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# *Investigation Into Using Air in the Permeability Testing of Granular Soils*

FINAL REPORT

ROBERT O. GOETZ



June 1971

Michigan Department of State Highways
Contract No. 70-0580
Lansing, Michigan

THE UNIVERSITY OF MICHIGAN 1817

Department of Civil Engineering

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THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
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Final Report

# INVESTIGATION INTO USING AIR IN THE PERMEABILITY TESTING OF GRANULAR SOILS

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ORA Project 335130



under contract with:

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## SYNOPSIS

The investigation involved the permeability testing of four soils using both water and air as the permeating fluid. The four soils selected for testing were a 20-30 standard Ottawa sand, a 2NS concrete sand, a dune sand, and a 22A gravel. The last three are representative of materials used as porous backfill by the Michigan Department of State Highways. From the results of the tests, it is concluded that, for the range of gradations tested, the coefficient of permeability determined by the air test is, for practical purposes, the same as that found using water.

## INTRODUCTION

The permeability test procedure used in the Testing Laboratory of the Michigan Department of State Highways for determining the coefficient of permeability of porous materials (bases, subbases, and backfills) was developed in the 1930's. The procedure follows, with some modification, "Method ST-22: Method of Test for the Permeability and Capillarity of Soils and Soil Mixtures" found in Ref. 1. In this method, the sample is placed in the permeameter at the required density. The sample is saturated and the rate of flow determined under a constant hydraulic gradient at least twice a day for 7 days or more to determine if a steady state has been reached. The apparatus used by the Department for performing the test does not readily permit the varying of the hydraulic gradient and the tests are usually run at only one gradient. If the coefficient of permeability is required at different densities, the whole procedure must be repeated for each density.

The above procedure is very time consuming. In addition, it is subject to the problems of using water-test procedures. The most bothersome of these is the clogging of the void spaces in the sample with air or solid contaminants. To minimize these problems, deaired distilled water is normally used, and the hydraulic gradients are kept low to prevent the movement of fines in the sample.

The purpose of the present investigation is to determine if air can be used as the permeating fluid instead of water in determining the coefficient of permeability, and, in this way, overcome the problems of the water-test procedure. The major advantages of using air are:

1. The problems of air dissolved in the water and trapped air in the sample are eliminated.

2. The density of the sample can be changed by vibrating the soil in the permeameter. The same sample can be tested over a wide range of densities without tearing down the entire apparatus.

3. Steady state flow can be reached in a short period of time.

4. The gradient through the sample can be varied readily.

5. Measurable flows for very dense soils can be attained without the use of excessive gradients.

The primary aim of this investigation is to find if the coefficient of permeability determined from water tests can be predicted from air tests with sufficient accuracy for practical purposes. With a test procedure that is less time consuming, the Department would be in a position to expand the routine permeability testing of porous materials.

## BACKGROUND INFORMATION

Taylor (Ref. 2) presents an equation for Darcy's Law for granular soils based on laminar flow through a nest of circular tubes:

$$v = \frac{q}{A} = \left(D_s^2 \frac{1}{\mu} \frac{e^3}{1+e} C\right) i_p \qquad (1)$$

where v = discharge or superficial velocity, q = rate of flow, A = cross-sectional area of flow, $D_s$ = effective or average particle diameter of the soil, $\mu$ = the viscosity of the permeating fluid, e = void ratio of the soil, C = a factor depending on the shapes and arrangement of the pores, and

$i_p$ = pressure gradient. For a given soil mass, the $D_s^2$, $e^3/(1+e)$, and C terms are constant and can be replaced by K, the permeability of the soil, as discussed in Muskat (Ref. 3). The permeability, K, then, is independent of the permeating fluid and depends only on the soil structure. Therefore, Equation (1) can be rewritten as:

$$v = \frac{q}{A} = \frac{K}{\mu} i_p \tag{2}$$

The study of seepage problems in Civil Engineering involves almost exclusively the flow of water through the soil under a hydraulic gradient. For this condition, the pressure gradient may be expressed as a hydraulic gradient and the viscosity, except for temperature effects, may also be absorbed in a new constant, k, the coefficient of permeability. Equation (2) then becomes:

$$v = \frac{q}{A} = ki \tag{3}$$

where i = hydraulic gradient = $i_p/\gamma_w$ and $\gamma_w$ = unit weight of water. The coefficient of permeability, then, is a function of both the permeating fluid and the soil structure. It will vary with temperature since the viscosity of water varies with temperature. Equating Equations (2) and (3) leads to the following relationship between K and k:

$$k = K \frac{\gamma_w}{\mu_w} \tag{4}$$

where $\mu_w$ = viscosity of water.

## SELECTION OF MATERIALS

Four granular materials were selected for testing: standard 20-30 Ottawa sand, 2NS concrete sand, a dune sand, and a 22A gravel. The gradations of the four samples were determined and are presented in Figure 1. In addition to the gradations, the specific gravities were found and are also given in Figure 1.

The standard 20-30 Ottawa sand was selected because it has been used by other investigators. The remaining three were chosen as typical of porous materials used by the Department.

## TESTING APPARATUS AND PROCEDURE

### WATER

A schematic drawing of the apparatus used in finding the coefficient of permeability using water as the fluid is shown in Figure 2(a). The essential elements are a source of distilled water, constant-head filter tank, overflow chamber, permeameter, two manometers, and the necessary piping and valves. The constant-head filter tank contains sand through which the water flows in order to remove any entrapped air that might be in the distilled water. This tank also contains an overflow weir. The head on the sample is controlled and kept constant by means of the overflow chamber. This chamber can be adjusted up and down so that the sample may be tested under different constant heads.

The permeameter is a plastic cylinder mounted between a top plate and a base plate. There is an inlet in the top plate and an outlet in the bottom plate to permit the flow of water through the sample. The plastic cylinder is fitted with two outlets for connection to the manometers for measuring the head loss through the sample. Figure 3 presents the main details of the permeameter.

The apparatus described in the previous paragraphs conforms to the standard test method for the "Permeability of Granular Soils (Constant Head)," ASSHO Designation: T215-70 and ASTM Designation: D2434-68. The test procedure used to find the permeability also followed these standard methods. Briefly, the procedure involves placing the sample in the permeameter and saturating it. The weight and height of the sample are determined so that the void ratio can be computed. Some difficulty was encountered with segregation in the 22A gravel, and with saturating the 22A gravel and the 2NS concrete sand.

After saturation, the inlet valve is opened, the overflow chamber is adjusted, and water is allowed to flow until a steady state is reached as indicated by little or no drift in the manometer levels. The head loss, $\Delta h$, as determined by the difference in level in the manometers, the quantity of flow, Q, the time, t, to collect Q, and the water temperature, T, are measured and recorded. The overflow chamber is then moved to produce a different constant head on the sample and the measurements are repeated. A typical data set is shown in Table 1. The whole procedure is repeated at a number of different void ratios for each soil.

AIR

The apparatus used to determine the coefficient of permeability using air as the fluid is shown in Figure 2(b). It consists of a constant pressure regulator, permeameter, well-type manometer, and flow meters. The constant pressure regulator is connected to the compressed air line in the laboratory. The regulator permits the reduction of the line pressure to the wanted value and then holds the pressure constant. The permeameter is the same one as used in the water tests. The well-type manometer is connected to the permeameter through three-way valves so that the pressure difference between outlets and pressure at the entering end can be measured. The quantity of air flowing through the sample under the pressure gradient is determined by means of the flow meters.

The soil is placed in the permeameter as loose as possible using the same procedure as in the water tests. The inlet pressure is adjusted by means of the regulator to give a measurable flow. After the steady state is achieved, the rate of flow, q, the pressure difference, $p_1$-$p_2$, and the inlet pressure, $p_1$, are measured and recorded, where $p_2$ is the outlet pressure. The inlet pressure is changed by means of the regulator and the measurements are repeated. A typical data set is presented in Table 2. The sample is vibrated to a lower void ratio and the measurements repeated, until the dense state is reached.

## DATA ANALYSIS

### WATER

Equation (3) is used to analyze the data from the water tests. From the recorded data the hydraulic gradient can be determined from:

$$i = \frac{\Delta h}{L}$$

where L = the distance between manometer outlets in the permeameter. The velocity can be computed from:

$$v = \frac{Q}{At}$$

where A = the cross-sectional area of the permeameter.

