ASPHALT MIX PERMEABILITY

FINAL REPORT
July 1989

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16. Abstract

The permeability of various asphalt concrete hot mix binder and surface courses was tested during the course of this study. This study concluded that permeabilities can be obtained such that a general comparison between various asphalt mixes is achieved. However, the attempts to determine which mix variables significantly change permeability were not conclusive because of the simplicity of the testing equipment and the complex nature of asphalt concrete hot mixes.

Also, this project was able to establish a range of permeabilities for the Arkansas asphalt surface and binder courses tested. Accepted permeability standards as suggested by the available literature are presented relative to this range of permeabilities.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

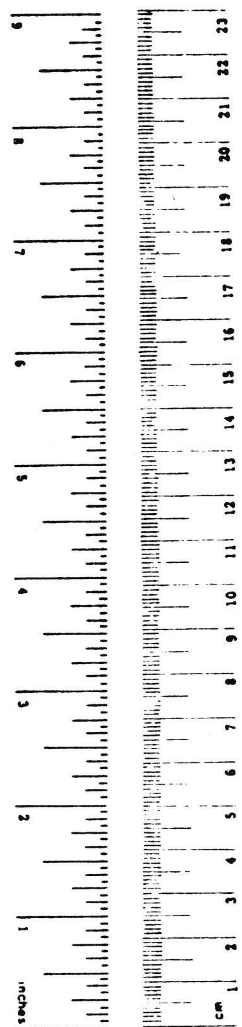
VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac

MASS (weight)

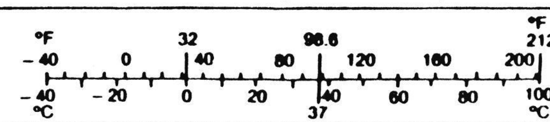
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

ASPHALT
MIX
PERMEABILITY

by

John M. James

Final Report
Transportation Research Project No. TRC-82

June 1988

EXECUTIVE SUMMARY

Permeability is the ability of a porous medium to transmit fluid. For this study the porous medium is asphalt concrete hot mixes and the fluid is air or water.

This study concluded that permeabilities can be obtained such that a general comparison between various asphalt mixes is achieved. However, the attempts to determine which mix variables significantly change permeability were not conclusive because of the simplicity of the testing equipment and the complex nature of asphalt concrete hot mixes.

Also, this project was able to establish a range of permeabilities for the Arkansas asphalt surface and binder courses tested. Accepted permeability standards as suggested by the available literature are presented relative to this range of permeabilities.

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METRIC CONVERSION FACTORS

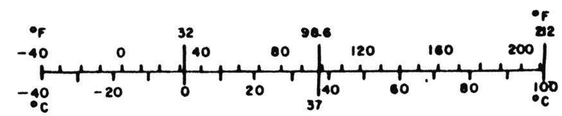
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



METRIC CONVERSION FACTORS

Chapter I

INTRODUCTION

One of the primary concerns in designing and constructing civil engineering structures is the negative influence of water. Whether the concern is with the pressure caused by a head of water, erosion, corrosion, freeze/thaw cycles or saturation of the construction material, the one common ingredient is water. To avoid or deter deterioration caused by water at least one of the following three alternatives must be recognized and provided.

1. Shield the structure or material from the water.
2. Provide an escape for the water or allow the water access and then an easy exit.
3. Accept the deterioration and provide the proper precautions.

Understanding how each of the above alternatives functions as a deterrent or a solution to the deterioration caused by the presence of water requires knowledge of permeability for the civil engineering structure and/or construction material.

Permeability is the ability of a porous median to transmit fluid. For this study the porous median is asphalt concrete hot mixes and the fluid is air and/or water. The presence of water at the surface of the asphalt pavement reduces the available skid resistance. Skid resistance can be enhanced by allowing rainfall to shed from the pavement surface as quickly as possible. A very permeable surface provides such drainage. On the other hand, water trapped within an asphalt pavement promotes stripping. A low permeable asphalt pavement surface layer inhibits moisture from entering the pavement structure and thus deters stripping. In order to better understand how to improve skid resistance without increasing the potential for stripping, one must study the permeability of the asphalt mixes and the pavement structure. The objectives of this study were to:

- Determine the permeability of the various types of asphalt mixes.
- Determine which mix variables significantly change the permeability.
- Correlate permeability to stripping test results.
- Determine acceptable permeability standards.

The approach used to meet these objectives consisted of performing a literature review, constructing air and water permeability apparatus and determining the permeability of asphalt mixes in the laboratory and on the asphalt pavement in the field. In conjunction with performing these tasks other pertinent information needed for the proper evaluation was obtained.

Chapter II

LITERATURE REVIEW

The permeability of an asphalt concrete mixture can be defined as the degree to which the asphalt concrete mixture will allow liquid to flow through. For this study the flow of both air and water through asphalt concrete was investigated. This chapter contains discussions on the theory of permeability, the various constituents of an asphalt concrete mixture and their influence on permeability, and the results of previous investigations.

Theory of Permeability

Darcy, in 1850, developed the fundamental theory of permeability for soil by establishing a relationship in which the rate of flow is directly proportional to the hydraulic gradient and area.

$$Q = k(\delta h/L)A = k i_1 A$$

where:

Q = rate of discharge through the soil

k = coefficient of permeability

A = total cross-sectional area

$(\delta h/L)$ = i_1 = hydraulic gradient, which is the loss of hydraulic head per unit distance of flow. The hydraulic head is equal to the pressure head plus the elevation head. The velocity head through the soil in most flow situations is negligible as compared to the pressure and elevation heads.

This relationship known as Darcy's law is only valid if the following assumptions are made:

1. homogeneous porous material,
2. continuous, saturated, two dimensional flow,
3. homogenous flow medium,
4. steady state flow conditions,
5. no change in voids of porous material,
6. incompressible flow medium, and
7. laminar flow.

The velocity for which the rate of discharge, Q, is established is termed discharge velocity, V.

$$V = Q/A$$

where:

V = discharge velocity

Q = rate of discharge through the soil

A = cross-sectional area measured perpendicular to the flow

Darcy's law states that the discharge velocity of a fluid flowing through porous granular media, under steady conditions, is proportional to the excess hydrostatic pressure causing the flow, and inversely proportional to the viscosity of the fluid (1).

$$V = Ki_2/\mu$$

where:

V = discharge velocity

K = absolute permeability

μ = dynamic viscosity of the fluid medium

$i_2 = P/L$ = pressure gradient, the pressure difference per unit length along the flow lines

and

$$P = \delta h \beta g$$

where:

P = pressure difference

δh = loss of hydraulic head

β = unit weight of fluid

g = acceleration due to gravity

and as previously defined

$$i_1 = \delta h/L$$

then

$$i_2 = i_1 \beta g$$

and

$$V = Ki_1\beta g/\mu$$

K, β, g and μ are all constant for a given fluid at temperature, t, therefore putting the constants together gives:

$$k = K\beta g/\mu$$

where:

k = coefficient of permeability

As can be seen in the above equations the coefficient of permeability, k, is dependent upon the particular properties of the fluid.

In dimensions, absolute permeability corresponds to an area. The absolute permeability is only influenced by the geometry of that given area. Seepage problems found in civil engineering deal with the flow of water where unit weight and viscosity of water remain fairly constant. Because of this the coefficient of permeability has been the more accepted form of reporting the degree to which a structure or material is permeable. According to McLaughlin and Goetz (2) the coefficient of permeability is related to the absolute permeability by the following:

$$k = K\beta/\mu$$

where:

K = absolute permeability (cm^2)

β = unit weight of the fluid (gm/cm^3)

μ = viscosity of the fluid ($gm\text{-}sec/cm^2$)

k = coefficient of permeability (cm/sec)

The coefficient of permeability, k, is not a constant because it is dependent on the properties of the porous material and the properties of the fluid. The value of the absolute permeability, K, is independent of the properties of the fluid. Because air and water have different physical properties and both were used as the flow median in this study, as well as in previous studies, (absolute) permeability, K, was selected for comparison in determining the degree of permeability for a porous material (asphalt concrete).

Influence of Mix Variables

As stated by Ford and McWilliams (1), several factors influence permeability. These are particle size distribution, particle shape, molecular composition of the asphalt cement, voids, degree of saturation, nature of the flow median, type of flow, and temperature. Aggregate size and shape as well as the molecular composition of the asphalt cement are constant for the given materials and gradation of the asphalt pavement mixture. The voids and degree of saturation can vary depending on the orientation and type of placement of the materials. Although the physical characteristics of the fluid and the temperature do not directly influence permeability each plays a vital role in determining the magnitude of permeability by affecting the flow of the fluid.

Ford and McWilliams (1) also stated that the permeability of an asphalt pavement mixture is influenced by the aggregate gradation, maximum size of the aggregate, and how the various sizes are distributed within the mixture. Each of these have an effect on the size and number of voids present. For the most part, permeability decreases as the voids decrease in an asphalt mixture. However, all of the materials which comprise an asphalt mixture should be considered. For a given gradation a particular permeability can be achieved if pore size and total pore volume are constant.

Hudson and Davis (3) concurred with Ford and McWilliams by stating that permeability of a bituminous mixture is more dependent on pore size than on the volume of the voids in the compacted aggregate. As proof of their statment Hudson and Davis showed that fines compacted to a VMA of 30 to 35 percent would be considerably less permeable than a well graded coarse aggregate compacted to a VMA of 12 to 15 percent.

The shape of the different materials in the asphalt concrete mixture influences permeability. Elongated or irregular particles create flow paths which are more tortuous than those created by spherical-shaped particles. This tends to reduce the vertical rate of flow through the asphalt concrete mixture.

Also described by Ford and McWilliams (1) the molecular composition of the asphalt cement, typically unknown, affects permeability. Different types of molecular structure and ionic charges attract and hold on to varying thicknesses of the flow medium, particularly water, and consequently changes the effective pore size.

Compaction affects permeability. The degree of compaction plays a role in the size and number of voids present and hence the permeability of the material. Also, air trapped in the asphalt concrete may inhibit flow by clogging the flow paths. When air is present permeability decreases.

Density, dynamic viscosity and temperature of the peremeating fluid affect the permeability. The effects of these properties are accounted for when determining permeability, K. However, as stated previously, these effects are generally not accounted for when calculating the coefficient of permeability, k, using the conventional soil permeability equations. These equations assume a constant flow medium water.

Past Investigations

McLauglin and Goetz in 1955 (2), hypothesized that using permeability gives a better measure of durability than using void content alone. Permeability, in their opinion, can be used to measure the capacity of a porous medium to transmit fluid, whereas the normal measure using voids in a bituminous mixture does not directly measure the forces producing disintergration.

McLaughlin and Goetz, after comparing water and air permeability, opted to use air permeability to do their investigation. The comparison of air and water permeability developed by McLaughlin and Goetz is presented in Figure 1. As could be anticipated a one to one relationship was established.

The results of the McLaughlin and Goetz study are presented in Figures 2, 3, 4, and 5 and Tables I and II. They concluded that a relationship between air voids and permeability was found which agrees with previous work on soils and other materials. However, at higher asphalt contents permeability is much more sensitive to changes in void content than at lower asphalt contents.

Hein and Schmidt (4) conducted a permeability study in which they suggested that permeability measurements are essential to routine mix design studies. They concluded as

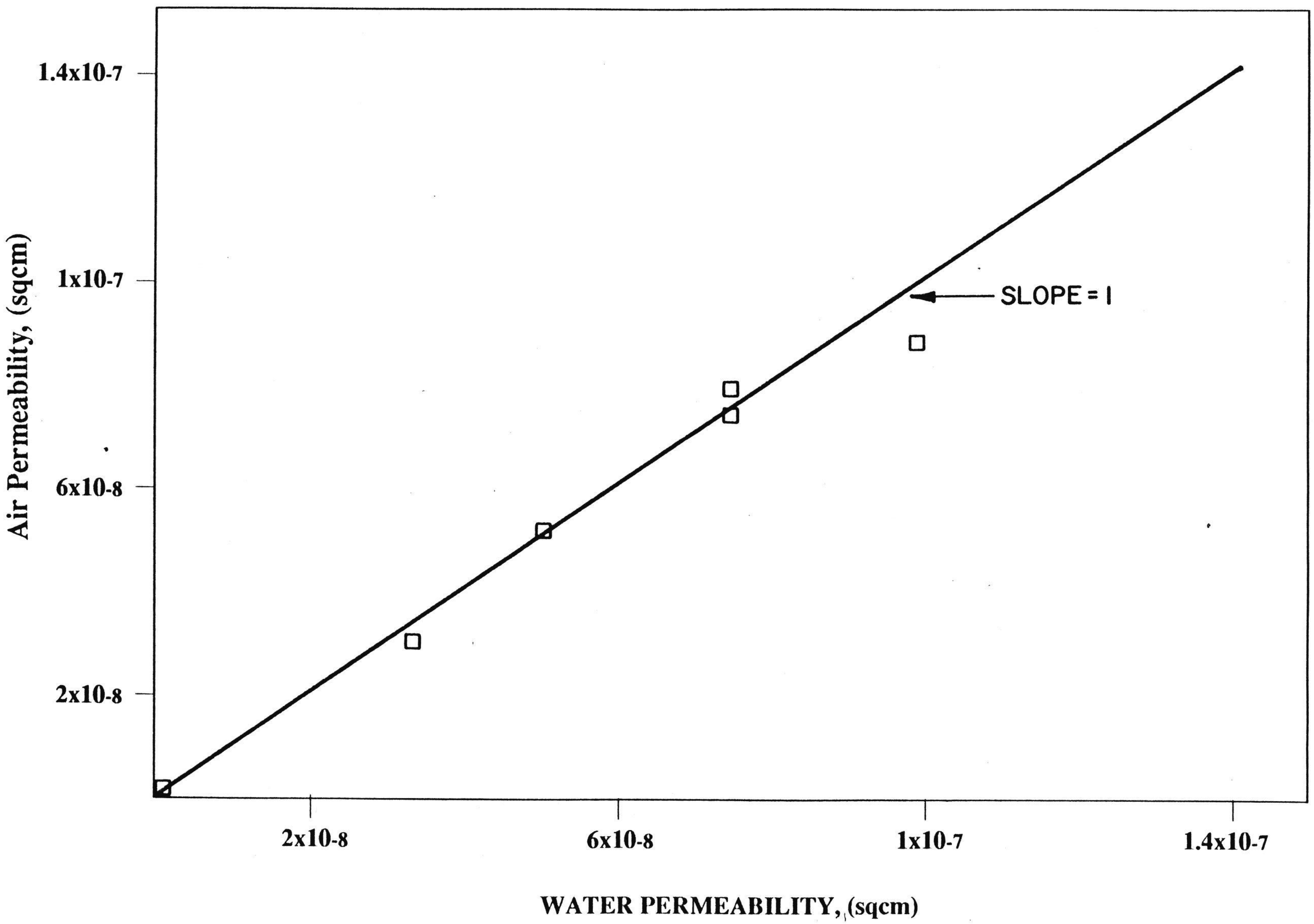


Figure 1. Comparison of Air and Water Permeability.
(After McLaughlin and Goetz, 1955)

