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Report No. CDOT-2008-5
Final Report

PERMEABILITY RESEARCH WITH THE ROMUS AIR PERMEAMETER

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June 2008

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

ACKNOWLEDGEMENTS

Many thanks to all of the CDOT and Contractor testers who helped with pavement density data and the Project Managers who made accommodations for me to test their projects.

Thanks as well to the CDOT testers in the Asphalt Program who went to the projects with me and helped operate the permeameter.

Special thanks to Dr. James Crovetti and Jay Schabelski of Marquette University for their study advice and guidance.

Technical Report Documentation Page

1. Report No. CDOT-2008-5	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PERMEABILITY RESEARCH WITH THE ROMUS AIR PERMEAMETER		5. Report Date June 2008 6. Performing Organization Code
7. Author(s) Neal Retzer		8. Performing Organization Report No. CDOT-2008-5
9. Performing Organization Name and Address Colorado Department of Transportation - Asphalt Program 4670 Holly St. Denver, Colorado 80216		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes Prepared in cooperation with the US Department of Transportation, Federal Highway Administration		

16. Abstract

This report evaluates the ROMUS air permeameter and analyzes the permeabilities of Colorado's asphalt pavements. The permeability of an HMA mixture is its ability to resist the passage of air and water through the pavement. Permeability is considered to be a large factor in the deterioration of Colorado's pavements because of the number of freeze-thaw cycles the Rocky Mountain Region experiences over the course of a year.

Since the 1950s, asphalt pavement permeability has been recognized as a factor that leads to degradation of pavements. Permeability concerns have resurfaced with the emergence of the Superpave design method. Many agencies and research organizations have recently conducted studies and devised various types of apparatus to measure permeability.

Previous studies have identified a number of variables that affect permeability such as lift thickness, nominal maximum aggregate size (NMAS), and the coarse or fine gradation characteristic. This study analyzed some of those same variables, as well as the use of pneumatic tire rollers during the compaction process. Other studies found differences between different NMASs and between coarse and fine gradations; this study found little or no difference between those variables. There are, however, similar trends between this study and others regarding permeability versus density trend lines.

The use of pneumatic tire rollers was identified in this study as the largest factor impacting permeability. Other variables have been proven to influence permeability, but the largest difference was between projects that used a pneumatic tire roller and projects that did not use this type of roller for compaction.

Implementation: This study will be used to encourage CDOT project designers and managers to allow for and use pneumatic tire rollers to compact asphalt mats. Currently, designers and project managers have the option to remove pneumatic tire rollers from their projects for various reasons.

17. Keywords hot mix asphalt (HMA), pneumatic tire rollers, rubber tire rollers, asphalt mats, compaction, asphalt pavement permeability		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161; www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 47	22. Price

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EXECUTIVE SUMMARY

This study was conducted to evaluate the performance of the hot mix asphalt testing device, the “ROMUS” air permeameter, on pavements in the field. The objectives for this study were to determine the repeatability and practicality of the device and determine its usefulness to the Colorado Department of Transportation (CDOT). To determine usefulness the device was used to generate trend lines similar to those generated by previous research on permeability with permeameters other than the ROMUS. The trend lines generated from other research compared permeability, nominal maximum aggregate size (NMAS), coarse and fine gradation characteristics, and field density. Generating similar trend lines with the air permeameter will mean that it is effective in that it measures permeability similarly to other devices and discloses the relations amongst permeability, NMAS, gradation characteristics and density. If the device does divulge the same relations as previous research, these properties should be taken into consideration for pavement design and/or material acceptance.

Other objectives of the research included the comparison of projects that use pneumatic or rubber tire rollers to those that exclusively use all steel wheel rollers. Conventional thinking has been that not only does the rubber tire roller achieve target compaction levels more easily than steel rollers, but it also seals the surface of the asphalt mat better than steel wheels, providing for less permeability. There has not recently been extensive research to prove whether or not this is actually the case.

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1.0 INTRODUCTION

1.1 Problem Title

Using the ROMUS air permeameter to determine permeability of hot mix asphalt pavement in relation to density, nominal maximum aggregate size, gradation characteristics and the use of pneumatic tire rollers.

1.2 Problem Statement

CDOT currently has no means for testing permeability or designing asphalt pavements to account for permeability. CDOT does not have any data on the permeability of current asphalt pavements in Colorado. There is currently not a widely accepted device, procedure or specifications for permeability on a national level through AASHTO or ASTM. Through this study and the continued research and development of the ROMUS air permeameter by Marquette University, the ROMUS air permeameter may be found to be repeatable and practical enough that it can be used for permeability acceptance testing by CDOT.

Asphalt pavement durability is affected by oxidation, stripping, and freeze-thaw degradation. Many studies[2,3,4] show the incidence of these factors are directly related to the amount of pavement permeability. It is generally accepted that the in place air void content of the asphalt mat is the leading factor in increased permeability.[6,7] The increased air void content means that it is more likely that the air voids are more interconnected, which allows the flow of air and water through the asphalt mat more easily. Other properties that have been found to influence permeability are aggregate size and layer thickness.[6,7]

Other devices used in the permeability studies have been found to be unreliable and impractical for regular field use.[1,8] Water permeameters do not produce repeatable enough results[1] and some air permeameters have been unsafe[8] or impractical. The water permeameters are considered impractical because they require a considerable amount of water to be transported in the field. The leading air permeameters require a sizeable air compressor.[8] The ROMUS air permeameter has been touted as safe, practical and repeatable.

1.3 Research Objectives

The primary objective of this research is to evaluate if the ROMUS air permeameter performs in the field as a device that produces repeatable test results and trends similarly to those already produced by previous research that investigated permeability. There has already been enough research conducted by numerous individuals that found there is a definite relationship relating permeability, density, aggregate particle size and layer thickness. This study will try and recreate those relationships using a different device to determine if the ROMUS air permeameter effectively measures permeability that may lead to performance issues.

The following steps will be taken to accomplish the objectives of the study.

A. Literature review of both ROMUS developers' data as well as other sources that have used other permeameters to research permeability.
B. Evaluate projects that the air permeameter may be used on. Consideration should be taken that many projects with varying lift thicknesses and particle sizes need to be tested.
C. Procure the ROMUS device and ensure proper functionality.
D. Take ROMUS device out to projects and test pavement permeabilities and gather density data from same locations.
E. Analyze data and write report.
F. Present to Materials Advisory Committee (MAC) for comments or more investigation.

1.4 Implementation

If the results of the study are found to be favorable, the results may impact how asphalt mixes are designed in Colorado with regard to aggregate particle size. It is also a possibility that the device may be used as a means of acceptance of material with a procedure and specifications.

1.5 Detailed Research Plan

In order to meet the objectives of this plan the following tasks in Table 1 must be performed in the following order:

Table 1: Time Table for Completing Various Activities of Research

	2006				2007			
Tasks	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Literature Review	**X**	**X**						
Project Selection		**X**	**X**		**X**	**X**		
Product Acquisition		**X**	**X**					
Visit Projects		**X**	**X**	**X**		**X**	**X**	
Data Analysis				**X**	**X**	**X**	**X**	
Write Final Report							**X**	
Present to MAC								**X**

In order to generate trend lines similar to other research, a large quantity of projects with varying aggregate size and lift thicknesses need to be tested. At least three different nominal maximum aggregate sizes need to be tested. The most common NMASs in Colorado are 3/8”, ½” and ¾”. At least a dozen data points for each size will need to be taken from the field. The lift thicknesses to be tested will likely be 2”, 2.5”, and 3”, but any lift thickness will be acceptable since lift thicknesses are inputs for the formulas for calculating permeability.

2.0 LITERATURE REVIEW

Permeability was first investigated in the 1950s and has reemerged in the mid 1990s with growing concerns over the adoption of the Superpave design method and the coarse gradations that came with it.

From some of the earliest research on the subject of permeability, McLaughlin and Goetz[2] indicated in 1955 that an asphalt pavement's durability is more dependent on permeability than upon in-place density. This conclusion would indicate how important some researchers thought permeability was, especially in comparison to what is thought of as a very important property of asphalt mixes by today's standards. Ernest Zube of the California Division of Highways (Caltrans) published his findings in 1962[3] on research conducted on pavements constructed in the 1950s. Some of Zube's observations were that highly permeable pavements may possibly prematurely fail due to the increased weathering and oxidation from interlocking air voids conducting air through the pavement. Zube also observed that the use of pneumatic tire rollers during compaction greatly decreases a pavement's permeability.

In the mid 1990s, the Florida DOT adopted the Superpave mix design method and was concerned about the more coarse aggregate in the mix that came as a result of the new mix design method. They assumed it was leading to more permeable pavements because water was weeping from the lower side shoulder joint of the pavement. Cores taken from some of these new Superpave designed roads reinforced their thoughts and showed that water was freely passing through the coarse aggregate Superpave layer and not penetrating the old Marshall designed layer. Shortly thereafter, Florida researched[4] a permeability measuring device that was used for testing field cores. They did not, however, develop a non-destructive device for testing in place pavement density in the field. Some of their conclusions were that their device was effective in detecting permeability and that the same air void content of two mixes does not translate into the same permeability. Permeability is more related to gradation according to their findings. They also concluded that lift thickness requirements for Marshall mixes is not adequate for Superpave mixes and a gyratory compacted sample and field compacted sample of the same mix do not have the same void structure.

The National Center for Asphalt Technology (NCAT) tested three different water permeameters.[5] The research indicated that the falling head water permeameter with variable size cylinders was the best and most practical device of the three. The device operates on the premise of Darcy's Law of permeability.[9] NCAT followed up that research with two other studies[6,7] using the falling head permeameter to establish trends between permeability and gradation and air voids and permeability and layer thickness and air voids. The trends from the studies indicate that the larger the NMAS or the more coarse the gradation, the more permeable the asphalt mix is. This trend increases exponentially when the in-place air voids go up. The trends also indicate that the smaller the ratio of layer thickness to NMAS, the more permeable a pavement is and the thicker a pavement is the less permeable it is.

The University of Kentucky made the first advances[8] in using vacuums to measure permeability instead of water or forced air. Forced air devices proved to be unsafe and not repeatable. Water devices were found to be impractical and not repeatable enough for a standard device and procedure to be established. They developed a permeameter that produced repeatable results. The only problem is the device may not be considered practical by some field testers. The Air Induced Permeameter (AIP) that was developed in the study requires a sizeable air compressor to create a vacuum of 68 psi. A large air compressor in the field may be considered cumbersome by some field testers.

Dr. James Crovetti and Jacques Menard found that the NCAT water permeameter was not very repeatable.[1] The more trials that they conducted, the more saturated the pavement became. As a result, the permeability decreased with every test. They used a device developed by Jay Schabelski, a former Marquette graduate student, called the "ROMUS" air permeameter that is both repeatable and practical. To this point, there has been little field data gathered by the device to correlate with the results of water permeameters. There is also limited data for trend lines that relate NMAS to permeability and density.

3.0 OPERATIONS AND PRINCIPLES OF THE ROMUS AIR PERMEAMETER

3.1 Principles and Calculations

Most water permeameters operate on the standard falling head principle. A graduated cylinder is filled with water and then released through the pavement or porous material and the time intervals are recorded between different levels of head. This is based on Darcy's principles of hydraulic conductivity where a porous material's ability to allow water flow is measured by the velocity across a hydraulic gradient.[9] The hydraulic conductivity or permeability can be measured using the standard falling head equation.

