A COMPREHENSIVE STUDY OF FIELD PERMEABILITY USING THE VACUUM PERMEAMETER

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by

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ABSTRACT

The permeability of coarse-graded asphalt mixtures has been a great concern in recent years. Asphalt mixes that are permeable are susceptible to a number of distresses such as moisture damage, raveling, cracking, and binder oxidation. This project examined three field devices for the determination of permeability. These methods were the NCAT falling-head field permeameter (NCAT), the Kuss constant-head field permeameter (KSFP), and the Kuss vacuum permeameter (VACP).

Seven sites were mapped according to the VACP method in order to determine the location and distribution of permeable voids. These results were compared to the permeability measurements obtained by the NCAT and KSFP methods. Mixes having three different nominal maximum aggregate sizes were tested, and field cores were cut in order to provide a relationship of permeability and density. Also, the variability of the pavement sites was evaluated as a means to determine the minimum required sample size for field permeability testing.

Overall, the various methods for determining field permeability do not yield similar results. In most cases, the falling head test (NCAT method) yielded the largest values.

Pavement sections that clearly failed the density specification had high permeability, and sections that clearly passed the minimum density specification were relatively impermeable. Pavements with marginal density were somewhat permeable, and contained variable levels of permeability. In general, high permeability was exhibited near the longitudinal joints.

The variability of the sites was evaluated in order to determine an appropriate sample size. Relatively impermeable pavements were consistent, and pavements with

moderate or high permeability were more variable. Relationships between sample size, reliability, and testing discrimination were presented. Based on the range of standard deviations measured in this project, a minimum sample size of 10 is recommended for pavements with marginal densities or variable consistency. This sample size is based on the variability of the pavement, not the variability of the device(s) used for testing.

Based on the results of this study, permeability test results are highly dependent upon the placement of the permeameter during testing and the variability of the pavement. Field permeability testing may have value as a forensic tool, but the large required sample size is not conducive to standard quality control procedures. Therefore, extreme caution should be exercised before implementing field permeability testing as a quality control or quality assurance measure.

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INTRODUCTION

As the Superpave method for hot-mix asphalt (HMA) mixture design was implemented, many states began to express concerns regarding the permeability of the mixes. Permeable pavements are susceptible to a number of distresses such as stripping, binder age hardening, raveling, and cracking. *(1)* Most Superpave HMA mixes are more coarsely graded than traditional mixes, and this coarse nature creates a greater potential for voids to be interconnected, exposing the pavement to the harmful effects of air and water.

As a result of these concerns, much research was performed in order to establish laboratory and field tests for determining the permeability of asphalt mixtures. The ability to measure permeability could help to reduce the likelihood of placing pavements that will experience durability problems. In a Virginia study, it was estimated that the identification and subsequent elimination of permeable (and thus non-durable) pavements could save the state as much as $350,000 per year. *(2)*

Field permeability testing is desirable because it is a non-destructive method for describing a pavement's susceptibility to distresses commonly caused by the penetration of air and water. In this project, three field methods for quantifying permeability were evaluated with respect to coefficient of permeability, as well as the location of permeable voids in each test section. Mixes of three nominal maximum aggregate sizes were also tested and the densities of field cores were used to relate permeability and density. The variability of permeability for sites of different mixture sizes and types was investigated. Based on these measures of variability, minimum sample size requirements were determined.

BACKGROUND

Permeability in hot-mix asphalt (HMA) mixes can lead to a multitude of pavement distresses. As the number of penetrable voids in a pavement surface increases, the likelihood of air and water to enter the pavement also increases. Air promotes the oxidation of asphalt cement, making the pavement more brittle and susceptible to longitudinal and fatigue cracking, as well as raveling. Water in the pavement structure leads to a variety of distresses including stripping and freeze/thaw damage. During the winter, water can "weep" from permeable pavements and freeze, creating slick spots. Overall, problems associated with permeability lead to a reduction in HMA pavement durability and performance.

Permeability can be defined as the rate of flow of fluid through a porous medium. Some of the earliest permeability work was performed by Henry Darcy in which he studied the flow of water through clean sand. *(3)* Based on this work, it was shown that the rate of water flow is dependent upon the hydraulic gradient and the cross-sectional area of the sample through which it flows, and is related by a coefficient of permeability, as given in Equation 1.

$$Q = k\,i\,A \qquad \textit{Equation 1}$$

where: Q = rate of flow

k = coefficient of permeability

i = hydraulic gradient

A = total cross-sectional area

In this equation, the following assumptions are made:

- The material is homogeneous
- Steady-state flow conditions exist
- The flow is laminar
- The fluid is incompressible
- The material is saturated
- The flow is one-dimensional

The hydraulic gradient can be defined as the head loss per unit length. When the water flow is laminar, the head loss increases linearly with the velocity of water transmitted through a medium. If the water flow is turbulent, then the relationship is nonlinear, and Darcy's law is invalid.

When using Darcy's law to measure the permeability of a material, a constant head test or a falling head test can be used. The constant head test measures the flow rate of water through a saturated sample while maintaining a constant head of water, and the coefficient of permeability is calculated according to Equation 2.

$$k = \frac{Q\,L}{h\,A\,L\,t} \qquad \textit{Equation 2}$$

where: k = coefficient of permeability

Q = total discharge volume

L = height of specimen

h = height of water head on specimen

A = cross-sectional area of specimen

t = time during which Q is measured

In a falling head test, the head of water above the sample decreases as the water flows through the sample. The coefficient of permeability for the falling head test is calculated as shown in Equation 3.

$$k = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \qquad \textit{Equation 3}$$

where: k = coefficient of permeability

a = cross-sectional area of water column above sample

L = length of sample

A = cross-sectional area of sample

t = time lapse during measured head loss

h_1 = head level at beginning of test

h_2 = head level at end of test

In general, constant head tests are most appropriate for materials with relatively high permeability, and falling head tests are most appropriate for materials with low permeability. *(3)* In order to measure the permeability of asphalt mixes by these methods, the assumption must be made that Darcy's law is valid. In the 1960s, Shikarski and Kimchi proved that this assumption was, in fact, true for sand asphalt mixes. *(4)*

Many factors are believed to affect the permeability of asphalt mixtures, and in most cases, a fairly logical relationship exists. First, the permeability of an HMA pavement is related to its density. As the density increases, the percentage of air voids decreases, thereby reducing the likelihood of interconnected void spaces. If a pavement does not receive adequate compaction, it is more likely to be permeable. Several case studies have determined that pavements not meeting minimum compaction requirements are much more susceptible to high levels of permeability. *(5, 6)*

Pavement thickness also affects permeability in that as thickness increases, permeability decreases. This is because a greater lift thickness decreases the potential for interconnected voids to extend the full length (i.e., thickness) of the pavement layer. Thus, some states have recommended an increase in required lift thickness as a way to avoid permeability problems. *(7, 8)*

The nominal maximum aggregate size (NMAS) and gradation of the mixture also affect permeability. As the size of the aggregate particles increases and the gradation becomes coarser, the size of the air voids increase, thereby increasing the potential for interconnected voids. A shift toward more finely graded mixes, especially for base and binder courses has been recommended for the purpose of reducing permeability. *(9, 10)*

LITERATURE REVIEW

For many years, it has been generally accepted that dense-graded HMA pavements exhibit optimum performance characteristics when compacted to an in-place air void content between 3 percent and 8 percent. *(1)* Pavements with in-place are voids that are too low are susceptible to distresses such as rutting, shoving, bleeding, and flushing. When the in-place air void content is too high, the pavement is susceptible to other distresses such as stripping, binder age-hardening, raveling, and cracking.

Several studies have been performed to establish the factors that most directly contribute to asphalt pavement permeability. In 1955, McLaughlin and Goetz correlated permeability and air void content to the durability of HMA mixtures, using an air permeameter. *(4)* They determined that permeability was dependent on gradation, compactive effort, and asphalt content. In 1961, Hein and Schmidt also investigated air permeability to evaluate HMA pavements. *(4)* In 1962, Zube demonstrated that dense-graded asphalt mixes become permeable to water at approximately 8 percent air voids. *(11)* This also showed that permeability is related to pavement density. In addition, this study indicated that mixes placed during the summer months were less permeable than those placed during the fall.

Although permeability was believed to be an important characteristic of HMA pavements, the measurement of this property was difficult to achieve. In the 1970's, Kumar and Goetz developed an improved method for measuring asphalt permeability. *(4)* This method became standardized as test method ASTM D3637, but was later discontinued due to its complicated nature.

In the 1980's, McWilliams performed a study in Arkansas to identify several factors that affect the permeability of HMA mixes. *(12)* The factors identified were aggregate gradation, particle shape, asphalt cement composition, compaction, degree of saturation, type of flow, and temperature. Fine gradations were shown to be less permeable than coarse gradations. Irregular, crushed particles also decreased the potential for permeability due to their ability to limit direct flow paths. It was also demonstrated that the permeability of a mix decreased as the size and number of voids decreased, and that permeability decreased as compaction increased.

In the 1990s, the Superpave (*Su*perior *Per*forming Asphalt *Pave*ments) mix design procedure gained recognition by many state agencies. Superpave gradations were restricted by a set of control points as well as an area called the restricted zone. This concept is illustrated in Figure 1. Originally, it was recommended that gradations avoid the restricted zone, preferably passing below. Even though the restricted zone has since been eliminated, this recommendation created a general move toward coarse-graded asphalt mixes, which are believed to be more resistant to rutting failures. *(13)*

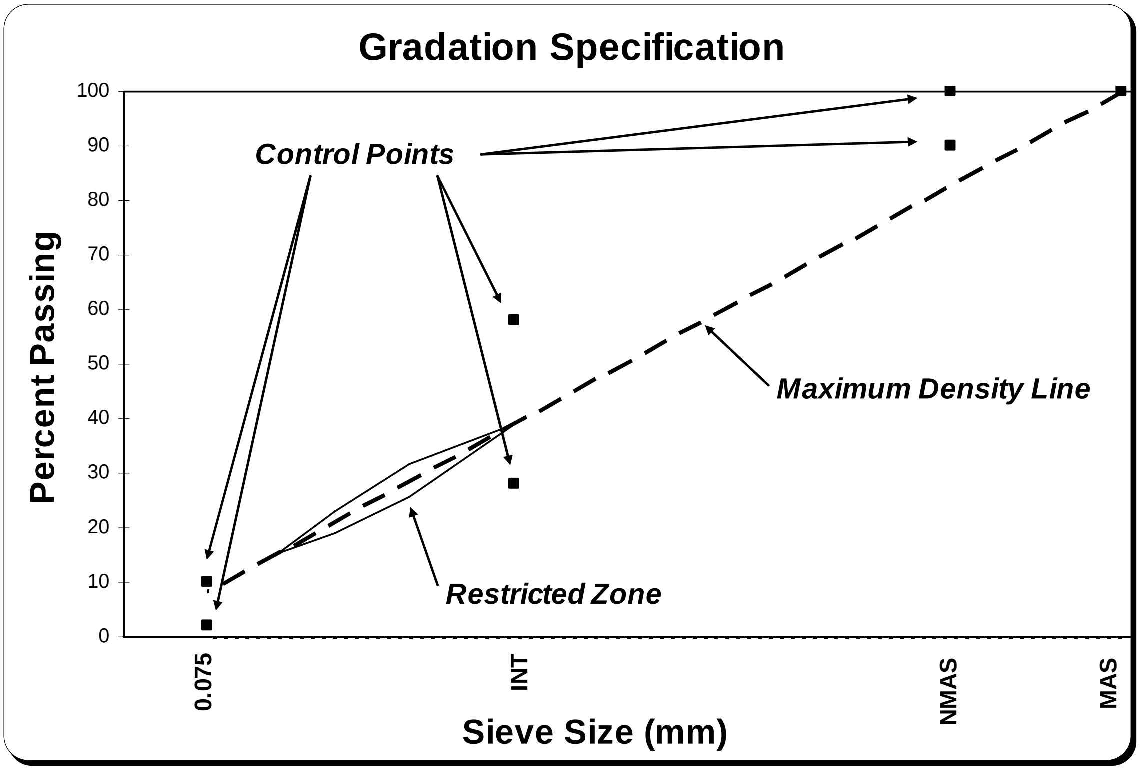


Figure 1. Superpave gradation specification

One reported difficulty with Superpave mixtures is high permeability. *(14, 15, 16)* This is especially true for mixes having a large nominal maximum aggregate size (NMAS). Because Superpave mixtures are coarser than their traditional counterparts, there are more large aggregate particles, and fewer fine aggregate particles available to fill and/or separate the void spaces. Larger particles create larger voids (when designed to the same air void content), and larger voids lead to a greater likelihood of interconnected voids. Thus, there is a greater risk of greater permeability.

Several studies have investigated the permeability of coarse-graded Superpave mixes. In many instances, water was reported to be "weeping" from the surface of a pavement, even after several days without precipitation. Thus, the water was determined to be coming from within the pavement, indicating permeability problems.

In many cases, inadequate compaction was blamed for the permeability problems. Since it was known that density and permeability were related, it was suggested that an appropriate density requirement would be a way to successfully limit the permeability of HMA mixes. Before proper limitations could be set, several items had to be considered:

- A standard method for accurately and consistently measuring permeability was not available.
- The relationship between permeability and in-place density (and any other significant factors) had to be further defined.
- An appropriate "limiting" value for permeability had to be established.

The results of a study in Arkansas also showed that lift thickness was a significant factor relating to pavement permeability. *(8)* For 12.5mm NMAS mixes, lift thicknesses of less than 2 inches had higher permeability. Thus, it was recommended that Superpave mixtures be placed with a minimum lift thickness of 4 times the NMAS. In addition, ranges of values for characterizing permeability were established as shown in Table 1.

Permeability Designation	Range of Permeability Coefficient, k
High Permeability	1×10^{-1} cm/s to 1×10^{-4} cm/s
Low Permeability	1×10^{-4} cm/s to 1×10^{-6} cm/s
Practically Impervious	1×10^{-6} cm/s to 1×10^{-9} cm/s

Table 1. Permeability ranges determined by Arkansas research *(8)*

A study in Florida recommended a maximum acceptable permeability value of 100 x 10^{-5} cm/s, which was consistent with the recommendations from the Arkansas study. The Florida study also discovered that coarse-graded Superpave mixes can be excessively permeable to water even when containing in-place air voids of less than 8 percent. *(14)* Thus, existing density requirements may not be stringent enough to guard against permeability problems for coarse-graded mixes. This conclusion led to the suggestion that field density requirements be increased during the construction of Superpave mixtures. Typical specifications required a minimum field density of 92 percent, so increasing this value to approximately 94 percent could be a way to reduce the permeability problems associated with Superpave mixtures.

Laboratory Permeability

As a result of their work, the Florida Department of Transportation (DOT) developed a laboratory asphalt permeameter to measure the permeability of field cores. This device, shown in Figure 2, was further refined and then marketed by Karol-Warner.

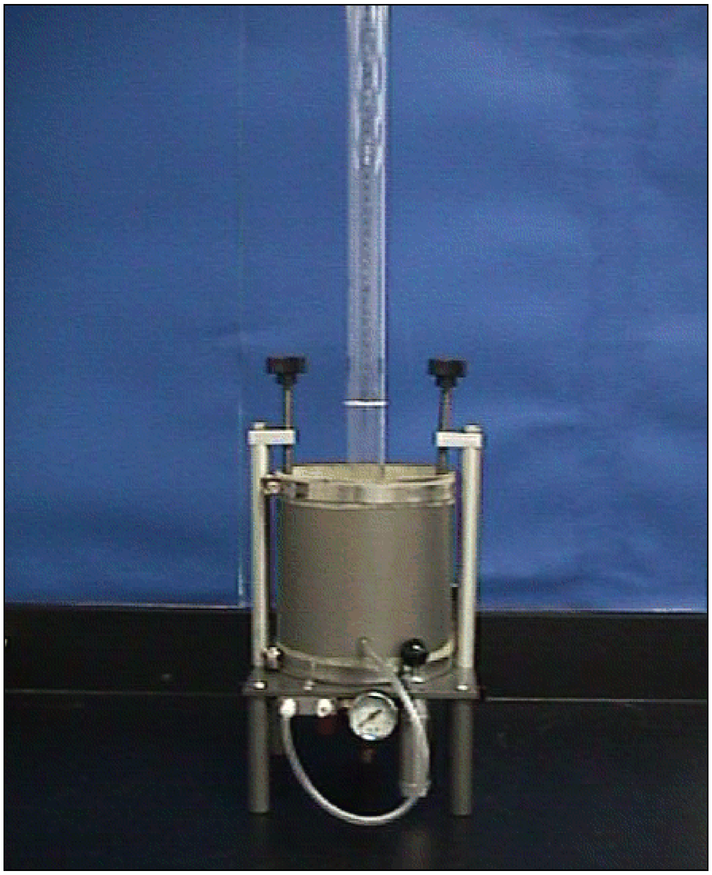


FIGURE 2. Karol-Warner falling head permeability device

In this falling head permeability test, as outlined in the ASTM provisional standard PS-129, a saturated asphalt sample is sealed on the sides and placed under a column of water so that water can only flow through the sample. *(14)* The time required for the water column to experience a specified change in elevation is determined. The permeability coefficient, k, is calculated based on the time elapsed during the test and the drop in water level during that time period, as shown in Equation 4. The test is repeated until four consecutive readings do not differ by more than ten percent. This process confirms that the sample was, in fact, saturated. Otherwise, it would be unclear whether movement of the water column was due to water infiltrating void spaces or actual flow through the sample.

$$k = \frac{a\,L}{A\,t} \ln\left(\frac{h_1}{h_2}\right) \qquad \textit{Equation 4}$$

where: k = coefficient of permeability

a = cross-sectional area of water column above sample

L = length of sample

A = cross-sectional area of sample

t = time lapse during measured head loss

h_1 = head level at beginning of test

h_2 = head level at end of test

Significant research was performed at the University of Arkansas to establish the validity of this laboratory permeameter. In one project, the effects of time and confining pressure were tested. *(17)* It was determined that neither factor had a significant effect on laboratory permeability results. Therefore, laboratory permeability procedures could be simplified and made more attractive.

In another project at the University of Arkansas, the effect of hydraulic gradient on permeability was investigated. *(18)* Although research in the 1960s had shown that Darcy's law was valid for sand asphalt mixes, research in 2001 indicated that the initial hydraulic gradient had a significant effect on the laboratory permeability measurements of HMA mixes, such that large initial gradients could result in turbulent flow. Thus, Darcy's law was deemed invalid in many cases. Based on this conclusion, it was recommended that a falling head / rising tail permeability test could be more appropriate for the determination of HMA permeability in the laboratory. Also, the hydraulic gradient during the test should be close to that typically experienced by in-service pavements.

Void Pathway Test

In using Darcy's law, the assumption is also made that the flow through the specimen is one-dimensional. In order to investigate this claim, a void pathway test (VPT) was developed. *(19)* In this method, pressurized air is forced through an HMA specimen. A soap solution is painted onto the surface of the specimen, and air is forced through the bottom of the specimen. Where air penetrates the depth of the sample, soap bubbles appear. Void pathways and characteristics of the specimen were related to the number and size of bubbles mapped on specimen surfaces.

The results of the study indicated that there are many more void openings on the perimeter surfaces than the cross-sectional surfaces of the samples. No pattern was noted regarding the location of the void openings on the cross-sectional surface area of the specimen. Overall, void pathways were determined to be convoluted, not straight and vertical, and most lead to the outer perimeter of the specimens within approximately 25mm of the "input" cross-sectional surface.

Gyratory-compacted specimens were shown to be denser in the bottom half than the top half, validating the existence of a density gradient for laboratory-compacted specimens. Field cores appeared to have more interconnected pathways than the laboratory-compacted specimens. Overall, most void pathways tended to extend from a cross-sectional surface in a curved manner to the perimeter walls of the sample. The pathways were not vertical (i.e., one-dimensional), so the laboratory permeability test was determined to have definite potential for underestimating true permeability.

Other problems with the laboratory permeability test were discovered during a research project in Virginia. *(20)* In this study, falling-head permeability tests were performed on both pavement cores and laboratory specimens compacted from field mix. In a comparison of specimen type, a fair correlation was noted. However, the act of sawing field cores was shown to decrease permeability. Field cores are often sawn in order to separate pavement layers, and to create smooth surfaces. This sawing action also appeared to seal some voids, thereby reducing permeability. Thus, some alternative method was stated to be necessary as a means to preserve actual in-place permeability characteristics.

While a standard laboratory permeability test provided great advancement toward the characterization of HMA permeability, the process was still rather involved, due to the need for cutting field cores. A non-destructive field permeability test was felt to be a desirable alternative because it would eliminate the need to cut cores, and would provide results more quickly, allowing for faster response when problems arose in the field. Due to high variability and inconsistencies in the method, the provisional ASTM standard (PS-129) for laboratory permeability was withdrawn in 2003.

Field Permeability

The National Center for Asphalt Technology (NCAT), among others, began working to find a suitable field test method that could replace the Florida laboratory test. However, field permeability was difficult to measure because Darcy’s law is based on one-dimensional flow in the vertical direction. In reality, water flow can occur in two directions, vertical and horizontal, and the actual pathways traveled by the water are unknown. In addition, the degree of saturation, flow boundaries, and flow type are difficult to determine and control in the field. Further difficulties arose from the fact that the specimen thickness (mat thickness) and the cross-sectional area of water flow must be assumed or estimated. Finally, the existence of laminar flow can only be assumed.

The advantages of a field test, however, outweighed the difficulties, and the idea was pursued. One of the most notable studies was performed by NCAT to evaluate four field permeameters. *(16)* The objective of the study was to select a field permeameter that best correlated with the Karol-Warner laboratory permeability test results (as per ASTM PS-129), was most repeatable, and was easiest to use. Three new construction projects were used to evaluate the four field permeameters, and cores were cut in order to determine laboratory permeability values.

The first permeameter was the simplest design. It was designed by NCAT and was a single diameter standpipe which was fitted into a base. Sealant was applied to the base in order to seal it to the pavement surface. In some cases, the sealant was placed directly on the pavement surface, and a weight was applied to the base to help maintain the seal when water was introduced into the standpipe.

The second permeameter was provided by a commercial supplier, and resembled a six-inch Marshall mold with a plastic cap. The standpipe fit into a hole in the top cap, and then a ring (50mm larger in diameter than the mold) fit around the outside of the assembly for sealing. Heated paraffin was poured between the permeameter and the ring to seal it to the pavement. The need for heated paraffin made this permeameter more difficult to use than the others, and was therefore less desirable.

The third permeameter was also designed by NCAT, and used a three-tiered standpipe, such that each tier had a different diameter. The smallest diameter was at the top and the largest diameter was at the bottom, which allowed for various levels of sensitivity and more flexibility in measuring different levels of permeability.

The fourth permeameter was very similar to the paraffin type, but it used a silicone-rubber caulk as a seal rather than the heated paraffin. Some difficulties were reported for sealing this permeameter to the pavement because it did not have a baseplate.

In terms of simplicity, the first NCAT-designed permeameter was the easiest to use. The tiered NCAT permeameter ranked second and the silicone-rubber caulk ranked third. The paraffin-seal permeameter was eliminated from the study due to its cumbersome nature and difficulties encountered in achieving an adequate seal. Based on data analyses using the remaining three methods, the simple NCAT permeameter was eliminated due to its inability to correlate with the laboratory permeameter.

Both the tiered NCAT permeameter and the silicone-rubber caulk permeameter provided results that were statistically similar to laboratory test results, and had similar levels of repeatability, so the final choice was based on ease of use. The tiered NCAT permeameter was recommended for the measurement of HMA permeability in the field.

The NCAT field permeameter was later used in a round-robin study. *(21)* From the resulting data, the permeameter-operator reproducibility was 10 x 10^{-5} cm/s, and the overall standard deviation on permeability measurements was found to be 24.4 x 10^{-5} cm/s.

Factors Affecting Permeability

Further research was performed by NCAT to determine the critical field permeability and pavement density values for coarse-graded Superpave pavements. *(9)* The primary objective of the project was to determine at what density level the Superpave mixes became excessively permeable. Eleven projects were selected, and a total of 15 test locations were selected from each project. At each test location, triplicate field permeability tests were performed, and a core was cut in order to determine the pavement density. The mixes tested were primarily coarse-graded Superpave mixes, and contained a variety of NMAS.

The results of the study varied according to NMAS such that mixes with a larger NMAS became more permeable at lower in-place air void contents. For 9.5mm and 12.5mm mixes, the critical permeability appeared to be approximately 100 x 10^{-5} cm/sec, which occurred at 7.7 percent air voids. For 19.0mm mixes, the critical permeability appeared to be 120 x 10^{-5} cm/sec, which occurred at about 5.5 percent air voids. For 25.0mm mixes, a critical permeability of 150 x 10^{-5} cm/sec was selected, which corresponded to an air void content of 4.4 percent. No 37.5mm mixes were tested. Overall, it was recommended that field permeability testing be incorporated into standard quality control and quality assurance procedures, and that using fine-graded mixtures for base and binder courses could help to mitigate permeability problems in those layers. It was suggested that some permeability may be acceptable for the base and binder layers, however, because it would likely be covered with a less permeable surface layer.

In a similar study by NCAT, the relationships of laboratory permeability, lift thickness, and density were investigated. *(22)* Similar findings were generated with respect to “critical” permeability values and field densities. Smaller NMAS mixes were less permeable than larger NMAS at the same air void content. A critical field permeability value of 150 x 10^{-5} cm/s was recommended, and it was also determined that permeability decreased as lift thickness increased.

Also in this NCAT study, a comparison of laboratory and field permeability was performed, and it was shown that the results are similar for permeability values of up to approximately 500 x 10^{-5} cm/s. *(22)* At higher permeability levels, the laboratory test provided greater values. This finding was unexpected since the direction of flow is limited in the laboratory, but not in the field.

The opposite trend was noted in another comparison of laboratory and field permeability tests. In Kansas, such a comparison was made using the NCAT permeameter in the field and the Karol-Warner laboratory permeameter for gyratory-compacted asphalt samples. *(23)* There was not a good correlation between the two methods, in that the field permeability values were much larger than those obtained from laboratory testing. This was assumed to be due to the probable violation of Darcy’s law for the field test situation. In fact, during some of the field tests, water was observed rising through the mat a few centimeters from the permeameter base. This was assumed to be due horizontal water flow, which does violate Darcy’s law. Although the laboratory and field results did not agree, the field permeability values were found to be a valuable tool for the relative assessment of compaction quality for Superpave mixtures.

Further study in Kansas evaluated several factors affecting the permeability of both 12.5mm and 19.0mm asphalt mixtures. *(24)* Fine-graded mixtures were shown to be less permeable than coarse-graded mixes. The percent passing the #30 sieve, film thickness, and air voids were statistically significant to the permeability of the 12.5mm mixtures. For the 19.0mm mixtures, air voids, percent passing the #30 sieve, and compactive effort were determined to be significant variables. An additional finding of this study was that mixes with lower permeability were less susceptible to rutting and stripping in the Hamburg wheel-tracking device.

Kentucky has also been responsible for a significant amount of research regarding permeability. One study evaluated the relationship of permeability and lift thickness. *(7)* This research was used as a basis for recommending an increase in the lift thickness / NMAS ratio, which would allow for better compaction and reduced permeability.

Other Field Permeameters

In addition to the NCAT field permeameter, other devices have been used to determine the permeability of asphalt mixtures in the field. One was developed for the University of Arkansas by Mr. Mark Kuss. The Kuss permeameter is a constant-head permeameter that uses a patented pressure-measurement device. As water infiltrates the pavement, a sensor measures the amount of air required to maintain a constant head of pressure above the sample test area, and this volume of air is metered into the head space above the water column.

