THE LABORATORIES

REPORT

WYLE LABORATORIES

WYLE RESEARCH REPORT

WCR 75-8

FLOW RESISTIVITY AND POROSITY TESTING OF SURFACE MATERIALS

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REPORT

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ABSTRACT

Flow resistivity and porosity measurements have been performed on a variety of ground surface materials using a forced airflow apparatus and a microglass-bead-calibrated porosity instrument. It is found that the flow resistivity ranges from over 10^6 cgs rayls/cm for concrete down to less than 10^2 for sand and gravel. The porosity ranges from 0.4 for dry soil to less than 0.01 for concrete. The data are to be used as inputs to analytical model studies of the effect of ground absorption for potential application to future vehicular noise certification procedures.

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1.0 INTRODUCTION

Most vehicular noises are monitored over a distance of 50 feet or more. The effect of various surface conditions between the source and receiver is often treated as an unknown factor and frequently ignored in assessing the noise level generated by the source.

It is a fact that different surface conditions between the source and receiver produce different amounts of sound absorption. In extreme cases where a very porous surface is involved, an error of several dB can be produced if the boundary absorption is not accounted for. This is especially significant when one considers the borderline case where, by ignoring the surface effect, vehicular noise levels would be certified as acceptable which were several dB above the threshold based on measurements over a non-absorbing plane. This report presents the results of an extended series of flow resistivity and porosity measurements of various ground surfaces that include concrete, asphalt, sand, gravel, soil, and soil containing grass roots. The data are to be used in analytical models of the effect of ground reflection for potential applicarion to future vehicular noise certification procedures.

This report contains discussions of the following:

- Section 2 — theoretical background.
- Section 3 — a detailed description of the experimental apparatus.
- Section 4 — a complete error analysis of the measuring equipment involved in the data acquisition.
- Section 5 — descriptions of the samples along with sample designations and sieve analyses.
- Section 6 — results including flow resistivity, porosity, and estimated absorption coefficients.

2.0 THEORY

The normal absorption coefficient (Ω_n) is defined as the fraction of the acoustic energy absorbed by the second medium when an acoustic wave with a frequency f is propagated perpendicularly across the boundary between the first and the second medium. Assuming the first medium is air, the equation for normal absorption coefficient has the following form:[1]

$$\Omega_n = \frac{4r_n}{(r_n + 1)^2 + x_n^2} \qquad (1)$$

where r_n and x_n are the real and imaginary parts of the normalized acoustic characteristic impedance of the second medium with respect to that of air (ρc), i.e., $z_n = r_n + ix_n = Z_c/\rho c$, where Z_c is the characteristic impedance of the second medium per unit area. The characteristic impedance of a porous material can be written:[1]

$$Z_c = \left[\left(\frac{K_R}{F\omega i}\right)\left(R + \frac{m\rho_o \omega i}{F}\right)\right]^{\frac{1}{2}} \qquad (2)$$

where

K_R	=	stiffness coefficient
F	=	porosity
ω	=	$2\pi f$
R	=	flow resistivity
m	=	density coefficient
ρ_o	=	equilibrium density of air in the porous material
i	=	$\sqrt{-1}$

Since we measure only the flow resistivity R and the porosity F, we assign to the other variables the specific values:

K_R = 1.02×10^6 (isothermal case, dynes/cm^2)

ω = $2\pi \times 200$ (sec^{-1})

m = 1

ρ_o = 1.21×10^{-3} (g/cm^3)

The porosity is measured by the following method: the sample is sealed in a cavity and the air pressure in the cavity is varied. A simple calculation yields the following expression for the porosity:[2]

$$F = 1 - \frac{V}{V_s} - \frac{P_o \Delta V_a'}{V_s \Delta P} \qquad (3)$$

where

V = total volume of the cavity

V_s = volume occupied by the sample mass

$\Delta V_a'$ = change of volume in cavity

ΔP = change of pressure in cavity

P_o = atmospheric pressure

The particle size distribution of the sample is determined using a series of sieves with openings ranging from 63 to 2000 microns (10^{-6}m). The moisture content (by weight) of the sample is determined by adding a known quantity of water to a dehydrated sample.

Three computer programs have been developed to compute the flow resistivity, porosity, normal absorption coefficient, and the particle size distribution. These programs are listed in Appendix A.

3.0 EXPERIMENTAL APPARATUS

3.1 Forced Airflow Resistivity Apparatus

A forced airflow resistivity apparatus was constructed for this program as shown in Figure 1. The main body of the apparatus consists of several sections of 6 inch ID steel pipe fastened together by Victaulic clamps. The flow regulator is capable of supplying air at flow rates from 0 to 10 cfm. There are two flowmeters available: Flowmeter 1 (0 - 1 cfm) and Flowmeter 2 (0 - 10 cfm). Two inclined water manometers cover a pressure range of 0 to 0.5 inches and 0 to 4 inches of water, respectively. A vertical water manometer with a range of 0 to 60 inches is also utilized. The mercury barometer has a range of 0 to 40 inches Hg which is equivalent to a range of 0 to 544 inches of water. For more porous material such as gravel, the inclined water manometer (0 - 0.5 in.) and Flowmeter 2 are employed.

A verification of the apparatus capability was carried out using Johns-Mansville (J-M) fiberglass materials. Due to the rapid change of the demand/supply picture in the fiberglass industry, most materials normally available for data comparison have been discontinued. Therefore, a discussion was held with the manufacturer to trace the historical evolution of various J-M fiberglass series. For example, J-M Spin-Glas 800 Series is a derivation of J-M Spintex 400 Series, and J-M Microlite (1974) is a variation of the earlier J-M Microlite B-305. A comparison is therefore drawn between these two series. In Figure 2, we have plotted the measured flow resistivity in CGS rayls/cm versus bulk density in g/cm^3 and lb/ft^3 of both J-M Microlite (1974) and J-M Spin-Glas 800 Series. The published data on J-M Microlite B-305 and J-M Spintex 400 Series have also been included in Figure 2 for comparison.[2] It is noted that our value for Microlite (1974) is lower than that of Microlite B-305 and the value for Spin-Glas 800 Series is higher than that of the Spintex 400 Series. Also, the slopes obtained from this study are not as steep as the previous ones. It is observed that the dominant fiber orientation in the new fiberglass material is layered crosswise to the direction of airflow. This fact agrees with an experimentally-observed slope of 1.3, which has been the empirical result of many other materials having approximately the same texture.