Equation 1: $$k = \left[\frac{aL}{tA}\right] \bullet \ln\left[\frac{h_1}{h_2}\right]$$

k = permeability (L/T)
a = cross sectional area of cylinder (L^2)
L = pavement layer thickness (L)
t = time of head drop (T)
A = area of being tested (L^2)
h_1 = initial amount of head (L)
h_2 = final amount of head (L)

There must be a water tight seal between the cylinder and the material being measured so all of the flow is through the pavement. Quite often a steady state flow isn't achieved until the pavement is saturated.[5,7] The formulas for falling head calculations also imply that all water flows vertically through the pavement. All of the aforementioned assumptions or techniques have created some questionable results.[1] Water is often observed flowing between the cylinder and pavement surface on top of the pavement surface, which would lead to false results. Waiting for steady state flow can take hours to run a single test in the field. Assuming that water flows vertically may be incorrect when the pavement becomes saturated or when the water meets an impenetrable layer that has tack on it. The water eventually flows horizontally in either case.

The air permeameter uses the same principles but a different fluid to measure the permeability. The original equation established by Darcy must be changed to accommodate the different fluid properties.[10]

Equation 2: $$K = \left[\frac{LV\mu}{TAP_a}\right] \bullet \ln\left[\frac{p_1}{p_2}\right]$$

K = absolute permeability (L^2)
L = pavement layer thickness (L)
V = volume of vacuum chamber (L^3)
μ = kinematic viscosity of air (M/LT)
T = time of head drop (T)
A = area of being tested (L^2)
P_a = pressure (atmospheric) (F/L^2)
p_1 = initial pressure (L)
p_2 = final pressure (L)

Since the absolute permeability disregards the fluid type and it is more common to use the hydraulic permeability, the following equation can be used to directly solve for hydraulic permeability even though the test was conducted with air:

Equation 3: $$k_w = \left[\frac{LV\mu\rho_w g}{TAP_a\mu_w}\right] \bullet \ln\left[\frac{p_1}{p_2}\right]$$

k_w = hydraulic permeability (L/T)
L = pavement layer thickness (L)
V = volume of vacuum chamber (L^3)
μ = kinematic viscosity of air (M/LT)
ρ_w = density of water (M/L^3)
g = gravitational acceleration (L/T^2)
T = time of head drop (T)
A = area of being tested (L^2)
P_a = pressure (atmospheric) (F/L^2)
μ_w = kinematic viscosity of water (M/LT)
p_1 = initial pressure (L)
p_2 = final pressure (L)

3.2 Field Operation of ROMUS Air Permeameter

The ROMUS air permeameter (Figure 1) uses air that is gathered from the atmosphere as the fluid to measure permeability. The machine has a vacuum pump that operates on a rechargeable battery and depressurizes the tank to negative 24 inches of head.

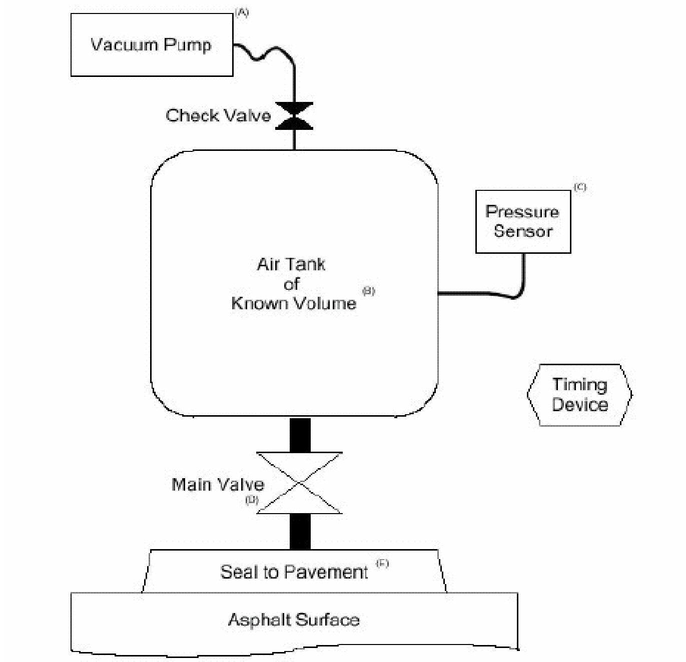

Figure 1: ROMUS Air Permeameter (taken from Figure 4 of Reference 1)

The device rests on top of the pavement surface and lithium grease is applied via a grease gun and tubes to a ring on the bottom of device (Figure 2). The grease is dispersed to holes on the ring to make an airtight seal between the pavement and the machine. The grease ring area is the test section area in the equations.

Figure 2: Air Permeameter Grease Ring

When the test is ready to begin, the air tank is pressurized to 24 inches of head if it is not already at the appropriate pressure. The air is then drawn through the pavement surface while a pressure sensor checks the pressure in the tank. At every 4 inches of pressure drop the time is recorded. The time is the only output for the device other than battery life. Other than Time (T) and Pavement layer thickness (L) all other variables are constant in Equation 3.

The test is repeated until the times between pressure drops are similar from different tests. This is to ensure that there is a good seal on the bottom. If there is not a good seal, air is escaping between the device and the pavement and the times will be different from one test to the next. More grease is pumped to the bottom between tests to ensure a better seal (Figure 3).

Figure 3: Air Permeameter Grease Seal

4.0 PROJECTS AND VARIABLES

Since the scope of this research covers both different construction methods (pneumatic versus all steel rollers) and different aggregate sizes and gradation features, a large number of projects was selected to be a part of the study. There were 20 total projects where data was collected and used for the study with 8 different combinations of material and construction methods (Figure 4).

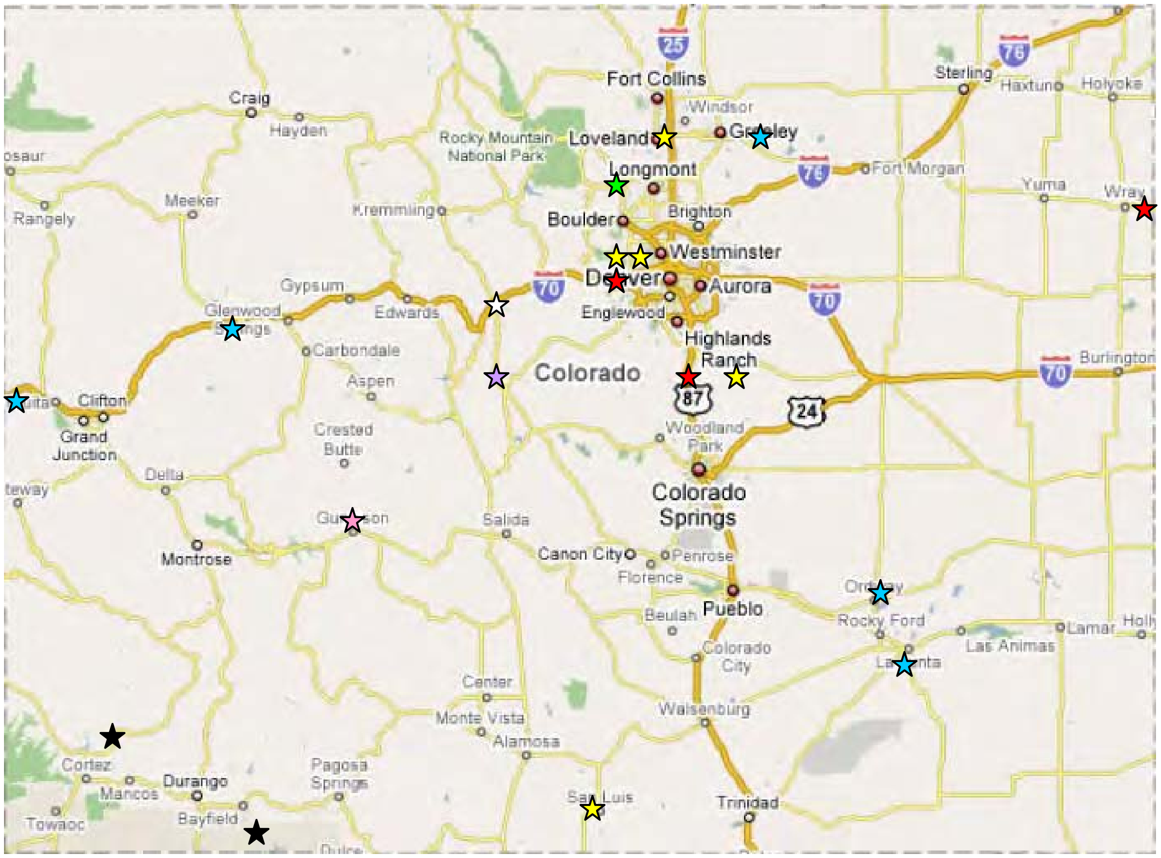

Figure 4: Project Locations and Variables

Table 2: Identified Variables

Locations Used	Mix Type Identified as Variable
★	Fine Mix, Grading S with Rubber Tire Roller
★	Fine Mix, Grading S with all Steel Rollers
★	Fine Mix, Grading SX with Rubber Tire Roller
★	Fine Mix, Grading SX with all Steel Rollers
★	Course Mix, Grading SX with Rubber Tire Roller
★	Course Mix, Grading SX with all Steel Rollers
☆	Fine Mix, Grading SX (3/8" NMAS) with Rubber Tire Roller
★	Fine Mix, Grading SX (3/8" NMAS) with all Steel Rollers

5.0 GENERAL RESULTS AND NMAS DIFFERENCES

The main objective of the study was to determine if the ROMUS air permeameter results correlated well with results and trends from other studies. Subsequently, if it did work properly, the next step would be to compare the permeability of Colorado pavements with those that have been tested in other studies. If asphalt pavements in Colorado were found to be more permeable than those in other states, changes would likely be recommended to decrease our pavements' permeabilities. These recommendations would likely come in the form of specifying different gradations on projects.

For the general aspect of the study, most of the variables listed in Table 2 were combined to more closely match what has been previously examined in other studies. Nominal Maximum Aggregate Size (NMAS) is typically identified as the largest variable affecting permeability. [4,6,7,8] Some studies[4,7] further suggest that the coarse or fine characteristic of the gradation is another variable that affects permeability. All of the previous studies share common trends. Permeability tends to exponentially increase below 93% density. For mixes with larger NMASs, this trend starts at lower air voids (Figure 5).

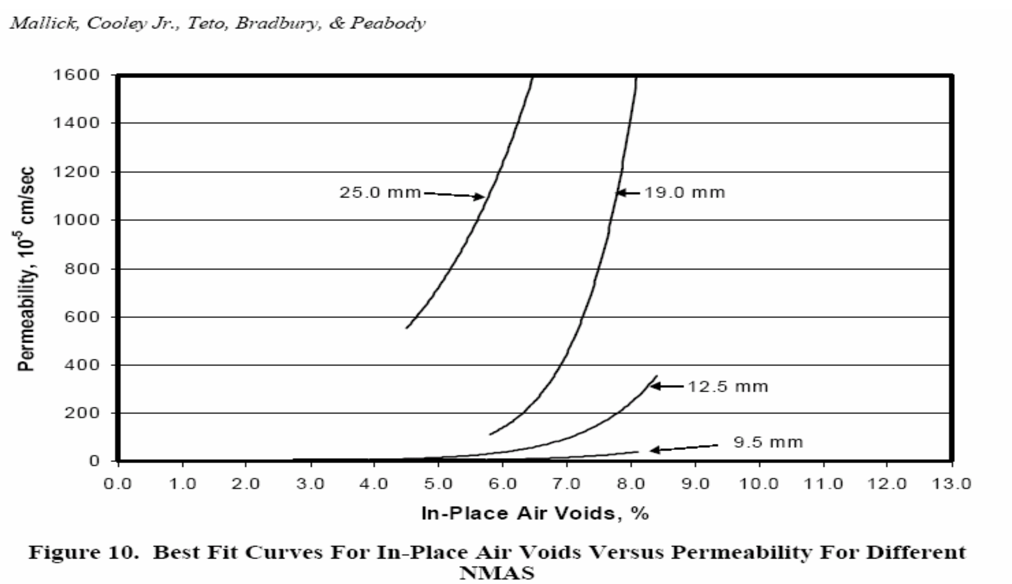

Figure 5: Permeability Trends per NMAS (Figure 10 from reference 6)

In addition to larger NMAS mixes having higher permeability with less field density, a common trend is that coarser mixes are more permeable with less density as well (Figures 6 and 7).