To evaluate this device, two test pads were constructed at the University of Arkansas in order to study the permeability of 12.5mm and 25.0mm coarse-graded Superpave mixtures. *(4)* One pad consisted of a 100mm thick 25.0mm binder course, and the other was a 75mm thick 12.5mm surface course placed over a 100mm thick 25.0mm binder course. No tack coat or prime coat was used between layers. A grid was marked on each pad, and field permeability was measured for each block of the grid. Then, cores were cut from each block and used for a laboratory permeability determination. Laboratory permeability was also measured for field mix compacted in the gyratory compactor. Seventeen field sites in the state of Arkansas were also tested. The Karol-Warner device was used for the laboratory permeability determinations, according to ASTM test method PS-129. The NCAT and Kuss permeameters were used to measure field permeability values.

In terms of critical values, cores having in-place air void contents of 6 percent or less were impermeable. Those with 7 to 9 percent air voids exhibited low permeability ($<100 \times 10^{-5}$ cm/s), and those with greater than 9 percent air voids were permeable.

In theory, the constant head test is believed to be more appropriate for materials having greater permeability, and the falling head test is most appropriate for materials having lesser permeability. Thus, it is reasonable that a constant-head test would be more appropriate for coarse-graded Superpave mixtures.

Overall, the test results for the three methods did not correlate well, especially at higher air void contents. The Kuss permeameter generated lesser permeability values than the NCAT field permeameter, and exhibited better agreement with laboratory values. Also, the Kuss permeameter exhibited slightly greater consistency than the NCAT permeameter for replicate measurements of field permeability.

Other observations included the following:

- Permeability data resulting from the NCAT permeameter appeared to be the most sensitive to changes in air void content.
- Field permeability values were dependent on the longitudinal and transverse slope of the pavement, such that on steep longitudinal slopes,

void pathways appeared to be connected horizontally more than vertically.

- Field permeability values seemed to be dependent on the time of testing (i.e., length of time since construction) even when no traffic was placed on the pavement.
- The assumption of laminar flow for laboratory permeability testing was demonstrated to be correct for samples of high permeability.

Another Arkansas study provided a comparison of the NCAT (falling-head) and Kuss (constant-head) field permeability devices. *(25)* The two methods were shown to yield significantly different permeability results, but had similar testing variability. The differences were attributed to differences in the initial applied hydraulic head, as well as differences in the testing footprint area of the devices.

In Maine, five pavements were tested using a field permeameter developed by the Worcester Polytechnic Institute (WPI) laboratory. *(10, 26, 27)* This permeameter was based on the NCAT tiered design, but used a flexible closed-cell sponge rubber material on the base, which aided in sealing the device to the pavement. Donut-shaped weights were used to help maintain the seal during the test. The objective of the study was to investigate various factors affecting the permeability of Superpave mixtures. The results of the study confirmed earlier conclusions that permeability is significantly affected by air void content, NMAS, and lift thickness. It was suggested that when designing base and binder mixes, more emphasis should be placed on stripping resistance than rutting resistance. Because rutting typically occurs in the top 75-mm of a pavement structure, the base and binder layers could be designed using a fine gradation, which would allow lower levels of permeability and provide greater resistance to moisture damage. Based on test results, permeability values were acceptable when air void contents were less than 5 percent. Thus, the state of Maine was able to validate its field density requirement of 95% of theoretical maximum density.

Air Permeameters

Air permeameters have also been used for many years as a way to measure the ability of harmful substances (i.e., air and water) to infiltrate the surface of asphalt pavements *(28)* Asphalt mixtures are more permeable to air than water. *(12)* Since both air and water can be detrimental to the performance of a pavement, this measure of permeability is informative. The air permeability of a mixture may even be more important, since a pavement that is resistant to penetration by air will also resist penetration by water.

In the 1980s, an air permeameter was developed by Pennsylvania State University and tested in New Mexico. *(29)* This device was sealed to the pavement and then compressed air from a chamber was forced through the pavement's surface. The pressure readings from the release chamber and airflow rate measurements were used to estimate permeability. This device was repeatable, but the test procedure was complex. It was difficult to perform on highly porous surfaces, and prone to seal failure when testing very tight surfaces.

Another air permeameter was developed by ASTM. This device measured the air flow rate through the pavement at low pressures. However, it was unable to correlate with other devices, was only marginally repeatable, and was determined to be theoretically inaccurate.

In Kentucky, another air permeameter was developed. *(29)* This device, known as the air-induced permeameter (AIP), utilizes a vacuum, rather than pressure, to detect permeability. The inside diameter of the testing area is 8 inches, which was believed to be large enough for all NMAS mixes tested. The sealing ring is 3 inches in width to prevent air from “short-circuiting”, and a silicone-rubber caulk is used as a sealant. Additionally, the vacuum enables the device to be self sealing. The AIP uses a multi-port venturi vacuum cube, forcing pressurized air at a constant pressure of 68 psi. This condition creates a vacuum to draw air through the pavement, registering a vacuum reading. The more difficult it is to draw air through the pavement, the lesser the permeability. Thus, high readings on the AIP represent low permeability.

Several features of the AIP provide advantages over other types. For instance, a test result using the AIP can be obtained in less than one minute, while the NCAT permeameter takes much longer, especially for pavements with low permeability. Also, the process of sealing the NCAT permeameter is sometimes difficult, and the test can be difficult to perform in superelevated areas.

One objective of the study was to correlate the AIP with the NCAT field permeameter and the Karol-Warner laboratory permeameter. In this effort, 11 construction projects were selected, and tests were performed at the longitudinal construction joint, 6 inches from the joint, 18 inches from the joint, and 6 feet from the joint (center of the lane). The field and laboratory permeability results did not correlate well, likely due to the fact that the laboratory test measures one-directional flow, while the field tests measure multi-directional flow. There was a good correlation between the NCAT permeameter and the AIP. It was assumed that the field permeability values were more realistic, and thus, the laboratory permeability values were inaccurate.

When comparing the AIP results to pavement density, there was a great deal of scatter, meaning that the relationship was weak. However, at 92 percent density, field permeability decreased significantly, and this value did not appear to be related to the NMAS of the mix. This supports the construction specification requirement of 92 percent minimum density.

A significant relationship was discovered relating permeability to the gradation of the mix. Specifically, the percent of material retained on the mid-range sieves (#8, #16, #30, and #50) was critical to reducing the permeability of a mix. Based on this finding, it was suggested that any gradation, regardless of NMAS, can be designed to have high or low permeability.

One of the most important findings of this research involved the variability of permeability across the width of a compacted mat. The lowest permeability occurs in the center of the lane, and the greatest permeability occurs near the construction joint, where the coefficient of permeability can be several times that measured in the center of the lane. Because of this concept, it was recommended that the permeability of a pavement be expressed in a probabilistic manner. A specification was also proposed that included requirements for the 50th and 15th percentile measurements. A minimum of 40 permeability tests were recommended per project, with randomly chosen locations, with 25 percent of these tests being performed within one foot of the longitudinal construction joint.

OBJECTIVES

The overall objective of this project was to determine the applicability of implementing field permeability testing as a standard tool for quality control. Specific objectives follow:

Map the location of permeable voids. By mapping an entire area, a measure of pavement variability may be obtained. At the very least, a qualitative measure of the number, size, and density of the permeable voids can be determined.

Compare the results of the Kuss vacuum permeameter to the results of other field permeameters. The vacuum permeameter can be used to determine the permeability of an asphalt pavement to air. Although pavements are not equally permeable to air and water, both elements present harmful effects to the pavement and should be considered. The NCAT field permeameter and the Kuss field permeameter were used to measure the water permeability of the pavement sections. The measure of permeability obtained by the Kuss vacuum permeameter was assumed to be the maximum permeability, or true (total) permeability. Relationships between the various measures were sought.

Use the air permeability maps to identify typical areas of concern. By mapping a complete test section of the HMA mat, trends in permeability can be established. It was anticipated the areas near a joint would be more permeable than areas in the central portion of the mat.

Evaluate the permeability of various pavement types. In order to assess the effects of factors such as pavement age, traffic level, and mix type, a variety of pavement sections were tested.

Determine the testing frequencies that would allow for reasonably accurate measures of field permeability. Based on the variability in permeability demonstrated by the vacuum permeameter maps, the choice of sample size for field permeability testing was investigated.

SCOPE

In this project, 3 test methods were used to estimate the permeability of asphalt pavements. Based on the results of these tests, conclusions were sought regarding the effects of various test methods, factors affecting permeability measurements, and the variability of permeability across the width of the pavement section.

Test Methods

Three field permeameters were used in this project in order to measure the permeability of in-place asphalt mixes. They were the NCAT falling-head field permeameter (NCAT), the Kuss constant-head field permeameter (KSFP), and the Kuss vacuum permeameter (KVAC).

NCAT Field Permeameter

The NCAT Field permeameter, shown in Figure 3, was developed at the National Center for Asphalt Technology (NCAT). This device is based on the principles of the falling head permeability test, and uses a three-tier system. Each tier of the standpipe has a different diameter, such that the smallest diameter is at the top and the largest diameter is at the bottom. This system allows for various levels of sensitivity and added flexibility in measuring pavements with different levels of permeability. For pavements having low levels of permeability, the top tier (smallest diameter) should be used, and for pavements with high levels of permeability, the bottom tier should be used.

Figure 3. NCAT Field Permeameter

In this method, a one foot square pavement section is chosen for testing. The area is then swept clean of all dust and debris in order to enable a watertight seal.

Moldable sealant is applied to the base plate of the permeameter such that the sealant extends approximately three inches beyond the gasket that defines the perimeter of the testing area. After applying the sealant, the permeameter is placed on the testing area and seated using uniform pressure, then weights are then added to aid in maintaining the seal during testing. Next, the permeameter is filled with water and the rate at which the water level drops is observed. Based on this rate, the appropriate tier for testing is selected, and then the height and time are noted at the beginning and ending of the test. Coefficient of permeability is then calculated according to Equation 5.

$$k = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right)$$ *Equation 5*

where: k = coefficient of permeability

a = cross-sectional area of water column above sample

(15.52cm^2 for the top tier, 38.32 cm^2 for the middle tier, and

167.53cm^2 for the bottom tier.)

L = length of sample

A = cross-sectional area of sample

(214cm^2)

t = time lapse during measured head loss

h_1 = head level at beginning of test

h_2 = head level at end of test

Kuss Field Permeameter

The Kuss Field Permeameter (KSFP), shown in Figure 4, operates using the constant head approach. To do this, a patented gas-measurement system is used to measure the amount of air needed to replace the water in order to maintain a constant pressure head. When the test begins, water is allowed to flow from the standpipe and cover the pavement testing surface to a depth of approximately 1 inch. A sensor is used to monitor the water level, and is connected to a flow valve in the flow meter box. As water infiltrates the pavement, the water level over the pavement drops, and the sensor alerts the flow valve, allowing air to enter the standpipe above the water column. This metered volume of air acts as a substitute for the head pressure originally applied by the water, thereby maintaining a constant head. A data acquisition system measures and records the flow rate of water through the pavement over time, and the permeability is calculated using the rate of flow of water into the pavement and the cross-sectional area of the pavement test section. The relationship is presented in Equation 6, and a schematic of the system is presented in Figure 5.

$$k = \frac{Q}{60 * \left(\frac{2.54 + L}{L} \right) * A}$$ *Equation 6*

Where: k = coefficient of permeability, cm/s

Q = flowrate, cm^3/min

A = area of base plate, $1264.5 cm^2$

L = pavement thickness

Equation 6 was derived from Darcy's law and utilizes the following assumptions:

1. A 25.0mm head of water on the testing surface is assumed to create a negligible pressure effect at the bottom of the testing layer.
2. Water flow is assumed to be vertical.
3. When the asphalt mat is placed over a relatively impermeable surface (i.e., a coarse-graded Superpave overlay placed on an aged dense-graded mix), the thickness of the underlying material is neglected.

Figure 4. Kuss Field Permeameter

The data acquisition system measures and records the data, providing a real-time plot of the flow rate of water over time. The test continues until a "constant" flow rate (i.e., little or no fluctuation in consecutive flow rate measurements) was achieved, or for a maximum of 30 minutes. If zero permeability was indicated for a span of 15 minutes, the test was terminated. The final flow rate used in the permeability calculation was taken to be the average of the flow rates recorded during the last five minutes of the test. A sample graph from this test is given in Figure 6.

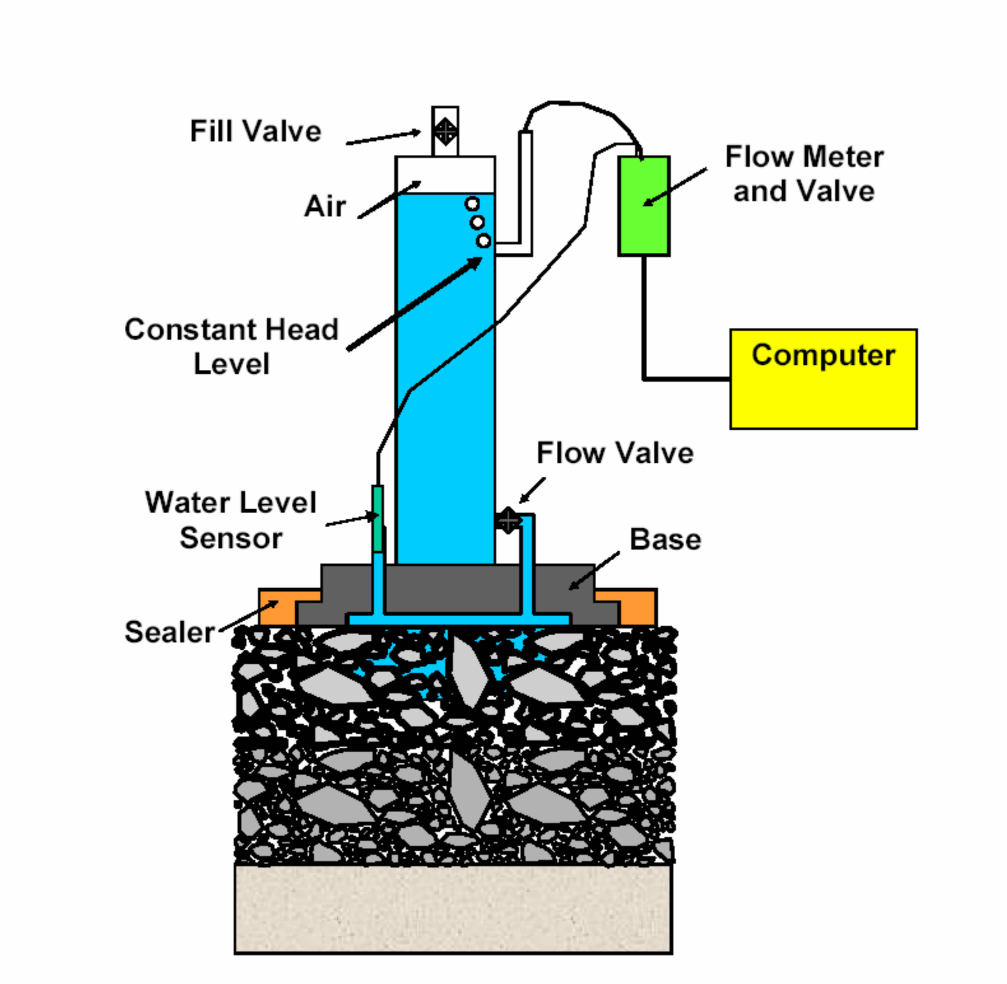


Figure 5. Schematic of Kuss Field Permeameter

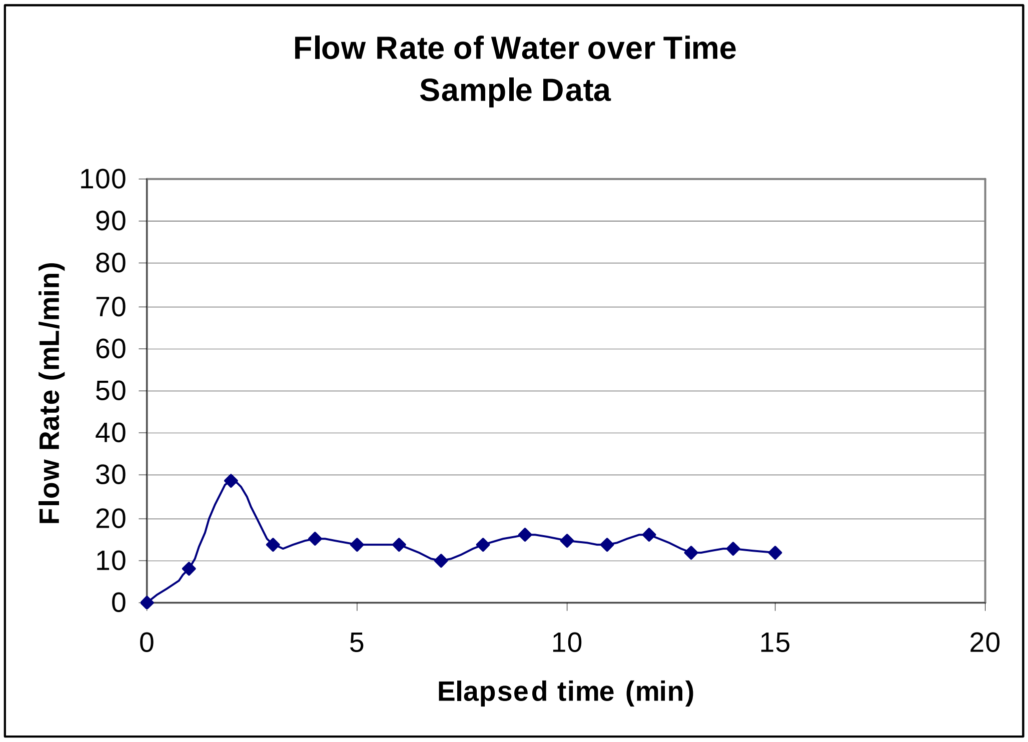


Figure 6. Typical Kuss Field Permeameter Data

Kuss Vacuum Permeameter

The Kuss Vacuum Permeameter (VACP), shown in Figure 7, was developed as a simple way to describe the location and density of void pathways connected to the surface of HMA pavements. The device consists of a large clear encasement that is connected to a vacuum source. The encasement is made of ½ inch thick plexiglass, and when placed upon the pavement, its inside dimensions are 23 in. x 23 in. x 3.5 in. A strip of foam is used to seal the encasement to the pavement.

Figure 7. Kuss Vacuum Permeameter

To perform the test, a 14 in. square pavement test area is selected and marked. Because the encasement is considerably larger than the pavement test area, any edge effects created by leaks at the seal are eliminated. To begin the test, the pavement surface is saturated with water, and the encasement is centered over the testing area. Next, the vacuum is applied, the encasement becomes sealed to the pavement, and bubbles appear where permeable voids exist. A video recorder is used to document the testing process for approximately 15 seconds, or until a consistent bubble pattern appears. After testing, the video is analyzed to document the locations and sizes of bubbles within each test section. A sample photo is presented in Figure 8.

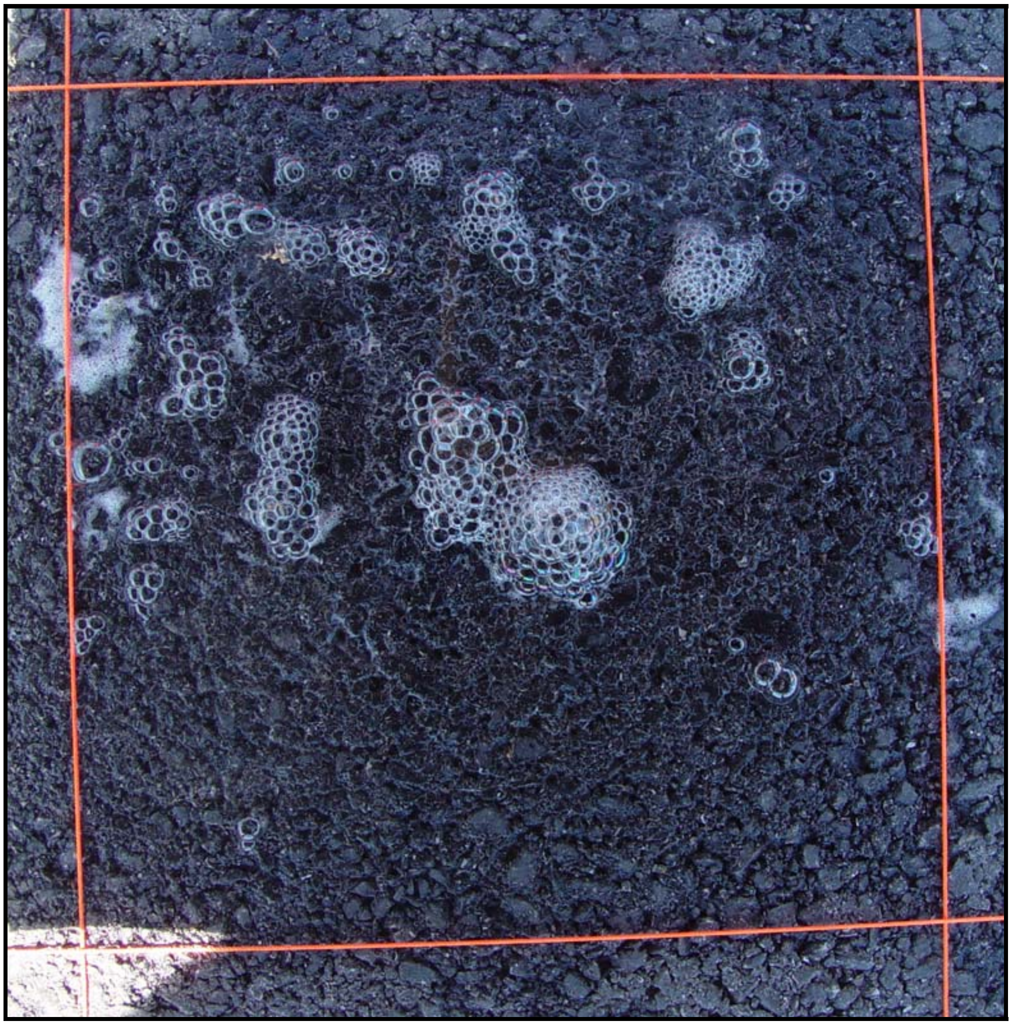


Figure 8. Sample Photo from VACP Test

Early trial testing with this device included coating the pavement surface with a mild soap solution as a means to enhance the visibility of the bubbles. However, the solution generated conglomerations of bubbles, which diminished the ability to discern individual bubble locations. Thus, all further testing was performed using plain water.

Although no numerical data value is directly generated during this test, a subjective "bubble-mapping" process was used to quantify the percent of the test area that contained permeability (i.e., bubbles). From this process, each square inch of the 14-

in. x 14 in. test square was characterized. A sample data map for a single 14-inch test square is given in Figure 9. For this sample, 47 of the 196 square inches exhibited some level of permeability (i.e., had a bubble). Thus, 24 percent of the sample area is said to be permeable to air.

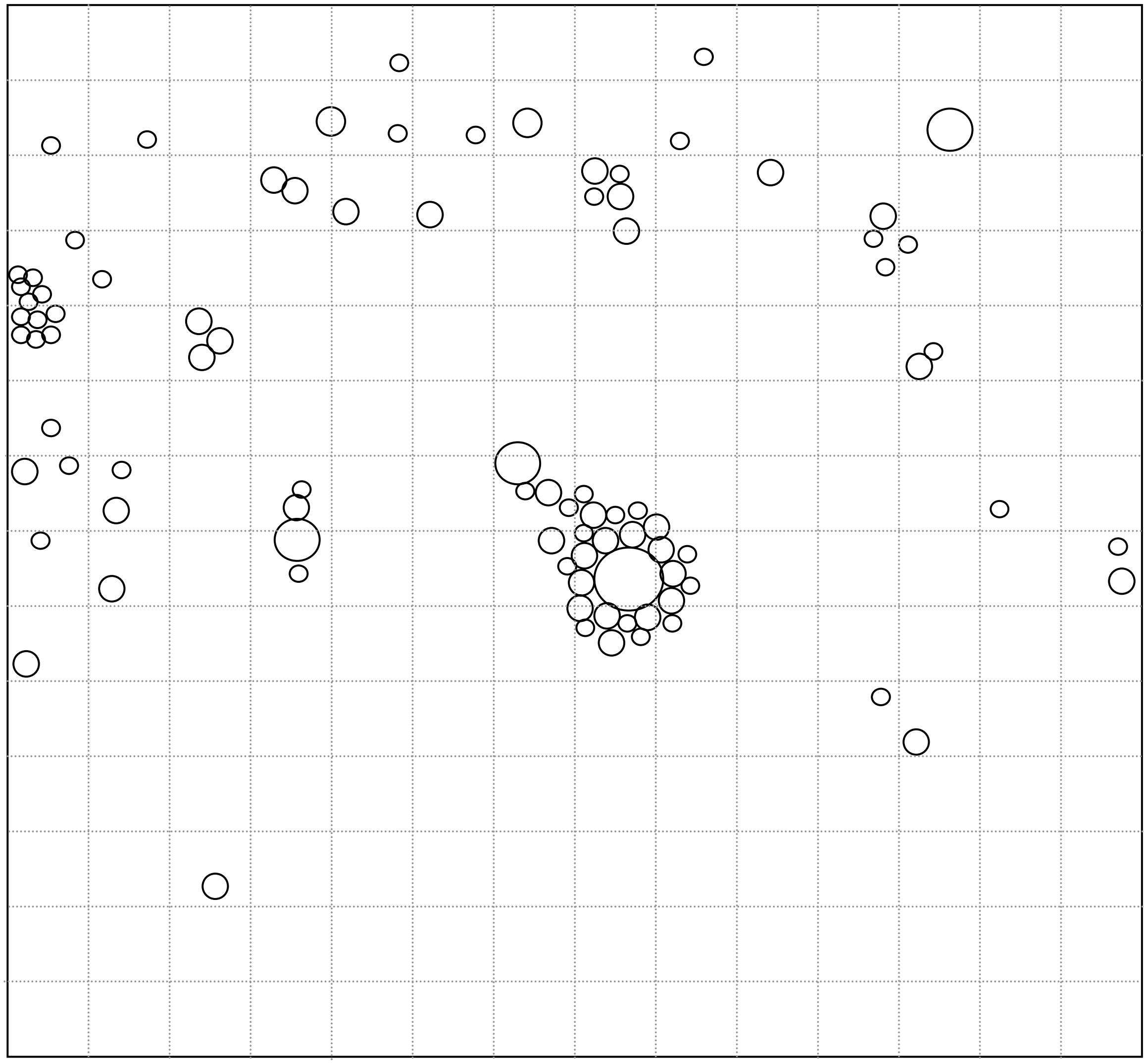
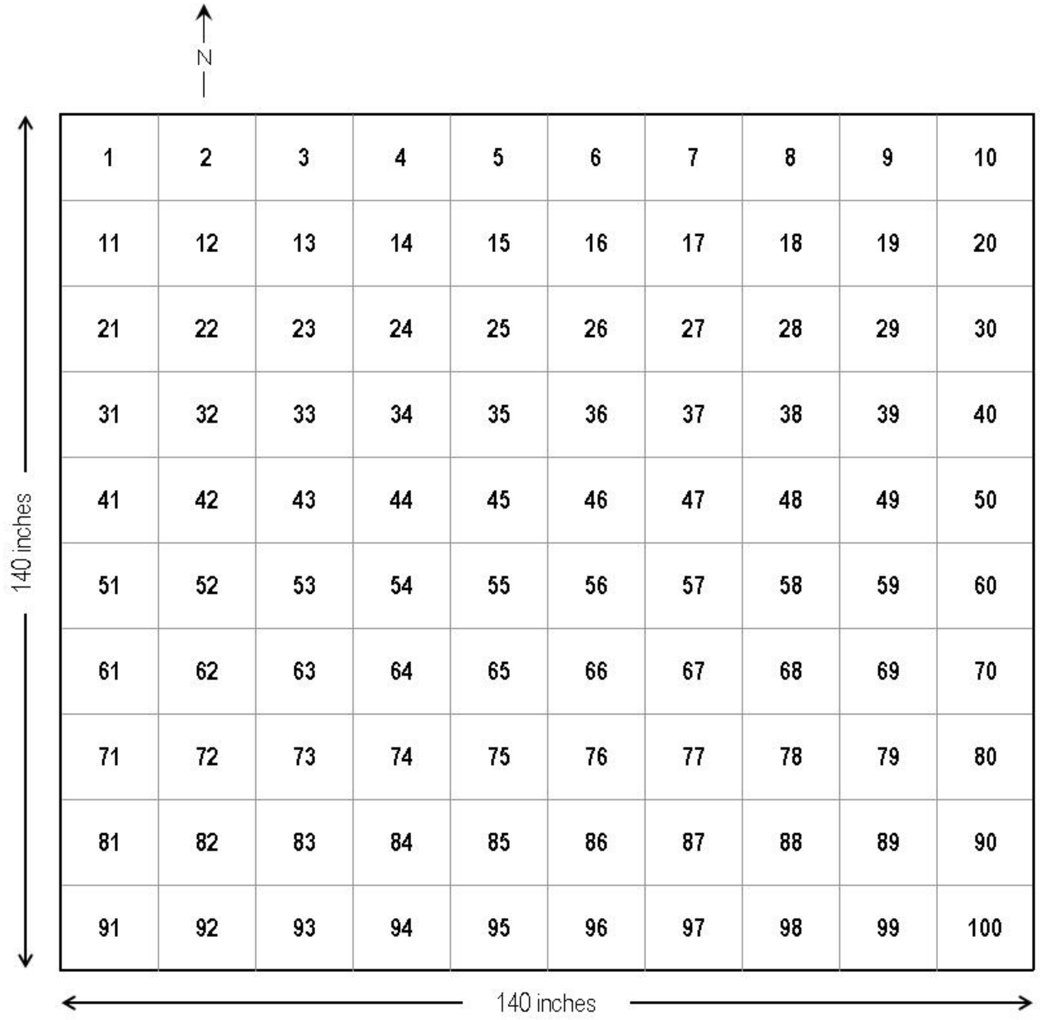


Figure 9. Sample square data map from VACP test – 24% air permeability

Test Sites

Seven sites were mapped using field permeability tests. At each site, a 140-inch by 140-inch area was chosen for mapping. This square area was then divided into a grid of 100 squares (10 rows and 10 columns), each having the dimensions required for the KSFP and VACP tests (14 in. x 14 in.). The squares were numbered, starting in the northwest corner, as shown in Figure 10. Because the width of the testing area was approximately that of one lane width, a complete characterization of permeability over the width of the lane at each site was obtained.



