Influence of Voids, Bitumen and Filler Contents on Permeability of Sand-Asphalt Mixtures

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•THE PURPOSE of this study was to ascertain experimentally the validity of Darcy's law for water flow through sand-asphalt mixtures as porous media and establish the relationship between the coefficient of permeability and the physical properties of the mixtures, namely, the bitumen, filler, and air voids (total mix) contents.

Mixtures were prepared with various amounts of bitumen and filler and the relation ship of these contents to that of air voids was established using the Marshall method of compaction (3 layers, 50 blows each).

The rate of water flow (distilled and de-aired) through the mixtures was measured with a specially constructed variable high-head permeameter and the coefficient of permeability of the water calculated.

The results of these tests have shown that sand-asphalt mixtures behave as porous media obeying Darcy's law; i.e., that the rate of water flow per unit time is proportional to the hydraulic gradient. It was also found from a plot of log total percent voids against log coefficient of permeability that the trend is linear and an increase in void content results in an increased coefficient of permeability, according to

$$\log_{10} K = m \log_{10} (p) + n \text{ or } K = 10^n . p^m$$

the general form being

$$K = a. (p)^m$$

in which K = Darcy's coefficient of permeability (cm/sec);
p = percent voids, total mix;
m, n = constants; and
a = the coefficient of permeability when p = 1 percent depending on the gradings of the mixtures tested.

The relationship of the bitumen and filler contents to the coefficient of permeability of these sand-asphalt mixtures was found to be directly related to its influence on the air voids (total mix) content.

Comparison of these test results with similar ones obtained by McLaughlin and Goetz (1) show obvious influence of the mix grading on the coefficient of permeability.

Properties of Mixture Ingredients

The sand-asphalt mixtures were composed of uniformly graded natural dune sand, crushed limestone dust as filler, straight-run bitumen (80/100 penetration) as binder. The natural dune sand served as skeleton of the entire asphalt mix; its apparent specific gravity is 2.66 and its dry density was found to be 1,650 kg per cu m (103 pcf) when compacted dry by the Marshall method described earlier.

The crushed limestone dust filler (by-product of local limestone quarries) has an apparent specific gravity of 2.81 and its grading is shown in Figure 1.

The straight-run bitumen with 80/100 penetration (product of the Haifa Refineries) has a specific gravity of 1.02 at 25 C, with physical properties according to ASTM specifications.

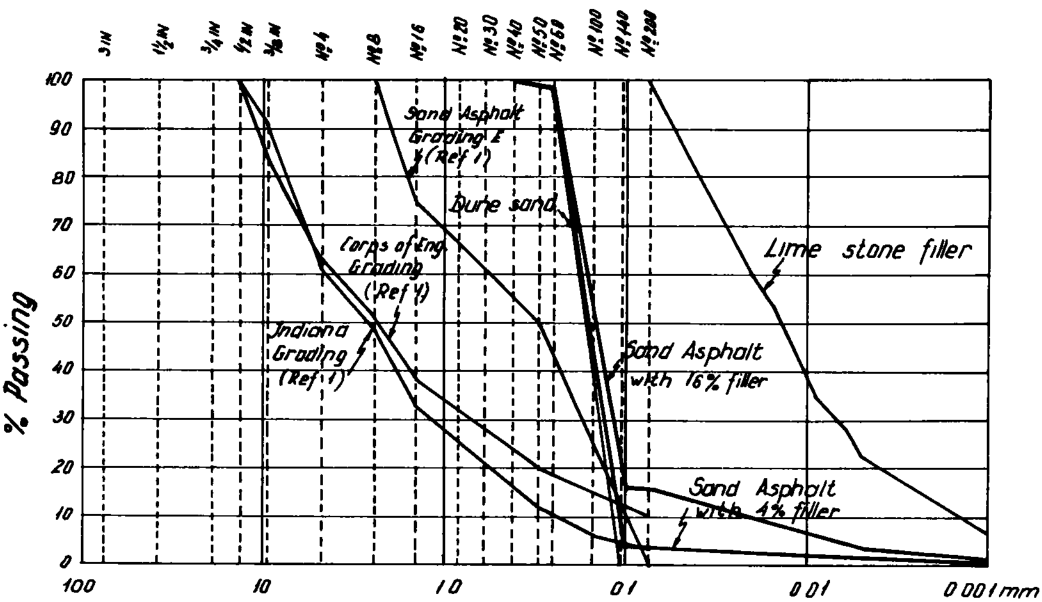

Figure 1. Grading chart.

Samples were prepared with different bitumen and filler contents (see Table 1), thus providing mixtures with different air voids contents in the total mix. The grading limits of the sand-asphalt mixtures are shown in Figure 1—the coarser limit for a minimum of 4 percent limestone dust filler and the finer limit for a maximum of 16 percent filler.