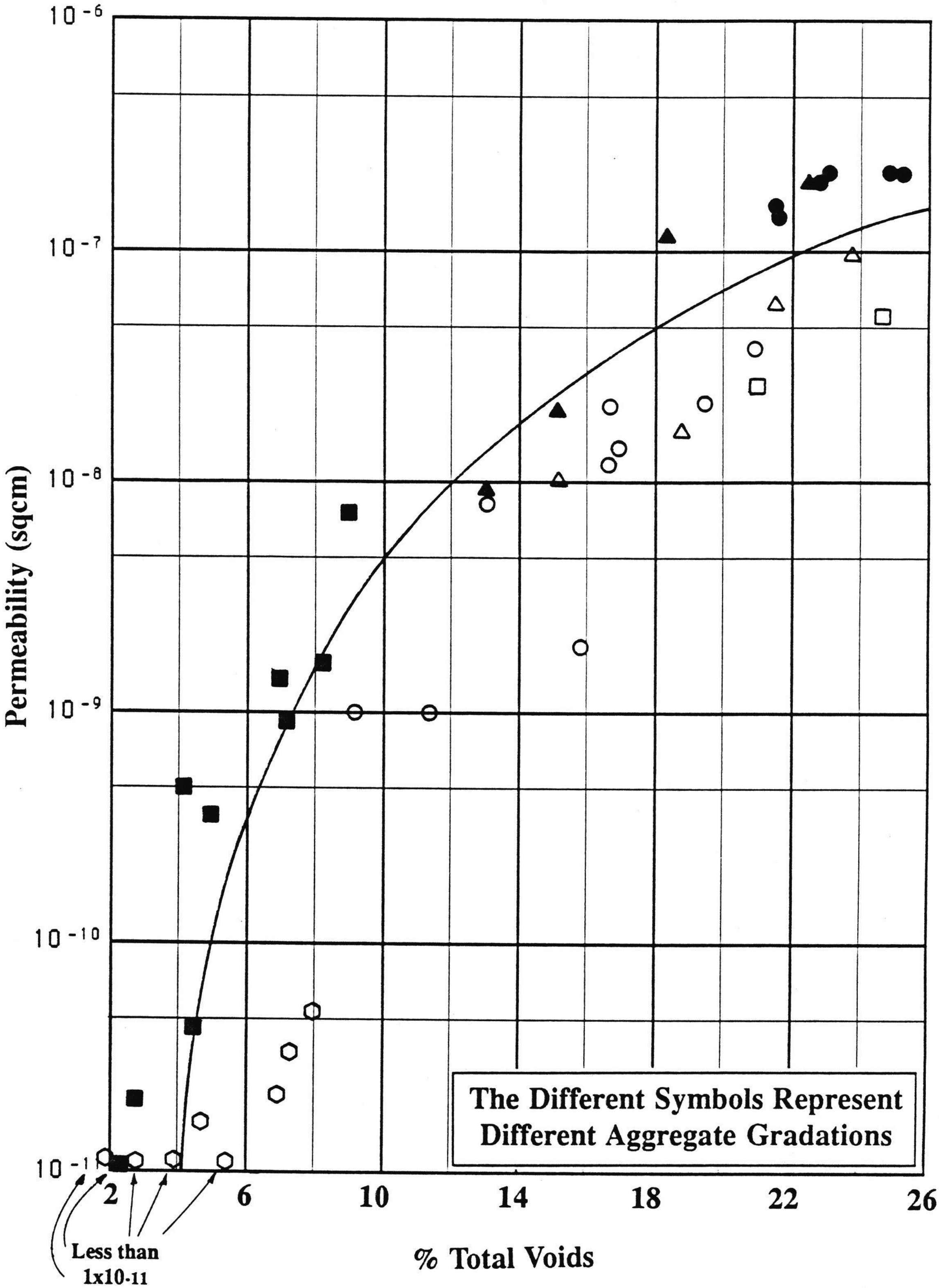


Figure 2. Permeability versus % Total Voids, for Sand Asphalt Mixtures and Bituminous Concrete.
(After McLaughlin and Goetz, 1955)

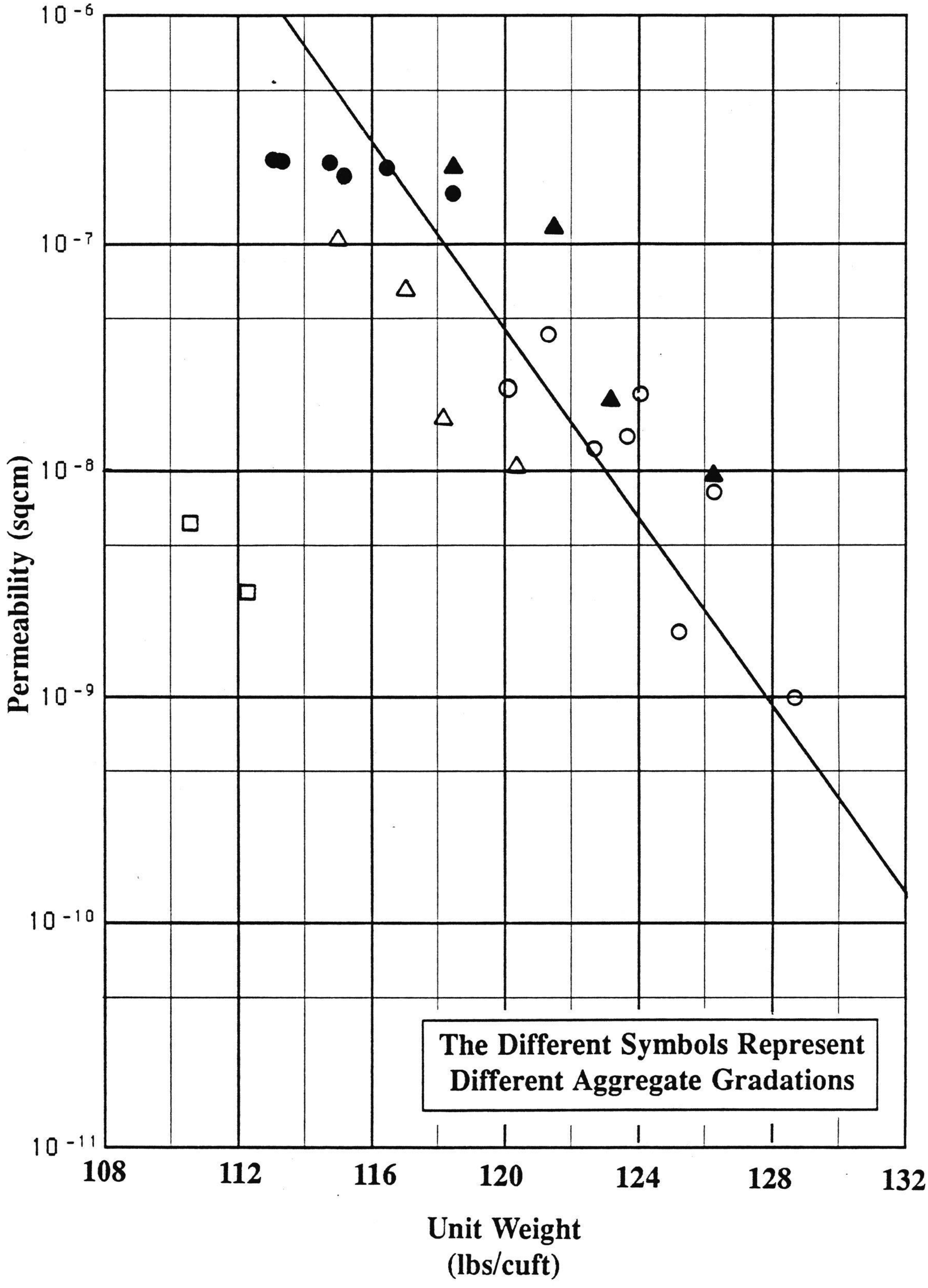


Figure 3. Permeability versus Unit Weight, for Sand Asphalt Mixtures. (After McLaughlin and Goetz, 1955)

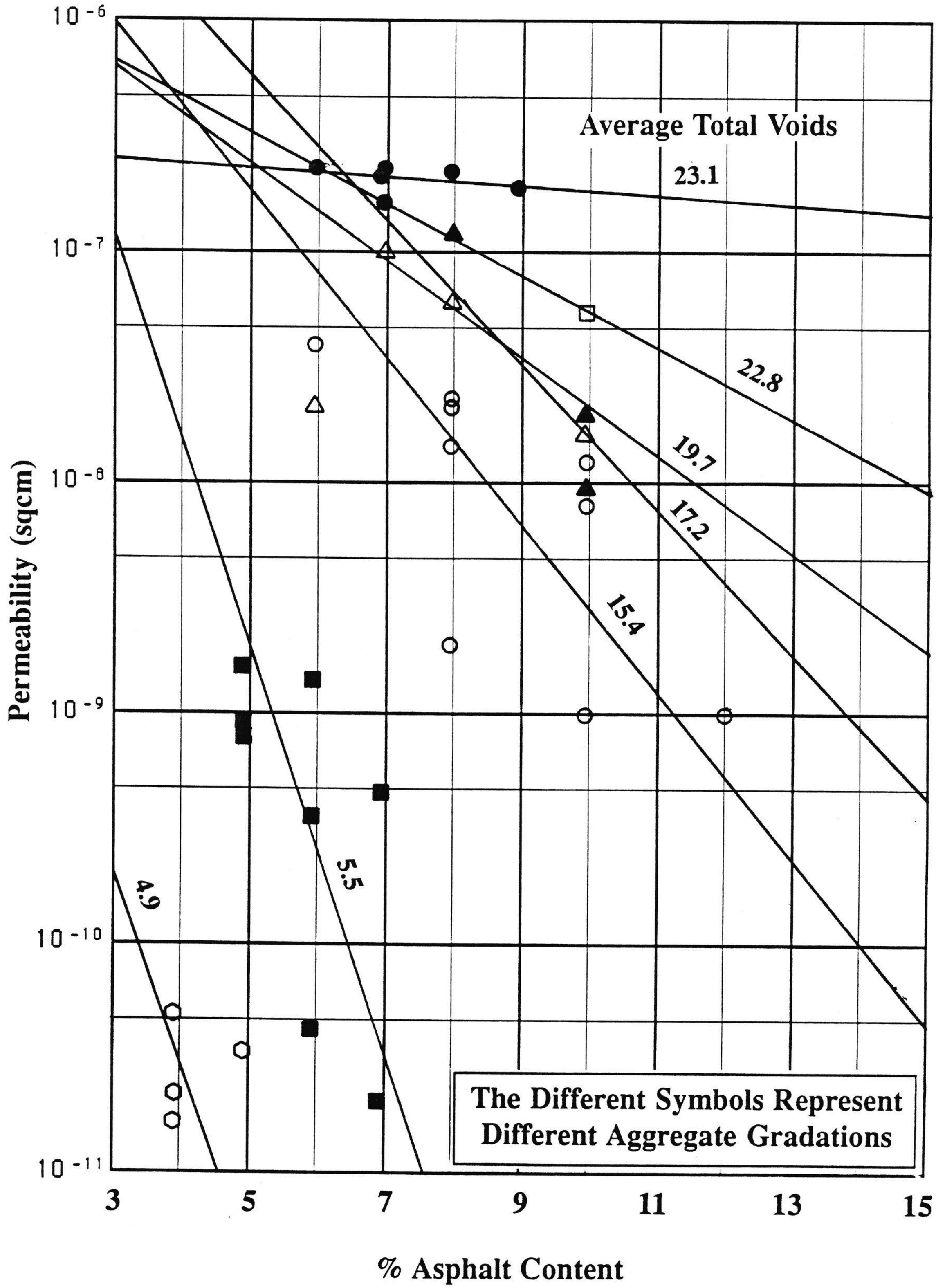


Figure 4. Permeability versus % Asphalt Content at varying % Total Voids for Sand Asphalt Mixtures and Bituminous Concrete. (After McLaughlin and Goetz, 1955)

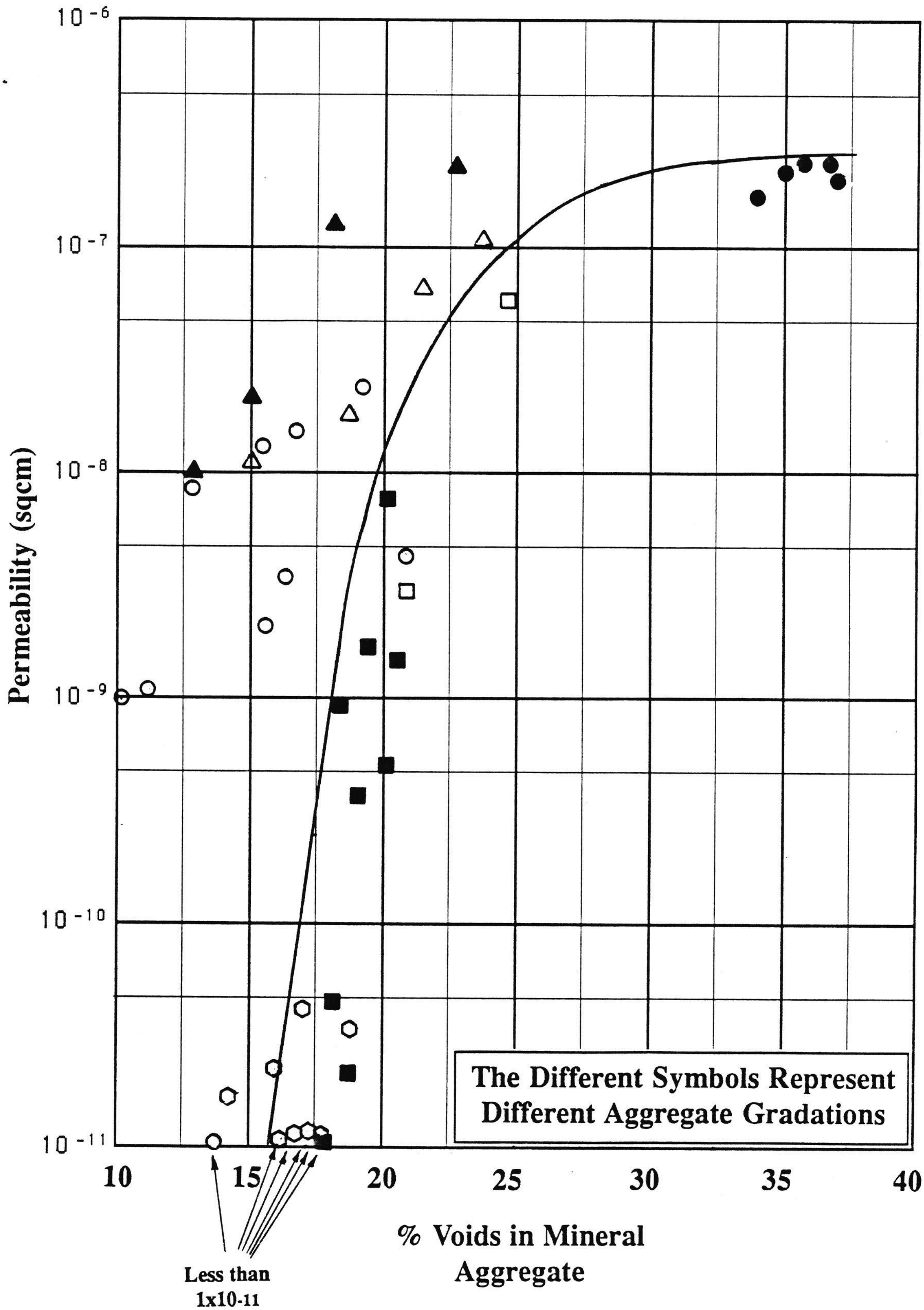


Figure 5. Permeability versus % Voids in Mineral Aggregate for Sand Asphalt Mixtures and Bituminous Concrete. (After McLaughlin and Goetz, 1955)

