-05	0.67	

Figure 21 shows the mean reduction factors for each sealer tested. The CHPF and CQS sealers had the highest mean reduction factors and the reduction factors were similar to each other. The CSS-1h, PMM, LD-7, and TRMSS sealers had the lowest mean reduction factors and the results were statistically indistinguishable from one another.

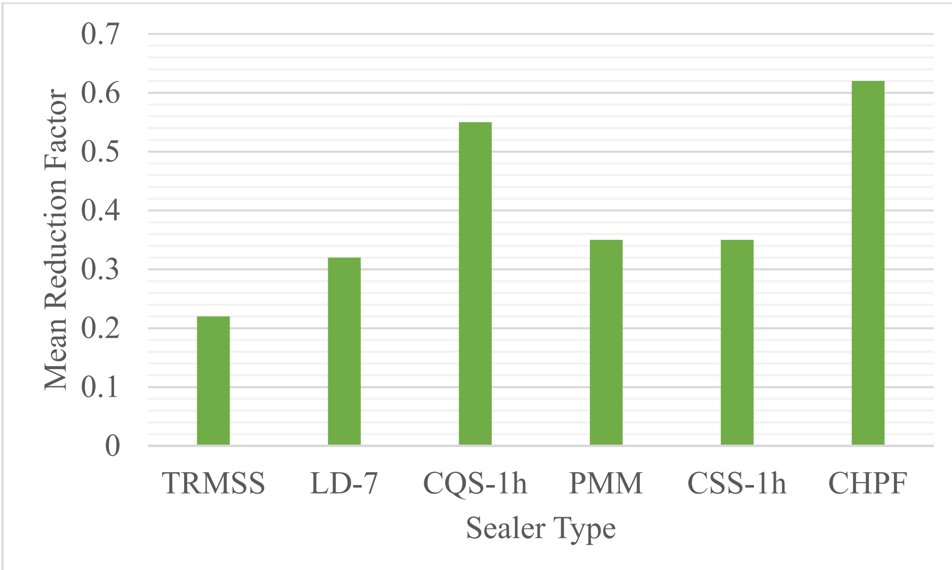

Figure 21. Mean reduction factor results for different sealers.

The permeability results show that all sealers lowered the permeability of the asphalt. The results show good consistency in the reduction factors for all sealers despite having a factor-of-three range of unsealed permeabilities.

Conclusions

The objective of this research was to develop testing protocols to evaluate and rank asphalt pavement sealers to produce a qualified product list (QPL). We used two parameters, wet track abrasion resistance and permeability, to evaluate the sealers in the laboratory. The wet track abrasion resistance was used to determine the potential longevity of the sealer on the road surface. Sealers with higher abrasion resistance should stand up to more prolonged wear from traffic loads and environmental conditions. The permeability was used to determine the potential sealing performance of the sealer. Sealers that produce greater reduction in permeability should better inhibit damage to the pavement from intrusion of air, water, or any liquids. The main findings of the research are discussed below.

Six wet track abrasion specimens were prepared, aged, and tested for each of six sealers using the test protocols as outlined in Appendix A (using asphalt disks as a substrate) and Appendix B (using asphalt shingles as a substrate). The results fell into three distinct groups. The CSS-1h and CHPF had the least mass loss using both shingles and disks as the substrate. For both substrates, the difference in mass loss between the two sealers was statistically insignificant (t-test, P-two-tail value > 0.19), so both sealers were assigned a ranking of 1 and are thus aggregated in Group A. The CQS-1h and PMM sealers had the next lowest mass loss for both substrates. Using shingles, the mean mass loss was identical for both sealers giving each a rank of 3. Using disks, the CQS-1h had a slightly greater mass loss. So PMM and CQS-1h were aggregated in Group B. The TRMSS and LD-7 showed the greatest mass loss, with the LD-7 having the slightly greater mass loss for both substrates. So TRMSS and LD-7 were aggregated in Group C. For both substrates, the difference in mass loss between sealers from one group to another were statistically significant. The rankings and group results are shown in Table 23 below.