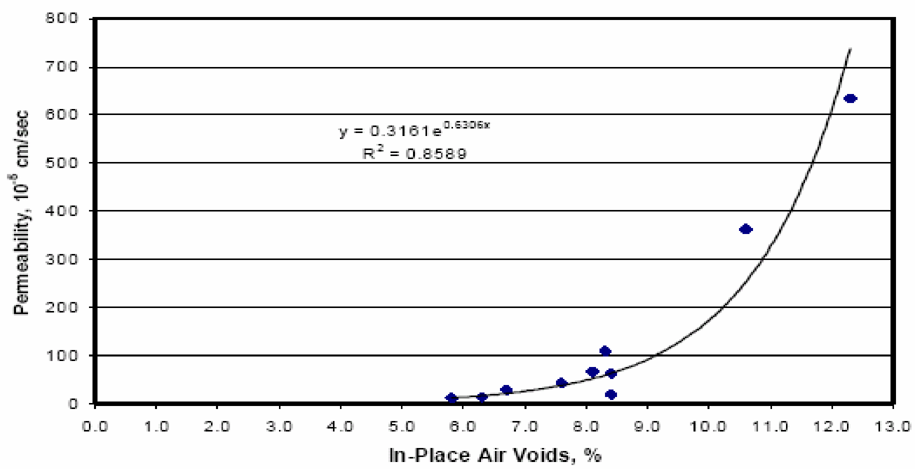

Figure 5. Plot of In-Place Air Voids Versus Permeability For 9.5 mm Fine Mix

Figure 6: Fine Mix Permeability (Figure 5 from Reference 6)

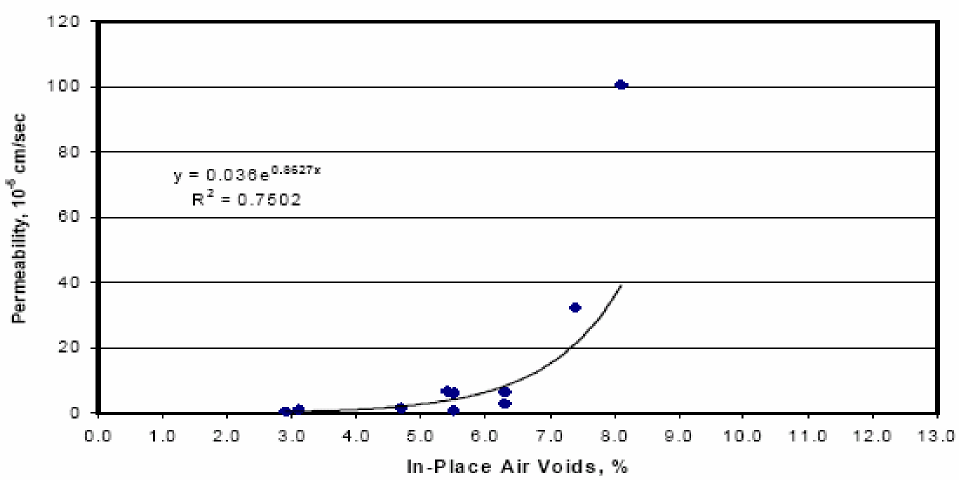

Figure 6. Plot of In-Place Air Voids Versus Permeability for 9.5 mm Coarse Mix

Figure 7: Coarse Mix Permeability (Figure 6 from Reference 6)

The results from previous studies indicate that larger particle NMAS mixes and coarser mixes are more permeable. Although 2 different mixes may have the same NMAS, the coarse/fine characteristic of the gradation may have completely different permeability characteristics.

The results from this study were somewhat different than results from other studies. The "SX" mix, which is defined as a ½" NMAS, has a very similar permeability trend line than the "S" or ¾" mix. This is contrary to what other studies have found. The ROMUS and CDOT mixes also produced very similar results with the shapes and values of the trend lines themselves. Where the trend lines cross the 200 * 10^{-5} cm/s permeability is very similar. The CDOT ¾" crosses at about 6.5% air voids and the 19.0 mm (¾") in the *Mallick* study also crossed 200 * 10^{-5} cm/s at about 6.5% air voids (comparing Figure 5 and figure 8).

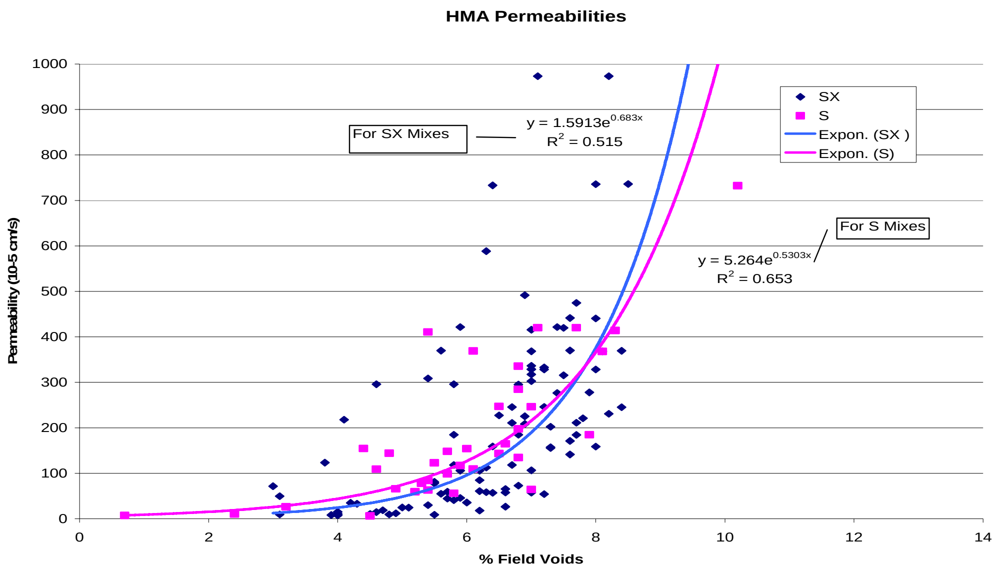

Figure 8: CDOT Overall Permeabilities

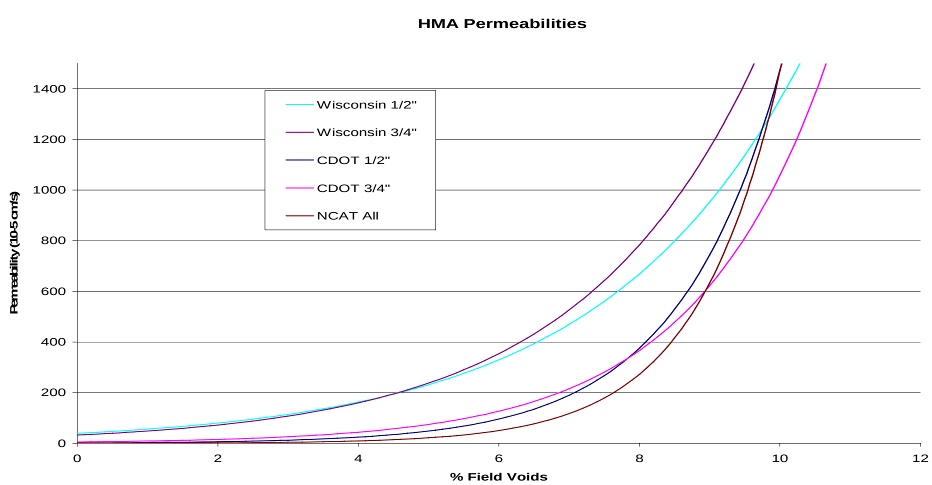

Figure 9: CDOT Permeabilities Compared to Others

6.0 COARSE AND FINE RESULTS

The first variable beyond NMAS that affects permeability is the coarse or fine characteristic of the gradation. This is defined by where the .45 gradation curve is in relation the maximum density line when it passes through the #8 screen. When it is above the maximum density line the gradation is considered to be "fine" and when it is below the line it is considered to be "coarse." Coarse gradations tend to have a rougher surface texture or appear rockier. This appearance or characteristic may translate into larger void areas which should, in turn, make the mix more permeable.

Other studies[4,6] have found that the coarse mixes tend to be more permeable. In Colorado the difference appears to be negligible (Figure 10), especially below 8% voids. Most recently, Colorado has only had fine gradations for their ¾" NMAS mixes so the comparison can only be drawn with ½" mixes.

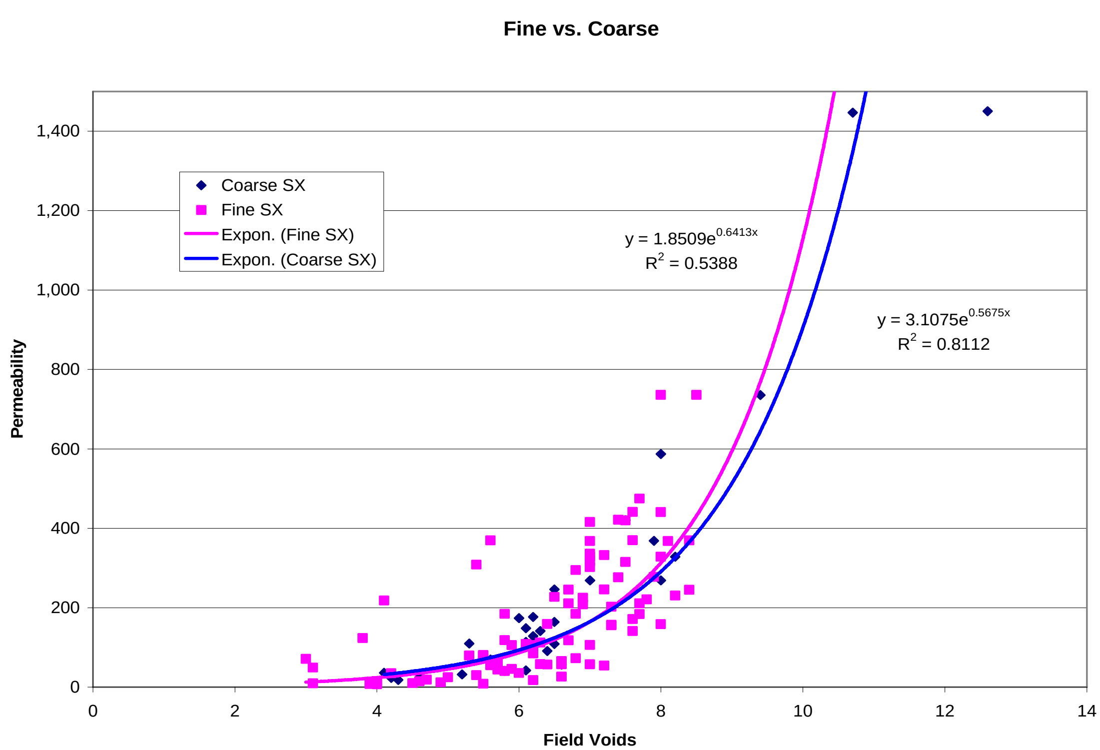

Figure 10: Fine vs. Coarse Mixes

7.0 PNEUMATIC ROLLER RESULTS

The next variable investigated beyond NMAS was the use of rubber tire rollers on the projects. The objective was to determine if the use of pneumatic rollers during construction sealed the pavement more than using only steel wheels. A surface that is sealed better would yield lower permeabilities. The theory that rubber tire rollers would seal the surface better is based on the fact that the surface texture of the rubber is softer than that of steel and it would knead or smooth out the surface of the mat better than steel. The only investigation into comparing the two construction methods was in the Caltrans study.[3] The study was conducted in 1961 and was aimed at determining better compaction methodologies. Subsequently they found that the use of pneumatic tire rollers, as well as the rubber tires from vehicle traffic over time, decreased permeability.