The following relationship between the voids content in the total mix with bitumen and filler content can be established on the assumption that the natural dune sand is the skeleton of the mix:

$$\frac{p}{100} = 1 - \frac{\gamma sa}{1 - \frac{wf}{100}} \frac{1}{\gamma_w} \left[\frac{Wb}{100} \frac{1}{G_b} + \frac{Wf}{100} \frac{1}{G_f} + \frac{1 - \frac{wf}{100}}{G_{sa}} \right]$$

in which

p = percent air voids, total mix;
γsa = dry density of the compacted sand (kg/m^3)
γ_w = density of water (kg/m^3);
W_f = filler content - percent (by weight) of dry mix (sand + filler);
W_b = bitumen content - percent (by weight) of dry mix;
G_b = specific gravity of bitumen;
G_f = apparent specific gravity of filler; and
G_{sa} = apparent specific gravity of sand.

This relationship for the range of Table 1 is shown graphically in Figure 2. Actual laboratory results have generally shown good agreement with these theoretical assumptions. All pertinent results are summarized in Table 1.

Measurements of Coefficient of Permeability

The Permeameter and Specimen Cell. — Figure 3 shows the variable-head device used for this study. It consisted of the specimen cell (J), two compressed air steel containers (a and b), CO_2 gas steel container (c), pressure regulator (e), two pressure gauges (g and p), Mercury manometer (m), two clocks (i and n), thermometer (f), two

TABLE 1

SUMMARY OF RESULTS OF PERMEABILITY TESTS OF SAND-ASPHALT MIXTURES

Grading	Bitumen (% wt of aggr.)	Filler (% wt. of aggr.)	Length of Spec. (cm)	Area of Specimens (sq cm)	Unit Wt. of Mix. (kg/m^3)	% Air Voids Total Mix	Coefficient of Permeability (cm/sec)
A_1	6.0	4.0	4.23	83.5	1,885	24.2	3.2×10^{-4}
A_2	6.0	4.0	4.22	83.4	1,775	27.5	2.0×10^{-4}
A_3	6.0	4.0	4.21	83.4	1,875	23.1	6.5×10^{-4}
C_1	10.0	4.0	4.18	83.5	1,910	17.5	5.5×10^{-6}
C_2	10.0	4.0	4.18	83.5	1,925	16.8	2.7×10^{-6}
C_3	10.0	4.0	4.08	83.5	1,933	16.5	1.3×10^{-4}
F_1	6.0	8.0	4.27	83.4	1,895	22.5	3.5×10^{-4}
F_2	6.0	8.0	4.33	83.4	1,892	22.7	1.4×10^{-4}
F_3	6.0	8.0	4.27	83.4	1,815	22.9	3.9×10^{-4}
G_1	8.0	8.0	4.27	84.0	1,940	15.7	1.6×10^{-4}
H_{11}	12.0	8.0	4.12	83.5	2,044	11.2	1.6×10^{-5}
H_{12}	12.0	8.0	4.12	83.5	2,044	11.2	1.1×10^{-5}
H_{13}	12.0	8.0	4.12	83.5	2,044	11.2	5.5×10^{-6}
H_{21}	12.0	8.0	4.21	83.5	2,046	11.0	3.6×10^{-5}
H_{22}	12.0	8.0	4.21	83.5	2,046	11.0	2.7×10^{-5}
H_{31}	12.0	8.0	4.16	83.5	2,052	10.5	1.8×10^{-5}
H_{32}	12.0	8.0	4.16	83.5	2,052	10.5	4.25×10^{-6}
K_1	6.0	12.0	4.42	83.4	1,937	21.0	6.1×10^{-4}
M_2	10.0	12.0	4.47	82.0	2,040	12.0	1.6×10^{-5}
R_2	10.0	16.0	4.22	83.5	2,077	10.8	8.2×10^{-7}
B_1	8.0	4.0	4.08	81.8	1,882	21.1	5.9×10^{-3}
D_1	12.0	4.0	4.13	83.7	1,935	15.0	2.65×10^{-5}
E_1	12 0	4.0	4.18	84.0	2,021	9.3	8.1×10^{-6}
G_2	8.0	8.0	4.13	82 3	1,950	18.7	2.5×10^{-4}
H	10.0	8.0	4.26	81.2	1,965	15.3	1.5×10^{-4}
I_2	12.0	8.0	4.35	82.0	2,040	10.4	1.4×10^{-5}
J_3	14.0	8.0	4.27	84.0	2,050	9.9	1.33×10^{-5}
L_2	8.0	12.0	4.41	84.0	1,965	17.5	1.0×10^{-4}
N_1	12.0	12.0	4.20	84.0	2,050	9.7	6.6×10^{-5}
O_1	14.0	12.0	4.37	84.0	2,060	7.4	3.7×10^{-8}
P_3	6.0	16.0	4.50	82.0	1,860	19.6	1.05×10^{-3}
Q_2	8.0	16.0	4.65	82.0	2,080	15.1	1.5×10^{-4}
R_1	10.0	16.0	4.27	83.5	2,064	11.3	8.0×10^{-6}
S_1	12.0	16.0	4.63	82.0	2,090	8.0	3.6×10^{-6}
T_2	14.0	16.0	4.63	82.0	2,120	5.3	1.25×10^{-9}
Y_1[a]	8.0	12.0	3.95	82.5	2,045	13.2	1.90×10^{-5}
Y_1	8.0	12.0			2,045	13.2	8.60×10^{-6}
Y_2	8.0	12.0	4.50	82.5	2,030	13.9	1.20×10^{-4}

[a] After 1 month.

graduated glass standpipes of 70-cc capacity each (o and y), 20-1 volume bottle for distilled de-aired water (g), measuring cylinder (x) for collecting the outflowing water, vacuum pump (z), air compressor; gas stopcocks for preventing leakage and water connections made of plastic tubing.