The next step in the analysis is to plot the velocity versus the gradient. The points should lie along a straight line which indicates laminar flow. Any significant and consistent departures from the line at higher gradients would be indicative of turbulent flow. A straight line is fitted to the points by means of linear regression techniques. The slope of this straight line is the best estimate of the coefficient of permeability for the sample.

Equation (1) indicated that the coefficient of permeability should be a function of $e^3/(1+e)$. Therefore for each soil, the coefficients of permeability at the different void ratios are plotted against $e^3/(1+e)$. Again, a straight line is fitted to the points by linear regression methods.

As discussed previously, the coefficient of permeability will vary with temperature. In the present series of tests, the average water temperature in each test was about 23°C. Therefore, the coefficients of permeability presented are for approximately 23°C.

AIR

The use of air introduces complicating factors into the analysis of the data. In contrast to water, air is compressible under the pressures used. At the entering end of the sample the air is at $p_1$. As the air passes through the sample, the pressure drops to $p_2$ resulting in an expansion of the air. Muskat discusses this situation and gives the equation,

$$K = \frac{\mu_a \bar{q} L}{A(p_1 - p_2)} \tag{5}$$

where $\bar{q}$ = rate of flow at the mean pressure $(p_1-p_2)/2$ and $\mu_a$ = viscosity of air, for computing the permeability of the soil. In addition, the flow meter measures the rate of flow, q, of the air at atmospheric pressure and not at the mean pressure in the sample. The ideal gas law can be used to determine $\bar{q}$ from q as follows:

$$\bar{q} = \frac{p_a q}{(p_1' + p_2')/2} = \frac{2p_a q}{p_1 + p_2 + 2p_a} \tag{6}$$

where $p_a$ = atmospheric pressure, $p_1' = p_1 + p_a$ and $p_2' = p_2 + p_a$. In analyzing the data for this project, $p_a$ is taken as 29.0 in. of Hg or 394.4 in. of water.

The next step in the analysis is to substitute Equation (5) into Equation (4) which gives

$$k = \frac{\mu_a \bar{q} L \gamma_w}{A(p_1 - p_2)\mu_w} \quad (7)$$

In this equation the hydraulic gradient is given by

$$i = \frac{p_1 - p_2}{L\gamma_w}$$

and the velocity is

$$v = \frac{\mu_a \bar{q}}{\mu_w A} \quad (8)$$

The average temperature of the air as measured during the tests was also 23°C, and this temperature was used in analyzing the data. The viscosity of the air was computed from the following equation given in Ref. 4:

$$\mu_a = 0.0001702\ (1 + 0.00329T + 0.0000070T^2)$$

where $\mu_a$ is in poises and T is in degrees centigrade.

After determination of the hydraulic gradient and the velocity of flow, the analysis followed the same procedure as is used for the water data. Plots of velocity versus gradient are made and straight lines put through the points by regression techniques. The coefficients of permeability are then plotted against $e^3/(1+e)$.

## DISCUSSION OF RESULTS

Figures 4 through 8 present the plots of the velocity versus the gradient for the four soils using water as the permeating fluid. The same relationships for the air tests are presented in Figures 9 through 12. On each figure, the void ratio, e, the equations of the regression lines, the correlation coefficients, r, and the computed test statistics, F, from the analysis of variance are given. The F value at the 5% significance level used in testing the hypothesis that the slope is zero is also given. As would be expected, the correlation coefficient and the F values show that the relationship between the gradient and the velocity can be considered linear.

Visual examination of the plots reveals that straight lines from the regression analysis fit the data very well with the possible exception of the 22A gravel with water as the fluid. Close study of the results shows that the slopes have a tendency to decrease as the gradient increases instead of being constant. In other words, curves might fit the points better than straight lines. While there is the possibility that there was turbulent flow, it is felt that results observed were due to movement of fines as the gradient increased.

In Figures 13 through 16, the coefficients of permeability are plotted versus $e^3/(1+e)$. For each soil, the water and air results are presented in the same figure for comparison purposes. As in Figures 4 through 12, the equations for the two regression lines and the results of the statistical analysis are given. Except for two cases, the r and F values indicate again that the relationship can be considered linear. The exceptions are for the 2NS concrete sand using water and the dune sand using air. Visual examination of these two lines reveal that they fit the points as well as or better than in some of the other cases. In these two cases the number of tests performed are too small for a significant statistical analysis. It is believed that if additional tests were run on these materials the results would be significant at the 5% level.

It should also be noted that the air test for the 22A gravel in the loosest state was not used in the regression analysis. It was not possible to conduct a test using water at this void ratio as the sample would compact during saturation. The indication is that the relationship is not linear at the higher void ratio.

When comparing the coefficients of permeability from the two methods, it should be kept in mind the practical use that is made of permeability test results. One is in the area of acceptance testing where the test is used to determine if a porous material has an acceptable coefficient of permeability. In this case, all that is needed is to know if the coefficient of permeability is greater than about $10^{-4}$ cm/sec. Whether it is 0.0053 or 0.0063 cm/sec is not significant. Another use is in the area of seepage computations. Here again, great accuracy in the permeability determination is not required in light of the other variables involved in the problem.

Study of Figures 13 through 16 show that, for all four materials, the value of the coefficient of permeability predicted from the regression line for the air data is, for practical purposes, the same as that predicted from the line for the water data. This conclusion is verified by the analyses which are presented in Tables 3 through 6. In these tables, the first column contains the void ratio and the second gives $e^3/(1+e)$. The third column is the measured coefficient of permeability, $k_m$. In the fourth column appears the coefficient of permeability, $k_w$, predicated from the water regression line while column five contains the predicted value, $k_a$, from the air regression line.

The last three columns give residuals. The residual $R_1$ is the difference between the measured value of the coefficient of permeability and the predicted value from the water line ($R_1 = k_m - k_w$). The average residual, $\bar{R}_1$, which is reported at the bottom of the column, is found by squaring each residual, summing the squares, dividing by the number of values, and taking the square root as indicated in the equation:

$$\bar{R} = \sqrt{\frac{\Sigma R^2}{n}}$$

Two comparisons are made in the final two columns. In column seven is shown the differences between the coefficients of permeability as predicted by the water and air regression lines ($R_2 = k_w - k_a$). These residual values and the average residual, $\bar{R}_2$, show how well the air predicated values duplicate the water predicted values. The last column presents the differences between the coefficients of permeability as measured in the water test and those predicted from the air regression line ($R_3 = k_m - k_a$). These residuals indicate how close the air regression line fits the water test data.

Table 3 presents the analysis of the residuals for the 20-30 standard Ottawa sand. Study of this table shows that the $R_2$ residuals are on the same order of magnitude as the $R_1$ values. The $\bar{R}_2$ value of 0.041 is only slightly greater than $\bar{R}_1 = 0.036$. These results indicate that the air regression line can predict, with the same degree of confidence, the coefficient of permeability with respect to the water regression line as the water line predicts the actual measured values. The $R_3$ residuals and the $\bar{R}_3 = 0.056$ indicate that the air regression line fits the measured water values almost as well as the water regression line. Examination of the residual analyses for the other three soils show the same behavior.

## CONCLUSIONS

The following conclusions can be reached on the basis of the study presented in this report.

1. The apparatus and procedures used in this study resulted in reliable and consistent measures of the coefficients of permeability, using water and air as the permeating fluid. Care must be exercised in placing the sample to prevent segregation, and to insure complete saturation.

2. The use of water as the fluid is more time consuming. It took 3 to 4 hours at each void ratio to determine the coefficient of permeability. A new sample has to be prepared for each void ratio.

3. The coefficient of permeability using air is much less time consuming. It took less than 2 hours to conduct the test for all void ratios. The steady state of flow is achieved faster, and the same sample is used for all void ratios.

4. The analysis of the data from the air test is more complicated. Charts or graphs could be developed to reduce the work.

5. For the range of soil gradations tested, the coefficient of permeability predicted from using air and one sample is within the accuracy needed for practical purposes.

6. Further study is needed to determine the lower limit that air can be used in permeability testing. Clays adsorb water on their surfaces which would have an effect on the permeability. Air would not duplicate this effect.

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Personnel of the Department's Testing Laboratory under the general supervision of Howard E. Barnes were most cooperative in providing the soil tested and sharing laboratory space. Special thanks are due to Louis D. Bertos of the Soils Section who aided in some of the testing.