The results indicate there is a difference between the two construction methods. The average difference below 8% air voids amounts to about 100 * 10^{-5} cm/s.

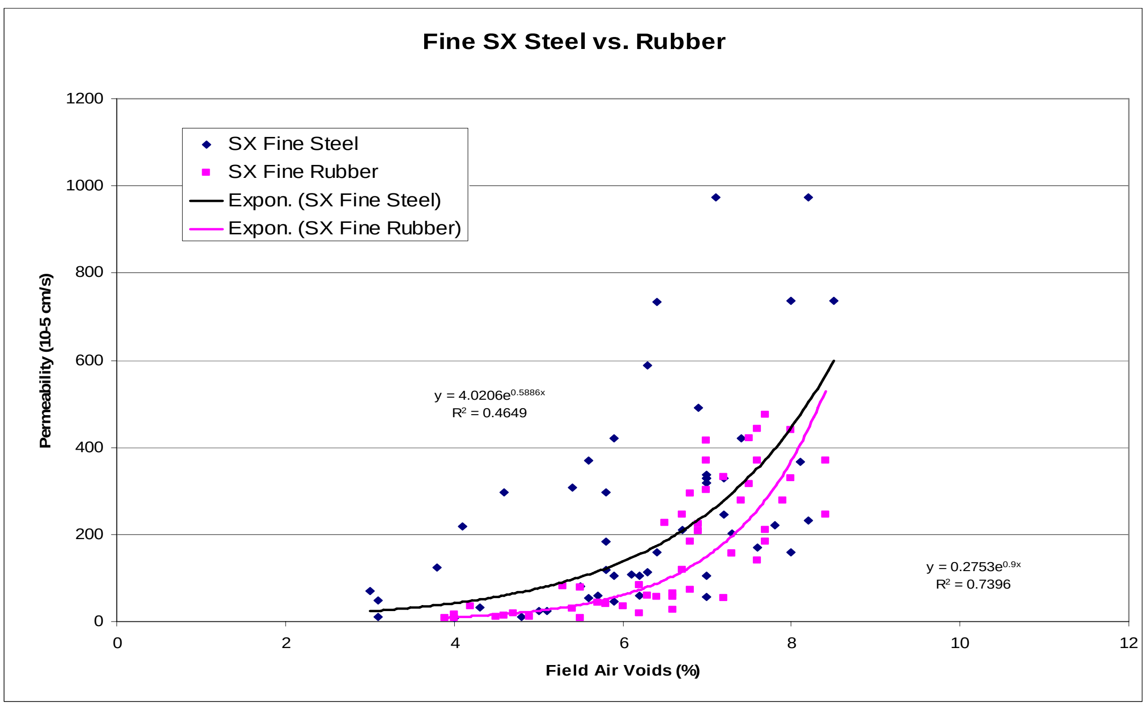

Figure 11: All Steel vs. Rubber Tire Rollers

8.0 CONCLUSIONS AND RECOMMENDATIONS

Although this study found that there is no difference between ¾” and ½” NMAS as well as between coarse and fine gradations, other studies have found that there are differences between these gradation characteristics in regard to permeability. It is still recommended that in regard to permeability, a smaller NMAS with a finer gradation should be used.

The permeability analysis of Colorado’s HMA pavements proved that there is nothing out of the ordinary or there are no extraordinary permeability issues with CDOT’s HMA pavements. Most permeability issues can be remedied in the design phase by specifying certain gradation types or NMAS. This study showed permeability can be further reduced with construction methodologies, such as the use of pneumatic tire rollers. Therefore, there is no recommendation to include any sort of permeability testing on projects for acceptance. Testing that is already required per CDOT specifications is another means to regulate permeability. Field density still proves to be the largest variable in relation to permeability and CDOT’s current specification of 92 to 96%[12] (CDOT Standard Specifications, Section 401.17) field density appears to be sufficient. Based on Figure 8, the permeabilities are still within reason within the allowable CDOT density range.

According to the results of this study the best way to improve permeability, aside from proper density, is by using pneumatic tire rollers for compaction. The use of these rollers is already specified per Section 401.17 of the CDOT Standard Specifications,[12] but this requirement is often waived by design engineers or project engineers. Pneumatic tire rollers will often pick up “pan cake” sized and shaped clumps of asphalt on mats. This happens more often with polymer modified binders. There are ways to mitigate this, such as keeping the rubber tires warm by continually moving the roller over the hot mat or by warming the tires before they are applied to the mat. There are also silicone release agents that can be applied and Michelin makes non-stick tires. Using pneumatic rollers as much as possible would increase Colorado’s asphalt pavements’ resistance to permeability-related distresses. Project personnel should try to accommodate for these rollers and/or encourage contractors to keep them on their projects.

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APPENDIX A

FIELD PROCEDURE

Colorado Procedure XX-08

Standard Method of Test for

Determining the Field Permeability of HMA using the ROMUS Air Permeameter

1. SCOPE

1.1 This method covers the determination of the permeability of field compacted Hot Mix Asphalt.

2. REFERENCED DOCUMENT

2.3 *Colorado Procedures:*

CP 41	Sampling Hot Mix Asphalt
CP-L 5101	Verification of Laboratory Equipment used to Test Bituminous Mixtures

3. APPARATUS

3.1 *Air Permeameter* – This procedure is specifically for the ROMUS air permeameters. The device contains a rechargeable battery and chord for charging

3.2 *Lithium Grease* – Canisters of lithium grease are needed for the grease gun attached to the apparatus. 14 ounce canisters of multi purpose lithium grease are most suitable.

4. CALIBRATION OF APPARATUS

4.1 A procedure has not yet been developed for calibration.

5. TEST LOCATIONS AND TIMES

5.1 Testing should be conducted at lest one foot from pavement edges. Pavement edges have extremely low densities and are open on the edge. This area is not representative the rest of the asphalt mat

5.2 Testing should be conducted as soon as possible after or even during construction. Testing post construction can lead to variable results due to debris and silts that deposit into the mat.

6. PROCEDURE

6.1 For each location, place the air permeameters on top of the desired location to be tested. Pump the grease gun approximately 5 to 10 times while holding the handle of the machine and applying downward pressure. Not holding on to the handle may cause the apparatus to rock and will break whatever seal has been made.

6.2 Turn the machine on and check that the battery and sensors are operating on the display panel. The machine will automatically run a test when it is turned on. Record the four numbers on the display.

6.3 Pump the grease gun 2 to 4 more times while holding the handle and applying downward pressure.

6.4 Push the test button and wait for the test to finish. The test is complete when the four numbers are displayed. While the testing is running the pressure remaining the air tank is displayed and is decreasing. When the test is complete record the four numbers off the display.

6.5 When two tests have been completed compare the results from each area of the display to the previous. If the tests are within 0.1, the testing is complete and the numbers are your final times to be used in the permeability calculation. If the two numbers are more than 0.1 apart then repeat steps 6.3 and 6.4 comparing each test's results with the one that preceded it. If the numbers decrease from the previous reading, using the previous reading as the results.

6.6 When testing is completed turn machine off before moving to next test section.

7. CALCULATION

7.1 Calculate the permeability of the test section as follows:

$$k_w = \left[\frac{LV\mu\rho_w g}{TAP_a\mu_w}\right] \bullet \ln\left[\frac{p_1}{p_2}\right]$$

[Equation 1]

Where:

k_w = hydraulic permeability (L/T)
L = pavement layer thickness (L)
V = volume of vacuum chamber (L^3)
μ = kinematic viscosity of air (M/LT)
ρ_w = density of water (M/L^3)
g = gravitational acceleration (L/T^2)
T = time of head drop (T)
A = area of being tested (L^2)
P_a = pressure (atmospheric) (F/L^2)
μ_w = kinematic viscosity of water (M/LT)
p_1 = initial pressure (L)
p_2 = final pressure (L)

NOTE 1: Pavement layer thickness is the thickness of the surface lift or the lift being tested. The layer of tack is to be considered impermeable.

For the device that CDOT purchased and the assumed constants:

V = 0.02186 m^3
μ = 1.84 * 10^{-5} kg/m*s
ρ_w = 1000 kg/m^3
g = 9.81 m/s^2
A = .01824 m^2
P_a = 101353 Pa
μ_w = .001 kg/m*s
p_1 =24,20,16, 12 in. for 1st through 4th readings respectively
p_2 =20,16,12 and 8 in. for 1st through 4th readings respectively

APPENDIX B
PROJECT DATA

Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

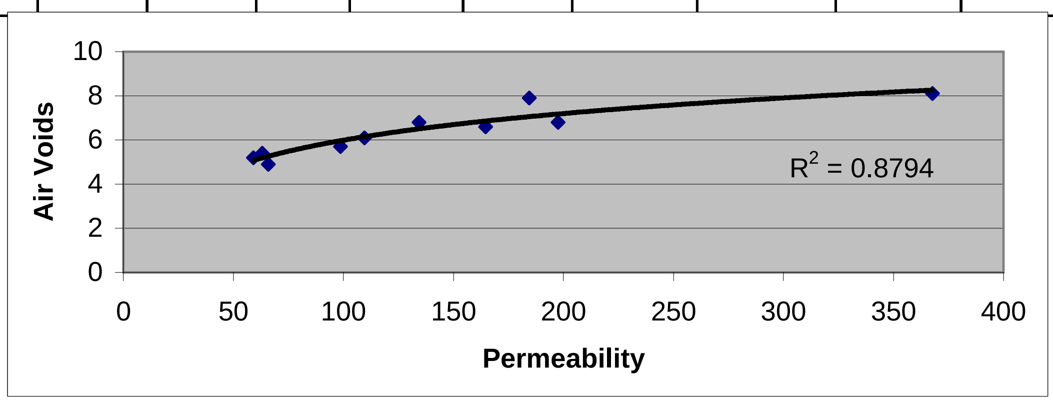
Viscosity of air	1.84E-05 kg/m*s			**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa			**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186			

