Research Report
KTC-01-19/SPR216-00-1F

KENTUCKY TRANSPORTATION CENTER

College of Engineering

DEVELOPMENT AND PROPOSED IMPLEMENTATION OF A FIELD PERMEABILITY TEST FOR ASPHALT CONCRETE

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DEVELOPMENT AND PROPOSED IMPLEMENTATION OF A FIELD PERMEABILITY TEST FOR ASPHALT CONCRETE

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Transportation Cabinet
Commonwealth of Kentucky

And

The Federal Highway Administration
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We would like to extend our thanks and appreciation to the volunteers on the advisory committee for this study (KYSPR-00-216). Their guidance and advice during the course of study was most helpful. In particular, we would like to thank Mr. Wesley Glass, Director of the Division of Materials and Chairman of the study advisory committee and Mr. Allen Myers, Manager of the Asphalt Branch of the Division of Materials, for their help in choosing construction projects to be included in this study, and also for helping to interface with district personnel of the Kentucky Transportation Cabinet. We would also like to thank them for their editorial comments on this report. In addition, we would like to express our appreciation to the contractors who assisted us in this study.

EXECUTIVE SUMMARY

Pavement drainage contributes greatly to long-term pavement performance. Pavements undergo surface, as well as subsurface, drainage during prolonged rain events. It is this subsurface drainage that is of concern in this study. In the advanced asphalt pavements of today, where a drainage layer may be incorporated to facilitate the movement of water out of the above overlying pavement layers, water can be a problem in areas with variable permeability. High permeability may also cause other problems related to drainage such as frost heave, stripping, asphalt emulsification, and water coming out of the pavement surface from deeper layers in the pavement structure, and water coming out of the pavement layers and freezing on the surface.

No standard methodology has been developed for measuring the permeability of pavement layers in the field. It is important to be able to quantify the estimated permeability of various pavement layers to better predict pavement performance and to reduce permeability in future mixtures. A device that could test the field permeability of a pavement could serve as a tool for establishing total quality management on a project.

The objectives of this study were as follows:

1) To review research performed by others and determine the state-of-the-art of field permeability measurements,
2) To review current laboratory permeability testing devices and their testing procedures for accuracy,
3) To develop a rapid and repeatable field test for measuring permeability of asphalt mixtures and aggregate bases or accept an already existing method,
4) To correlate this device with known laboratory testing procedures,
5) To determine if a correlation exists between field permeability and other measurable pavement parameters,
6) To define acceptable permeability rates for asphalt mixtures and aggregate base courses, and
7) To develop a QC/QA specification and procedure for application in construction practices.

An air-induced field permeameter (AIP) was developed on this study and was correlated with a water permeameter developed by the National Center for Asphalt Technology (NCAT). An attempt was also made to correlate the device with a laboratory permeameter developed by the Florida Department of Transportation but the attempt was not considered successful. The AIP was tested on twelve construction projects in Kentucky.

The results and conclusions of this study include the following:

- The air-induced permeameter (AIP) works well for measuring pavement porosity (permeability) and usually requires less than one minute to obtain a reading.
- The water permeameter developed by the National Center for Asphalt Technology (NCATP) also is effective in measuring pavement permeability; however, on pavements with low permeability, this device requires an extensive amount of time.
- The laboratory permeameter used in this study could not be calibrated with either the NCATP or the AIP. Therefore, it appears that the laboratory permeameter does not give a good description of field permeability.
- There was a good correlation between the NCATP and the AIP.
- Density has a highly significant influence on permeability. It appears that at approximately 92 percent of maximum theoretical density there is a dramatic decrease in field permeability (Figure 46). From the data in this study, the value of 92 percent of maximum theoretical density does not appear to be related to the size of the mixture.

- There is a wide variation in permeability across an asphalt mat. The lowest permeability nearly always occurs in the center of the lane with the highest permeability occurring at the construction joint. In most of the projects in this study, the permeability at the joint was several orders of magnitude greater than at the center of the lane. The recent Kentucky specification that sets a minimum acceptable density at the joint is an attempt to address and improve this situation.
- Because of the wide variation of field permeability on a particular project, it would not be appropriate to express permeability as a simple number, or a deterministic value. Rather, permeability should be expressed statistically as a mean and a standard deviation or expressed probabilistically as explained in the section of this report entitled *Permeabilities of Individual Projects*.
- It appears the mean field permeability can be "estimated" from the aggregate gradation using Equation 4.0 (Figure 57).
- Equation 4.0 can only provide an estimate of the *mean* field vacuum. However, construction factors and procedures may cause the mean, measured, field vacuum to be different from the estimate.
- It appears that any gradation, regardless of the nominal top-size aggregate can be designed for either a "low" or a "high" permeability.
- The data in Figure 47 clearly support the current Kentucky specification that requires a minimum of 92 percent of theoretical maximum density (in the lane) for 100 percent pay.

A number of recommendations were also presented in this report, and they are listed below.

- It is recommended that a Kentucky Method be written for measuring the permeability of asphalt pavements using the AIP developed in this study, and that the procedures described in this report under the section titled *Test Procedures* be used as a basis for that proposed method.

- It is postulated that the AIP developed in this study may be able to quantify segregation in asphalt pavements. To test that hypothesis, there is a separate research study currently ongoing to attempt to measure or quantify segregation in asphalt pavements.

- It is recommended that the AIP technology be transferred to the Division of Materials, Kentucky Transportation Cabinet, and that the AIP be used regularly on construction projects for measuring permeability. It is further recommended that a trial permeability specification be developed for asphalt pavements. This specification will permit the development of a database of permeability values that will help to further confirm or deny the validity of Equation 4.0.

- It is recommended that the specification proposed in this report be adopted on a "trial" basis (without actual application of incentives or disincentives) for a period of one to two years to allow the Transportation Cabinet and the contractors to gain experience and knowledge of permeability in asphalt pavements.

- In view of the wide differences in permeability between the center of the lane and the construction joint, it is recommended that a further study of joint construction techniques be initiated, with a goal of reducing permeability at the joint. This study would be a follow-up to a previous study on joint construction techniques (Report No. KTC-02-10/SPR208-00-1F, *Compaction at the Longitudinal Construction Joint in Asphalt Pavements*). From the data developed in this study (Figures 33 through 46), it may be necessary to "tighten" the current joint specification to reduce water intrusion at the joint. Some of the techniques used in the previous joint study should be tested on more projects to determine if those techniques can economically be used to consistently reduce permeability at the joint.

INTRODUCTION

Pavement drainage contributes greatly to long-term pavement performance. Pavements undergo surface, as well as subsurface, drainage during prolonged rain events. It is this subsurface drainage that is of concern in this study. Groundwater from below and rainwater from above may invade these subsurface materials, saturating the void space within these layers. Spellman[1] has indicated that when high pore pressures are developed in asphalt layers during repetitive highway loadings, water, as well as the fines that make up the asphalt matrices, is pumped out of the subsurface.

Even in the advanced asphalt pavements of today, where a drainage layer may be incorporated to facilitate the movement of water out of the above overlying pavement layers, water can be a problem in areas with variable permeability. High permeability may also cause other problems related to drainage such as frost heave, stripping, asphalt emulsification, and water coming out of the pavement surface from deeper layers in the pavement structure (Figure 1), and water coming out of the pavement layers and freezing on the surface.

No standard methodology has been developed for measuring the permeability of pavement layers in the field. It is important to be able to quantify the estimated permeability of various pavement layers to better predict pavement performance and to reduce permeability in future mixtures.

Figure 1. Water Coming Through an Asphalt Surface.

Scope

Permeability measurements of pavement materials largely have been limited to laboratory settings. The challenge of quantifying pavement drainage (permeability) has created a need for a field-applicable device. This device might ultimately lead to the ability to design projects with permeability limits resulting in improved pavement durability. Through quantifying field permeability, more accurate performance models could be developed from established mix designs and density requirements. Additionally, QC/QA specifications could be developed to link pay factors to in-situ permeability measurements. Finally, a device that could test the field permeability of a pavement could serve as a tool for establishing total quality management on a project.

Objectives

The objectives of this study were as follows:

1. To review research performed by others and determine the state-of-the-art of field permeability measurements,
2. To review current laboratory permeability testing devices and their testing procedures for accuracy,
3. To develop a rapid and repeatable field test for measuring permeability of asphalt mixtures and aggregate bases or accept an already existing method,
4. To correlate this device with known laboratory testing procedures,
5. To determine if a correlation exists between field permeability and other measurable pavement parameters,
6. To define acceptable permeability rates for asphalt mixtures and aggregate base courses, and
7. To develop a QC/QA specification and procedure for application in construction practices.

It was anticipated that permeabilities of aggregate bases also would be studied in this project; however, during the closing of this study sufficient time was not available to collect and analyze data on aggregate bases. This may require a second research effort in the future.

REVIEW OF RESEARCH BY OTHERS

Previous Attempts to Measure Permeability

To fulfill Objective No.1, a literature review was conducted to determine the current state-of-the-art in measuring field and laboratory permeability. Also, a number of personal conversations were conducted with some of the researchers by members of this research team.

Previous attempts have been made to develop a device that could quantify permeability in asphalt concrete pavements. In a report published by the New Mexico Engineering Research Institute (NMERI)[2], a study was conducted evaluating the permeability of different types of surfaces and also evaluating the devices used in the study. Four devices were evaluated by NMERI -- two using water and two using air as a medium for the test procedure.

The first device, to measure field permeability, was developed by Pennsylvania State University, used compressed air directed to a release chamber and then forced through the pavement. This release chamber was sealed to the pavement surface using a commercially available sealant. Using pressure readings from the release chamber and airflow rate measurements, this device appeared to provide the most promising results. The static air permeability test data plotted against the static water readings resulted in a correlation coefficient, R^2, of 0.92. The device also had a high degree of repeatability. Some of the disadvantages associated with this equipment were the high cost of the equipment, the inability to read porous surfaces accurately, ring-seal blowout on tight surfaces, and the complex testing method that could result in frequent user error.

A second device, for measuring field permeability, was developed by the American Society for Testing and Materials (ASTM). This device measured the rate at which air could be forced or drawn at low pressures through the pavement. Results using this device were inconclusive due to the theory behind the device. This procedure did not meet the requirements for ideal flow because of the falling head used to develop air pressure. The device created a constantly decreasing pressure, for which compensation had to be made to obtain accurate results. A correlation would have to be used to convert to an average constant pressure, and this would depend on the permeability for each pavement. No correlation was made between this device and the other devices tested, but there appeared to be a good correlation between this device and core permeabilities. Repeatability of this gauge was marginally acceptable. Other disadvantages included frequent user error and low air pressure output resulting in the inability to measure permeable pavements.

The third device, for measuring field permeability, was developed and modified by Birmingham University; the University experimented with an outflow water permeability meter to measure the surface drainage capacity of laboratory specimens. The Birmingham University outflow meter consists of a transparent cylinder with a hole on the pavement-contact end through which water outflow is controlled. A rubber ring is used to provide a seal, and a weight is applied to the top of the device to help provide a seal. This device uses a falling head to measure the combined flow through a test sample. The disadvantages associated with this device are leakage around the seal from over-pressurization and an extended amount of time required to perform a test[2].

The last device was for measuring laboratory permeability and was developed by the Army Corps of Engineers. This device used a simple graduated cylinder to measure permeability. This device could use either a constant-head or a falling-head. The device proved to be user-friendly, but the results from the tests were inconclusive. The sample size of 2.5 inches (diameter) was too small to be a representative sample of the matrix. The time required to perform the test with this device was a problem as well as the inability to measure highly permeable surfaces.

Apparently none of these gauges could yield accurate results while, at the same time, deal with time constraints, have a low degree of user error, and deal with the problems associated with measuring highly permeable surfaces.

The National Center for Asphalt Technology (NCAT) In-Place Field Permeameter

The National Center for Asphalt Technology (NCAT) published a study entitled *Permeability of Superpave Mixtures: Evaluation of Field Permeameters*[3], in which four types of in-place water permeameters were evaluated. After extensive testing, NCAT chose a three-tier device comprised of different sizes of graduated cylinders (Figure 2). This device measures a falling head of water over a measured period of time. This time period, as well as the differences in head loss, can be used to determine the coefficient of permeability. This type of test is more suitable for less permeable materials.

Several assumptions are made when using this device. The falling-head test involves determining the amount of head loss through a representative sample area over a measured period of time. In the equation for calculating permeability (Darcy's law), the length of the sample must be specified. In field applications, it is impractical to determine the length of the sample; therefore, an effective depth of one inch is assumed. Also, the sample was assumed to be saturated and flow through the sample to be laminar.

Figure 2. NCAT Field Permeameter.

The coefficient of permeability is calculated as follows:

$$k = (a*L / A*t) * \ln(h_1 / h_2) \qquad \text{Eq. 1.0}$$

where:
k = coefficient of permeability,
a = area of stand pipe,
L = estimated effective thickness of sample,
A = cross-sectional area of sample,
t = time elapsed during head loss,
h_1= water level at upper mark, and
h_2= water level at lower mark.

In the NCAT study, it was indicated that several factors were identified that influence the permeability of hot-mix asphalt (HMA). These factors include particle size distribution, particle shape, molecular composition of the asphalt binder, air voids, degree of saturation, type of flow, and temperature. It was also suggested that permeability decreases as the size and number of voids decrease. This suggestion agrees with the general assumption that if water is forced through a network of pipes, the system with the smallest pathways (pipes), or the least number of pathways, would result in lower flow rates. Particle shape influences permeability, in that the more angular particles result in a more turbulent flow of water, leading to lower flow rates.

The degree of saturation greatly affects the rate at which water flows through the pavement. This point was also shown by the NCAT study. The degree of saturation depends on the amount of water present within the HMA void space. As testing has shown, the amount of time required for a pavement to fully saturate is inversely proportional to the permeability of the pavement. That is, the more permeable the surface, the less time it takes a sample to saturate. Another factor that may affect the coefficient of permeability is the compactive effort used to compact the mixture to achieve density. Intuitively, the more a sample is compressed, the tighter and less permeable it would be.

The majority of previous work on asphalt pavements was conducted in falling-head permeameters using cores cut from the roadway. It is important to note that Darcy’s law is applicable to one-dimensional flow as is the case during a laboratory test. Measuring in-place permeability is more difficult, because of water flow in both horizontal and vertical directions.

A conclusion of the NCAT report indicated that the NCAT device might be a solution for the measurement of in-place permeability of HMA layers. This conclusion led the Kentucky Transportation Center to purchase a gauge and perform its own testing and analysis on the device. The device was purchased at the end of the 1999 construction season and was used on a 0.5-inch Superpave surface mixture on a three-mile section of US 150 in Lincoln County. There was no analysis of this data because the project was only used to acquaint the research team with the use of the device.

While the overall impression of the device was favorable, some problems were recognized by the Transportation Center during the project. The most recognizable problem was the inability of the gauge to achieve saturation in a reasonable period of time. The time required to apparently reach saturation on low permeability layers occasionally was over an hour for one test location. After tests ran over the one-hour mark for a single site, it was quickly recognized that this test method might not be the most efficient way of measuring permeability in the field. Also, due to the extended nature of the testing procedure, the silicone sealant used to seal the device to the pavement actually cured while testing, proving difficult to remove at the end of the test.

An additional problem was the inability of the gauge to test in superelevated areas, due to the sliding of the gauge on the pavement. However, when the gauge was placed on a level surface and given ample time to reach saturation, results appeared to be reasonable. Because the results did appear to be reasonable when the test was performed properly, it was decided to use this device as a “referee test” against which to compare other methods and permeameters to be developed and/or tested in this study.

Florida Department of Transportation / Karol-Warner

To accomplish Objective 2 of this study, a review of the available laboratory permeameters for testing HMA was performed. One notable device was developed by the

Florida Department of Transportation (FDOT) for testing the permeability of asphalt pavements in the laboratory. After gaining approval of the FDOT, the device quickly gained popularity around the transportation industry as the standard for laboratory testing and has now been adopted as an ASTM test method. Karol-Warner, Incorporated manufactures a modified version of the FDOT device. The device is shown in Figure 3.

Figure 3. Laboratory Permeability Device.

Being a laboratory test, it is by default a destructive test, as cores must be cut from the pavement. Unlike the device developed by the FDOT, which used epoxy resin, the device manufactured by Karol-Warner uses a flexible latex membrane to seal the sidewalls of the core. Based on the practicality of this device, as well as its recent adoption by ASTM, the Kentucky Transportation Center purchased one of these chambers and used it as a standard in this study for calculating the laboratory permeability of a sample.

The apparatus consists of a vertical graduated standpipe, two expandable pressure rings, a six-inch aluminum containment cylinder fitted with a latex membrane, a water-release valve, and a manual air pump with a gauge. As part of the testing procedure, the sample must be saturated in a deaeration chamber under 26 inches of Hg for 15 minutes. The sample is then placed into the chamber where the latex membrane is pressurized to prevent the bypass of water around the sample. The standpipe is then filled with water; the valve is released, and the time for the water level to fall from an initial head to a final head is recorded. The time, as well as the core dimensions, are entered into Equation 1.0 to calculate a coefficient of permeability.

Overall, the device appeared to be reasonably effective for testing one-dimensional flow through the pavement core samples. The device appeared to work well when great care and time were used to run the test. The high possibility of human error and the complex, time-consuming process were the only negative aspects found concerning the device.

DESIGN AND DEVELOPMENT OF THE AIR INDUCED PERMEAMETER (AIP)

After completion of the evaluation of previously tested permeability devices, the next objective (Objective 3) was to develop a rapid and repeatable field test for measuring permeability of asphalt mixtures and aggregate bases. As described in the earlier sections of this report, most of the permeameters had relatively the same problems. One of these problems was the permeameters' inability to measure highly porous surfaces. So naturally, this was the first goal of a new permeameter. Another desirable feature of the device was portability and efficiency. The construction of this permeameter had to be user-friendly and lightweight while, at the same time, have sufficient durability to withstand repeated use in the field. Most importantly, the device had to be repeatable. Also, the other methods were too labor-intensive to be used in the field, and the device in development needed to be quick and error-free.

It was decided that vacuum, rather than water or pressurized air, would be used. The use of a vacuum would enable the permeameter to be self-sealing. The use of vacuum rather than water increases the portability, as well as the user-friendly aspect, of the device. The gauge was constructed out of heavy-duty LEXAN®, which produced a lightweight and transparent device. Being able to see through the device during testing proved to be a great asset.

The overall dimensions of the gauge were calculated based on the nominal-maximum size of aggregate to be tested. A fault of some of the other devices was that they did not measure a representative sample size. Therefore, the inner chamber of the AIP device was chosen to be eight inches in diameter. The sealing ring, which is in contact with the surface of the pavement, needed to be of sufficient size to close off any surface pathways that would enable air to pass under the gauge. A ring of three inches in width was chosen, as this dimension is twice the largest nominal aggregate size of 1.5 inches found in some HMA base mixtures. Figure 4 is a photograph of the AIP.

Figure 4. Air-Induced Permeameter.

A multi-venturi vacuum cube was used to produce the volume and vacuum required for this device. A multi-venturi, in simple terms, is a series of nozzles arranged from largest to smallest through which pressurized air passes at a constant pressure. A multi-venturi can evacuate four times more air than a single-venturi. It was then necessary to find a digital vacuum gauge with less than 0.01 percent error and with a range of 0 to 700 mm Hg. A gauge manufactured by DCT Instruments was used.

The AIP works on the principle of forcing pressurized air at a constant pressure of 68 pounds per square inch through a multi-port venturi. This condition creates a vacuum within the chamber that draws air through the pavement voids and registers a vacuum reading on the gauge. The theory behind the AIP gauge is based on the simple principle that the more difficult it is to draw air through the pavement, the smaller the voids space must be in the underlying pavement layers. As discussed previously, it is assumed that a smaller percentage and size of voids in the pavement indicate a lower permeability. In the following discussions, it is important to remember that high readings on the AIP mean a low permeability, and low reading mean a high permeability – an inverse relationship.

During the initial testing phase, the gauge experienced some problems. The original design called for a closed-cell neoprene sealing ring to be used. This neoprene ring did not seal sufficiently when testing highly permeable samples. The neoprene seal had to be abandoned. The seal was changed to a 0.5-inch bead of liquid silicone applied just inside of the outside ring base. This approach proved very effective and repeatable.

The hose connecting the vacuum chamber to the venturi was found to generate a residual vacuum of 51 mm Hg during open air testing. To resolve this problem the digital vacuum gauge was moved from the venturi to the vacuum chamber itself. After these modifications, the gauge appeared to work well, producing repeatable results.

To test the repeatability of the AIP, a series of tests were performed on KY 4, Fayette County. These tests were used for the repeatability study and were not analyzed further. Approximately 30 tests were performed at the same location on the pavement. The repeatability tests were performed on a 0.5-inch surface mixture and a 0.75-inch base mixture. The results can be seen in Figures 5 and 6. The mean vacuum reading for the 0.75-inch base was 451 mm Hg with a standard deviation of 2. The mean vacuum for the 0.5-inch surface was 219 mm Hg with a standard deviation of 1. From this information, it appeared that the AIP could be correlated to field permeability rates and was ready to be applied to several experimental projects.

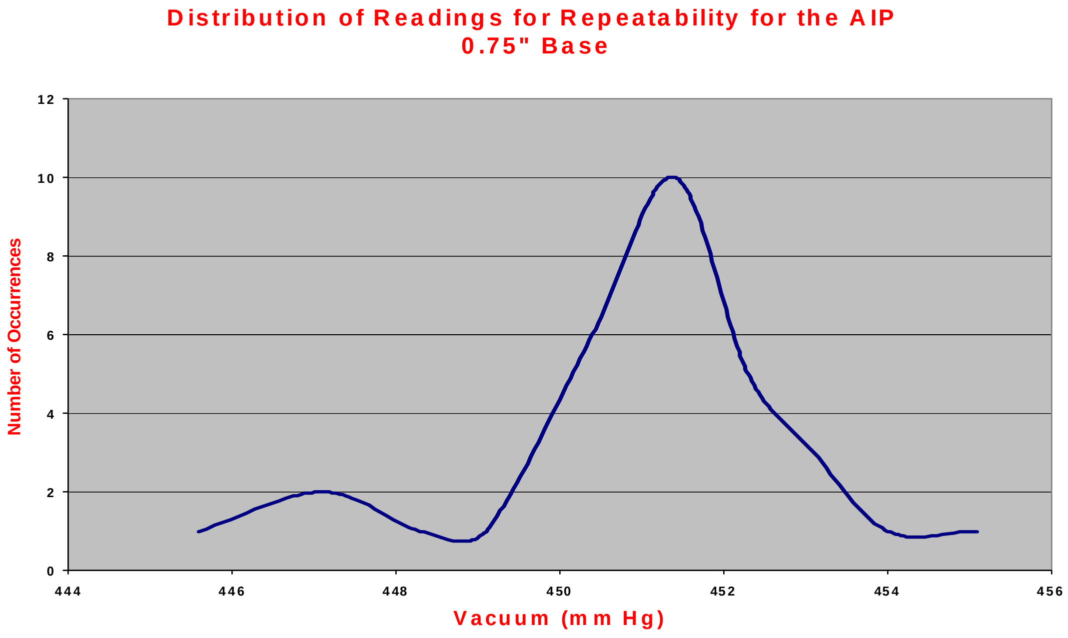

Figure 5. Distribution of Repeatability Readings for AIP, 0.75" Base.

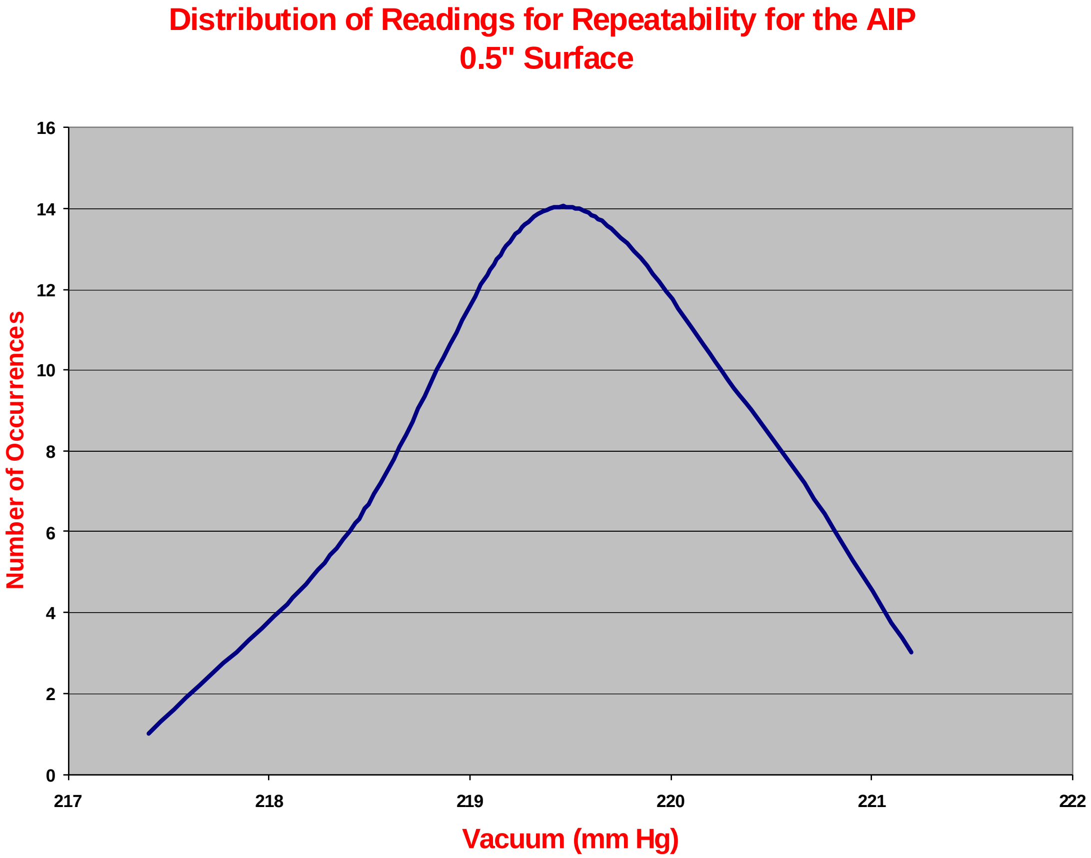

Figure 6. Distribution of Repeatability Readings for AIP, 0.50” Surface.