Thanks are also due to Ronald E. Miller, graduate student at The University of Michigan, who assembled and built the apparatus used. He also made most of the tests and aided in the analysis of the data and the preparation of this report.

LIST OF REFERENCES

1. Housel, W. S., Applied Soil Mechanics, Laboratory Manual of Soil Testing Procedures, Edwards Brothers, 1957, pp. 119-130.

2. Taylor, D. W., Fundamentals of Soil Mechanics, Wiley, 1948, p. 111.

3. Muskat, M., The Flow of Homogeneous Fluids Through Porous Media, McGraw-Hill, 1937, pp. 69-79.

4. Lamb, H., Hydrodynamics, 6th Ed., Cambridge University Press, p. 576.

TABLE 1

TYPICAL PERMEABILITY TEST DATA USING WATER

Test No: 7 Date of Test: 1-7-71

Description of Soil: 20-30 Ottawa Sand

Remarks:

Diameter, $D = 11.43$ cm  Height Before, $H_1$ = 14.3 cm

Area, $A = 102.609\ cm^2$  Height After, $H_2$ = 14.3 cm

Length, $L = 11.43$ cm  Weight of Soil, W = 2501 gm

Specific Gravity, G = 2.66  Void Ratio, $e = \frac{GAH}{W} - 1$ = 0.561

| $\Delta h$ (cm) | Q ($cm^3$) | t (sec) | $i = \frac{\Delta h}{L}$ | $v = \frac{Q}{At}$ (cm/sec) | $k = \frac{v}{i}$ (cm/sec) |
|---|---|---|---|---|---|
| 0.10 | 70 | 300 | 0.00875 | 0.00227 | 0.260 |
| 0.28 | 163 | 300 | 0.0245 | 0.00530 | 0.216 |
| 0.50 | 237 | 300 | 0.0437 | 0.00770 | 0.176 |
| 1.00 | 408 | 300 | 0.0875 | 0.0132 | 0.151 |
| 1.35 | 625 | 300 | 0.118 | 0.0203 | 0.172 |
| 1.65 | 470 | 200 | 0.144 | 0.0229 | 0.159 |
| 1.95 | 570 | 200 | 0.171 | 0.0278 | 0.163 |
| 2.60 | 730 | 200 | 0.227 | 0.0356 | 0.156 |
| 3.20 | 875 | 200 | 0.280 | 0.0426 | 0.152 |
| 3.70 | 515 | 100 | 0.324 | 0.0502 | 0.155 |
| 4.20 | 590 | 100 | 0.367 | 0.0575 | 0.156 |
| 5.05 | 725 | 100 | 0.442 | 0.0706 | 0.160 |
| 5.70 | 500 | 60 | 0.499 | 0.0812 | 0.163 |
| 6.40 | 570 | 60 | 0.560 | 0.0926 | 0.165 |
| 6.80 | 620 | 60 | 0.595 | 0.101 | 0.169 |
| 7.40 | 670 | 60 | 0.647 | 0.109 | 0.168 |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

TABLE 2

TYPICAL PERMEABILITY TEST DATA USING AIR

Test No: 2 Date of Test: 4-27-71

Description of Soil: 20-30 Ottawa Sand

Remarks:

Diameter, D = 11.43 cm Height Before, $H_1$ = 16.5 cm

Area, A = 102.609 $cm^2$ Height After, $H_2$ = 16.5 cm

Length, L = 11.43 cm Weight of Soil, W = 2652 gm

Specific Gravity, G = 2.66 Void Ratio, $e = \frac{GAH}{W} - 1$ = 0.698

| $p_1 - p_2$ (in $H_2O$) | $p_1$ (in $H_2O$) | q (lpm) | $\overline{q}$ (lpm) | $i = \frac{p_1 - p_2}{L\gamma_w}$ | $v = \frac{\mu_a \overline{q}}{\mu_w A}$ (cm/sec) | k (cm/sec) |
|---|---|---|---|---|---|---|
| 0.05 | 1.40 | 2.0 | 1.99 | 0.0111 | 0.00634 | 0.571 |
| 0.13 | 4.65 | 4.0 | 3.95 | 0.0289 | 0.0126 | 0.435 |
| 0.20 | 9.80 | 6.0 | 5.86 | 0.0444 | 0.0186 | 0.419 |
| 0.25 | 13.60 | 8.0 | 7.74 | 0.0556 | 0.0246 | 0.443 |
| 0.32 | 21.70 | 10.0 | 9.48 | 0.0711 | 0.0302 | 0.424 |
| 0.30 | 9.05 | 10.0 | 9.78 | 0.0667 | 0.0311 | 0.467 |
| 0.40 | 13.10 | 13.0 | 12.59 | 0.0889 | 0.0400 | 0.451 |
| 0.45 | 14.90 | 15.0 | 14.46 | 0.100 | 0.0460 | 0.460 |
| 0.60 | 24.10 | 20.0 | 18.86 | 0.133 | 0.0600 | 0.450 |
| 0.75 | 35.70 | 25.0 | 22.94 | 0.167 | 0.0730 | 0.438 |
| | | | | | | |

$$\overline{q} = \frac{2p_a q}{p_1 + p_2 + 2p_a} = \frac{788.8q}{2p_1 - (p_1 - p_2) + 788.8}$$

$$i = \frac{p_1 - p_2}{L\gamma_w} = \frac{p_1 - p_2}{(11.43)(0.9976)} \times \frac{\text{in. } H_2O}{(\text{cm})(\text{gm/cm}^3)} \times \frac{(2.54)(0.9976\text{gm/cm}^3)}{\text{in.}}$$

$$= 0.2222(p_1 - p_2)$$

$$v = \frac{\mu_a \overline{q}}{\mu_w A} = \frac{(1.8371 \times 10^{-4})(\overline{q})}{(9.38 \times 10^{-3})(102.609)} \times \frac{(\text{poises})(\text{lpm})}{(\text{poises})(\text{cm}^2)} \times \frac{(1000 \text{ cm}^3)(\text{min})}{(\text{liter})(60 \text{ sec})}$$

$$= 0.003181\overline{q}$$

TABLE 3

ANALYSIS OF RESIDUALS FOR 20-30 STANDARD OTTAWA SAND

| Void Ratio e | $\frac{e^3}{1+e}$ | $k_m$ (cm/sec) | $k_w$ (cm/sec) | $k_a$ (cm/sec) | $R_1 = k_m - k_w$ | $R_2 = k_w - k_a$ | $R_3 = k_m - k_a$ |
|---|---|---|---|---|---|---|---|
| 0.557 | 0.111 | 0.262 | 0.226 | 0.255 | 0.036 | -0.029 | 0.007 |
| 0.561 | 0.113 | 0.165 | 0.232 | 0.259 | -0.067 | -0.027 | -0.094 |
| 0.577 | 0.122 | 0.284 | 0.259 | 0.278 | 0.025 | -0.019 | 0.006 |
| 0.646 | 0.164 | 0.388 | 0.385 | 0.366 | 0.003 | 0.019 | 0.022 |
| 0.682 | 0.189 | 0.478 | 0.461 | 0.419 | 0.017 | 0.042 | 0.059 |
| 0.688 | 0.193 | 0.459 | 0.472 | 0.427 | -0.013 | 0.045 | 0.032 |
| 0.701 | 0.203 | 0.542 | 0.502 | 0.448 | 0.040 | 0.054 | 0.094 |
| 0.715 | 0.213 | 0.493 | 0.534 | 0.470 | -0.041 | 0.064 | 0.023 |
| | | | | | $\bar{R}_1 = 0.036$ | $\bar{R}_2 = 0.041$ | $\bar{R}_3 = 0.056$ |

TABLE 4

ANALYSIS OF RESIDUALS FOR 2NS CONCRETE SAND

| Void Ratio e | $\frac{e^3}{1+e}$ | $k_m$ (cm/sec) | $k_w$ (cm/sec) | $k_a$ (cm/sec) | $R_1 = k_m - k_w$ | $R_2 = k_w - k_a$ | $R_3 = k_m - k_a$ |
|---|---|---|---|---|---|---|---|
| 0.374 | 0.0382 | 0.0174 | 0.0164 | 0.0158 | 0.0010 | 0.0006 | 0.0016 |
| 0.461 | 0.0669 | 0.0382 | 0.0378 | 0.0339 | 0.0004 | 0.0039 | 0.0043 |
| 0.501 | 0.0839 | 0.0400 | 0.0504 | 0.0446 | -0.0104 | 0.0058 | -0.0046 |
| 0.514 | 0.0897 | 0.0638 | 0.0548 | 0.0482 | 0.0090 | 0.0066 | 0.0156 |
| | | | | | $\bar{R}_1 = 0.0069$ | $\bar{R}_2 = 0.0048$ | $\bar{R}_3 = 0.0084$ |