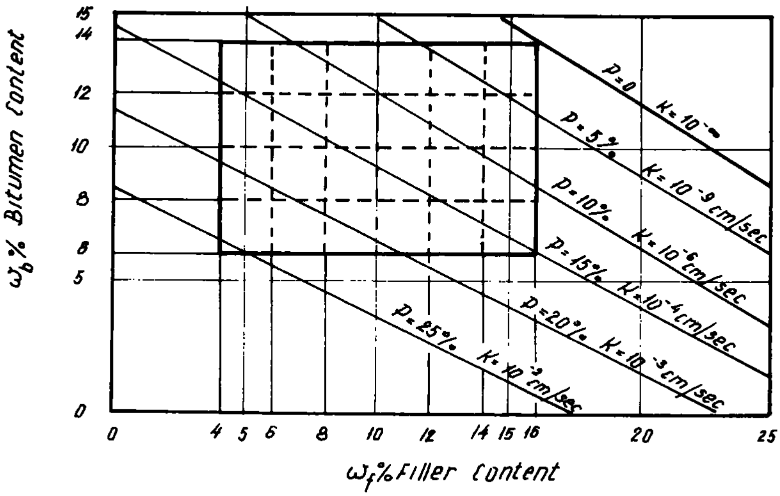

Figure 2. Percent voids total mix. Bitumen and filler contents.

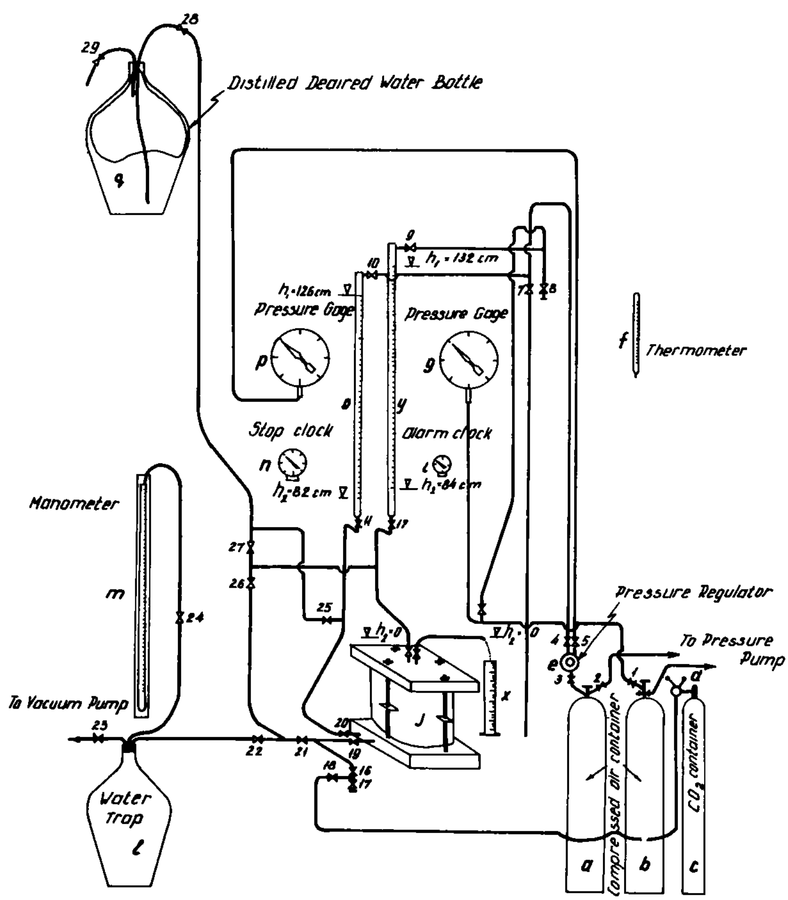

Figure 3. Setup for variable head permeability test.