TEST PROCEDURES

The procedures described in this section were developed during this study, and detail how the AIP is to be used for measuring vacuum. Additionally, these procedures could be used as a basis for development of a Kentucky Method that describes a procedure for determining field permeability using the AIP

Initial Setup

The first step in the testing procedure is to do a complete check of the AIP. Look to see if any damage has occurred to the gauge. Check all seams and orifices to see if they are in good working order. Turn on the digital vacuum pressure gauge, and check to see that it is in the *mm Hg* read mode (Figure 7). The display should read *mm Hg* when turned on. Next, zero the gauge by holding down the button marked "zero" for five seconds. This operation should be performed only once per day. When using the device, be sure that the silicone pressure ring is free of debris before each test. The presence of debris can decrease the reading, making it difficult to obtain an accurate reading.

Figure 7. Digital Pressure Gauge.

Silicone Pressure Seal

Once the silicone pressure ring is checked for debris, apply a one-half-inch bead of non-acrylic silicone rubber caulk one inch inside of the outside face of the silicone ring. This practice will seal surface voids that are too deep to be sealed by the silicone ring. It is important to keep the bead to the outside of the pressure plate; the vacuum will draw the silicone towards the center, thereby distributing the silicone across the sealing surface. Figure 8 illustrates the above procedure.

Figure 8. Placement of Silicone Bead.

Placement

Once the above procedure has been completed, the AIP can be placed on the asphalt mat. Place the permeameter in the center of the marked area, using caution not to move the permeameter in the lateral direction during or after placement. As the permeameter is placed on the pavement, apply a downward force of no more than 50 pounds while twisting it about 1/8 of a turn (see Figures 9 and 10). The twisting motion rids the silicone of any gaps and air bubbles trapped in the caulk and ensures a good seal on the pavement. It is important not to "over-twist" the device; this action can cause the penetration of silicone into the pavement, increasing the value recorded on the digital pressure gauge.

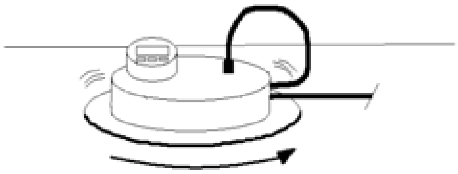

Figure 9. Seating of Silicone Pressure Ring.

Figure 10. Placement of AIP.

Reading Phase

Once the above steps are completed, the reading can begin. Open the valve on the permeameter to permit the flow of air through the venturi. The number on the LCD of the digital vacuum gauge will begin to climb. When this number reaches its peak, the test is finished, and the valve can be shut. The test time will vary depending on the permeability of the pavement and type of pavement being tested, but should not exceed 15 seconds.

Clean the bottom of the gauge, and record the highest reading attained by the permeameter by pressing the button marked *HI/LO* once. It is important not to let the permeameter run for an extended period of time. This practice may cause delamination, or "humping," of the pavement. This point is especially important for hot, fresh-laid pavements. A rule of thumb is not to test any pavement above 130° F. Figure 11 shows a reading in progress.

Figure 11. An AIP Reading in Progress.

CORRELATIONS BETWEEN THREE PERMEAMETERS

From the previous section, it was clearly demonstrated that the readings from the AIP were very repeatable. However, can this device be correlated with other instruments or permeameters? Objective No. 4 of this study was "to correlate this device with known laboratory testing procedures." However, it was also important to correlate the AIP with a field permeameter. Therefore, it was decided by the research team to attempt to correlate the AIP with the NCAT field permeameter (Figure 12) and the Karol-Warner laboratory permeameter.

Eleven field construction projects were selected from which to collect data and make the correlations. Table 1 lists the projects and the types of tests that were performed on each project, and the "raw" data for each project are listed in Appendix A. All tests were not performed on all projects due to the contractors' schedules and traffic control conditions. There were two 0.375-inch surfaces, six 0.5-inch surfaces, one 0.75-inch binder/bases, two1.0-inch bases, and one 1.5-inch base.

Figure 12. NCAT Permeameter in Place and Being Filled with Water.

Table 1. Projects Used in This Study and Types of Data Collected.

PROJECT	Test Data Collected															
	0.38” Surface				0.5” Surface				0.75” Base				1.0”/1.5” Base			
	F.D.	F.P.	L.P.	VAC	F.D.	F.P.	L.P.	VAC	F.D.	F.P.	L.P.	VAC	F.D.	F.P.	L.P.	VAC
US 127, Casey County					X		X	X								
US 68, Barren County	X		X	X												
US 31W, Hardin-Meade Counties					X		X	X								
US 460, Menifee County	X		X	X												
KY 80, Laurel County					X		X	X								
US 60B, Daviess County					X		X	X								
KY 3005, Hardin County										X		X				
KY 491, Grant County														X	X	X
I-75, Madison County															X	X
I-75, Laurel County					X	X		X								
Bluegrass Parkway, Nelson County						X		X						X		X

F.D. B **Field Density**
F.P. B **Field Permeability (NCAT Permeameter)**
L.P. B **Laboratory Permeability (Karol-Warner)**
VAC B **Field Vacuum (AIP)**

Permeability tests in the field were performed at the longitudinal construction joint, at six inches from the joint, at 18 inches from the joint, and at six feet from the joint (centerline of the lane). The sequence of testing was as follows: a test location was marked, a field density test (nuclear density gauge) was performed, the AIP test was performed, the NCAT permeameter was used, and finally, cores were extracted at the test location (where possible) for the purpose of performing the laboratory permeability test. Laboratory density tests were not preformed on the cores. Figure 13 shows field testing and coring in progress.

Figure 13. AIP Reading and Coring at Test Site.

Correlations of AIP with Laboratory Permeameter

Figures 14 through 21 show the correlations that were developed between the AIP and the laboratory permeameter.

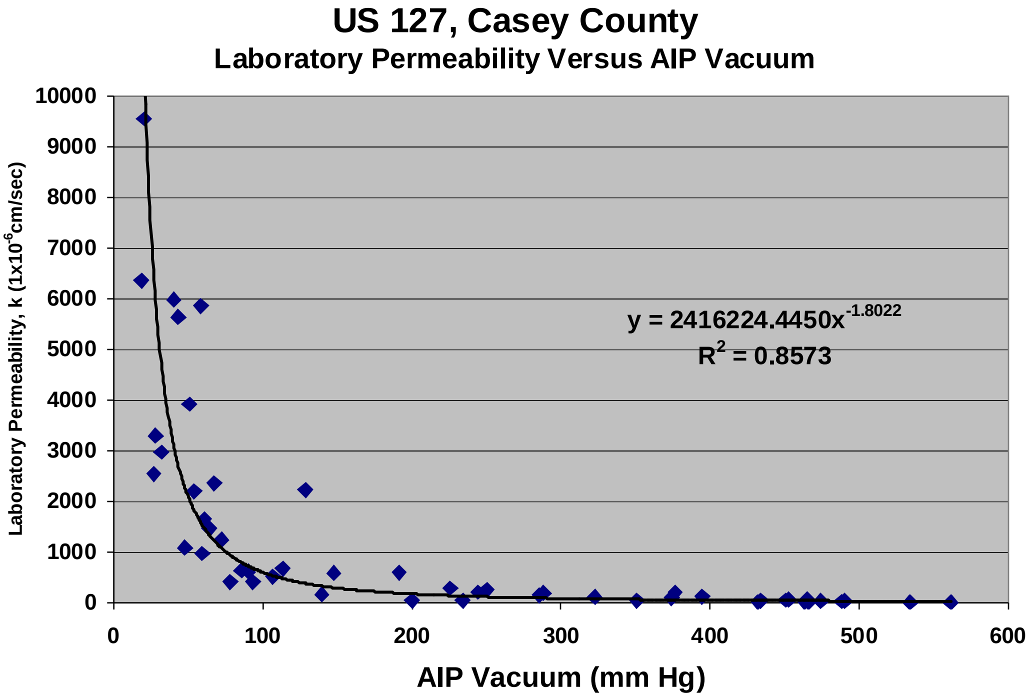

Figure 14. Laboratory Permeability Versus AIP Vacuum, US 127, Casey County.

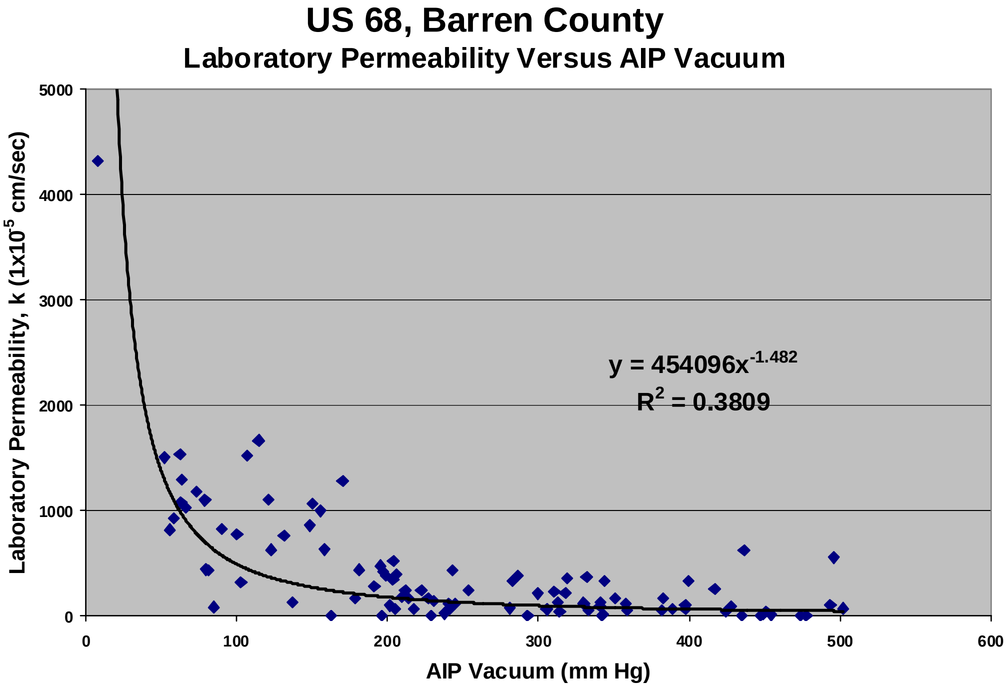

Figure 15. Laboratory Permeability Versus AIP Vacuum, US 68, Barren County.

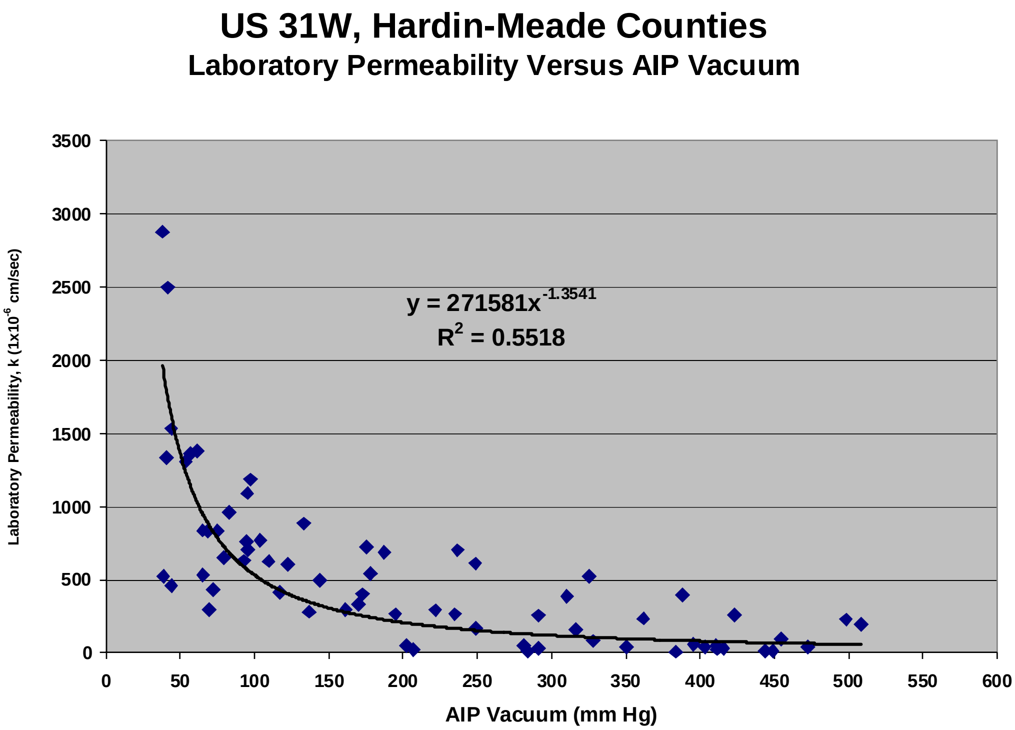

Figure 16. Laboratory Permeability Versus AIP Vacuum, US 31W, Hardin-Meade Counties.

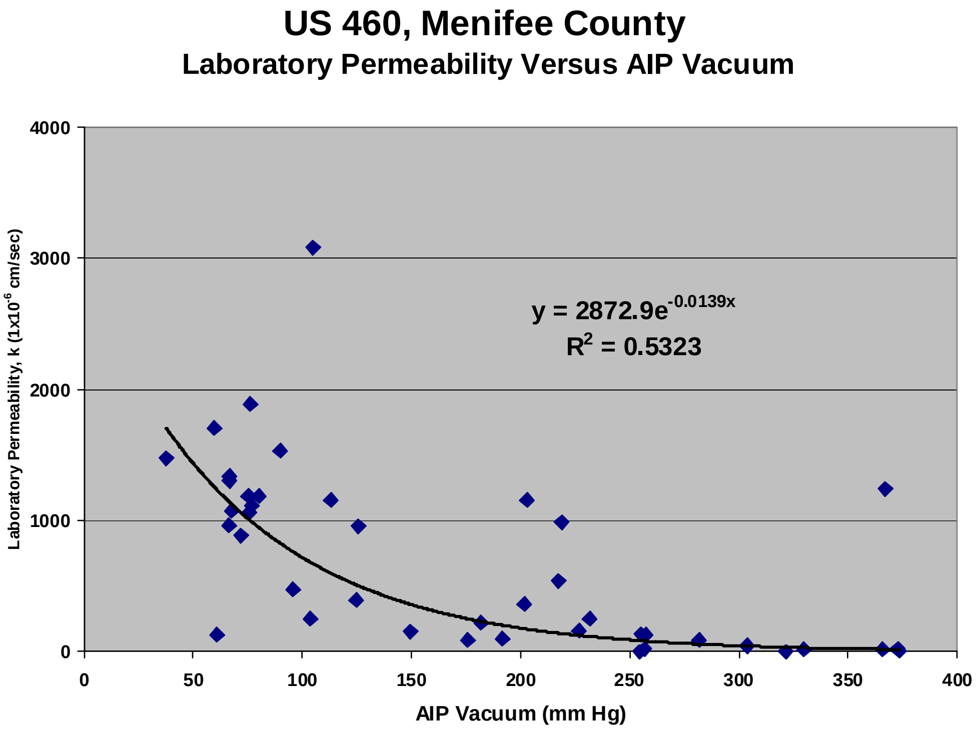

Figure 17. Laboratory Permeability Versus AIP Vacuum, US 460, Menifee County.

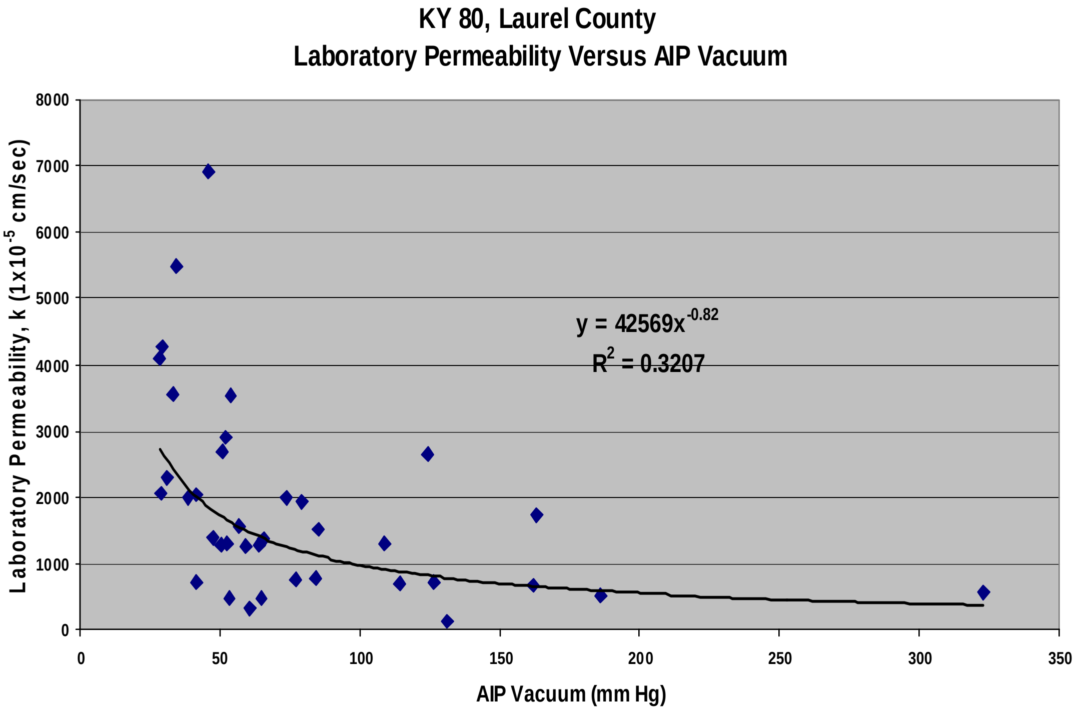

Figure 18. Laboratory Permeability Versus AIP Vacuum, KY 80, Laurel County.

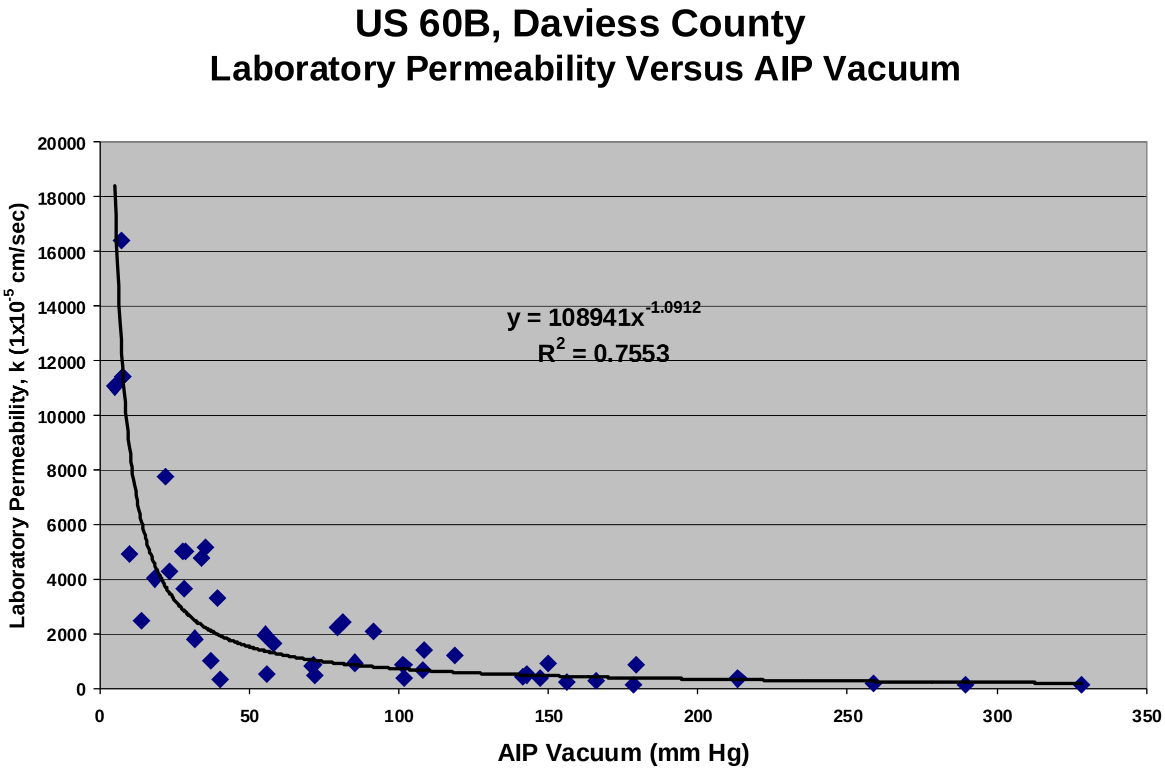

Figure 19. Laboratory Permeability Versus AIP Vacuum, US 60B, Daviess County.

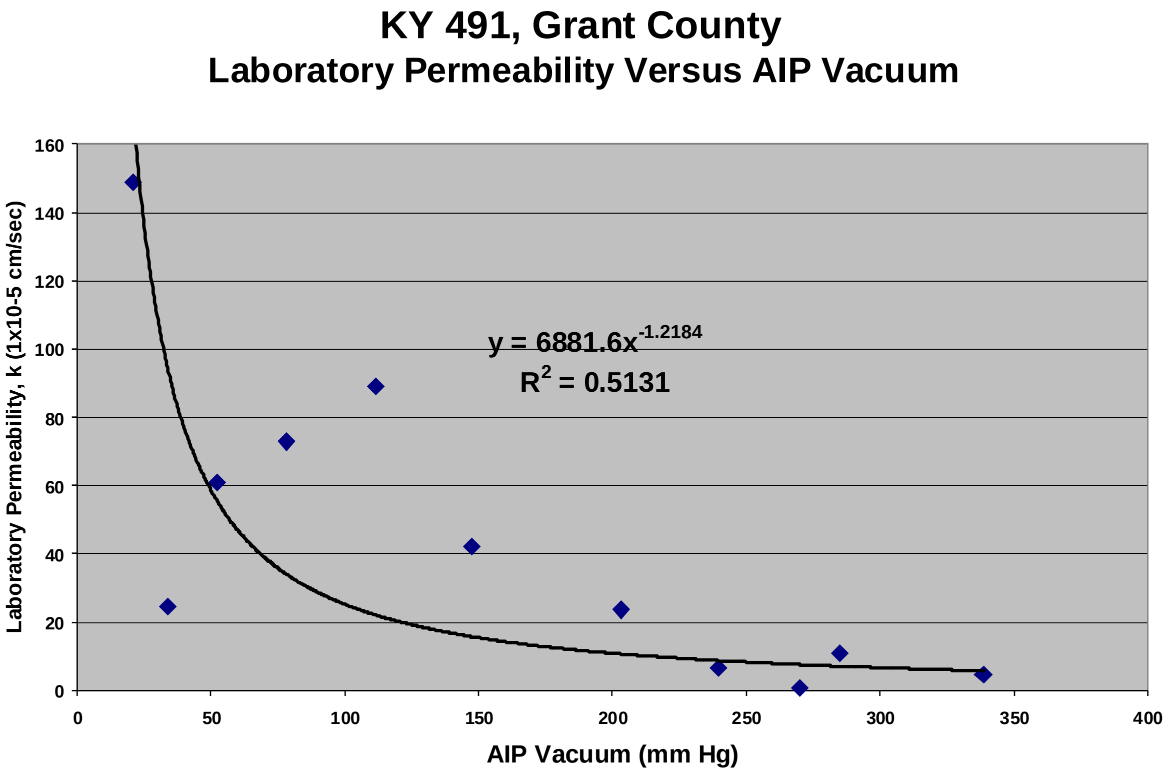

Figure 20. Laboratory Permeability Versus AIP Vacuum, KY 491, Grant County.

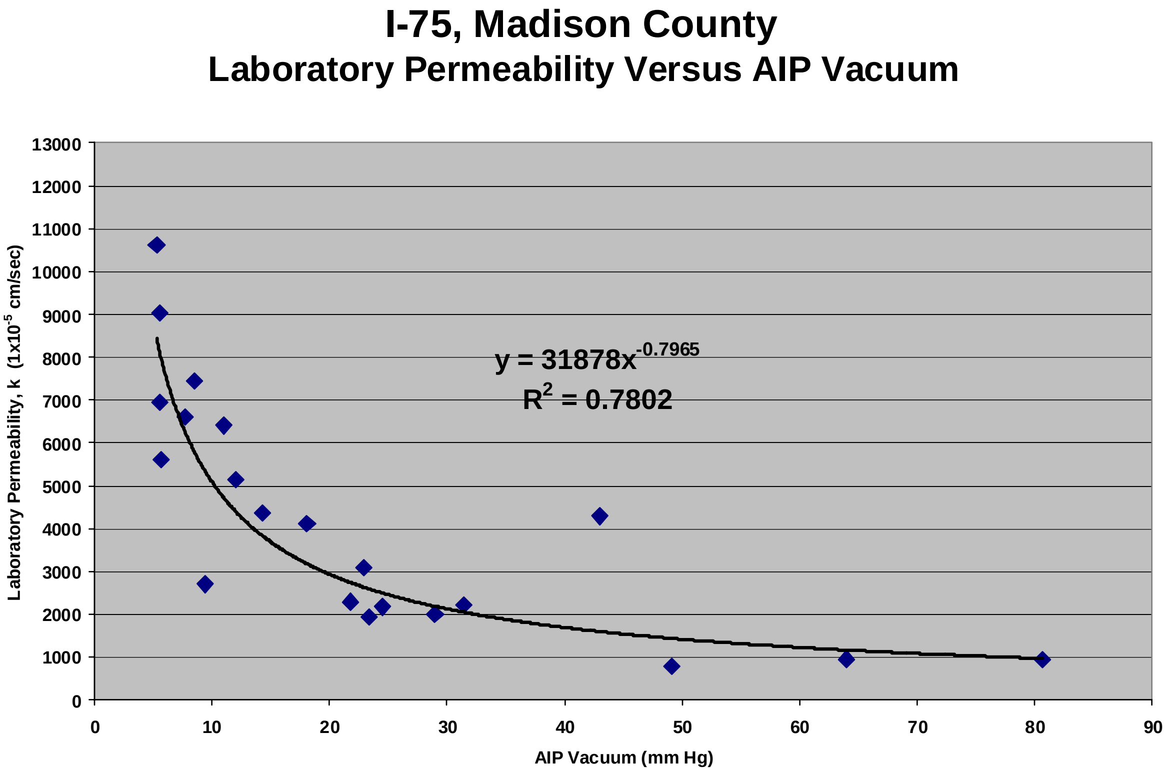

Figure 21. Laboratory Permeability Versus AIP Vacuum, I-75, Madison County.