1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

Figure 10. Example test site map

The first site was in the traveled way of a relatively low-volume city street (LVST), which had been in-service for approximately five years. A diagram of this site is given in Figure 11. The second site was a paved portion in the median of this same city street (LVSM), shown in Figure 12. Although the median area of this pavement had also been in service for five years, it had experienced only minimal U-turn traffic. The median and traveled way portions were used to represent this pavement in "before" and "after" traffic situations. For both of these sites, the mat thickness was estimated to be approximately 2.5 inches.

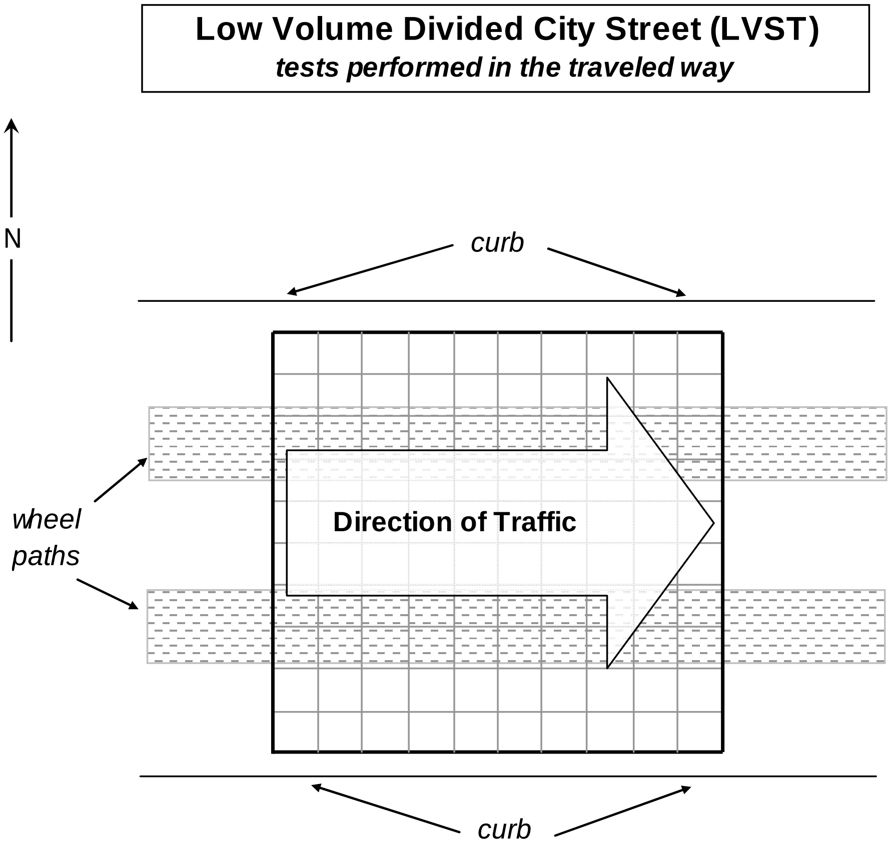


Figure 11. Sketch of LVST site

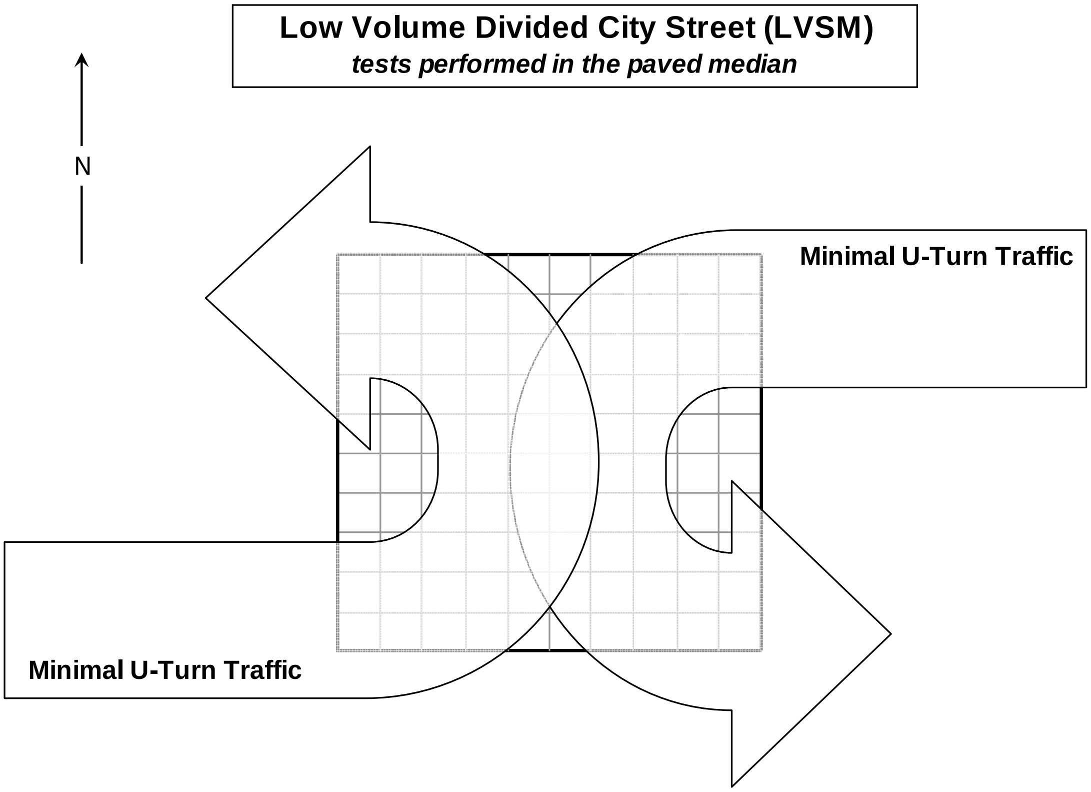


Figure 12. Sketch of LVSM site

The third site, shown in Figure 13, was a special events parking lot (PKLT), which had been in service for approximately two years, experiencing only low volumes of traffic in somewhat random traffic patterns, and standing passenger car loadings. The mat thickness at this site was estimated to be 2.5 inches.

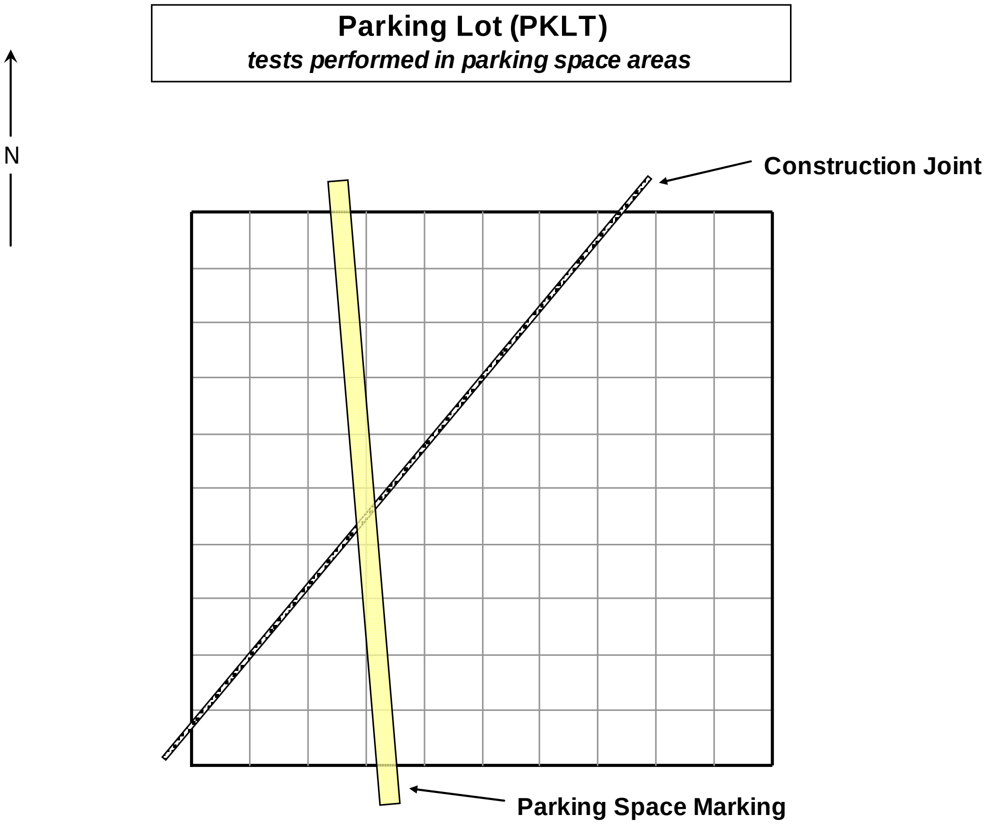


Figure 13. Sketch of PKLT site

Three sites were mapped on a newly constructed city street expected to handle moderate volumes of traffic. These three sites were mapped for each layer of the asphalt pavement so that the location of testing was the same for each layer. Sketches of these sites are presented in Figures 14 - 16. The base layer was a 37.5mm Superpave mix placed in a 6.5-inch lift (BASE). The intermediate, or binder, layer was a 25.0mm Superpave mix placed in a 5.5-inch lift (BIND), and the final surface was a 12.5mm Superpave mix placed in a 3-inch lift (SURF). All permeability testing for these three sites was conducted shortly after construction and prior to the pavement being opened to traffic.

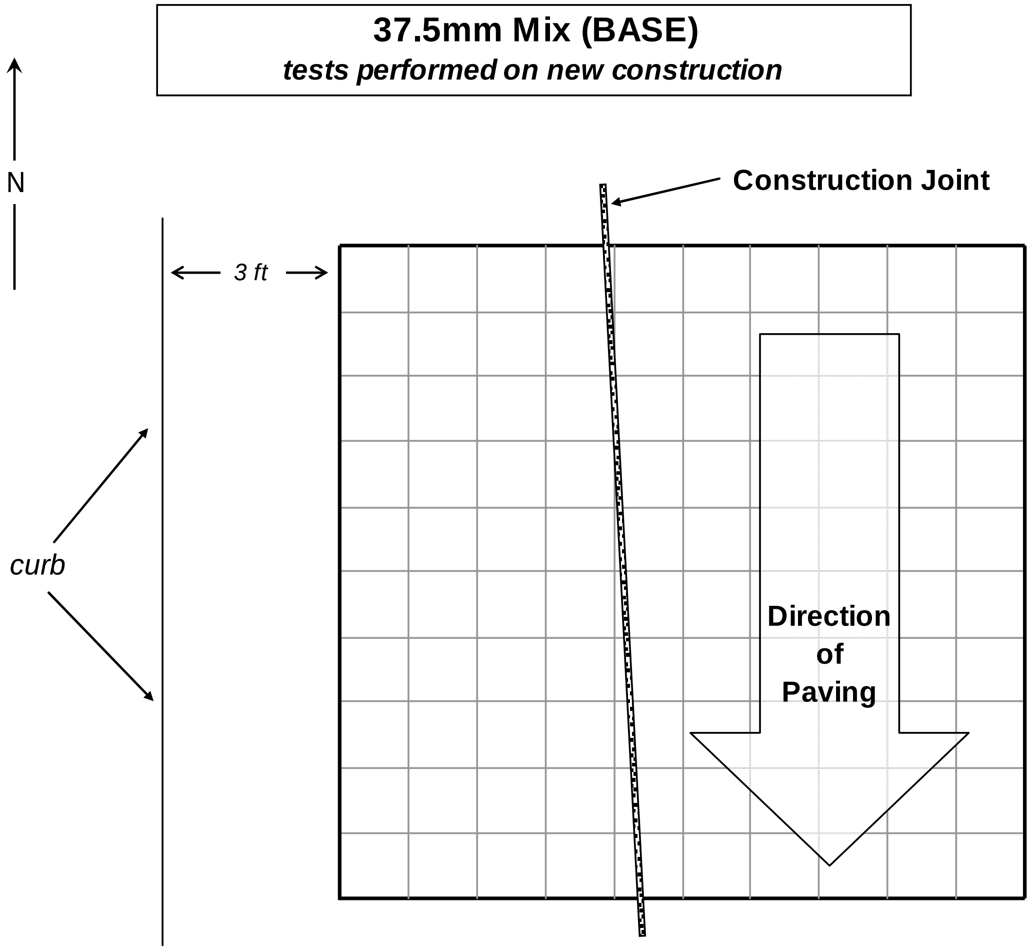


Figure 14. Sketch of BASE site

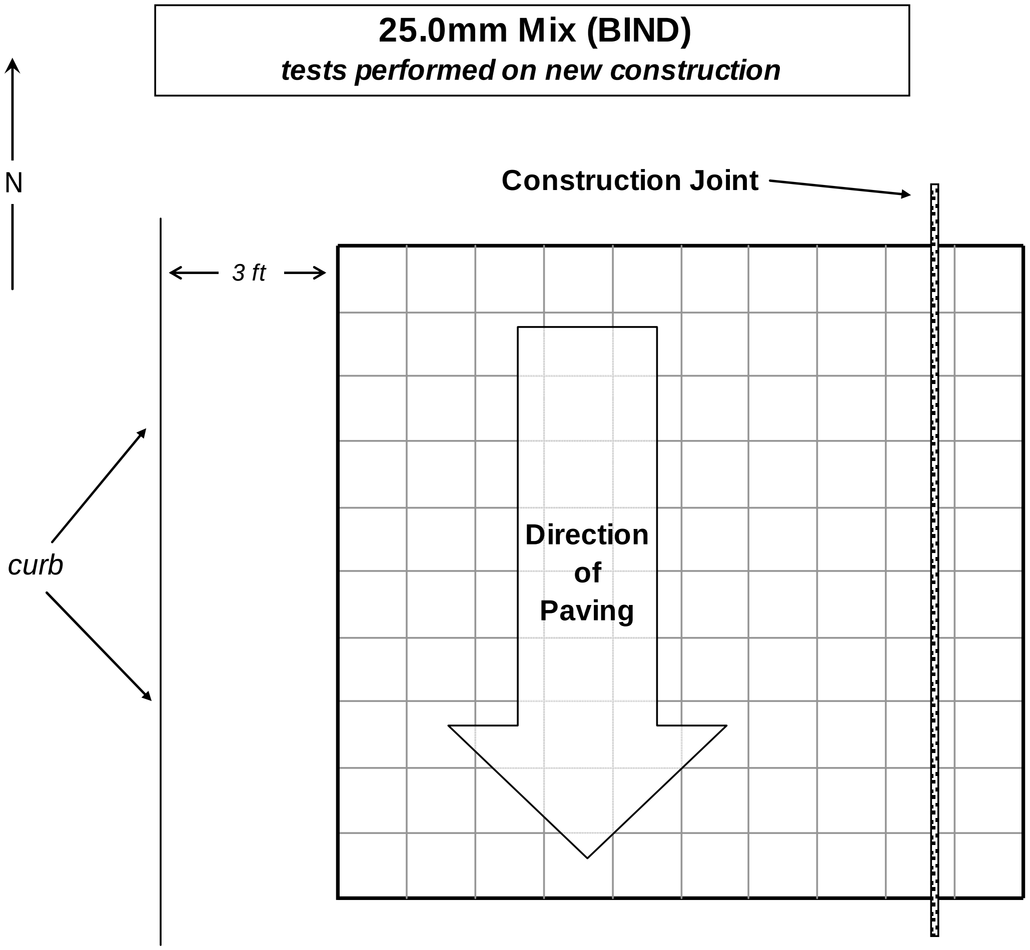


Figure 15. Sketch of BIND site

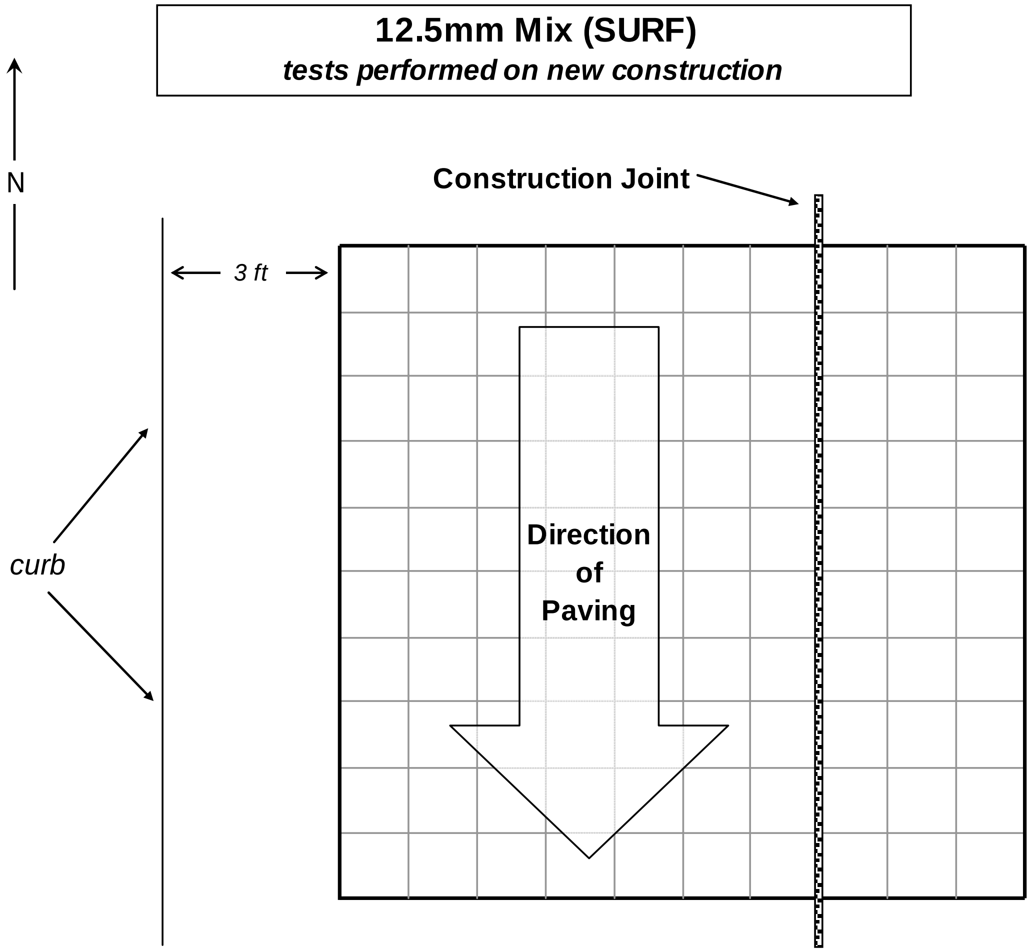


Figure 16. Sketch of SURF site

The final site, shown in Figure 17, was a state highway route that had been in service for approximately three years, carrying medium to high traffic volumes (SHWY). A 4-inch thick surface of 12.5mm Superpave and a 4-inch thick binder course of 25.0mm Superpave were placed over a 6-inch thick 37.5mm Superpave base. Although the highway route existed previously, the area tested was a newly constructed lane.

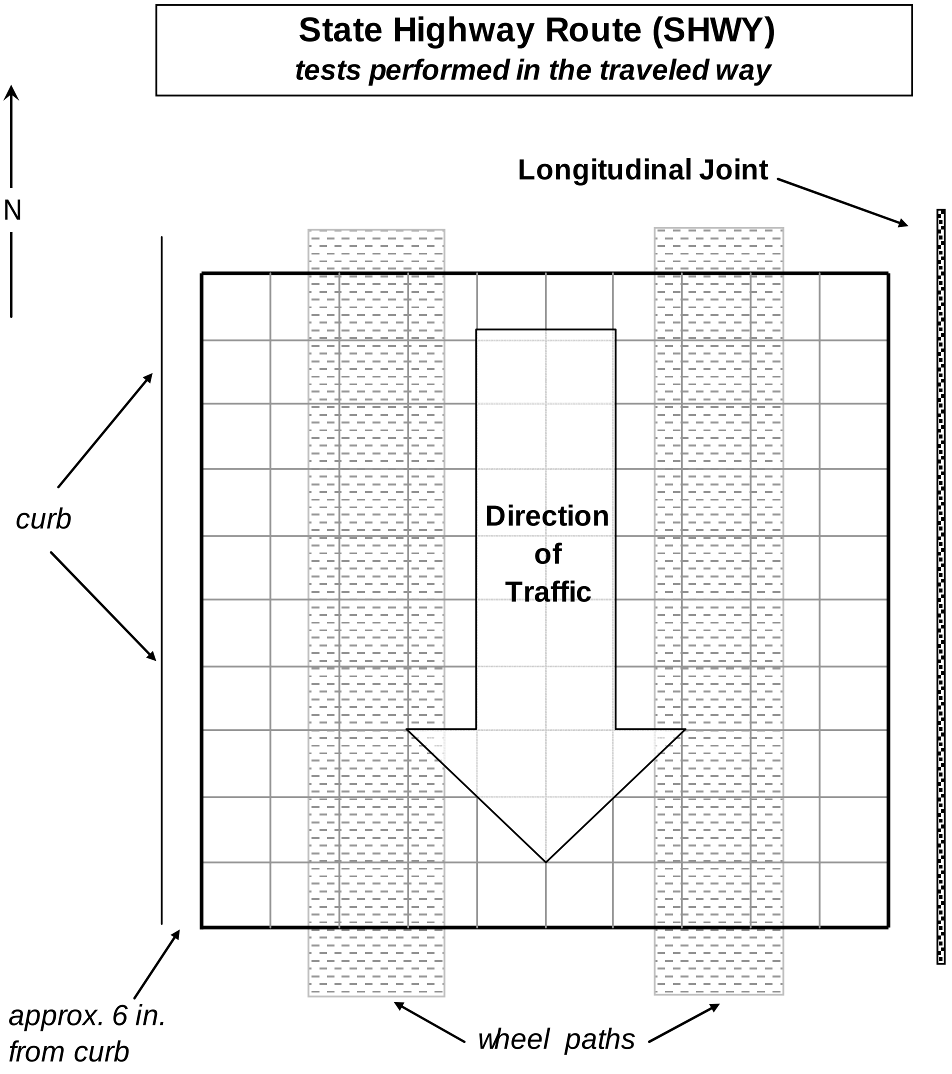


Figure 17. Sketch of SHWY site

Testing Plan

For the first three sites (LVST, LVSM, and PKLT), the complete testing area was mapped using the Kuss vacuum permeameter. Then, three to five squares were randomly selected from each site for testing according to the Kuss and NCAT field permeameters. The objective of this phase of testing was to determine whether a correlation existed between the various methods.

Next, testing was performed on each of three layers of a new construction project. The focus of this portion of the study was to investigate the permeability of newly constructed pavements of various nominal maximum aggregate sizes. At this site, the vacuum permeameter was used to map the sites, and then field cores were cut in order to relate permeability to pavement density. Limited testing was also performed using the Kuss and NCAT field permeameters.

At the final testing site, the vacuum permeameter was used to map the site. This provided a measure of permeability of a relatively high-volume pavement in service. Limited testing was performed using the Kuss and NCAT field permeameters.

TEST RESULTS AND DISCUSSION

The first portion of the project involved a comparison of three methods for measuring field permeability. Three sites (LVST, LVSM, and PKLT) were mapped according to the vacuum permeability test. Photos of each square were pieced together to form a complete photo map of each site. These maps are presented in Figures 18 - 20 In two of the photo maps (LVST and PKLT), the photos of some individual squares were missing. For the PKLT site, the photo files for a large section of data were lost. Because this area represented such a large portion of the photo map, “typical” photo squares were substituted to complete the map. In all cases of missing or lost photos, data maps were documented prior to the loss of files. Therefore, datasets are complete even when the photo maps are not.