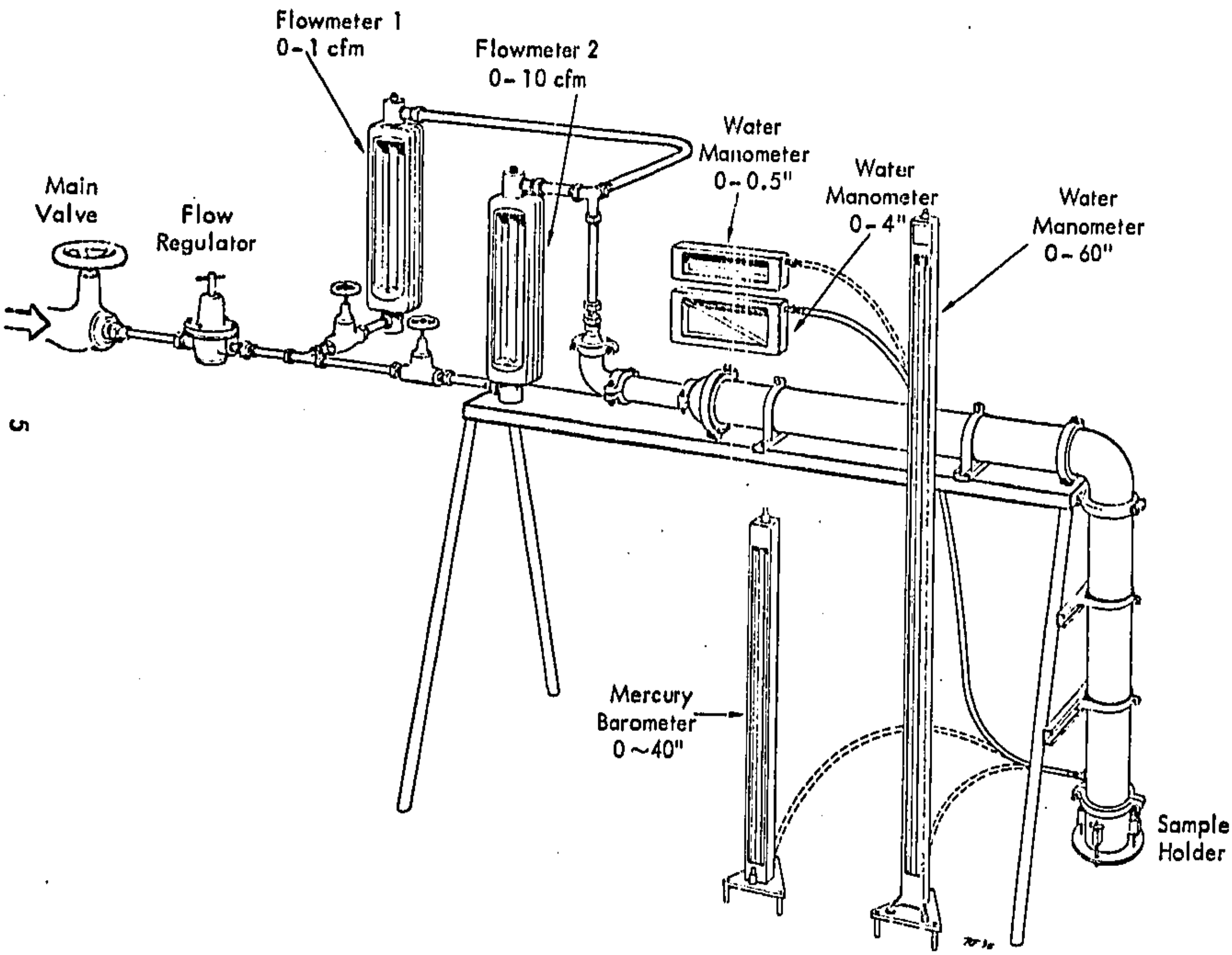

Figure 1. Flow Resistivity Apparatus

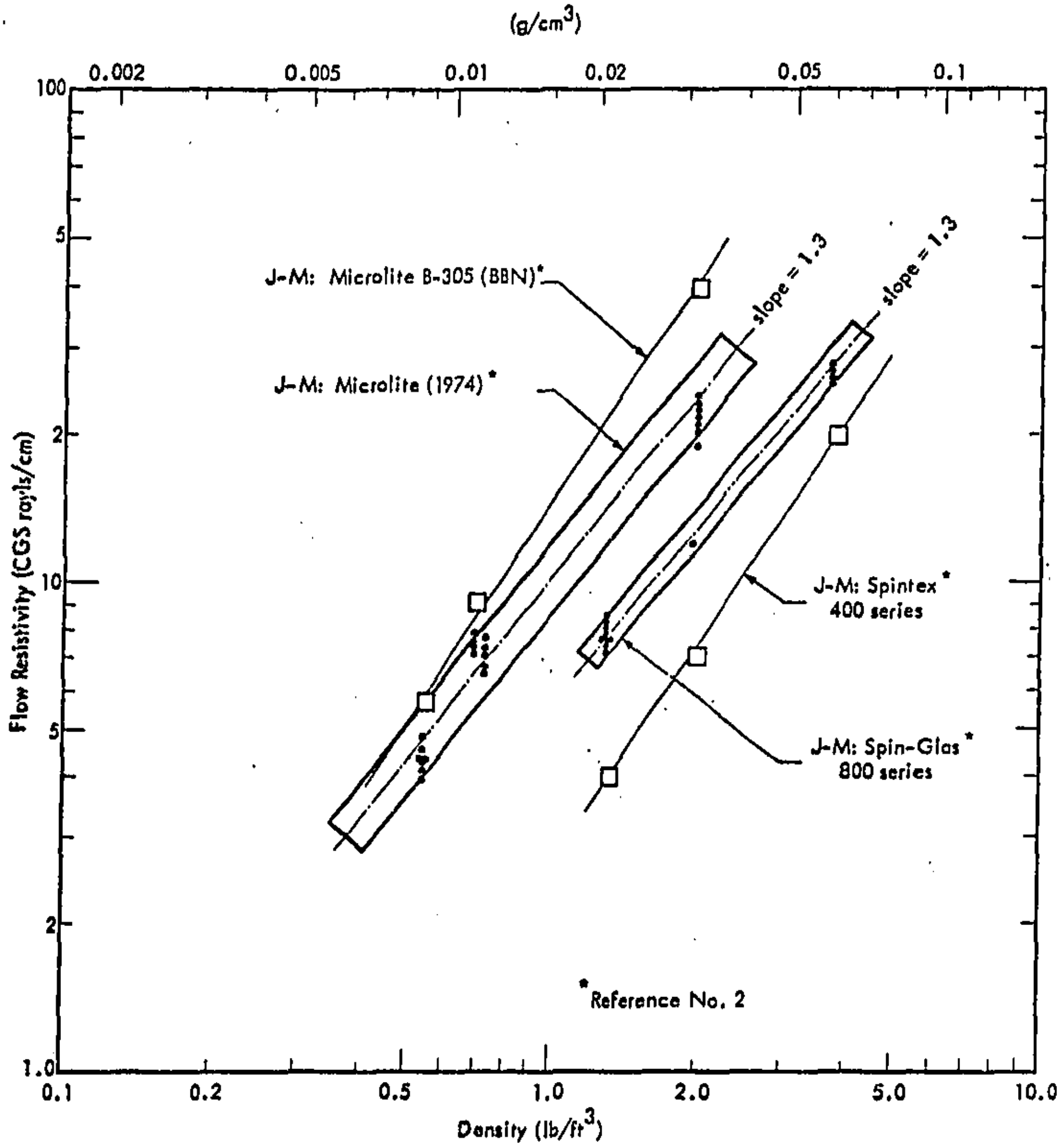

Figure 2. Flow Resistivity Apparatus Verification
(rectangular boxes enclose the data
obtained from present investigation)

3.2 Sample Holders

There were two sample holders developed during this project. Sample holder number one (S.H. #1) is a section of 6 inch ID steel pipe 6 inches in length. There are two variations for the bottom screen retainer. The first is a set-screw positioning type which is primarily used for soil and soil containing grass roots samples. The pipe section of the sample holder (with one end sharpened) is first driven all the way into the earth. The pipe and the sample are extracted from the ground without being disturbed and the bottom retainer is then fastened on. The second variation is a fixed-bottom retainer type and the sample is loaded from the top, and is used for samples such as sand, asphalt, and concrete.

As the program progressed, it was found that one of the major difficulties encountered was leakage of air around the sample holder perimeter, especially for those samples which had to be extracted from the ground in the field. This was due to the difficulty of driving the sample holder straight into the ground without introducing any lateral movement. This was particularly true when the ground was well settled and hardened. As a result, the sample was no longer in close contact with the holder perimeter and a leak was established. Therefore, a more sophisticated sample holder was developed and fabricated as shown in Figure 3. The core of this sample holder (S.H. #2) is a thin steel pipe of 4.8 inches ID and a length of 4 inches. The thin wall increases the ease of driving the holder into the ground. In addition, after the sample is removed from the ground, the upper and lower-lipped flanges are driven into the sample from the top and bottom, sealing off the perimeter from the main body of the sample and therefore converting the perimeter from a low resistance path to a high resistance path. Four snap-on, threaded rods provide a quick loading and unloading of the sample from the flow resistivity apparatus. S.H. #2 was also designed to be compatible with the porosity apparatus so that not only could the porosity of the sample be measured more readily, but also nondestructively. This holder represents a great improvement over S.H. #1 providing greater efficiency and higher accuracy.