A review of the previous figures shows that there is not a “good” ($R^2 > 0.80$) correlation between the AIP and the laboratory permeameter. Only US 127, Casey County, had an R^2 greater than 0.80. It is suspected that the reasons for the poor correlations are because the laboratory permeameter measures permeability in only one direction (vertical) while the AIP also measures some horizontal flow in addition to the vertical flow.

Also, to perform the laboratory permeability test, it is necessary to saw off the pavement layer to be tested from the rest of the core. It is suspected that this process may, in some way, alter the face of the core by “smearing” some of the asphalt binder and possibly sealing small voids. Conversely, the sawing operation may “open” some voids and change the permeability.

Correlations of NCAT Field Permeameter (NCATP) with Laboratory Permeameter

There were only two field construction projects where both the laboratory and the NCAT field permeability tests were conducted. Those projects were KY 3005, Hardin County and KY 491, Grant County. Figures 22 and 23 show the relationship between the NCATP and the laboratory permeameter for those two projects.

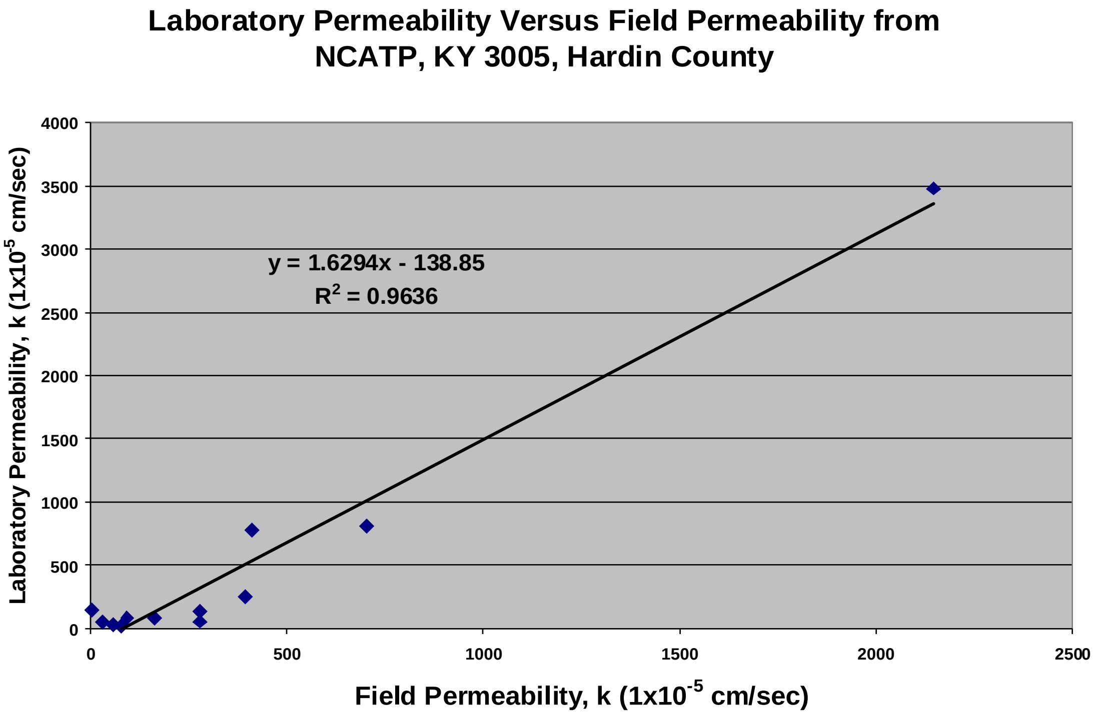

Figure 22. Laboratory Permeability Versus NCATP Field Permeability, KY 3005, Hardin County.

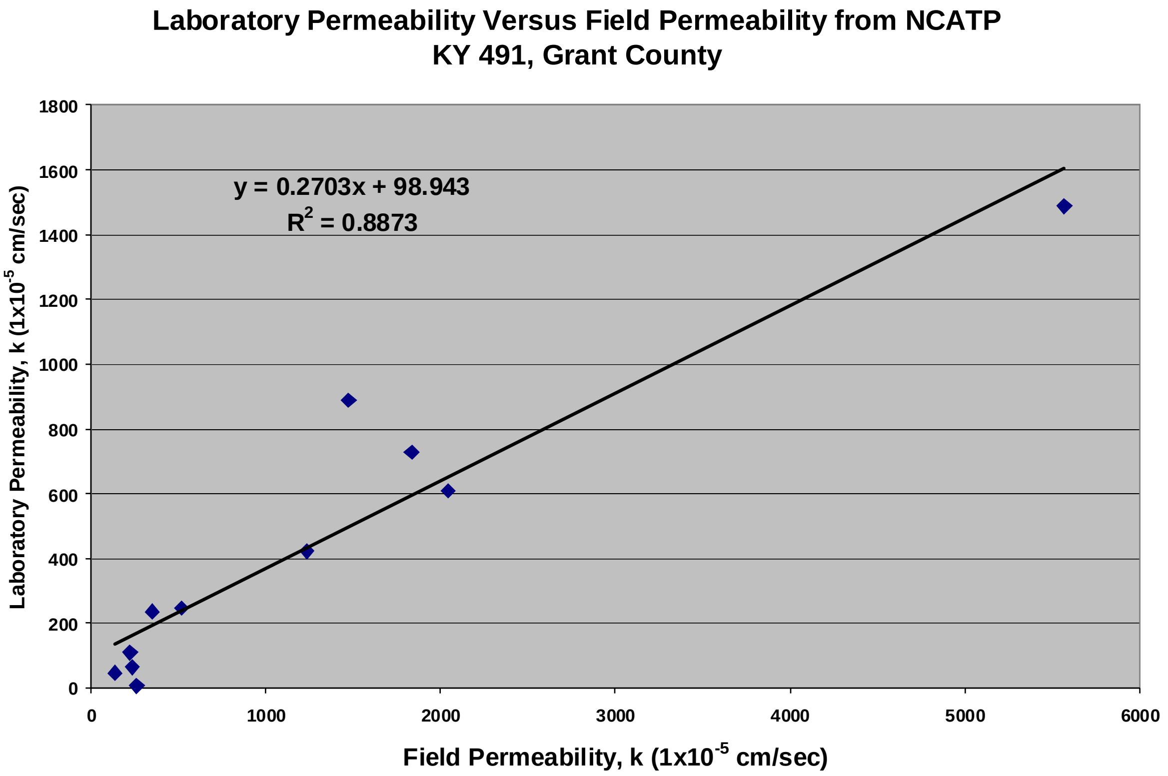

Figure 23. Laboratory Permeability Versus NCATP Field Permeability, KY 491, Grant County.

Good correlations were developed between the laboratory permeability and the field permeability determined by the NCATP for the two projects (when analyzing project- specific data). KY 3005 had an R^2 of 0.96, and R^2 for KY 491 was 0.89. However, the slopes of the regression equations were significantly different between the two projects. The slope of the regression line for KY 3005 was 1.63 and the slope for KY 491 was 0.27. This value indicates that the reported laboratory permeability for KY 3005 was over 150 percent higher than the reported field permeability. However, for KY 491, the reported laboratory permeability was approximately 30 percent of the field permeability. It is not clear why there was such a significant difference in the calibrations between the two methods for the two projects. Although it would appear that this difference would preclude the development of a calibration between the laboratory and NCATP permeameters, more data would be needed to determine if, in fact, a calibration exists between the two permeameters.

Summarizing this section of the report, Figures 14 through 21 show that there is clearly a strong trend between laboratory permeability and AIP vacuum; however, because of the large amount of “scatter” in the data it would be unadvisable to develop of a predictive calibration equation between the AIP and the laboratory permeamter. Although the correlation between the NCATP and the laboratory permeameter appeared to be good on a project-level basis, the calibrations were very different between the two projects. To be a viable calibration, it must be essentially the same among all projects. Figure 24 shows the two projects plotted together. A regression analysis on the combined data clearly shows a very poor correlation (R^2=0.39). Because of the low R^2 value, no calibration was developed between the NCATP and the laboratory permeameter.

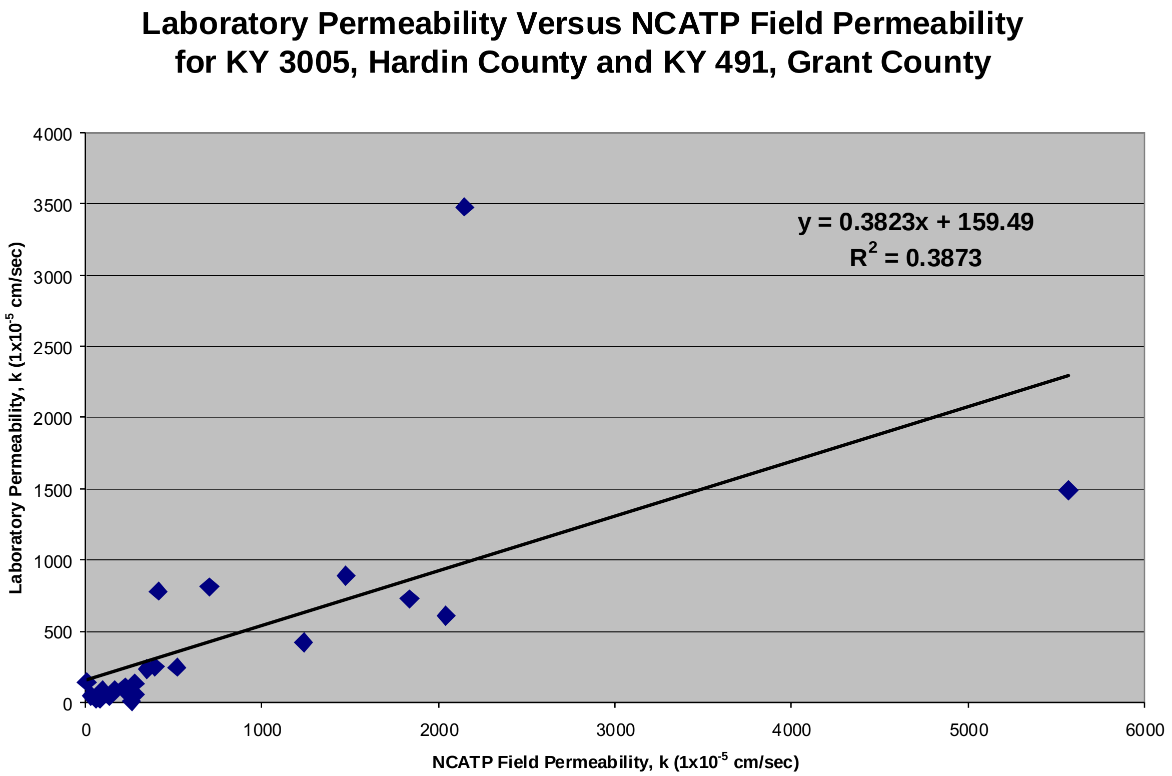

Figure 24. Laboratory Permeability Versus NCATP Field Permeability for KY 3005, Hardin County and KY 491, Grant County.

Correlations Between AIP and NCATP

To compare data and to develop correlations between the AIP and the NCATP, data from six construction projects were used in the analysis. These comparisons and analyses are shown in Figures 24 through 29.

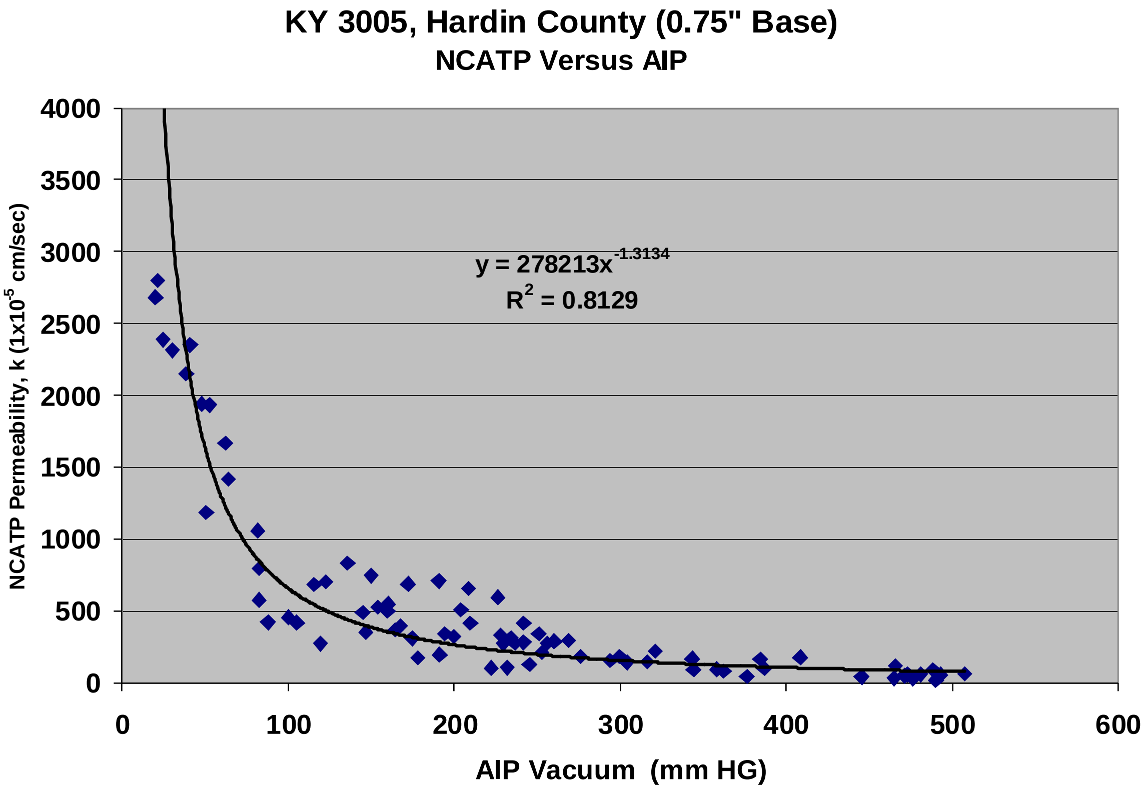

Figure 25. NCATP Permeability Versus AIP Vacuum, KY 3005, Hardin County.

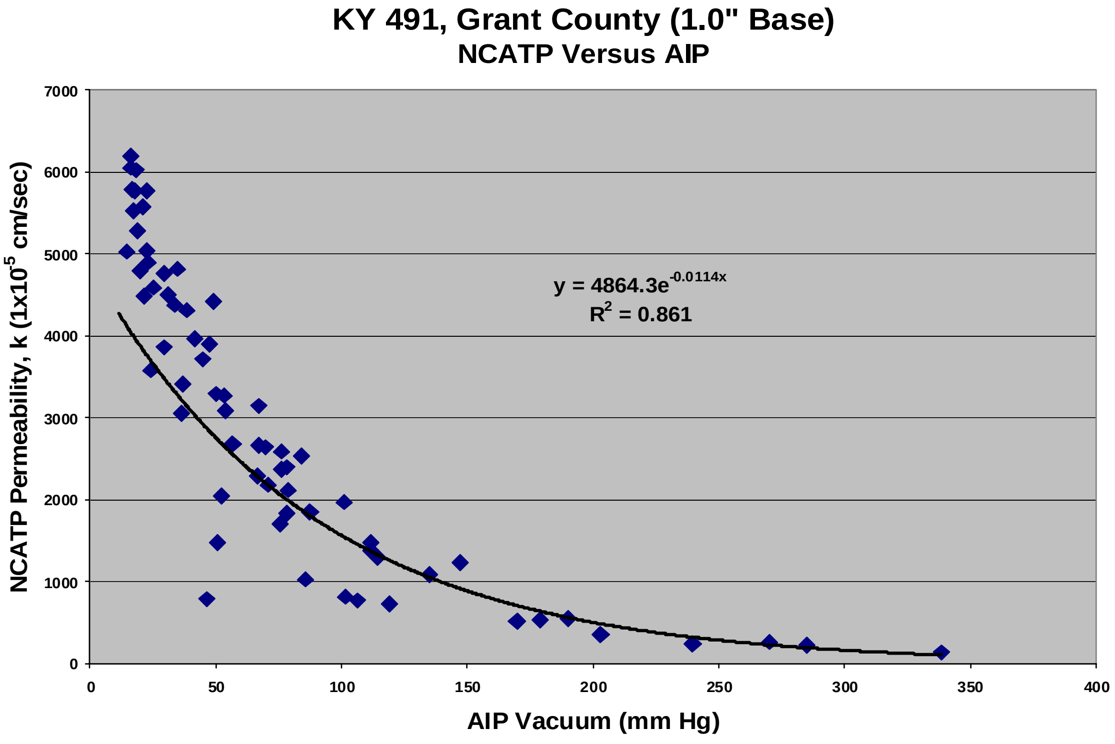

Figure 26. NCATP Permeability Versus AIP Vacuum, KY 491, Grant County.

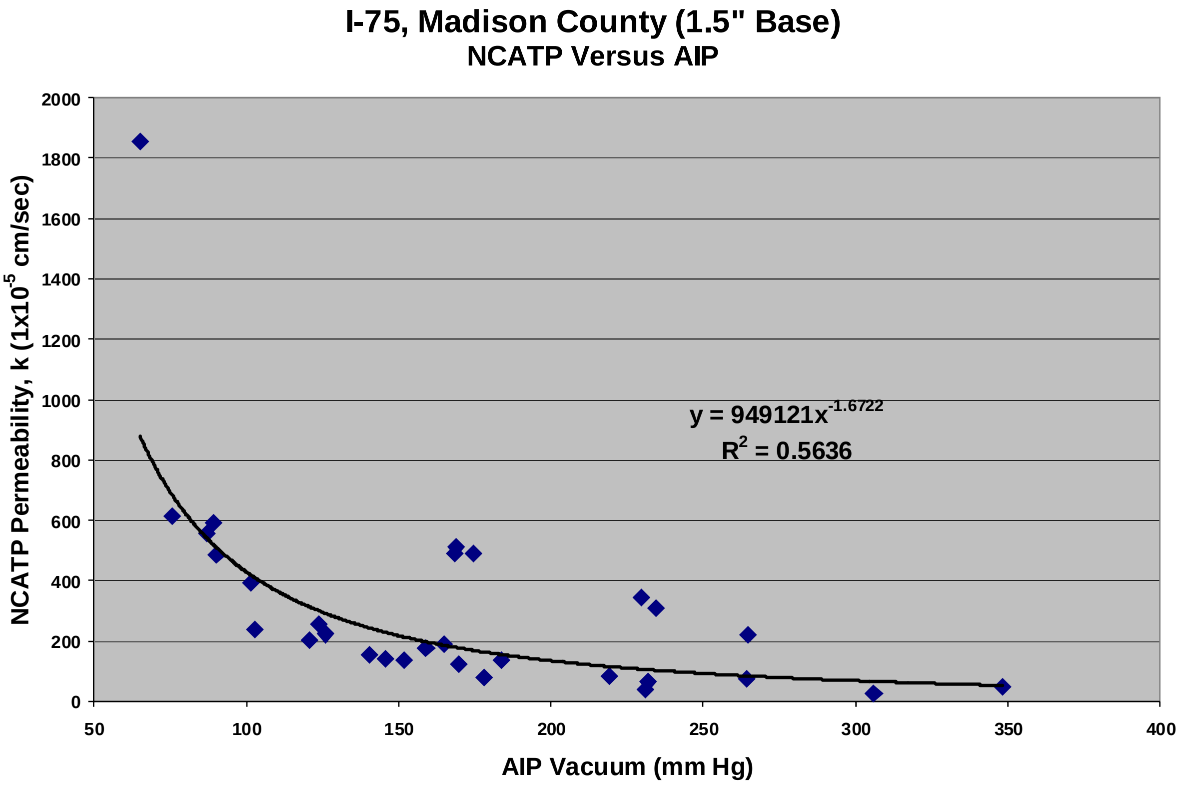

Figure 27. NCATP Permeability Versus AIP Vacuum, I-75, Madison County.

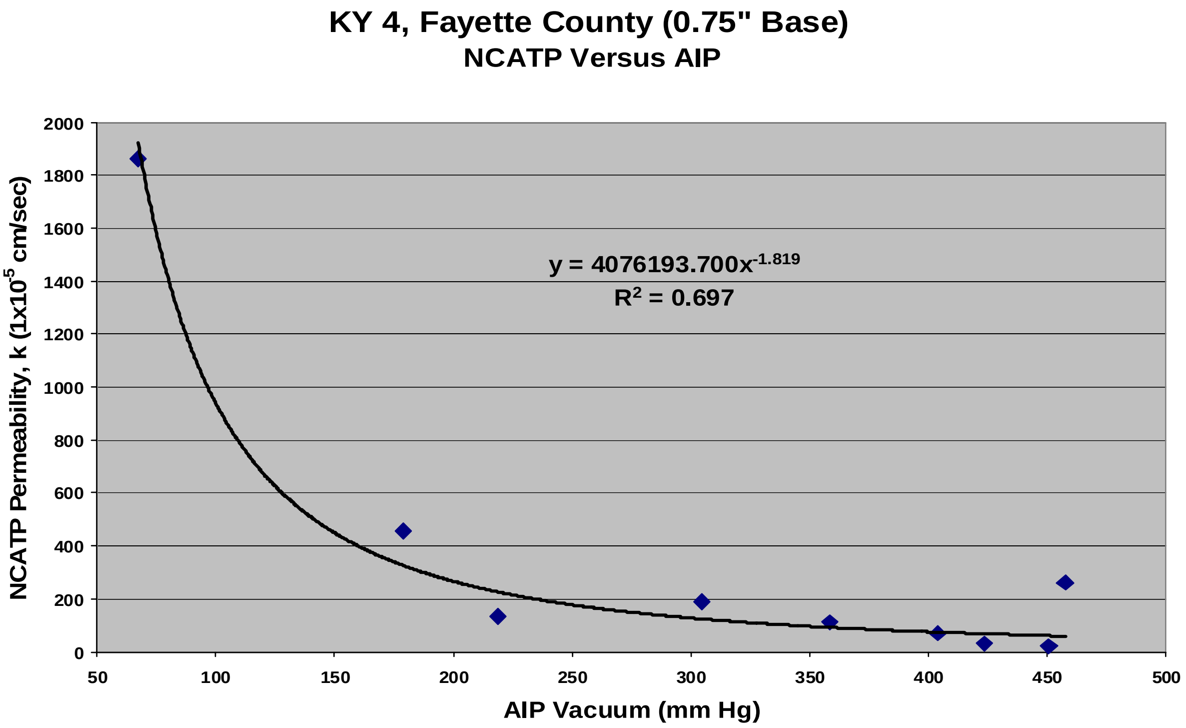

Figure 28. NCATP Permeability Versus AIP Vacuum, KY 4, Fayette County.

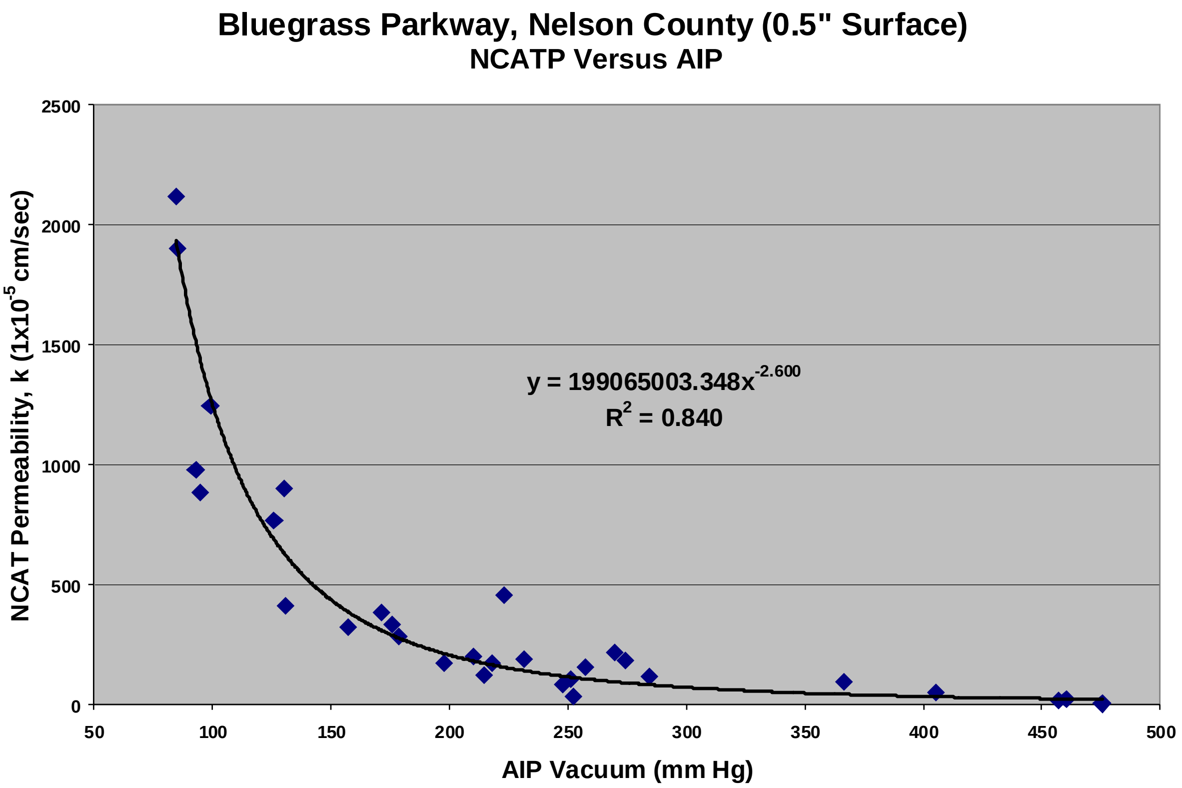

Figure 29. NCATP Permeability Versus AIP Vacuum, Bluegrass Parkway, Nelson County.