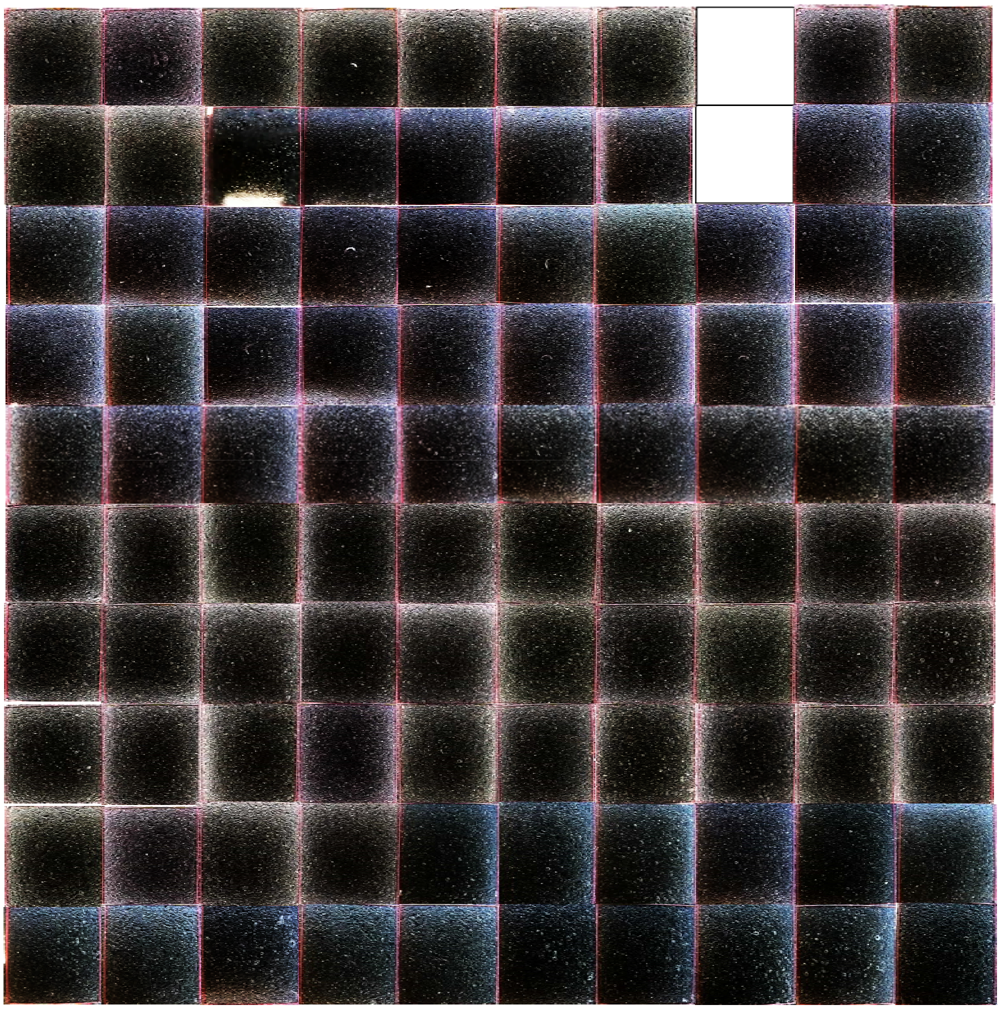


Figure 18. Photo map of LVST site

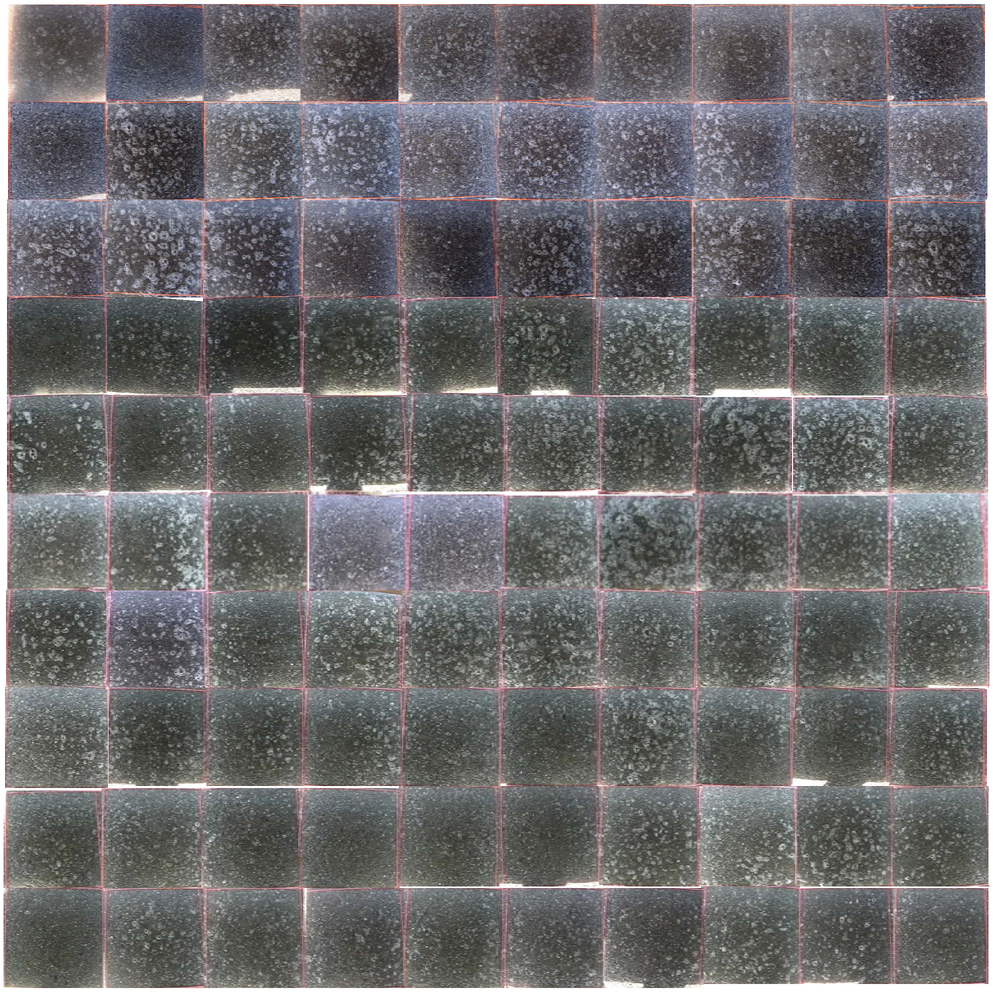


Figure 19. Photo map of LVSM site

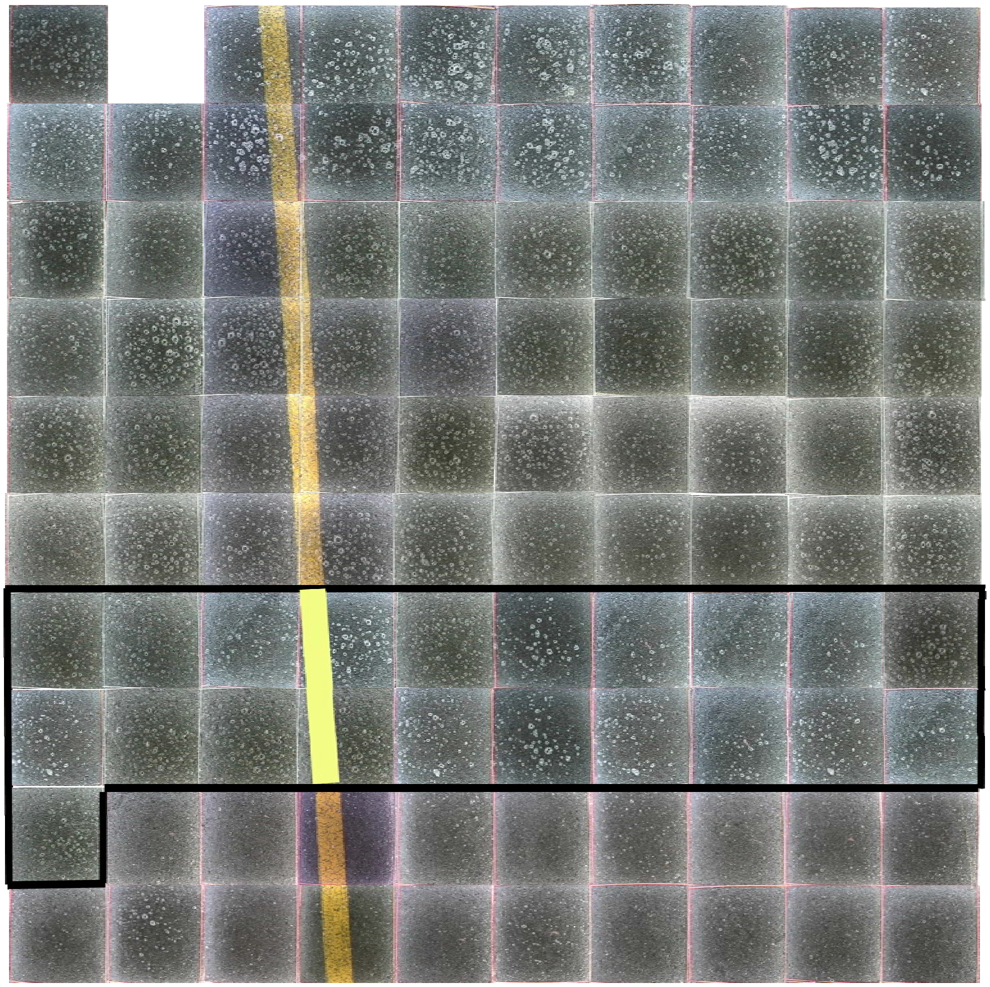
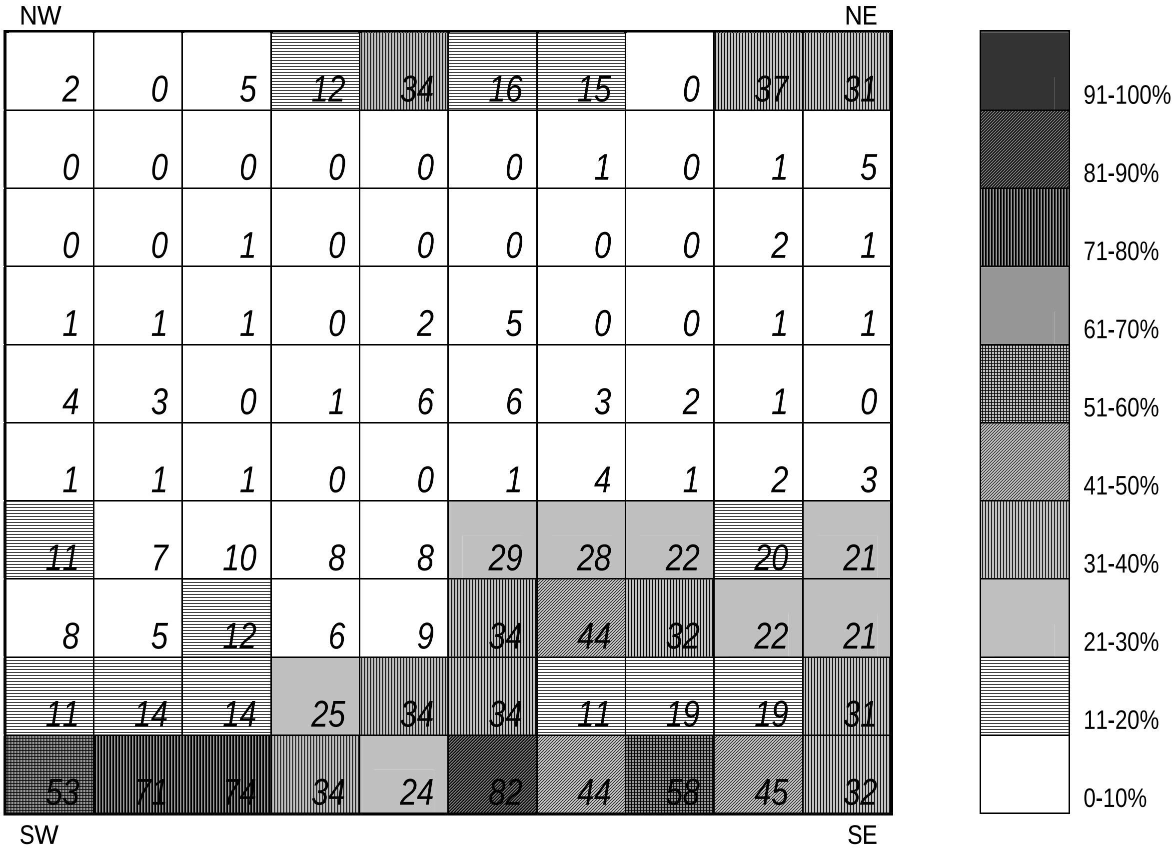


Figure 20. Photo map of PKLT site

After analyzing the bubble patterns in each of the squares, the percent permeability was calculated for all 100 squares, and a data map for each site was developed as shown in Figures 21 - 23. In these figures, the data was represented graphically, and the squares were shaded according to percent permeability such that the darker shades represent greater permeability. The numerical value in each square corresponds to the percent of the area containing permeable voids.



NW NE

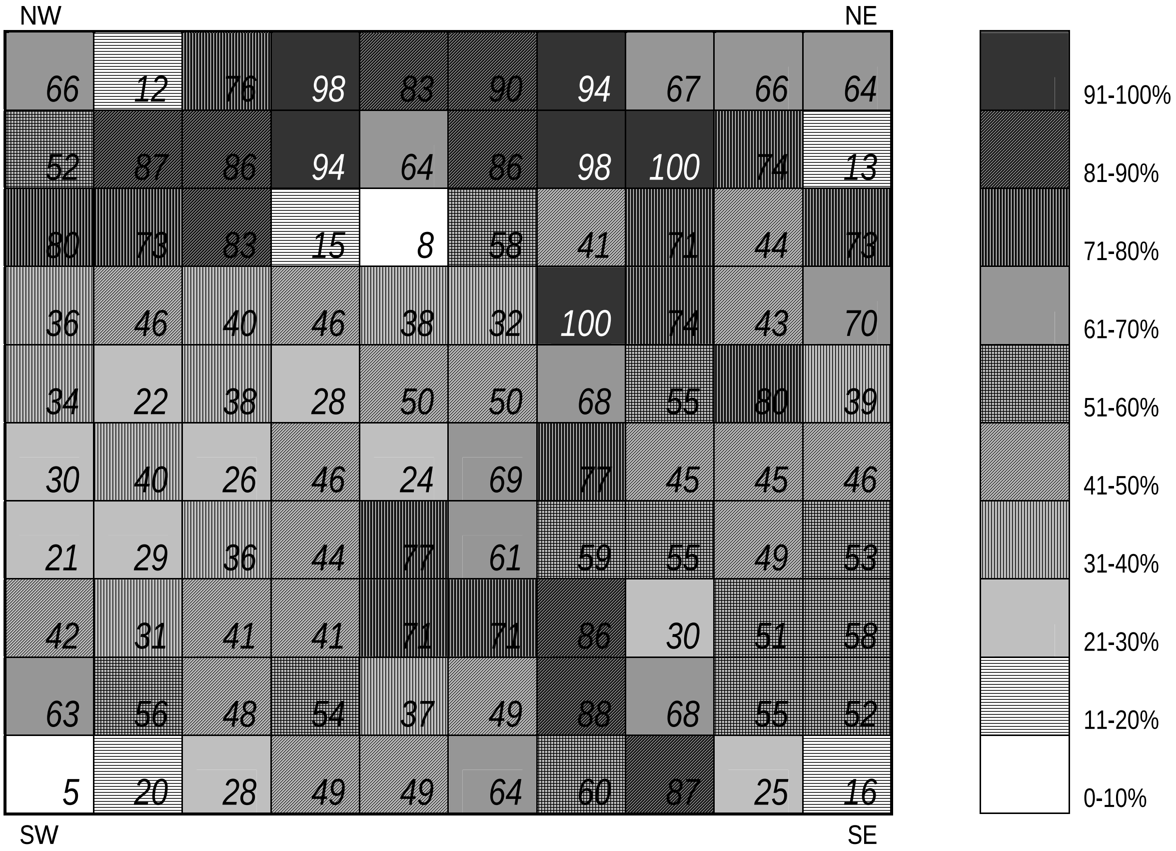
2	0	5	12	34	16	15	0	37	31
0	0	0	0	0	0	1	0	1	5
0	0	1	0	0	0	0	0	2	1
1	1	1	0	2	5	0	0	1	1
4	3	0	1	6	6	3	2	1	0
1	1	1	0	0	1	4	1	2	3
11	7	10	8	8	29	28	22	20	21
8	5	12	6	9	34	44	32	22	21
11	14	14	25	34	34	11	19	19	31
53	71	74	34	24	82	44	58	45	32

SW SE

91-100%
81-90%
71-80%
61-70%
51-60%
41-50%
31-40%
21-30%
11-20%
0-10%

Figure 21. Data map of LVST site

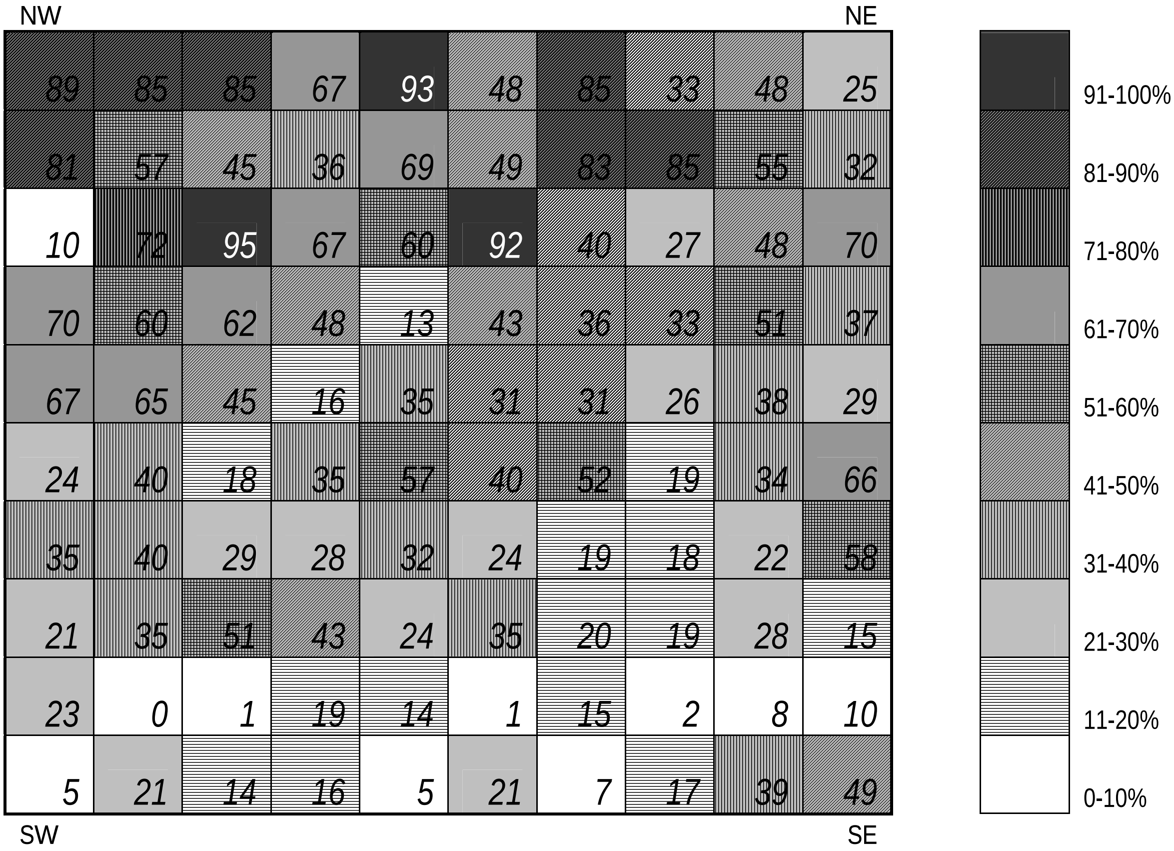
At the LVST site, traffic moves from west to east. From this graphical representation, it is evident that the central portion of the lane was less permeable. This is logical since vehicle traffic aids in further densification of the mat, thereby reducing permeability. The areas at the edges of the traveled path and near the curbs have greater levels of permeability. Since these areas have experienced less traffic, they are probably also less dense.



66	12	76	98	83	90	94	67	66	64
52	87	86	94	64	86	98	100	74	13
80	73	83	15	8	58	41	71	44	73
36	46	40	46	38	32	100	74	43	70
34	22	38	28	50	50	68	55	80	39
30	40	26	46	24	69	77	45	45	46
21	29	36	44	77	61	59	55	49	53
42	31	41	41	71	71	86	30	51	58
63	56	48	54	37	49	88	68	55	52
5	20	28	49	49	64	60	87	25	16

Figure 22. Data map of LVSM site

In the LVSM data map, no significant patterns are evident, and the permeability seems to be fairly random. Vehicle traffic does not appear to have consolidated specific areas of the pavement. This is reasonable since this portion of the pavement experiences very low volumes of traffic.



89	85	85	67	93	48	85	33	48	25
81	57	45	36	69	49	83	85	55	32
10	72	95	67	60	92	40	27	48	70
70	60	62	48	13	43	36	33	51	37
67	65	45	16	35	31	31	26	38	29
24	40	18	35	57	40	52	19	34	66
35	40	29	28	32	24	19	18	22	58
21	35	51	43	24	35	20	19	28	15
23	0	1	19	14	1	15	2	8	10
5	21	14	16	5	21	7	17	39	49

Figure 23. Data map of PKLT site

At the PKLT site, permeability again seems to be fairly random. Somewhat higher permeability values are noted in the northwest portion of the site. Since a construction joint runs diagonally across that portion of the site, it is likely that less compaction was achieved on that side of the joint. Again, traffic patterns are random, which supports the lack of significant consolidation by traffic.

Test Methods

From each site, squares were randomly selected for testing according to the Kuss and NCAT permeameters. A summary of results is presented in Table 2. For the VACP method, the percent area containing permeable voids is reported; for the KSFP and NCAT methods, the coefficient of permeability is reported. Data maps and corresponding permeability values of the selected squares are presented in the Appendix.

Site	Square #	VACP (% area)	KSFP (x 10^{-5} cm/s)	NCAT (x 10^{-5} cm/s)
LVST	23	0.51	0.68	141.82
	29	1.53	1.02	4.75
	56	1.02	0.34	99.48
	83	13.78	0.51	63.87
	89	19.39	0.68	7.21
LVST Average		*7.25*	*0.64*	*63.43*
LVSM	34	46.43	0.00	34.42
	72	30.61	2.03	12.94
	85	36.73	25.08	33.62
LVSM Average		*37.92*	*9.04*	*27.00*
PKLT	14	36.22	2.54	109.61
	26	91.84	201.66	5051.57
	33	62.24	0.68	288.61
	83	0.51	31.69	129.51
	100	48.98	0.00	77.57
PKLT Average		*47.96*	*47.31*	*1131.37*

Table 2. Comparison of field permeability test methods

Based on the average values generated for each site, all three methods identified the PKLT site as having the greatest permeability. The KSFP and VACP ranked all three sites in the same order – the LVST site having the least permeability, the LVSM site having greater permeability, and the PKLT having the greatest permeability. According to the NCAT test, however, the LVSM site was the least permeable. Because the LVSM has experienced fewer traffic loadings, the KSFP and VACP rankings seem more logical

By inspection of the individual data points, it is apparent that the various test methods did not provide similar results. Due to the various testing configurations, it was anticipated that the different test methods would provide varying results. For example, the VACP method measures air permeability rather than water permeability. Also, the resulting data is expressed as a percentage of the area containing permeable voids rather than an actual coefficient of permeability. A coefficient of permeability is calculated for both the KSFP and NCAT methods, however one is a constant head test and the other is a falling head test. These methods have been previously reported to provide significantly different results. *(4, 25)* Although both methods are acceptable for testing permeability, they are both based on Darcy's law, which assumes uni-directional flow. This assumption is most likely violated for field permeability tests and thus, test results may be misleading.

To further consider the data and provide a fairer comparison of permeameter type, ranges of permeability were assigned for each method. These categories are shown in Table 3.

Permeability Category	VACP (% area)	KSFP (x 10^{-5} cm/s)	NCAT (x 10^{-5} cm/s)
Relatively Impermeable (I)	0 – 10	0 – 1	0 – 10
Low Permeability (L)	10 – 25	1 – 10	10 – 50
Moderate Permeability (M)	25 – 50	10 – 50	50 – 100
High Permeability (H)	50 – 100	> 50	> 100

Table 3. Permeability categories for three test methods

Using these categories, each selected square was assigned a permeability ranking. The rankings are presented in Table 4. According to the VACP and KSFP tests, the LVST site was relatively impermeable. The LVSM site was moderately permeable, although the KSFP indicated significant variability. The PKLT site was also variable, and had the greatest permeability of the sites. According to the NCAT test, the LVST was the most variable site, and overall exhibited moderate permeability.

Site	Square #	VACP	KSFP	NCAT
LVST	23	I	I	I
	29	I	L	I
	56	I	I	M
	83	L	I	M
	89	L	I	H
LVSM	34	M	I	L
	72	M	L	L
	85	M	M	L
PKLT	14	M	L	H
	26	H	H	H
	33	H	I	H
	83	I	M	H
	100	M	I	M

Table 4. Comparison of selected squares based on permeability category

Although it was anticipated that the three methods would not provide similar results, it was expected that they would at least provide similar *trends* in permeability. However, this was not true in all cases. For instance, LSVT#23 appeared to have high permeability according to the NCAT method, but low permeability by the KSFP and VACP methods. Since the falling head test begins with a greater initial head, water could flow faster (i.e., generate higher permeability values) in the NCAT method. So when an NCAT test provided greater permeability values than the corresponding KSFP test, the difference in the testing configuration could logically account for the difference. The VACP test indicated that LSVT#23 was relatively impermeable. Since asphalt mixes are more permeable to air than to water, the VACP test would be expected to provide the greatest values. A similar situation was noted for PKLT#83. This phenomenon can occur when a single large void (or small area of large voids) exists in the testing area, constituting a very small percent area of permeability, but allowing a significant amount of water flow.

A paired t-test was performed as a means to statistically describe the data. For this analysis, only the KSFP and NCAT methods could be compared since they generate permeability values in the same units. The results of this test indicated that there was no statistically significant difference between the two methods. However, practical differences obviously existed. The large amount of variability in the data was blamed for this result, making the results of the statistical test inconclusive.

When measuring field permeability, careful consideration must be given to the type of permeability test that is being performed, exactly what is being measured, and what that measurement actually means. The NCAT field permeameter is a falling head test that measures the quantity of water that flows through the pavement during a period of time. Based on this information alone, a relative measure of permeability can be obtained. However, using this information to calculate a coefficient of permeability may not be prudent, because in many cases, the underlying assumptions of Darcy's law are probably violated. The falling head test begins with a column of water that creates downward pressure on the pavement, which essentially "forces" water through the pavement.

When the Kuss field permeameter is used, a constant head test is used to quantify the permeability. Again, the quantity of water that flows through the pavement during a period of time is determined, and this information is useful as a relative measure of permeability. Approximately one inch of water is maintained across the surface of the sample, so less force is applied to push the water through the pavement. Therefore, the KSFP test may provide smaller values of permeability. This concept is consistent with the fact that, in general, the NCAT method generated higher coefficients of permeability than the KSFP method – especially at higher levels of permeability. As with the NCAT method, the assumptions of Darcy's law are likely to be violated. Thus, the actual resulting coefficient of permeability from the KSFP method is suspect.

The vacuum permeameter is also a way to characterize the interconnected void spaces in a pavement, but is based on a very different concept. Air, rather than water, is used as the flowable element, and this element is pulled through the pavement from the bottom rather than being forced through from the top. Pavements have been demonstrated to be more permeable to air than to water, but since both elements can have harmful effects, it is important to measure both. This means, though, that air permeability is not necessarily an indication of water permeability, and thus, measurements from the various methods are not likely to correlate.

Overall, the simple theory behind the VACP test method gives it the potential to be the most realistic determination of permeable voids. Therefore, it was taken to be the "true" value. While there are obviously many reasons for the various test methods to provide differing values for permeability, it is still evident that a significant correlation between the methods is lacking.

Another comparison that can be made with the data generated in this portion of the project is an evaluation of permeability before and after traffic loadings have been applied. Because the median area had experienced minimal traffic, it was assumed that the LVSM site represented a new pavement. The LVST site represented the pavement after traffic loadings had been applied. The data maps for these sites clearly demonstrate the potential of traffic to reduce the permeability of a pavement.

Pavement Density and NMAS

In order to investigate the effects of pavement density and nominal maximum aggregate size, three sites were tested during the construction of a new pavement (BASE, BIND, SURF). The three sites had the exact same physical location, but were performed on the different layers of the pavement. Cores were cut from selected squares of each layer in order to determine a measure of pavement density. This testing site is shown in Figure 24.

Figure 24. Testing setup at BASE, BIND, SURF sites

Each layer was mapped using the VACP test, and the resulting photo maps are presented in Figures 25 - 27. The corresponding data maps are given in Figures 28 - 30, which provide the percent permeability for each test square.