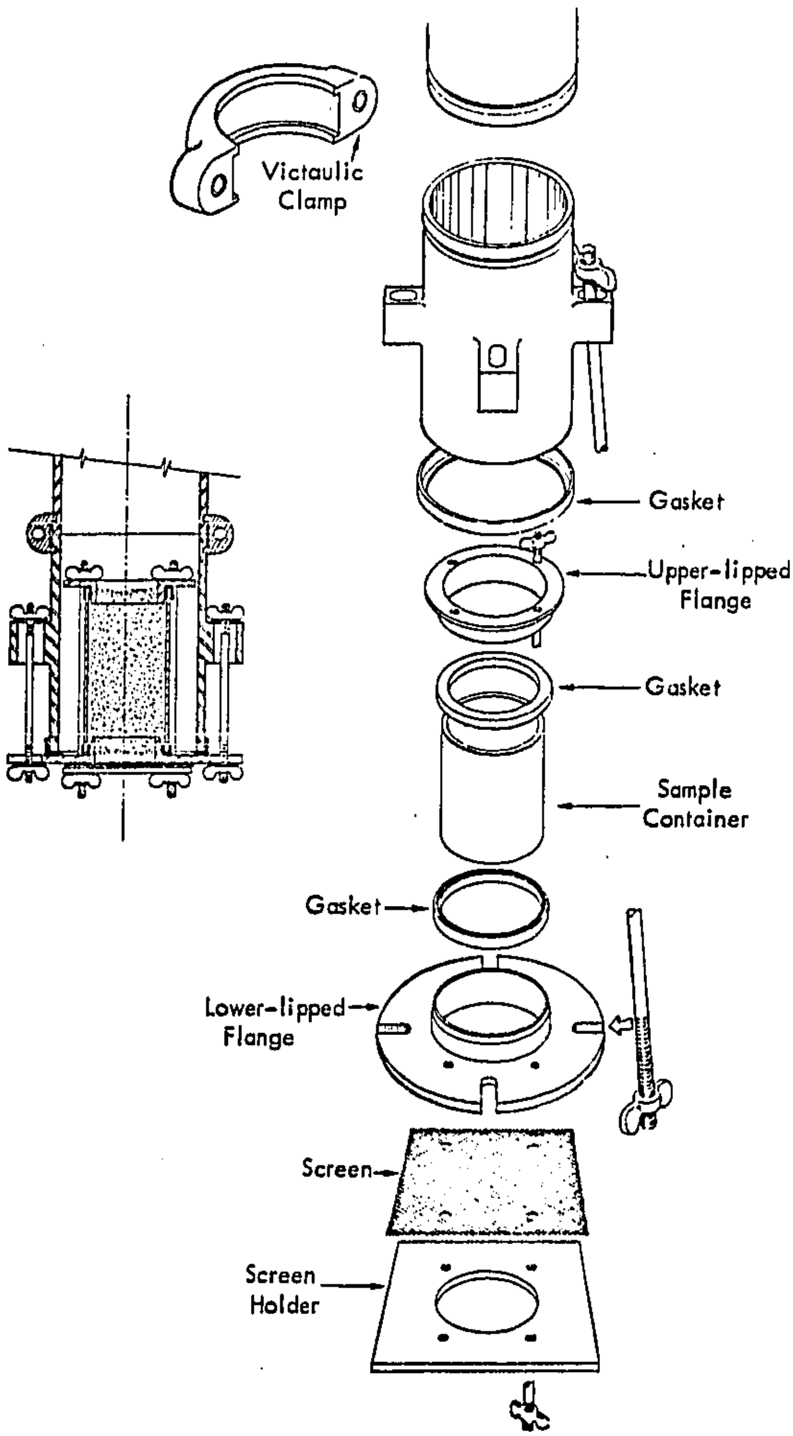

Figure 3. Sample Holder #2

3.3 Porosity Apparatus

In the initial phase of the program the porosity was measured using the formula $F = 1 - \rho_{bulk}/\rho_{base}$, where ρ_{bulk} was the bulk density of the sample, and ρ_{base} was the base material density.[2] It was assumed that when the above formula was employed, the sample must have been totally dehydrated. The bulk density of the sample was measured by weighing the sample and dividing it by its volume. The base material density was found by breaking down the sample into its constituent granules and weighing it before immersing it in water to measure the volume displacement. This technique had two drawbacks: (1) the sample had to be dehydrated completely, because in most cases, the sample density was different from that of water, and (2) the procedure was destructive.

Consequently, a porosity apparatus which was capable of measuring porosity in a nondestructive manner, and at any moisture content of the sample, was developed, constructed, and utilized (see Figure 4). S.H. #2 is used for the sample cavity. Two additional flanges — one on top and the other at the bottom — seal off the cavity. A pressure relief valve on the top (not shown in Figure 4) permits the pressure on both sides of the U-tube to reach equilibrium at atmospheric pressure. The U-tube is connected to the sample cavity through a quick-disconnect. The water in the U-tube is colored to improve its visibility. A metric scale is placed behind each water column to measure its height.

A measurement sequence consists of the following steps:

a) The sample is installed in the holder and attached to the apparatus.
b) The top relief valve is opened and the water columns are allowed to equalize and this valve is then closed.
c) Water column #2 is then raised until a difference of approximately 10 cm is observed between the two columns.
d) The column height difference is then used to compute the change in cavity volume and the change in pressure in the cavity and Eq (3) is utilized to calculate the sample porosity.