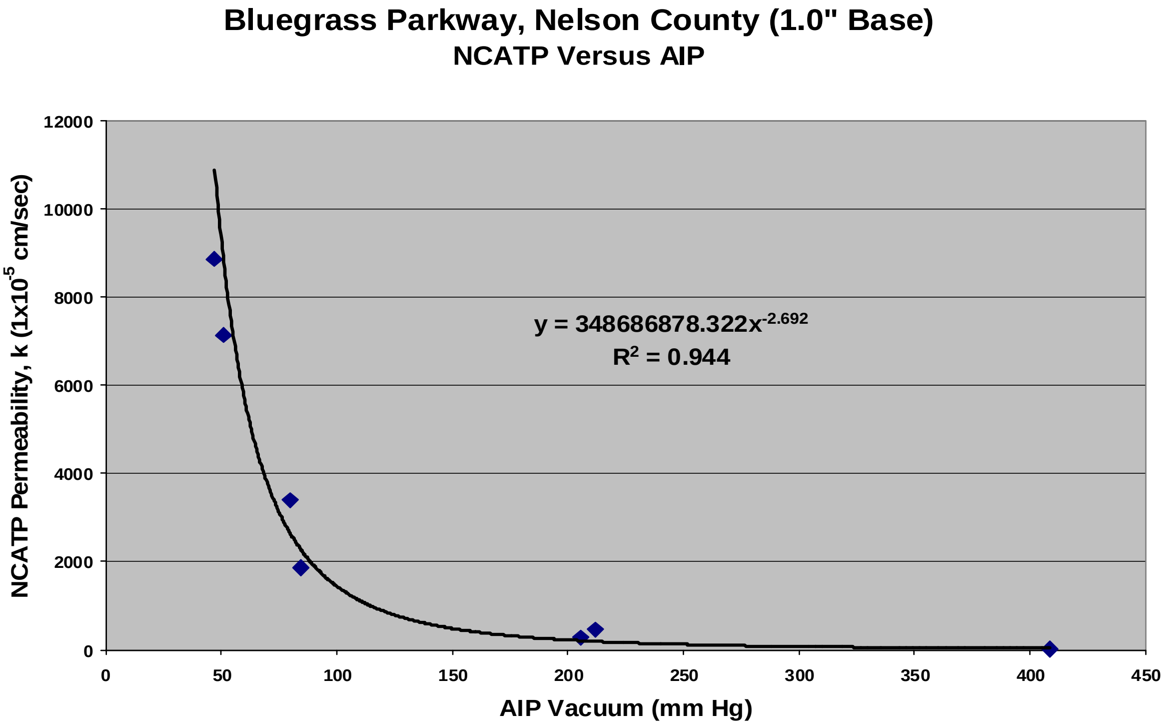

Figure 30. NCATP Permeability Versus AIP Vacuum, Bluegrass Parkway, Nelson County.

Four of the six projects had R^2 values greater than 0.80. I-75, Madison County (1.5" base), and KY 4, Fayette County (0.75" base), had R^2 values of 0.56 and 0.70, respectively. Because the majority of the projects yielded "good" R^2 values, it was decided to combine the data from all of the projects in an attempt to develop a "universal" correlation between the AIP and the NCATP. Figure 31 shows the results of all the data combined.

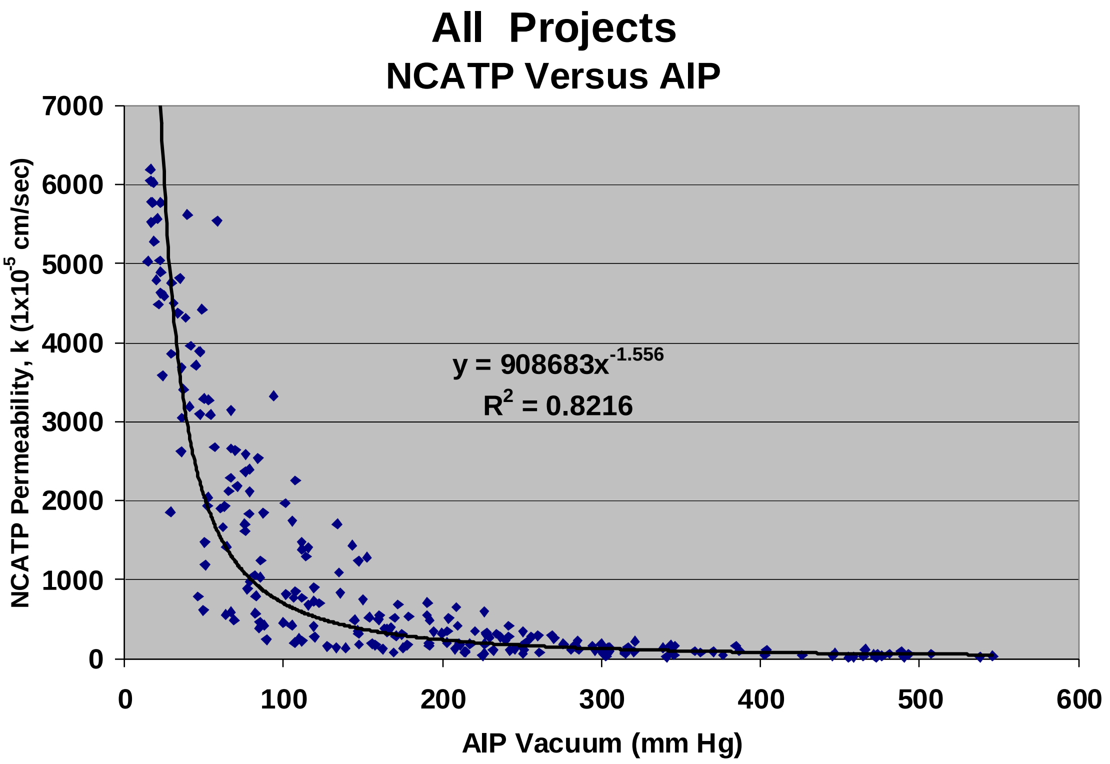

Figure 31. Correlation Between NCATP Permeability and AIP Vacuum for All Projects.

A regression analysis on the combined data yielded a "good" relationship with an R^2 of 0.82. Based on this analysis, it was decided to use the regression equation as the calibration equation between the two devices. That calibration equation is as follows:

$$\text{Permeability} = 908683 * (\text{AIP Vacuum})^{-1.556} \qquad \text{Eq. 2.0}$$

Would the calibration factor between the two devices be different for base mixtures versus surface mixtures? To answer this question, a regression analysis was performed on the data from the base mixtures and also on the surface mixtures only. The results of those analyses are shown in Figure 32.

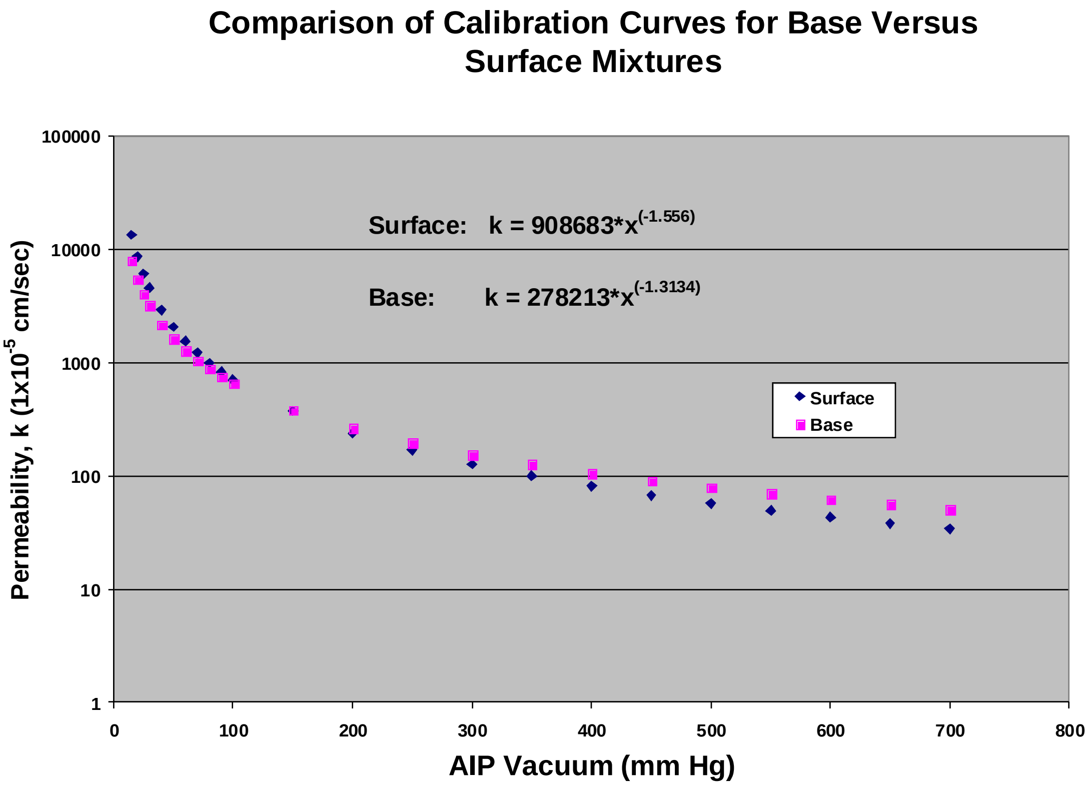

Figure 32. Comparison of Regression Analyses Between NCATP Permeability and AIP Vacuum.

It is clear from Figure 32 that the two regressions are very similar, and that the calibration between the two devices was not particularly sensitive to mixture type. As a result, it was decided to use Equation 2.0 as the calibration between the two permeameters.

COMPARISON OF AIP WITH FIELD DENSITY

Because density is the only property that is monitored in the field, an analysis was performed comparing the percent of maximum theoretical density (hereafter referred to as “percent maximum density” or “percent density”) of the asphalt mat (measured by a nuclear density gauge) with vacuum readings from the AIP. The average maximum specific gravity from all the sublots was used for this analysis. Figures 33 through 39 show the relationships that were developed for seven of the 12 projects in this study.

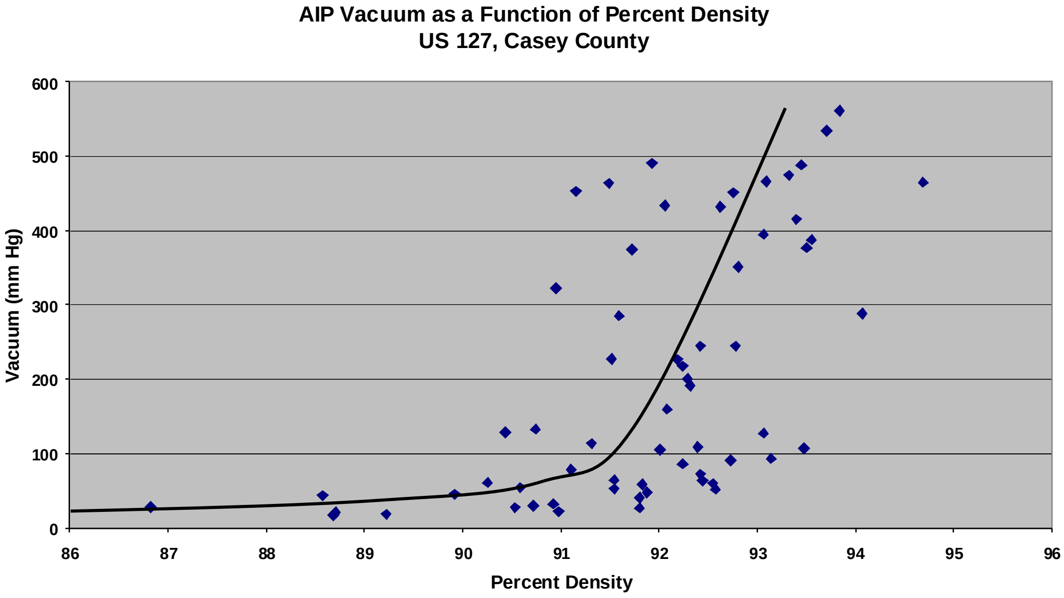

Figure 33. AIP Vacuum Versus Percent Density, US 127, Casey County.

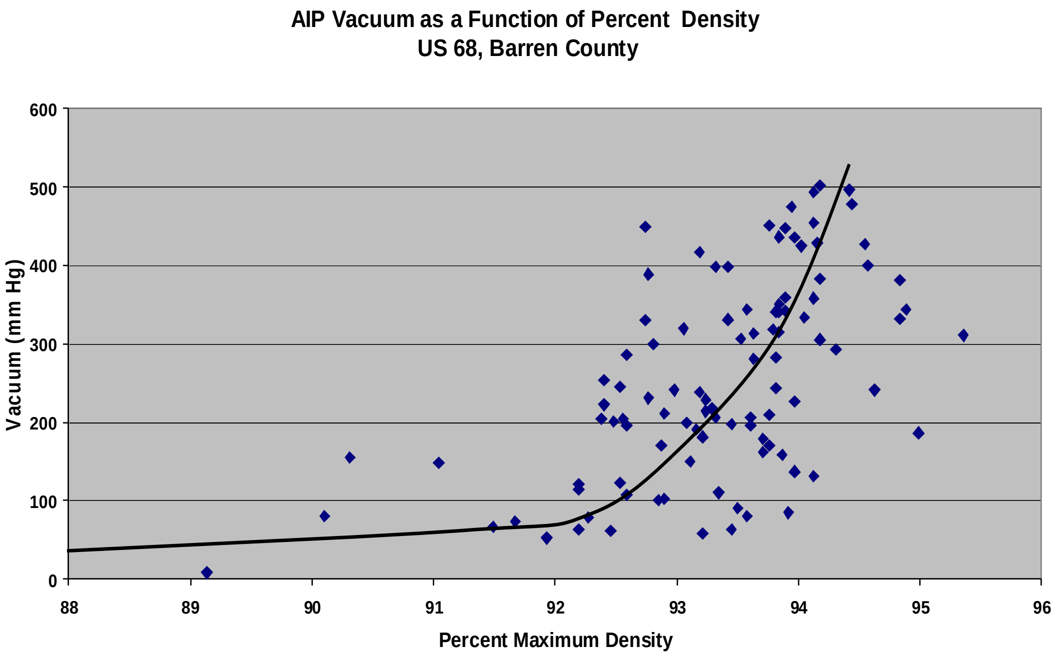

Figure 34. AIP Vacuum Versus Percent Density, US 68, Barren County.

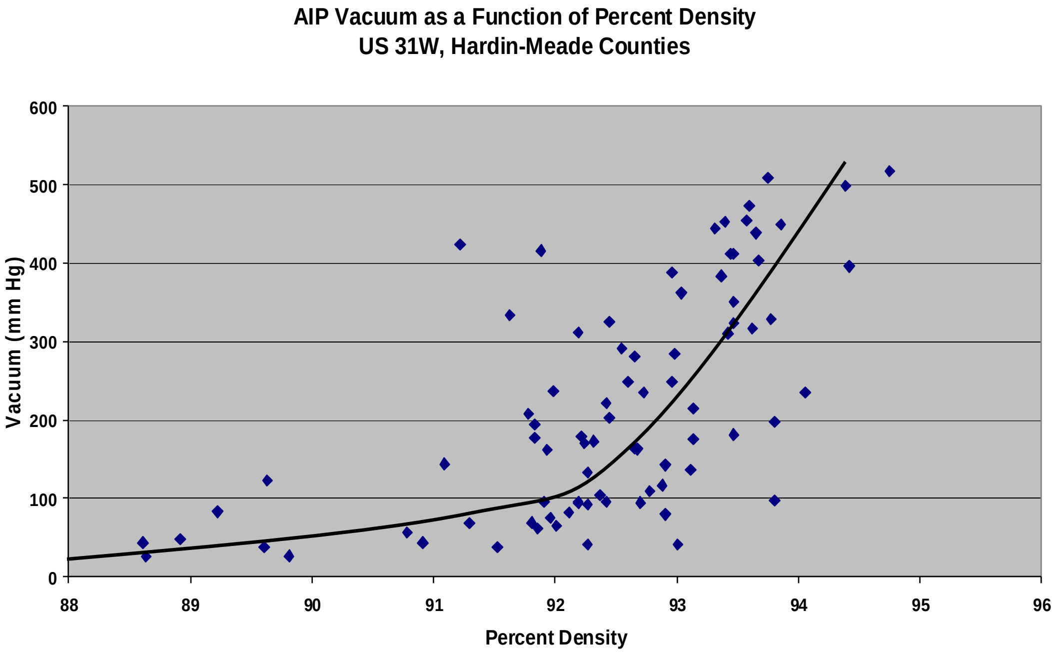

Figure 35. AIP Vacuum Versus Percent Density, US 31W, Hardin-Meade Counties.

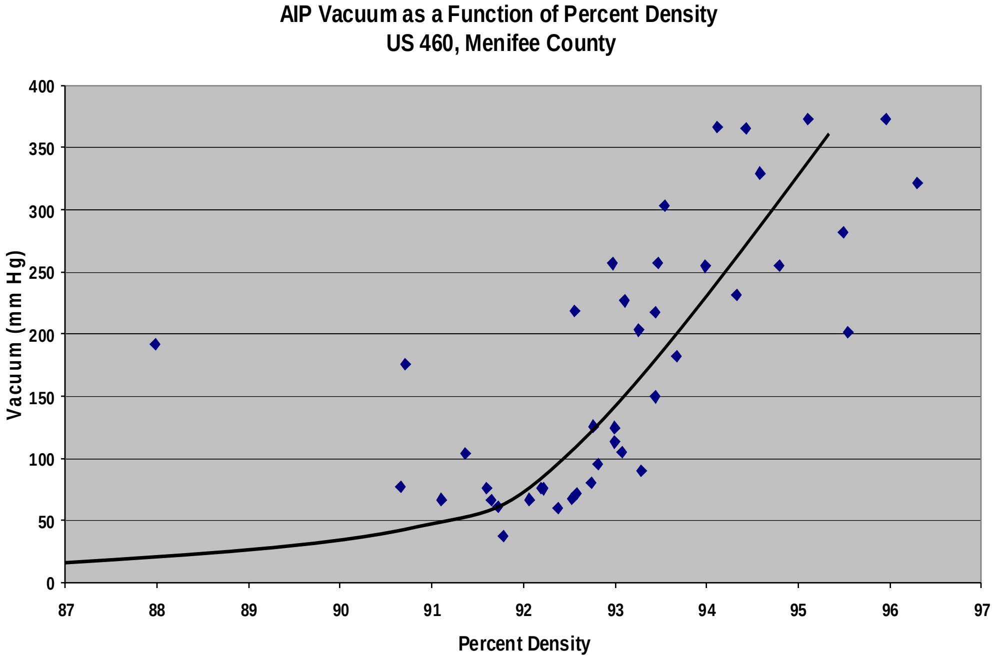

Figure 36. AIP Vacuum Versus Percent Density, US 460, Menifee County.

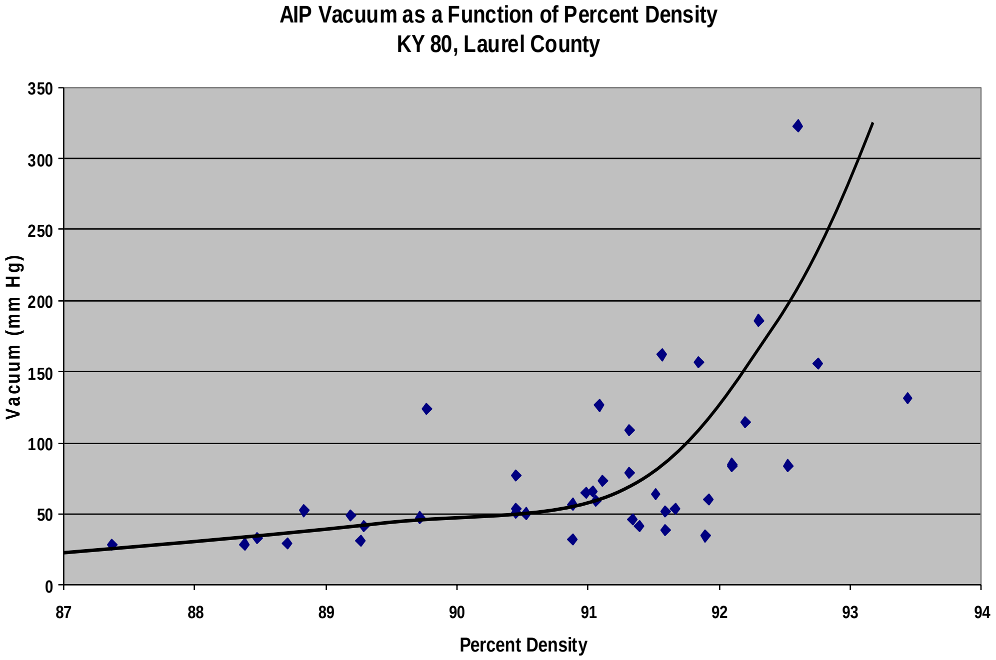

Figure 37. AIP Vacuum Versus Percent Density, KY 80, Laurel County.

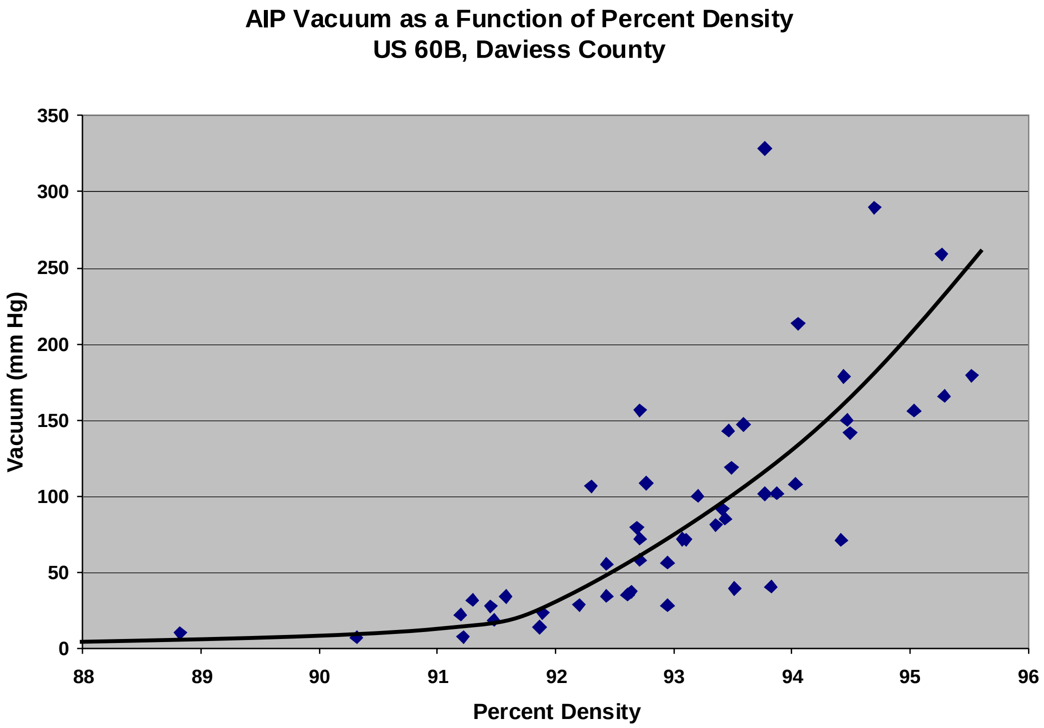

Figure 38. AIP Vacuum Versus Percent Density, US 60B, Daviess County.

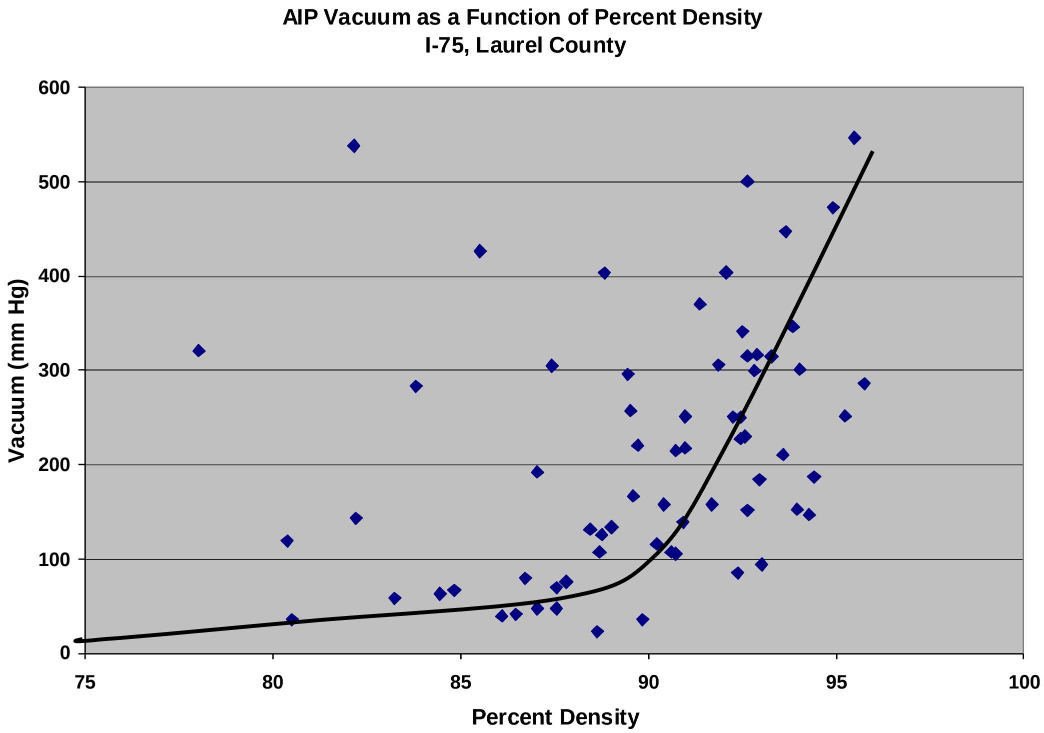

Figure 39. AIP Vacuum Versus Percent Density, I-75, Laurel County.