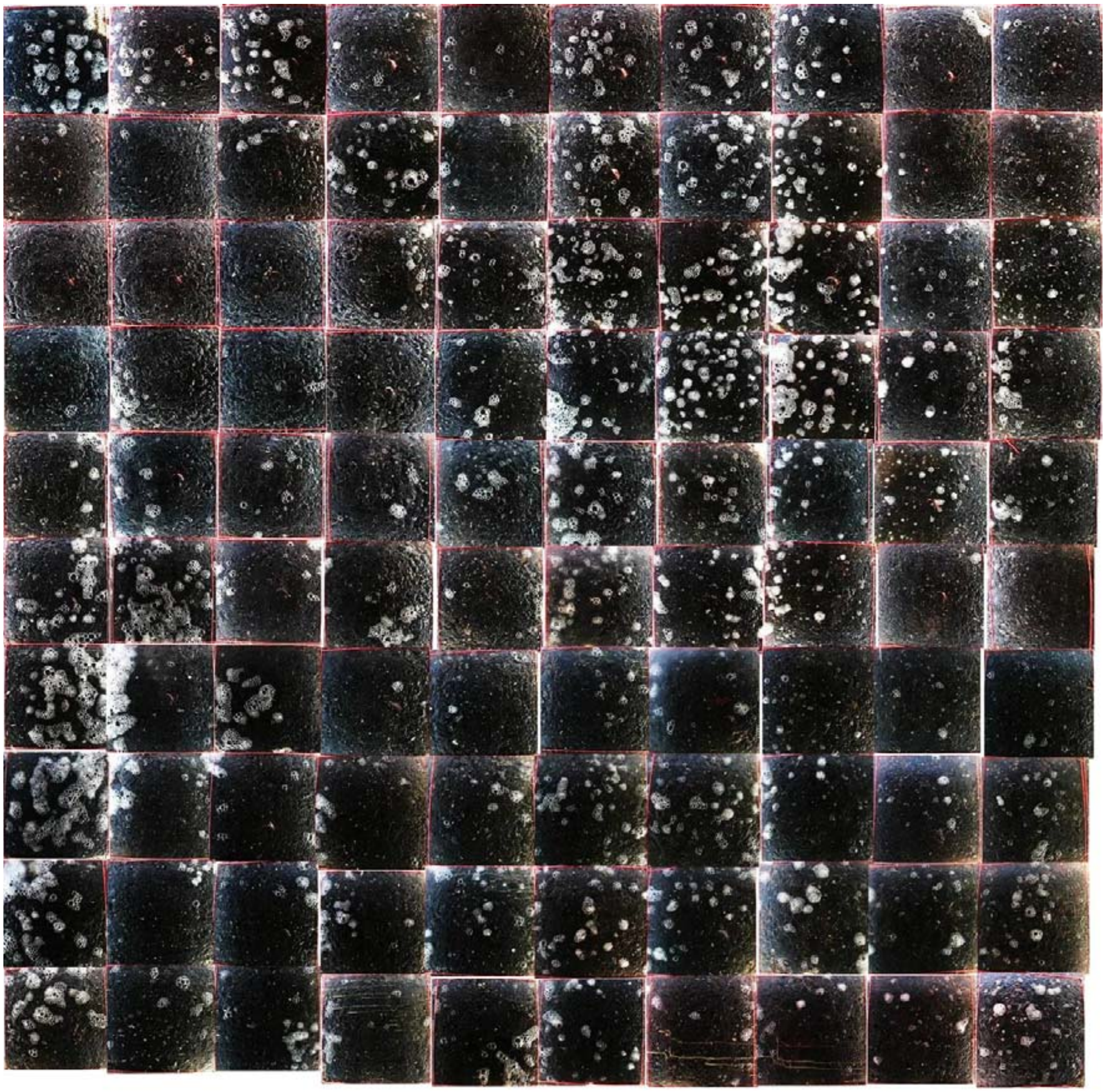


Figure 25. Photo map of BASE site

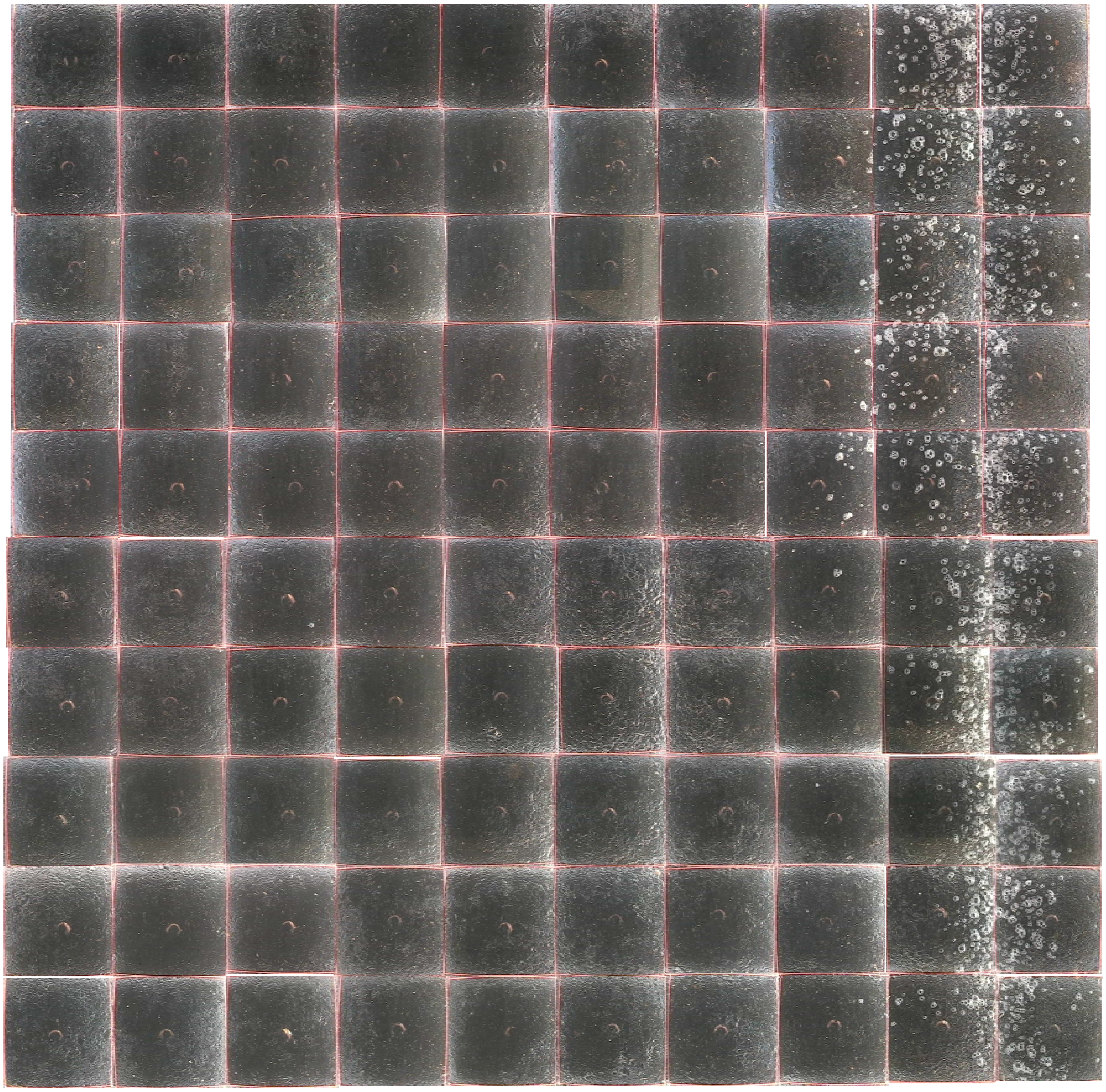


Figure 26. Photo map of BIND site

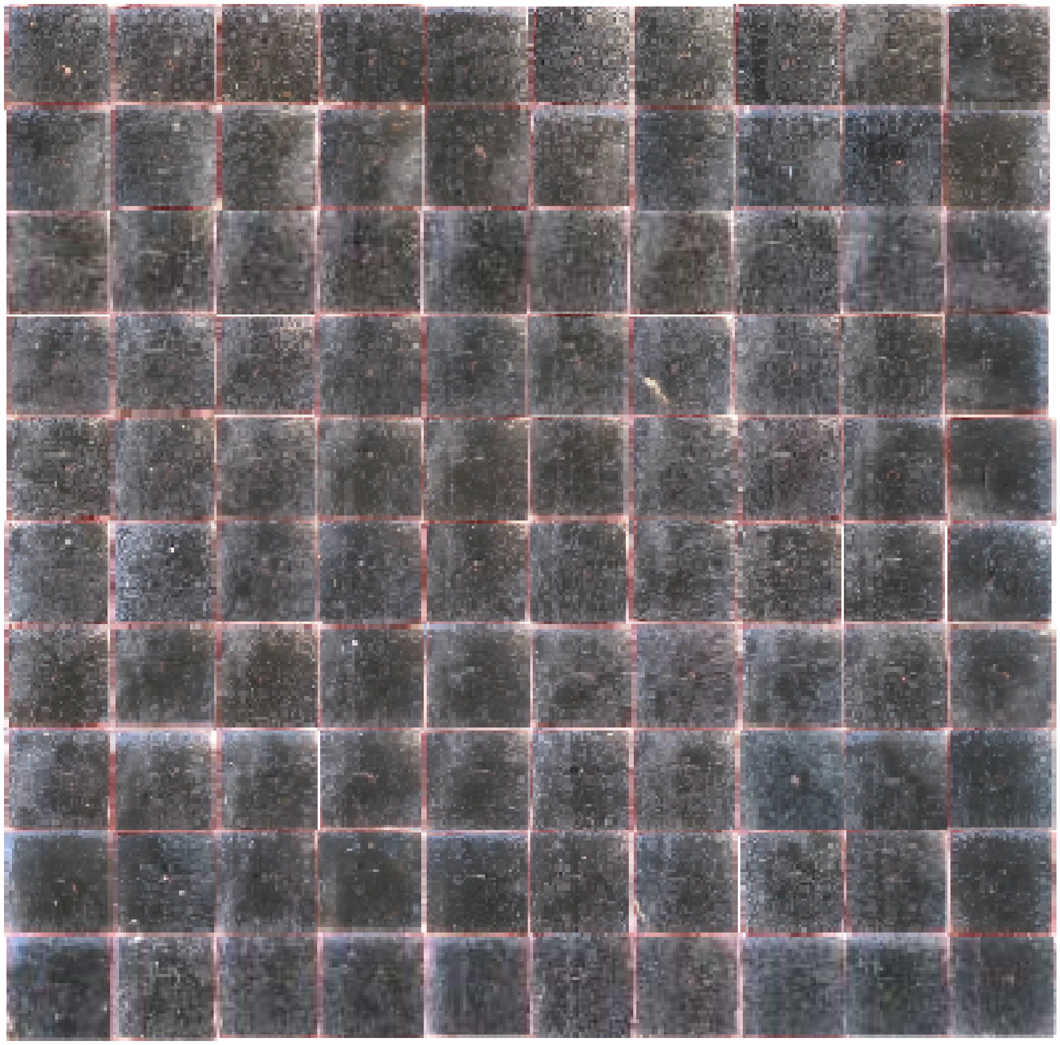
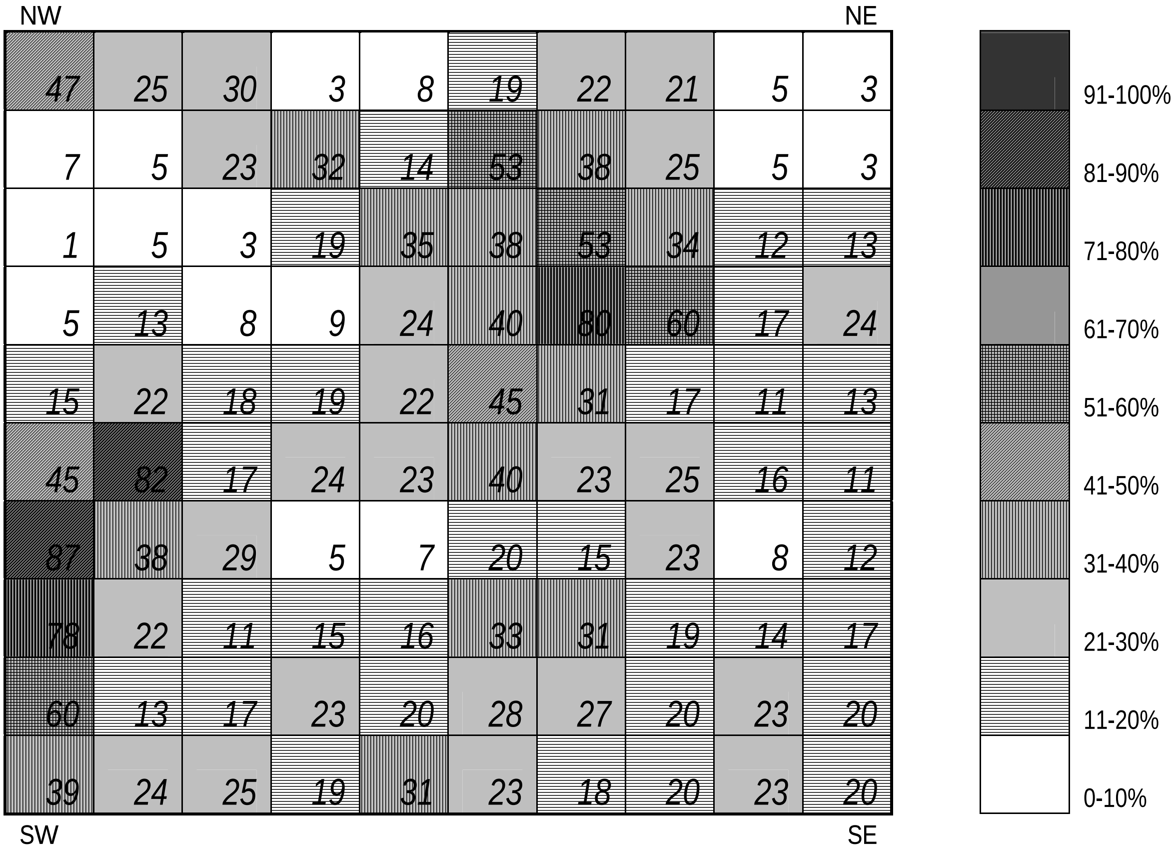
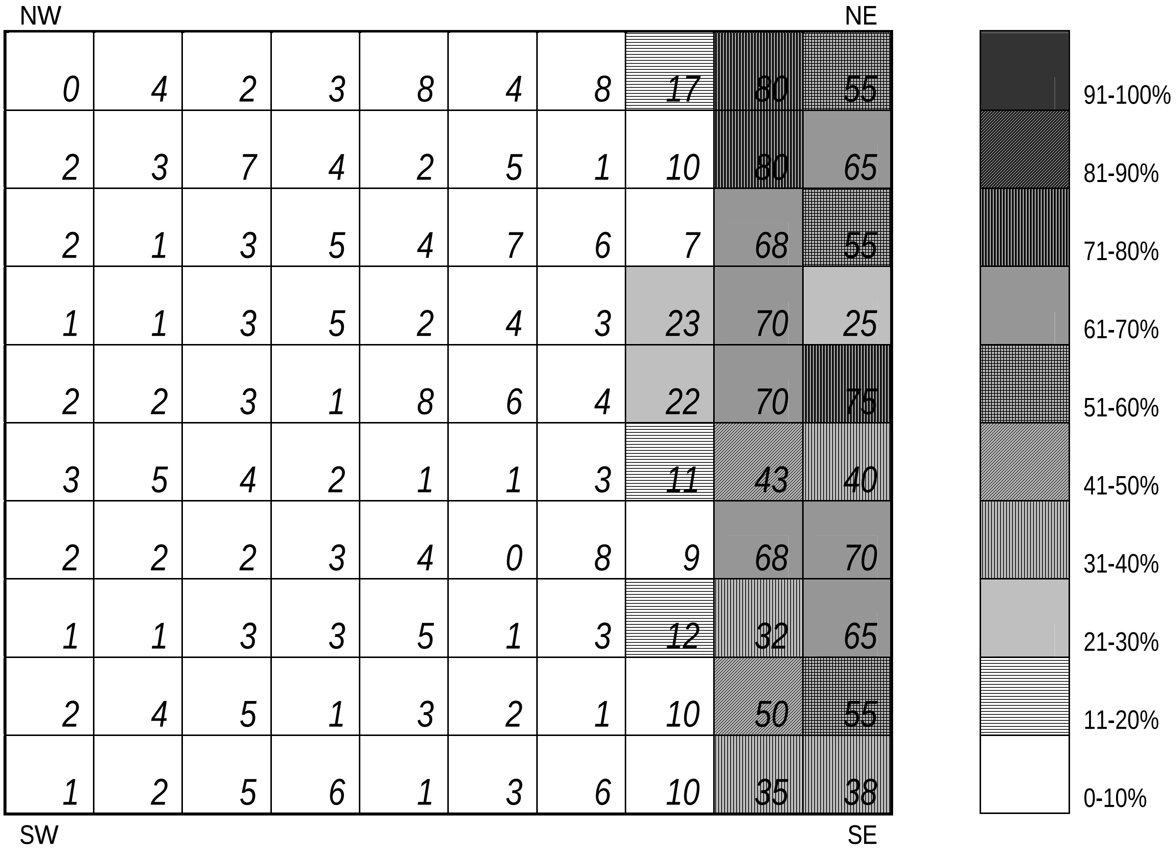


Figure 27. Photo map of SURF site



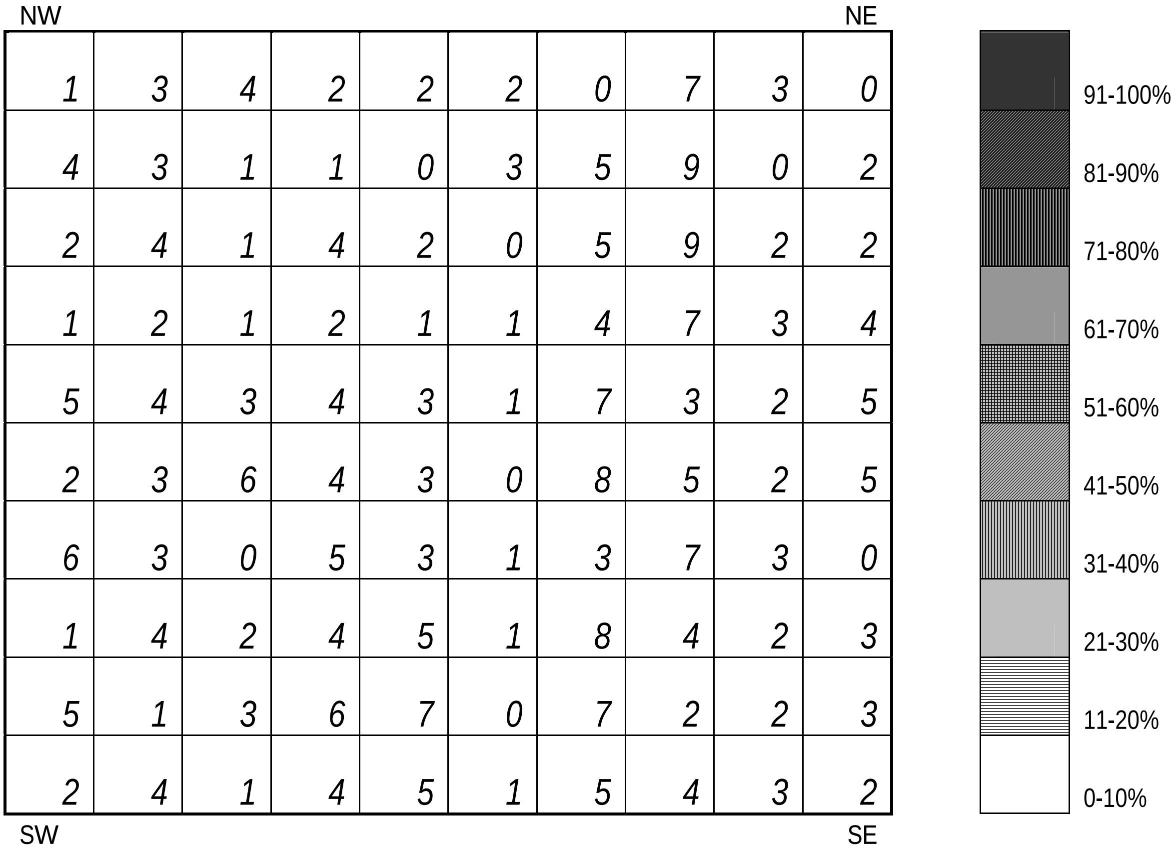
47	25	30	3	8	19	22	21	5	3
7	5	23	32	14	53	38	25	5	3
1	5	3	19	35	38	53	34	12	13
5	13	8	9	24	40	80	60	17	24
15	22	18	19	22	45	31	17	11	13
45	82	17	24	23	40	23	25	16	11
87	38	29	5	7	20	15	23	8	12
78	22	11	15	16	33	31	19	14	17
60	13	17	23	20	28	27	20	23	20
39	24	25	19	31	23	18	20	23	20

Figure 28. Data map of BASE site



0	4	2	3	8	4	8	17	80	55
2	3	7	4	2	5	1	10	80	65
2	1	3	5	4	7	6	7	68	55
1	1	3	5	2	4	3	23	70	25
2	2	3	1	8	6	4	22	70	75
3	5	4	2	1	1	3	11	43	40
2	2	2	3	4	0	8	9	68	70
1	1	3	3	5	1	3	12	32	65
2	4	5	1	3	2	1	10	50	55
1	2	5	6	1	3	6	10	35	38

Figure 29. Data map of BIND site



1	3	4	2	2	2	0	7	3	0
4	3	1	1	0	3	5	9	0	2
2	4	1	4	2	0	5	9	2	2
1	2	1	2	1	1	4	7	3	4
5	4	3	4	3	1	7	3	2	5
2	3	6	4	3	0	8	5	2	5
6	3	0	5	3	1	3	7	3	0
1	4	2	4	5	1	8	4	2	3
5	1	3	6	7	0	7	2	2	3
2	4	1	4	5	1	5	4	3	2

Figure 30. Data map of SURF site

Of the three layers, the 37.5mm Superpave base layer appears to have the greatest overall permeability, and the 12.5mm Superpave surface layer appears to be the least permeable. The 25.0mm Superpave binder layer is interesting in that the longitudinal joint is very evident, both in the photo map and the data map. The other areas of the binder layer appear to be relatively impermeable. The base layer exhibits the greatest amount of variability, and the surface layer is very consistent, even in the location of the longitudinal joint. One interesting discovery during testing was that a portion in the northwest area of the BASE site displayed significant segregation. However the level of permeability exhibited in this location was minimal. Test square

BASE#22, which was in the segregated area, is shown in Figure 31. Based on this finding, it was determined that it is possible for segregation to occur in only the upper portion of the layer, and may not exist in throughout its full depth. KSFP and NCAT tests were attempted on this square (BASE#22), but due to the extremely coarse and segregated nature of the mat, an adequate seal could not be obtained for either device.

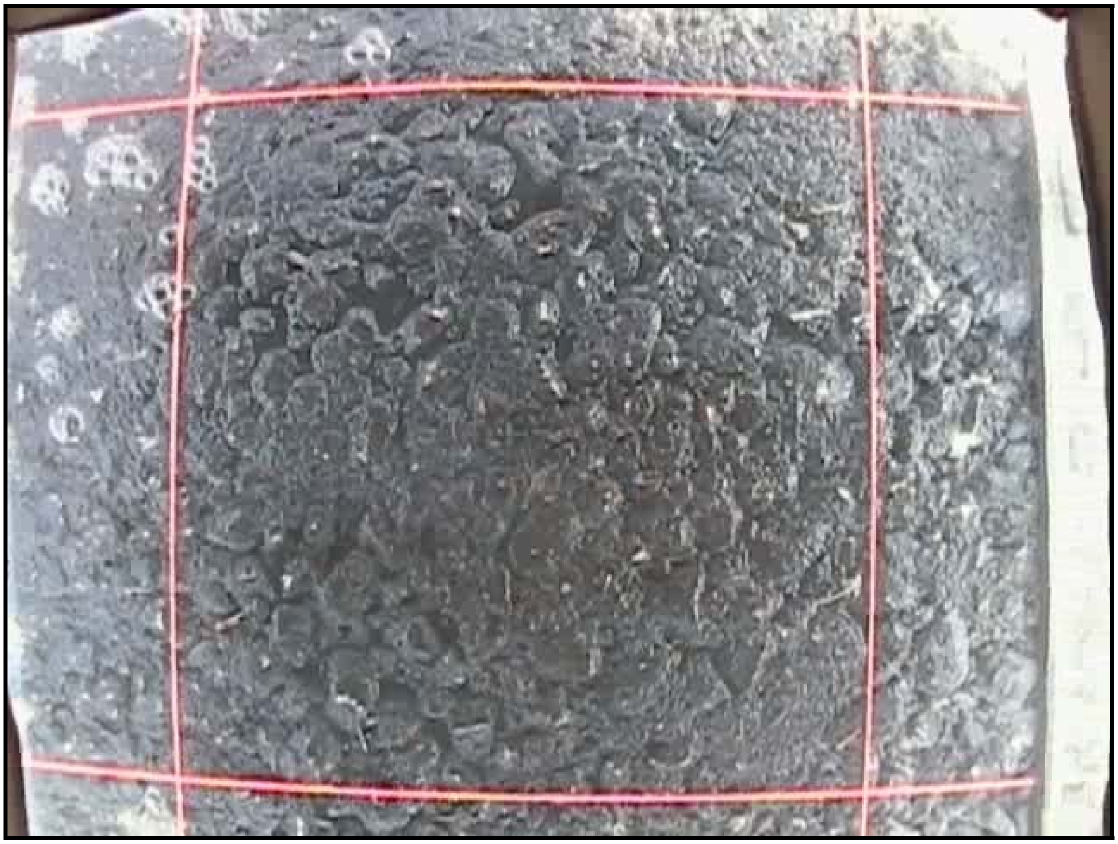


Figure 31. Photo of test square BASE#22

In order to characterize the relationship between VACP test results and pavement density, field cores were tested from each layer. Three cores were cut from the base and binder layer after the binder layer was placed. One core was cut from square #23, which was relatively impermeable in both layers. Cores were also cut from squares #19 and #90, which were both near the longitudinal joint of the binder layer. Mix layers were separated by sawing before density determinations were made. From the surface layer, two cores were cut, one from the central portion of the mat (square #54) and one near the longitudinal joint (square #27). VACP results and corresponding densities are reported in Table 5.

Site	Square #	VCAP Permeability (%)	Density (%)
BASE	19	5	95.0
	23	3	94.4
	90	20	95.8
BIND	19	80	92.3
	23	3	98.0
	90	55	91.0
SURF	27	5	88.2
	54	4	94.4

Table 5. Summary of density and permeability data for three test sites

Of the three layers, the base layer exhibited the most overall variability in permeability values as determined by the VACP method. Even so, the field core densities were relatively consistent for the squares tested (a range of 1.4 percent), and easily met the specification limits, which require a minimum of 92 percent density. *(30)* Thus, permeable voids may exist for this mix even when the density specification is met.

Although there was a longitudinal joint in this test site, excessive permeability at the joint was not evident. Thus, it was concluded that either the overall permeability was similar to that at the joint, or the variability of the site was able to disguise the presence of the joint.

For the binder layer, excessive permeability was shown to exist near the longitudinal joint, but the remainder of the test site was relatively impermeable. The core cut from square #23 (away from the joint) had high density and low permeability. In fact, the density actually exceeded the maximum value of 96 percent. On the other hand, the cores taken from near the joint were less dense. One met the minimum specification and one did not, but both appeared excessively permeable. This data supports the conclusion that pavements having low or marginal density may be susceptible to high permeability, even when the minimum specification for density is met.

Results from the surface layer are interesting. One core was cut near the longitudinal joint (square #27) and one was not (square #54). The one near the joint had a much lower density than the other. However, both were relatively impermeable by the VACP test. The KSFP test was also performed for each of these squares. Square #27 was extremely permeable. In fact, the water ran through the standpipe so quickly that an actual flow reading could not be obtained. Square #54 was completely impermeable. Upon close inspection of the VACP data map for Square #28 (shown in Figure 32), it was determined that permeability did exist, but was limited to a very small portion of the testing area – just along the longitudinal joint. Thus, it is entirely possible that these voids, while limited in area, could allow a large amount of water to enter the pavement.