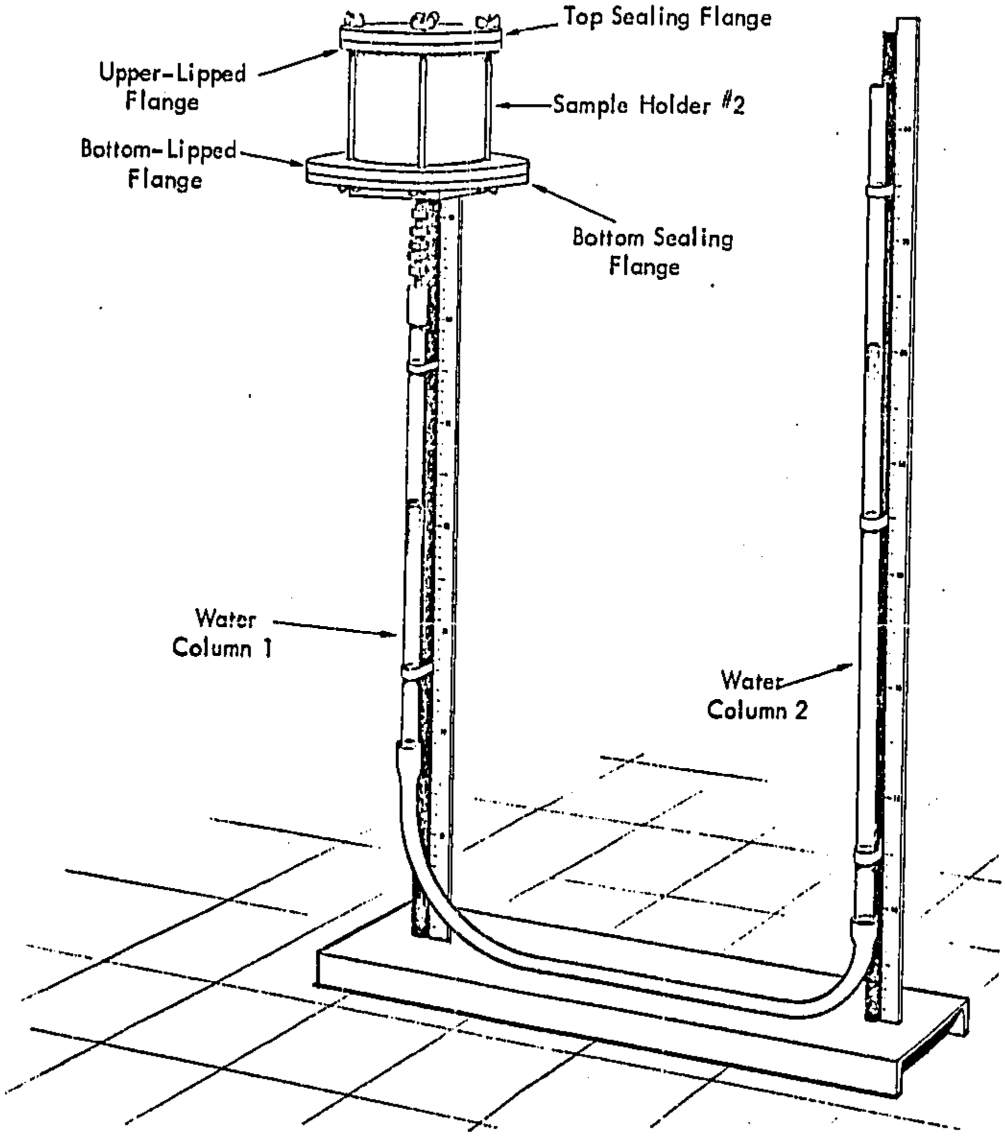

Figure 4. Porosity Measurement Apparatus

The porosity apparatus was calibrated using Unisphere Microglass Beads* which have an average diameter of 180u. The glass beads were poured into S.H. #2 while the outside wall of the holder was gently tapped. The tapping action ended only when the volume of glass beads in the holder ceased to decrease. Then we assume that a hexagonal-close-pack (HCP) arrangement has been established by the glass beads since this is the smallest volume condition that can be reached. The theoretical porosity based on this HCP model is 0.192, whereas several measurements of this sample yielded an average value of 0.197. The error involved in measurements using this apparatus was therefore put at less than 3%.

3.4 U.S. Standard Sieve Analysis

Six U.S. Standard Sieves** were purchased. The sieve numbers and their corresponding openings are as follow:

Sieve Number	Opening Size in Microns
10	2000μ
16	1180μ
40	420μ
60	250μ
200	74μ
230	63μ

The sample to be sieved was first dehydrated and broken down into its final granular constituents. About 800 grams were placed in sieve number 10. Vertical and lateral shaking action required approximately 20 minutes for each sample. Each sieve was then weighed to determine the gross weight of granules trapped in it. A computer program was then utilized to compute the particle size distribution of each sample.

*Obtained from Ferro Corporation, Microbead Department, Huntington Beach, Calif.

**Obtained from Sargent-Welch Scientific Company

4.0 EQUIPMENT ACCURACY

In Table 1, a complete list of all the measuring equipment is tabulated together with its range, absolute accuracy, relative accuracy, and percentage errors.

Table 1

Equipment Accuracy

Equipment	Range	Absolute Accuracy*	Relative Accuracy**	Percentage Error***	Remarks
Flowmeter 1	0 - 1 cfm	0.02 cfm	0.01 cfm	2%	
Flowmeter 2	0 - 10 cfm	0.2 cfm	0.1 cfm	2%	
Inclined Manometer 1	0 - 0.5 cfm	0.01 cfm	0.005 cfm	2%	
Inclined Manometer 2	0 - 4 cfm	0.1 cfm	0.05 cfm	2.5%	
Water Manometer 3	0 - 60 cfm	0.2 cfm	0.1 cfm	0.3%	
Mercury Manometer	0 - 40 cfm	0.2 cfm	0.1 cfm	0.5%	
Scale 1	0 - 250 lb	0.1 lb	0.05 lb	0.04%	Moisture content of the sample by weight
Scale 2	0 - 610 gm	0.2 gm	0.1 gm	0.03%	Sieve analysis
Porosity Apparatus	0 - 50 cm	0.2 cm	0.1 cm	0.4%	
Burette	0 - 50 cc	0.1 cc	0.05 cc	0.2%	For adding water to the sample
Sample Thickness	10 cm	0.25 cm	0.13 cm	2.5%	
Cross-sectional Area	130 cm^2	3.2 cm^2	1.6 cm^2	2.5%	

* Absolute accuracy is defined as the reproducibility of the reading for the same sample.

** Relative accuracy is defined as the accuracy of reading the scale itself.

*** Percentage error = (absolute accuracy/Range) x 100%

Errors in equipment utilized for the same purpose are exclusive.
Maximum error expected from measuring equipment is approximately 10%

5.0 SAMPLE DESCRIPTIONS

There were a total of 72 samples including derivatives obtained, prepared, and measured. In Table 2, a grand list of all the samples together with their source, brief description, sample designation, and sample holder utilized are tabulated. Basic samples are shown separated by solid lines with their derivatives which were obtained by adding moisture or, in the case of asphalt, sealing with an emulsion. The sieve analysis of each basic sample (not its derivatives) is listed in Table 3. The estimated bulk density for all the dry samples is shown in Table 4. A more detailed description will be given in the following paragraphs.

5.1 Concrete Samples (5)*

The sieve analysis of the sand used in all the concrete samples is the same as the one listed in Table 3 under 20-CS-00.

a) The first sample was formulated using (1-C-31)**

- 3 volumes sand,
- 1 volume Portland Cement,
- 1 volume 3/4 inch crushed rock,
- 2 volumes water.

The sample was allowed to cure for 4 days before it was tested. The sample was 1.9 cm (3/4 inch) thick. It is noted that this type of concrete is typical for highway construction.

b) The second sample was formulated using (2-C-31)

- 3 volumes sand,
- 1 volume Portland Cement.

This sample was prepared in an effort to reduce the density and strength of concrete sample 1-C-31. The thickness of the sample was 2.8 cm (1.1 inches). The cure time was 4 days.

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*Total number of samples and derivatives in this category.

**Sample designation (see Table 2).

Table 2

Sample Designation

No.	Type	Source	Description	Designation*	Remarks**
1	Concrete	Portland Cement	3 to 1 mix	1-C-31	In S.H. #1
2	Concrete		3 to 1 mix	2-C-31	
3	Concrete		6 to 1 mix	3-C-61	In S.H. #1
4	Concrete		6 to 1 mix	4-C-61	
5	Concrete		9 to 1 mix	5-C-91	
6	Asphalt	Industrial Asphalt of Santa Ana	0 blows unsealed	6-AU-00	
7			0 blows sealed	7-AS-00	
8			35 blows unsealed	8-AU-35	
9			35 blows sealed	9-AS-35	
10			75 blows unsealed	10-AU-75	Damaged
11			75 blows unsealed	11-AU-75	In S.H. #1
12			75 blows sealed	12-AS-75	In S.H. #1
13			75 blows unsealed	13-AU-75	
14			75 blows sealed	14-AS-75	
15	Gravel	Calif. Material Co.	1/4" in size	15-G	
16	Beach Sand	Hermosa Beach	Dry	16-BS-00	
17	Beach Sand		5% moisture	17-BS-05	
18	Beach Sand		10% moisture	18-BS-10	
19	Beach Sand		15% moisture	19-BS-15	
20	Coarse Sand	Calif. Material Co.	Dry	20-CS-00	
21			4.3% moisture	21-CS-04	
22			8.6% moisture	22-CS-09	
23			12.9% moisture	23-CS-13	
24			Dry	24-CS-00	
25			Dry	25-CS-00	In S.H. #1
26			4.8% moisture	26-CS-05	
27			9.2% moisture	27-CS-09	
28			9.8% moisture	28-CS-10	
29	Coarse Sand	Calif. Material Co.	12.2% moisture	29-CS-12	In S.H. #1