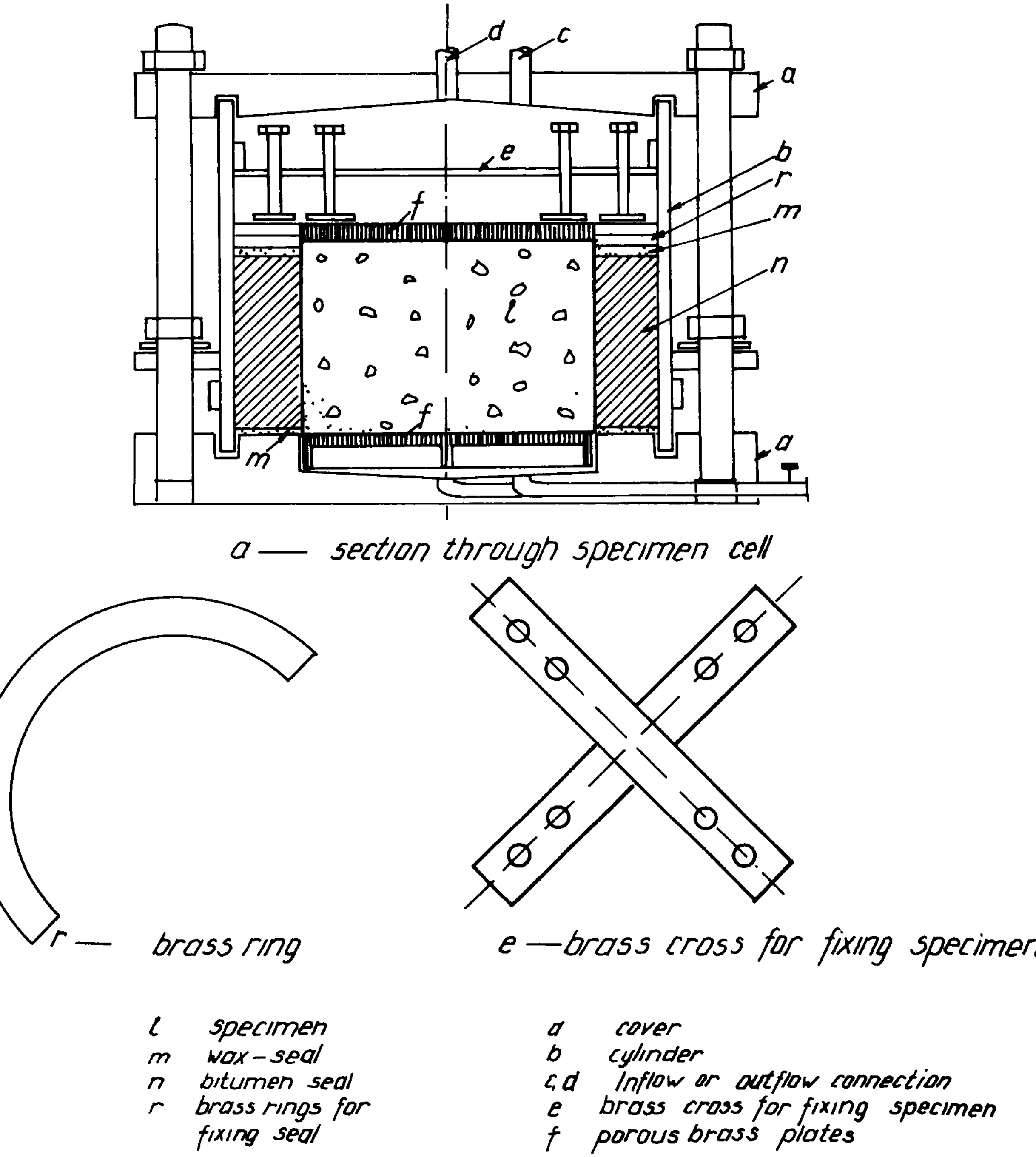

Figure 4. Details of specimen cell.

Figure 4 shows a detailed section of the specimen cell (J in Fig. 3); the cell consists of a 6-in. internal diameter steel cylinder (b) a cover with a conical undersurface (a) provided with water inlets (c and d), as well as vacuum and air exits.

The bottom is recessed to take a porous brass plate (f) on which the specimen 1 rests. The space between the 4-in. diameter specimen and the 6-in. cylinder is sealed with a mixture of wax and bitumen. A brass cross (e) over the specimen fixes it in place.

Experimental Procedure.—The following experimental procedure was used. First, vacuum was applied to the cell for about 15 min; then the specimen was saturated, allowing water to penetrate upwards through its bottom, thus driving out air bubbles; after water had started flowing into the graduated measuring cylinder (x) the rate of flow was measured and checked; the test was re-run thrice for each hydraulic gradient. The coefficient of permeability K, cm per sec at the temperature of the water was calculated according to (2).

$$K_t = 2.3 \frac{a.L}{A(t_1 - t_o)} . \log_{10} \frac{h_o}{h_1}$$

The permeability obtained for temperature T, K_T was reduced to that at 20 C, $K_{20\,C}$ by (2).

$$K_{20\,C} = K_T \frac{\mu_T}{\mu_{20\,C}}$$

When a high hydraulic gradient was required, use was made of appropriate compressed air pressure, taking care to keep air from penetrating the water passing through the specimen.

TEST RESULTS

The rate of flow over a range of various hydraulic gradients was measured in specimens having different voids contents in the total mix and a good linear relationship was found between the hydraulic gradient and rate of flow, thus confirming the validity of Darcy's law for the sand-asphalt mixtures tested. Figures 5, 6, 7, 8, and 9 show the results of the tests in specimens H_{31}, H_{32}, y_1, and y_2. Specimen y_1 (see Fig. 7 for results) was stored, after its test, for one month in a saturated condition and then re-tested at various hydraulic gradients; again, a linear relationship was found between hydraulic gradients and the rate of flow, but the coefficient of permeability was lower (see Fig. 8).