An examination of Figures 33 through 39 clearly indicates a significant amount of scatter in the data for all projects. Because of the scatter, regression analyses were not attempted. The lines in those figures are hand-drawn trend lines only. However, in six of the seven projects, the trend line tends to "break" at approximately 91 to 92 percent maximum density (in most cases, it was 92 percent). Although there is a significant amount of scatter, this trend would indicate that density is very important in reducing field permeability. It appears that at approximately 91 or 92 percent maximum density, permeability begins to decrease rapidly (higher vacuum) with increasing density.

The vacuum information shown in Figures 33 through 39 can be converted to permeability measured in centimeters per second by using Equation 2.0 and then using the appropriate conversion factors to convert to feet per day. Figures 40 through 46 show permeability in feet per day as a function of percent maximum density. These figures also illustrate the great influence of density on permeability. As densities increase, the "collapse," or convergence, of the data towards low permeabilities at approximately 92 percent density should be noted in all the figures.

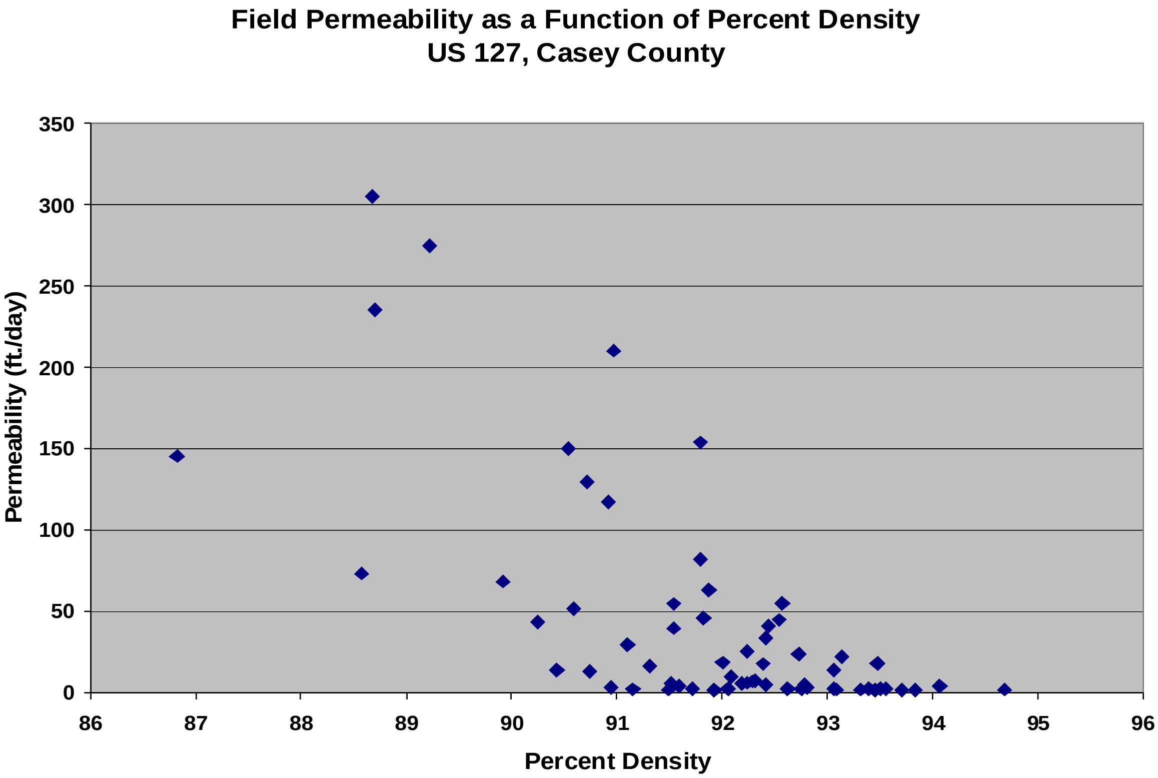

Figure 40. AIP Permeability Versus Percent Density, US 127, Casey County.

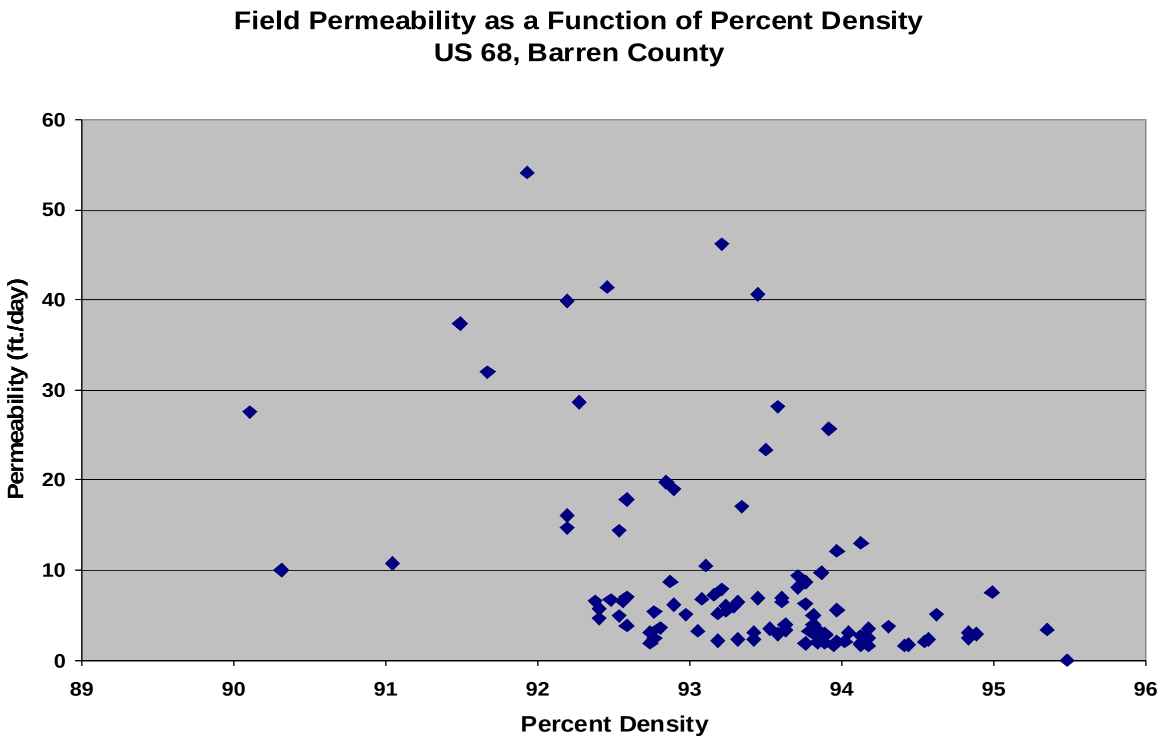

Figure 41. AIP Permeability Versus Percent Density, US 68, Barren County.

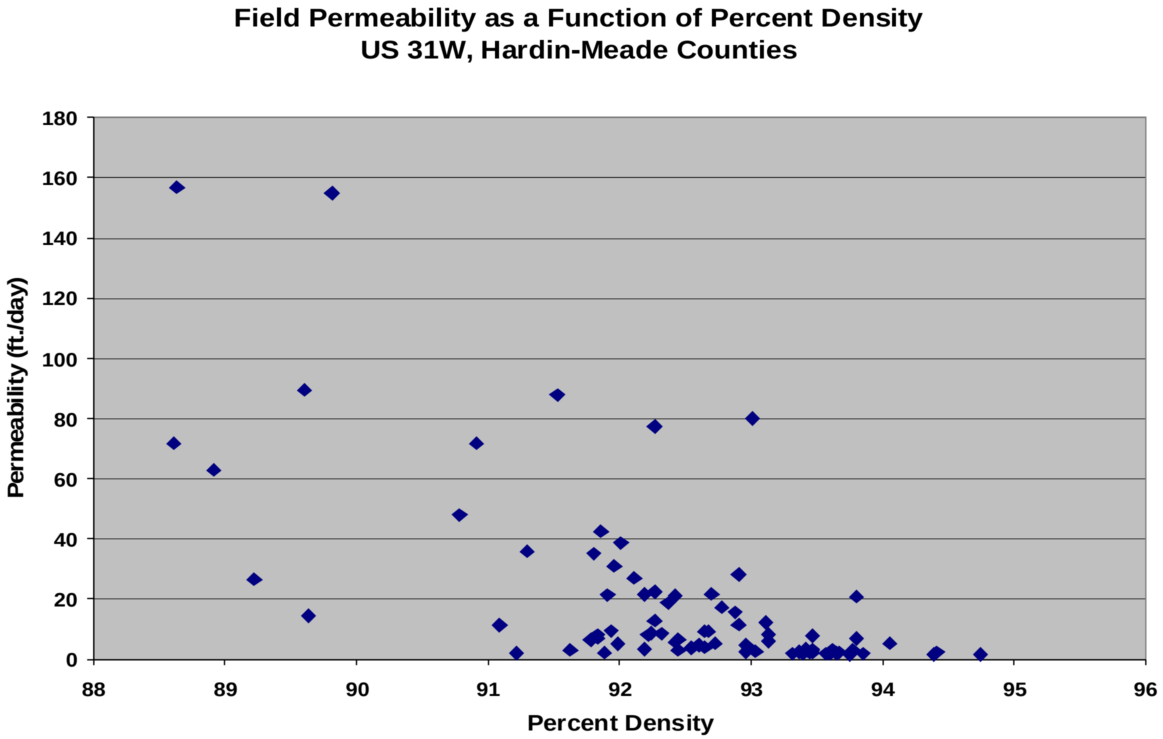

Figure 42. AIP Permeability Versus Percent Density, US 31W, Hardin-Meade Counties.

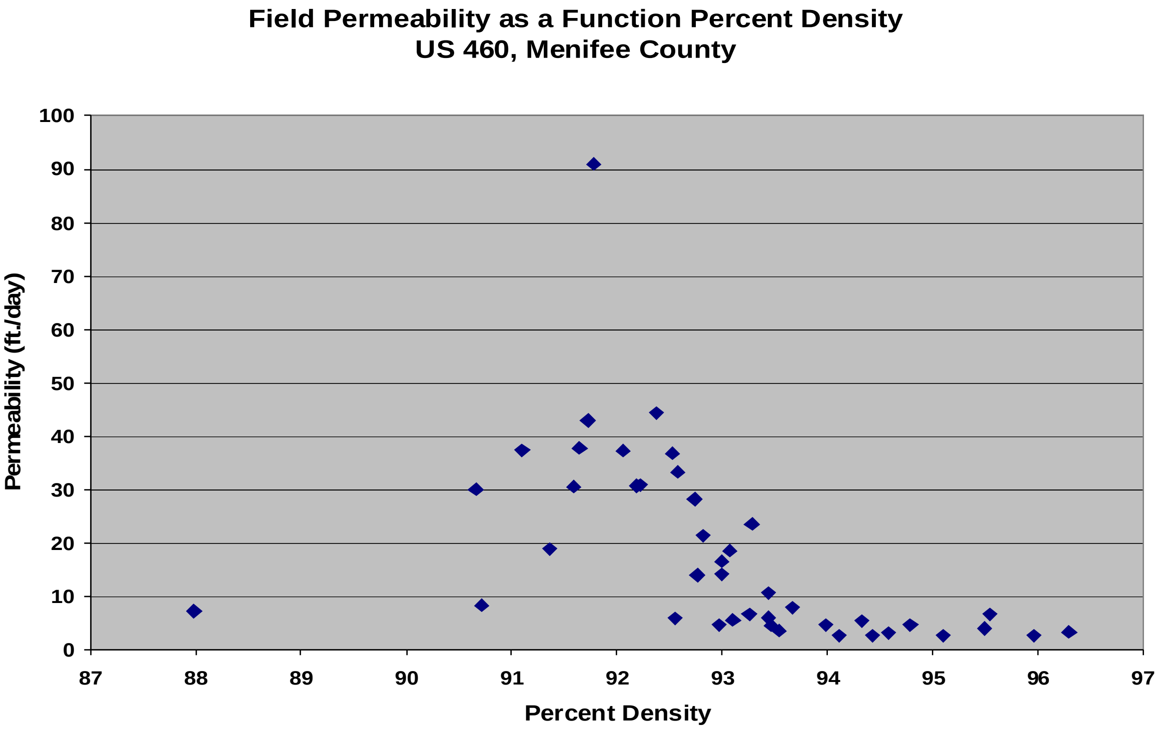

Figure 43. AIP Permeability Versus Percent Density, US 460, Menifee County.

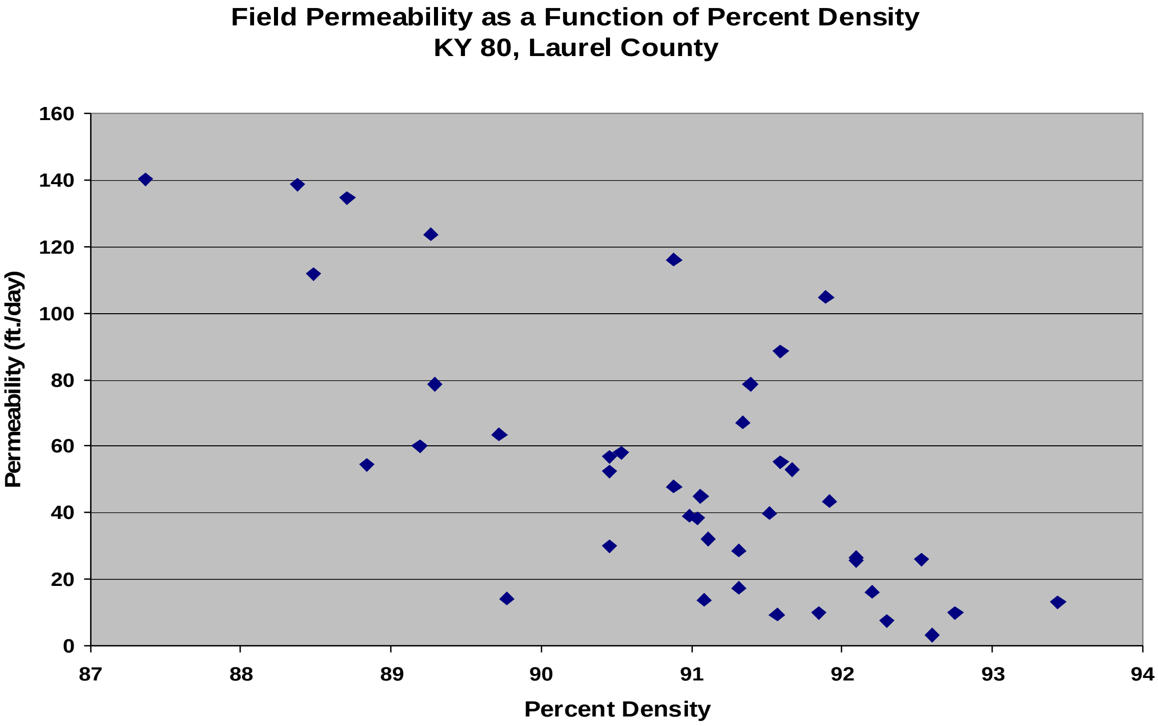

Figure 44. AIP Permeability Versus Percent Density, KY 80, Laurel County.

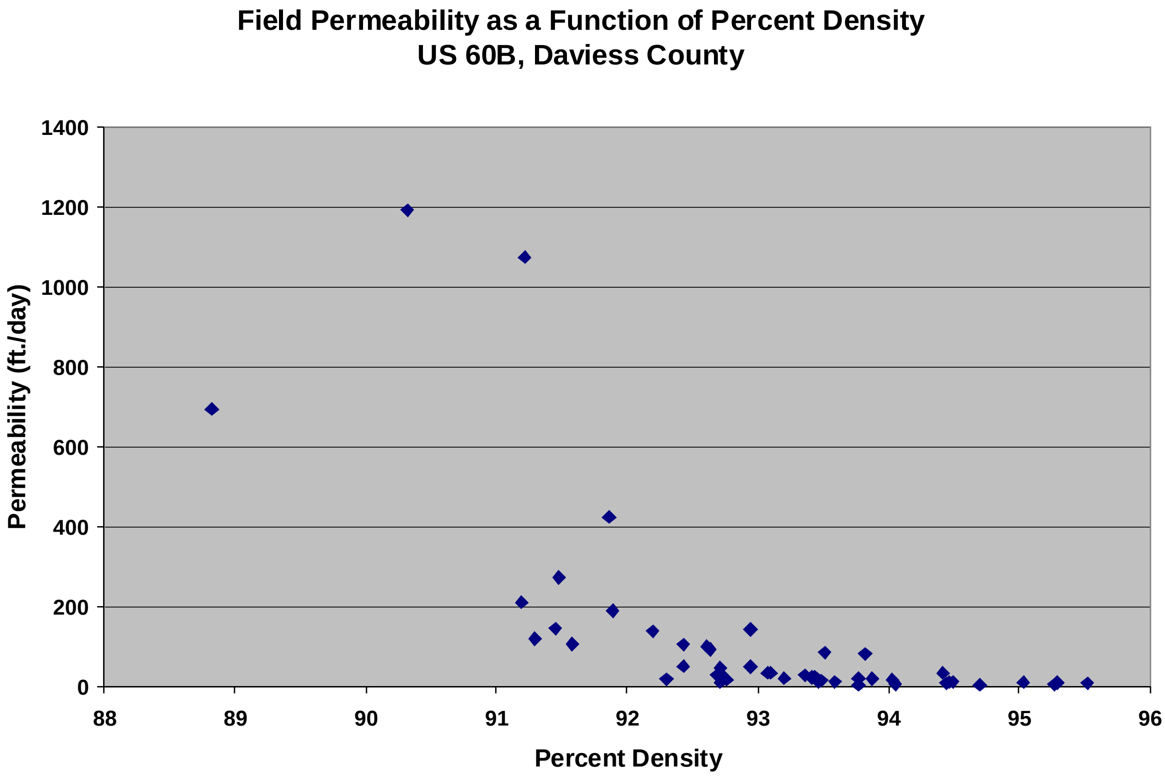

Figure 45. AIP Permeability Versus Percent Density, US 60B, Daviess County.

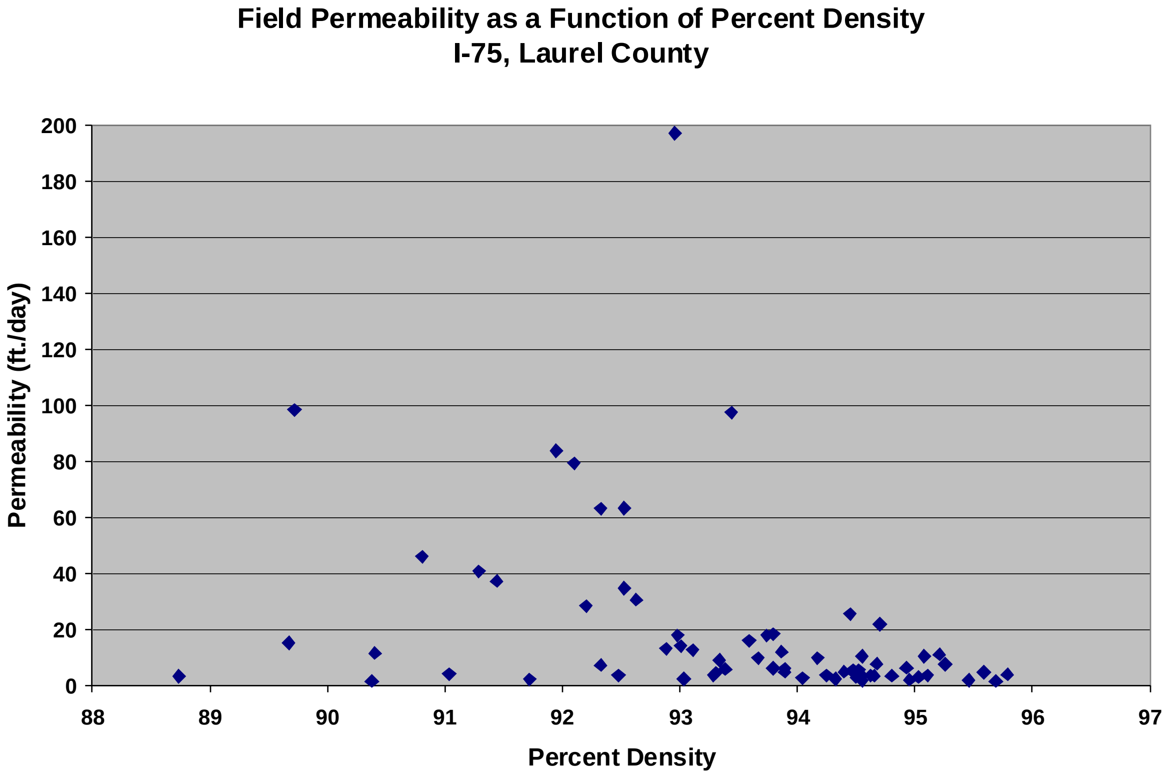

Figure 46. AIP Permeability Versus Percent Density, I-75, Laurel County.

The data in Figures 40 through 46 are summarized in Figure 47. All of the permeability values (from all of the projects combined), and in the weight ranges shown in Figure 47, were averaged and plotted. The results show most dramatically the effects of density on permeability. The greatest change occurs at approximately 92 percent of maximum density.

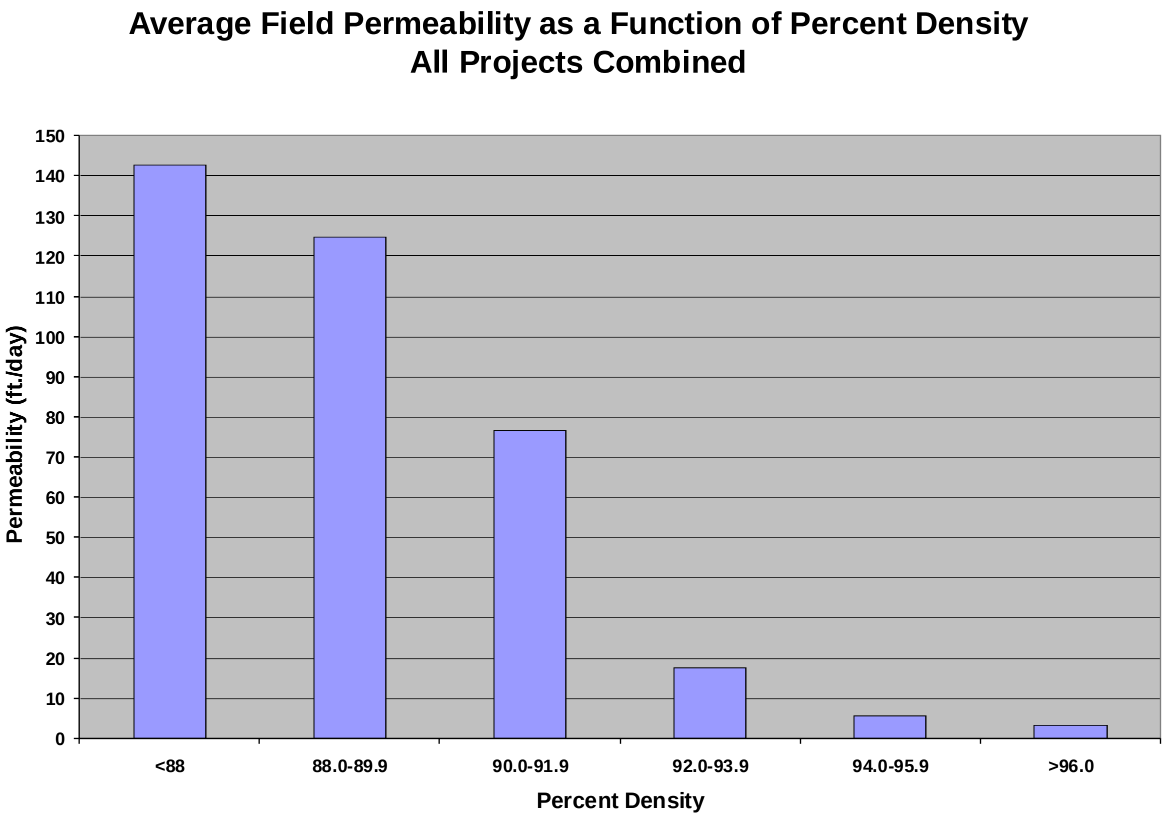

Figure 47. Average Permeability Versus Percent Density for All Projects.

Currently, the Kentucky Transportation Cabinet requires 92 percent density (for the lane) in order to receive 100 percent pay. The data from this study clearly supports that requirement. Therefore, it must be concluded that to construct a pavement that is practically "impermeable," it is absolutely essential to have a minimum of 92 percent density.

PERMEABILITIES OF INDIVIDUAL PROJECTS

Objective 6 of this study was "to define acceptable permeability rates for asphalt mixtures and aggregate base courses." As previously stated, the lack of available construction projects with aggregate bases made it impossible to collect sufficient data to analyze and report. An additional research effort will be necessary to quantify the permeability characteristics of aggregate bases.