Significantly, the shingles and disks produced the same rankings. This suggests that asphalt shingles are a suitable alternative to the asphalt disk substrates. Asphalt shingles are inexpensive and require no preparation other than cutting them to size and punching holes for the mounting screws. Another advantage is that the white mineral granules provide an easy visual reference as to the amount of sealer remaining after testing.

Table 23. WTA ranking for different sealers

Sealer Type	Rank		Group
	Shingles	Disks	
CSS-1h	1	1	A
CHPF	1	1	
PMM	3	3	B
CQS-1h	3	4	
TRMSS	5	5	C
LD-7	6	6	

Future research is needed to validate the laboratory test results in the field to determine if sealers having lower wet track abrasion mass loss will actually last longer in the field.

Six permeability specimens were also prepared, aged, and tested for each of six sealers as outlined in Appendix C. For each specimen, a permeability reduction factor was calculated as the percentage drop in permeability of each specimen from the unsealed to the sealed condition. A mean permeability reduction factor was calculated for each sealer by averaging the individual reduction factors for each specimen. The sealers were ranked from 1 to 6 with 1 representing the greatest reduction in permeability. The results fell into two distinct groups. The CHPF and CQS-1h sealers had the greatest mean reduction in permeability. The difference in reduction factors between the two sealers was statistically insignificant (t-test, two-tail-P-value = 0.54), so they are aggregated into Group A. The CSS-1h, PMM, LD-7, and TRMSS had the lowest mean reduction factors and the mean reduction factors were similar to each other. The difference in mean reduction factors between any two of the four sealers was statistically insignificant (t-test, two-tail-P-value > 0.28), so they are aggregated into Group B. The ranking and group lists are shown in Table 24 on the next page.

Comparing the results in Tables 23 and 24, the CHPF sealer was best in both abrasion resistance and permeability reduction and the TRMSS was worst in both categories. The CSS-1h sealer currently used by TDOT showed excellent abrasion resistance and adequate permeability reduction.

Table 24. Permeability ranking for different sealers

Sealer Type	Rank	Group
CHPF	1	A
CQS-1h	2	
CSS-1h	3	B
PMM	3	
LD-7	3	
TRMSS	6	

Future research is needed to validate the laboratory test results in the field to determine if sealers having a higher reduction in permeability in the laboratory will have similar higher reduction in permeability in the field and whether this reduction persists over time. This can be done in conjunction with wet track abrasion field validation testing by measuring the field permeability of sealed and unsealed test strips over time.

We developed both the wet track abrasion ranking and permeability ranking for six asphalt sealers separately. These rankings each have their own significance. The ranking based on wet track abrasion test determines how long the sealer will last on the pavement whereas the ranking based on the permeability test determines how well the sealer seals off the pavement. The project engineer may choose to weight one attribute higher than the other in selecting a sealer, or may weight both attributes equally and select a sealer that performed adequately in both rankings.

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Appendix A
Wet track abrasion test protocol using asphalt disks as a substrate

1. Prepare gyratory specimens per ASTM D6925 using the procedures for Reheated Plant Mix Laboratory Compacted (RPMLC) Test Specimens. The specimens should be compacted to the air void content specified in the job mix formula.
2. Determine the bulk specific gravity (ASTM D 2726), theoretical maximum specific gravity (ASTM 2041), and air void content (ASTM D3203) of the gyratory specimens to confirm the compaction results.
3. Cut ½-inch-thick disks from each side of the gyratory specimen using appropriate methods
4. Place disks in the oven for drying at 140°F for 24 hours.
5. Wrap ¾-inch-wide clear cellophane tape around the outer edge of the disks and then press it gently. This makes a dam so that the sealer cannot drain off and also eliminates seepage from the edges.
6. Shake the sealer bottle and pour the sealer in a disposable cup (normal Styrofoam coffee cup). Dilute the sealer with water and/or mix with fine sand based upon specification. Uniformly mix the prepared sealer by using a mechanical stirrer similar to that used for hydrometer analysis of fine-grained soils (ASTM D7928).
7. Place a 6-inch square of craft paper on top of an electronic balance (0.01g precision) and place the disk on the craft paper. Zero out the electronic balance.
8. Apply the appropriate mass of sealer to the disk with a foam brush at the rate specified by the manufacturer. Then, place the sealed disk on a perfectly level table to allow the sealer to set.
9. After 4 days setting under ambient laboratory conditions, remove the tape from the sealed disks.
10. Place the sealed disks in a forced air draft oven for five days at 185°F to age the sealer.