TABLE 5

ANALYSIS OF RESIDUALS FOR DUNE SAND

| Void Ratio $e$ | $\frac{e^3}{1+e}$ | $k_m$ (cm/sec) | $k_w$ (cm/sec) | $k_a$ (cm/sec) | $R_1 = k_m - k_w$ | $R_2 = k_w - k_a$ | $R_3 = k_m - k_a$ |
|---|---|---|---|---|---|---|---|
| 0.609 | 0.140 | 0.0154 | 0.0153 | 0.0149 | 0.0001 | 0.0004 | 0.0005 |
| 0.722 | 0.218 | 0.0250 | 0.0252 | 0.0244 | -0.0002 | 0.0008 | 0.0006 |
| 0.772 | 0.260 | 0.0307 | 0.0306 | 0.0295 | 0.0001 | 0.0011 | 0.0012 |
| | | | | | $\bar{R}_1$ = 0.0002 | $\bar{R}_2$ = 0.0008 | $\bar{R}_3$ = 0.0009 |

TABLE 6

ANALYSIS OF RESIDUALS FOR 22A GRAVEL

| Void Ratio $e$ | $\frac{e^3}{1+e}$ | $k_m$ (cm/sec) | $k_w$ (cm/sec) | $k_a$ (cm/sec) | $R_1 = k_m - k_w$ | $R_2 = k_w - k_a$ | $R_3 = k_m - k_a$ |
|---|---|---|---|---|---|---|---|
| 0.245 | 0.0118 | 0.0110 | 0.0081 | 0.0103 | 0.0029 | -0.0022 | 0.0007 |
| 0.292 | 0.0194 | 0.0238 | 0.0214 | 0.0245 | 0.0024 | -0.0031 | -0.0007 |
| 0.360 | 0.0342 | 0.0358 | 0.0475 | 0.0525 | -0.0117 | -0.0050 | -0.0167 |
| 0.413 | 0.0498 | 0.0814 | 0.0749 | 0.0818 | 0.0065 | -0.0069 | -0.0004 |
| | | | | | $\bar{R}_1$ = 0.0070 | $\bar{R}_2$ = 0.0047 | $\bar{R}_3$ = 0.0084 |