PROJECT DATA

Location	US 34 East of Wray	**Grading**	S	**Rollers**	Steel
Region	4	**NMAS**	3/4 in		Rubber
Contractor	Simons	**Lift Thickness**	2 in		Steel
PE	Craig Schumacher	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	**Air Voids**	**$L^{(1)}$ (m)**	**A (m^2)**	**t_1 (sec)**	**t_2 (sec)**	**t_3 (sec)**	**t_4 (sec)**	**k_{w1} (10^{-5}cm/s)**	**k_{w2} (10^{-5}cm/s)**	**k_{w3} (10^{-5}cm/s)**	**k_{w4} (10^{-5}cm/s)**	**k_{avg} (10^{-5}cm/s)**	**$k_{overall}$ (10^{-5}cm/s)**
1	6.8	0.051	0.01824	0.986	1.182	1.492	2.361	200	204	209	186	200	198
2	7.9	0.051	0.01824	1.063	1.287	1.611	2.486	186	188	193	177	186	184
3	6.8	0.051	0.01824	1.444	1.761	2.247	3.397	137	137	139	129	135	134
4	6.1	0.051	0.01824	1.794	2.194	2.787	4.083	110	110	112	107	110	110
5	5.7	0.051	0.01824	2.044	2.488	3.169	4.354	97	97	98	101	98	99
6	6.6	0.051	0.01824	1.177	1.426	1.795	2.824	168	169	173	155	166	165
7	8.1	0.051	0.01824	0.563	0.664	0.825	1.182	351	364	377	371	366	368
8	5.4	0.051	0.01824	3.144	3.844	4.995	6.853	63	63	62	64	63	63
9	5.2	0.051	0.01824	3.304	4.139	5.35	7.321	60	58	58	60	59	59
10	4.9	0.051	0.01824	3.027	3.706	4.719	6.618	65	65	66	66	66	66



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

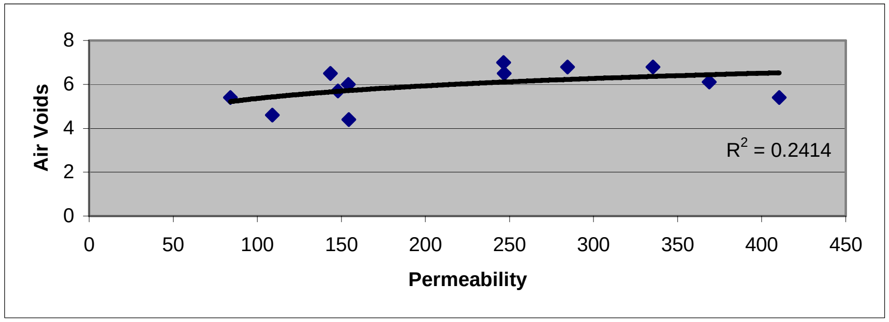
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	SH 7 Northwest of Lyons	**Grading**	S	**Rollers**	Steel
Region	4	**NMAS**	3/4 in		Steel
Contractor	Aggregate Industries	**Lift Thickness**	2.5 in		Steel
PE	Gerald Fielding	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	4.4	0.064	0.01824	1.620	1.945	2.451	3.608	152	155	159	152	155	154
2	4.6	0.064	0.01824	2.344	2.81	3.515	4.959	105	107	111	111	109	109
3	6.5	0.064	0.01824	1.78	2.127	2.647	3.81	139	142	147	144	143	143
4	5.4	0.064	0.01824	0.644	0.742	0.91	1.326	383	407	428	414	408	410
5	6.8	0.064	0.01824	0.921	1.085	1.345	1.873	268	278	289	293	282	285
6	6.5	0.064	0.01824	1.023	1.213	1.503	2.283	241	249	259	240	247	247
7	6.1	0.064	0.01824	0.7	0.813	0.995	1.522	352	371	391	360	369	369
8	7	0.064	0.01824	1.006	1.195	1.48	2.351	245	253	263	233	249	246
9	6.8	0.064	0.01824	0.787	0.918	1.118	1.609	313	329	348	341	333	335
10	5.7	0.064	0.01824	1.673	2.016	2.536	3.821	147	150	153	144	149	148
11	6	0.064	0.01824	1.625	1.954	2.445	3.62	152	155	159	152	154	154
12	5.4	0.064	0.01824	2.924	3.606	4.596	6.546	84	84	85	84	84	84



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

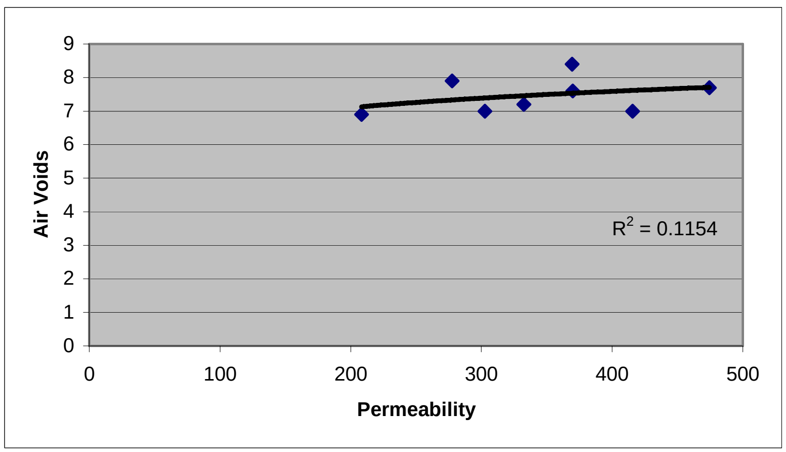
Viscosity of air	1.84E-05 kg/m*s			**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa			**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186			

PROJECT DATA

Location	SH 109 South of La Junta	**Grading**	SX	**Rollers**	Steel
Region	4	**NMAS**	1/2 in		Rubber
Contractor	Lafarge	**Lift Thickness**	2.25 in		Steel
PE	Terry Woodward	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	7.6	0.057	0.01824	0.584	0.689	0.863	1.481	380	394	406	333	378	370
2	7	0.057	0.01824	0.541	0.637	0.787	1.253	410	427	445	394	419	416
3	7.2	0.057	0.01824	0.675	0.799	0.994	1.555	329	340	352	318	335	333
4	8.4	0.057	0.01824	0.62	0.729	0.91	1.363	358	373	385	362	370	369
5	7.7	0.057	0.01824	0.45	0.516	0.637	1.216	493	527	550	406	494	475
6	7	0.057	0.01824	0.731	0.867	1.07	1.753	304	313	327	282	307	303
7	7.9	0.057	0.01824	0.794	0.932	1.162	1.931	280	292	301	256	282	278
8	6.9	0.057	0.01824	1.09	1.301	1.594	2.437	204	209	220	203	209	208



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

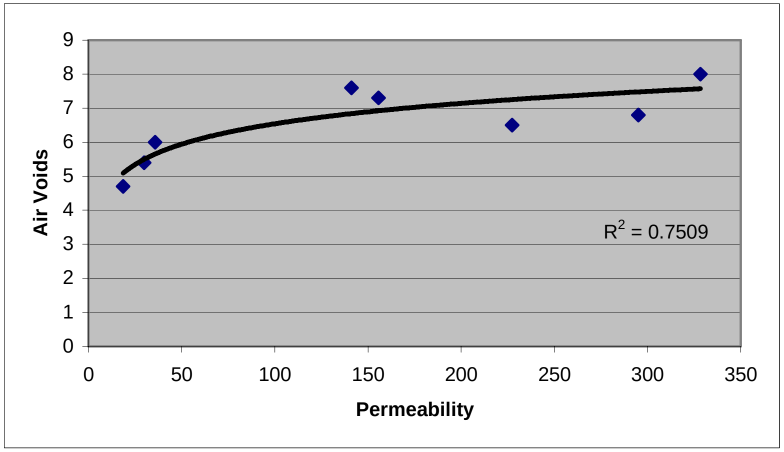
Viscosity of air	1.84E-05 kg/m*s			**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa			**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186			

PROJECT DATA

Location	I 70 Utah State Line	**Grading**	SX	**Rollers**	Steel
Region	3	**NMAS**	1/2 in		Rubber
Contractor	United	**Lift Thickness**	2 in		Steel
PE	Devin Ray	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	8	0.051	0.01824	0.640	0.734	0.890	1.357	308	329	350	323	328	328
2	4.7	0.051	0.01824	10.588	14.096	17.614	21.386	19	17	18	21	18	19
3	6	0.051	0.01824	5.73	7.028	8.922	11.635	34	34	35	38	35	36
4	6.5	0.051	0.01824	0.924	1.079	1.301	1.928	214	224	239	228	226	227
5	6.8	0.051	0.01824	0.731	0.834	1.003	1.463	270	290	310	300	293	295
6	7.3	0.051	0.01824	1.379	1.614	1.955	2.692	143	150	159	163	154	156
7	5.4	0.051	0.01824	6.442	8.281	10.737	14.279	31	29	29	31	30	30
8	7.6	0.051	0.01824	1.483	1.746	2.142	3.054	133	138	145	144	140	141



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

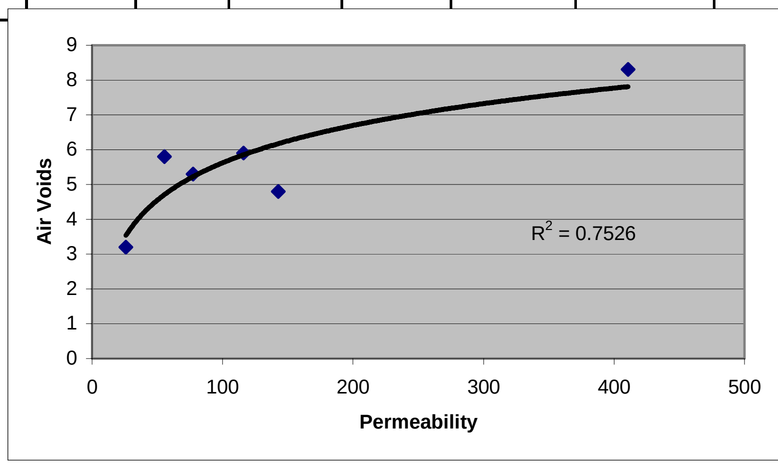
Viscosity of air	1.84E-05 kg/m*s		**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa		**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186		

PROJECT DATA

Location	I 25 Larkspur	**Grading**	S	**Rollers**	Steel
Region	1	**NMAS**	3/4 in		Rubber
Contractor	Lafarge	**Lift Thickness**	2.5 in		Steel
PE	Mike stanford	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	5.9	0.064	0.01824	2.199	2.632	3.299	4.686	112	115	118	117	115	116
2	3.2	0.064	0.01824	9.324	12.466	16.016	19.446	26	24	24	28	26	26
3	4.8	0.064	0.01824	1.794	2.134	2.707	3.778	138	141	144	145	142	143
4	5.3	0.064	0.01824	3.101	3.861	5.117	7.138	80	78	76	77	78	77
5	8.3	0.064	0.01824	0.639	0.732	0.892	1.356	386	412	436	405	410	411
6	5.8	0.064	0.01824	4.298	5.48	7.218	9.827	57	55	54	56	56	55



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

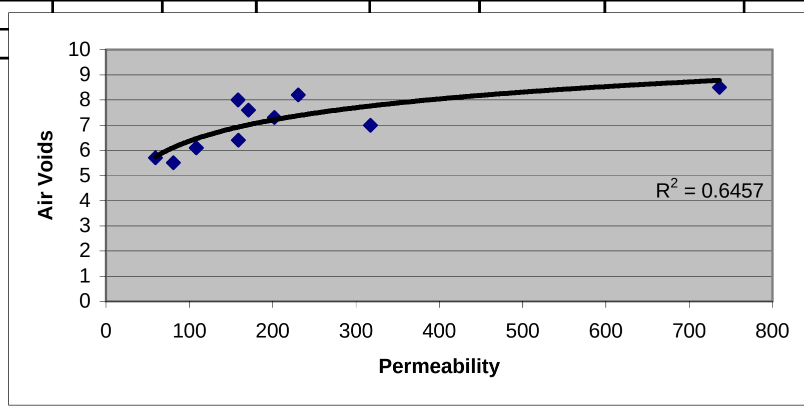
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	US 34 West of I 25	**Grading**	SX	**Rollers**	Steel
Region	4	**NMAS**	1/2 in		Steel
Contractor	Coulson	**Lift Thickness**	3 in		Steel
PE	Miranda Roskop	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	6.1	0.076	0.01824	2.731	3.330	4.260	6.111	108	109	110	108	109	109
2	8.2	0.076	0.01824	0.761	0.895	1.116	4.959	389	405	419	133	336	231
3	7	0.076	0.01824	0.922	1.099	1.369	2.231	321	330	341	295	322	317
4	5.5	0.076	0.01824	3.592	4.474	5.775	8.199	82	81	81	80	81	81
5	7.6	0.076	0.01824	1.735	2.098	2.684	3.908	171	173	174	168	171	171
6	7.3	0.076	0.01824	1.485	1.784	2.267	3.288	199	203	206	200	202	202
7	6.4	0.076	0.01824	1.853	2.247	2.879	4.247	160	161	162	155	160	159
8	8	0.076	0.01824	1.873	2.266	2.859	4.251	158	160	163	155	159	159
9	8.5	0.076	0.01824	0.38	0.43	0.529	1.084	779	843	883	607	778	736
10	5.7	0.076	0.01824	5.041	6.276	8.106	10.657	59	58	58	62	59	59