11. After aging, determine the mass of the each sealed disk, W_1, in grams.
12. Perform the wet track abrasion test per ISSA TB 100 using a modified specimen holder and abrasion hose. The specimen holder consists of a ½-inch rubber sheet cut to fit the original specimen pan, with a 150-mm-diameter hole to accept the sealed disks. The abrasion hose has been shortened to 85 mm and metal spacers added at each side to center the hose in the testing head.
13. After testing, remove the disk and place in a 140°F oven for drying.
14. Remove the dried specimen from the 140°F oven and allow it to cool to room temperature.
15. Determine the mass of each specimen, W_2, in grams.
16. Compute the abrasion loss as the mass difference (W_1-W_2).

Appendix B
Wet track abrasion test protocol using asphalt shingles as a substrate

1. Cut mineral surfaced roll roofing into 6.5-in squares with the help of a paper cutter or scissors.
2. Mark a 6-in square boundary using a colored permanent marker in the center of the 6.5-in-square shingles leaving a ¼-inch wide band on all sides.
3. Shake the sealer bottle and pour the sealer in a disposable cup (normal Styrofoam coffee cup). Dilute the sealer with water and/or mix with fine sand per manufacturer specifications. Uniformly mix the prepared sealer using a mechanical stirrer similar to that used for hydrometer analysis of fine-grained soils (ASTM D7928).
4. Place a 7-inch square of craft paper on top of an electronic balance (0.01g precision) and place the shingle on the craft paper. Zero out the electronic balance.
5. Apply the appropriate mass of sealer to the disk with a foam brush at the rate specified by the manufacturer. Then, place the sealed disk on a perfectly level table to allow the sealer to set for 4 days under ambient laboratory conditions.
6. Cut the ¼-inch-wide unsealed part from all four sides, leaving a 6-inch-square sealed shingle.
7. Place the sealed shingle in a forced air draft oven for five days at 185^{o}F to age the sealer.
8. Make four 3.5-mm-diameter holes in the asphalt shingle at all four corners such that the location of each hole is a quarter inch from all sides. A leather punch tool (used for punching holes in leather belts) or any equivalent tool can be used for making holes.
9. Determine the mass of each sealed shingle, W_1, in grams.
10. Perform the wet track abrasion test per ISSA TB 100 using a modified specimen holder and abrasion hose. The specimen holder consists of a ½-inch-thick circular plastic plate on which the

shingle is fixed by screwing at the four corners. The abrasion hose has been shortened to 85 mm and metal spacers added at each side to center the hose in the testing head.

11. After testing, remove the shingle and place it in a 140^{o}F oven for drying.
12. Remove the dried specimen from the 140^{o}F oven and allow it to cool to room temperature.
13. Determine the mass of each specimen, W_2, in grams.
14. Calculate the abrasion loss at the mass difference (W_1-W_2).

Appendix C
Permeability test protocol

1. Prepare gyratory specimens per ASTM D6925 using the procedures for Reheated Plant Mix Laboratory Compacted (RPMLC) Test Specimens. The specimens should be compacted to the upper limit of the production air void content specified in the job mix formula.
2. Determine the bulk specific gravity (ASTM D 2726), theoretical maximum specific gravity (ASTM 2041), and air void content (ASTM D3203) of the gyratory specimens to confirm the compaction results.
3. Cut 1-inch-thick disks from each side of the gyratory specimen using appropriate methods.
4. Place the disks in the oven for drying at 140^{o}F for 24 hours.
5. Apply silicone gel (White DAP® 100% Silicone Window, Door, & Siding Sealer) instead of petroleum jelly around the outer edges of the disk with a finger or spatula in one single pass to make a surface smooth. For safety, use a breathing mask while applying the silicone gel. Allow the silicone gel to cure for 2 days in the laboratory environment.
6. Place the plastic spacer on the permeameter specimen pedestal and align the outer edges. The 70-mm plastic spacer makes up the difference in height between the 1-inch disks and a typical gyratory specimen.
7. Secure the plastic spacer to the pedestal with duct tape to make a watertight seal.
8. Adjust the outlet pipe upward such that the pipe outlet elevation and the top of the spacer are at the same elevation.
9. Open the outlet valve and fill the spacer to the top with water, then place the specimen on the spacer. The cut surface of the specimen should face downward.
10. Assemble the rest of the permeameter and perform the permeability test per Standard FM 5-565. The measured permeability is called the “unsealed permeability”.