Table 2. Continued

No.	Type	Source	Description	Designation*	Remarks**
30	Fine Sand	Calif. Material Co.	Dry	30-FS-00	In S.H. #1
31	Fine Sand		2.7% moisture	31-FS-03	
32	Fine Sand		3.3% moisture	32-FS-03	
33	Fine Sand		5.0 % moisture	33-FS-05	
34	Fine Sand		6.5% moisture	34-FS-07	In S.H. #1
35	Soil	San Fernando Valley	Dry	35-S-SFV00	
36			5.2% moisture	36-S-SFV05	
37			10.3% moisture	37-S-SFV10	
38			15.5% moisture	38-S-SFV16	
39			18.1% moisture	39-S-SFV18	
40		El Segundo	Dry	40-S-ES00	
41			4.8% moisture	41-S-ES05	
42			9.7% moisture	42-S-ES10	
43			14.5% moisture	43-S-ES15	
44			Dry	44-S-ES00	In S.H. #1
45			6.8% moisture	45-S-ES07	
46			8.1% moisture	46-S-ES08	
47			8.6% moisture	47-S-ES09	
48			10.4% moisture	48-S-ES10	In S.H. #1
49		Redondo Beach	In Situ	49-S-RBIS	Damaged
50			Dry	50-S-RB00	
51			5.3% moisture	51-S-RB05	
52			10.5% moisture	52-S-RB11	
53			15.8% moisture	53-S-RB16	
54		Orange County	Dry	54-S-OC00	
55			5.9% moisture	55-S-OC06	
56			11.7% moisture	56-S-OC12	
57			17.6% moisture	57-S-OC18	
58	Soil	Orange County	20.5% moisture	58-S-OC21	

Table 2. Continued

No.	Type	Source	Description	Designation*	Remarks**
59	Soil with Grass Roots	San Fernando Valley	In Situ	59-SG-SFVIS	
60		El Segundo	In Situ	60-SG-ESIS	
61			Dry	61-SG-ES00	In S.H. #1
62			17.6% moisture	62-SG-ES18	
63			18.1% moisture	63-SG-ES18	
64			20.0% moisture	64-SG-ES20	
65			21.0% moisture	65-SG-ES21	In S.H. #1
66		Redondo Beach	In Situ	66-SG-RBIS	Damaged
67		Redondo Beach	In Situ	67-SG-RBIS	
68		Orange County	Dry	68-SG-OC00	
69			6.9% moisture	69-SG-OC07	
70			13.8% moisture	70-SG-OC14	
71			20.7% moisture	71-SG-OC21	
72	Soil with Grass Roots	Orange County	24.1% moisture	72-SG-OC24	

*Abbreviations:

C Concrete
AU Asphalt unsealed
AS Asphalt sealed
G Gravel
BS Beach Sand

CS Coarse Sand
FS Fine Sand
S Soil
SG Soil with Grass Roots
S.H. Sample Holder

SFV San Fernando Valley
ES El Segundo
RB Redondo Beach
OC Orange County

**In S.H. #2 if unspecified.

Table 3

Sieve Analysis By Percentage Passing

	U.S. Standard Sieve Number/Sieve Opening (microns)					
Sample Designation	10/2000	16/1180	40/420	60/250	200/74	230/63
Sand						
16-BS-00		100	51	11	0	
30-FS-00	88		29		3	1
20-CS-00	89	73	30	16	2	1
Soil						
35-S-SFV00	92	83	55	42	18	3
44-S-ES00		99	65	26	13	3
40-S-ES00	97		69		34	3
50-S-RB00	98	96	42	16	7	3
54-S-OC00	97	94	80	60	8	6
Soil with Grass Roots						
59-SG-SFV00	82	74	47	34	11	2
60-SG-ESIS	95	92	58	22	8	5
61-SG-ES00	96		54		4	2
67-SG-RB00	99	98	47	20	6	4
68-SG-OC00	96	90	75	58	11	8

TABLE 3a

PARTICLE SIZE ANALYSIS BASED ON SIEVE DATA OF TABLE 3

SAMPLE DESIGNATION	PERCENTAGE OF PARTICILES IN SIZE RANGE (MICRONS) SHOWN						
	Greater Than 2000	2000-1180	1180-420	420-250	250-74	74-63	Less Than 63
SAND							
~~16-DS-00~~	~~0.00~~	0.00	49.00	45.39	5.61	0.00	0.00
30-FS-00	12.00 *1	------	62.48 *2	------	24.75	0.76	0.01
20-CS-00	11.00	24.03	45.48	16.37	3.06	0.06	0.00
SOIL							
35-S-SFV00	8.00	15.64	34.36	24.36	14.56	3.08	0.10
44-S-ES00	0.00	1.00	34.65	47.62	14.56	2.11	0.07
40-S-ES00	3.00 *1	------	30.07 *2	------	44.17	22.07	0.68
50-S-RB00	2.00	3.92	54.57	33.19	5.88	0.43	0.01
54-S-OC00	3.00	5.82	18.24	29.18	40.27	3.29	0.21
SOIL W/GRASS ROOTS							
59-SG-SFV00	18.00	21.32	32.16	18.82	8.63	1.05	0.21
60-SG-ESIS	5.00	7.60	36.71	39.54	10.26	0.85	0.04
61-SG-ES00	4.00 *1	------	44.16 *2	------	49.77	2.03	0.04
67-SG-RB00	1.00	1.98	51.42	36.48	8.57	0.53	0.02
68-SG-OC00	4.00	9.60	21.60	27.22	33.45	3.80	0.33

*1 - PERCENTAGE RETAINED FOR SIEVE OPENING RANGE OF >2000-1180u
*2 - PERCENTABE RETAINED FOR SIEVE OPENING RANGE OF 1180-250u

Table 4

Approximate Sample Bulk Density*

Sample	Bulk Density (g/cm^3)
Concrete	
3 to 1 mix	2.3
6 to 1 mix	1.7 - 1.8
9 to 1 mix	1.7
Asphalt	
0 Blows	1.6
35 Blows	1.8
75 Blows	2.0 - 2.2
Sand	
Beach	1.6
Coarse, Building	1.5
Fine, Building	1.6

Sample	Bulk Density (g/cm^3)
Soil	
San Fernando	1.6
El Segundo	1.6 - 1.7
Redondo Beach	1.5
Orange County	1.8
Soil Containing Grass Roots	
El Segundo	1.3
Orange County	1.2

*For totally dehydrated samples only.

c) This concrete sample was prepared using (3-C-61)

- 6 volumes sand,
- 1 volume Portland Cement.

The thickness of the sample was 0.6 cm (1/4 inch) and was allowed to cure for 3 days before being tested in sample holder #1. This sample was structurally weak and would not represent a commercial grade of concrete.

d) This sample was prepared the same as item c) except it (4-C-61) was loaded to sample holder #2. The thickness of the sample was 2.5 cm (1 inch).

e) This sample was prepared using (5-C-91)

- 9 volumes sand,
- 1 volume Portland Cement.

The sample was measured in sample holder #2. The thickness was 2.8 cm (1.1 inches).