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

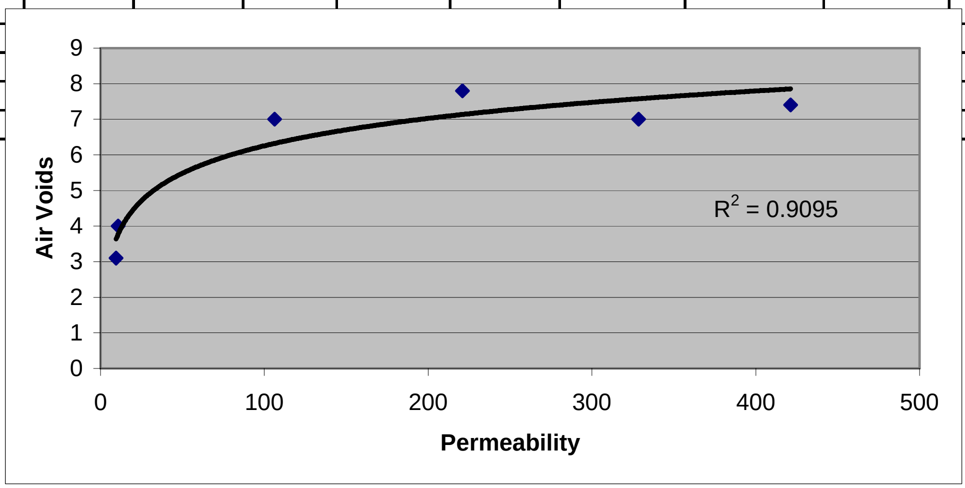
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	SH 93 North of Golden	**Grading**	SX	**Rollers**	Steel
Region	6	**NMAS**	1/2 in		Steel
Contractor	Asphalt Paving	**Lift Thickness**	2 in		
PE	Jamal Mhared	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	7.8	0.051	0.01824	3.740	0.428	0.508	0.707	53	564	613	621	463	221
2	7	0.051	0.01824	2.059	2.344	2.897	3.88	96	103	107	113	105	106
4	4	0.051	0.01824	19.839	26.023	30.622	34.093	10	9	10	13	11	11
5	7.4	0.051	0.01824	0.525	0.59	0.701	1.006	376	409	444	436	416	421
6	7	0.051	0.01824	0.617	0.703	0.841	1.459	320	344	370	301	334	329
7	3.1	0.051	0.01824	22.505	29.448	34.349	39.351	9	8	9	11	9	9



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

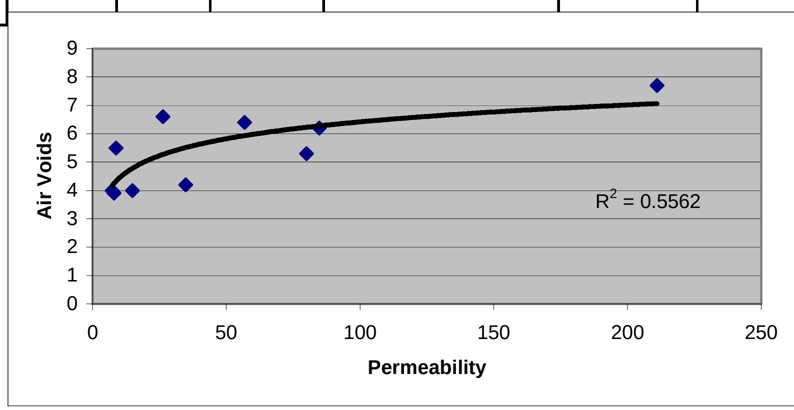
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	SH 6 New Castle	**Grading**	SX	**Rollers**	Steel
Region	3	**NMAS**	1/2 in		Rubber
Contractor	United	**Lift Thickness**	2 in		Steel
PE	Jim Shea	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	6.2	0.051	0.01824	2.600	3.022	3.631	4.777	76	80	86	92	83	85
2	3.9	0.051	0.01824	30.059	37.495	40.766	40.266	7	6	8	11	8	8
3	4	0.051	0.01824	32.229	40.595	44.106	45.518	6	6	7	10	7	7
4	7.7	0.051	0.01824	1.027	1.179	1.397	2.031	192	205	223	216	209	211
5	5.5	0.051	0.01824	29.95	32.817	34.998	37.122	7	7	9	12	9	9
6	5.3	0.051	0.01824	2.713	3.198	3.88	5.07	73	76	80	87	79	80
7	4	0.051	0.01824	14.743	18.583	21.948	24.599	13	13	14	18	15	15
8	4.2	0.051	0.01824	6.08	7.495	9.245	11.324	32	32	34	39	34	35
10	6.6	0.051	0.01824	7.997	10.07	12.02	14.957	25	24	26	29	26	26
11	6.4	0.051	0.01824	3.604	4.47	5.529	7.317	55	54	56	60	56	57



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

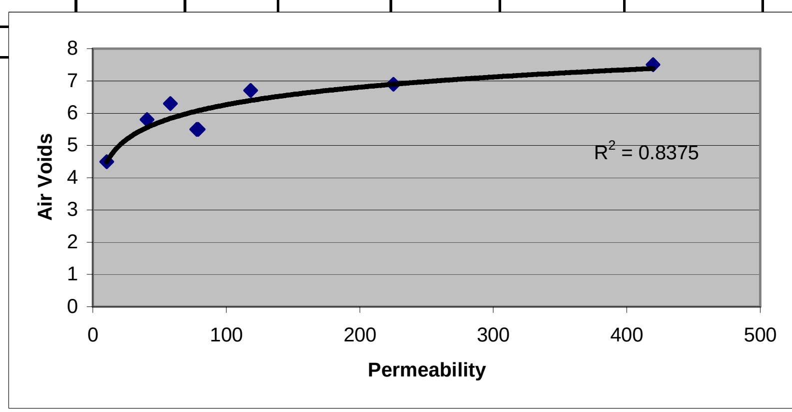
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	SH 96 Ordway	**Grading**	SX	**Rollers**	Steel
Region	2	**NMAS**	1/2 in		Rubber
Contractor	Lafarge	**Lift Thickness**	2 in		Steel
PE	Tim McGhgy	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
2	6.3	0.051	0.01824	3.63	4.266	5.316	7.228	54	57	59	61	58	58
4	4.5	0.051	0.01824	21.485	26.821	31.031	35.224	9	9	10	12	10	10
5	5.5	0.051	0.01824	2.56	3.092	3.87	5.535	77	78	80	79	79	79
6	6.7	0.051	0.01824	1.735	2.073	2.578	3.678	114	117	121	119	118	118
7	5.5	0.051	0.01824	2.634	3.173	3.954	5.515	75	76	79	80	77	78
8	5.8	0.051	0.01824	5.023	6.166	7.839	10.308	39	39	40	43	40	41
9	6.9	0.051	0.01824	0.88	1.037	1.277	2.088	224	233	244	210	228	225
10	7.5	0.051	0.01824	0.515	0.589	0.718	1.012	383	410	434	434	415	420



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

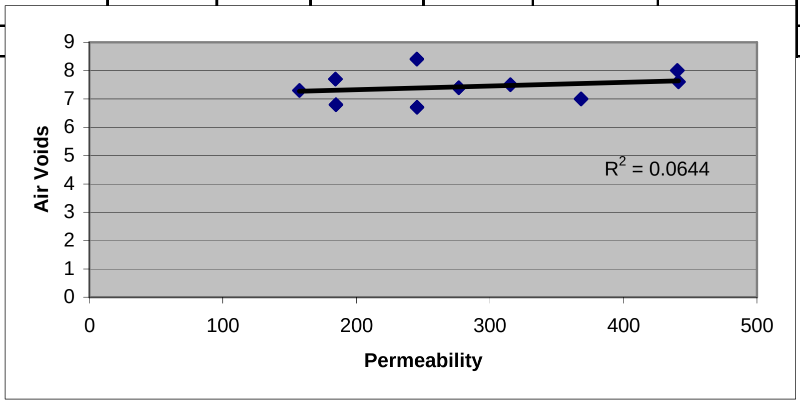
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	US 34 east of Kersey	**Grading**	SX	**Rollers**	Steel
Region	4	**NMAS**	1/2 in		Rubber
Contractor	Aggregate Industries	**Lift Thickness**	1.5 in		Rubber
PE	Nicki Upright	**Coarse/Fine**	Fine		Steel

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	7	0.038	0.01824	0.442	0.508	0.612	0.860	335	357	382	383	364	368
2	7.3	0.038	0.01824	0.661	0.771	0.948	1.639	224	235	246	201	227	157
3	7.6	0.038	0.01824	0.355	0.403	0.489	0.774	417	450	478	425	442	441
4	7.4	0.038	0.01824	0.554	0.639	0.78	1.252	267	284	299	263	278	277
5	7.5	0.038	0.01824	0.516	0.592	0.728	0.993	287	306	321	331	311	315
6	6.8	0.038	0.01824	0.817	0.95	1.173	1.89	181	191	199	174	186	185
7	8	0.038	0.01824	0.317	0.358	0.435	0.915	467	506	537	360	467	440
8	8.4	0.038	0.01824	0.64	0.75	0.92	1.327	231	242	254	248	244	245
9	6.7	0.038	0.01824	0.599	0.693	0.858	1.484	247	261	272	222	251	245
10	7.7	0.038	0.01824	0.837	0.987	1.229	1.79	177	184	190	184	184	184



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

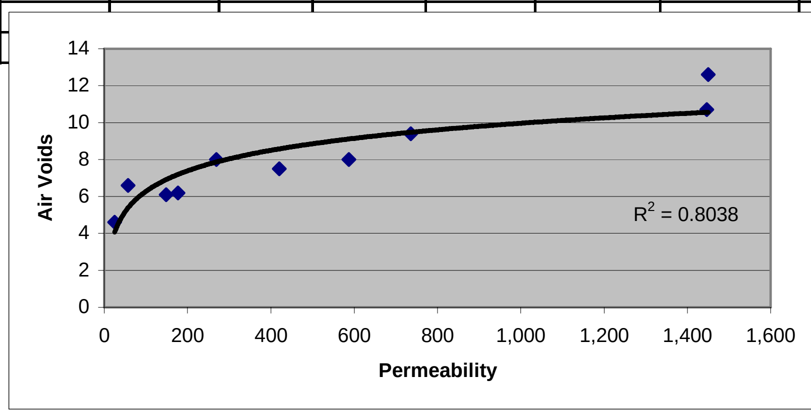
Viscosity of air	1.84E-05 kg/m*s		**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa		**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186		