TABLE I

Results of Tests on Sand Asphalt Mixtures
(from McLaughlin and Goetz, 1955)

1	2	3	4	5	6	7	8	9
Grading	% Asphalt by wt. Agg.	Compaction*	Unit Wt. Mix	Est. Pore Diam.†	Permeability	% Total Voids	% Voids in Aggregate	% Agg. Voids Filled
			lb. per ft³	*microns*	*cm²*			
A	6	Normal	113.1	100	2.5×10^{-7}	25.2	35.6	29.2
A	7	Low	113.3	100	2.5×10^{-7}	24.8	36.6	32.2
A	7	Normal	116.4	90	2.3×10^{-7}	22.7	34.9	34.9
A	7	High	118.4	80	1.8×10^{-7}	21.4	33.8	36.6
A	8	Normal	114.7	90	2.5×10^{-7}	23.0	36.6	37.1
A	9	Normal	115.1	90	2.1×10^{-7}	21.5	36.8	41.5
B	7	Normal	115.0	50	1.1×10^{-7}	23.7	35.8	33.7
B	8	Normal	117.0	40	6.7×10^{-8}	21.4	35.3	39.3
B	10	Normal	118.1	40	1.8×10^{-8}	18.7	35.9	47.9
B	12	Normal	120.3	30	1.1×10^{-8}	15.1	35.8	57.8
C	10	Normal	109.6	40	6.0×10^{-8}	24.6	40.5	39.2
C	12	Normal	112.3	30	2.9×10^{-8}	20.9	40.1	47.8
D	6	Normal	118.4	140	2.3×10^{-7}	22.6	33.4	32.3
D	8	Normal	121.4	100	1.3×10^{-7}	18.2	32.7	44.3
D	10	Normal	123.1	80	2.2×10^{-8}	15.1	33.1	54.3
D	10	High	126.2	70	1.0×10^{-8}	13.0	31.4	58.5
E	6	Normal	121.2	40	4.2×10^{-8}	20.8	31.8	34.5
E	8	Normal	124.0	30	2.3×10^{-8}	16.6	31.3	46.9
E	8	Low	120.0	30	2.4×10^{-8}	19.3	33.6	42.5
E	8	Int	123.6	30	1.5×10^{-8}	16.9	31.6	46.5
E	8	High	125.2	20	2.0×10^{-9}	15.8	30.7	48.5
E	10	Normal	126.2	20	8.4×10^{-9}	13.0	31.4	58.5
E	10	Low	122.6	20	1.3×10^{-8}	15.6	33.5	53.4
E	10	High	128.7	20	1.0×10^{-9}	11.4	30.1	62.1
E	12	Normal	128.7	10	1.0×10^{-9}	9.2	31.3	70.6

* A compactive effort was arbitrarily selected as "Normal" and variations from this were made in order to obtain other densities.

† These figures are merely relative and should not be thought to represent precise determinations.

TABLE II

Results of Tests on Bituminous Concrete
(from McLaughlin and Goetz, 1955)

% Asphalt by Wt. Mix	Compaction	% Total Voids	% Voids in Aggregate	Permeability, cm^2	Original E, Psi $\times 10^{-6}$	% Orig E after 60 cycles Freeze & Thaw
Indiana Grading						
5	High	7.2	18.6	9.0×10^{-10}	3.2	70
5	Medium	8.2	19.6	1.6×10^{-9}	3.3	70
5	Low	9.0	20.2	7.8×10^{-9}	2.7	62
6	High	4.5	18.4	4.0×10^{-11}	3.5	75
6	Medium	5.0	19.3	3.5×10^{-10}	3.6	74
6	Low	7.0	20.6	1.4×10^{-9}	3.0	76
7	High	2.5	18.8	5.2×10^{-12}	3.5	85
7	Medium	2.8	18.9	1.9×10^{-11}	3.4	85
7	Low	4.2	20.2	4.6×10^{-10}	2.8	85
Corps of Eng. Grading						
4	High	4.8	14.5	1.5×10^{-11}	4.0	76
4	Medium	7.0	16.4	2.0×10^{-11}	3.3	65
4	Low	8.0	17.2	4.7×10^{-11}	3.2	41
5	High	2.9	14.0	1.0×10^{-12}	4.2	78
5	Medium	5.5	17.3	4.8×10^{-12}	3.5	69
5	Low	7.3	18.9	3.1×10^{-11}	2.8	57
6	High	2.0	16.4	1.7×10^{-14}	4.0	80
6	Medium	2.8	17.1	7.5×10^{-13}	3.9	78
6	Low	4.0	18.1	4.4×10^{-12}	3.4	79

McLaughlin and Goetz did that permeability is directly proportional to air voids for a particular mix gradation and asphalt cement content. Their results indicated that the void content of mixtures is not necessarily proportional to permeability when the variation is caused by gradation.

Kari and Santucci (5) examined in-place permeability and permeability of cores removed from the pavement. Their relationship is illustrated in Figure 6. For laboratory specimens (cores) the flow must be vertical, because air can only enter or exit through the bottom or top of the core. For pavements tested in-place, air can also pass laterally through the void structure.

In summary each previous researcher has concluded in one way or another that permeability and air void content are related, but that many factors influence this relationship. Furthermore, unlike soil where water is the binding ingredient (cohesion) asphalt concrete has asphalt as the "glue" of the structure. Asphalt cement by itself is impermeable for all practical purposes, and in turn, the permeability of an asphalt mixture is very dependent on the quantity, type, location and distribution of the asphalt cement. Other variables include type of aggregate, aggregate gradation, and unit weight, as previously

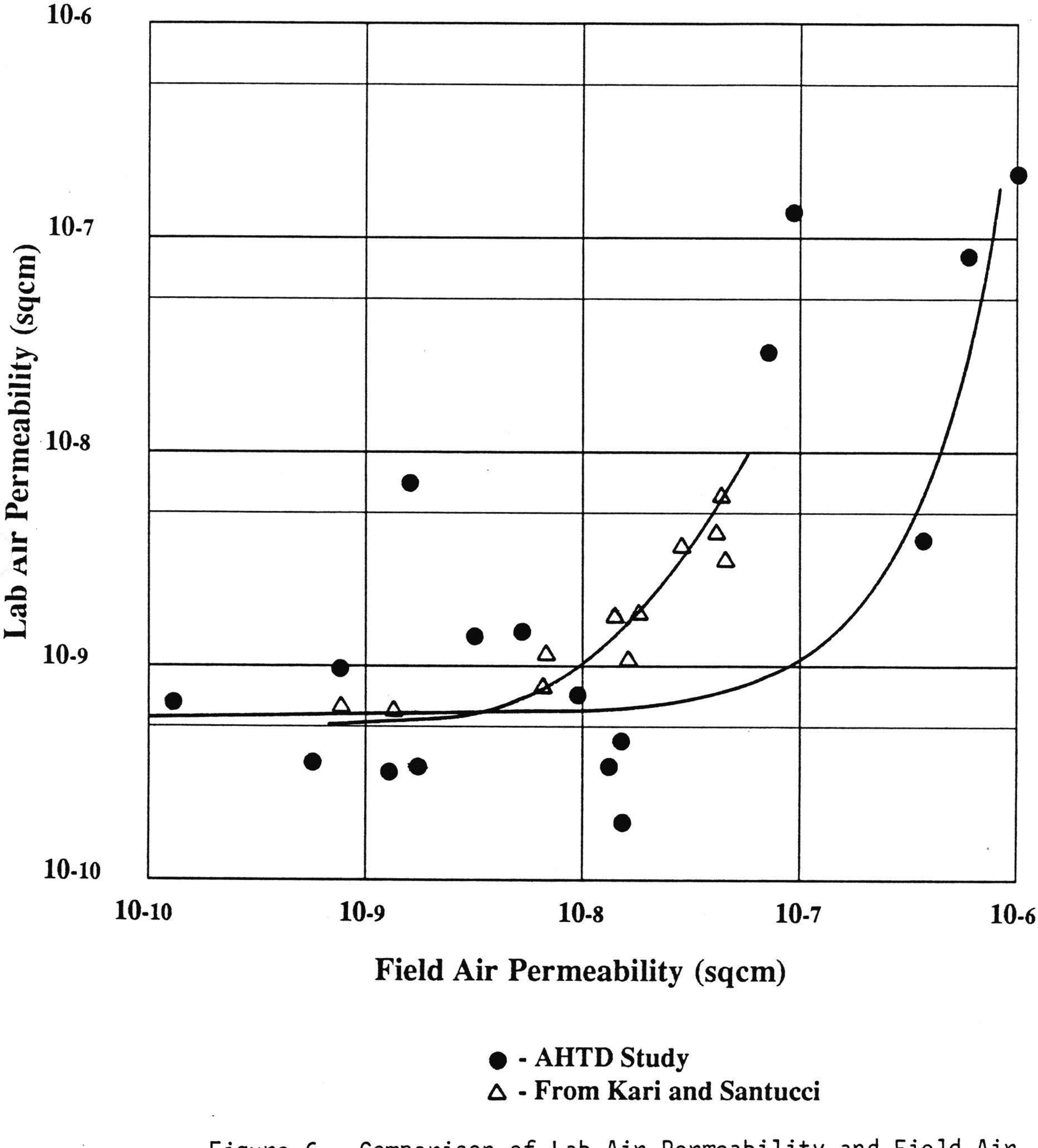


Figure 6. Comparison of Lab Air Permeability and Field Air Permeability. (from Kari and Santucci, 1953)

discussed. The type and number of variables associated with asphalt mixtures strongly inhibits the formation of any kind of consistency in developing a relationship between permeability and the asphalt mix variables. Only general relationships and trends can be obtained.

CHAPTER III

PERMEABILITY EQUIPMENT AND TEST METHODS

The Civil Engineering Department at the University of Arkansas in Fayetteville was subcontracted to construct and develop the permeability apparatus to be used in this study. The two apparatus were an air permeameter (ASTM D3637-84) and a water permeameter. A list of parts, detailed drawings, and the test procedures for each apparatus is presented in the Appendices by Ford and McWilliams (1).

Both the air and water permeabiity apparatus were designed for easy maintenance and repair. The simplicity of the equipment generally made for easy operation but in turn caused two major difficulties.

1. Air is less viscous and therefore lower pressures could be utilized to force the air through the specimens. However, for low permeable asphalt mixes the air flow was very slow. Several minutes or even hours were required to obtain sufficient flow to measure. Changes in temperature and barometric pressure during this time frame significantly influenced the rate of flow and hence the permeability. Tests longer than about five (5) minutes were discontinued.

2. For the water permeabiity test, very high pressures were required to generate a flow through the specimen, especially when testing low permeable asphalt mixes with air voids less than four (4) percent. These high pressures usually caused the paraffin seal around the speciment to break. Once the seal was broken, the flow of water would then be down the side of the specimen and the permeability results would not be valid. Asphalt was also used in an effort to properly seal the specimens; however, this type of seal was not strong enough either. For this reason, the testing of specimens using the water permeability apparatus was discontinued and only the air permeability apparatus was used to perform field tests.

Field testing was performed at four new construction sites on both the binder and surface courses. The field test pattern was the same for both the binder and surface courses and involved testing at twenty-five (25) foot intervals and in the outside wheelpath, inside wheelpath, and between the wheelpaths.

The field apparatus was rather bulky and required two persons to move it from one test location to the next. The field plate was placed firmly on the pavement by setting four ten-pound weights on top of the plate. Further pressure was applied by the person taking notes standing on the weights during testing. The tests began by determining a target pressure and adjusting the flow rate to maintain that pressure. The flow of water was measured at defined intervals and timed to get a precise flow rate. Usually, three tests at different pressures were used at each location to form a plot of flow rate versus pressure. The slope of this line was used to calculate the permeability. Reading of the manometer proved to be difficult since it would sometimes stick at certain pressures. The exact reasons for this are not known but may be related to kinks or turns in the air line leading to the field cell. Also, the manometer may vary a measurable amount depending on the amount of wind at the time of test. A windy day made field testing extremely difficult.

After the field tests were performed, cores were taken at the precise locations of the field tests. Four cores were retrieved at each of the construction sites. These cores were taken to the laboratory for further permeability testing and to determine the characteristics of the asphalt mixes.

The test procedure for the field air permeability test is similar to that described for the laboratory air permeability test in Appendix A. The only significant difference is that a twelve-inch diameter test plate is used in the field instead of the laboratory test cell. This test plate has a rubber pad which provides a seal around the four-inch diameter opening in the center of the plate. To initiate the test, air is forced through the four-inch opening and enters the pavement structure. Once in the pavement, the air can flow vertically or laterally, thus creating a three dimensional flow. For this reason, the author questions the basic assumption that the cross sectional area of the air flow can be gauged by the four-inch diameter of the test plate. In contrast, the laboratory test method only allows air flows in a vertical direction through the length of the core. Nevertheless, the four-inch diameter was utilized in analyzing the permeability as recommended by the available literature.

CHAPTER IV

DISCUSSION OF TEST RESULTS

Permeability of Arkansas Asphalt Mixes

The permeabilities of various Arkansas asphalt mixes came from tests conducted on Marshall mix specimens, in-place asphalt pavement and cores of the asphalt pavement. The results of these tests are contained in Tables III and IV.

To better illustrate these findings, a general distribution of the permeabilities from the various types of asphalt mixes was provided in Figure 7. Also shown in Figure 7 for comparison purposes is the permeability and drainage of soils as determined by Lenards (7). The varying widths of the area representing each type of asphalt mix indicate the number of that type of mix found in that particular permeability range. Thus for example, the binder courses tested were found to have permeabilities which ranged from 10^{-2} to 10^{-6} centimeters per second with the greatest concentration in the area of 10^{-4} to 10^{-5} centimeters per second.