What are acceptable permeability rates for asphalt mixtures? Obviously, how the mixture is to be used will be the major determining factor. If the mixture is to be used for a drainage blanket, then a "high" permeability will be required; however, if the mixture is to prevent water from entering the pavement structure, than a "low" permeability will be required. The data, as collected in this study, cannot definitively quantify those acceptable permeabilities because of the wide range of possible uses. However, in Kentucky, the general objective is to prevent water from entering the pavement. Most of the projects in this study (nine) involved surface mixtures. Consequently, it would appear that a "low" permeability would be desirable for these mixtures.

The Florida Department of Transportation (FDOT) has conducted extensive research into the permeability characteristics of Superpave mixtures. Musselman et al[4], reporting on the Florida research, stated that fine-graded mixtures, designed using the Marshall method, typically had permeabilities that were less than 100 x 10^{-5} cm/sec. Therefore, it would appear this number may be considered as "practically impermeable." Based on that information, FDOT changed their Superpave specifications to read "if the in-place density is not achieved, the pavement coefficient of permeability as measured with the Florida apparatus must not exceed 100 x 10^{-5} cm/sec." The research team on this study decided to use FDOT's criterion for impermeability as a "benchmark" for comparing the permeabilities of the surface mixtures in this study.

Data from six of the projects in this study (the first six projects listed in Table 1) were collected in conjunction with another research study concerning construction methods for longitudinal joints. The results of that study were reported by Fleckenstein et al[5]. In that study, permeability measurements were made with the AIP at the construction joint, at six inches from the construction joint, at 18 inches from the joint, and at the centerline (six feet from the joint) of the paving lane.

The results of that testing, for each project, are shown in Figures 48 through 53. The data are plotted as accumulative distribution functions (also called "probability density functions"). The accumulative distribution functions in Figures 48 through 53 were constructed by arranging the vacuum readings for each of the projects and at each of the four locations listed above in ascending order (horizontal axis). It was then determined at each vacuum reading what percentage of the readings were less than that particular reading (vertical axis). For example: in Figure 48, the curve labeled "centerline" shows that at 300 mm Hg of vacuum, approximately 39 percent of the readings taken at the centerline of the lane were less than that value and approximately 61 percent were greater than 300 mm Hg of vacuum. A general interpretation of those curves indicates that the further to the right of the graph the curve is "shifted," the more impermeable the asphalt surface. Also, the more "vertical" the curve is, the more "uniform" the permeability.

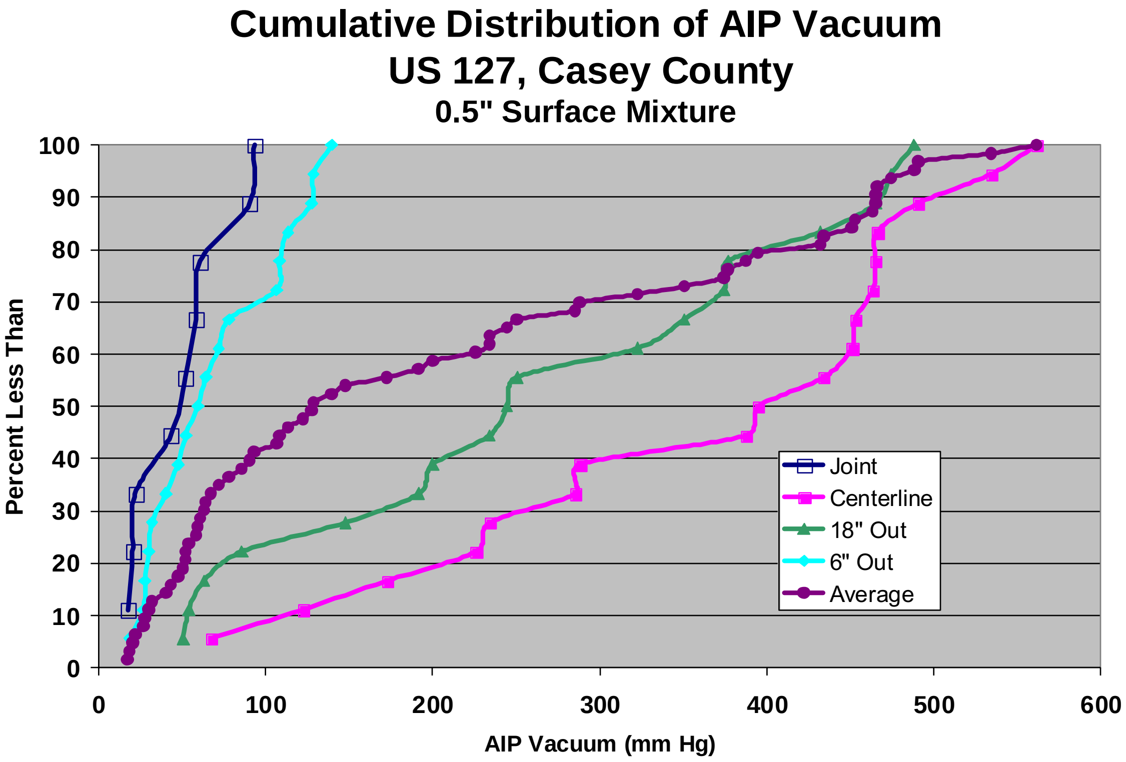

Figure 48. Cumulative Distribution of AIP Vacuum, US 127, Casey County.

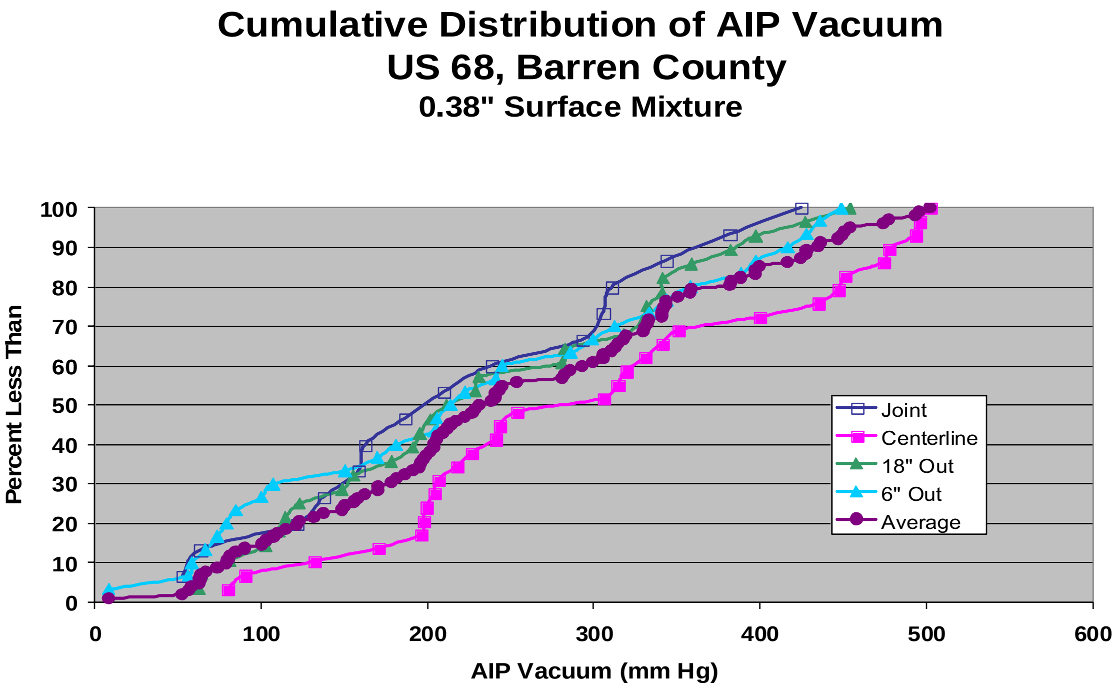

Figure 49. Cumulative Distribution of AIP Vacuum, US 68, Barren County.

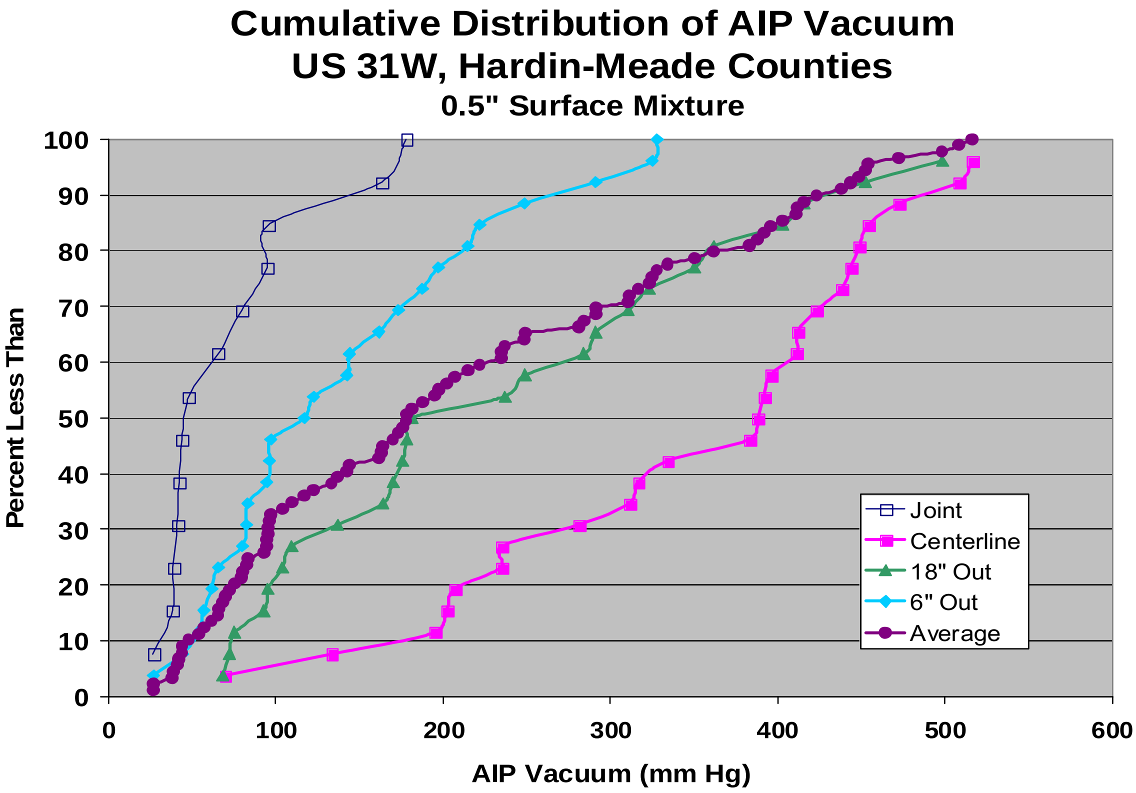

Figure 50. Cumulative Distribution of AIP Vacuum, US 31W, Hardin-Meade Counties.

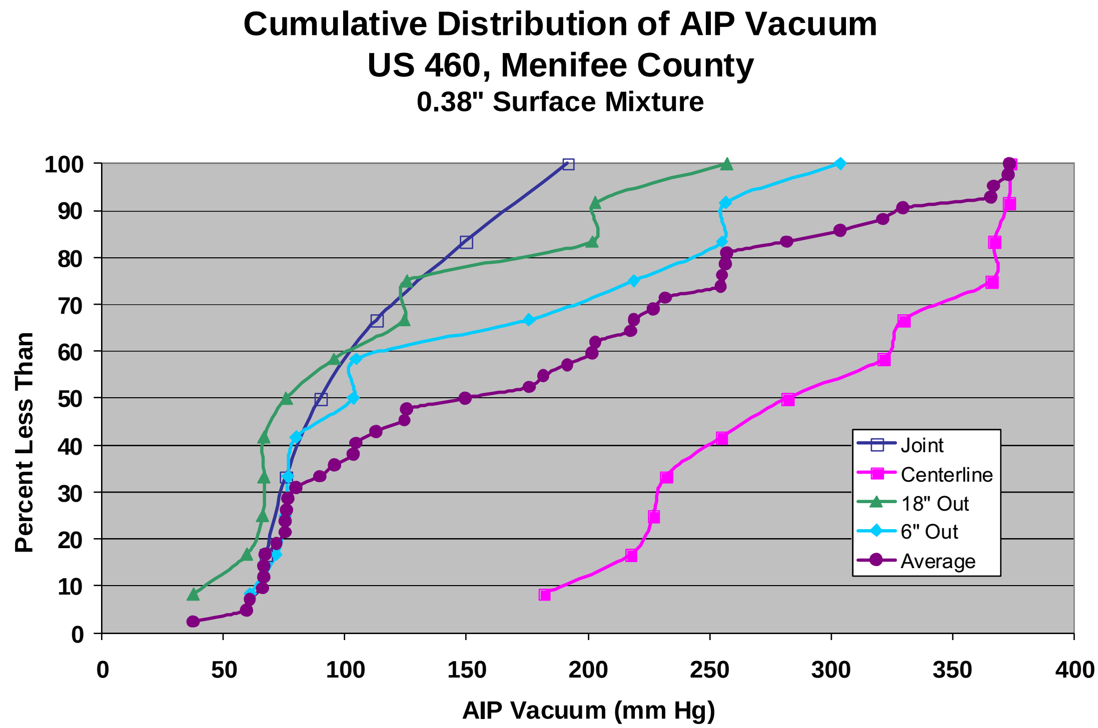

Figure 51. Cumulative Distribution of AIP Vacuum, US 460, Menifee County.

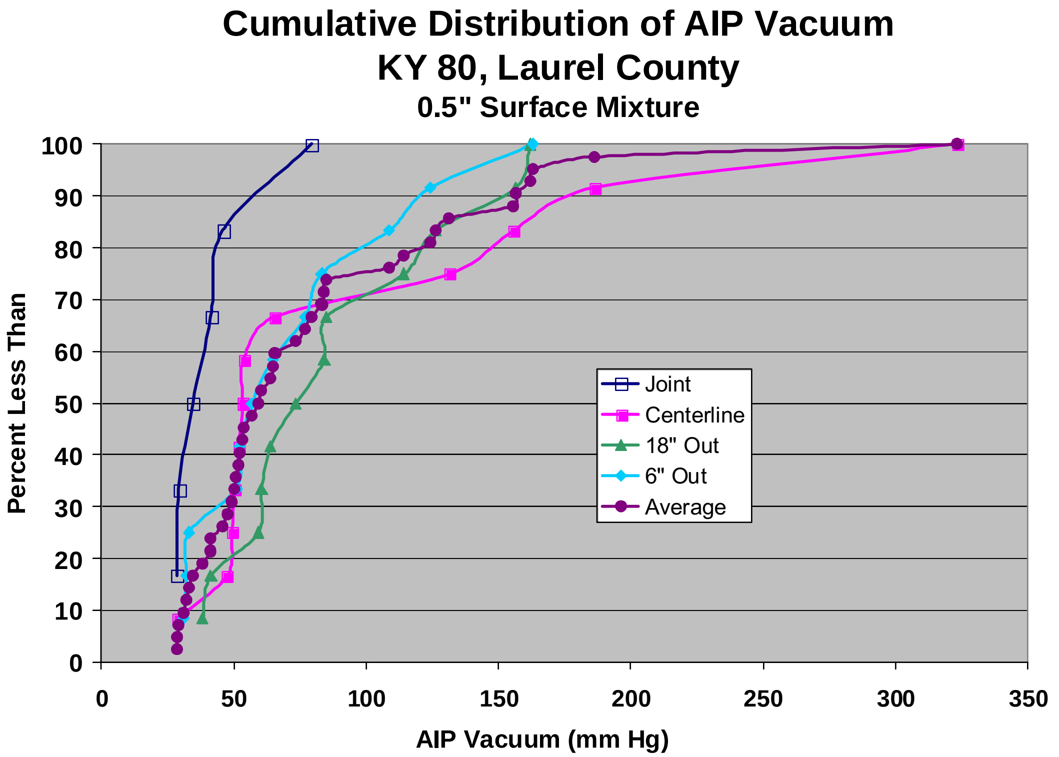

Figure 52. Cumulative Distribution of AIP Vacuum, KY 80, Laurel County.

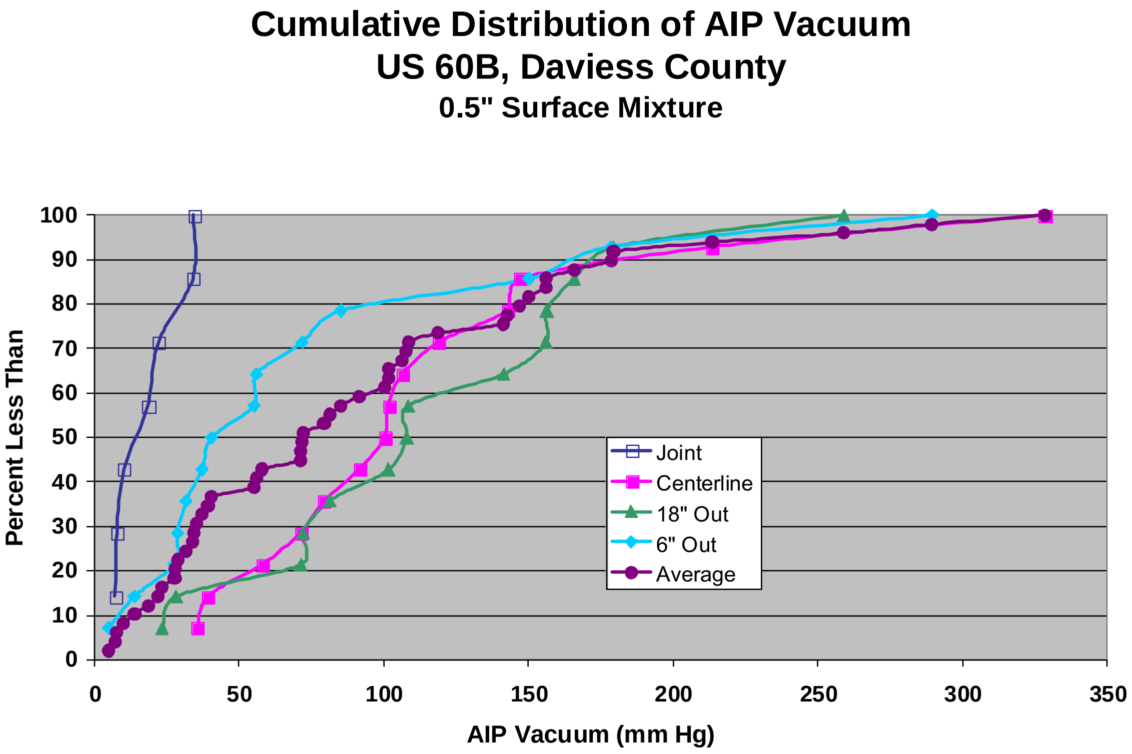

Figure 53. Cumulative Distribution of AIP Vacuum, US 60B, Daviess County.

A quick review of Figures 48 through 53 clearly shows a significant difference in permeability transversely across the mat. In general, the permeability at the joint, and the few inches on either side of the joint, is several orders of magnitude greater than at the center of the lane. The exceptions to this statement were US 68, Barren County, and to a lesser degree, US 460, Menifee County. Figure 49 (US 68, Barren County) shows a relatively uniform permeability across the mat. Two projects (KY 80, Laurel County, and US 60B, Daviess County) had relatively high permeabilities at most locations on the mat. Three projects, the two previously mentioned and US 127, Casey County, had very high permeabilities at the construction joint.

It should be noted that the distribution curves for the tests performed at the center of the lane have a very wide range of permeabilities (shallow slope). This trend indicates a high variability in permeability even at the center of the lane. It must be concluded from the data that the permeability of an asphalt mat is highly variable and to attempt to describe the permeability as a single number (deterministic) is inappropriate. It would appear that a better approach to describing permeability would be statistically (using means and standard deviations) or probabilistically. To describe permeability probabilistically, would be to calculate the probability that any particular site on the pavement mat (chosen randomly) would be greater than, or less than, some arbitrarily preset permeability value of interest. This will be described more fully later in the report.

To look at the data in Figures 48 through 53 statistically, all of the permeability readings were averaged for each project and the standard deviation was determined. The results are summarized in Figure 54. That figure shows that KY 80, Laurel County, had the lowest mean (most "permeable") and the lowest standard deviation (the mat was uniformly "permeable"). US 68, Barren County, had the highest mean indicating that the mat was the least permeable of all the projects. Figure 55 shows the coefficient of variation (standard deviation divided by the mean) for each project. This analysis indicates US 68 had the lowest coefficient of variation which is also an indication of a higher degree of uniformity the mat.

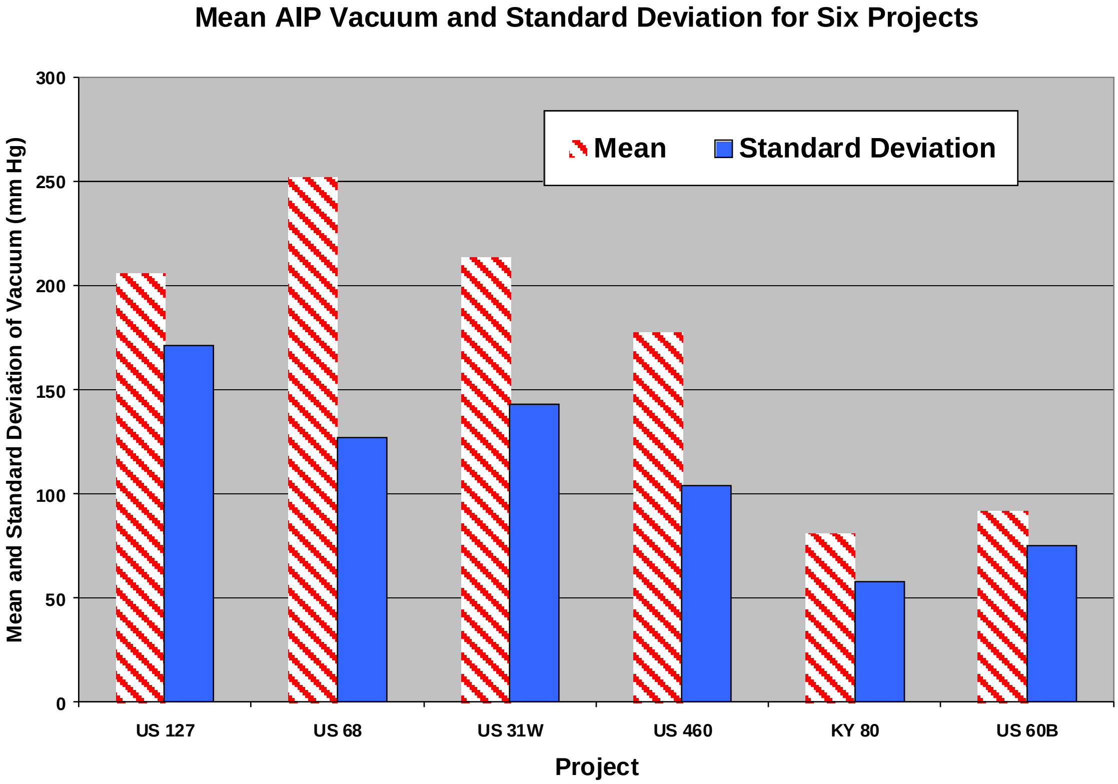

Figure 54. Mean AIP Vacuum and Standard Deviation for Six Projects.

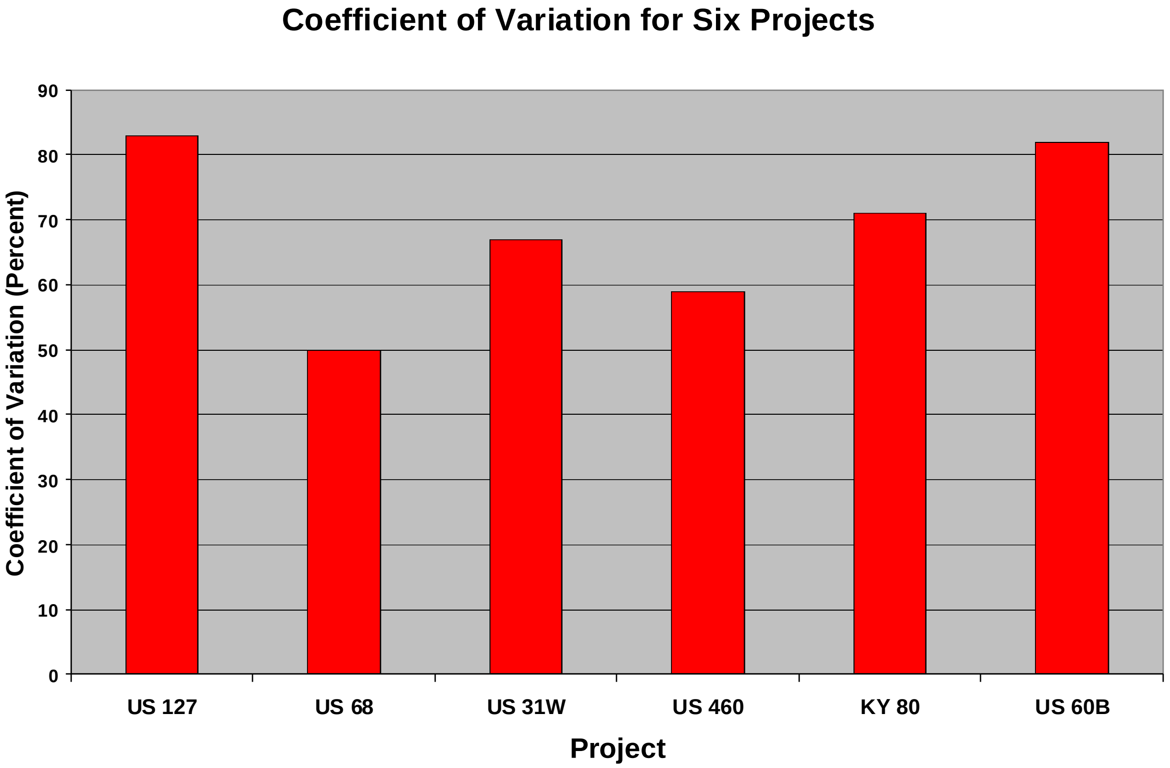

Figure 55. Coefficient of Variation for Six Projects.