In Figure 9, test results of specimen y_2 are shown. Experiments with this specimen comprised series with the hydraulic gradient varied in small intervals; the rate of flow for each value of the gradient was found linear but its absolute values decreased through the series, reaching a constant value after 10 variations. This phenomenon was observed on most of the specimens tested.

Permeability vs Percent Voids, Total Mix

To establish the relationship of the coefficient of permeability calculated from the experiments a log log scale plot was chosen: a linear trend was found between log percent voids, total mix, and log coefficient of permeability (Fig. 10). This linear relationship can be expressed by

$$\log_{10} K = m \log_{10} p + n$$

or

$$K = 10^n . p^m$$

the general expression being

$$K = a . p^m$$

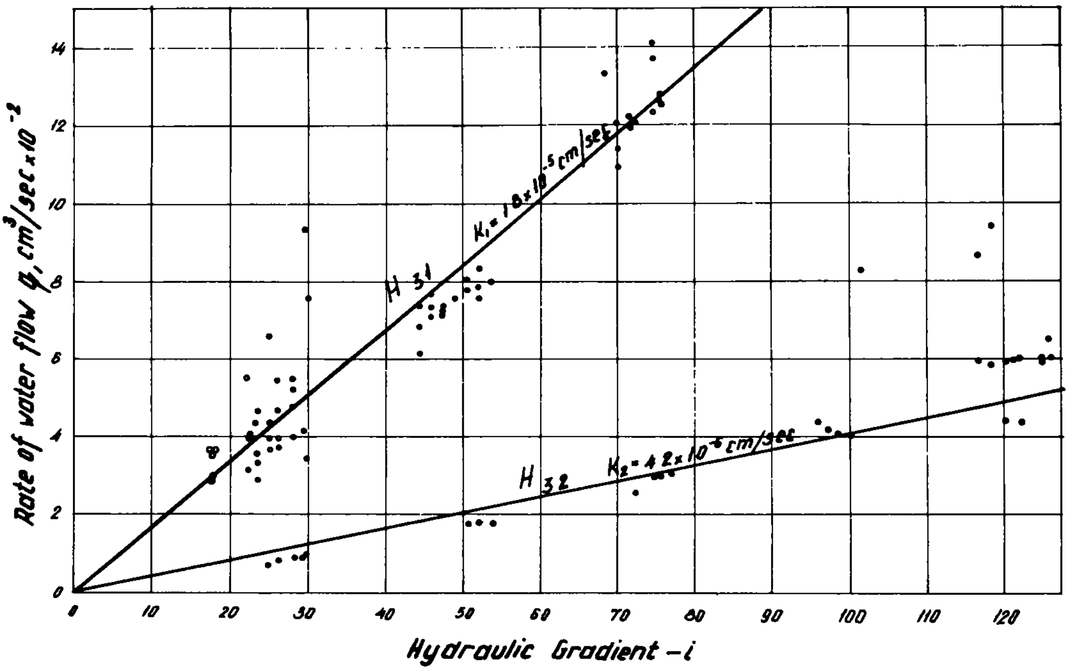

Figure 5. Rate of water flow vs hydraulic gradient (specimens—H_{31} and H_{32}).

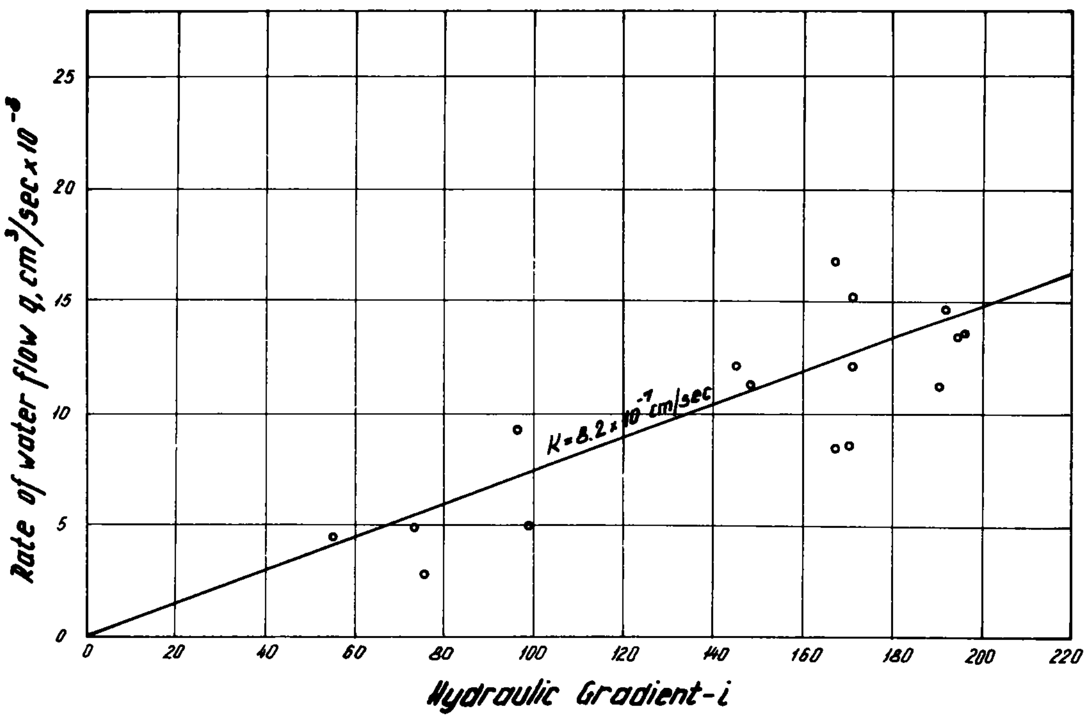

Figure 6. Rate of water flow vs hydraulic gradient (specimen R_2).