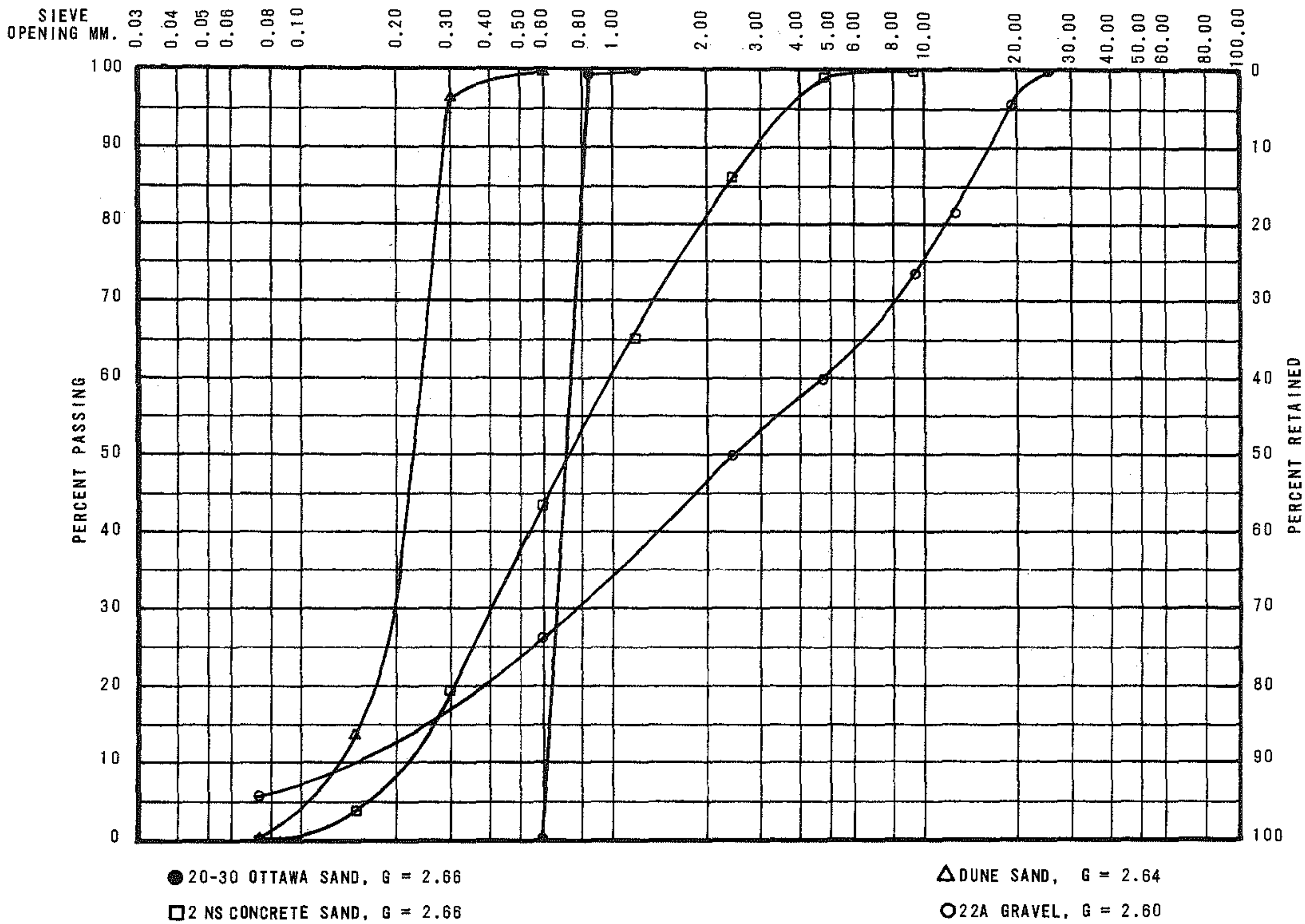



FIGURE 1. GRADATION CURVES FOR SAMPLES TESTED

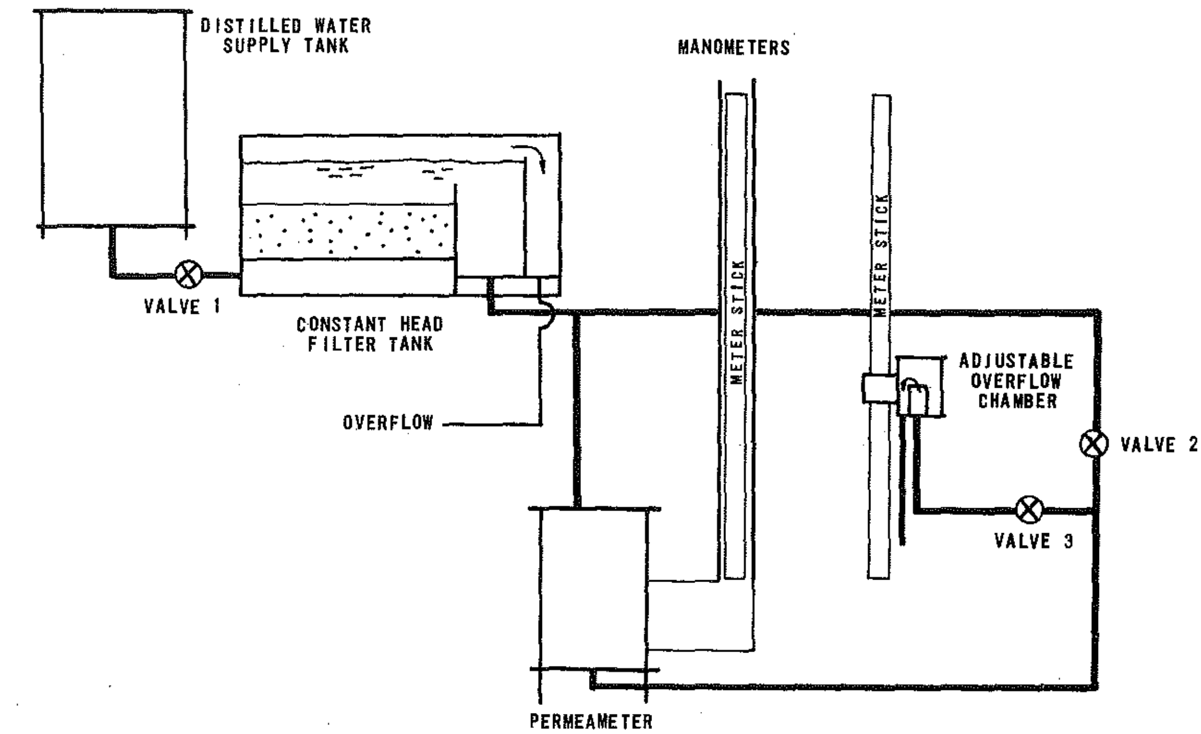



FIGURE 2A
SCHEMATIC DIAGRAM OF PERMEABILITY APPARATUS FOR WATER