The overlapping of permeabilities - particularly the binder and surface courses - indicates that some binders

TABLE III

Air Permeability
Field Versus Laboratory

SAMPLE NUMBER	DENSITY lbs/cuft	AIR VOIDS %	ASPHALT* CONTENT %	FIELD AIR PERMEABILITY sqcm	LAB AIR PERMEABILITY sqcm
NLR 1S	140.4	7	5.7	7.1E-08	9.5E-10
NLR 2S	137.6	8.9	5.7	4.5E-08	1.3E-09
NLR 3S	140	7.3	5.7	8.1E-08	2.6E-09
NLR 4S	139.3	7.8	5.7	4.9E-08	4.6E-09
NLR 5S			5.7	5.1E-08	
NLR 6S			5.7	5.9E-08	
NLR 1B	137.4	10.1	4.6	1.3E-06	
NLR 2B	140.2	8.3	4.6	6.3E-07	
NLR 3B	135.5	11.4	4.6	5.4E-07	7.8E-07
NLR 4B	140.7	8	4.6	3.4E-07	
NLR 5B			4.6	3.9E-07	
NLR 6B			4.6	1.3E-07	
FAY 1S	143.6	5	5	5.4E-10	3.0E-09
FAY 2S	141.8	6.2	5	4.5E-09	3.5E-09
FAY 3S	141.1	6.7	5	1.5E-09	6.0E-09
FAY 4S	141.1	6.7	5	2.2E-08	6.4E-09
FAY 5S			5	5.2E-08	
FAY 6S			5	9.3E-09	
FAY 1B	145.8	4.7	4.4	5.3E-08	1.8E-10
FAY 2B	147.4	3.7	4.4	1.7E-08	
FAY 3B	147.5	3.5	4.4	1.5E-08	3.2E-09
FAY 4B	146.1	4.5	4.4	1.7E-08	
FAY 5B			4.4	7.6E-09	
FAY 6B			4.4	4.5E-07	
CON 1S	143	6.5	5.8	2.9E-08	
CON 2S			5.8	8.5E-09	9.0E-12
CON 3S			5.8	2.7E-07	1.2E-07
CON 4S			5.8	1.4E-08	
CON 5S			5.8	7.8E-08	
CON 6S			5.8	4.4E-08	
CON 1B	135.6	12.1	4.7	2.2E-06	1.2E-06
CON 2B	139.9	9.3	4.7	6.3E-06	5.1E-07
CON 3B	141.7	8.2	4.7	4.0E-06	2.6E-08
CON 4B			4.7	6.6E-06	
CON 5B			4.7	7.8E-06	
CON 6B			4.7	9.8E-06	
CAM 1S			5.2	1.8E-08	
CAM 2S			5.2	5.8E-09	
CAM 3S			5.2	4.7E-09	
CAM 4S	138.4	7.9	5.2	2.6E-08	
CAM 5S	138	8.2	5.2	1.4E-08	6.3E-08
CAM 6S	136.9	8.9	5.2	5.2E-09	1.8E-09
CAM 1B	139.9	8.1	4.2	5.9E-08	
CAM 2B	140.3	7.8	4.2	1.3E-08	
CAM 3B	137.8	9.4	4.2	2.9E-08	1.3E-08
CAM 4B			4.2	8.5E-08	
CAM 5B			4.2	5.2E-08	
CAM 6B			4.2	5.8E-08	

* Asphalt Content taken from mix design

TABLE

Air Permeability Versus Water Permeability

SAMPLE NUMBER	TYPE MIX	STABILITY lbs	PERCENT RETAINED STRENGTH	DENSITY lbs/cuft	FLOW	AIR VOIDS %	VMA %	ASPHALT CONTENT %	AIR PERMEABILITY sqcm	WATER PERMEABILITY sqcm
3-263	T-2 S	1705	85.3	144.8	8	2.9	15.2	5.6	1.15E-07	
4-259	SB-2	2225	100	150.8	10	4.8	14	3.9		8.86E-10
6-260	T-2 B	1680	79	152.1	8.5	3.1	13.1	4.3	9.86E-09	8.46E-09
8-257	T-3 S	1545	93.9	149.5	8.3	3.1	15.8	5.5	4.40E-10	
9-262	SEAL	1875	78.7	139.3	10.9	7.4	20.1	5.8	2.81E-08	9.26E-09
10-258	SEAL	2325	79.8	136.7	10	7.3	21.5	6	5.55E-07	4.49E-08
11-264	400-1 B	2325	83.4	151.6	9.8	3.1	13.2	4.3	4.42E-09	
13-267	T-2 B	1730	81.8	145.7	8.9	5.5	16.2	4.7	1.13E-08	5.69E-10
14-269	T2S 408-2	1180	74.6	147.4	6.1	3.8	15.8	5.3		9.69E-11
18-274	400-1 S	2610	87.7	145.7	10	3	15.1	5.3	5.38E-10	
20-273	T-2 B	2438	72.6	142.7	9.9	5	15.5	4.7	2.04E-09	
21-279	GB-3	1620	70.1	152.6	7.8	4.8	14.1	4.2	1.63E-09	1.77E-09
28-284	T-2 B	1575	83.8	155.8	9.8	3.3	13.4	4.2	1.35E-08	
29-286	T-2 S	2295	87.8	147	10.2	3	15.6	5.5	6.26E-11	2.00E-07
30-003	T2B 400-1	1645	81.2	156.2	8.8	3.3	13.6	4.2	5.44E-09	2.30E-11
32-292	SB-2	2390	72.8	152.1	10.3	5	14.5	4	4.83E-09	
33-294	GB-3	2110	90.1	144.6	10.8	5.7	15.8	4.5	1.69E-08	1.99E-09
34-291	SP 400-1	2500	85	146.2	9.2	3	15.8	5.6	5.92E-10	
35-298	SB-2	2720	80.5	145.9	13.6	5.3	15.3	4.3	5.16E-10	
36-296	400-1 B	3408	85.8	147.6	12.5	3.5	13.6	4.4	2.74E-09	
37-301	T-3 S	2005	79.6	153.6	8.3	3.1	16.2	5.5	2.40E-11	
38-302	T-2 S	1450	78.2	152.1	6.5	3.6	16	5.3	3.54E-09	
39-303	T-3 S	2128	79.7	151.3	8.4	3.1	15.5	5.2	5.00E-09	

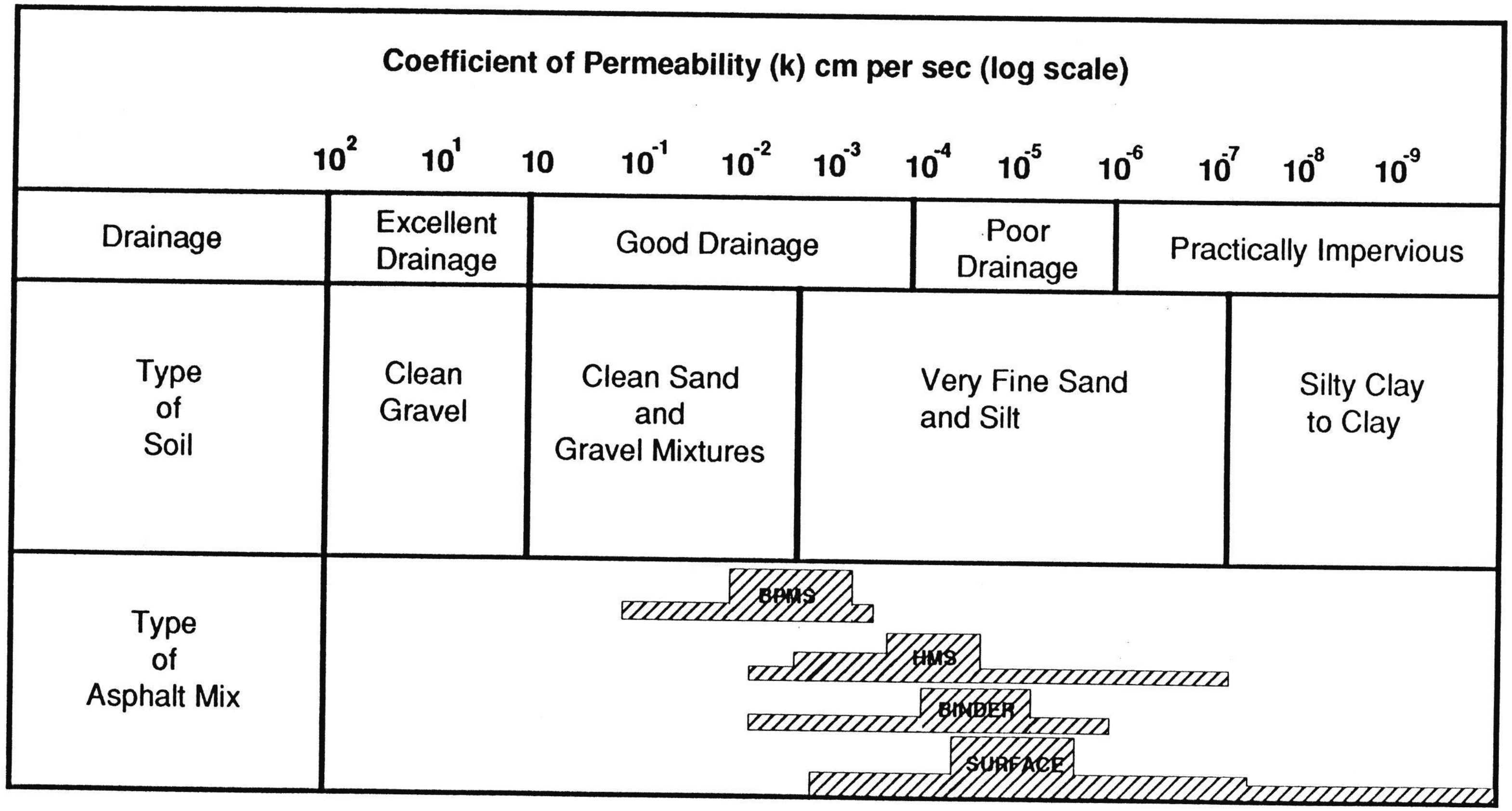


Figure 7

COMPARISON of SOIL and ASPHALT MIX PERMEABILITY

are less permeable than some surfaces. However, for each construction project where both the binder and surface courses were tested, the binder was always more permeable than the respective surface.

Figure 7 also provides some answers to other questions on permeability. Regarding the amount of water which can safely pass through the surface without harming the mix, Zube (9) suggested that "a tentative average water permeability value not exceeding 150 ml per minute for a 6-inch diameter area [which equates to .0137 cm/sec] will be low enough to prevent the entrance of excessive moisture into the pavement from the surface." Figure 7 indicates that all of the tested surfaces had permeabilities at this level or lower. Thus, based on the available literature, these surface courses have a sufficiently low permeability to keep water infiltration to a minimum and to attempt to construct surface courses with a lower permeability would possibly lead to the introduction of other problems.

Another concern of many people is whether the binder can become a reservoir for water. This potential problem is magnified by the possibility of weather-induced interruptions in the construction sequence which allows rain to fall on an uncovered binder. As noted in Figure 7, the tested binder courses appear to be just as permeable as the hot mix seal courses. For this reason, no one should be surprised when an uncovered, rain-saturated binder later shows evidence of stripping or other moisture-related problems when it is not allowed to dry properly before the surface course is applied.

Relationship of Permeability and Asphalt Mix Variables

As stated previously the relationships between permeability and the various asphalt mix variables are difficult to establish. Furthermore, this investigation encountered an additional obstacle in that the testing apparatus did not provide a proper seal on the tested specimens. This problem was more evident when testing specimens with air voids less than four (4) per cent. Nevertheless, the study's findings on air and water permeability relative to the various asphalt mix variables are illustrated in Figures 8 through 13. As can be seen, these findings are inconclusive and no relationship can be established.