11. Disassemble the permeameter, remove the specimen, and carefully remove the silicone gel from the specimen.
12. Place the specimen in a forced air draft oven for 48 hours to dry.
13. Apply a new layer of silicone gel around the outer edge of the disk to fill the voids, then wrap 1¼-inch wide cellophane tape immediately around the outer edge of the disks before the silicone cures and press it gently against the sealer.
14. Shake the sealer bottle and pour the sealer in a disposable cup (normal Styrofoam coffee cup). Dilute the sealer with water and/or mix with fine sand per manufacturer specifications. Uniformly mix the prepared sealer using a mechanical stirrer similar to that used for hydrometer analysis of fine-grained soils (ASTM D7928).
15. Place a 6-inch square of craft paper on top of an electronic balance (0.01g precision) and place the disk on the craft paper. Zero out the electronic balance.
16. Apply the appropriate mass of sealer to the disk with a foam brush at the rate specified by the manufacturer. Then, place the sealed disk on a perfectly level table to allow the sealer to set.
17. After 4 days setting under ambient laboratory conditions, remove the cellophane tape and the silicone gel from the sealed disks.
18. Place the sealed disks in a forced air draft oven for five days at 185^{o}F to age the sealer.
15. Apply silicone gel again to the outer edge of the disks, let the sealer cure for 2 days, and then measure the permeability as described in Steps 8, 9, 10, and 11 above. The measured permeability is called the “sealed permeability”.
16. Calculate the permeability reduction factor as one minus the ratio of the sealed and unsealed permeabilities.

Appendix D
Permeability results for all sealers

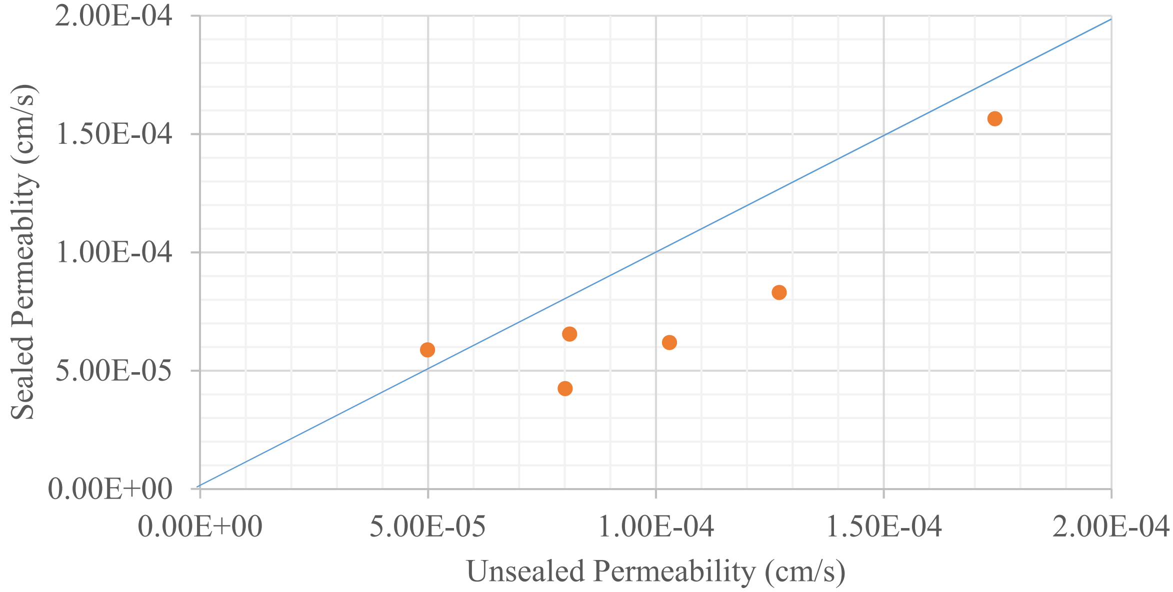

Figure 22. Permeability results for TRMSS sealer.