The data in Figures 48 through 53 can also be interpreted probabilistically. There is an "average" cumulative distribution curve in each of those figures. This curve represents the distribution of all the vacuum readings from that project. Using FDOT's criterion for "impermeability" (previously discussed) of 100 x 10^{-5} centimeters per second (350 mm Hg of vacuum), then from the average distribution curve, the probability of any site on that particular asphalt mat being considered "impermeable" can be determined.

Figure 48 can be used as an example of how to determine that probability. Determine at what percent the "average" curve for US 127, Casey County, crosses the "350 mm Hg" line. In this case, it is at approximately 72 percent. Therefore, the probability that the vacuum reading would be greater than 350 mm Hg is 100 – 72, or 28 percent. Therefore, 28 percent of the surface area of the mat would be considered "impermeable." Table 2 lists those probabilities for each of the six projects.

Table 2. Probability That Any Particular Site on an Asphalt Mat Would Be "Impermeable" for Six Projects.

Project	Probability (%)
US 127, Casey County	28
US 68, Barren County	23
US 31W, Hardin-Meade Counties	21
US 460, Menifee County	9
KY 80, Laurel County	0
US 60B, Daviess County	0

By the probabilistic method, US 127, Casey County, was the most "impermeable" of the projects in this study. Again, the term "impermeable" is based on FDOT's criterion of 100 x 10^{-5} centimeters per second, or 350 mm Hg. Figure 54 shows that from the statistical analysis, US 68, Barren County, would be considered the most "impermeable," because it had the highest mean value. This clearly illustrates that the results may be different depending on which method is used.

Neither method can be considered superior to the other; the two methods simply provide different information. The statistical method provides some insight into the "overall" permeability of the mat by use of the mean value, and also some indication of variability is provided by use of the standard deviation or coefficient of variation. The probabilistic method provides information on the percentages of the pavement that are at various levels of permeability, but it does not *directly* provide information on the variability of permeability.

RELATIONSHIP BETWEEN FIELD PERMEABILITY AND GRADATION

As stated in the previous section, field permeability varies widely. Therefore, to describe field permeability with one number would be inappropriate. However, in this study, it was decided to try to correlate the *mean* field permeability (or vacuum reading) with some parameter or parameters of the gradation. Table 3 lists the gradations of nine of the mixtures in this study (three of the gradations were unavailable).

Table 3. Gradations of Nine Mixtures in This Study.

Sieve Size	Percent Passing								
	US 127	**US 68**	**US 31W**	**US 460**	**KY 80**	**US 60B**	**KY 3005**	**I-75 Madison**	**I-75 Laurel**
1.5 in.								100	
1.00 in.	100	100	100	100	100	100	100	92	100
0.75 in.							94	77	
0.5 in.	96	100	94	100	95	96	72		99
0.38 in.	87	97	86	95	80	80	65	60	89
#4		67		68	47	51		30	55
#8	37	41	32	45	28	30	26	21	33
#16	18	26	20	26	19	18	19	14	22
#30	12	17	13	17	14	11	14	10	17
#50	8	10	9	10	9	8	6	7	10
#100					5	5			7
#200	4.0	5.0	5.0	4.5	4.5	4.0	5.0	5.0	3.5
Mean Vacuum (mm Hg)	216	252	247	176	82	92	260	23	213

Numerous regression analyses were performed on the data in Table 3 with varying degrees of success. Most of the analyses involved regressions between various ratios of the sieve fractions from the nine gradations. The various ratios were used as the independent variables, and the mean vacuum was the dependent variable. Table 4 is a summary of the regression analyses that were attempted. It is clear from Table 4 that those regression attempts were not very successful in developing an equation that could predict mean field vacuum from gradation. The last attempt listed in the table lists four independent variables that were used in the analysis with a resultant R^2 of 0.73. This value would appear to be a “fair” correlation. However, a correlation analysis was performed to determine the degree of co-linearity between the “independent” variables used in the analyses. Those results are listed in Table 5.

Table 4. Summary of Types of Regression Analyses Performed on Nine Gradations.

Types of Regression Analyses Attempted on the Gradations Listed in Table 3 with Mean Vacuum as the Dependent Variable		
Number of Independent Variables	**Regression Type**	**R^2**
1	Percent Passing #8 Sieve Versus Mean Vacuum	0.41
1	Percent Passing #16 Sieve Versus Mean Vacuum	0.27
1	Percent Passing #30 Sieve Versus Mean Vacuum	0.18
1	Difference Between Percent Passing #8 and #50 Versus Mean Vacuum	0.45
1	Ratio of #8 Sieve to #50 Sieve Versus Mean Vacuum	0.45
2	Difference Between #8 Sieve and #50 Sieve (Independent Variable No. 1), and Ratio of #8 Sieve to #50 Sieve (Independent Variable No. 2) Versus Mean Vacuum	0.51
4	Ratio of #8 Sieve to #50 Sieve (Independent Variable No. 1), Difference Between #8 Sieve and #50 Sieve (Independent Variable No. 2), #8 Sieve Plus #16 Sieve (Independent Variable No. 3), and Independent Variable No. 2 Divided by Independent Variable No.3 (Independent Variable No. 4)	0.73

Table 5. Correlation Table for Regression Variables.

	#8/#50	**#8-#50**	**#8+#16**	**(#8-#50)/(#8+#16)**
#8/#50	1.00			
#8-#50	0.76	1.00		
#8+#16	0.60	0.96	1.00	
(#8-#50)/(#8+#16)	0.91	0.79	0.61	1.00

It should be noted that the closer the values in Table 5 are to 1.0, the greater the co-linearity that exists between those two variables. In other words, they are not truly independent of each other. All of the variables have a relatively high degree of co-linearity, and therefore, they are not independent. Because of the low R^2 values, and because of the high degree of linearity between the independent variables, it was decided to attempt a different approach or procedure to develop a prediction equation between gradation and mean field vacuum.

US 127, Casey County will be used as an example to illustrate how this new procedure was performed. In this procedure, each of the nine gradations was plotted arithmetically as illustrated in Figure 56. A regression analysis was performed on each gradation plot using a second-degree polynomial. This regression analysis is illustrated in Table 6 for US 127, Casey County.

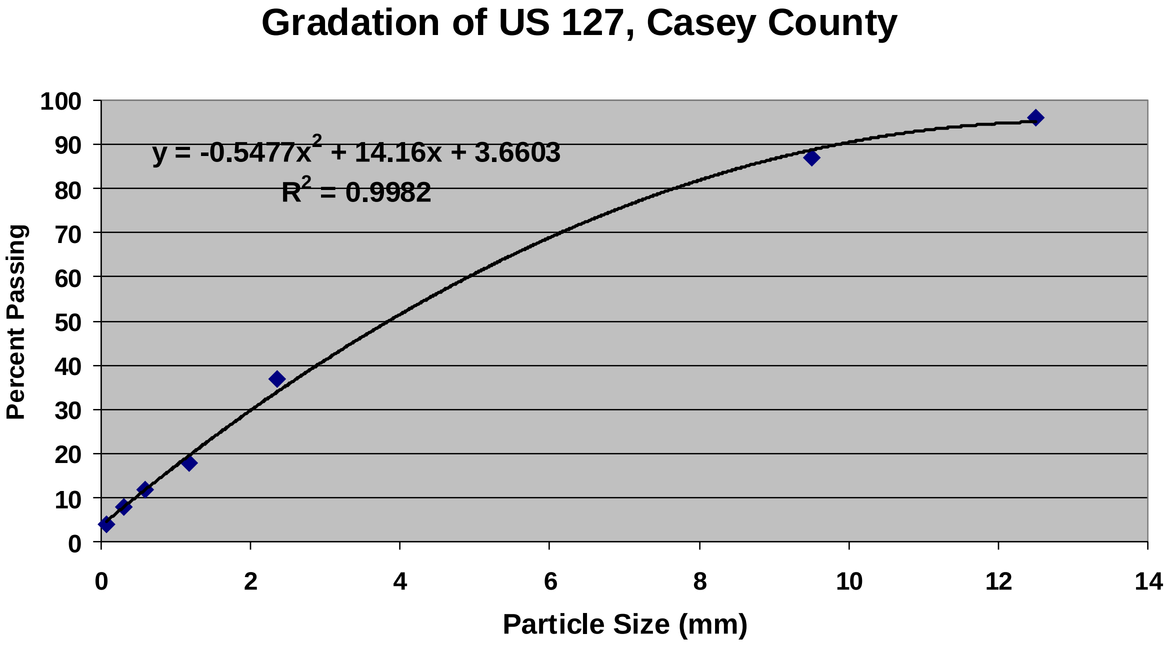

Figure 56. Gradation of US 127, Casey County, with Regression Equation.

Table 6. Illustrated Regression Variables for US 127, Casey County.

Sieve No.	Sieve Size (mm) Independent Variable No. 1 X	Sieve Size (squared) Independent Variable No. 2 X^2	Dependent Variable (Percent Passing)
1 in.	25.4	645.1600	100
3/4 in.	19	361.0000	
1/2 in.	12.50	156.2500	96
3/8 in.	9.50	90.2500	87
1/4 in.	6.30	39.6900	
#4	4.75	22.5625	
#8	2.36	5.5696	37
#16	1.18	1.3924	18
#30	0.60	0.3600	12
#50	0.30	0.0900	8
#100	0.150	0.0225	
#200	0.075	0.0056	4

A multi-variant regression analysis was performed on the numbers in Columns 2 through 4 in Table 6 to yield an equation of the following form:

$$\text{Percent Passing} = C_2{*}X^2 + C_1{*}X + C_0 \qquad \text{Eq. 3.0}$$

Where: C_0, C_1, and C_2 = coefficients determined from regression analysis.

See Figure 56 for an example equation. This regression analysis was repeated for each of the nine gradations. The results of those regression analyses are shown in Table 7.

Table 7. Coefficients of Regression Equations for Nine Gradations.

Project	C_2	C_1	C_0	**Ratio** $\lvert C_1/C_2 \rvert$	**Mean Vacuum (mm Hg)**
US 127	-0.55	14.16	3.66	25.64	216
US 68	-0.74	16.70	5.73	22.57	252
US 31W	-0.46	12.90	4.86	28.04	247
US 460	-0.77	17.04	5.97	22.08	176
KY 80	-0.25	10.17	6.05	40.4	82
US 60B	-0.28	10.77	4.75	38.21	92
KY 3005	-0.36	9.7	5.68	26.94	260
I-75, Mad.	-0.17	7.37	4.99	43.53	23
I-75, Laur.	-0.45	13.03	5.97	28.89	213

Is there a relationship between mean, measured, field vacuum and the regression coefficients in Table 7, and are the coefficients of Table 7 co-linear? To determine if the coefficients in Tables 7 are co-linear, a correlation analysis was performed as shown in table 8.

Table 8. Correlation Table for Regression Variables.

	C_2	C_1	C_0	Ratio $\lvert C_1/C_2 \rvert$
C_2	1			
C_1	0.97	1		
C_0	0.12	0.10	1	
Ratio $\lvert C_1/C_2 \rvert$	-0.91	-0.85	-0.06	1

A review of the information in Table 8 shows that the two variables that are most independent are the intercept (C_0) and the absolute value of the ratio of the C_1 coefficient to the C_2 coefficient (correlation coefficient of –0.06). Negative correlation coefficients in Table 8 indicate an inverse relationship. Therefore, it was decided to perform a multi-variant regression analysis between these two independent variables (from Table 7) and the mean, measured, field vacuum (the dependent variable), to determine if a relationship exists for the purpose of predicting field vacuum from gradation. Equation 4.0 is the result of that regression analysis.

$$\text{Mean Field Vacuum} = 483.8 - 11.6{*}R + 11.3{*}C_0 \qquad \text{Eq. 4.0}$$

Where: R = ratio of the C_1 to C_2, and
C_0 = intercept.

The adjusted R^2 for this analysis was 0.92, indicating a “good” correlation. Figure 57 shows the predicted values, as calculated from Equation 4.0, versus the mean, measured, field vacuum. From that figure, it would appear that Equation 4.0 could be used to predict mean field vacuum based on gradation alone.

It should be noted that Equation 4.0 only predicts the *potential* for an asphalt mixture to be either “permeable” or “impermeable.” Although Equation 4.0 may predict a “low” permeability for a particular gradation, this will not negate the need for good construction practices. It has already been demonstrated in another section of this report that obtaining density is critically important to achieving low permeabilities.

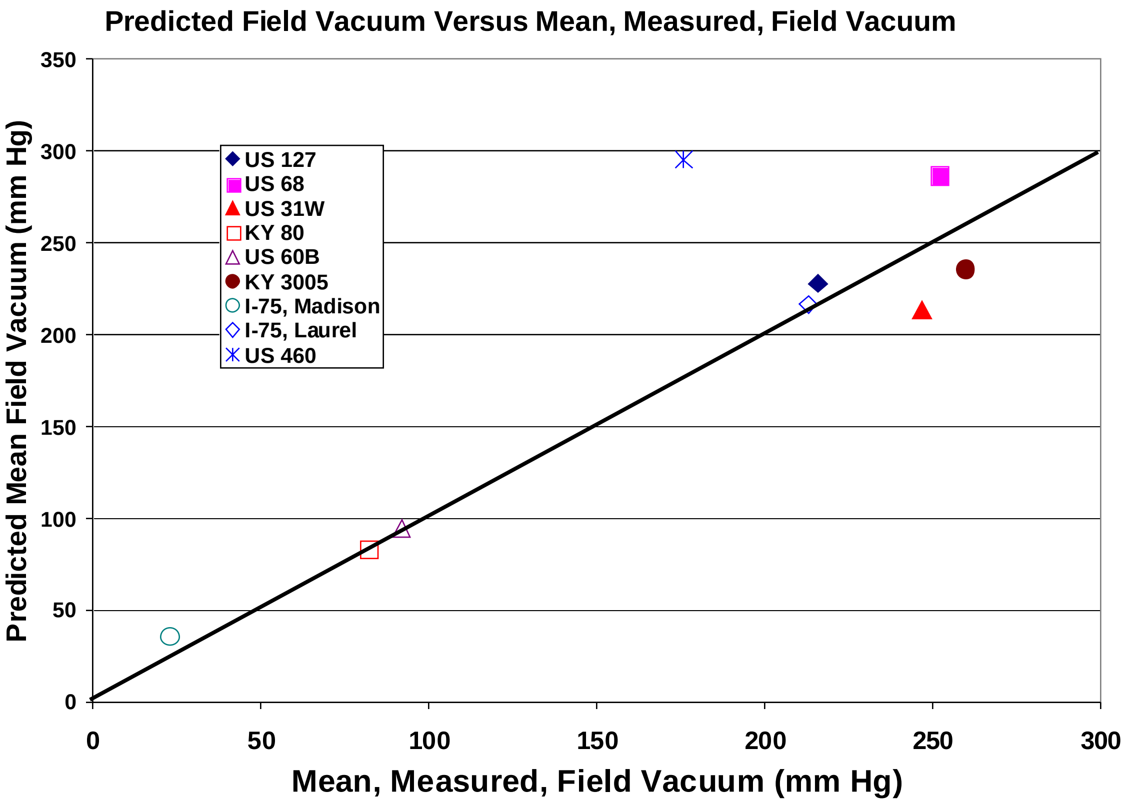

Figure 57. Predicted Mean Field Vacuum Versus Mean, Measured, Field Vacuum.

Figure 57 shows that Equation 4.0 does not predict very accurately the field vacuum for US 460, Menifee County. This is an example where construction practices in the field may have produced results different from those predicted by Equation 4.0. Although, for the most part, it appears that densities were achieved in the field (see Figures 36 and 43), yet vacuum readings at and near the construction joint were very low (Figure 51). The mean vacuum reading for this project was 176 mm Hg. However, if only the vacuum readings from the centerline are averaged, the mean vacuum reading for US 460, Menifee County, becomes 293 mm Hg, and Equation 4.0 predicts a mean vacuum of 295 mm Hg for this project. Therefore, it appears that some construction practice or procedure may have produced the difference in results between predicted mean vacuum and mean, measured vacuum. Although not confirmed in the field, there may have been segregation at or near the construction joint which would have lowered the measured vacuum.

From Table 3, it appears that high vacuum (low permeability) can be achieved with any gradation regardless of the nominal top-size aggregate used in the gradation. Therefore, it appears that any nominal-size gradation (1.5”, 1.0”, 0.75”, 0.5”, and 0.38”) can be designed to have either “low” or “high” permeability. Preliminary work with Equation 4.0 indicates that the amount of material retained on the mid-range sieves (#8, #16, #30, and #50) is very critical to “shutting down” the permeability in any particular gradation. More research with Equation 4.0 will help to develop a clearer picture of the relationship between the mid-range sieves and the permeability.

PROPOSED SPECIFICATION

From the information gained in this study, it is possible to develop a specification to help control permeability of an asphalt pavement (surface mixture). In developing a specification for a surface mat, it must be remembered that the primary objectives are to provide a mat with "low" permeability and a mat that is as "uniform" as possible. If a standard statistical approach is used, then there are two parameters that would be of concern in any proposed specification. They are the overall *mean* permeability of the mat and the variability of the permeability around that mean (standard deviation). Using a probabilistic approach, it is necessary to establish "control points" on the probability density curve or accumulative distribution curve. Because the data in this study was presented in the form of accumulative distribution curves, this approach was chosen as a basis for a proposed specification for surface mats.

A review of Figures 48 through 53 shows a wide range of permeability values among the various projects and within each individual project. However, US 68, Barren County was the most uniform across the mat (all of the curves are in close proximity). Therefore, the data from the "average" curve in Figure 49 will be the basis for a proposed specification. The two points of interest on that curve are the 50th percentile and the 15th percentile. A recommended specification should permit no more than 50 percent of the vacuum readings to be less than 225 mm Hg (a permeability of 5.6 ft./day). This is from the "average" curve in Figure 49. Also, no more than 15 percent of the vacuum readings may be less than 100 mm Hg (a permeability of 19.9 ft./day). The following list contains the basic items that should be included in a proposed specification.

1. The permeability of asphalt surface mixtures shall be determined in accordance with Kentucky Method XXX. (A Kentucky Method should be developed that is based on the procedures listed in the section entitled "Test Procedures" of this report.)

2. A minimum of 40 permeability tests shall be performed per project. The test locations shall be chosen randomly (using the computer program titled *Random Number Generator*). However, 25 percent of the tests shall be performed within one foot of the longitudinal construction joint. Each project will be equally divided into 10 "blocks." The computer program will randomly chose the "blocks" where the tests are to be performed, and will chose the exact locations within each "block."

3. On a two-lane facility, 20 tests will be performed on each direction. On a four-lane facility, 40 tests will be performed in each direction (20 tests per lane, per direction). On

a facility with more than four lanes, each additional lane must have a minimum of 20 tests per lane.

4. No more than 50 percent of the vacuum readings may be less than 225 mm Hg. No more than 15 percent of the readings may be less than 100 mm Hg.

A proposed specification (based on the items listed above) and a proposed Kentucky Method (based on the section entitled “Test Procedures”) are included in Appendix B.

CONCLUSIONS

- The air-induced permeameter (AIP) works well for measuring pavement porosity (permeability) and usually requires less than one minute to obtain a reading.

- The water permeameter developed by the National Center for Asphalt Technology (NCATP) also is effective in measuring pavement permeability; however, on pavements with low permeability, this device requires an extensive amount of time.

- The laboratory permeameter used in this study could not be calibrated with either the NCATP or the AIP. Therefore, it appears that the laboratory permeameter does not give a good description of field permeability.

- There was a good correlation between the NCATP and the AIP.

- Density has a highly significant influence on permeability. It appears that at approximately 92 percent of maximum theoretical density there is a dramatic decrease in field permeability (Figure 46). From the data in this study, the value of 92 percent of maximum theoretical density does not appear to be related to the size of the mixture.

- There is a wide variation in permeability across an asphalt mat. The lowest permeability nearly always occurs in the center of the lane with the highest permeability occurring at the construction joint. In most of the projects in this study, the permeability at the joint was several orders of magnitude greater than at the center of the lane. The recent Kentucky specification that sets a minimum acceptable density at the joint is an attempt to address and improve this situation.

- Because of the wide variation of field permeability on a particular project, it would not be appropriate to express permeability as a simple number, or a deterministic value. Rather, permeability should be expressed statistically as a mean and a standard deviation or expressed probabilistically as explained in the section of this report entitled *Permeabilities of Individual Projects.*

- It appears the mean field permeability can be “estimated” from the aggregate gradation using Equation 4.0 (Figure 57).

- Equation 4.0 can only provide an estimate of the *mean* field vacuum. However, construction factors and procedures may cause the mean, measured, field vacuum to be different from the estimate.

- It appears that any gradation, regardless of the nominal top-size aggregate can be designed for either a “low” or a “high” permeability.

- The data in Figure 47 clearly support the current Kentucky specification that requires a minimum of 92 percent of theoretical maximum density (in the lane) for 100 percent pay.

RECOMMENDATIONS

● It is recommended that a Kentucky Method be written for measuring the permeability of asphalt pavements using the AIP developed in this study, and that the procedures described in this report under the section titled *Test Procedures* be used as a basis for that proposed method.

● It is postulated that the AIP developed in this study may be able to quantify segregation in asphalt pavements. To test that hypothesis, there is a separate research study currently ongoing to attempt to measure or quantify segregation in asphalt pavements.

● It is recommended that the AIP technology be transferred to the Division of Materials, Kentucky Transportation Cabinet, and that the AIP be used regularly on construction projects for measuring permeability. It is further recommended that a trial permeability specification be developed for asphalt pavements. This specification will permit the development of a database of permeability values that will help to further confirm or deny the validity of Equation 4.0.

● It is recommended that the specification proposed in this report be adopted on a "trial" basis (without actual application of incentives or disincentives) for a period of one to two years to allow the Transportation Cabinet and the contractors to gain experience and knowledge of permeability in asphalt pavements.

● In view of the wide differences in permeability between the center of the lane and the construction joint, it is recommended that a further study of joint construction techniques be initiated, with a goal of reducing permeability at the joint. This study would be a follow-up to a previous study on joint construction techniques (Report No. KTC-02-10/SPR208-00-1F, *Compaction at the Longitudinal Construction Joint in Asphalt Pavements*). From the data developed in this study (Figures 33 through 46), it may be necessary to "tighten" the current joint specification to reduce water intrusion at the joint. Some of the techniques used in the previous joint study should be tested on more projects to determine if those techniques can economically be used to consistently reduce permeability at the joint.

- It is recommended that a second research study be conducted to quantify the permeability characteristics of aggregate bases, including dense-graded aggregates, crushed stone bases, and drainage blankets.