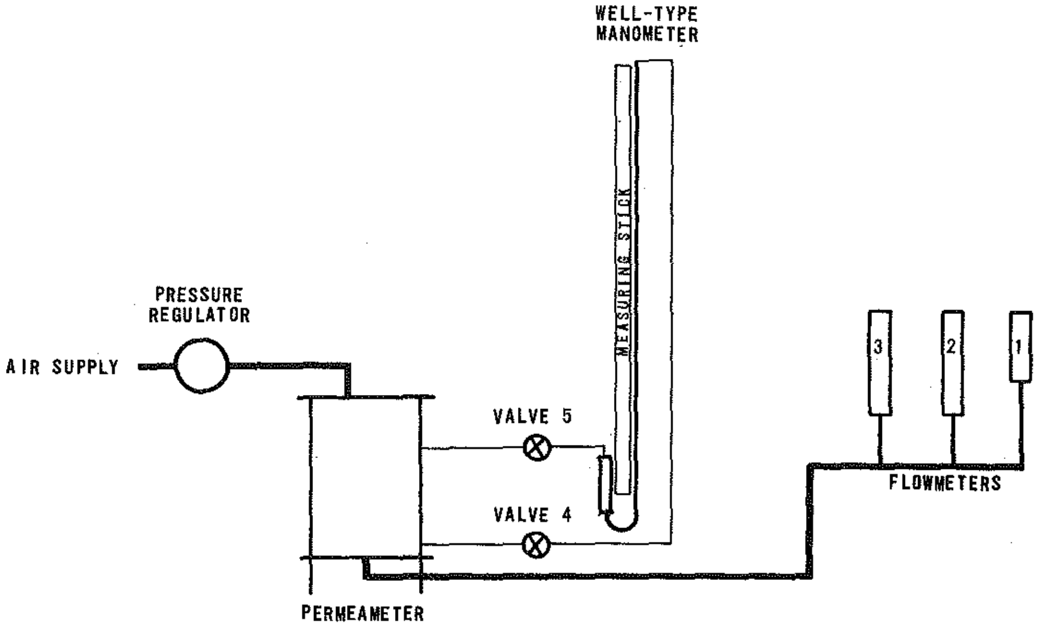



FIGURE 2B
SCHEMATIC DIAGRAM OF PERMEABILITY APPARATUS FOR AIR

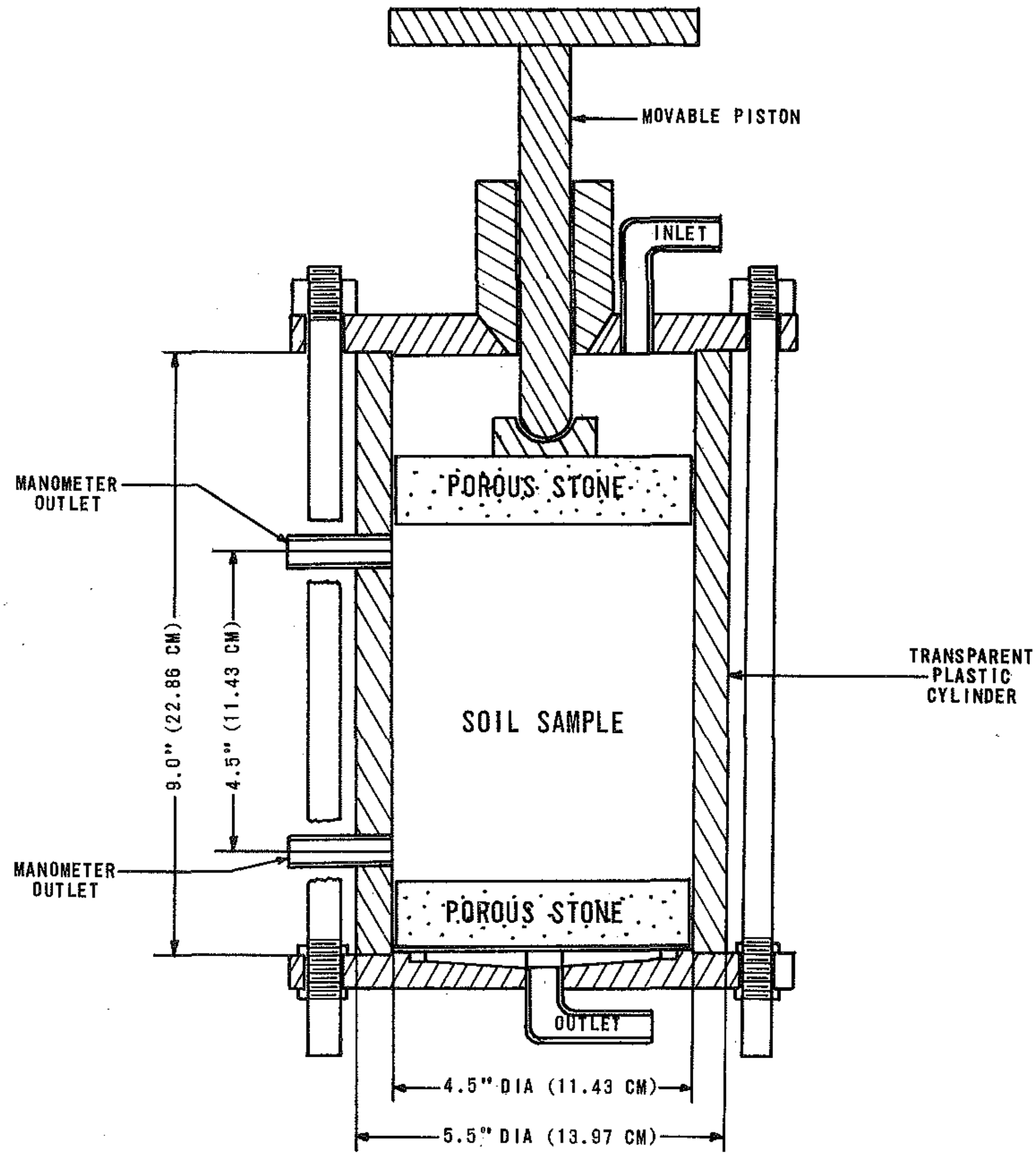
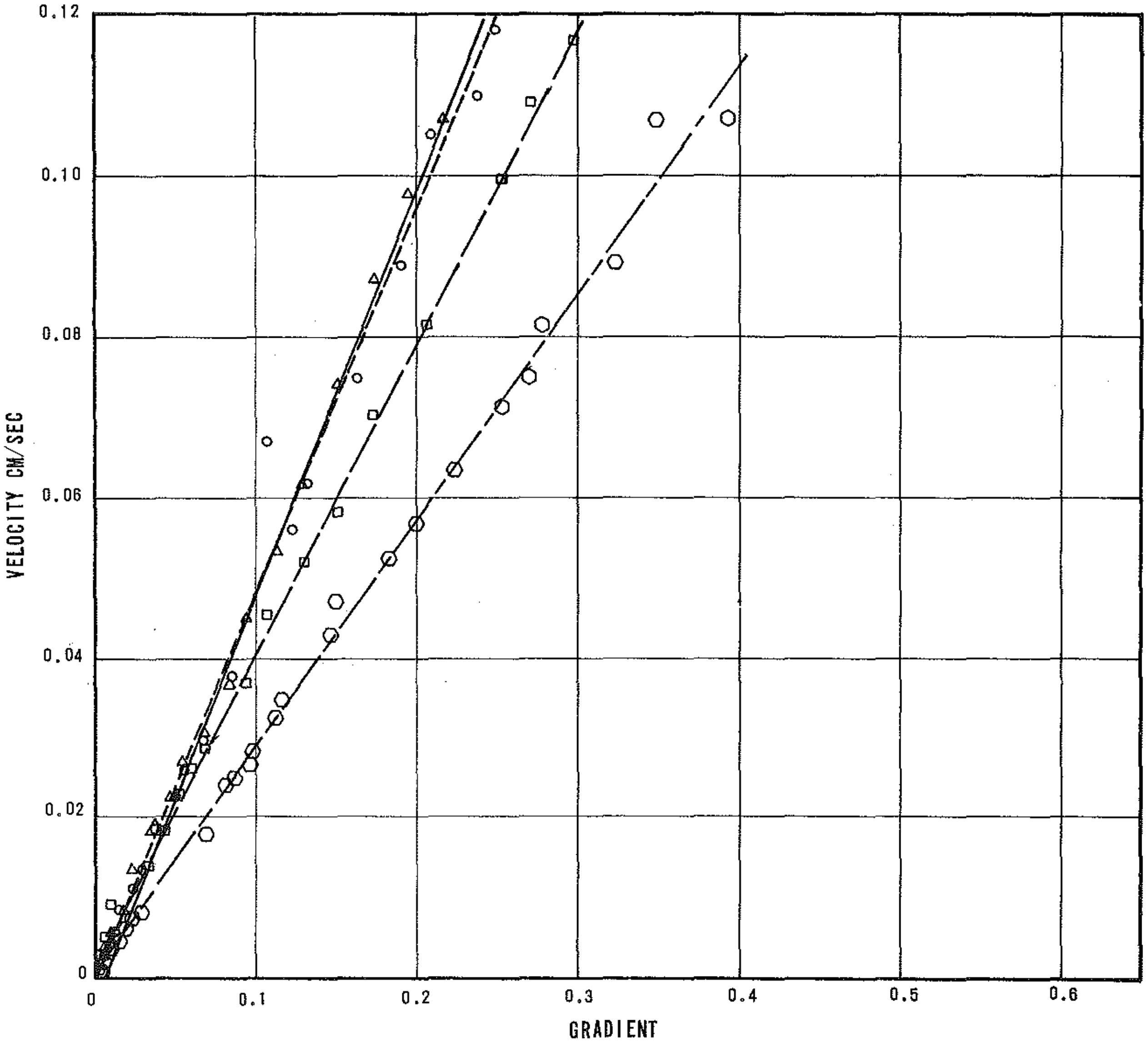