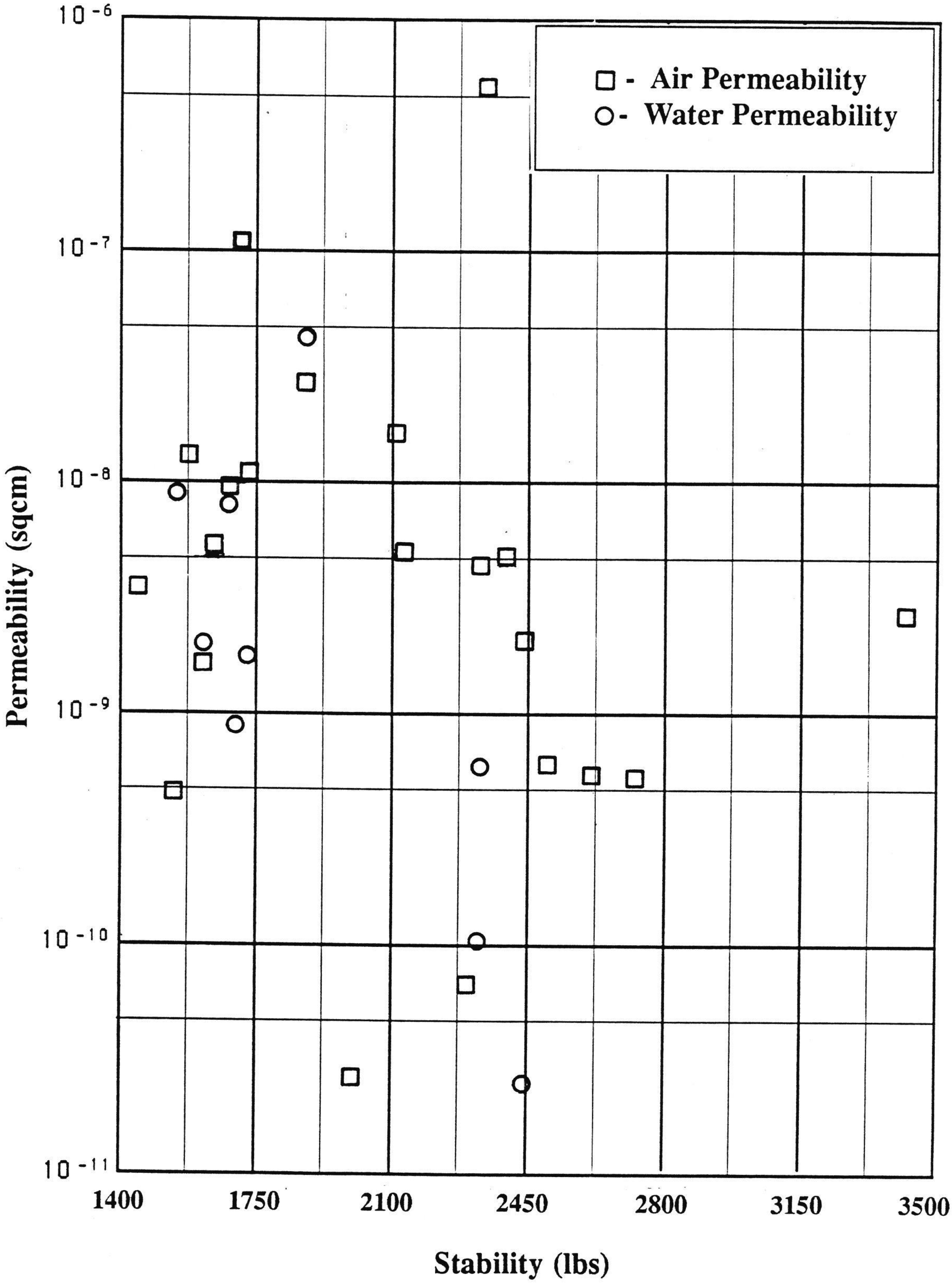


Figure 8: Permeability versus Stability

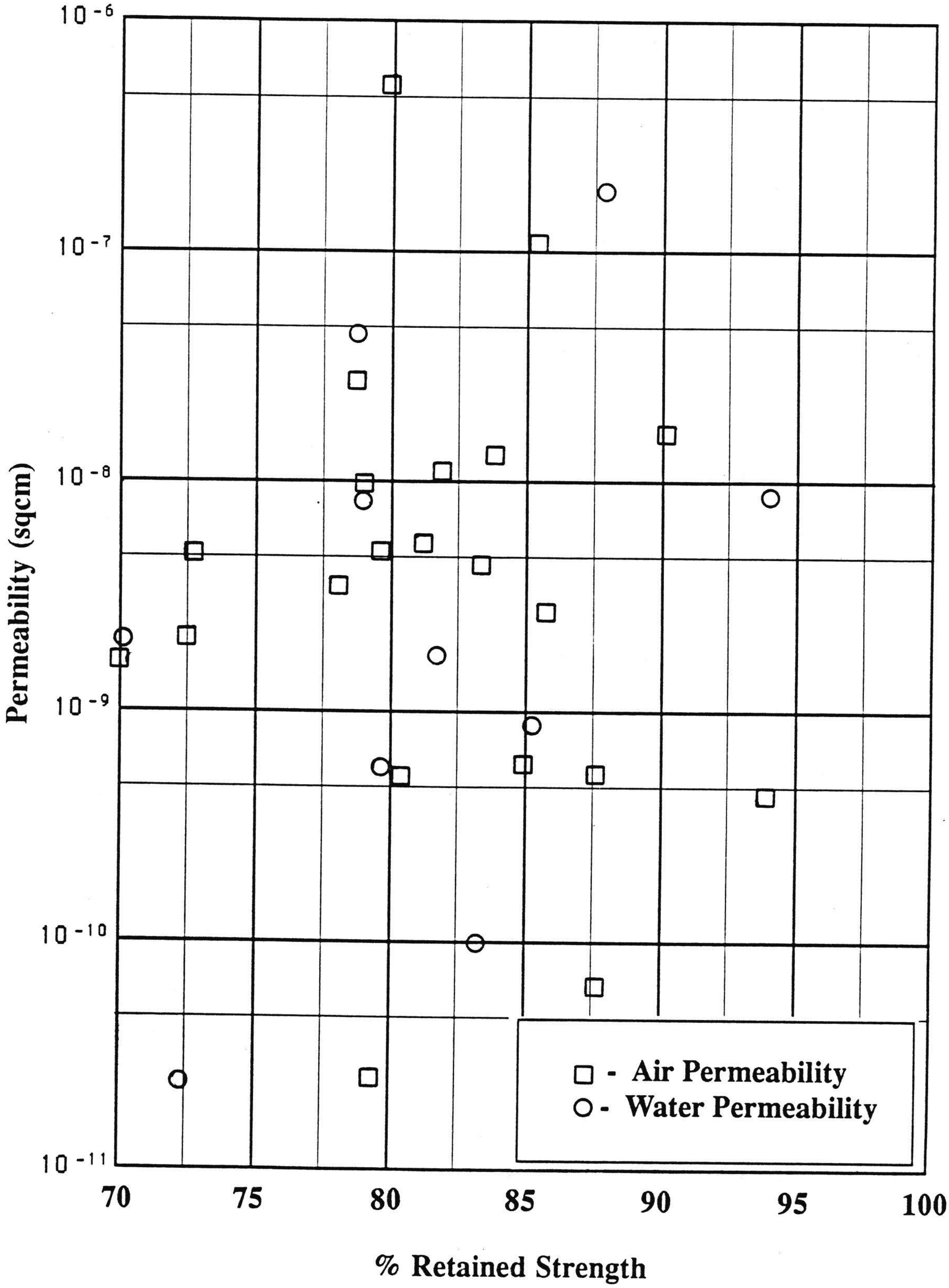


Figure 9: Permeability versus % Retained Strength

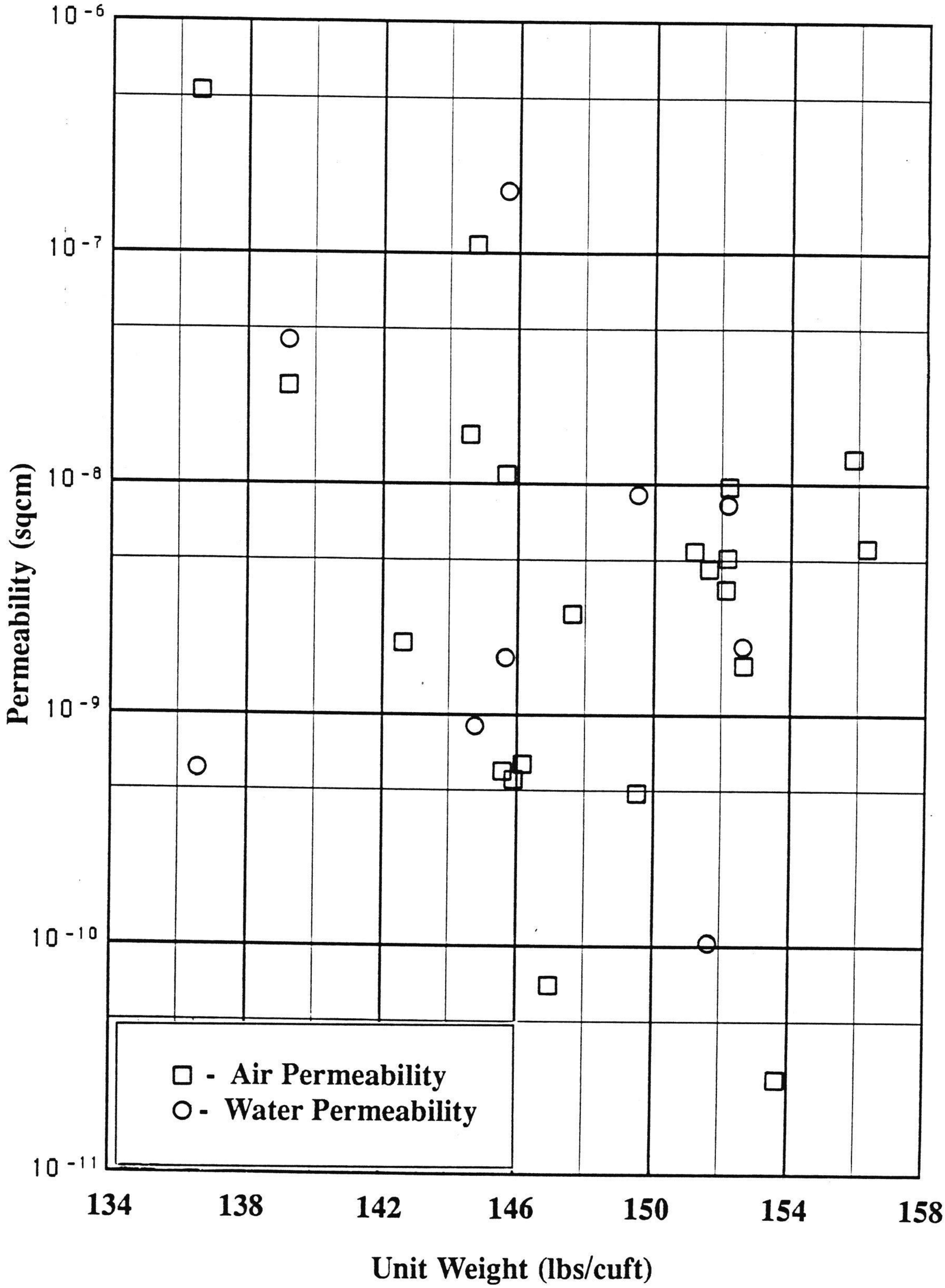


Figure 10: Permeability versus Unit Weight (lbs/cuft)