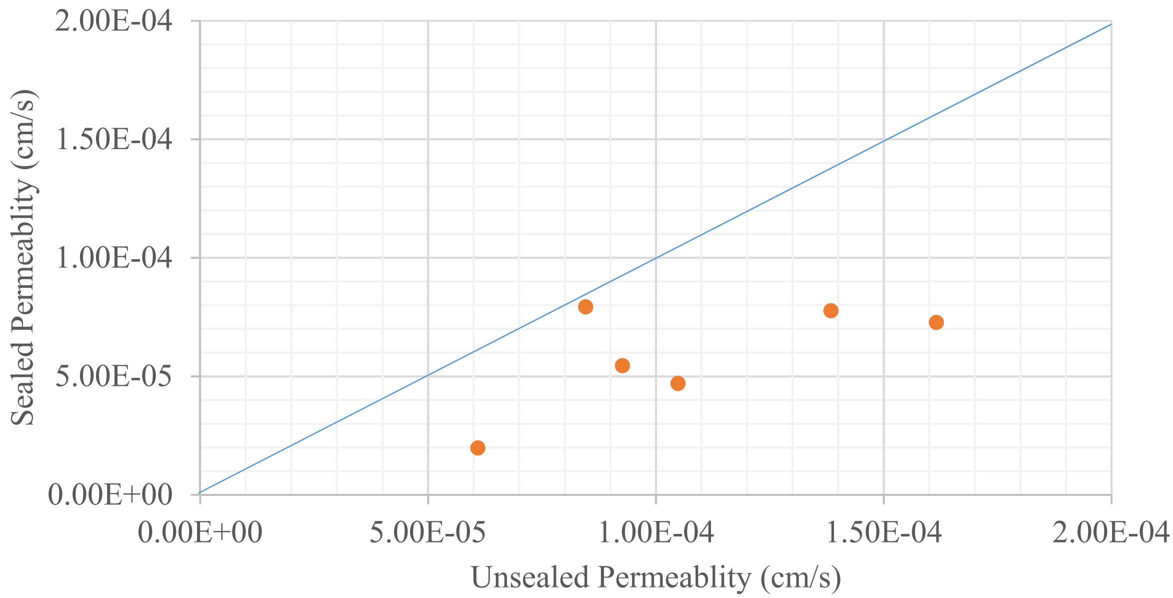

Figure 23. Permeability results for LD-7 sealer.