FIGURE 3
DETAILS OF PERMEAMETER



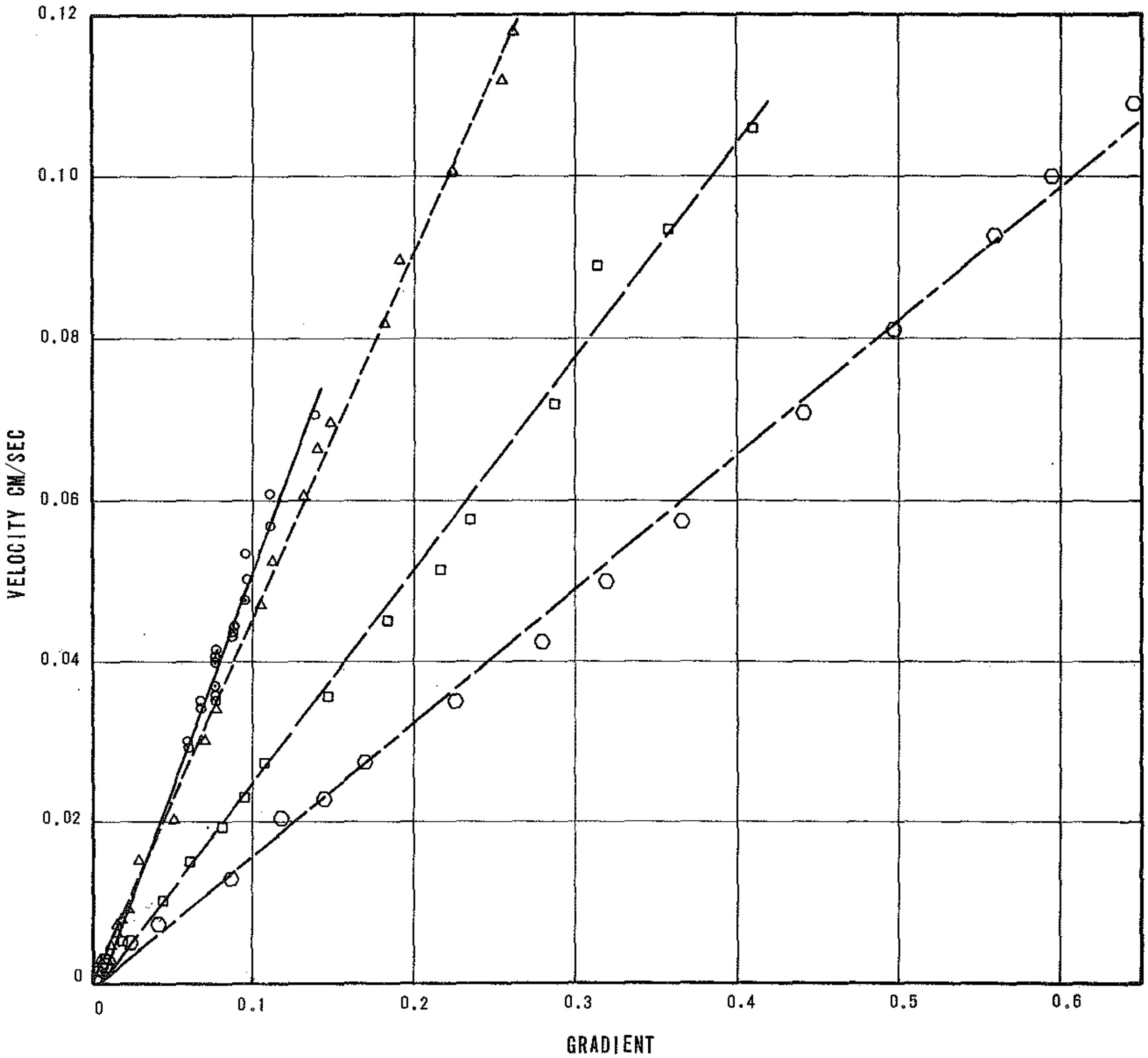

e = 0.682 (○——○) VEL = -0.0008 + 0.4778 GRAD
$r = 0.994$, $F = 1600.6$, $F_{.95(1,18)} = 4.41$

e = 0.715 (△- - -△) VEL = -0.0012 + 0.4933 GRAD
$r = 0.999$, $F = 9055.3$, $F_{.95(1,15)} = 4.54$

e = 0.646 (□—— ——□) VEL = 0.0015 + 0.3879 GRAD
$r = 0.999$, $F = 11617.2$, $F_{.95(1,15)} = 4.54$

e = 0.577 (⬡— — —⬡) VEL = 0.0001 + 0.2842 GRAD
$r = 0.997$, $F = 4907.8$, $F_{.95(1,23)} = 4.28$

FIGURE 4
VELOCITY vs GRADIENT FOR 20-30 OTTAWA SAND USING WATER




e = 0.701 (○———○) VEL = -0.0034 + 0.5417 GRAD
$r = 0.977,\ F = 486.2,\ F_{.95(1,23)} = 4.28$

e = 0.688 (△- - - -△) VEL = -0.0010 + 0.4588 GRAD
$r = 0.999,\ F = 11754.6,\ F_{.95(1,21)} = 4.32$

e = 0.557 (□—— ——□) VEL = -0.0014 + 0.2622 GRAD
$r = 0.997,\ F = 2290.7,\ F_{.95(1,14)} = 4.60$

e = 0.561 (⬡— — —⬡) VEL = -0.0007 + 0.1655 GRAD
$r = 0.998,\ F = 4962.4,\ F_{.95(1,14)} = 4.60$

FIGURE 5
VELOCITY vs GRADIENT FOR 20-30 OTTAWA SAND USING WATER

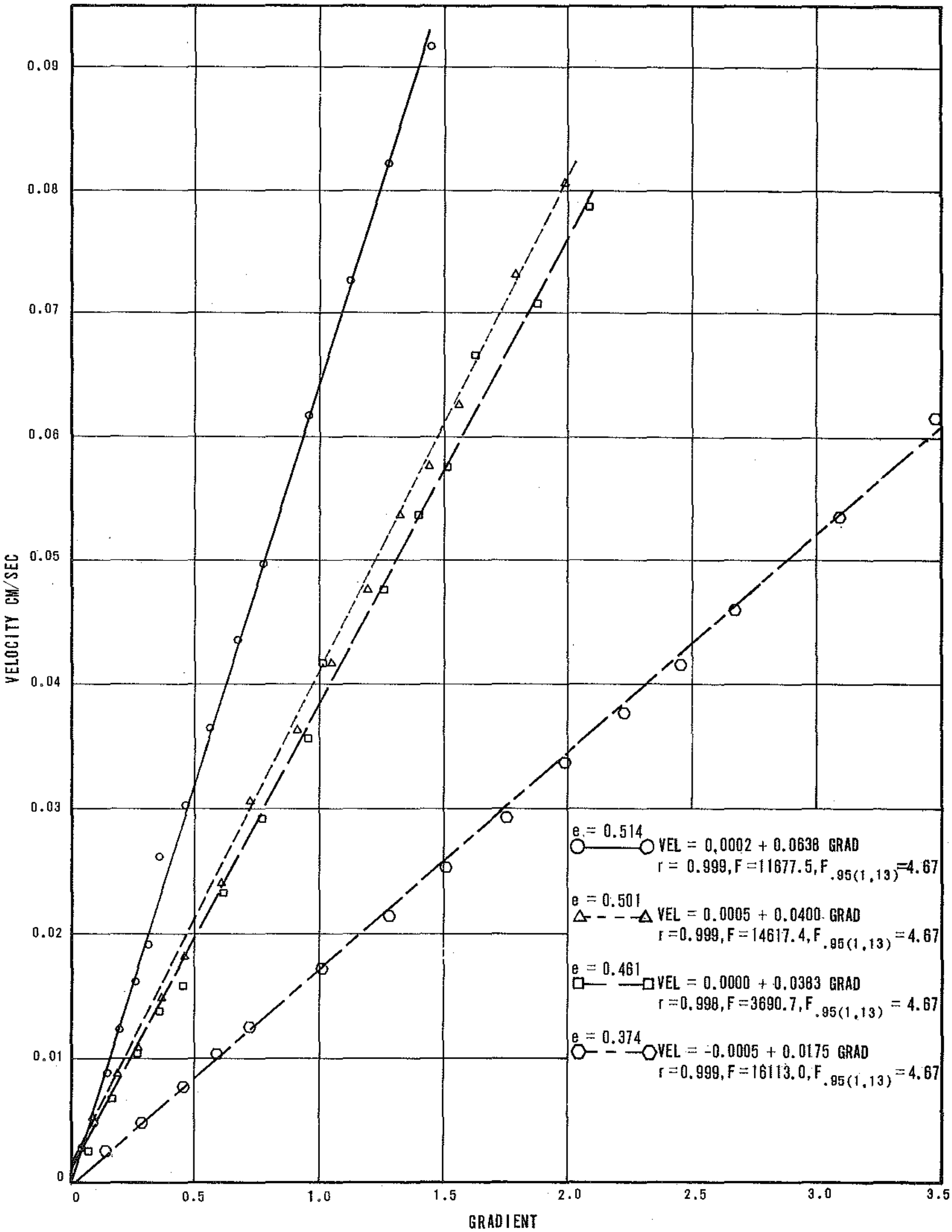
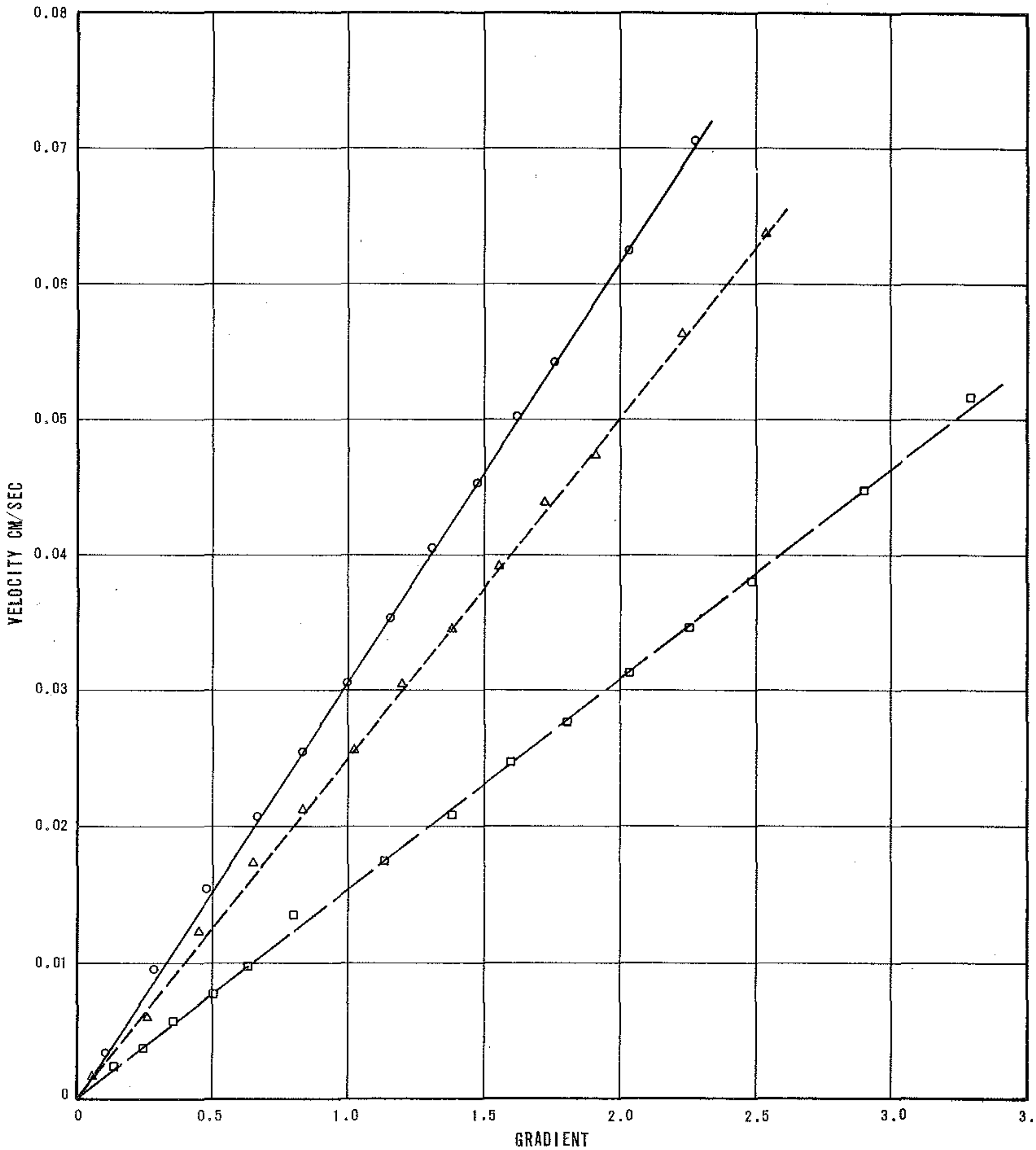