PROJECT DATA

Location	SH 172 Ignacio South	**Grading**	SX	**Rollers**	Steel
Region	5	**NMAS**	1/2 in		Rubber
Contractor	4 Corners Materials	**Lift Thickness**	2 in		Steel
PE	Kyle Lester	**Coarse/Fine**	Course		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-3}cm/s)	k_{w2} (10^{-3}cm/s)	k_{w3} (10^{-3}cm/s)	k_{w4} (10^{-3}cm/s)	k_{avg} (10^{-3}cm/s)	$k_{overall}$ (10^{-3}cm/s)
1	6.6	0.051	0.01824	3.582	4.335	5.438	7.467	55	56	57	59	57	57
2	9.4	0.051	0.01824	0.253	0.276	0.325	0.763	780	875	958	575	797	735
3	10.7	0.051	0.01824	0.161	0.175	0.204	0.282	1,226	1,380	1,526	1,556	1,422	1,447
4	8	0.051	0.01824	0.822	0.947	1.137	1.519	240	255	274	289	264	269
5	7.5	0.051	0.01824	0.516	0.592	0.728	0.993	382	408	428	442	415	420
6	12.6	0.051	0.01824	0.132	0.148	0.169	0.371	1,495	1,632	1,843	1,183	1,538	1,450
7	8	0.051	0.01824	0.317	0.358	0.435	0.915	623	675	716	480	623	587
8	6.2	0.051	0.01824	1.098	1.281	1.884	2.458	180	189	165	179	178	177
9	4.6	0.051	0.01824	8.038	10.131	12.811	16.295	25	24	24	27	25	25
10	6.1	0.051	0.01824	1.394	1.651	2.047	2.933	142	146	152	150	147	148



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

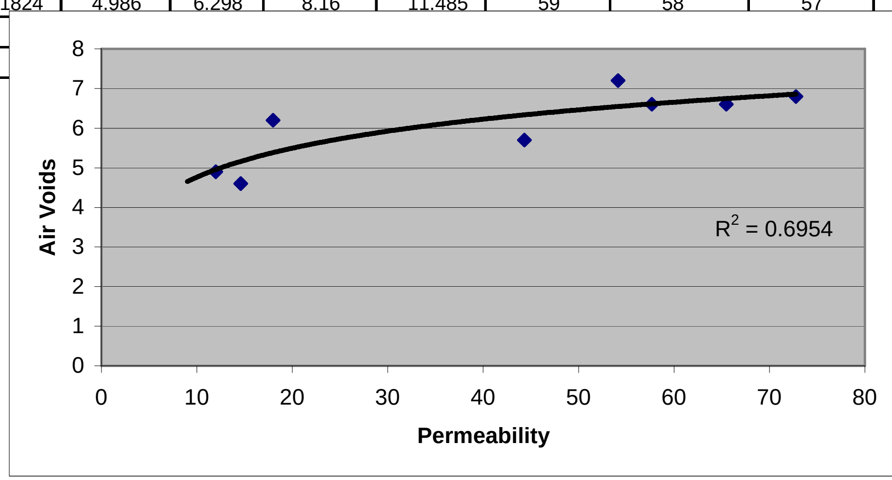
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	I70 East of Silverthorne	**Grading**	SX	**Rollers**	Steel
Region	1	**NMAS**	3/8 in		Rubber
Contractor	Everist	**Lift Thickness**	3 in		Steel
PE	Kevin Brown	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	6.6	0.076	0.01824	4.617	5.646	7.256	9.728	64	64	64	68	65	65
2	4.9	0.076	0.01824	27.292	36.497	39.962	44.866	11	10	12	15	12	12
3	5.7	0.076	0.01824	6.912	8.538	10.862	13.951	14	42	43	47	37	44
4	6.8	0.076	0.01824	4.138	5.087	6.523	8.771	72	71	72	75	72	73
5	7.2	0.076	0.01824	5.488	6.775	8.771	11.915	54	53	53	55	54	54
6	4.6	0.076	0.01824	19.806	28.505	34.533	39.285	15	13	14	17	14	15
7	6.2	0.076	0.01824	17.747	22.492	26.717	32.277	17	16	17	20	18	18
8	6.6	0.076	0.01824	4.986	6.298	8.16	11.485	59	58	57	57	58	58



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

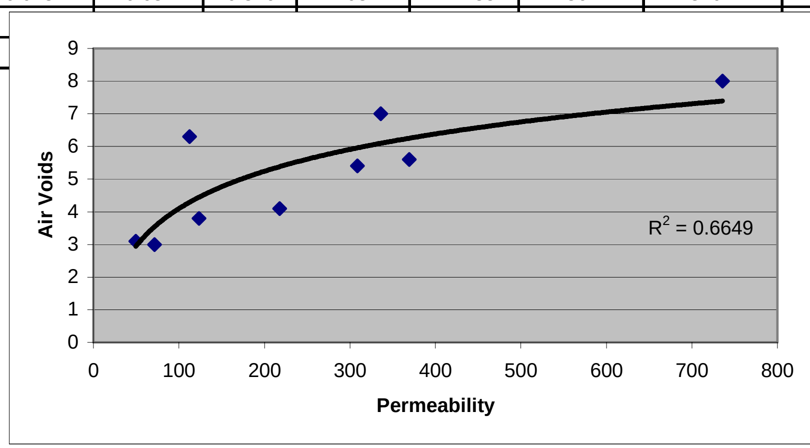
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	Wadsworth at 90th	**Grading**	SX	**Rollers**	Steel
Region	6	**NMAS**	1/2 in		Steel
Contractor	Brannan	**Lift Thickness**	2.5 in		Steel
PE	Jerome Millender	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	3	0.064	0.01824	3.315	4.155	5.445	7.902	74	73	71	69	72	71
2	6.3	0.064	0.01824	2.185	2.668	3.424	4.94	113	113	114	111	113	112
3	5.4	0.064	0.01824	0.78	0.938	1.202	1.897	316	322	324	289	313	309
4	8	0.064	0.01824	0.334	0.381	0.481	0.824	739	792	809	666	752	736
5	7	0.064	0.01824	0.715	0.854	1.086	1.766	345	354	358	311	342	336
6	3.8	0.064	0.01824	1.964	2.397	3.104	4.577	126	126	125	120	124	123
7	3.1	0.064	0.01824	4.749	6.016	8.067	11.213	52	50	48	49	50	49
8	4.1	0.064	0.01824	1.122	1.351	1.718	2.631	220	223	227	209	220	218
9	5.6	0.064	0.01824	0.684	0.816	1.037	1.485	361	370	375	369	369	370



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

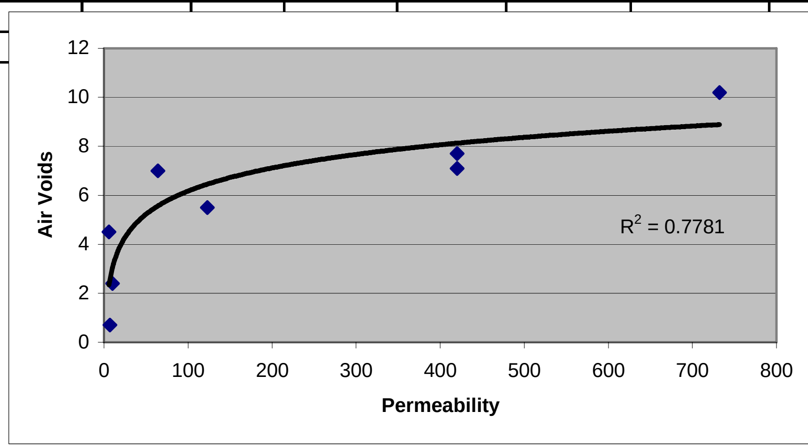
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	Hogback Park and Ride	**Grading**	S	**Rollers**	Steel
Region	1	**NMAS**	3/4 in		Rubber
Contractor	Asphalt Paving	**Lift Thickness**	2 in		Steel
PE	Martin Herbaugh	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	7	0.051	0.01824	3.434	3.980	4.783	6.294	57	61	65	70	63	64
2	4.5	0.051	0.01824	31.549	51.702	55.674	58.931	6	5	6	7	6	6
3	2.4	0.051	0.01824	22.011	28.625	32.103	34.286	9	8	10	13	10	10
4	0.7	0.051	0.01824	34.929	42.292	44.832	46.467	6	6	7	9	7	7
5	7.7	0.051	0.01824	0.489	0.552	0.654	1.135	404	438	476	387	426	420
6	7.1	0.051	0.01824	0.508	0.568	0.671	1.084	388	425	464	405	421	420
8	5.5	0.051	0.01824	1.775	2.091	2.546	3.252	111	116	122	135	121	123
9	10.2	0.051	0.01824	0.264	0.293	0.35	0.717	748	824	890	612	768	732



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

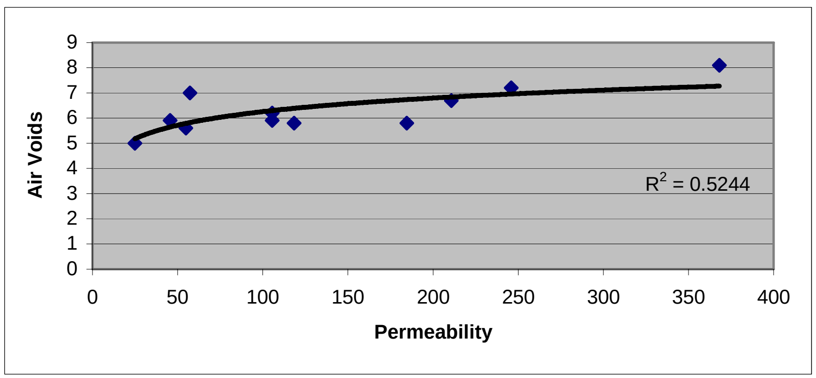
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	SH9 Fairplay to Alma	**Grading**	SX	**Rollers**	Steel
Region	1	**NMAS**	3/8 in		Steel
Contractor	Everist Materials	**Lift Thickness**	2 in		
PE	Mike Voxokis	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	7	0.051	0.01824	3.441	4.221	5.557	7.518	57	57	56	58	57	57
2	5.8	0.051	0.01824	1.638	2.004	2.584	3.82	120	121	121	115	119	118
3	5.9	0.051	0.01824	4.174	5.32	6.945	9.657	47	45	45	45	46	46
4	5	0.051	0.01824	7.559	9.999	13.037	17.169	26	24	24	26	25	25
5	7.2	0.051	0.01824	0.835	1	1.255	1.748	236	242	248	251	244	246
6	6.7	0.051	0.01824	0.965	1.163	1.475	2.039	205	208	211	215	210	211
7	6.2	0.051	0.01824	1.855	2.275	2.956	4.175	106	106	105	105	106	106
8	5.9	0.051	0.01824	1.856	2.298	2.974	4.134	106	105	105	106	106	106
9	8.1	0.051	0.01824	0.555	0.648	0.802	1.226	356	373	388	358	369	368
10	5.6	0.051	0.01824	3.416	4.367	5.753	8.166	58	55	54	54	55	55
11	5.8	0.051	0.01824	1.081	1.302	1.646	2.414	183	186	189	182	185	185