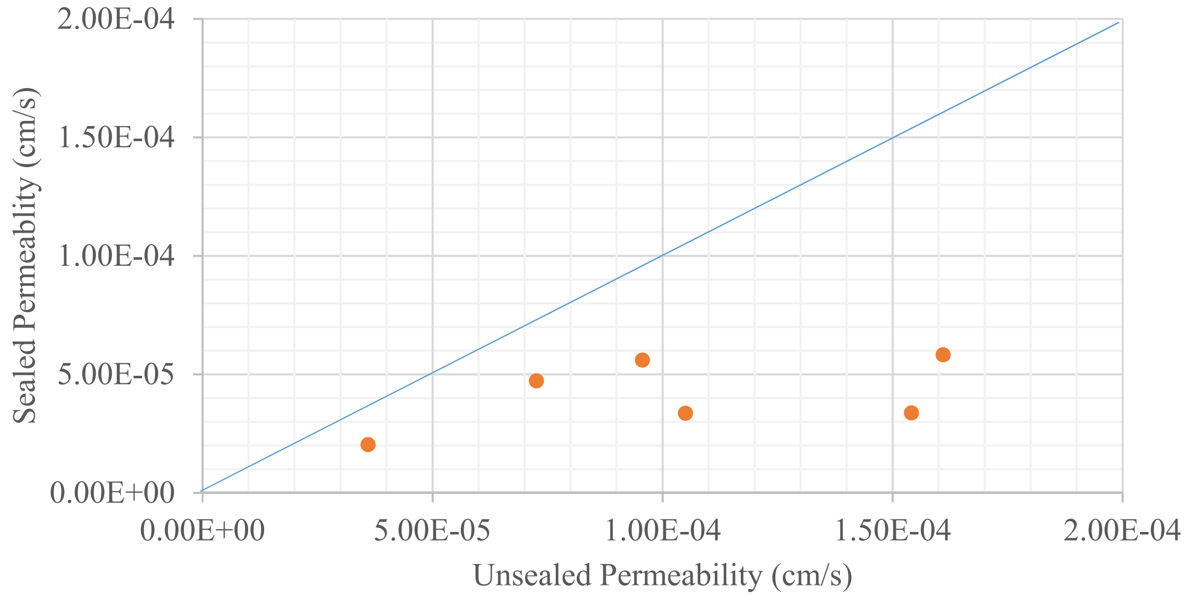

Figure 24. Permeability results for CQS-1h sealer.

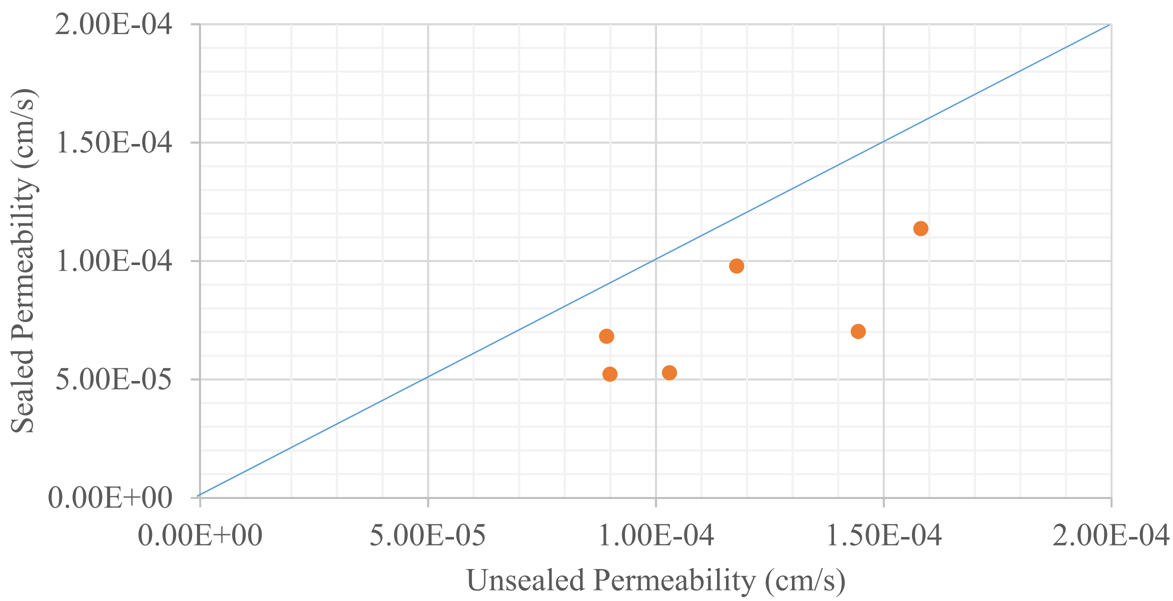

Figure 25. Permeability results for PMM sealer.