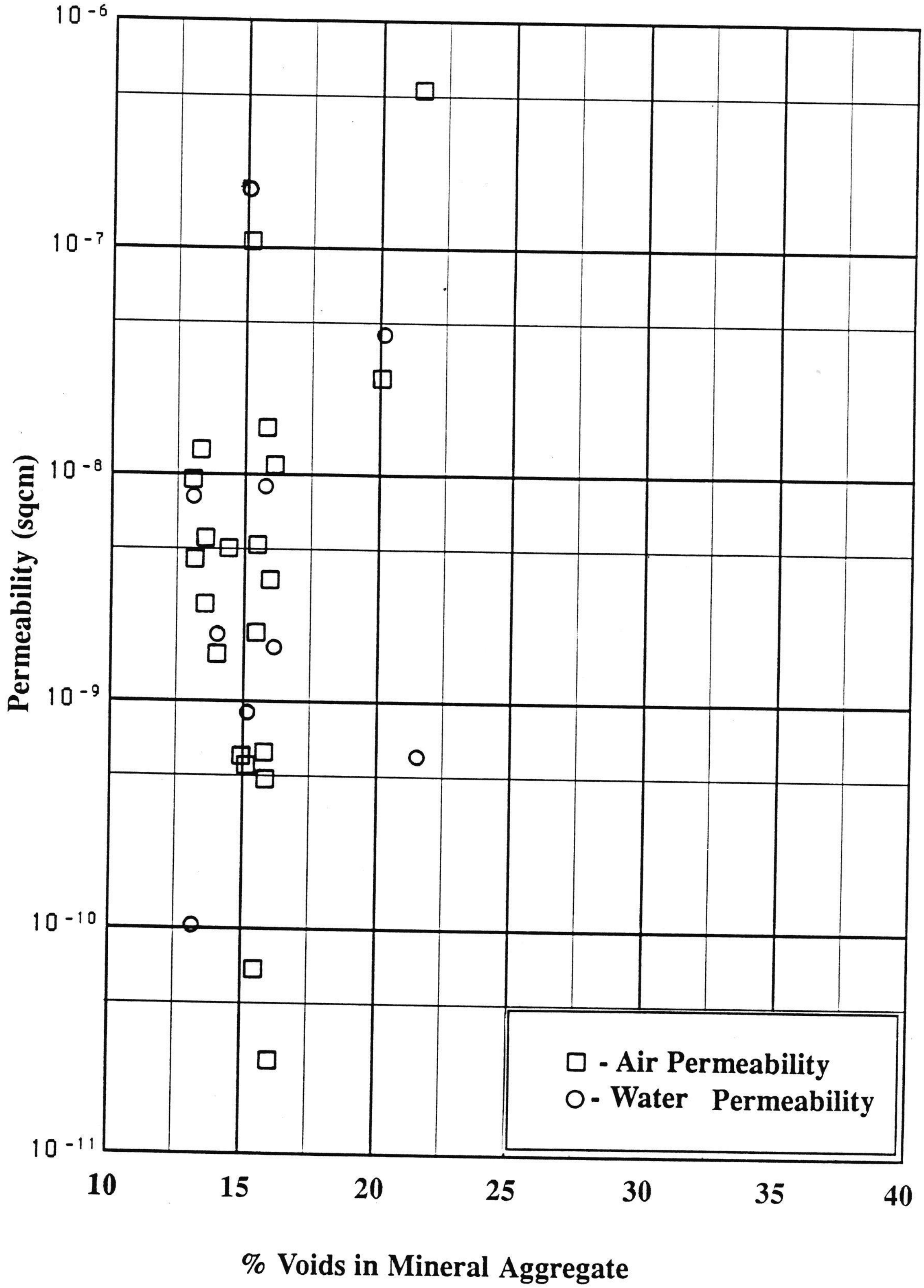


Figure 11: Permeability versus % Voids in Mineral Aggregate

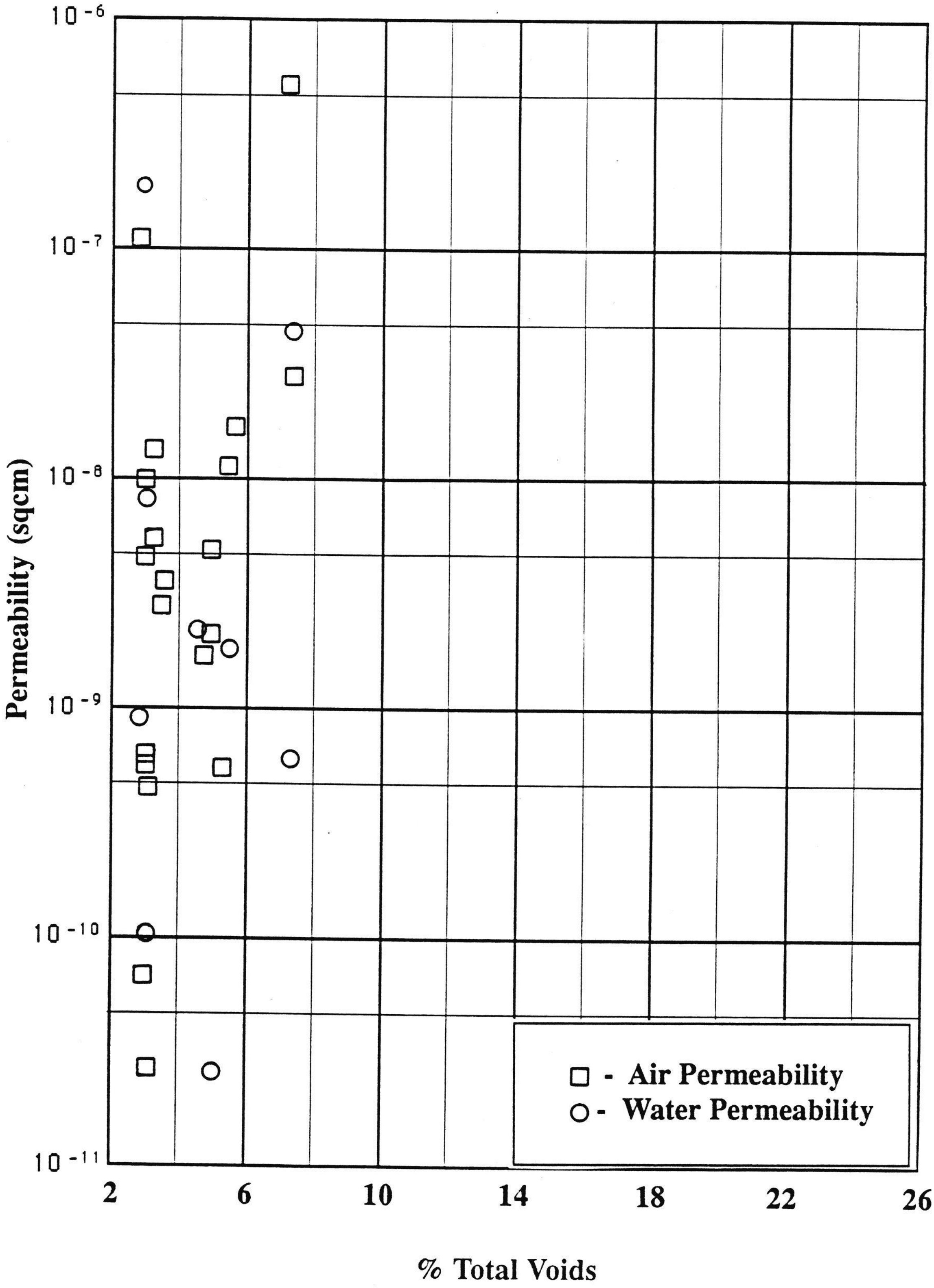


Figure 12: Permeability versus % Total Voids

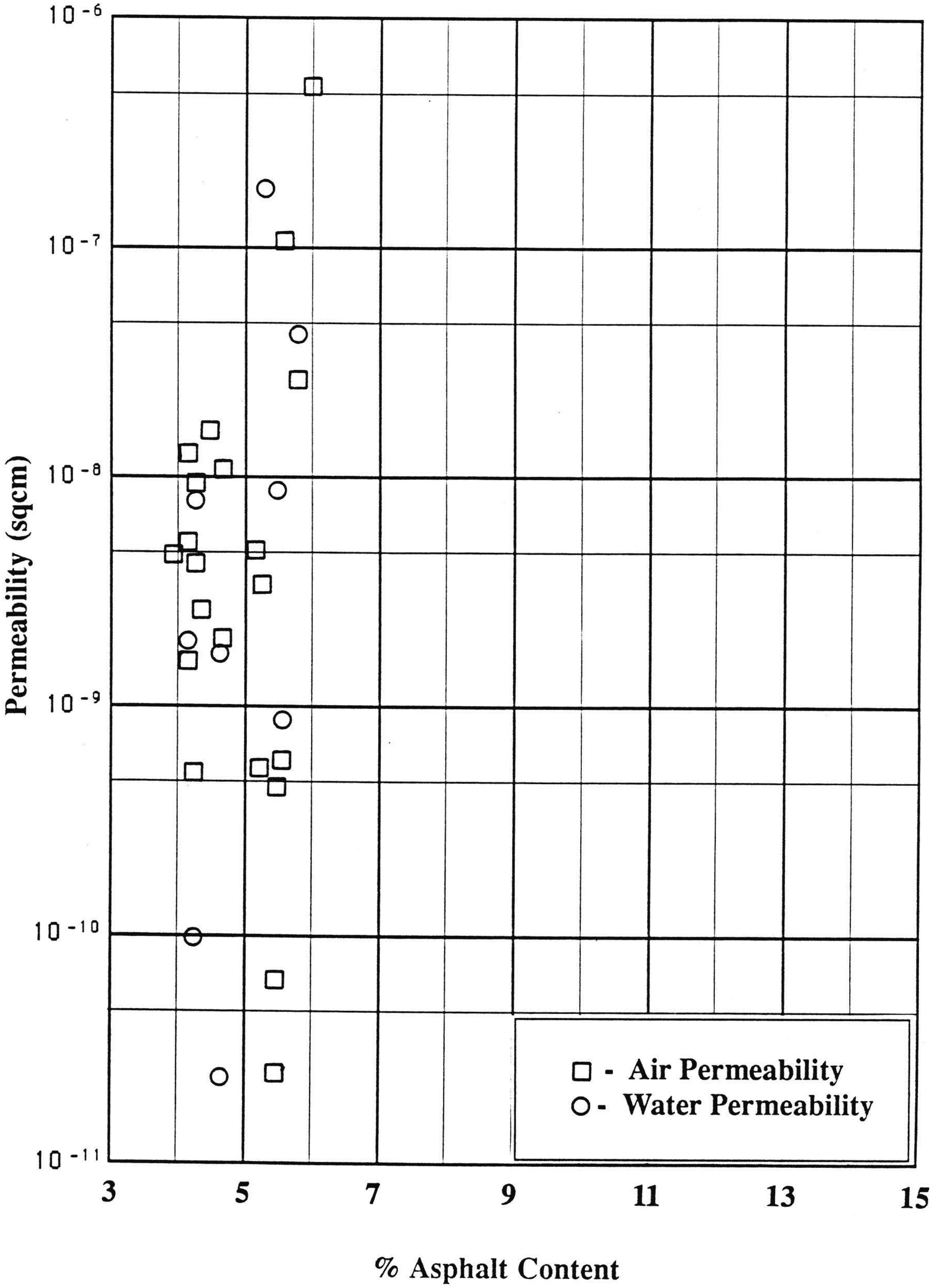


Figure 13: Permeability versus % Asphalt Content

Chapter V

CONCLUSIONS

This study demonstrated that the permeability of asphalt mixes can be measured using both water and air as a flow medium. However, because of the simplicity of the testing equipment, the precision of the tests decreases as the permeability of the sample decreases. For samples with permeabilities greater than 10^{-5} cm^2, the permeability apparatus should provide a precision of less than one order of magnitude. Tests on lower permeable samples should be within two orders of magnitude, if readings can be taken. The air permeability apparatus was much easier to use and allowed permeability measurements down to 10^{-9} cm^2. The water permeability apparatus was not able to accurately test samples with permeabilities less than 10^{-6} cm^2.

Based upon the results of this project, the following conclusions are drawn:

1. Permeabilities can be obtained such that a general comparison between various asphalt mixes is achieved.
2. A range of permeabilities for Arkansas asphalt surface and binder courses has been measured. The permeability coefficient of surface courses ranges from about 10^{-3} to less than 10^{-9} cm/sec while the

permeability of the binder courses ranges from 10^{-2} to 10^{-6} cm/sec.

3. Acceptable permeability standards are not stated here. However, surface courses with permeability values of 10^{-2}cm/sec or greater are viewed as unsuccessful at preventing the intrusion of water. Furthermore, binder courses with permeabilities of greater than 10^{-5} cm/sec should be viewed as potential reservoirs for water.

4. Because of the complex nature of asphalt concrete, a theoretical model considering friction between the flow medium and the various constituents of asphalt concrete in conjunction with the probability of voids being interconnected would perhaps be a better alternative in determining permeability.

5. The variability of permeability measurements taken from in-place asphalt concrete results from the flow medium varying from a gas (water vapor) to a liquid and the development of cracks in the pavement. This information, if available, would give a better insight to the significance of permeability.

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APPENDIX A

AIR PERMEABILITY
EQUIPMENT AND
TEST METHODS

Reprinted from "Asphalt Mix Permeability," by Miller C. Ford and Clark E. McWilliams at the University of Arkansas. Fayetteville, Arkansas, 1988

The air permeameter utilizes a constant pressure differential along with volumetric flow measurements in order to measure the permeability of a specimen. The constant pressure differential is accomplished by manual adjustment of flow from an elevated tank of water. This water also serves as a volumetric measurement of the amount of flow, as calibrated with a pipet. Pressure differentials are measured with a manometer and flow measurements are read from the pipet.

The air permeameter designed for this project differs from the apparatus found in ASTM D3637-84 (6) due to difficulties encountered during its construction. Modifications were necessary in order to improve and correct the design. A comparison can be made between this project's design and the ASTM D3637-84 permeameter as presented below. One problem associated with the ASTM permeameter involves the specified valves. The valves listed are of different sizes and require different types of connections. This would make the connections between the valves overly cumbersome and lengthy. Thus, since the smallest orifice was 0.062 inches, smaller valves were suitable for this apparatus. Additionally, the laboratory cell was altered to be more compact and less cumbersome.

The altered cell consists of a plexiglass cylinder with a retainer collar, an area ring, and a tightening ring. Several other minor modifications were also made.

The procedures described herein may be used to evaluate the permeability of compacted asphalt mixtures. The ideal test conditions are prerequisites for the required laminar flow of air through the porous material under constant head conditions: continuity of flow with no volume change during a test, flow with the voids fully saturated with the air, flow in the steady state with no changes in pressure gradient, and direct proportionality of flow velocity with pressure gradients below certain values. All other types of flow involving partial saturation of mix, turbulent flow, and unsteady state of flow are transient in character and yield variable and time-dependent permeability.

Apparatus

This permeameter is capable of measuring airflow rates of up to 5000 ml./min. at low-pressure differentials. The general layout of the permeameter is shown in Figure 14.

The Pressure Control Device is made with a water reservoir of a capacity of 2000 ml., two cylinders (one having a capacity of 500 ml. and the other with a capacity of 1000 ml.), a rubber pressure bulb, valves, and calibrated sight tubes (pipets).

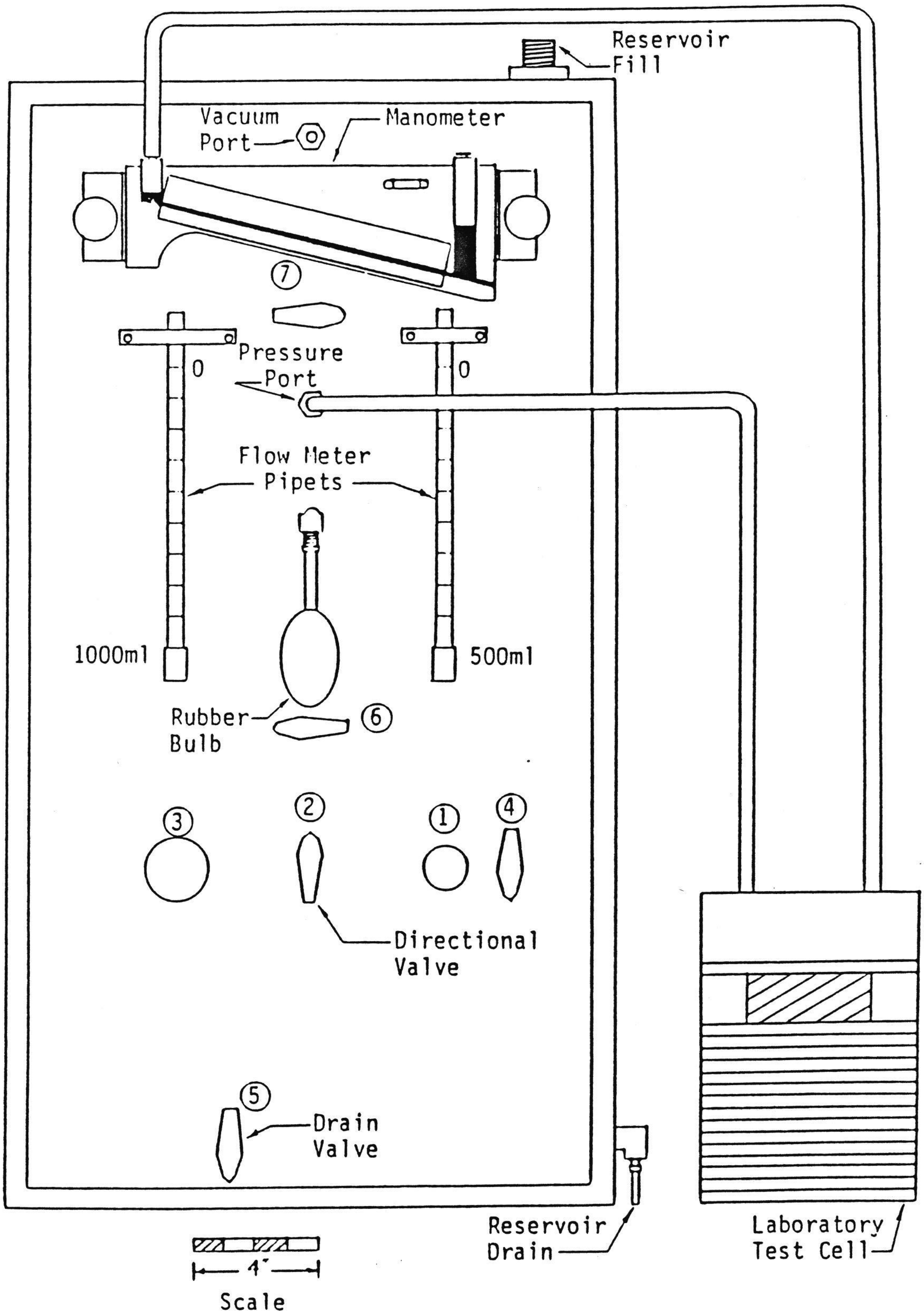

Figure 14. Air Permeameter - Front Elevation

The Stationary Manometer is solid, plastic-inclined style, with a range from 0.10 to 2.0 inches of water and calibrated to 0.01 inch of water (2.5 Pa).

The Laboratory Cell is made of a polymethyl methacrylate cylinder 10 inches long, with an inside diameter of 6 inches and a wall thickness of 1/2 inch. One end of the cylinder is closed by a 1/2 inch machined top plate with two 1/4 inch copper fittings screwed to the top plate. A 1/2 inch thick polymethyl methacrylate retainer collar is fitted into the cylinder 2 inches from the closed end. The inside diameter of the retainer collar is 3 inches. The ring is glued firmly and air-tight to the cylinder wall. The cylinder is threaded approximately 6 inches from the open end.

A Stop Watch is needed with a minimum range of 5 minutes graduated to 0.1 second. If permeability is smaller than 1.0 x 10-12 cm./sec., a stop watch of larger range may be required.

Preparation of Apparatus

Filling Reservoir (See Figure 14):

1. close all valves and remove cap from filler neck located at the top of the apparatus;
2. position #2 for exhaust and open #4;

3. slowly fill 2000 ml. reservoir with de-aired distilled water via the filler neck;

4. close #4 and replace cap on filler neck.

<u>Filling Calibrated Volumetric Cylinders:</u>

1. Select appropriate cylinder (i.e., use 1000 ml. volumetric cylinder for pavements with high permeability and 500 ml. volumetric cylinder for pavements with low permeability);

2. fill the calibrated volumetric cylinder by positioning #2 to "bulb" and #7 for appropriate cylinder, open #6, open #3 (when using 1000 ml. cylinder) or #1 (when using 500 ml. cylinder);

3. squeeze rubber bulb to pump air into the water reservoir which will force water from the reservoir into the appropriate calibrated volumetric cylinder;

4. once the appropriate cylinder is full close #3 or #1, as applicable, and #6;

5. position #2 to exhaust in order to purge excess air pressure in water reservoir;

6. position #2 to "pressure port".

<u>Connection of rubber tubes:</u>

1. for pressure system connect one of the two rubber tubes from the cell to the pressure port and the other to the manometer pressure port;

2. for vacuum system connect one of the two rubber tubes from the cell to the vacuum port and the other to the manometer vacuum port. The apparatus is now ready for the test to be performed.

Preparation of Laboratory Specimen

To prepare a specimen for the test:

1. decrumb specimen and measure height;
2. disassemble inverted test cell and coat specimen contact areas (i.e., retainer collar and area ring) with high vacuum grease;
3. slip the latex membrane over the specimen and leave ends extended approximately one inch, fold membrane extension back over itself and down the side of the specimen leaving a membrane ring (top and bottom) smaller than the inside diameter holes of the test cell and area ring;
4. center membraned specimen on the vacuum greased retainer collar as it is placed in the test cell, follow with the vacuum grease area ring;
5. screw tightening ring into end of cell with the tightening key, turn the tightening ring to apply pressure on the sample until some sealing compound is squeezed out from the inside of the area ring,

allow some time for the plastic deformation of the sealing compound and make a final tightening;

6. place the cell upright on an open grid to allow free passage of air;

7. laboratory test is now ready to be performed.