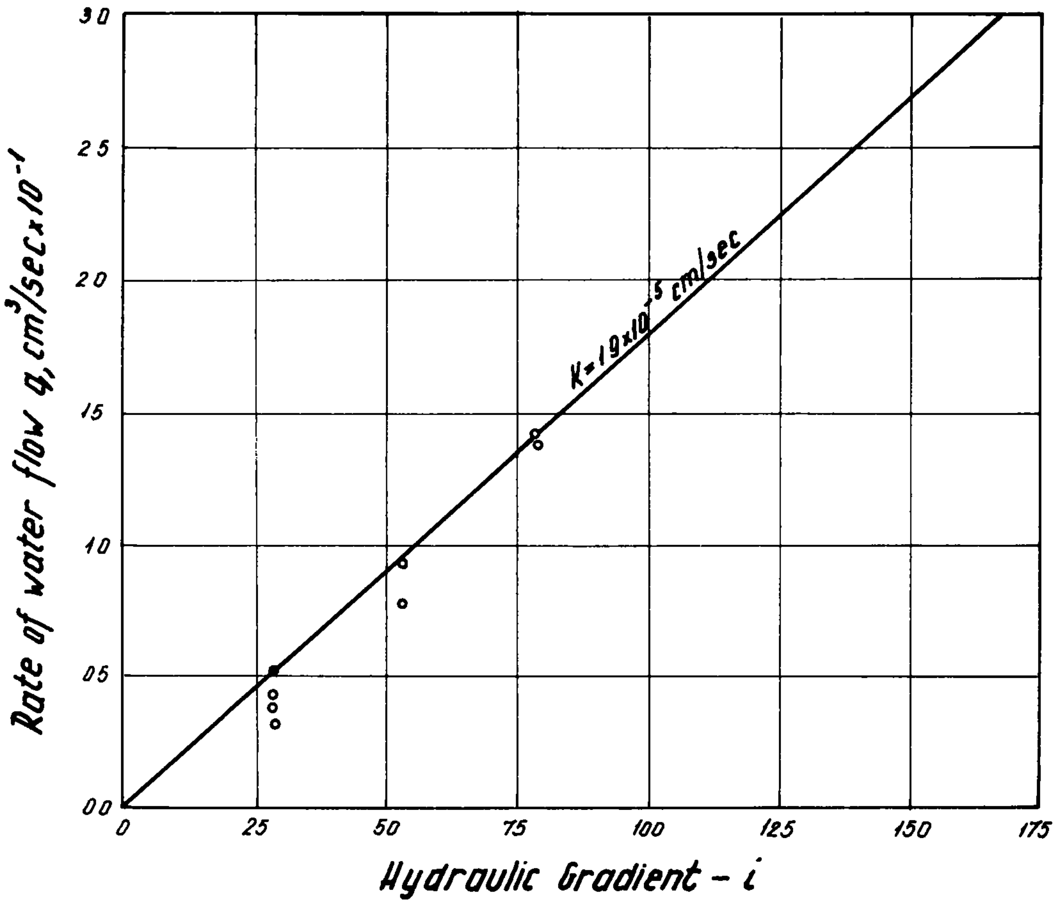

Figure 7. Rate of water flow vs hydraulic gradient (specimen Y_1).

For the range of mixtures tested (Fig. 9) this expression becomes

$$\log_{10}K = 10 \log_{10}p - 16$$

or

$$K = 10^{-16} . p^{10}$$

Values of K for a range of voids contents are given in Figure 2.

Permeability vs Bitumen and Filler Contents

The influence of the bitumen and filler contents on the permeability of the sand-asphalt mixtures is expressed indirectly by its influence on the voids content in the total mix (Fig. 2). A combination, for instance, of 6 percent bitumen and 16 percent filler gives a mixture with 15 percent air voids and the estimated coefficient of permeability based on these experiments, would be $K = 5.5 \times 10^{-5}$ cm per sec. The same value can be obtained by using 8 percent bitumen and 12 percent filler, or 10 percent bitumen and 9 percent filler; i.e., for the same voids content 2 percent of filler is equivalent to about only 1 percent of bitumen.