5.2 Asphalt Samples (9)

A general description will be given to the unsealed and sealed samples. The details of sample variation will be explained categorically.

a) Unsealed asphalt (5) (6-AU-00, 8-AU-35, 10-AU-75, 11-AU-75, 13-AU-75)

The asphalt sample was type II, 1.3 cm (1/2 inch) medium mix as specified by Section 39, DOT, January 1971. The asphalt was placed in the sample holder at 320°F and compacted with a certain number of uniform blows across the entire surface area from a 10-pound weight dropped from a height of 46 cm. The size of the weight was 5 cm in diameter. This is in accordance with ASTM 1559.[3] The sample was obtained from Industrial Asphalt of Santa Ana and their seive analysis of the sample was estimated as follows:

	Sieve Size						
	1/2"	3/8"	#4	#8	#30	#50	#200
Percent Passing (range)	74-88	62-76	38-52	28-40	12-22	6-14	2-6

The asphalt binder was estimated at 4.5 to 5.8% by weight.

The thickness of sample 11-AU-75 was 3.2 cm (1-1/4 inches) whereas the remainder were approximately 2.5 cm (1 inch).

For the sample with no compaction, the hot asphalt was simply poured into the sample holder and the excess material was removed using a straight edge against the top end of the sample holder.

b) Sealed asphalt (4) (7-AS-00, 9-AS-35, 12-AS-75, 14-AS-75)
An asphalt-sealing emulsion, SS1-h, manufactured by Douglas Oil Co., was added to the unsealed sample. The sealer was diluted with 50% water by volume to yield an effective seal of 0.05 cc/cm^2 (1/10 $gal./yd^2$).

5.3 Gravel (1) (15-G)

The gravel was purchased from a commercial material company and was comprised of particles of with an average size of 0.64 cm (1/4 inch) and was sharp and dry.

5.4 Sand (19)

The following descriptions apply primarily to the dry samples only. The procedure of adding water to the sample was the same for sand, soil, and soil with grass roots. A 50 cc burette was utilized to produce a fine water spray on the sample surface. Each change in moisture content required approximately 100 cc water. For the sand samples, the waiting period before each water application was about 30 minutes. However, for soil and soil with grass roots samples, the waiting period was extended to as long as 2 hours to allow complete moisture dispersal within the heavily clayed samples.

a) Beach sand (16-BS-00 to 19-BS-15)

The beach sand was obtained from Hermosa Beach, California. The sample was 10 cm (4 inches) thick. The average particle size was about 400μ, as can be seen in Table 3.

b) Coarse building sand (20-CS-00 to 29-CS-12)

The building sand was obtained from California Material Company. This is a common construction-grade sand with a sieve analysis as shown in Table 3. The sample was 10 cm (4 inches) thick.

c) Fine building sand (30-FS-00 to 34-FS-07)

This sand sample, 9.8 cm (3-7/8 inches) thick and classified as fine, was actually quite similar to the coarse sample as evidenced by the sieve analysis in Table 3. It was obtained from the same supplier as was the coarse building sand.

5.5 Soil and Soil Containing Grass Roots (38)

Samples were obtained from four different geographic areas in Los Angeles and Orange Counties: San Fernando Valley in the north; El Segundo and Redondo Beach in the South Bay Section along the Pacific coast; and Orange County in the far south. Since each pair of soil and soil with grass roots samples were taken from the same general location at the same time for each geographic area, the sample in these two categories will be described according to its source. The thickness of all samples was 10 cm (4 inches) unless otherwise specified.

a) San Fernando Valley (5) (35-S-SFV00 to 39-S-SFV18, 59-SG-SFVIS)

Samples were taken from the backyard of a residence located at 9724 Columbus Avenue, Sepulveda, California at 7:30 PM on Sunday, April 13, 1975. The house was built in 1948. Both samples were taken from ground within 10 feet of each other. The samples were wrapped in aluminum foil and stored in the garage until Monday morning. The samples were taken from ground close to some grape vines, and part of the soil possibly contained decomposed leaves from these vines.

Vegeiation in the grass sample appeared to be mixed; however, the dominant component was identified as Bermuda. The root system was heavy and dense.

Prior to the sample removal, it had been raining for several weeks; however, the day the samples were taken, there was no rain.

b) El Segundo (9)

Two sets of soil and soil containing grass roots samples were obtained in El Segundo. One sample was taken and measurement results were submitted in the preliminary report and are repeated here for completeness. This sample was measured in sample holder #1 and a later sample in sample holder #2.

(1) Preliminary sample (44-S-ES00 to 48-S-ES10, 61-SG-ES00 to 65-SG-ES21)

One soil sample was obtained 2 days after a rainstorm, and the moisture content was later determined to be 10.4% by weight. The top surface of the soil sample, which was 8.6cm (3-3/8 inches) thick, appeared moist at the time it was obtained. It appeared firm, dark, and fertile, and also devoid of bugs or sizeable gravel. The sample was obtained near the intersection of Maryland Street and Grand Avenue in El Segundo in an oil-producing area but with no evidence of oil in the sample. A sieve analysis following all measurements produced the results shown in Table 3.

Near the same area that produced the soil sample, a gentle slope covered by 5cm (2 inches) growth of Dallisgrass (Paspalum Dilatatum) was found. A sample 11cm (4-1/2 inches) thick with a moisture content of 21% was obtained. Dallisgrass, when fully grown, can reach a height of 200cm (6 feet) but due to the climate in this area, it rarely exceeds several inches in height. The roots are not as heavy as Bermuda grass; however, it is an extensive root system that can penetrate 20cm (8 inches) into the earth. The roots are almost immune to bugs and worms. This sample felt light and spongy compared to the soil alone. The sieve analysis produced the values shown in Table 3 and the weight of the roots and leaves combined amounted to less than 1/2 percent of the total sample weight.

(2) Final sample (40-S-ES00 to 43-S-ES15, 60-SG-ESIS)

A second set of samples was obtained one block away from the first site. The top surfaces of the samples were hard and dry when first removed. The site of the extractions had been heavily used as a bicycle track by neighborhood children for many years. The vegetation was primarily Dallisgrass.

c) Redondo Beach (50-S-RB00 to 53-S-RB16, 67-SG-RBIS)

On the evening of April 15, 1975, two samples were obtained from a 60 year old residence in Redondo Beach, located approximately 900 meters from the ocean near the top of a low hill. The soil in this area is relatively sandy but when dry, it cakes and hardens. Both samples were taken from a level area of the yard which had been undisturbed for many years. The grass — primarily Bermuda — is not extremely healthy and contains many bugs but has a good appearance and requires little maintenance. The soil sample was extracted from the edge of the lawn a short distance away in an area which had been weeded and cleared but not spaded. Weather conditions prior to this date had been periodic rain for several weeks and light rain on the day these samples were taken, making them quite moist but not completely saturated.

d) Orange County (54-S-OC-00 to 58-S-OC21, 68-SG-OC00 to 72-SG-OC24)

Two samples were obtained from the backyard of a residence in Westminster, California on April 18, 1975. Primarily, this location served as a vegetable garden and lawn. For many years prior to 1960, the entire housing tract (of which this site was a part) had been a dairy farm, resulting in rich topsoil.

The spot where the sample was taken received regular watering, a very small amount of fertilizer (there had been no planting since late summer of 1974), and direct sunlight about two-thirds of the day. The soil appeared to be heavily clayed.

The soil sample with grass roots was taken from a lawn 15 years old that was not planted but grew voluntarily. The grass type was Saint Augustine with a very thick and well-established root system. Large earthworms were common. The lawn had been cared for most of the 15 years with regular watering and mowing. It had not been fertilized.

A 6-hour rainfall had just ended 10 minutes before digging. Rain had fallen intermittently during the previous 2 to 3 weeks.