Operation of Apparatus

Pressure System Operation (See Figure 14 and 15:

1. close all valves;
2. connect rubber tubes as described in "Preparation of Apparatus" for the pressure system;
3. level manometer by loosening the manometer hand screws on either side of it and observing the level bubble on top of the manometer;
4. set manometer at zero reading by sliding the scale until the zero reading coincides with the level of the manometer fluid;
5. position #2 to "pressure port", position #7 to appropriate cylinder, open #3 or #1 slowly and continuously adjust so that constant pressure is read on the manometer at all times;
6. check for steady-state conditions by taking several flow rate measurements using sufficient periods of time and flow reading for precise results;

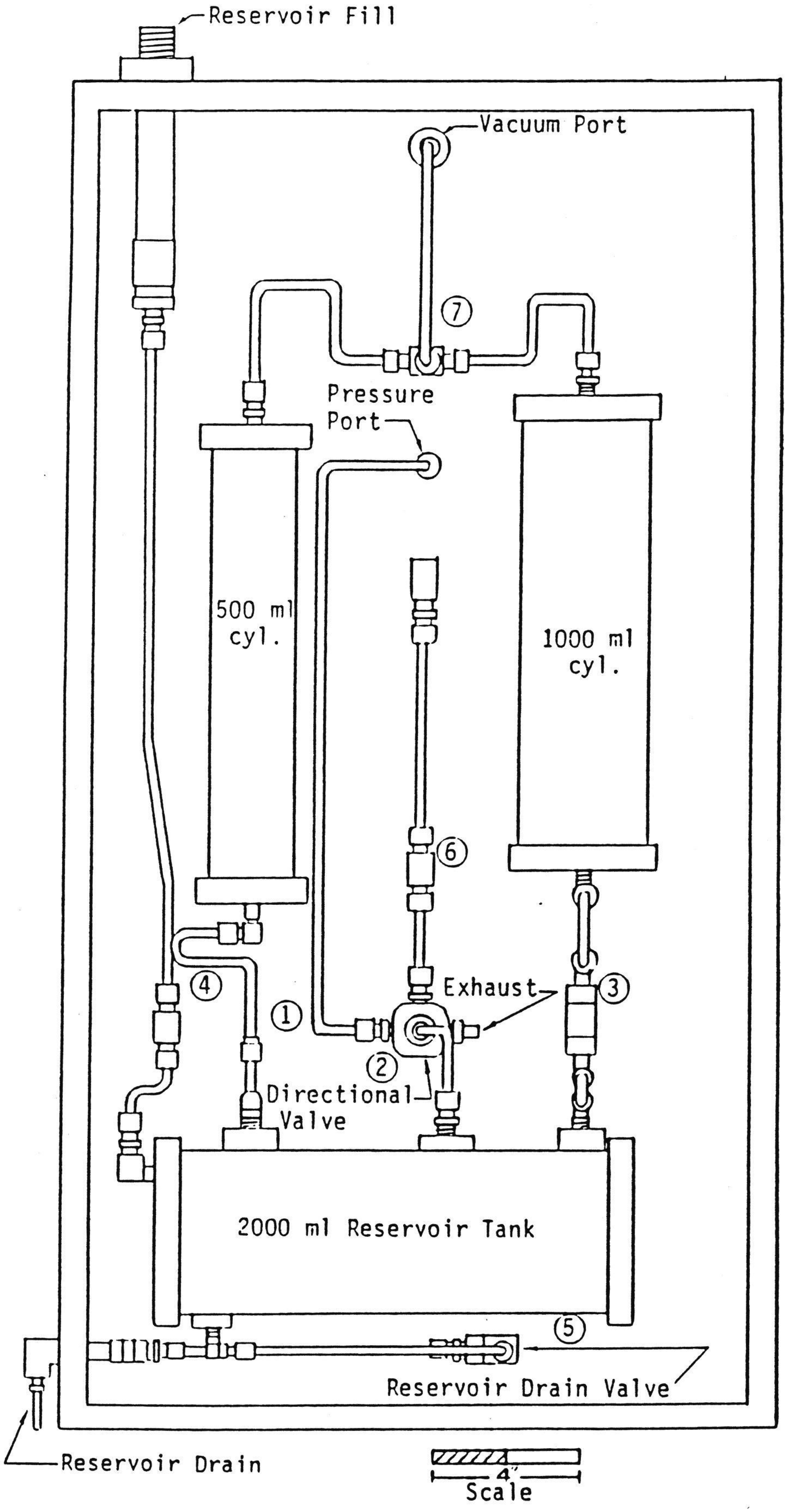

Figure 15. Air Permeameter - Rear Elevation

7. when a steady-state condition is established record pressure reading and several flow rate measurements, record air temperature;

8. repeat this process at least three times at different pressure readings;

9. close #3 or #1.

Calculations

The air permeability (Ka) can be expressed as derived from Darcy's law on the flow of fluids through a porous medium as follows:

$$Ka = (QuL)/(Apt) \qquad \text{(EQ.)}$$

where:

Ka = permeability, sq. cm.

Q = volume of air forced (or drawn) through the sample, cu. cm.

L = thickness of sample, cm.

u = viscosity of air, Pa. s.

A = area of sample, sq. cm.

P = pressure in the cell as measured with the manometer, Pa.

t = time required for water level to drop from one mark on the site tube to another, s.

So that K can be corrected for a reference temperature, the permeability measured at a particular temperature must be reduced to that of a reference temperature by use of the following equation:

$$K(tr) = K(t)\ u(t)/u(tr)$$

where the subscript tr indicates a reference temperature and the subscript t indicates the test temperature. For standardization, K at 20 C is recommended.

APPENDIX B

WATER PERMEABILITY EQUIPMENT AND TEST METHODS

Reprinted from "Asphalt Mix Permeability," by Miller C. Ford and Clark E. McWilliams at the University of Arkansas, Fayetteville, Arkansas, 1988

The design of the water permeameter was developed following an extensive literature review of the many different air and water permeameters. Like the air permeameter discussed above, this apparatus utilizes a constant pressure differential with volumetric flow measurements to measure the permeability of a specimen. The constant pressure is achieved and maintained through the use of an air pressure regulator. Pressure differentials are monitored from a gage. Pressurized by the regulator, water flows through the specimen and is collected in a U-shaped buret where it is measured. Knowing the pressure differential and the flow measurements, the permeability can be calculated.

Problems associated with this apparatus include the pressure gage. In order to achieve the correct pressure at the top of the specimen, thirty-six inches of water pressure must be subtracted from the actual gage reading. But to avoid such a correction and to increase the precision of the results, the slope of the flow rate versus pressure differential curve is used in the calculations. This calculation procedure was recommended by Kumar and Goetz (7).

The procedure described in Appendix B may be used to evaluate the permeability of asphalt mixtures. The following ideal test conditions are prerequisites for the laminar flow of water through porous material under constant head conditions: continuity of flow with no volume change during a test; flow with the voids fully saturated with the water; flow in the steady state with no changes in pressure gradient; and direct proportionality of velocity of flow with pressure gradients below certain values, at which turbulent flow starts. All other types of flow involving partial saturation of mix, turbulent flow, and unsteady state of flow are transient in character and yield variable and time-dependent permeability.

Apparatus

This permeameter is capable of measuring differential pressures up to 10 p.s.i. The general layout of the apparatus is shown in Figure 16 and a list of parts follows:

a) Pressure Regulator - output pressure range from 0 to 50 p.s.i., used to establish pressure differential,

b) Water Trap - to protect the pressure regulator,

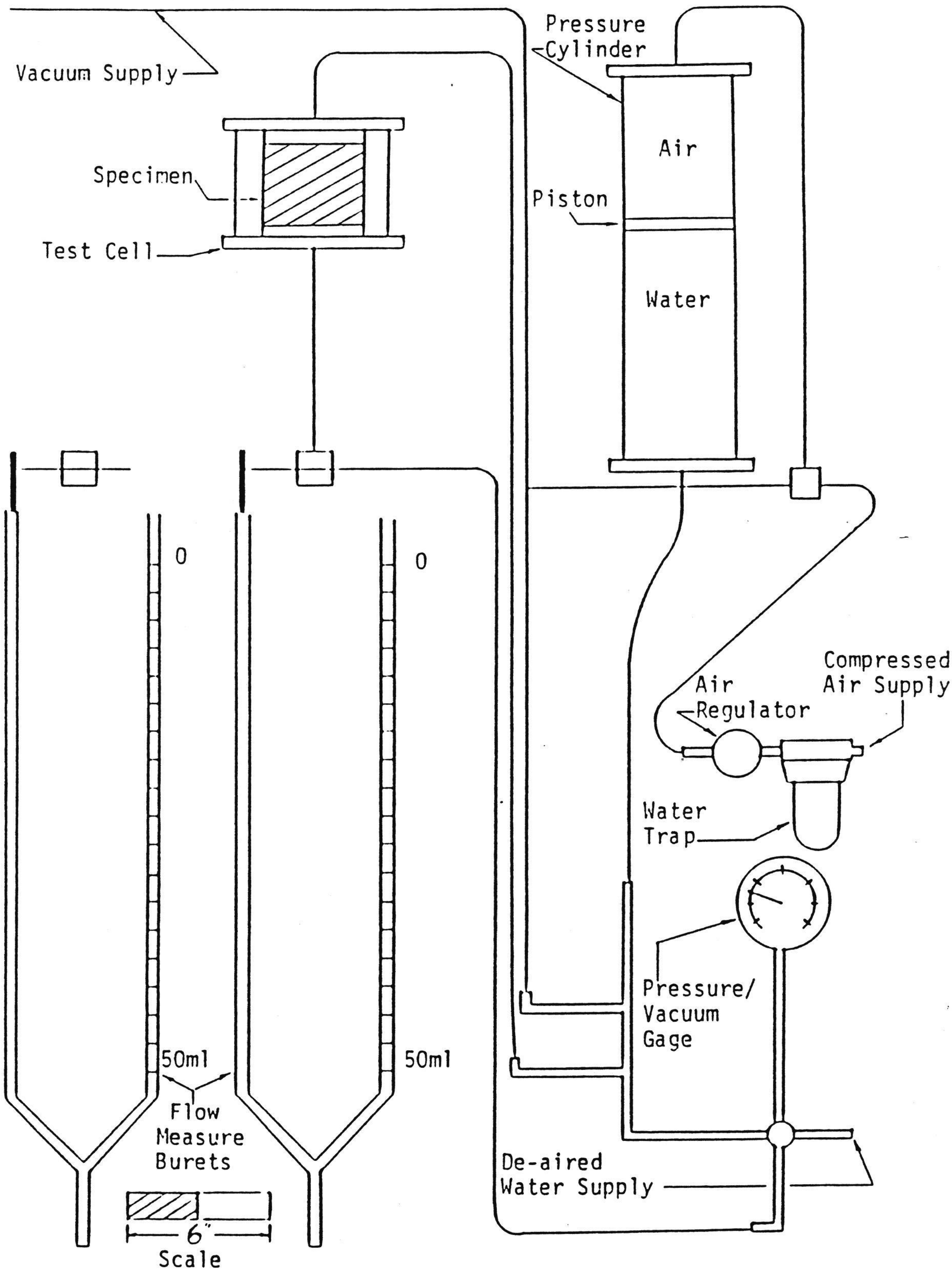

Figure 16. Water Permeameter - General Elevation Layout

c) Compound Gage - capable of measuring pressure from 0 to 30 p.s.i. and vacuum from 0 to 30 inches of mercury,

d) Pressurized Plexiglass Reservoir - capacity of 3500 ml. and aluminum plate interface (piston) in order to protect the de-aired water from exposure to air,

e) Plexiglass Laboratory Cell - with a threaded cylinder 4 3/4 in. I.D. and 5 1/2 in. O.D.), aluminum mounting plates (6 in. X 6 in.) with recessed O-rings, mounting bolts, spacer rings (3 1;/2 in. I.D. and 4 3/4 O.D. and 1/2 in. thick), aluminum tightening ring (3 1/2 in. I.D. and4 3/4 in. O.D. and 1/2 in. thick), and aluminum tightening key (H-shaped made of 1/2 in. X 1/2 in. flat bars with two pins to fit the tightening ring,

f) Calibrated U-tube Buret - 100 ml. capacity to measure outflow rate,

g) Assorted on-off and 3-way ball valves with necessary pipe fittings and connections,

h) Thermometers - mercury type with a range from 40 to 100 degrees F and a sensitivity of 0.5 degrees F, and

i) Stop Watch - with a range of 5 minutes and 0.1 second graduations.

Apparatus Operation

Operation of the water permeameter includes filling the reservoir, preparing the test specimen, and vacuum saturation of the sample.

Filling Reservoir Cylinder (See Figure 17 and 18):

1. close all valves;
2. connect de-aired water supply to #6;
3. open #6, #5, and #2;
4. slowly turn #1 to "vacuum" and observe piston in cylinder moving upward while drawing water from the supply;
5. once tank is full, close #2, #5, #6, and #1;
6. dissipate vacuum still in tank by turning #1 to "pressure" and listen until sound from air regulator quits, (Note: Air regulator must not be in service in order to dissipate vacuum.);
7. close #1.

Preparing Test Specimen in Test Cell (See Figure 19):

1. decrumb specimen and measure height;
2. disassemble test cell and measure diameter of the primary spacer rings (i.e. those that will contact the specimen);