Permeability vs Grading

To evaluate the influence of the grading of the mixture (in addition to that of the

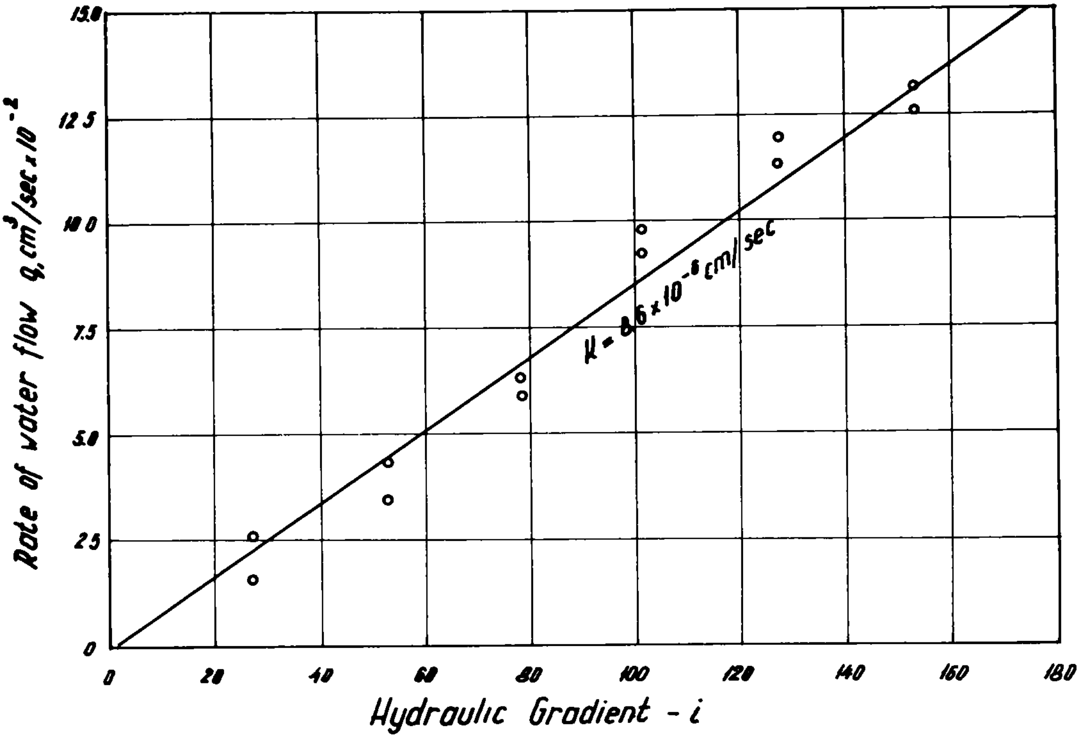

Figure 8. Rate of water flow vs hydraulic gradient (specimen Y_1 after one month).

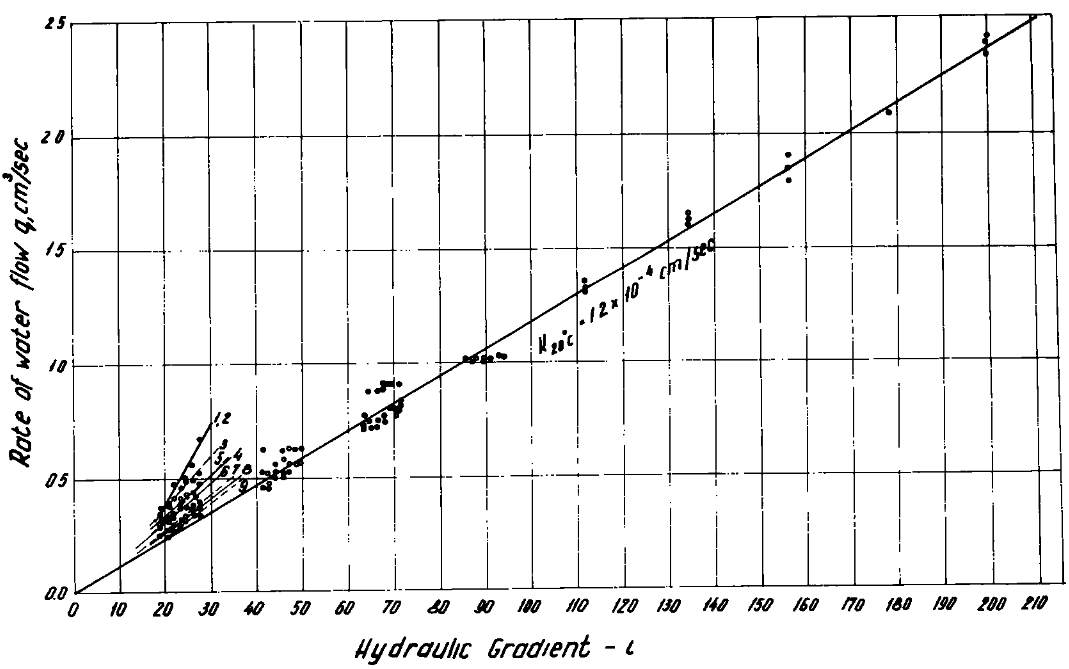

Figure 9. Rate of water flow vs hydraulic gradient (specimen Y_2).