6.0 RESULTS

Measurements of the flow resistivity and porosity of 24 samples with a total of 72 variations have been made. In Appendix B, we have shown an example of the log sheet used for recording the test data. Three sets of numbers were entered: (1) percentage flow rate; (2) pressure in inches of H_20 or of Hg; and (3) data for porosity, which included equilibrium height, h, and displaced heights, h_1 and h_2. All these values plus the numbers obtained for sieve analysis were processed using the three computer programs listed in Appendix A. Results of the calculations were then tabulated and the values for flow resistivity, porosity, and estimated normal absorption coefficient at 200 Hz are shown in Table 5. The sieve analysis in terms of percentage passing has already been shown in Table 3.

It may be noted that, from the data log sheet (Appendix B), a correction has been made for the flow rate to reduce it to standard conditions. Each flow resistivity data value listed in Table 5 represents an average of at least 16 numbers covering the entire flow range.

For concrete samples, the resistivity for the two 3-to-1 mixes are so high that we tentatively assume it is infinite. The other three concrete samples permitted only a minimum amount of air flow and the absorption coefficients at 200 Hz were less than 0.05.

For asphalt samples, a great change in flow resistivity is observed between sealed and unsealed specimens. The normal absorption coefficient at 200 Hz is always less than 0.01 for a typical asphalt utilized for surface pavement.

It was observed that for sand samples, the flow resistivity is extremely sensitive to the sample loading condition and this is illustrated by the data from samples 20-CS-00 and 24-CS-00, respectively. The former was poured into the sample holder naturally, whereas the latter was accompanied by a tapping action on the outer surface of the sample holder.

The resistivity of sand, soil, and soil with grass roots samples increases as the moisture content in the specimen is increased. The flow resistivity values obtained during this project agreed very well with published data.[4]

Table 5

Data Summary

Sample Designation	Moisture Content (by weight)	Flow Resistivity (CGS Rayls/cm)	Porosity	Estimated Normal Absorption Coefficient (200 Hz)	Remarks
Concrete					
1-C-31	0	∞	<0.01	~0	S.H. #1
2-C-31	0	∞	<0.01	~0	
3-C-61	0	0.76×10^6	0.24	0.02	
4-C-61	0	0.92×10^6	0.17	<0.01	S.H. #1
5-C-91	0	0.19×10^6	0.26	0.05	
Asphalt					
6-AU-00	0	0.97×10^3	0.31	0.07	
7-AS-00	0	0.14×10^5		0.02	
8-AU-00	0	0.11×10^4	0.21	0.06	
9-AS-00	0	0.92×10^5		<0.01	
13-AU-75	0	0.75×10^5	0.08	<0.01	
11-AU-75	0	0.33×10^5	0.14	<0.01	S.H. #1
14-AS-75	0	0.10×10^6		<0.01	
12-AS-75	0	0.65×10^5	0.14	<0.01	S.H. #1
Gravel					
15-G	0	0.2×10^2	0.28	0.41	
Sand					
16-BS-00	0	0.11×10^3	0.29	0.19	
17-BS-05	5%	0.13×10^3			
18-BS-10	10%	0.14×10^3			
19-BS-15	15%	0.19×10^3			
20-CS-00	0	0.20×10^3	0.22	0.13	
21-CS-04	4.3%	0.21×10^3			
22-CS-09	8.6%	0.22×10^3			
23-CS-13	12.9%	0.35×10^3			
24-CS-00	0	0.41×10^3			

Table 5. Continued

Sample Designation	Moisture Content (by weight)	Flow Resistivity (CGS Rayls/cm)	Porosity	Estimated Normal Absorption Coefficient (200 Hz)	Remarks
Sand					
25-CS-00	0	0.45×10^2	0.30	0.30	S.H. #1
26-CS-05	4.8%	0.50×10^2			
27-CS-09	9.2%	0.55×10^2			
28-CS-10	9.8%	0.70×10^2			
29-CS-12	12.2%	0.12×10^3			
30-FS-00	0	0.47×10^2	0.24	0.27	
31-FS-03	2.7%	0.58×10^2			
32-FS-03	3.3%	0.67×10^2			
33-FS-05	5.0%	0.77×10^2			
34-FS-07	6.5%	0.11×10^3			S.H. #1
Soil					
35-S-SFV00	0	0.24×10^3	0.33	0.14	
36-S-SFV05	5.2%	0.30×10^3			
37-S-SFV10	10.3%	0.31×10^3			
38-S-SFV16	15.5%	0.33×10^3			
39-S-SFV18	18.1%	0.49×10^3			
40-S-ES00	0	0.49×10^3	0.31	0.10	
41-S-ES05	4.8%	0.51×10^3			
42-S-ES10	9.7%	0.57×10^3			
43-S-ES15	14.5%	0.81×10^3			
44-S-ES00	0		0.22		S.H. #1
45-S-ES07	6.8%	0.84×10^3			
46-S-ES08	8.1%	0.84×10^3			
47-S-ES09	8.6%	0.85×10^3			
48-S-ES10	10.4%	0.93×10^3			S.H. #1

Table 5. Continued

Sample Designation	Moisture Content (by weight)	Flow Resistivity (CGS Rayls/cm)	Porosity	Estimated Normal Absorption Coefficient (200 Hz)	Remarks
<u>Soil</u>					
50-S-RB00	0	0.20×10^3	0.33	0.16	
51-S-RB05	5.3%	0.25×10^3			
52-S-RB11	10.5%	0.26×10^3			
53-S-RB16	15.8%	0.51×10^3			
54-S-OC00	0	0.38×10^3	0.40	0.13	
55-S-OC06	5.9%	0.52×10^3			
56-S-OC12	11.7%	0.66×10^3			
57-S-OC18	17.6%	0.88×10^3			
58-S-OC21	20.5%	0.10×10^4			
<u>Soil Containing Grass Roots</u>					
59-SG-SFVIS	in situ	0.44×10^3	0.09	0.06	
60-SG-ESIS	in situ	0.35×10^3	0.27	0.11	
61-SG-ES00	0		0.37		S.H. #1
62-SG-ES18	17.6%	0.34×10^3			
63-SG-ES18	18.1%	0.38×10^3			
64-SG-ES20	20.0%	0.47×10^3			
65-SG-ES21	21.0%	0.49×10^3			S.H. #1
67-SG-RBIS	in situ	0.33×10^3	0.24	0.11	
68-SG-OC00	0	0.54×10^3	0.41	0.11	
69-SG-OC07	6.9%	0.55×10^3			
70-SG-OC14	13.8%	0.66×10^3			
71-SG-OC21	20.7%	0.90×10^3			
72-SG-OC24	24.1%	0.12×10^4			

7.0 CONCLUSIONS

Flow resistivity and porosity data have been gathered during this program. The estimated 200 Hz normal acoustic absorption coefficient reveals that the sound absorption of concrete and asphalt surfaces is negligibly small and can usually be ignored. However, for other types of surfaces – notably gravel and sand – an error of approximately 2 dB might be produced if the surface absorption is not properly accounted for. The increase in moisture content in various surfaces usually reduces the absorption coefficient.

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3. "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus, Test for," ASTM Standard 1559 (1965).

4. Dickinson, P. J. and Doak, P. E., "Measurements of the Normal Acoustic Impedance of Ground Surfaces," J. Sound and Vib., 13, 309 (1970).