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APPENDIX A

Data Collected on All Projects

Test Data Collected, US 127, Casey County

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
142.0		25.3	490.6
144.3		21.0	488.3
144.4		514.2	106.6
141.8		5866.4	58.4
139.7		2228.1	128.6
143.0		19.0	432.0
142.2		42.7	434.0
142.1		60.2	452.8
142.8		634.9	85.9
140.4		794.4	30.0
140.5		985.5	22.0
140.1		2973.6	32.0
142.5		99.1	63.1
140.8			122.5
142.2		6.6	534.3
139.8		36.2	350.8
137.8		2550.1	26.9
137.0		10542.4	17.3
141.8		6362.4	18.5
143.3		3920.3	50.7
144.7			172.4
141.3		20.5	463.4
140.1		97.2	374.3
140.7		1083.3	47.7
136.8		5640.3	43.3
141.9		408.7	78.1
141.7		588.8	147.7
141.3		46.7	234.2
138.9		7.7	466.1
139.9		39.2	200.0
134.1		5982.3	40.4
137.0		9562.1	20.5
141.8		3295.0	27.9
142.5		2199.1	54.1
143.8		2359.0	67.2
144.5		6.8	561.4
142.7		24.9	474.4
142.7		162.9	139.5
143.8		415.8	93.2
144.1			108.4
144.9		252.5	250.4
145.3		698.4	387.5
142.6		145.7	285.3
142.7		210.5	244.5
139.4		1469.5	64.3
141.4		1652.3	60.8
143.3		1246.1	72.0

Test Data Collected, US 127, Casey County

(Continued)

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
141.5		598.5	191.5
143.7		192.8	288.2
144.4		49.5	450.8
141.4		67.3	465.1
143.0			127.7
143.7			52.1
144.2			52.3
143.2		202.3	376.7
142.5		121.3	394.8
142.4		68.1	465.1
141.0		114.0	322.6
143.2		971.9	59.5
142.9		606.1	90.4
140.5		675.0	113.3
146.2		1871.5	234.0
		283.3	225.7

Test Data Collected, US 68, Barren County

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
140.5		55.4	121.4
142.1		587.2	416.7
144.1		817.6	427.3
142.5		1101.8	90.2
142.6		251.2	305.8
144.6			332.0
144.2		828.1	241.1
143.1		59.3	158.4
142.7		369.6	205.5
142.0		70.7	191.3
143.0		629.8	243.4
143.1		65.8	314.2
142.9		278.4	178.5
141.5		433.7	100.3
142.5		39.9	63.2
139.7		170.4	73.7
140.5		776.5	64.0
141.7		1081.7	240.9
142.7		1183.6	80.0
137.4		1297.2	81.1
140.1		112.3	8.5
139.5		440.7	52.6
141.6		431.7	66.7
143.3		4321.8	103.1
143.9		1504.0	226.8
143.0		1031.5	495.7
140.8		319.7	341.0
142.1		167.3	203.9
143.1		554.2	238.1
143.6		127.7	436.2
140.9		517.1	382.4
142.4		21.7	253.7
143.0		625.6	330.7
141.9		166.0	317.9
142.9		245.0	150.5
142.7		111.2	209.8
140.5		218.7	312.8
142.9		1066.8	114.6
143.1		177.3	170.3
141.0		125.8	446.9
142.1		1666.9	201.7
145.4		1283.1	214.0
141.1		6.2	310.7
141.1		97.5	245.0
141.9		165.3	195.3
142.7		232.3	199.0
143.1		111.1	196.2

Test Data Collected, US 68, Barren County

(Continued)

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
142.7		476.0	341.7
143.3		381.0	343.6
142.3		6.2	424.4
142.4		6.0	397.4
142.3		336.0	397.4
143.3		36.7	206.1
142.1		64.9	434.9
142.1		106.4	229.0
144.6		391.8	181.2
141.1		2.8	343.2
137.7		3.8	107.3
141.9		438.8	155.5
143.1		16.4	319.1
143.1		1520.1	350.6
143.4		997.2	358.8
143.6		352.6	333.3
141.1		166.8	305.4
141.4		53.1	286.1
144.2		48.9	329.4
142.5		64.9	399.6
141.1		381.2	197.4
140.7		120.2	123.1
143.3		331.1	79.1
143.5		420.1	137.3
143.0		627.9	428.0
142.2		1098.3	282.7
141.1		127.6	217.3
138.8		89.6	203.7
142.1		328.2	148.7
143.8		68.1	58.2
140.9		349.5	293.0
141.6		857.2	222.4
143.5		924.6	211.8
143.2		5.5	131.5
140.9		240.1	474.0
143.2		241.2	62.5
144.8		757.4	84.9
141.4		5.2	186.3
143.5		1538.5	448.9
144.0		82.4	454.1
143.5			477.6
145.6		14.1	493.4
143.5		8.7	358.1
144.6		4.3	381.5
141.5		101.2	299.4
141.4			230.8
143.1		112.0	340.8
142.9		55.3	451.1
142.3		210.1	110.3
141.6		140.3	170.0
142.9		92.7	162.5

Test Data Collected, US 31W, Hardin-Meade Counties

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
143.5		884.7	133.1
142.0		830.9	68.4
139.7			26.8
137.8			26.5
142.8		1379.4	61.4
143.0		830.5	75.2
141.9		261.2	423.3
145.6		162.0	316.6
145.7		40.8	403.0
149.4		687.0	187.4
144.1			163.0
145.8		83.2	327.7
145.2		1.6	452.7
145.1		13.4	443.5
144.1		48.4	281.1
144.6		10.8	284.0
143.7		292.5	221.7
142.8		544.3	177.7
143.8		523.8	325.2
145.3		389.5	310.5
145.6			438.0
149.4		30.2	291.1
147.7		653.1	79.4
145.9		1185.6	97.1
143.5		630.2	92.8
142.5		0.8	334.2
144.2		264.1	235.0
144.8		280.0	136.9
144.4		413.7	116.9
143.1		835.7	65.3
148.9		531.0	65.4
147.3		430.7	72.1
142.8		297.6	69.4
143.8		47.1	202.2
142.9		30.1	415.7
143.0		294.5	161.4
143.4		0.1	94.7
144.2		759.5	94.7
143.4		545.9	178.4
146.3		0.2	234.7
145.5		93.4	454.4
145.4		38.2	350.4
144.6		611.7	248.7
142.9		706.9	95.4
141.2		1362.2	56.8
143.6		770.5	103.8
142.8		265.4	194.8

Test Data Collected, US 31W, Hardin-Meade Counties

(Continued)

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
147.3			516.4
146.8		229.2	498.3
143.6		400.9	172.9
141.4		1532.4	43.9
145.9			197.2
144.1		4.0	163.8
139.1		1.2	391.8
145.4		25.9	411.7
144.3		628.3	109.5
137.8		460.8	43.9
139.3		2878.0	38.1
144.5			142.6
144.8		724.2	175.6
146.0		13.0	448.8
146.8		59.8	395.6
144.7		235.1	361.7
139.4		603.5	122.4
143.5		2497.0	41.8
143.7			96.2
145.4			181.3
145.3		47.5	411.0
145.8		197.2	508.4
145.4			323.3
138.7		962.0	83.1
142.3		524.8	38.5
143.2			82.4
143.4		1092.5	95.1
145.2		7.6	383.4
143.4			311.1
144.0		167.6	248.9
141.7		494.7	144.1
138.3		2.6	47.8
144.8		14608.7	214.7
143.9		256.1	291.3
145.6		41.5	472.5
144.6		397.0	388.2
143.4		335.4	169.9
147.9		1304.3	53.5
144.6		1334.8	40.9
144.5			79.9
143.0		702.5	236.8
142.7		25.5	207.1

Test Data Collected, US 460, Menifee County

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
144.0		1.3	254.7
141.6		1705.1	59.7
142.6		3083.0	104.7
141.8		1075.5	67.5
138.9		1115.5	76.8
142.2		958.6	125.7
144.7		14.9	365.9
143.6		221.1	181.7
140.7		1474.5	37.6
140.6		130.6	61.0
141.3		1061.0	75.7
142.7		86.6	175.9
142.9		1156.5	203.1
144.2		1241.4	367.0
143.2		542.6	217.4
139.6		1339.9	66.7
141.9		884.6	71.9
143.0		1533.4	89.8
141.3		1186.9	75.4
140.5		964.5	66.3
142.7		155.8	226.8
145.0		15.0	329.6
141.1		1304.0	66.8
142.5		20.9	256.7
143.2		153.7	149.5
140.0		250.7	103.6
142.2		474.5	95.7
147.1		24.0	372.9
145.7		4.9	373.4
143.2		128.2	257.3
143.4		43.9	303.8
142.5		1153.8	113.0
142.1		1187.2	80.0
140.4		1884.9	76.0
144.6		251.7	231.8
146.3		87.5	281.9
142.5		393.0	124.6
145.3		133.0	255.2
142.2		95.7	191.5
141.8		987.6	219.0
146.4		363.8	201.8
147.6		1.1	321.4

Test Data Collected, KY 80, Laurel County

Field Density (lb./ft.^{3})	Field Permeability (1×10^{-5} cm/sec)	Laboratory Permeability (1×10^{-5} cm/sec)	Field Vacuum (mm Hg)
144.4		486.7	53.3
144.8		328.2	60.5
143.3		486.7	64.9
143.9		706.3	41.3
142.5		766.4	76.9
144.7		17.5	156.6
145.4		518.8	186.2
142.6		1281.0	50.3
143.4		1253.7	59.2
143.1			32.2
139.7		4279.6	29.3
139.4		3546.6	33.0
140.6		2043.5	41.3
141.3		1387.2	47.4
139.2		2063.1	28.7
144.3		1999.7	38.3
140.6		2291.2	30.9
137.6		4096.1	28.5
143.1		1570.7	56.8
143.5		717.8	126.3
143.4		1355.8	65.6
144.3		2912.4	51.9
145.1		1510.5	85.0
145.9		1295.1	52.3
143.9		6909.7	45.8
145.1		15.0	83.2
143.5		2003.0	73.5
140.5			49.2
147.2		125.9	131.1
145.7		782.9	84.1
145.3		1729.6	163.1
143.8		1928.8	79.2
143.8		1299.0	108.8
144.2		669.0	161.9
146.1		7.2	155.7
145.8		564.4	323.1
145.2		692.3	114.3
141.4		2651.8	124.3
144.7		5482.2	34.4
142.5		2683.6	50.9
144.1		1288.0	64.0
142.5		3526.5	53.6

Test Data Collected, US 60B, Daviess County

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
145.9		811.8	71.2
147.6		854.2	179.4
146.3		114.9	289.5
141.5		4791.1	34.1
142.4		5009.0	28.8
143.2			72.1
142.6			106.5
144.4		1188.5	118.8
147.2		181.4	258.9
146.0		914.5	150.1
140.9		7766.4	22.0
142.8		1960.4	55.3
143.2			156.3
144.0			100.2
145.3		349.8	213.5
146.0		438.0	141.4
145.9		137.0	178.5
142.8			34.4
141.1		1816.0	31.7
144.2		2414.1	81.3
144.9		145.8	328.3
144.6		359.8	147.1
143.8		876.6	71.4
143.6		507.3	56.1
137.2		4925.6	10.2
141.3		5017.6	27.8
143.3		1385.9	108.5
143.2		2235.7	79.4
143.1		5186.6	35.5
142.0		4273.5	23.5
143.4		11055.2	5.1
139.5		16400.4	7.2
144.4		930.5	85.2
145.0		392.1	101.7
144.9		861.3	101.6
144.4		496.7	142.8
146.8		220.5	156.0
143.1		1005.9	37.3
141.3		4020.9	18.6
143.8		483.6	71.9
145.3		667.9	107.9
144.3		2085.5	91.5
143.2		1628.3	58.1
147.2		259.8	165.9
145.0		332.6	40.5
140.9		11410.7	7.7
141.9		2488.9	14.0
143.6		3636.9	28.2
144.5		3312.7	39.3

Test Data Collected, KY 3005, Hardin County

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
	265.3		51.4
			0.8
			1.5
			9.0
	1830.6		230.7
	185.0		276.0
	58.5		481.0
	1417.3		64.2
	1933.0		52.4
	795.2		82.6
	342.9		194.4
	90.8		488.5
	1938.0		48.0
	313.5		234.0
	212.9		252.9
	595.0		226.3
	2800.7		21.6
			20.4
			9.2
			16.7
	687.0		172.1
	118.1		465.7
	278.0		255.8
	416.9		241.7
	273.5		119.6
	143.9		303.9
	195.1		191.3
	1186.4		50.7
	418.2		105.4
	102.2		222.2
	2388.1		24.5
	2682.3		20.1
			15.9
	183.1		299.8
	157.2		294.1
	455.0		99.9
	683.4		115.6
	41.0		445.3
	62.1		507.5
	56.6		493.1
	421.0		87.9
	104.2		232.0
	576.1		82.5
	91.6		344.0
	2313.5		30.2
	343.2		250.8

Test Data Collected, KY 3005, Hardin County

(Continued)

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
			10.6
	173.9		178
	310.2		174.5
	709.1		190.6
	498.5		159.9
	487.2		144.7
	271.7		229.6
	654.3		208.7
	294.1		268.7
	1922.9		89.3
	100.4		386.6
	833.4		135.8
	353.5		146.7
	370.1		164.8
	44.9		376.4
	746.6		150.1
	509.8		204
	548.6		160.2
	48.7		471.1
	789.5		249.1
	525.2		154.1
	125.2		245.4
	176.920969		408.4
	323.9158149		199.9
	332.99828		227.7
	31.74618012		464.8
	34.82785501		245.4
	218.3966467		321.2
	59.3177209		473.2
	482.5045814		39.9
	2350.23131		41.1
			15.6
	1664.893994		62.1
	1057.60409		81.8
	702.1715423		122.6
	2147.938673		38.5
	395.1198342		167.6
	168.705348		343.4
	5.601245697		545.2
	144.9035887		316.4
	30.94538309		476.5
	20.48804275		490
			493.4
	22.18490025		293.7
	79.27996749		362.3
			191.1

Test Data Collected, KY 3005, Hardin County

(Continued)

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
			75.5
			176.2
			557
			52.1
			574.3
			486.9
	289.9436799		260.3
	277.8989725		236.4
			83.7
			95.4
	94.43035551		358.4
			33.9
			494.7
			490.4
			436
	165.09868		384.3
			57.1
			82.5
			407.6
			16.1
	413.1086526		209.7
			226.3
			206.7
	280.4613416		241.7

Test Data Collected, KY 491, Grant County

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
	2043.4	608.0	52.5
	1475.6	888.7	111.5
	1235.5	421.2	147.3
	1383.3		111.6
	2677.7		56.8
	3893.7		47.3
	261.1	6.3	270.1
			214.0
			15.7
	550.5		190.2
	135.3	46.4	338.5
	533.1		178.8
			14.3
	1834.5	728.0	78.4
	1704.3		75.6
	237.2	63.3	239.7
			15.2
	1025.6		85.6
	2537.2		83.9
	725.1		119.2
			11.3
	768.1		106.6
	3711.1		44.8
	2395.7		78.4
			11.8
	3087.3		54.1
	4500.3		31.0
	786.4		46.4
	6193.9		16.4
	1847.6		87.5
	2658.2		67.0
	223.2	109.1	285.0
	5772.8		18.0
	2180.4		71.0
	2585.2		76.3
	1088.3		135.0
			17.1
	2116.7		78.8
	3144.5		67.0
	0.0		86.7
			11.5
	4589.3		25.1
	5521.0		17.1
	4758.7		29.6
	3406.0		37.1
	6022.4		18.1
	5037.6		22.5

Test Data Collected, KY 491, Grant County

(Continued)

Field Density ($lb./ft.^3$)	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
	349.7	235.3	203.1
	5782.3		16.7
	4895.9		23.0
	4375.8		33.7
	518.8	246.7	169.7
			9.5
	5569.6	1488.1	20.8
	4814.6		35.0
	4791.4		20.1
			10.1
	3271.6		53.2
	4310.8		38.6
	3290.1		50.1
			10.9
			10.6
	3962.4		41.8
	4420.3		49.0
			6.4
			6.2
	2364.8		76.1
	1967.8		101.2
			19.4
			9.8
	5768.0		22.7
	6048.6		16.4
	2637.1		69.7
			8.7
			13.9
			12.0
			6.1
			12.4
	3579.4		24.1
	1473.7		50.6
			7.5
			11.7
	5026.7		14.8
	2290.9		66.7
			6.2
	4480.0		21.4
	3052.1		36.3
	1294.0		114.3
			7.6
	5282.2		18.7
	3859.2		29.5
	816.0		101.7
			8.5
			9.1
			13.0
			79.3

Test Data Collected, I-75, Madison County

Field Density (lb./ft.^{3})	Field Permeability ($1x10^{-5}$ cm/sec)	Laboratory Permeability ($1x10^{-5}$ cm/sec)	Field Vacuum (mm Hg)
		6932.3	5.6
		947.0	80.7
		2166.1	24.5
		4283.4	43.0
		6399.1	11.0
		2291.1	21.8
		7440.0	8.5
		9016.5	5.6
		1941.5	23.4
		5134.1	12.0
		10623.8	5.3
		4349.4	14.3
		2216.1	31.4
		5618.9	5.7
		1990.4	29.0
		953.0	64.0
		3085.3	22.9
		2698.7	9.4
		4124.4	18.1
		777.8	49.1
		6606.5	7.7

Test Data Collected, I-75, Laurel County

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
149.0	107.5		299.4
146.4	4632.0		22.9
147.7	1740.9		105.6
145.7	3094.2		47.5
144.8	5619.0		39.7
142.4	1434.6		143.2
148.8	459.6		85.3
148.8	312.0		227.4
145.4	487.2		192.0
146.4	2257.4		107.5
146.6	1706.8		133.9
147.4	1407.3		115.6
148.1	92.7		370.1
147.6	848.8		107.5
149.5	198.0		210.3
149.3	84.8		314.6
150.7	32.2		546.0
149.8	1279.3		152.5
149.7	164.0		346.2
149.6	63.5		446.7
148.8	156.4		250.1
145.1	3192.1		41.1
145.4	3880.7		47.6
147.1	348.7		220.4
148.4	133.6		305.5
147.9	185.3		217.4
150.9	116.1		285.6
146.5	75.1		403.1
148.3	174.5		157.8
142.3	23.0		537.9
148.7	71.0		250.7
148.6	111.1		403.6
145.9	1616.4		75.9
149.8	65.3		301.1
139.8	90.2		320.6
144.5	42.0		426.3
143.8	1930.7		63.1
148.9	70.8		315.0
149.1	109.4		316.5
145.2			79.6
149.2	3326.3		94.0
146.9	107.6		295.9
148.9			151.7
145.6	92.5		304.8
150.0			146.8
145.7			69.9

Test Data Collected, I-75, Laurel County

(Continued)

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
147.2	3681.6		36.0
147.8			139.1
150.3	14.1		472.4
150.5	112.5		251.5
147.9	1.3		251.0
150.0			186.9
144.0			67.0
141.3	2622.2		35.8
141.2			119.3
147.7	88.3		214.6
147.0			257.2
148.8	21.3		340.9
149.1			184.1
146.5			125.6
143.0	5542.9		58.4
143.4	172.7		283.2
147.5			158.0
148.9			230.0
148.9	6.5		500.2
147.0			166.7
146.3			131.3

Test Data Collected, Bluegrass Parkway, Nelson County

0.5" Surface

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
	1904.0		60.6
	2121.3		65.6
	898.9		119.1
	884.4		77.5
	1244.7		85.7
	767.6		111.7
	104.8		242.4
	321.9		147.1
	383.3		163.8
	981.6		78.9
	455.4		220.4
	170.7		191.6
	411.4		119.0
	32.4		248.4
	82.8		244.6
	286.5		170.8
	188.8		226.6
	173.7		210.9
	333.1		165.5
	94.7		363.2
	184.5		269.9
	202.7		203.0
	120.1		207.9
	23.1		458.6
	51.6		402.7
	216.6		265.6
	157.3		252.9
	3.7		473.8
	17.0		455.3
	115.9		280.9

Test Data Collected, Bluegrass Parkway, Nelson County

1.0" Base

Field Density (lb./ft.^{3})	Field Permeability (1x10^{-5} cm/sec)	Laboratory Permeability (1x10^{-5} cm/sec)	Field Vacuum (mm Hg)
	1858.9		64.1
	463.1		202.6
	3389.4		59.1
	8856.8		23.5
	14.5		408.5
	7136.1		27.6
	273.9		195.8

APPENDIX B

Proposed Specification for Field Permeability and Proposed Kentucky Method for Determining Field Permeability

SPECIAL NOTE FOR ACCEPTANCE OF PERMEABILITY OF ASPHALT SURFACE PAVEMENTS

This Special Note will apply when indicated on the plans or in the proposal. Section references herein are to the Department's 2000 Standard Specifications for Road and Bridge Construction.

1.0 DESCRIPTION.

1.1 General. This note specifies permeability acceptance testing required for asphalt surface mixtures. The Kentucky Transportation Center (KTC) developed this note as part of a research effort to produce a field test for measuring permeability and a specification for application in construction practices. The primary objective of this specification is the construction of an asphalt surface mat that has both a low and uniform permeability.

1.2 Approach to Specification Development. Because the data in the KTC study was compiled and presented in the form of accumulative distribution curves, KTC selected this approach as a basis for this note. Using a probabilistic approach to develop this specification, KTC established control points for probability density, or accumulative distribution, curves to quantify the maximum allowable level of permeability. The two points of interest on the accumulative distribution curves are the 15th and 50th percentiles.

2.0 MATERIALS AND EQUIPMENT.

2.1 Air-Induced Permeameter (AIP). The Department will utilize the AIP as developed by KTC during the research study to measure the permeability of the asphalt surface.

2.2 Computer Programs. The Department will utilize the computer spreadsheets produced by KTC to choose the permeability test locations, calculate permeability from the AIP data, and develop the accumulative distribution curves.

3.0 CONSTRUCTION.

3.1 Number of Permeability Tests. The Department will perform a minimum of 20 permeability tests in each direction on two-lane facilities. On four-lane facilities, the Department will perform a minimum of 20 permeability tests in each lane in each direction. For facilities with more than four lanes, the Department will perform a minimum of 20 additional permeability tests per each additional lane and direction.

3.2 Location of Permeability Tests. The Department will select the test locations using the *Random Number Generator* computer program. This spreadsheet ensures that 25 percent of the permeability test locations are within one foot of the longitudinal construction joint. This program also divides the project into ten equal blocks, randomly selects the blocks to be tested, and randomly chooses the precise location for the permeability test within the block.

3.3 Performance of Permeability Tests. The Department will perform each permeability test using the AIP and according to Kentucky Method 64-XXX.

3.4 Calculation of Permeability Results. The Department will calculate the permeability results using the *Permeability Specification Program* computer spreadsheet.

3.5 Permeability Requirements. Based on the average accumulative distribution of all permeability results, the Department will require that no more than 50 percent of the vacuum readings be less than 225 mm Hg and no more than 15 percent of the vacuum readings be less than 100 mm Hg.

4.0 MEASUREMENT. The Department will not measure for payment any extra materials, methods, equipment, or construction techniques used to satisfy the requirements of this note. The Department will consider all such items incidental to the asphalt mixture.

5.0 PAYMENT.

5.1 Lot Pay Adjustment. Contrary to Subsection 402.05.02, the Department will use the following Lot Pay Adjustment Schedule to assign pay values for AC, AV, VMA, Lane Density, Joint Density, and Permeability within each sublot.

5.2 Permeability Deductions. Due to a lack of experience with permeability requirements, the Department will not enforce net project deductions resulting from Permeability values as given in the following Lot Pay Adjustment Schedule. However, when bonuses exceed deductions for the total project, the Department will apply the Permeability values and pay the net difference.

LOT PAY ADJUSTMENT SCHEDULE

Lot Pay Adjustment = (Unit Price) (Quantity) [{0.05(AC Pay Value) + 0.20(AV Pay Value) + 0.20(VMA Pay Value) + 0.25(Lane Density Pay Value) + 0.15(Joint Density Pay Value) + 0.15(Permeability Pay Value)} - 1.00]

WEIGHTED VALUES

	AC	AV	VMA	Lane Density	Joint Density	Permeability
Weight (%)	5	20	20	25	15	15

AC

Pay Value	Deviation From JMF (%)
1.00	≤ ± 0.5
0.95	± 0.6
0.90	± 0.7
(1)	≥ ± 0.8

VMA

Pay Value	Deviation From Minimum
1.00	≥ min. VMA
0.95	0.1-0.5 below min.
0.90	0.6-1.0 below min.
(1)	> 1.0 below min.

AV

Pay Value	Test Result (%)
1.05	3.5-4.5
1.00	3.0-5.0
0.95	2.5-5.5
0.90	2.0-6.0
(1)	< 2.0 or > 6.0

LANE DENSITY

Pay Value	Test Result (%)
1.05	94.0-96.0
1.00	92.0-93.9
0.95	91.0-91.9 or 96.1-96.5
0.90	90.0-90.9 or 96.6-97.0
(1)	< 90.0 or > 97.0

JOINT DENSITY

Pay Value	Test Result (%)
1.05	91.0-96.0
1.00	89.0-90.9
0.95	88.0-88.9 or 96.1-96.5
0.90	87.0-87.9 or 96.6-97.0
0.75	< 87.0 or > 97.0

PERMEABILITY

Pay Value	% < 225 mm Hg	% < 100 mm Hg
1.05	≤ 49	≤ 14
1.00	50-59	15-30
0.95	60-69	31-39
0.90	70-79	41-49
(1)	≥ 80	≥ 50

(1) *The Department will evaluate the acceptability of the work. When the Department allows the Contractor to leave the work in place, the Department will determine its value and may pay up to, but no case more than, 85 percent. In addition to the reduction in pay, the Department may require the Contractor to perform corrective action to the work.*

Kentucky Method
64-XXX-XX

DETERMINING PERMEABILITY FOR IN-PLACE HOT-MIX ASPHALT (HMA) MATS

1. SCOPE - This method describes the procedure for determining in-place permeability of an HMA mat using an air-induced permeameter. This method is applicable to all nominal-maximum sizes and gradations.

2. APPARATUS -

   2.1 Permeameter - Provide a device consisting of the following components:

      2.1.1 Vacuum Chamber – Ensure the chamber is constructed of heavy-duty, transparent LEXAN® or its commercial equivalent and conforms to the dimensions in Figure 1. Ensure that a three-inch, ±1/4 inch, sealing ring is attached to the bottom of the chamber.

      2.1.2 Sealing Ring – Provide a silicone sealing ring conforming to the dimensions in Figure 1. Ensure the vacuum chamber fits snugly in the ring opening and is tightly sealed to prevent air leakage.

      2.1.3 Multi-venturi Vacuum Cube – Provide a multi-venturi vacuum cube with an air compressor hose attachment. Ensure the cube attaches to the top of the vacuum chamber according to Figure l. In addition, ensure the cube contains a valve to restrict air flow though the cube.

      2.1.4 Digital Gauge – Provide a digital vacuum gauge mounted to the top of the vacuum chamber that is capable of reading from 0 to 700 mm Hg with less than a 0.01 percent error.

   2.2 Air Compressor - Provide an air compressor capable of delivering a constant pressure of 68 pounds per square inch, ±3 pounds per square inch.

   2.3 Caulking Gun - Provide a caulking gun capable of extruding material from commercially available caulking tubes.

3. MATERIALS - Provide a silicone-based, commercially available, rubber caulk that can be purchased in tubes.

4. PROCEDURE -

4.1 Setup -

4.1.1 Connect the air compressor to the multi-venturi vacuum cube.

4.1.2 Check the digital gauge to ensure its proper operation and that it is in the "mm Hg" mode.

4.1.3 Ensure all seams and orifices are in good condition.

4.1.4 Zero the gauge according to the manufacturer's instructions. This needs to be performed only once per day.

4.1.5 Ensure the sealing ring is free of debris.

4.2 Sealing and Placement of Permeameter -

4.2.1 Apply approximately a one-half-inch bead of silicone rubber caulk approximately one inch inside the outer edge of the sealing ring.

4.2.2 Place the permeameter in the center of the area to be tested, using caution not to move the permeameter laterally during or after placement.

4.2.3 When placing the permeameter, apply a downward force of no more than 50 pounds while twisting the permeameter approximately one-eighth of a turn. It is important not to "over-twist" the device; this action may cause penetration of the silicone into the pavement voids, increasing the value recorded on the gauge.

4.3 Obtaining Readings -

4.3.1 Open the valve on the multi-venturi vacuum cube to permit the flow of air.

4.3.2 The reading on the digital vacuum will begin to increase. When this number reaches a peak, the test is finished and the valve can be shut. The test time will vary depending on the permeability of the pavement, but the time should not exceed 15 seconds. It is important not to permit the permeameter to run for an extended period of time. This practice may cause delamination or "humping" of the pavement. This point is especially important for hot, fresh-laid pavements. A "rule-of-thumb" is not to test any pavement above 130° F.

4.3.3 Record the highest reading attained by the permeameter by pressing the button marked "*HI/LO*." It is necessary to obtain only one reading per site.

5. CALCULATIONS -

5.1 Permeability of the mat in units of feet per day (ft./day) may be calculated from the following equation:

$$k = 25{,}757.53 * V^{-1.556}$$

where k = permeability (ft./day), and
V = vacuum reading in mm Hg.

5.2 Record the permeability to the nearest 0.1 ft./day.

Approved ____________________
Director, Division of Materials

Date_________________________