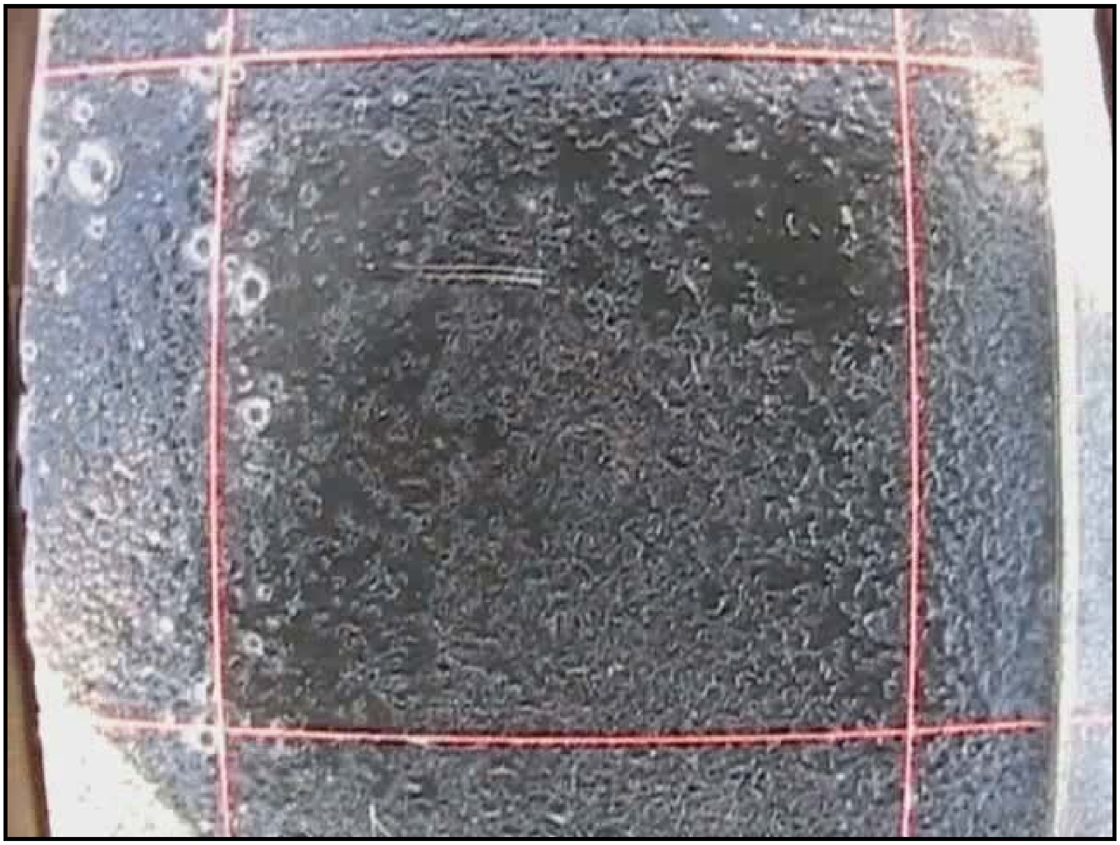


Figure 32. Photo of test square SURF#28

A final site (SHWY) was tested according to the VACP method. Testing this pavement provided a measure of permeability for a moderately high-volume roadway that had been in service for approximately three years. The photo map and data map are presented in Figures 33 and 34, respectively.

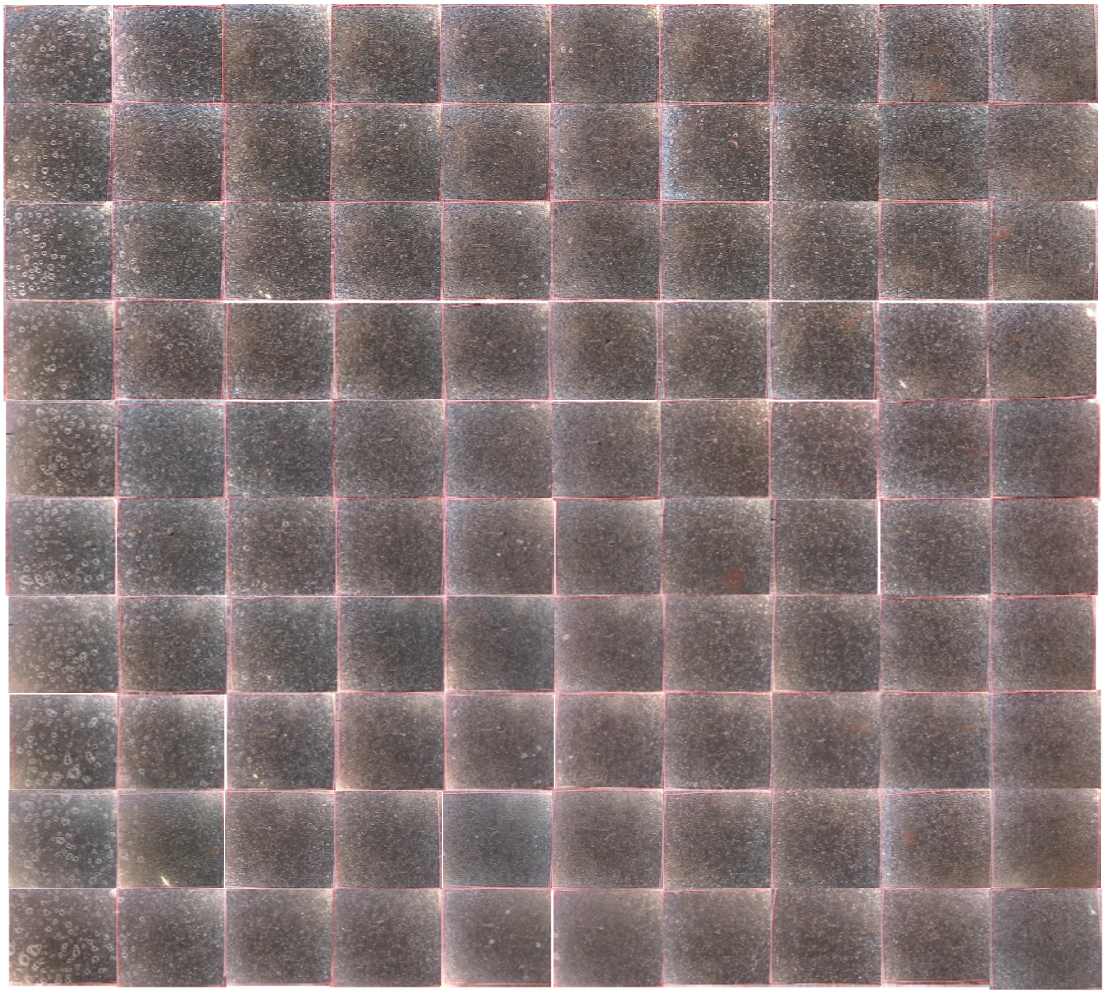
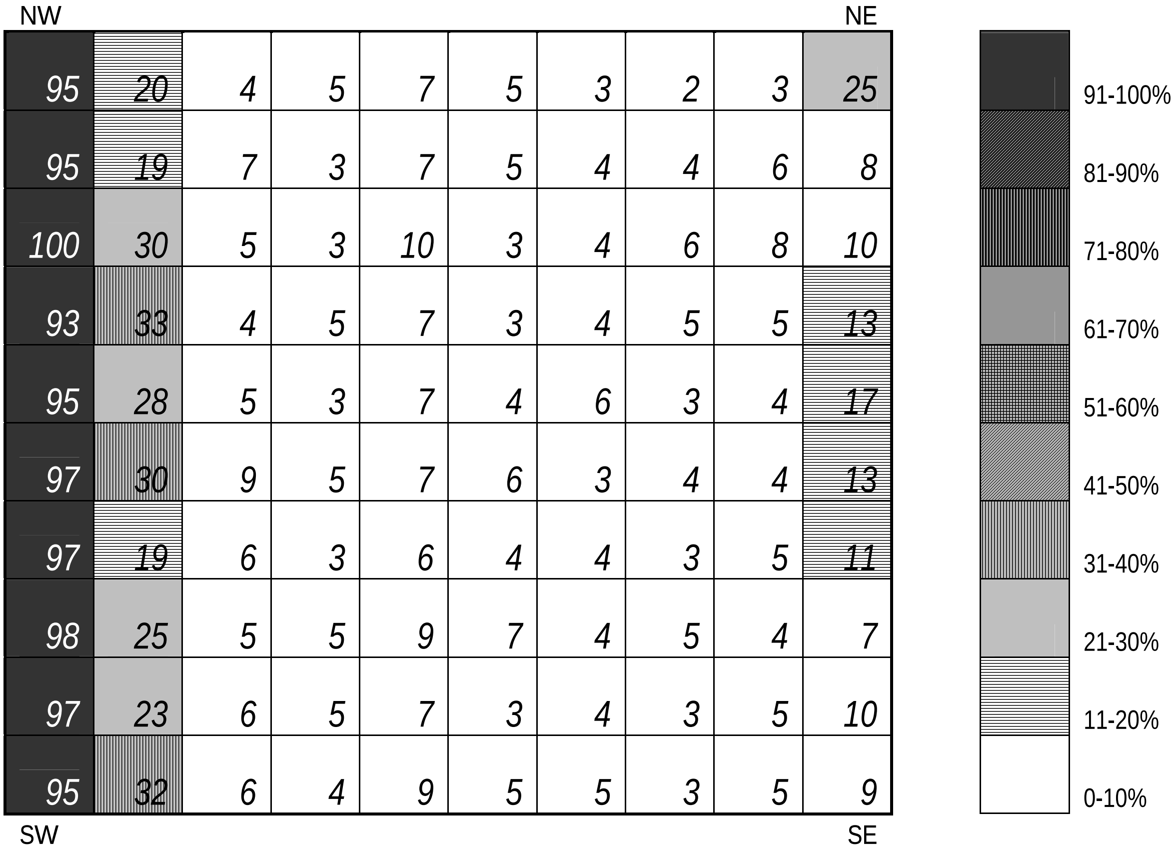


Figure 33. Photo map of SHWY site



95	20	4	5	7	5	3	2	3	25
95	19	7	3	7	5	4	4	6	8
100	30	5	3	10	3	4	6	8	10
93	33	4	5	7	3	4	5	5	13
95	28	5	3	7	4	6	3	4	17
97	30	9	5	7	6	3	4	4	13
97	19	6	3	6	4	4	3	5	11
98	25	5	5	9	7	4	5	4	7
97	23	6	5	7	3	4	3	5	10
95	32	6	4	9	5	5	3	5	9

Figure 34. Data map of SHWY site

Limited testing was performed at this site using the KSFP and NCAT devices. The test results are presented in Table 6. Test squares #1, #6, and #20 were chosen for testing. KSFP results were obtained for all three squares, but an NCAT result was obtained only for square #1.

Site	Square #	VACP (% area)	KSFP (x 10^{-5} cm/s)	NCAT (x 10^{-5} cm/s)
SHWY	1	95	32.4	576.0
	6	5	0.0	NA
	20	8	13.9	NA
SHWY Average		*36*	*15.4*	*NA*

Table 6. Summary of field permeability results for the SHWY site

Square #1 was located very near the curb at the outer edge of the pavement. This square exhibited moderate to high levels of permeability, depending on the test method considered. Square #6 was positioned in the central portion of the traveled way, and was judged to be relatively impermeable by both the VACP and KSFP methods. Square #20 was located at the other edge of the test site and was approximately 8 inches from the longitudinal lane joint. This site was relatively impermeable according to the VACP test, and exhibited low permeability according to the KSFP method. Overall, the results from this site indicate that permeability is very low in the traveled way, slightly higher at the lane joint, and very high at the curb.

If any significant permeability had been present at the time of construction, the consolidating effects of three years of traffic had eliminated it from the central portion of the lane. It has been reported that permeability should only be considered for new pavements because after approximately one year in service, permeability is no longer a problem. *(31)* Based on the SHWY test site results, this conclusion can only be considered to be true for the vehicle pathway.

Variability

One of the most informative features of the vacuum permeability test is the ability to completely characterize the locations of permeability within a pavement section. The greatest difference in the VACP method and the others is that no quantity of flow through a pavement is measured. Only the *locations* of the permeable voids are indicated. Thus, there is no actual measurement of true permeability – just the percent of the test area containing permeable voids. A small area of very large voids can generate large permeability and a small percent permeable area. This is demonstrated in test square LVST#23. Conversely, a large percent of the area could contain very small voids that are permeable only to air. In this case, the VACP test result would indicate a high level of permeability while another test type would not. Thus, the size of the void space is critical to its permeability, yet none of the methods used in this project have the capability to measure the size of individual void pathways. Initially, it was believed that larger bubbles represented larger voids; however, the size of the bubble is dependent on its surface tension, which may not be consistent. Therefore, this assumption could not be verified.

Based on the situations previously discussed, it is clear that the placement of the permeameter is critical to the detection of permeability, especially for variable pavements. Thus, the information gained from the VACP test is critical in determining sample size appropriate for detecting true permeability with a high level of confidence. Since all pavements cannot be tested by a complete mapping process, an appropriate number of sample tests should be tested. In general, more void spaces indicate more potential permeability. But more importantly, a greater number of void spaces increases the likelihood of detecting those voids. Also, the arrangement of voids is important. If many voids are present, but are generally positioned in clusters, there is a greater likelihood that the sample test area will not encompass a cluster. Thus, a measure of variability (expressed in this project as standard deviation) of these locations is also important.

The larger the sample test area, the more likely a test method is to detect permeability. The test area for the KSFP method is 1264.5 cm2, and that of the NCAT method is 214 cm2, which is just 16.9 percent of that for the KSFP. Thus, the KSFP method is over five times more likely to detect locations of permeability. Also, depending on the arrangement of the void pathways, there is a chance that if the permeable area of a square is less than 80 percent, the NCAT permeameter will not detect it. Based on the data at the BASE site, the probability of a square exhibiting less than 80 percent permeability is more than 95 percent. This situation describes the "worst case" scenario. However, as the variability of permeable voids increases, the likelihood of experiencing this situation also increases.

In several field permeability studies found in the literature, tests were taken at locations that were a specified distance from the edge of the pavement. *(16, 22, 23)* By "lining up" the testing positions, the resulting permeability values were expected to be more consistent. This purposeful restriction on randomization was beneficial for evaluating various types of field permeameters, but created bias in the characterization of the pavement's permeability. If a field permeameter is to be used to describe the acceptability of a pavement, then the variability across the width of the pavement must be considered. Also, if a field permeameter is to be considered for use as a quality control tool, an appropriate sampling frequency must be determined.

The vacuum permeameter data was used to describe the variability of permeability within each pavement section. Summary data, including the mean percentage of permeable area, standard deviation, and coefficient of variation at each site, is presented in Table 7.

Site	Mean (%)	Standard Deviation	Coefficient of Variation(%)
LVST	13.1	17.86	136.4
LVSM	54.71	23.61	43.15
PKLT	39.26	24.02	61.18
BASE	23.93	17.25	72.07
BIND	14.95	22.66	151.6
SURF	3.16	2.16	68.32
SHWY	16.91	27.46	162.4

Table 7. Comparison of field permeability test methods

Overall, the variability of permeability within a test area was extremely large – the coefficient of variation was greater than 100 percent in several cases. This indicates that a large sample size would likely be necessary to adequately describe the permeability of a pavement section. It also supports the claim that field permeability is extremely dependent upon the placement of the testing device.

In order to use field permeability as an accurate assessment of pavement quality, an adequate sample size must be obtained so that the pavement is properly represented. Sample size is dependent upon the variability of the pavement. If a pavement is consistently impermeable, a very small sample size would be adequate for this determination. Likewise, if a pavement is consistently permeable, a very small sample size would be adequate for conveying this information with confidence. However, a pavement that contains areas of both high permeability and low permeability (i.e., a high level of variability) would require a larger sample size in order to characterize this property with confidence.

For most applications, the identification of very good or very bad materials is relatively simple. It is the accurate identification of marginal materials that is most difficult, and at the same time most critical. When considering permeability, the relationship between permeability and pavement density has been firmly established. *(9, 10, 11, 12, 14, 22, 24, 26, 29, 31)* In general, pavements that fail the field density specifications are likely to have high permeability. Thus, the existing density specification is adequate for identifying these problems. For pavements that are clearly compacted well within the required density specification (i.e., greater than approximately 95 percent density), permeability levels are likely to be low. It is the intermediate portion of the permeability / density relationship (92 to 95 percent density) that is less informative.

It is quite possible that a pavement could narrowly satisfy the density requirement, yet still experience high levels of permeability. This situation was demonstrated for the BIND site. In such a case, the density specification could fail to prevent an excessively permeable pavement. Since factors other than density also affect permeability, some additional measure of quality would be necessary for the identification of permeability in pavements of marginal density. Also, pavements of marginal density may be more sensitive to variability. Thus, the detection of excessive permeability in variable pavements with marginal density is most critical.

Based on the VACP test results, it was determined that several of the pavements included in this study exhibited significant variability. Therefore, the number of samples required to adequately characterize the permeability of a pavement was investigated. For each site, the dataset resulting from the entire map (100 data points) was considered to be the population, and the probability of correctly determining the percent permeability, within a range, was calculated for a series of standard deviations. This probability represents the reliability of the test. Based on the variability data obtained from the seven sites, the range of standard deviation included in the calculations was 1 to 40. A 95 percent level of significance was used in all cases.

Another point of consideration is the discrimination of the test, or the range of error that would be considered acceptable. For instance, a range (δ) of 10 percentage points would mean that "missing" the actual permeability value by 10 percent would be considered acceptable. Based on the permeability ranges previously stated for the VACP test, sample size relationships were established for three ranges (10, 20, and 30 percent). These relationships are given in Figures 35 - 37.

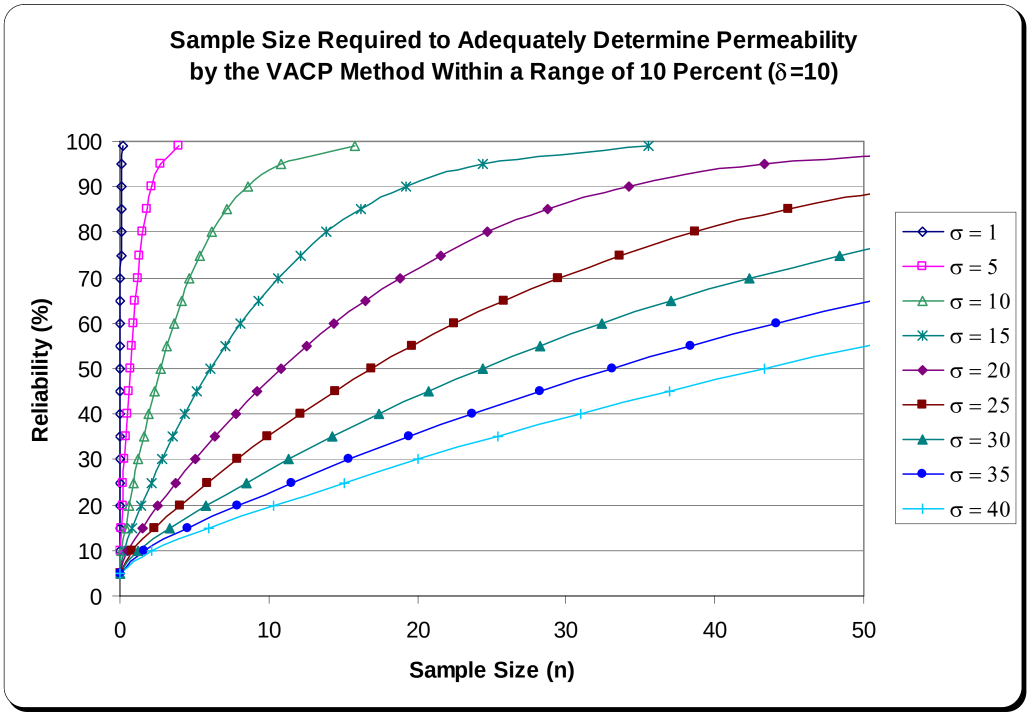


Figure 35. Reliability and sample size relationship for VPAC (δ=10)

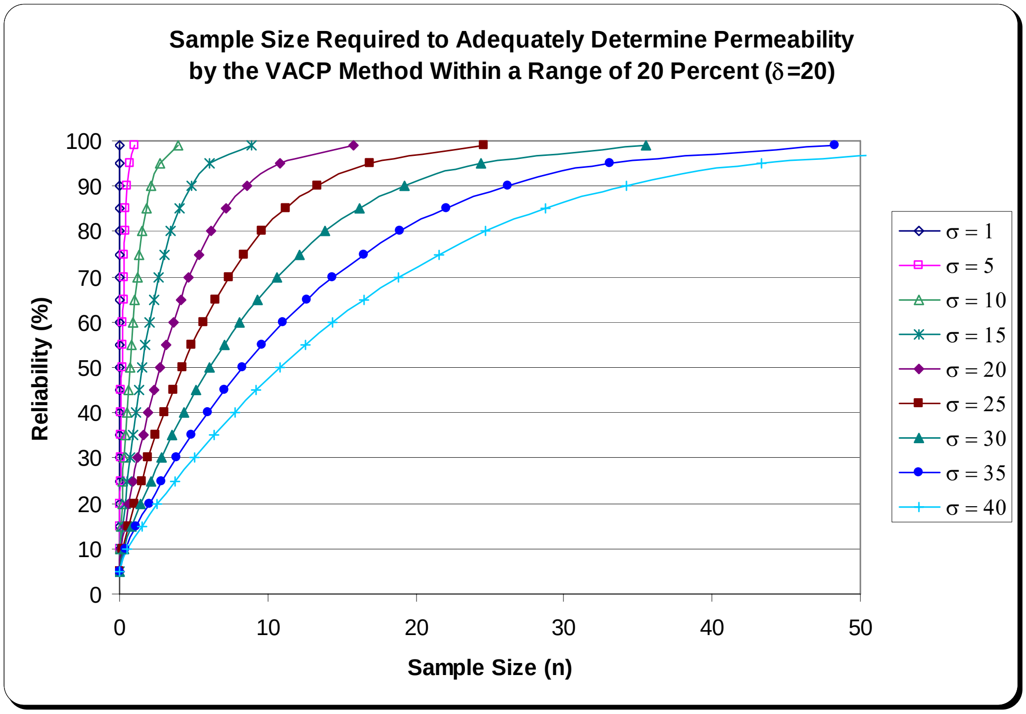


Figure 36. Reliability and sample size relationship for VPAC (δ=20)

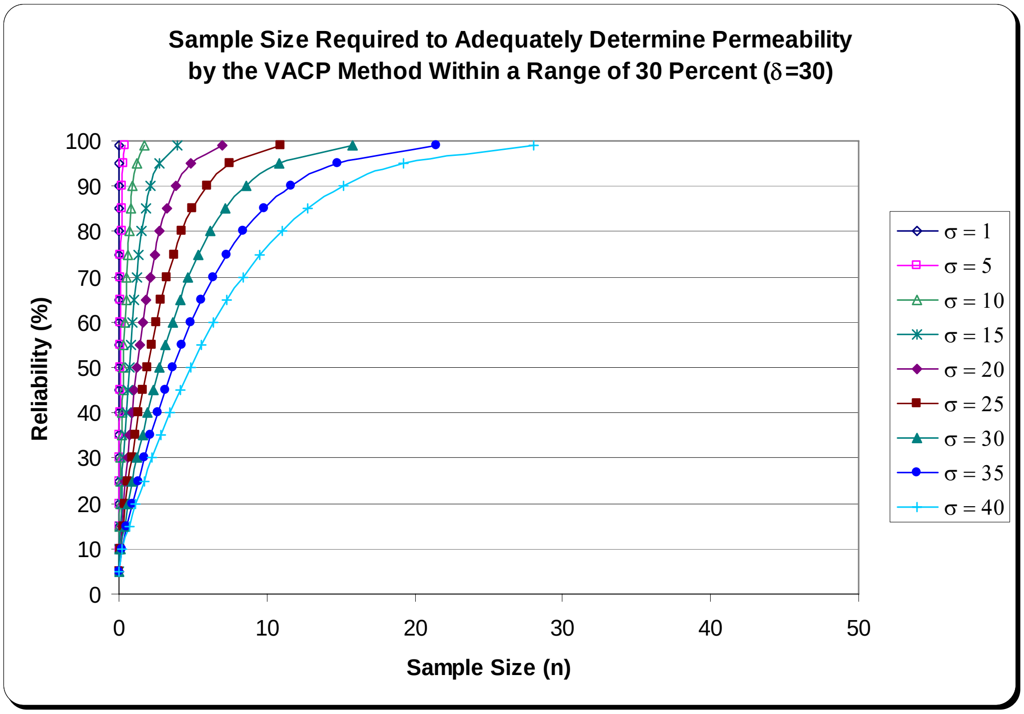


Figure 37. Reliability and sample size relationship for VPAC (δ=30)

The required sample size increases as testing discrimination and reliability improve. Also, as the variability of the pavement increases, the required sample size increases. For the BASE site, the standard deviation was 17.25. Thus, for a testing discrimination of 10 percent and a reliability of 90 percent, the required sample size is approximately 25. Since the spans of percent permeability for the categories of low and moderate permeability for the VACP test were 15 and 25 percent, respectively, a discrimination of 20 percent could be reasonably tolerated. For a discrimination of 20 percent and a reliability of 90 percent, the required sample size is approximately 7. If a discrimination of 10 was desired, but a reliability of 80 percent was acceptable, the required sample size would be slightly less than 20. In general, reducing the discrimination of the test decreases the required sample size more quickly than reducing the reliability.

Based on the measures of variability determined at each site, required sample sizes were calculated for 4 combinations of testing discrimination (δ) and reliability (R). The results are shown in Table 8. For very consistent pavements, very small sample sizes are necessary. In several cases, a sample size of 1 is adequate. For variable pavements, much larger sample sizes are required. Because the sample size depends greatly on standard deviation, this parameter was considered further. For two of the test sites (BIND and SHWY), the standard deviations were relatively large, however much of the measured variability could be attributed to the presence of a longitudinal joint. To more accurately characterize the variability, the test squares were analyzed separately with respect to their proximity to a longitudinal joint. In both cases, the variability in the wheel path areas (i.e., away from the joint) was reduced drastically, leaving most of the site variability to be associated with the longitudinal joint.

	Required Sample Size (n)			
	δ=10% R=90%	δ =10% R=80%	δ =20% R=90%	δ =20% R=80%
LVST *(σ=17.86)*	27	20	7	5
LVSM *(σ=23.61)*	48	35	12	9
PKLT *(σ=24.02)*	49	36	12	9
BASE *(σ=17.25)*	26	18	6	5
BIND *(σ=22.66)*	44	32	11	8
BIND – wheel path *(σ=4.25)*	2	1	1	1
BIND – joint *(σ=16.70)*	24	17	6	4
SURF *(σ=2.16)*	1	1	1	1
SHWY *(σ=27.46)*	65	47	16	12
SHWY – wheel path *(σ=1.71)*	1	1	1	1
SHWY – joint *(σ=37.65)*	121	88	30	22

Table 8. Sample sizes required for desired testing discrimination (δ) and reliability (R)

For pavements with significant variability, large sample sizes are required in order to accurately and reliably characterize permeability. Overall, a sample size of 40 could be considered appropriate for most pavements when a testing discrimination (δ) of 10 percent and a reliability of 90 percent are desired. For a testing discrimination of 10 percent and a reliability of 80 percent, a sample size of 30 would be reasonable. If the testing discrimination were reduced to detect differences of 20 percent, a sample size of 10 would provide approximately 90 percent reliability and a sample size of 7 would provide approximately 80 percent reliability. Note that the variability characterized by these sample size calculations accounts only for the variability of the pavement, and does not consider the accuracy of the test method.