APPENDIX A

COMPUTER PROGRAMS
(Super FORTRAN)

```
      C: THIS PRØGRAM CØMPUTES FLØW RESISTIVITY, PØRØSITY AND
      NØRMAL ABSØRPTIØN CØEFFICIENT FØR SAND, SØIL, SØIL
      CØNTAINING GRASS RØØTS, CØNCRETE AND UNSEALED
      AND SEALED ASPHALT
      REAL FRATE(8),DELTAP(8),FRATEC(8),FRESIS(8),THICKNESS,
      SVØL,EVØL,TVØL,H(2),H1(2),H2(2),PØRØSITY(2)
      CØMPLEX C1,C2,Z,Z1
      STRING S(50)
10    ACCEPT "TYPE ØF SAMPLE:", S
      C:FLØW RESISTIVITY IN CGS RAYLS/CM
      ACCEPT"NUMBER ØF EVENTS:",N
      ACCEPT"FLØW RATE IN CFM=",(FRATE(I),I=1,N)
      ACCEPT "PRESSURE DIFFERENCE=",(DELTAP(I),I=1,N)
      ACCEPT"SAMPLE THICKNESS=",THICKNESS
      SUMA=0.
      DØ 20 I=1,N
      FRATEC(I)=FRATE(I)*SQRT((DELTAP(I)+406.9)/406.9)
      FRESIS(I)=250.2*DELTAP(I)/(FRATEC(I)*THICKNESS)
      SUMA=SUMA+FRESIS(I)
20    CØNTINUE
      AFRESIS=SUMA/N
      C:PØRØSITY
      ACCEPT "HEIGHT ØF EQUIBRIUM WATER CØLUMN=",H
      IF (H(1) .EQ. 0) GØ TØ 39
      ACCEPT "HEIGHT ØF WATER CØLUMN 1=", H1
      ACCEPT "HEIGHT ØF WATER CØLUMN 2=", H2
      ACCEPT"SVØL+EVØL=",TVØL
      SVØL=3.1416*((4.75*2.54)**2)*THICKNESS
      EVØL=TVØL-SVØL
      SUMB=0.
      DØ 30 I=1,2
      PØRØSITY(I)= 1-(SVØL+EVØL+(59.0-H(I))*.495)/SVØL+(1033.6*
      (H1(I)-H(I))*.495)/(SVØL*(H2(I)-H1(I)))
      SUMB=SUMB+PØRØSITY(I)
30    CØNTINUE
      APØRØSITY=SUMB/2.
      C:NØRMAL ABSØRPTIØN CØEFFICIENT
      C1=CMPLX(0,1.02E06/(-400.*3.1416*.495*APØRØSITY))
      C2=CMPLX(AFRESIS/.495, (1.21E-03)*400.*3.1416/
      (.495*APØRØSITY))
      Z=((SQRT(C1*C2))*.495)/41.503
      Z1=Z*(0,1)
      C: IMAGINARY PART ØF Z1 IS THE REAL PART ØF Z
      ABSØRCØEFF=(4.*IMAG(Z1))/((IMAG(Z1)+1)**2+IMAG(Z)**2)
      C: ØUTPUT
      WRITE(1,38) APØRØSITY, ABSØRCØEFF
38    FØRMAT("APØRØSITY=",F4.2,2X,"ABSØRCØEFF=",E9.2)
39    WRITE(1,40) AFRESIS
40    FØRMAT("AFRESIS=",E9.2)
      GØ TØ 10
      STØP
      END
```

```
      C:THIS PRØGRAM GIVES SIEVE ANALYSIS
      REAL A(8), NW(8),P(8),PP(8)
      STRING S(50)
10    ACCEPT"TYPE ØF SAMPLE:",S
      ACCEPT"GRØSS WEIGHT IN GM=",A
      NW(1)=A(1)-435.3
      NW(2)=A(2)-413.0
      NW(3)=A(3)-386.5
      NW(4)=A(4)-371.6
      NW(5)=A(5)-335.6
      NW(6)=A(6)-347.6
      NW(7)=A(7)-364.1
      C:NW(8) IS THE TØTAL WEIGHT ØF THE SAMPLE
      NW(8)=A(8)-364.1
      DØ 20 I=1,7
      P(I)=NW(I)/NW(8)
20    CØNTINUE
      C:PERCENTAGE PASSING
      DØ 30 I=1,6
      PP(I)=0
      DØ 40 J=I+1,7
      PP(I)=PP(I)+P(J)
40    CØNTINUE
30    CØNTINUE
      PP(7)=0.
      DISPLAY(P(I),I=1,7)
      DISPLAY(PP(I),I=1,7)
      GØ TØ 10
      STØP
      END
```

```
      C: THIS PRØGRAM CØMPUTES NØRMAL ABSØRPTIØN CØEFFICIENT
      WHEN THE VALUES ØF FLØW RESISTIVITY AND PØRØSITY ARE GIVEN

      CØMPLEX C1,C2,Z,Z1
      STRING S(50)
10    ACCEPT "TYPE ØF SAMPLE:", S
      C:FLOW RESISTIVITY IN CGS RAYLS/CM
      ACCEPT"AFRESIS=",AFRESIS
      ACCEPT"APØRØSITY=",APØRØSITY
      C:NØRMAL ABSØRPTIØN CØEFFICIENT
      C1=CMPLX(0,1.02E06/(-400.*3.1416*.495*APØRØSITY))
      C2=CMPLX(AFRESIS/.495, (1.21E-03)*400.*3.1416/
                                        (.495*APØRØSITY))
      Z=((SQRT(C1*C2))*.495)/41.503
      Z1=Z*(0,1)
      C: IMAGINARY PART ØF Z1 IS THE REAL PART ØF Z
      ABSØRCØEFF=(4.*IMAG(Z1))/((IMAG(Z1)+1)**2+IMAG(Z)**2)
      C: ØUTPUT
      WRITE(1,38) APØRØSITY, ABSØRCØEFF
38    FØRMAT("APØRØSITY=",F4.2,2X,"ABSØRCØEFF=",E9.2)
39    WRITE(1,40) AFRESIS
40    FØRMAT("AFRESIS=",E9.2)
      GØ TØ 10
      STØP
      END
```

DATA SHEET

Date of Measurement 4/21/75

Sample Soil

Description Orange County Dry

Sample Holder Weight 518.9 gm

Sample + Holder Weight 2227.3 gm

Sample Thickness h(in.): 4.07"

Base Material Density ρ (Kg/m^3): ______

Bulk Density ρ_m (Kg/m^3): ______

Flow Rate: Low or High?

Correction Factor = $\sqrt{\frac{\Delta P \text{ (in. water)} + 406.9}{406.9}}$

SCFM = Correction Factor × CFM

Porosity = $1 - \rho_m/\rho$ (For Dry Sample Only)

$R = 250.2 \times \frac{\Delta P \text{ (in. of water)}}{U \text{ (SCFM) } h \text{ (in.)}}$ cgs rayls/cm

Flow Rate U			ΔP		Correction Factor	Flow Resistivity MKS rayls/m	Comments
%	CFM	SCFM	In H_2O	In Hg			
100			7.30 / 7.30				
90			6.55 / 6.45				
80			5.25 / 5.56				
70			4.90 / 4.80				
60			4.10 / 4.10				
50			3.30 / 3.30				
40			2.60 / 2.55				
30			1.85 / 1.90				
20			1.20 / 1.20				
10			.45 / .45				

h (cm) = 41.1/40.2

ℓ (cm)(glass portion) = 59.0

h_1 (cm) = 52.6/51.7

h_2 (cm) = 61.4/60.3

$Y = 1 - \frac{V}{V_s} - \frac{P_o \Delta V_a'}{V_s \Delta P_o} =$

V_s = Sample Volume (c.c.)

$V = V_s + \ell S$ + Volume not contained in the sample

$\Delta V_a' = (h - h_1)S$ (c.c.)

$\Delta P_o = h_2 - h_1$

$P_o = 1033.6$

Sieve Analysis (NBS Number)	Opening (Microns)	Sieve Weight (gm)	Gross Weight (gm)	Net Weight (gm)	%	% Passing
10	2000	435.3				
16	1180	417.0				
40	420	386.5				
60	250	371.6				
200	74	335.6				
230	63	347.6				
Pan		364.1				