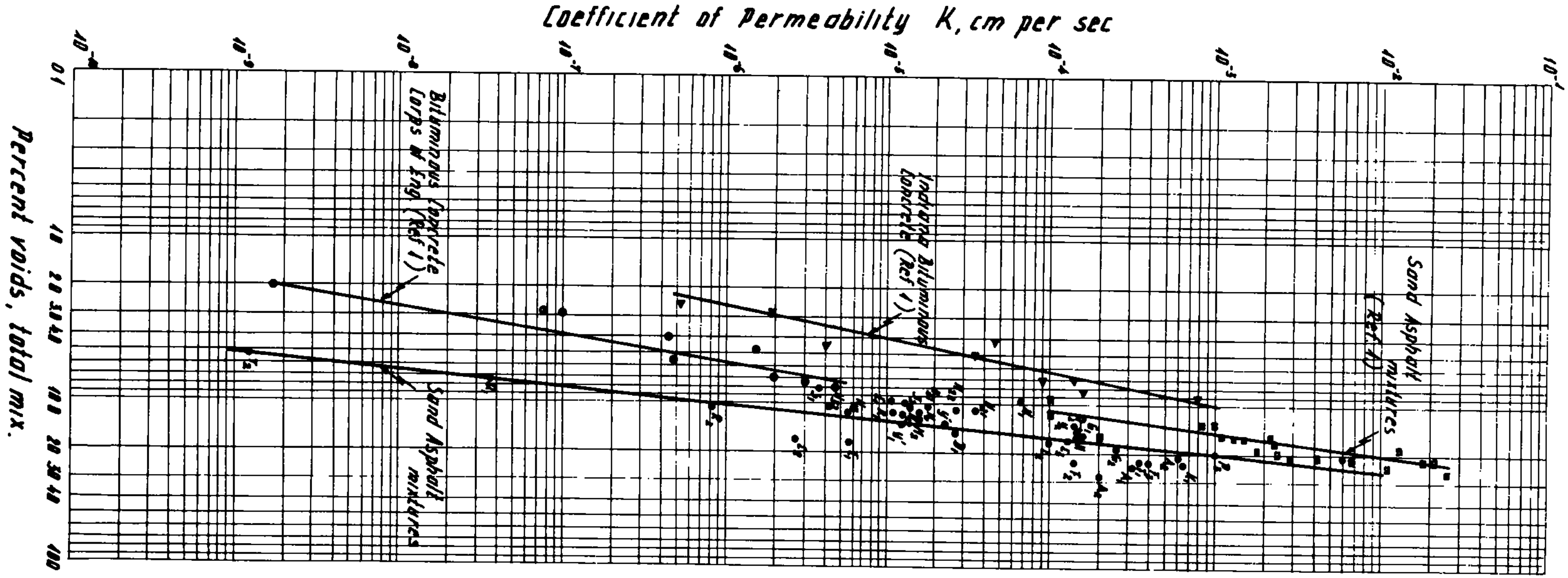

Figure 10. Coefficient of permeability K (cm/sec) vs percent voids total mix. (log-log scale).

voids content) on the value of coefficient of permeability, comparison is made with results of similar test by McLaughlin and Goetz (1).

Figure 1 gives the gradings of the bituminous concrete and sand-asphalt mixtures of (1) and Figure 10 their respective coefficients of permeability vs percent voids total mix (log log scale). The comparison clearly shows that for a given grading, the coefficient of permeability is dependent on the voids content and that varying gradings correspond to different coefficients of permeability—for the same voids content in the total mix, the finer the grading the smaller its coefficient of permeability. Figure 10 shows that for 5 percent voids the coefficient of permeability of the Indiana bituminous concrete grading is $K = 3 \times 10^{-5}$ cm per sec that of the Corps of Engineers bituminous concrete grading 5×10^{-7} cm per sec; that of the sand-asphalt mixtures, about 2×10^{-7} cm per sec; and that of the sand-asphalt mixtures of the present study (which had the finest grading), 1×10^{-9} cm per sec.

CONCLUSIONS

From the limited results of the present study and those elsewhere (1), the following conclusions can be drawn:

1. Permeability measurements showed a linear relationship between the hydraulic gradient and rate of water flow—the medium is porous and Darcy's law is valid.
2. At the beginning of the permeability tests, the rate of flow of water was high; on repeating the test, a gradual decrease was observed tending to a constant limit.
3. For a given grading, a linear trend was found on a log log scale, between the coefficient of permeability K (cm per sec) and p - voids content of the total mix, the equation of the line being K (cm per sec) = $a.p^m$ with the constants a and m depending on the parameters of the mixture including the bitumen and filler contents.
4. The bitumen and filler contents of the sand-asphalt mixtures tested affect the coefficient of permeability indirectly; namely, through their influence on the voids content. For a given mixture, an increase in bitumen content by 1 percent decreases the voids content by almost the same amount as an increase of 2 percent in dust filler, thus rendering the coefficient of permeability more sensitive to changes in the bitumen content to those in filler content.

In the light of the limited but encouraging results, further research is called for, mainly with a view to establishing a more definite correlation between the coefficient of permeability, voids content and grading parameters over a wide range of fine, medium, and coarse mix gradings each covering a wide range of percent voids.

ACKNOWLEDGMENT

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