If a field permeability test were desired for use as a measure of quality control for pavement construction, a testing discrimination of 20 percent would be reasonable. Combined with a desired reliability of 90 percent, the recommended sample size for general use is 10 samples per unit of material tested. In the context of the current Arkansas quality control / quality assurance (QC/QA) system, this would mean that the average of 10 field permeability tests would be used to generate a lot or sublot permeability value. This testing frequency is quite large and would represent a major commitment to the value of the field permeability test. This frequency is not conducive for routine QC/QA testing. In order to justify this level of commitment, work should be done to more definitively describe the meaning of the values obtained from such a test. Thus, the implementation of this type of test should be reserved only for areas of a pavement having marginal density, or when a problem is suspected. In this way, field permeability would be more of a forensic test than a QC/QA test.

CONCLUSIONS

Three field test methods were used to describe the permeability of in-service asphalt pavements. They were a falling head (NCAT) test, a constant head (KUSS) method, and a vacuum permeability method (VACP). Based on the sites tested in this project, the following conclusions were drawn:

- The methods used for testing field permeability did not generate similar results.
- The falling head test usually provided the largest measures of coefficient of permeability.
- In some cases, the rankings provided by the various test methods indicated similar levels of permeability, but in other cases did not.

> *For the testing performed in this research, the various measures of field permeability provided rankings that were only vaguely similar. Overall, the test methods did not generate similar permeability results.*

Pavements having three different nominal maximum aggregate sizes were mapped according to the vacuum permeability test. Cores were cut from each pavement in order to compare the permeability and density of the pavements. For these sites, the following conclusions were made:

- Pavements that clearly failed the density specification had high permeability.
- Pavement sections that clearly passed the minimum density specification were relatively impermeable.

- Pavements with marginal density were somewhat permeable, and had variable levels of permeability.
- Pavements with larger NMAS (i.e., 25.0mm and 37.5mm) are likely to be permeable at higher densities than mixes with a small NMAS (i.e., 9.5mm and 12.5mm).
- The 37.5mm mix demonstrated consistent densities for the cores tested, but was the most variable in terms of permeability as measured by the VACP test.
- Pavement areas showing visible signs of segregation were not necessarily permeable.
- In general, high levels of permeability were exhibited near the longitudinal joints.

The density specification in the state of Arkansas appears to be capable of detecting pavements that exhibit very high and very low levels of permeability. Pavements with marginal densities may or may not be permeable – even in areas of visible segregation. Thus, factors other than density are believed to affect permeability.

One site was tested to characterize locations of permeability after servicing moderately high levels of traffic for approximately 3 years. The following observations were made for this site:

- Permeability was low for the wheel path area.
- Permeability was much higher near the longitudinal joints.

Pavements that have been in service are not likely to be permeable in the wheel path area. However, even after significant traffic loadings, pavements are likely to be permeable near the longitudinal joints. Thus, pavements may continue to be susceptible to the distresses caused by the penetration of air and water, even long after construction.

From the permeability maps generated by the VACP test method, the percentage of the test area that exhibited permeability was calculated for each test square. Based on these percentages, the following conclusions were made:

- The measure obtained by a field permeameter is dependent upon the placement of the device during testing, the effective test area for the device, and the variability of the pavement.
- The distributions of permeability were very consistent for some test sites, but quite variable for others.
- Impermeable areas exhibited low variability.
- For the pavement sites tested, the standard deviation of the percent of permeable area ranged from 1.71 to 37.65.
- Based on the range of standard deviations measured in this project, a minimum sample size of 10 is recommended for pavements with marginal densities or variable consistency.
- The required sample size for field permeability testing is relatively large, and thus the tests evaluated in this study are not conducive to implementation as a tool for routine QC/QA testing.

Based on the results of this study, field permeability testing may have value as a forensic tool, but is not recommended for standardized use. Extreme caution *should be exercised before implementing field permeability testing as a quality control or quality assurance measure.*

FUTURE RESEARCH

The results of this research clearly demonstrate that the longitudinal joints of a field-compacted HMA pavement are more permeable than the rest of the pavement, even after several years of service. Further research should be done regarding longitudinal joints and methods for minimizing the permeability of the pavement at these locations. By improving the quality of the pavement at the joints, the pavement structure can be better protected from the detrimental effects of air and water.

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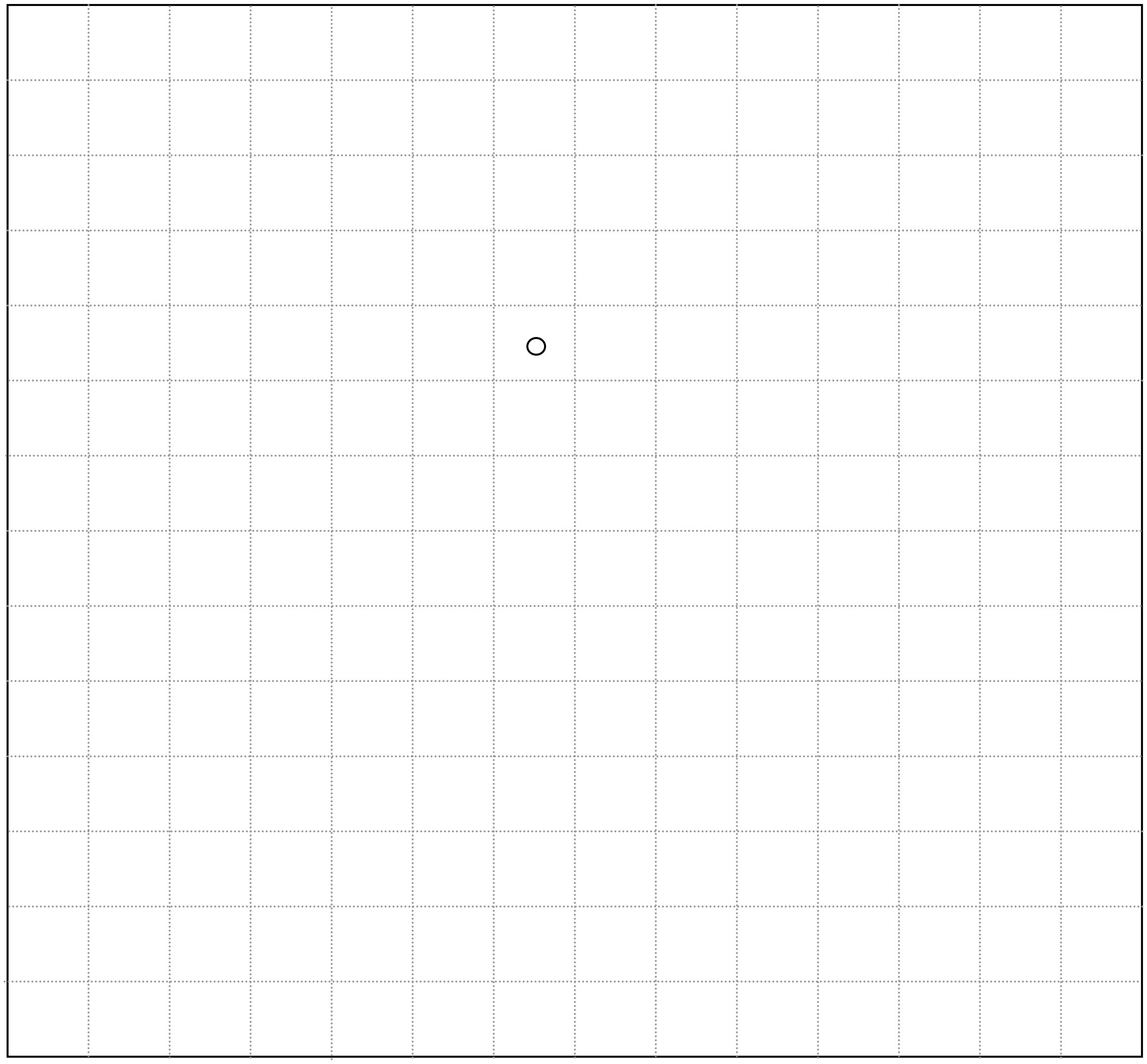
APPENDIX

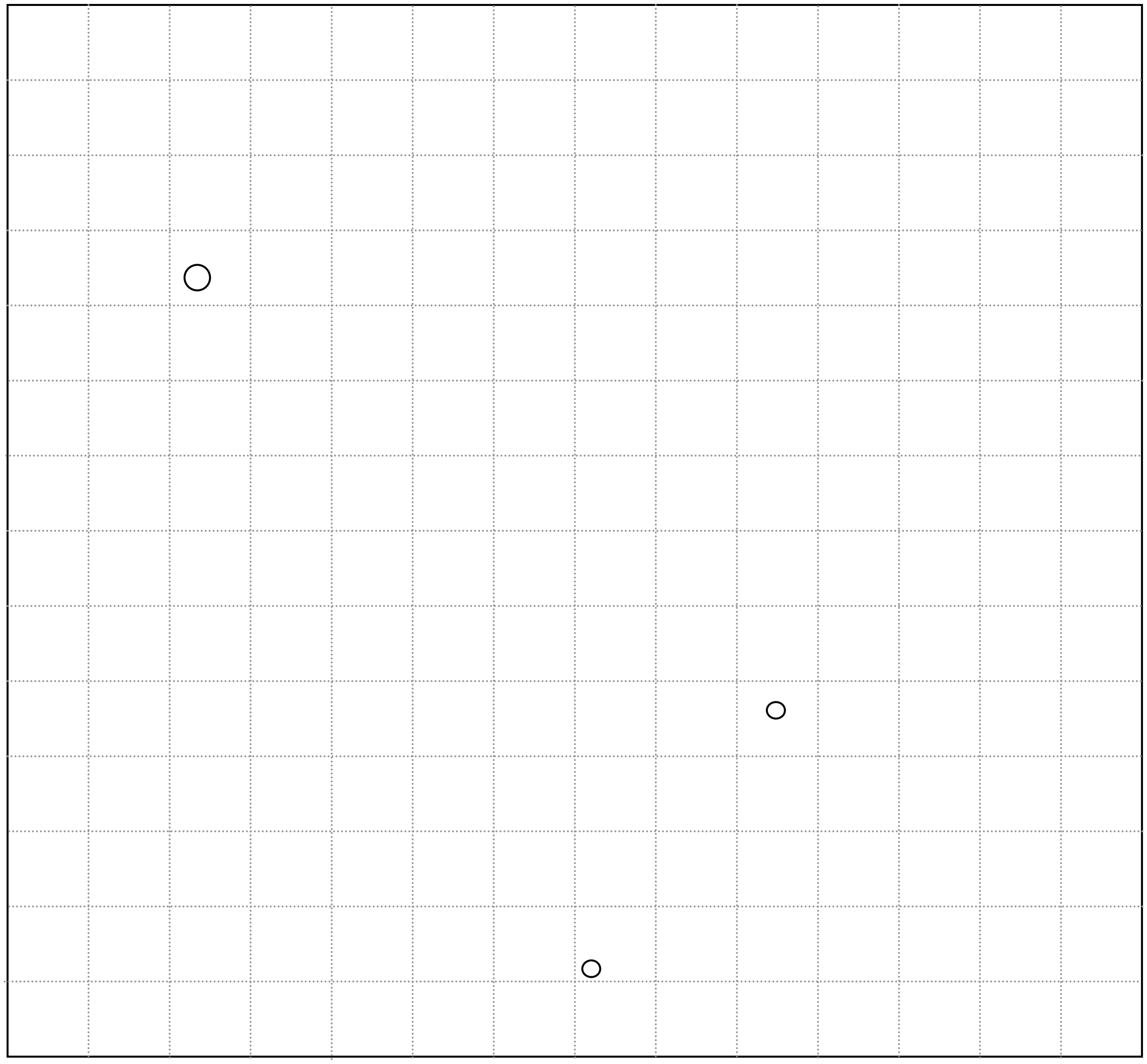


Test Square ID: LVST#23

VACP (% permeable area): 0.51

KSFP (x 10^{-5} cm/s): 0.68

NCAT (x 10^{-5} cm/s): 141.82



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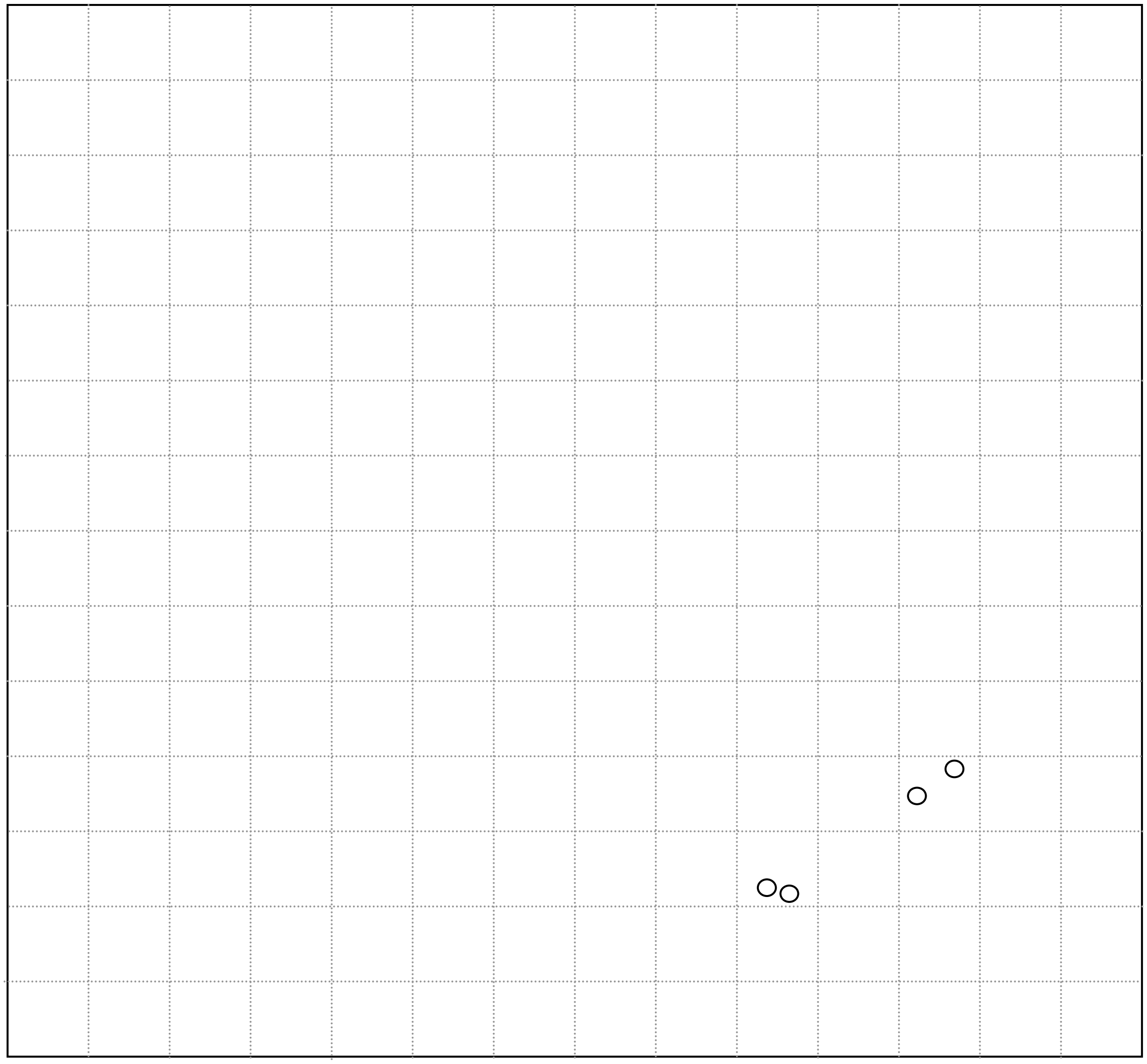
VACP (% permeable area): 1.53