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

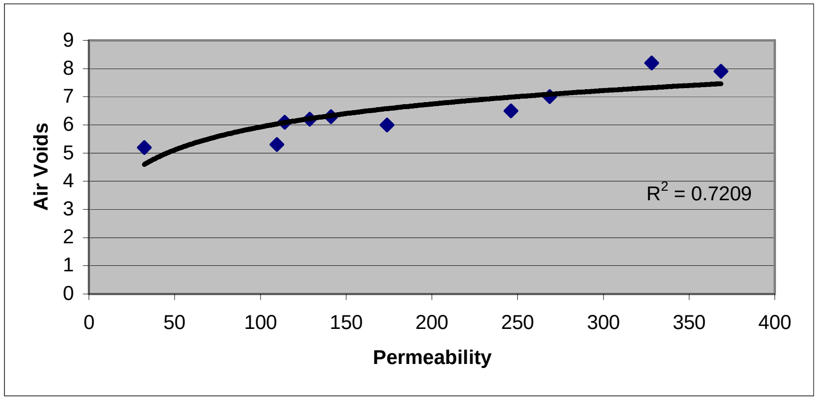
Viscosity of air	1.84E-05 kg/m*s			**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa			**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186			

PROJECT DATA

Location	US 135 North of Gunnison	**Grading**	SX	**Rollers**	Steel
Region	3	**NMAS**	1/2 in		Steel
Contractor	APC Southern	**Lift Thickness**	2 in		Steel
PE	Cole Golden	**Coarse/Fine**	Course		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	8.2	0.051	0.01824	0.691	0.785	0.928	1.220	286	308	336	360	322	328
2	6.3	0.051	0.01824	1.519	1.76	2.114	3.031	130	137	147	145	140	141
3	6.1	0.051	0.01824	1.911	2.206	2.64	3.667	103	109	118	120	113	114
4	7	0.051	0.01824	0.847	0.956	1.127	1.496	233	253	276	293	264	269
5	6.2	0.051	0.01824	1.714	2.009	2.402	3.119	115	120	130	141	126	129
6	7.9	0.051	0.01824	0.585	0.66	0.78	1.202	337	366	399	365	367	369
7	6.5	0.051	0.01824	0.851	0.983	1.172	1.825	232	246	266	240	246	246
8	5.2	0.051	0.01824	6.989	8.475	9.984	11.484	28	29	31	38	32	32
9	5.3	0.051	0.01824	1.958	2.3	2.789	3.801	101	105	112	115	108	110
10	6	0.051	0.01824	1.237	1.452	1.752	2.404	160	166	178	183	172	174



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

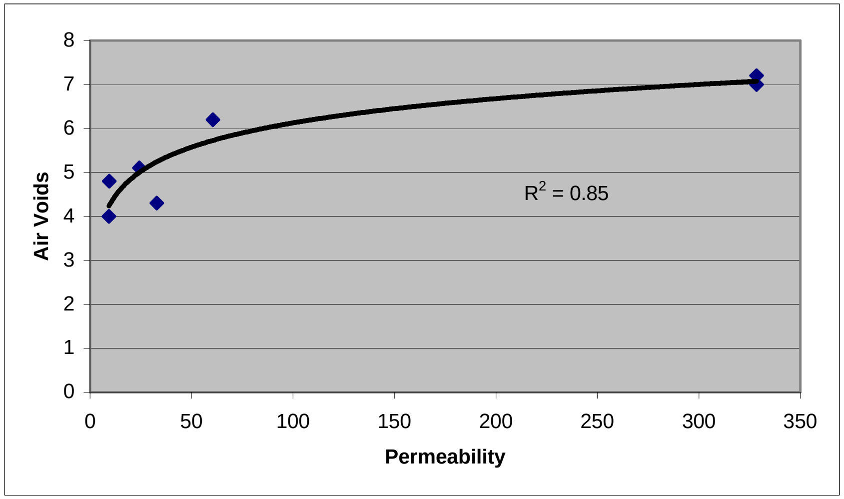
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	SH 86 East of Franktown	**Grading**	SX	**Rollers**	Steel
Region	1	**NMAS**	1/2 in		Steel
Contractor	Lafarge	**Lift Thickness**	2 in		Steel
PE	Brad Dugger	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	7	0.051	0.01824	0.660	0.769	0.933	1.258	299	314	334	349	324	329
2	7.2	0.051	0.01824	0.642	0.747	0.925	1.307	307	323	337	336	326	328
3	5.1	0.051	0.01824	8.11	10.374	13.317	17.037	24	23	23	26	24	24
4	4	0.051	0.01824	20.622	30.06	36.439	40.569	10	8	9	11	9	9
5	6.2	0.051	0.01824	3.26	4.025	5.215	7.123	61	60	60	62	60	61
6	4.8	0.051	0.01824	23.524	29.758	33.946	37.659	8	8	9	12	9	10
7	4.3	0.051	0.01824	6.096	7.511	9.678	12.833	32	32	32	34	33	33



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

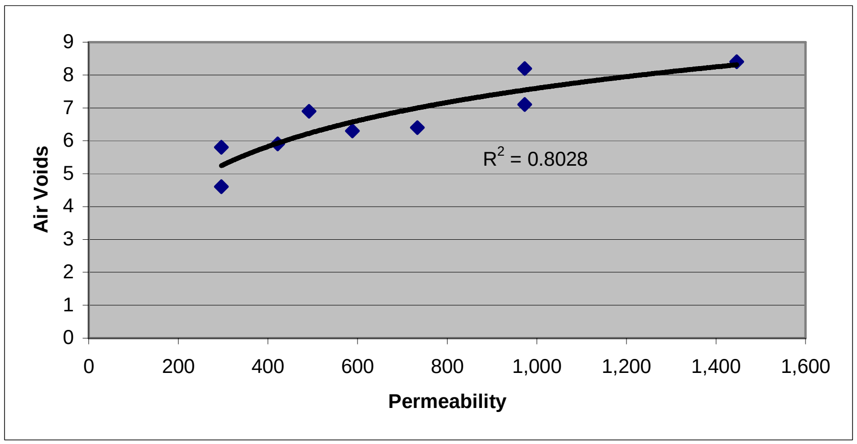
Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	Cuchara on SH 12	**Grading**	SX	**Rollers**	Steel
Region	2	**NMAS**	1/2 in		Steel
Contractor	APC Southern	**Lift Thickness**	2 in		Steel
PE	Joe Trevizo	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	5.9	0.051	0.01824	0.496	0.566	0.687	1.073	398	427	453	409	422	421
2	5.8	0.051	0.01824	0.718	0.833	1.003	1.469	275	290	310	299	294	296
3	7.1	0.051	0.01824	0.225	0.247	0.293	0.457	877	978	1,063	960	970	973
4	6.4	0.051	0.01824	0.313	0.347	0.417	0.545	631	696	747	805	720	733
5	6.9	0.051	0.01824	0.397	0.454	0.546	1.022	497	532	570	429	507	492
6	8.4	0.051	0.01824	0.154	0.175	0.209	0.284	1,282	1,380	1,490	1,545	1,424	1,447
7	4.6	0.051	0.01824	0.692	0.799	0.969	1.561	285	302	321	281	298	296
8	8.2	0.051	0.01824	0.225	0.254	0.303	0.44	877	951	1,028	998	963	973
9	6.3	0.051	0.01824	0.362	0.404	0.484	0.771	545	598	643	569	589	588



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

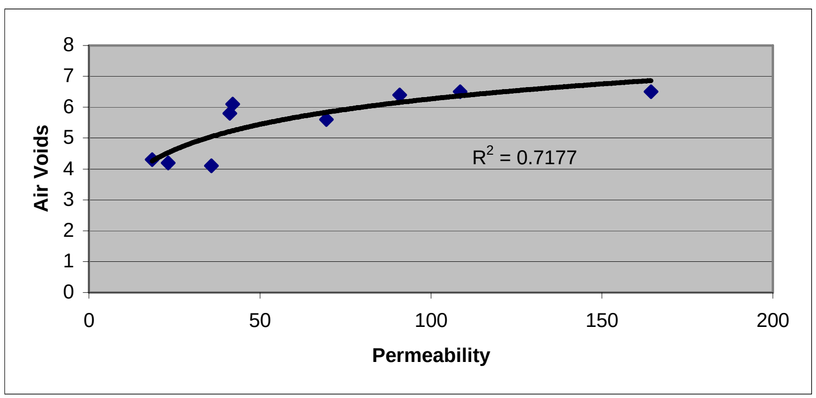
Viscosity of air	1.84E-05 kg/m*s			**Density of water**	1000 kg/m^3
Atmospheric Pressure	101353 Pa			**Viscosity of water**	0.001 kg/m*s
Volume of air Chamber	0.02186 m^3	0.02186			

PROJECT DATA

Location	US 145 Dolores	**Grading**	SX	**Rollers**	Steel
Region	5	**NMAS**	1/2 in		Rubber
Contractor	Kirkland	**Lift Thickness**	3 in		Steel
PE	Tom Allen	**Coarse/Fine**	Course		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)	$k_{overall}$ (10^{-5}cm/s)
1	6.5	0.076	0.01824	3.011	3.592	4.283	5.547	98	101	109	119	107	109
3	6.1	0.076	0.01824	7.352	9.493	11.495	14.124	40	38	41	47	41	42
4	5.8	0.076	0.01824	8.478	10.084	11.454	13.322	35	36	41	49	40	41
5	6.4	0.076	0.01824	3.78	4.227	5.127	6.495	78	86	91	101	89	91
6	6.5	0.076	0.01824	2.039	2.331	2.754	3.728	145	155	170	177	162	164
7	4.3	0.076	0.01824	19.194	23.399	25.692	28.437	15	15	18	23	18	18
8	4.1	0.076	0.01824	8.681	11.023	13.657	16.409	34	33	34	40	35	36
9	4.2	0.076	0.01824	15.867	17.916	20.63	22.658	19	20	23	29	23	23
10	5.6	0.076	0.01824	4.837	5.912	6.739	8.209	61	61	69	80	68	69



Equivalent Water Permeability Calculations Using ROMUS Air Permeameter Data

CONSTANTS

Viscosity of air	1.84E-05 kg/m*s	
Atmospheric Pressure	101353 Pa	
Volume of air Chamber	0.02186 m^3	0.02186

Density of water	1000 kg/m^3
Viscosity of water	0.001 kg/m*s

PROJECT DATA

Location	US 34 East of Kersey	**Grading**	RCI	**Rollers**	Steel
Region	4	**NMAS**	# 8		Steel
Contractor	Aggregate Industries	**Lift Thickness**	1 in		Steel
PE	Nicki Upright	**Coarse/Fine**	Fine		

FIELD RESULTS

Sample	Air Voids	$L^{(1)}$ (m)	A (m^2)	t_1 (sec)	t_2 (sec)	t_3 (sec)	t_4 (sec)	k_{w1} (10^{-5}cm/s)	k_{w2} (10^{-5}cm/s)	k_{w3} (10^{-5}cm/s)	k_{w4} (10^{-5}cm/s)	k_{avg} (10^{-5}cm/s)
1	4.4	0.025	0.01824	45.339	53.890	59.094	64.434	2	2	3	3	3
3	4.3	0.025	0.01824	46.462	61.875	65.547	66.546	2	2	2	3	2
4	3.7	0.025	0.01824	42.958	51.091	54.467	61.075	2	2	3	4	3
5	4.6	0.025	0.01824	47.776	62.197	69.373	72.263	2	2	2	3	2
6	6.6	0.025	0.01824	40.852	53.319	58.158	59.667	2	2	3	4	3
7	7.5	0.025	0.01824	36.162	41.953	45.648	46.731	3	3	3	5	3
8	7.2	0.025	0.01824	31.257	36.954	41.285	42.637	3	3	4	5	4
9	5.5	0.025	0.01824	44.438	56.385	63.936	65.133	2	2	2	3	3
10	6.4	0.025	0.01824	38.327	46.955	50.348	53.992	3	3	3	4	3