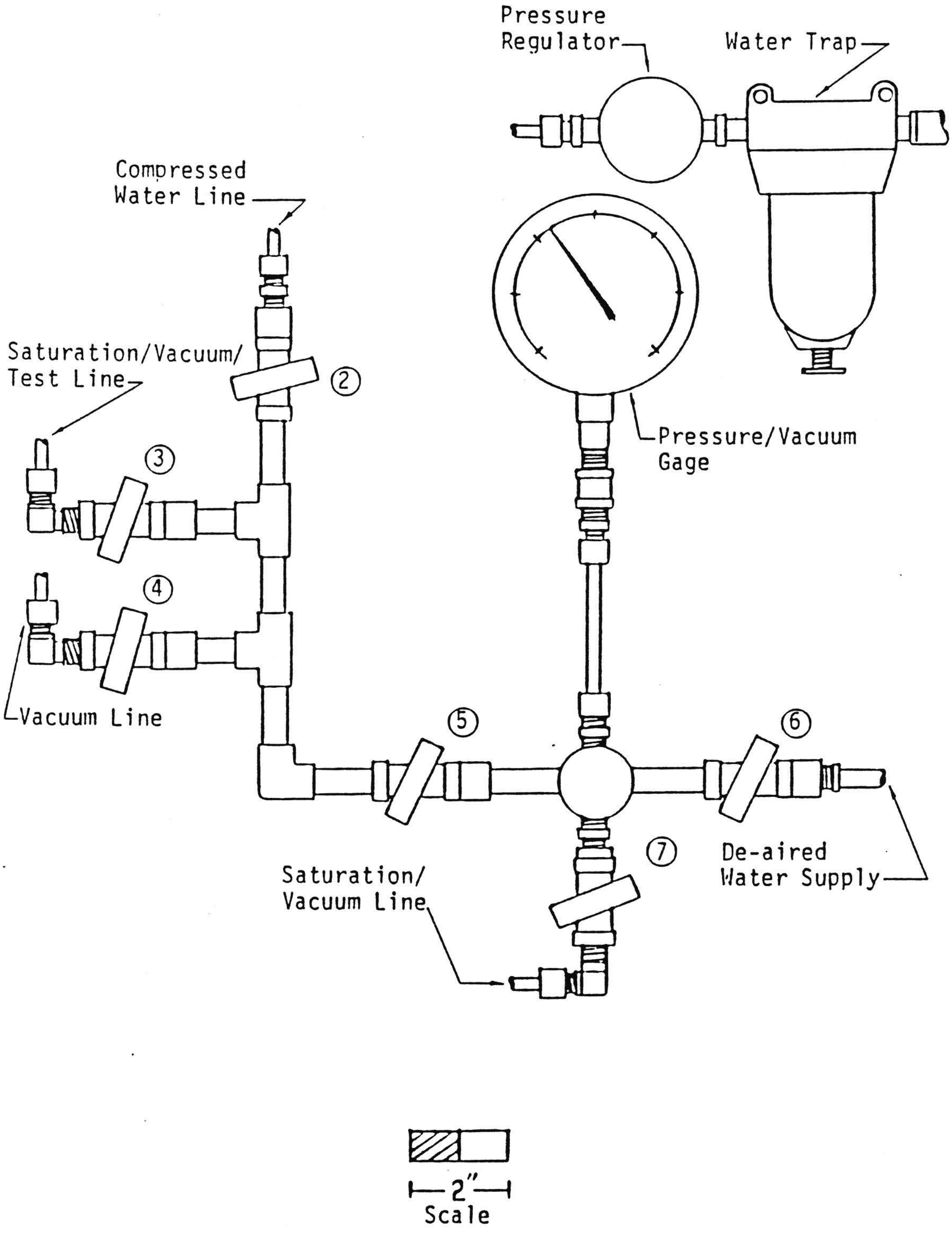

Figure 17. Water Permeameter - Control Manifold

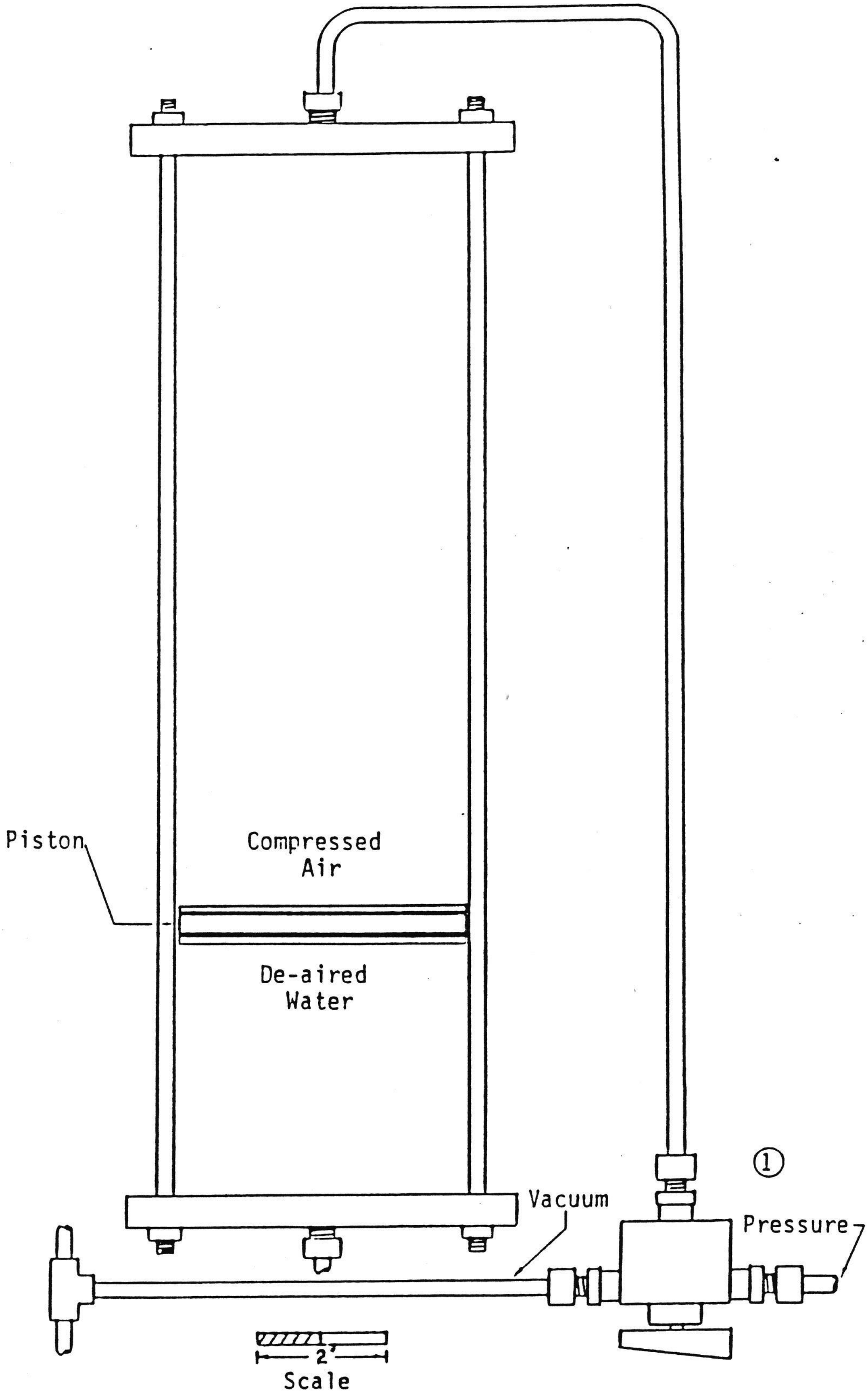

Figure 18. Water Permeameter - Water Reservior

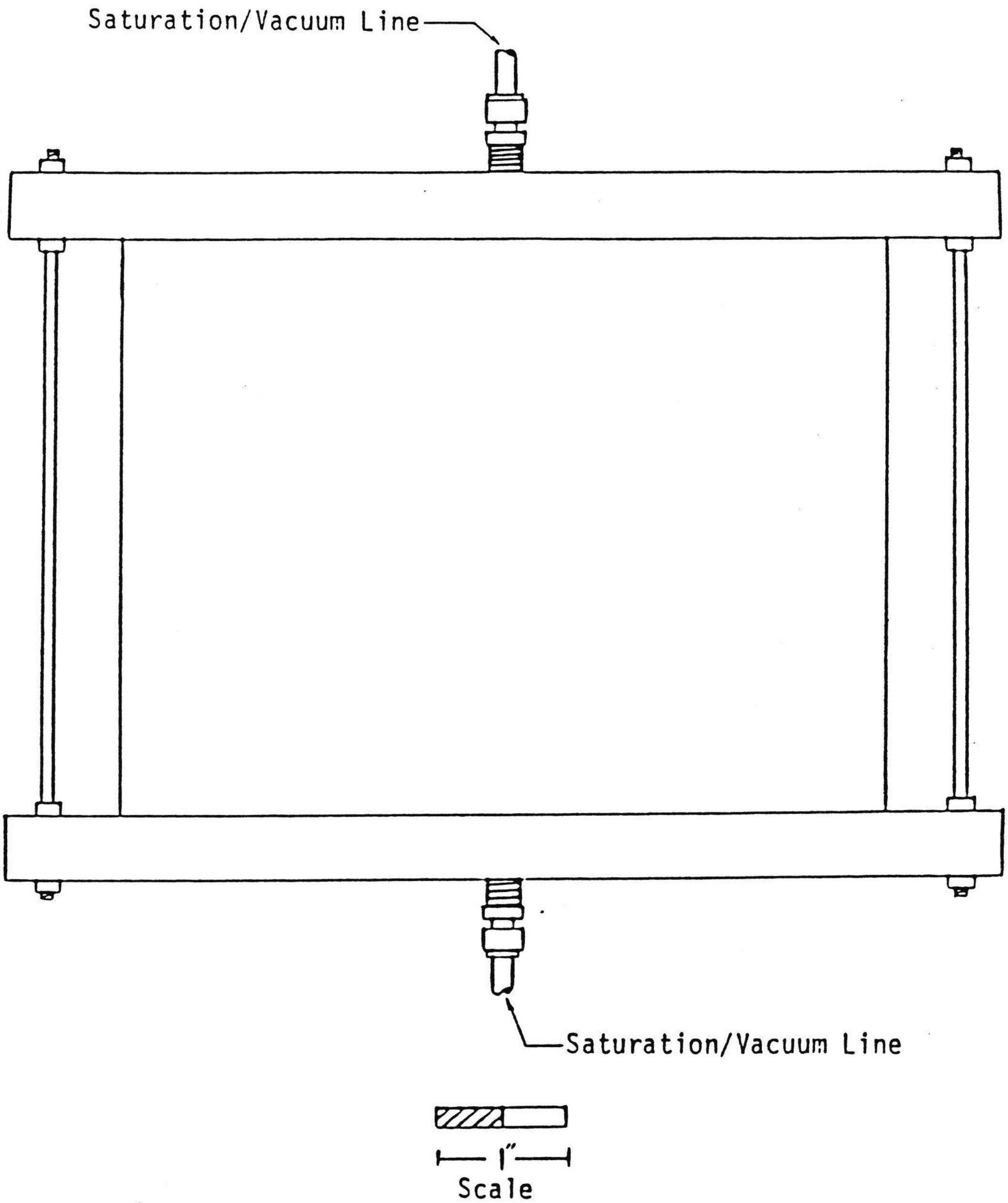

Figure 19. Water Permeameter - Laboratory Test Cell

3. coat specimen contact areas of the primary spacer rings with high vacuum grease;

4. assemble test cell in following order -

   a) begin with bottom plate,

   b) place a sufficient number of bottom spacer rings on the bottom plate so that the specimen will be above the bottom of the threads within the cell,

   c) place cylinder on bottom plate and press vertically until it seats into the plate,

   d) place specimen in the cylinder and center its position,

   e) pour hot paraffin around sample until it forms a meniscus around the top of the sample (Note: Shrinkage due to the cooling of paraffin increases with the temperature used for melting. Also for test peformed by AHTD, asphalt cement was used in place of paraffin in the top 1 inch of the seal.),

   f) insert top primary spacer,

   g) screw tightening ring just snug on top of spacer,

   h) install top plate and secure with nuts;

5. allow test cell to cool 15 min.;

6. test is now ready to be performed.

Vacuum Saturation of Sample (See Figures 17, 18, and 20):

1. close all valves;
2. with specimen connected to apparatus open #7, #5, and #4, turn to "saturate", open #3
3. proceed to evacuate air from system and specimen for 15 min.;
4. close #4 and #5;
5. slowly open #6 and allow de-aired water to enter through bottom of sample, observe water level as it fills test cell (Note: If de-aired water has difficulty flowing through specimen, slowly open #5 and allow de-aired water access to top of specimen.);
6. once de-aired water is on both sides of specimen close #6 and #5;
7. open #4 and resume vacuum for 30 min.;
8. close #4 and #7, open #5, and slowly open #6 to allow de-aired water access to the top of the specimen, thus filling voids remaining in the line
9. open #7 in order to dissipate all vacuum left within the system;

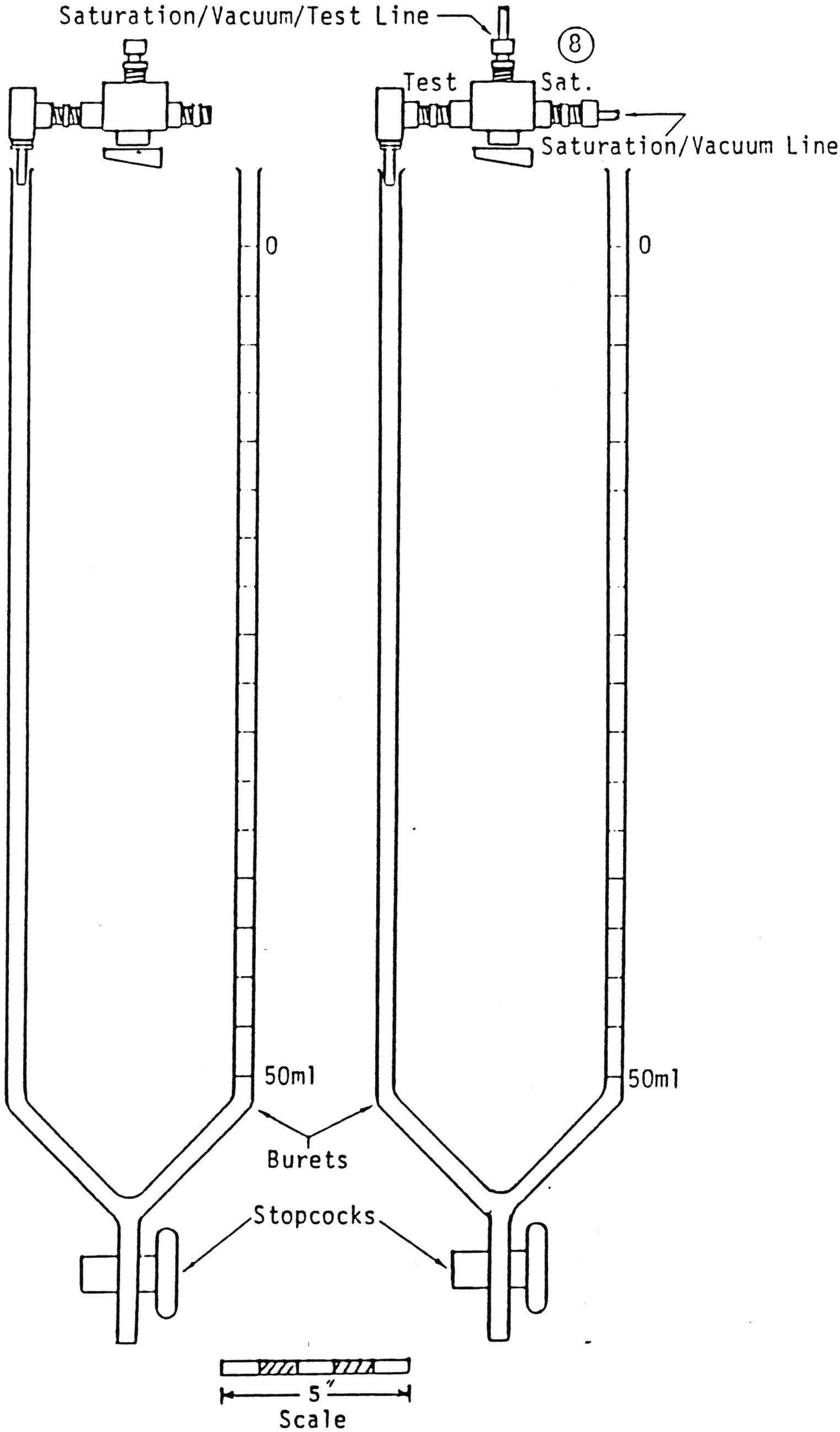

Figure 20. Water Permeameter - Flow Measuring Burets

10. close #7;

11. turn #8 to test; 12) test is now ready to

12. test is now ready to be performed.

<u>Permeameter Operation</u> (See Figures 17, 18, and 20):

1. loosen all valves;

2. open #2, #3, #5, turn #8 to "test", and turn #1 "pressure";

3. adjust pressure regulator to some appropriate constant reading as observed at the pressure gage;

4. as water begins to collect in the buret, occasional purging via the stopcock may be required in order to continue the test;

5. check for steady-state conditions by taking several flow rate measurements;

6. when a steady-state condition is established record pressure reading on dial gage and several flow rate measurements;

7. repeat above process three times at different pressure readings;

8. adjust pressure regulator to zero when test is completed;

9. close #2, #3, and #5.

Calculations

The water permeability (Kw) can be expressed as derived from Darcy's law on the flow of fluids through a porous medium as follows:

$$Kw = (QuL)/(Apt) \qquad \text{(EQ. 9)}$$

where:

K = permeability, sq. cm.

Q = volume of water forced through the sample, cu. cm.

L = thickness of sample, cm.

u = viscosity of water, Pa. s.

A = area of sample, sq. cm.

p = pressure in the cell as measured with the manometer, Pa.

t = time required for water level to drop from one mark on the site tube to another, s.

So that K can be corrected for a reference temperature, the permeability measured at a certain temperature must be reduced to that of a reference temperature by use of the following equation:

$$K(tr) = K(t)\ u(t)/u(tr)$$

where the subscript tr indicates a reference temperature and the subscript t indicates the test temperature. For standardization, K at 20 C is recommended.