KSFP (x 10^{-5} cm/s): 1.02

NCAT (x 10^{-5} cm/s): 4.75

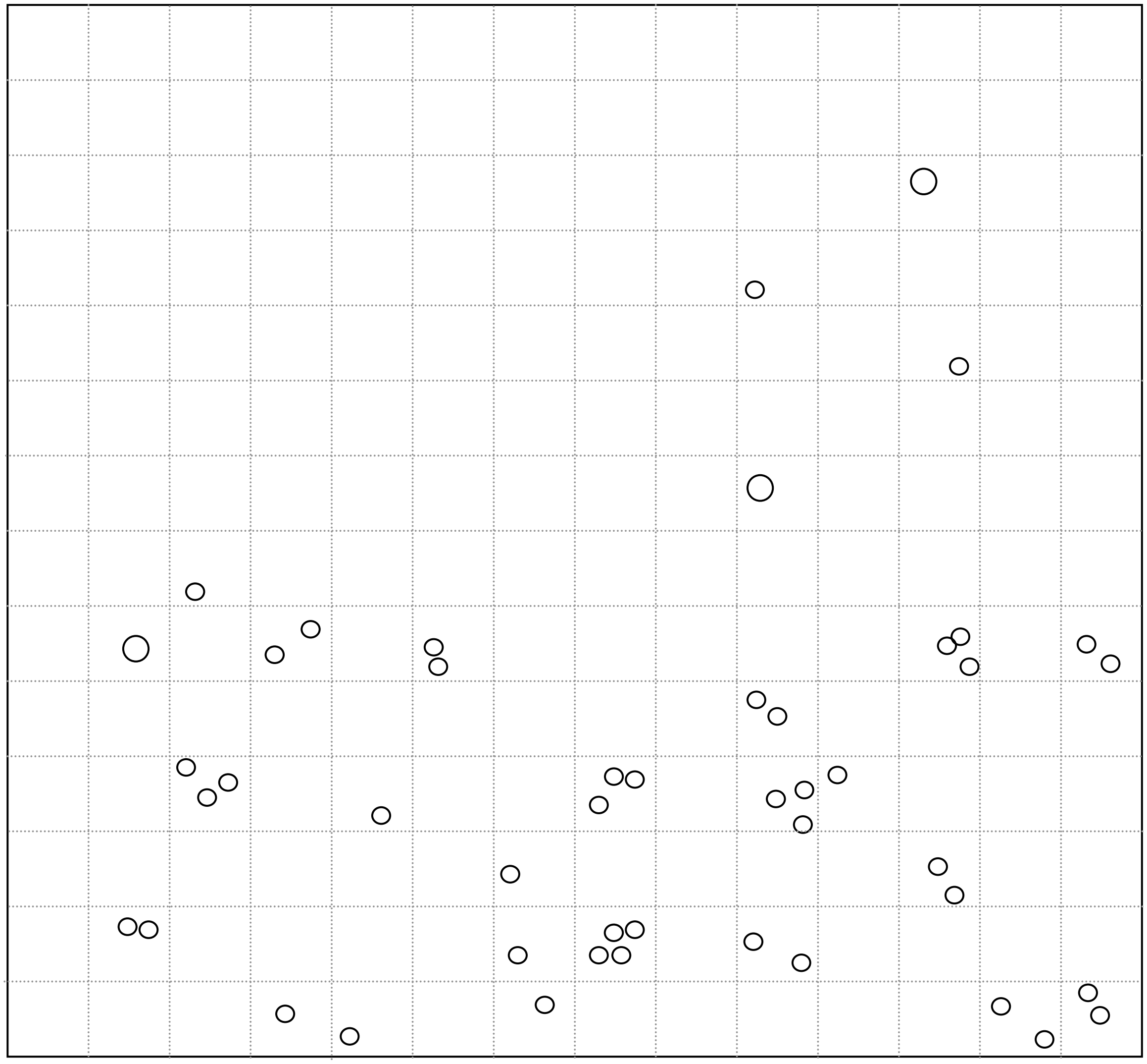


Test Square ID: LVST#56

VACP (% permeable area): 1.02

KSFP (x 10^{-5} cm/s): 0.34

NCAT (x 10^{-5} cm/s): 99.48

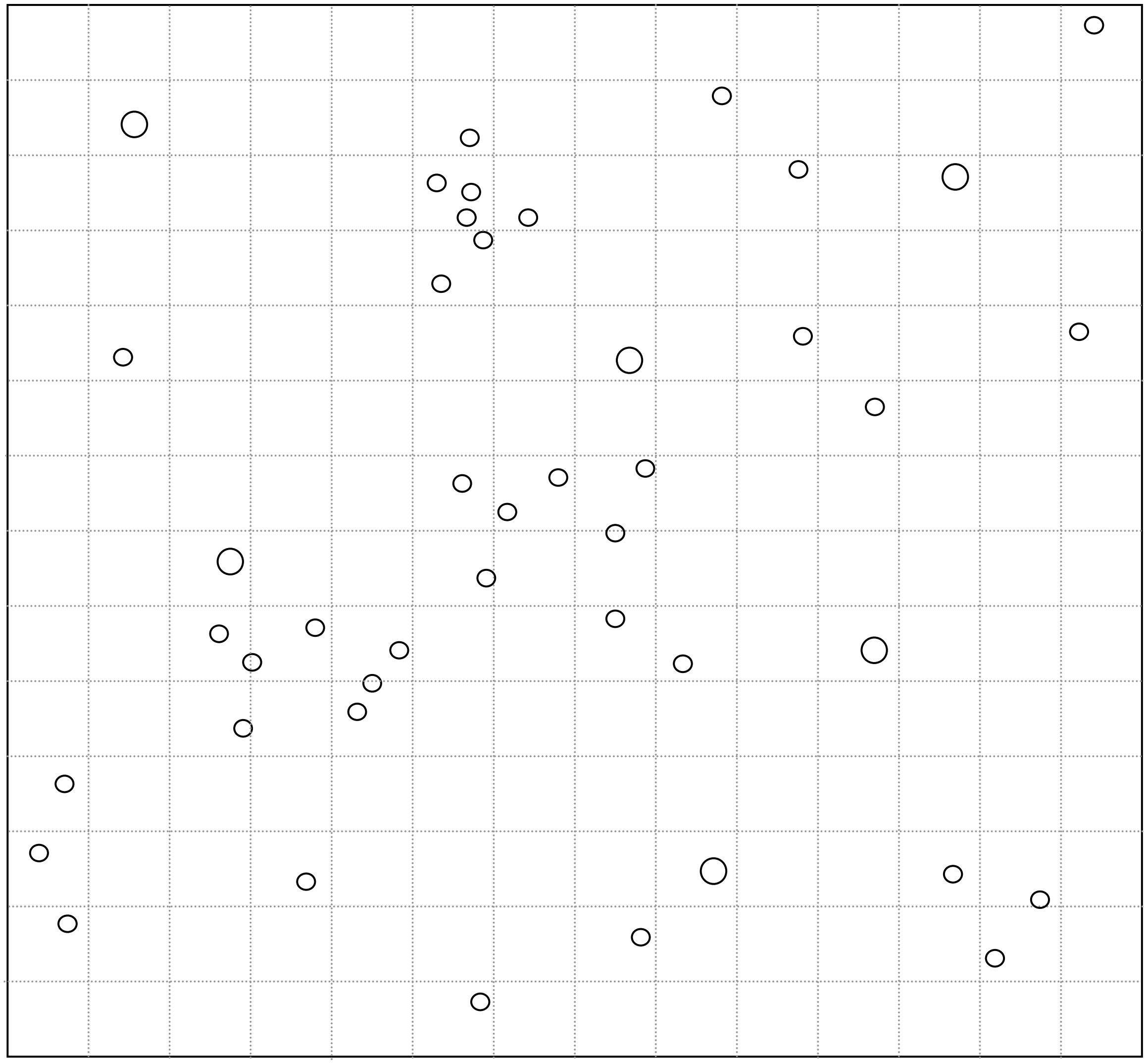


Test Square ID: LVST#83

VACP (% permeable area): 13.78

KSFP (x 10^{-5} cm/s): 0.51

NCAT (x 10^{-5} cm/s): 63.87

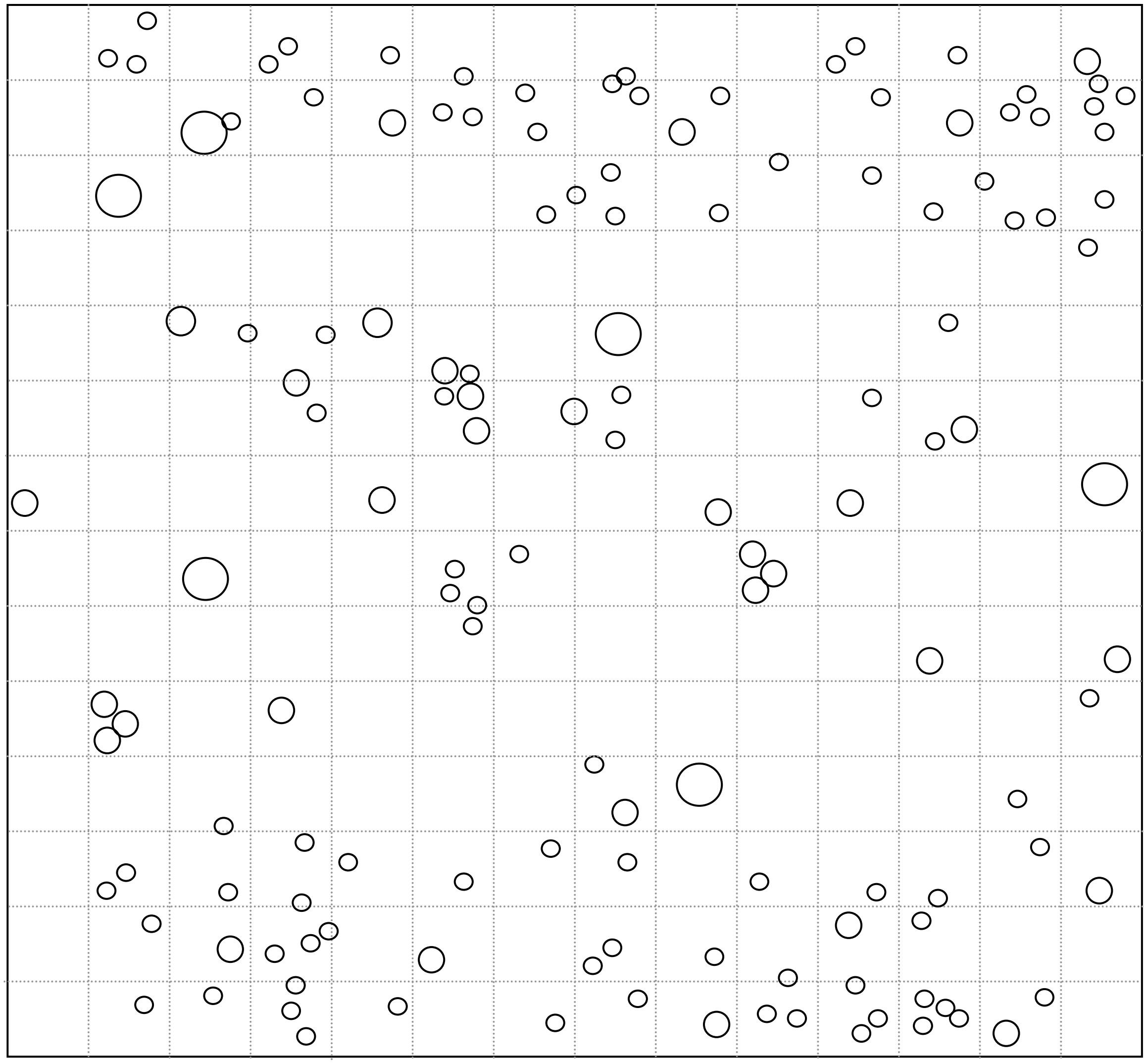


Test Square ID: LVST#89

VACP (% permeable area): 19.39

KSFP (x 10^{-5} cm/s): 0.68

NCAT (x 10^{-5} cm/s): 7.21

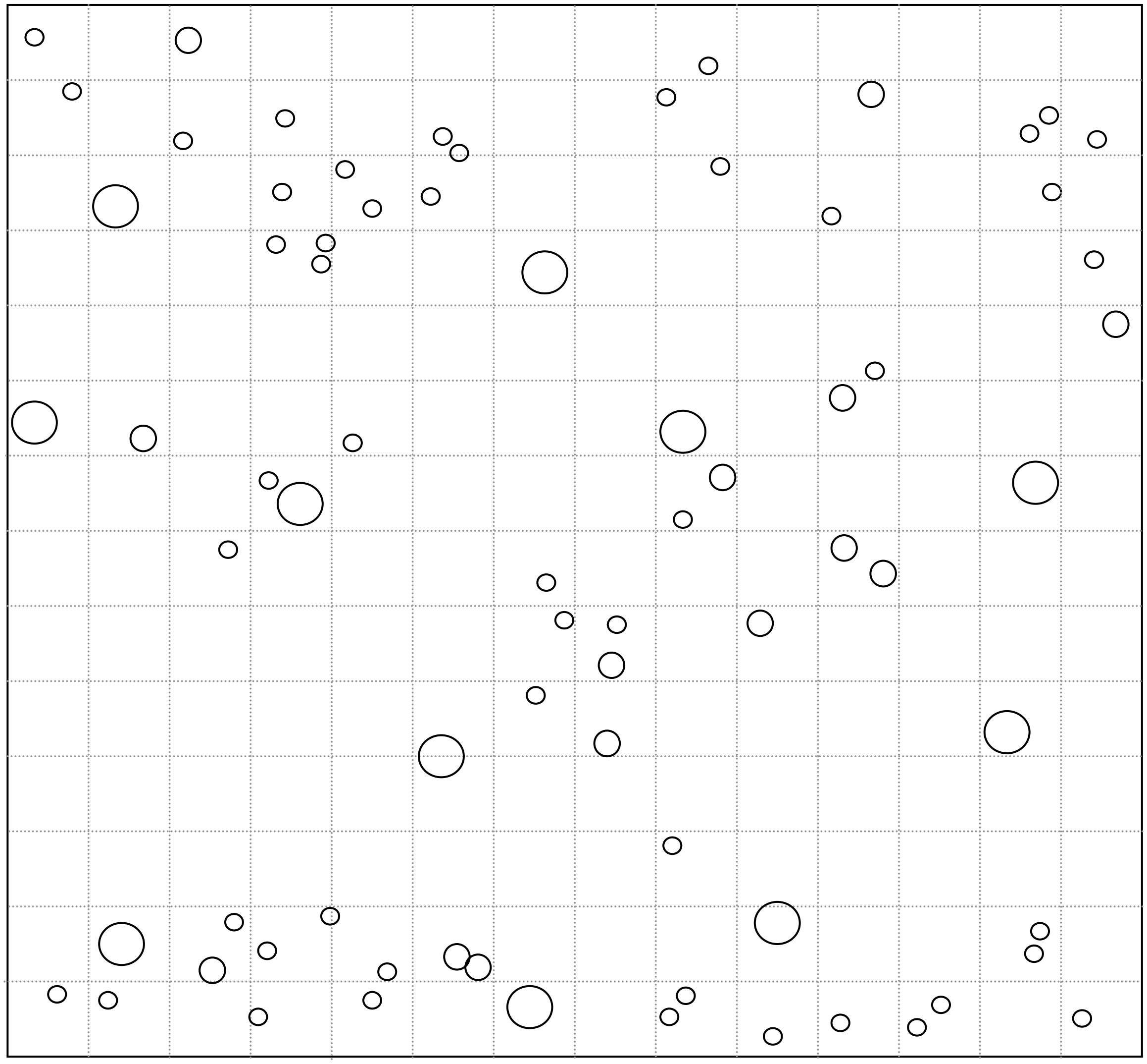


Test Square ID: LVSM#34

VACP (% permeable area): 46.43

KSFP (x 10^{-5} cm/s): 0.00

NCAT (x 10^{-5} cm/s): 34.42

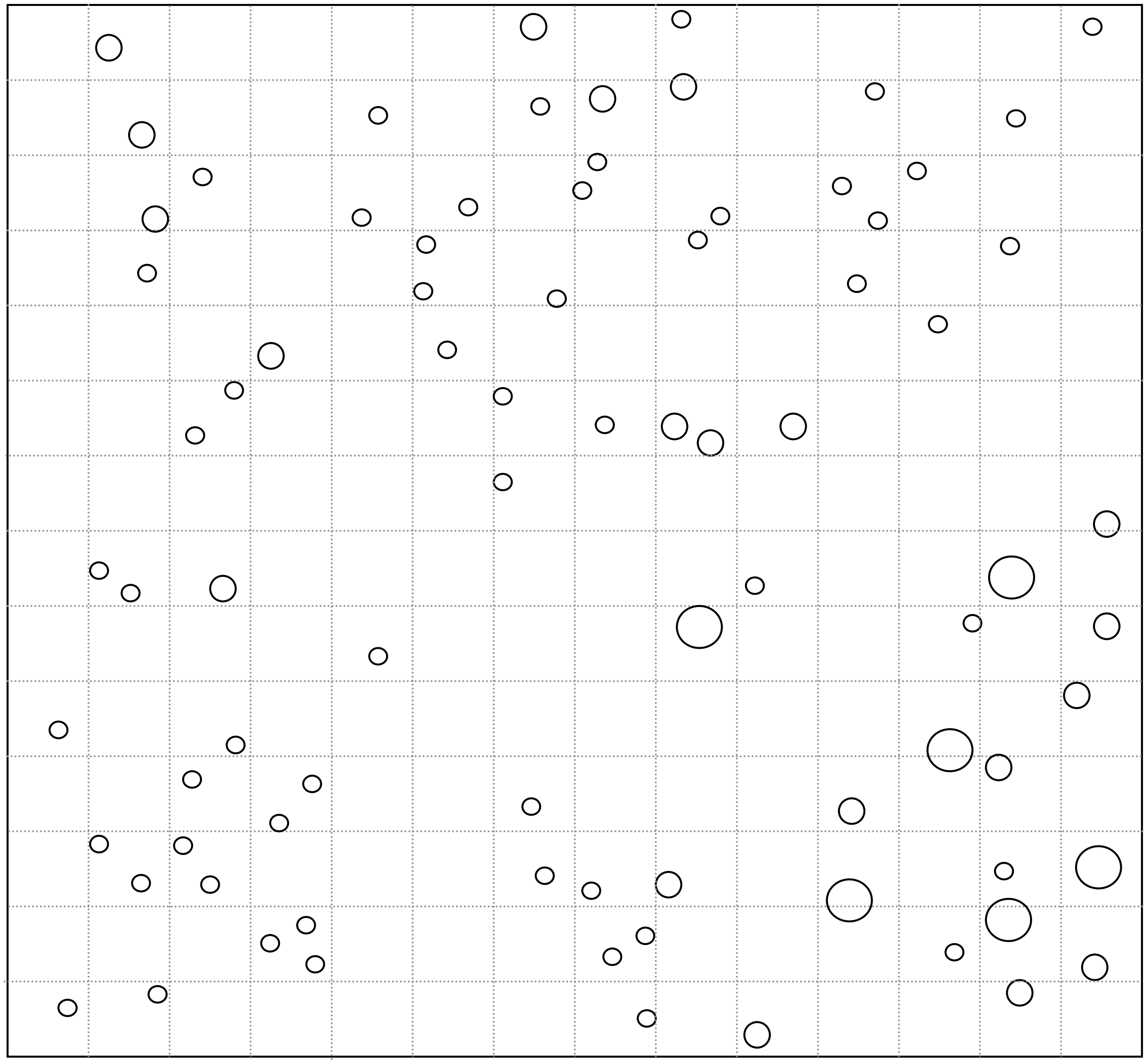


Test Square ID: LVSM#72

VACP (% permeable area): 30.61

KSFP (x 10^{-5} cm/s): 2.03

NCAT (x 10^{-5} cm/s): 12.94

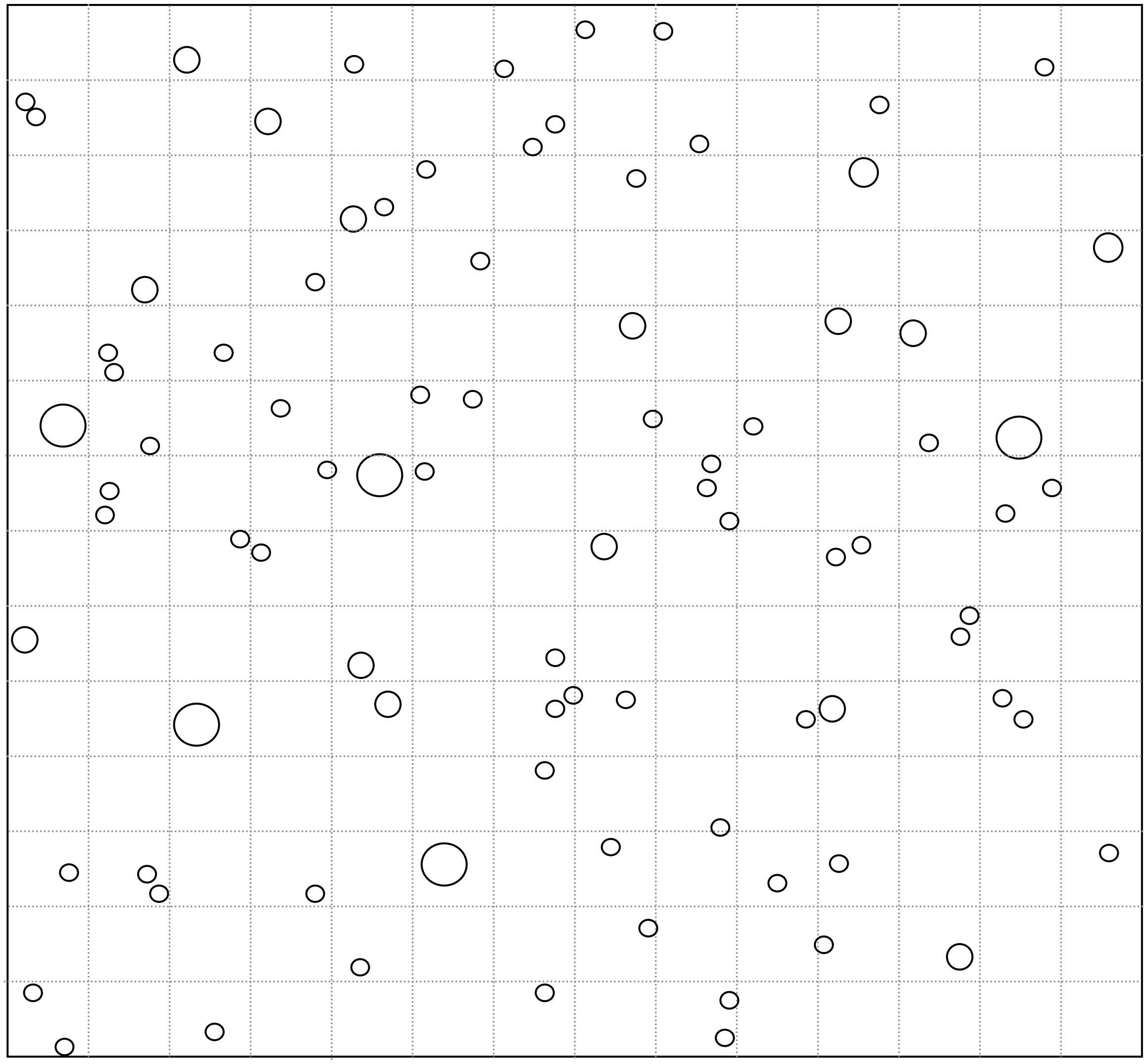


Test Square ID: LVSM#85

VACP (% permeable area): 36.73

KSFP (x 10^{-5} cm/s): 25.08

NCAT (x 10^{-5} cm/s): 33.62

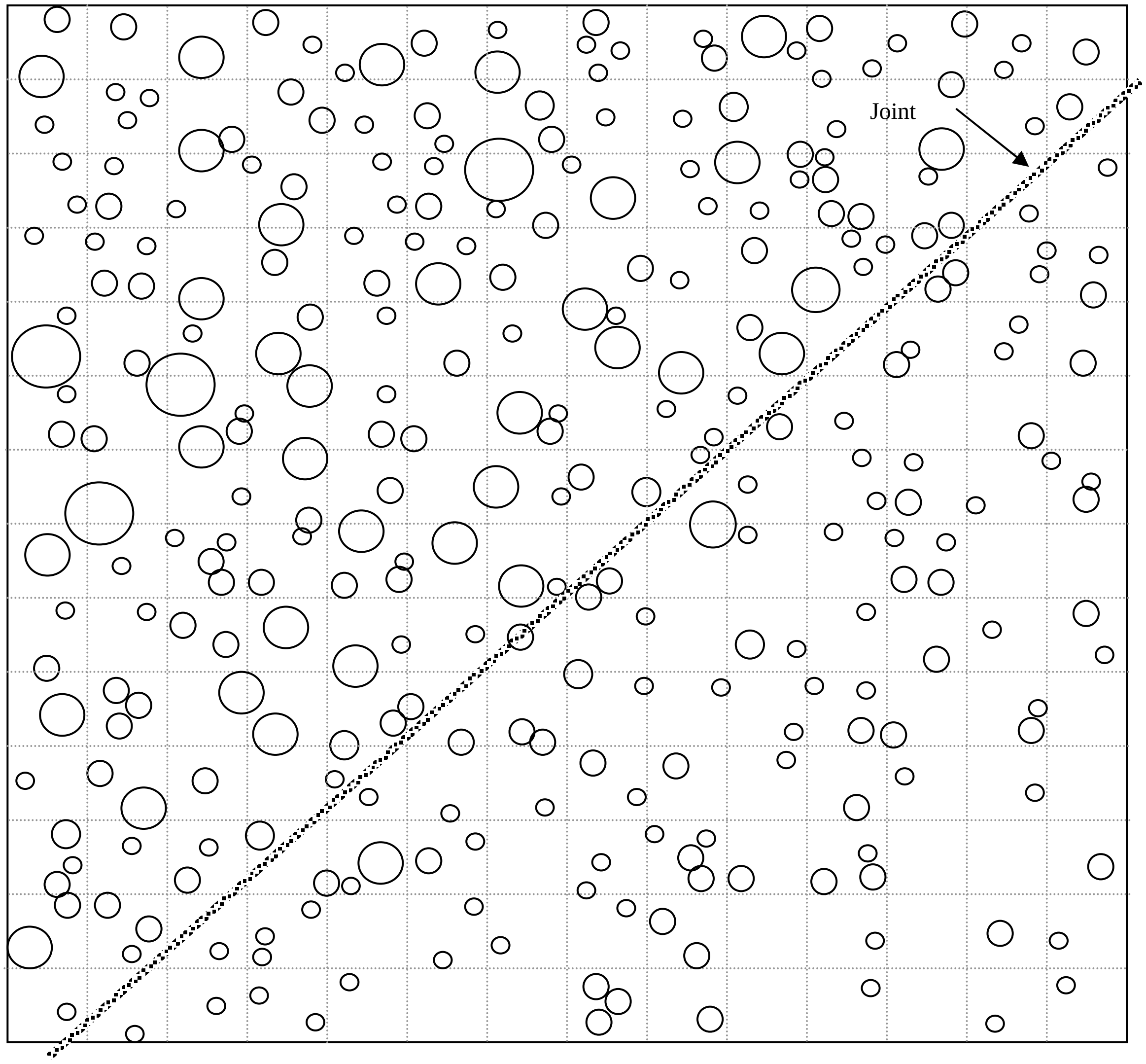


Test Square ID: PKLT#14

VACP (% permeable area): 36.22

KSFP (x 10^{-5} cm/s): 2.54

NCAT (x 10^{-5} cm/s): 109.61

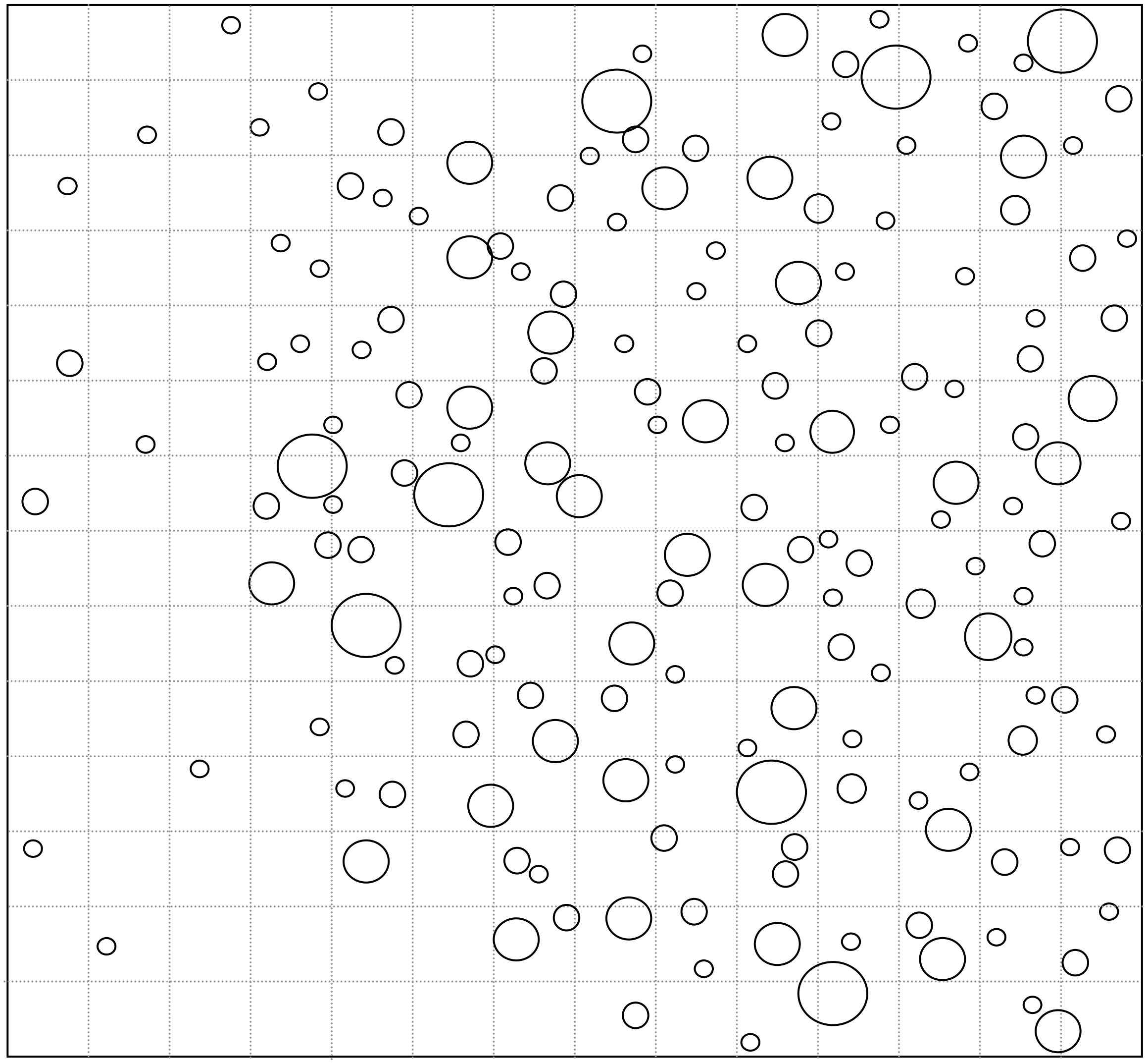


Test Square ID: PKLT#26

VACP (% permeable area): 91.84

KSFP (x 10^{-5} cm/s): 201.66

NCAT (x 10^{-5} cm/s): 5051.57

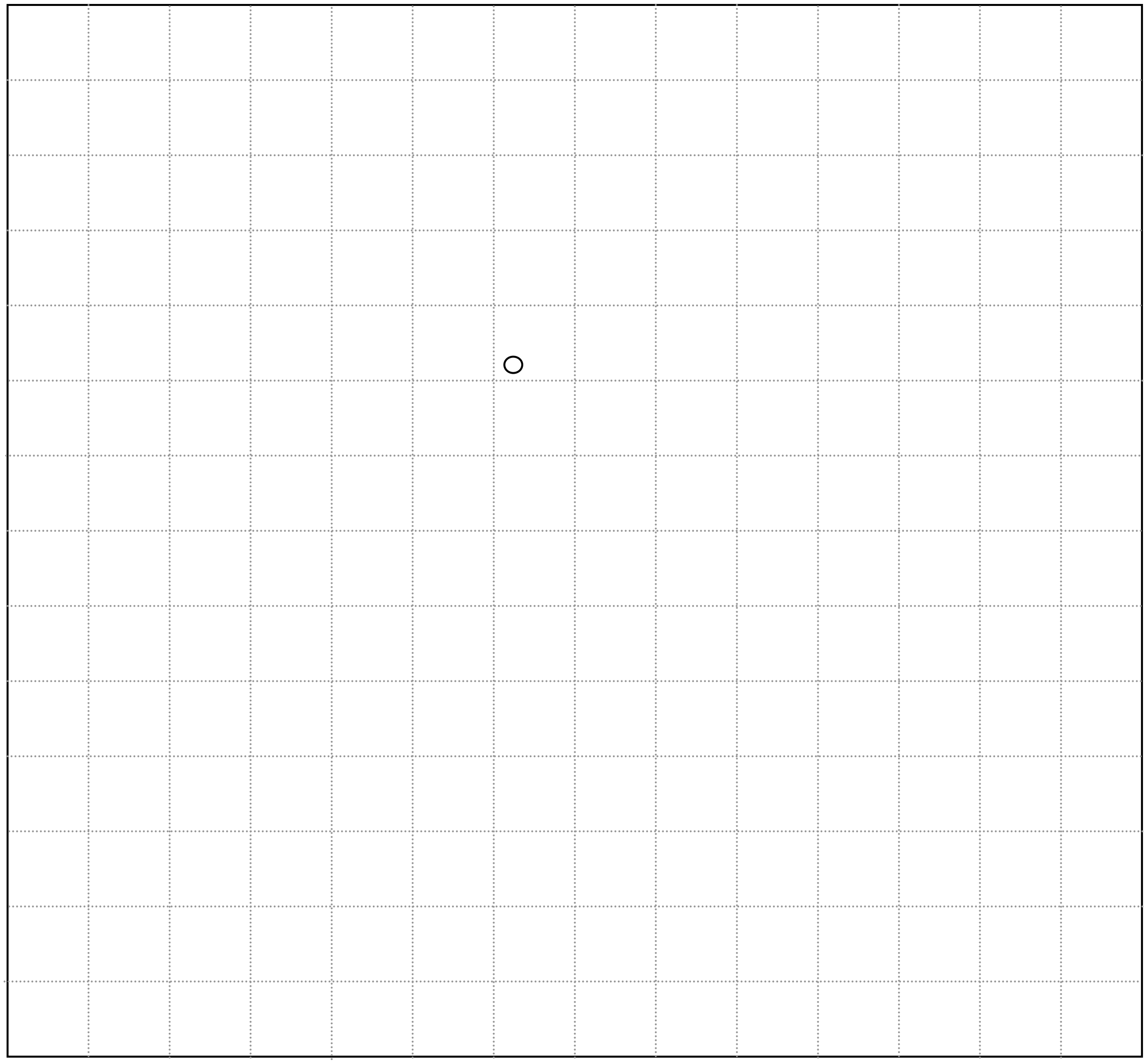


Test Square ID: PKLT#33

VACP (% permeable area): 62.24

KSFP (x 10^{-5} cm/s): 0.68

NCAT (x 10^{-5} cm/s): 288.61

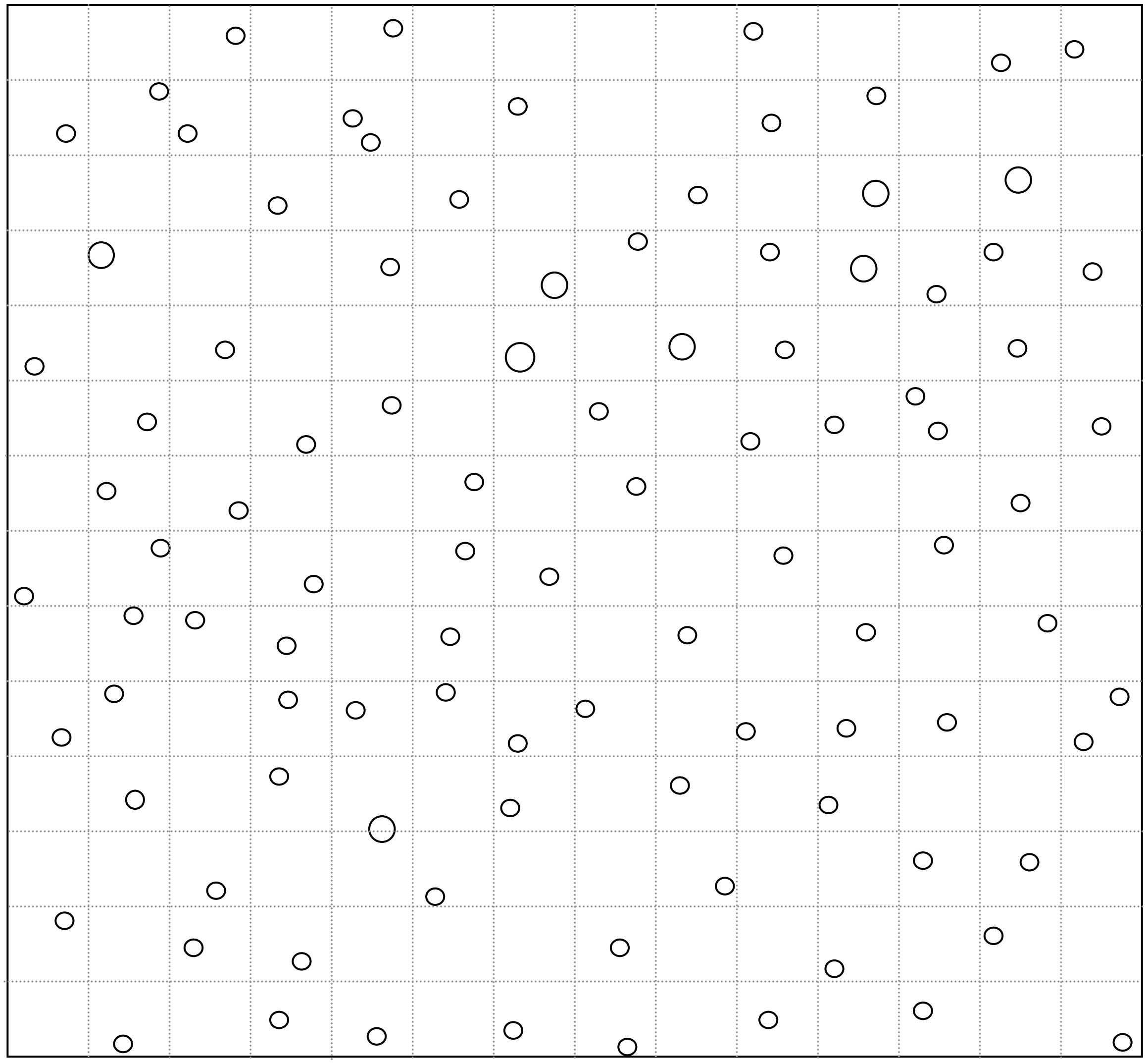


Test Square ID: PKLT#83

VACP (% permeable area): 0.51

KSFP (x 10^{-5} cm/s): 31.69

NCAT (x 10^{-5} cm/s): 129.51



Test Square ID: <u>PKLT#100</u>

VACP (% permeable area): <u>48.98</u>

KSFP (x 10^{-5} cm/s): <u>0.00</u>

NCAT (x 10^{-5} cm/s): <u>77.57</u>