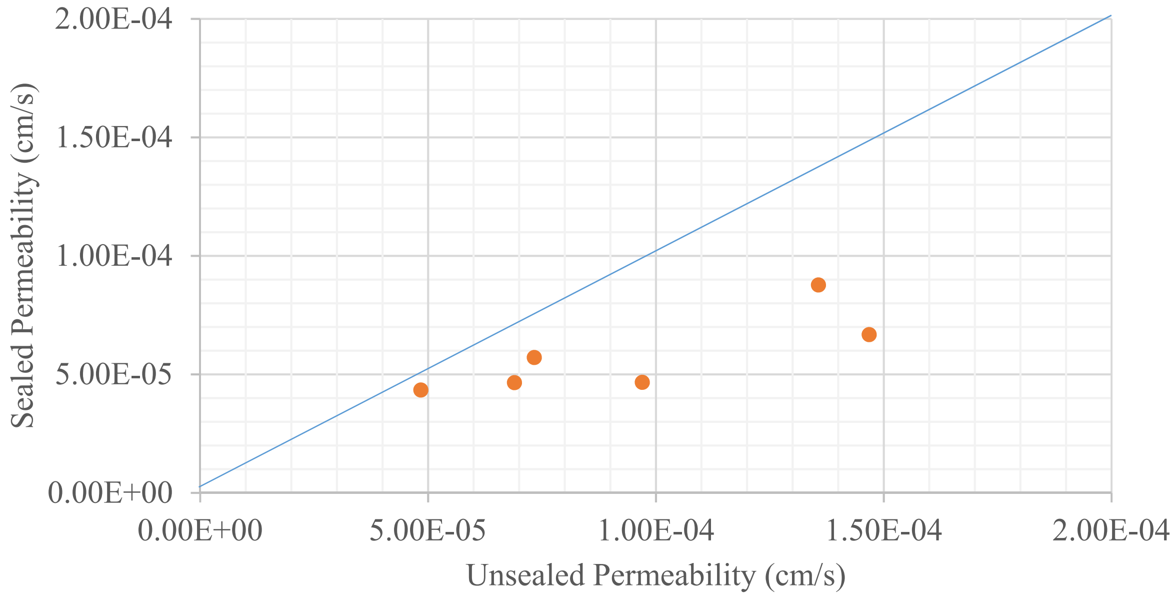

Figure 26. Permeability results for CSS-1h sealer.

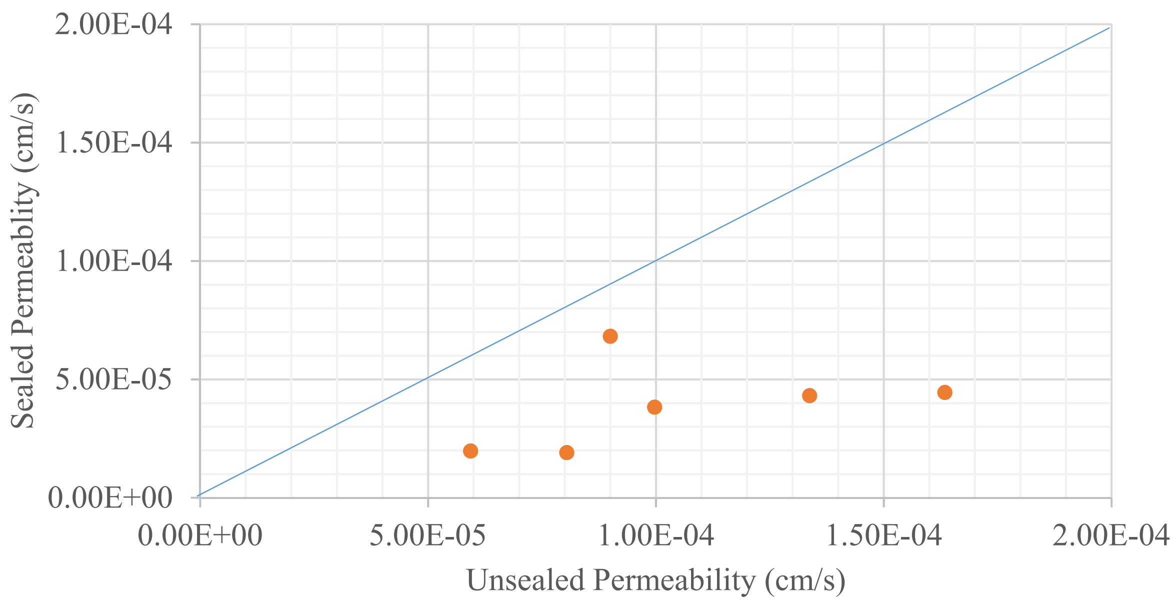

Figure 27. Permeability results for CHPF sealer.

DISCLAIMER

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