FIGURE 6

VELOCITY vs GRADIENT FOR 2NS CONCRETE SAND USING WATER




e = 0.772 ○———○ VEL = 0.0000 + 0.0307 GRAD, r = 0.999, F = 34380.8, $F_{.95(1,11)} = 4.84$

e = 0.722 △- - - -△ VEL = 0.0001 + 0.0250 GRAD, r = 0.999, F = 25550.7, $F_{.95(1,11)} = 4.84$

e = 0.609 □—— ——□ VEL = 0.0000 + 0.0154 GRAD, r = 0.999, F = 13057.2, $F_{.95(1,13)} = 4.67$

FIGURE 7
VELOCITY vs GRADIENT FOR DUNE SAND USING WATER

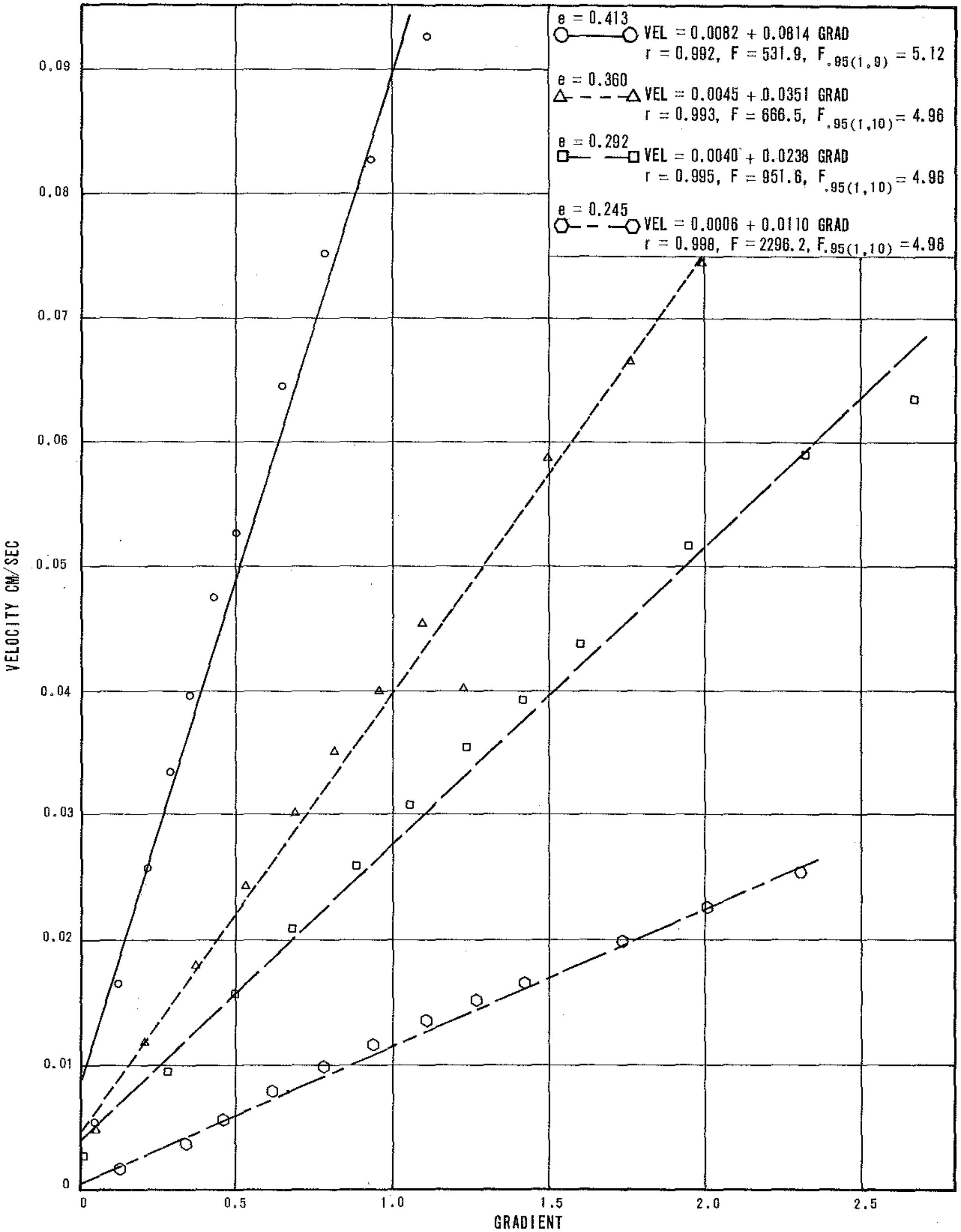
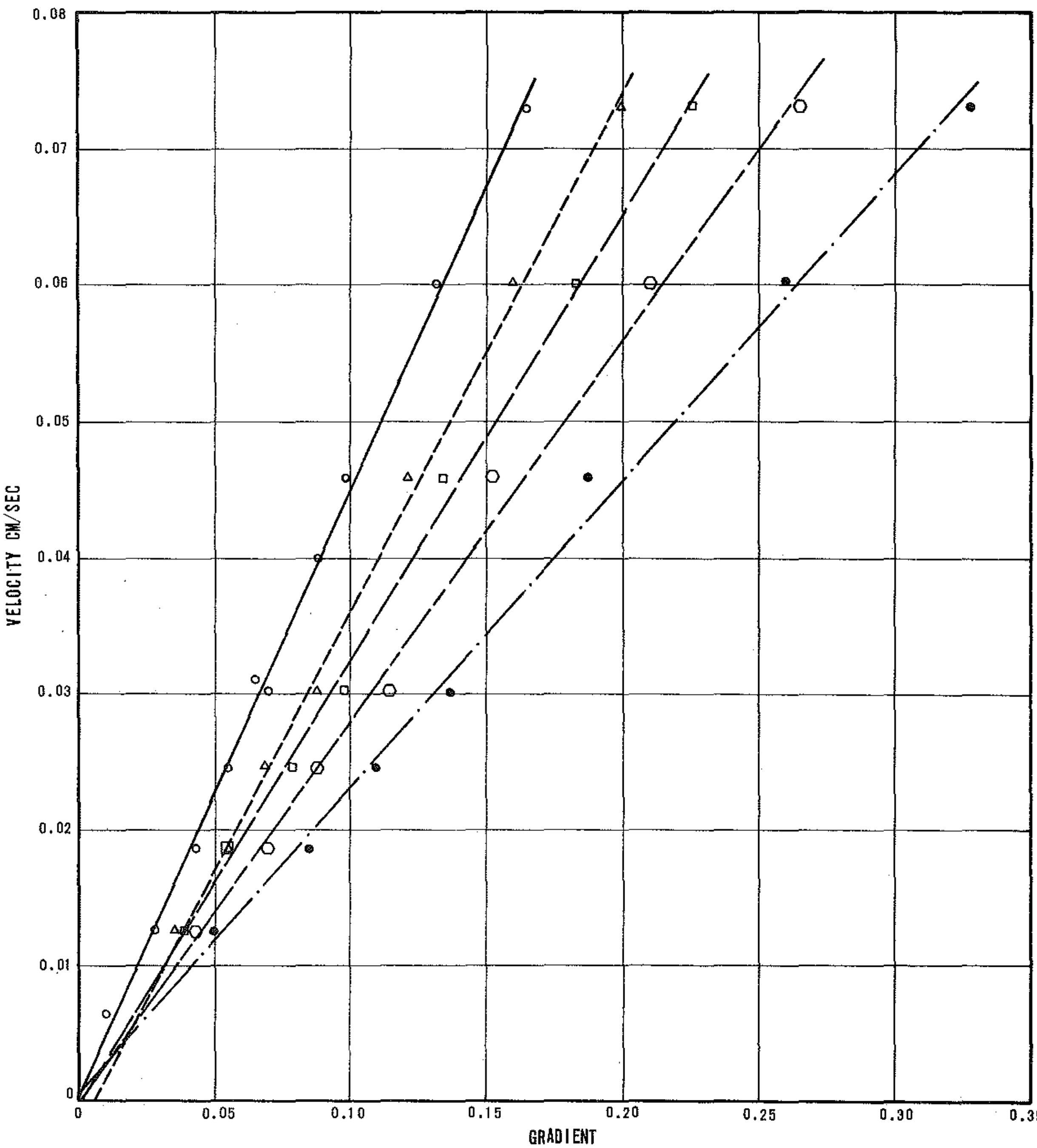



FIGURE 8
VELOCITY vs GRADIENT FOR 22A GRAVEL USING WATER




e = 0.698 ○——○ VEL = 0.0004 + 0.4414 GRAD, r = 0.998, F = 2729.4, $F_{.95(1,8)}$ = 5.32

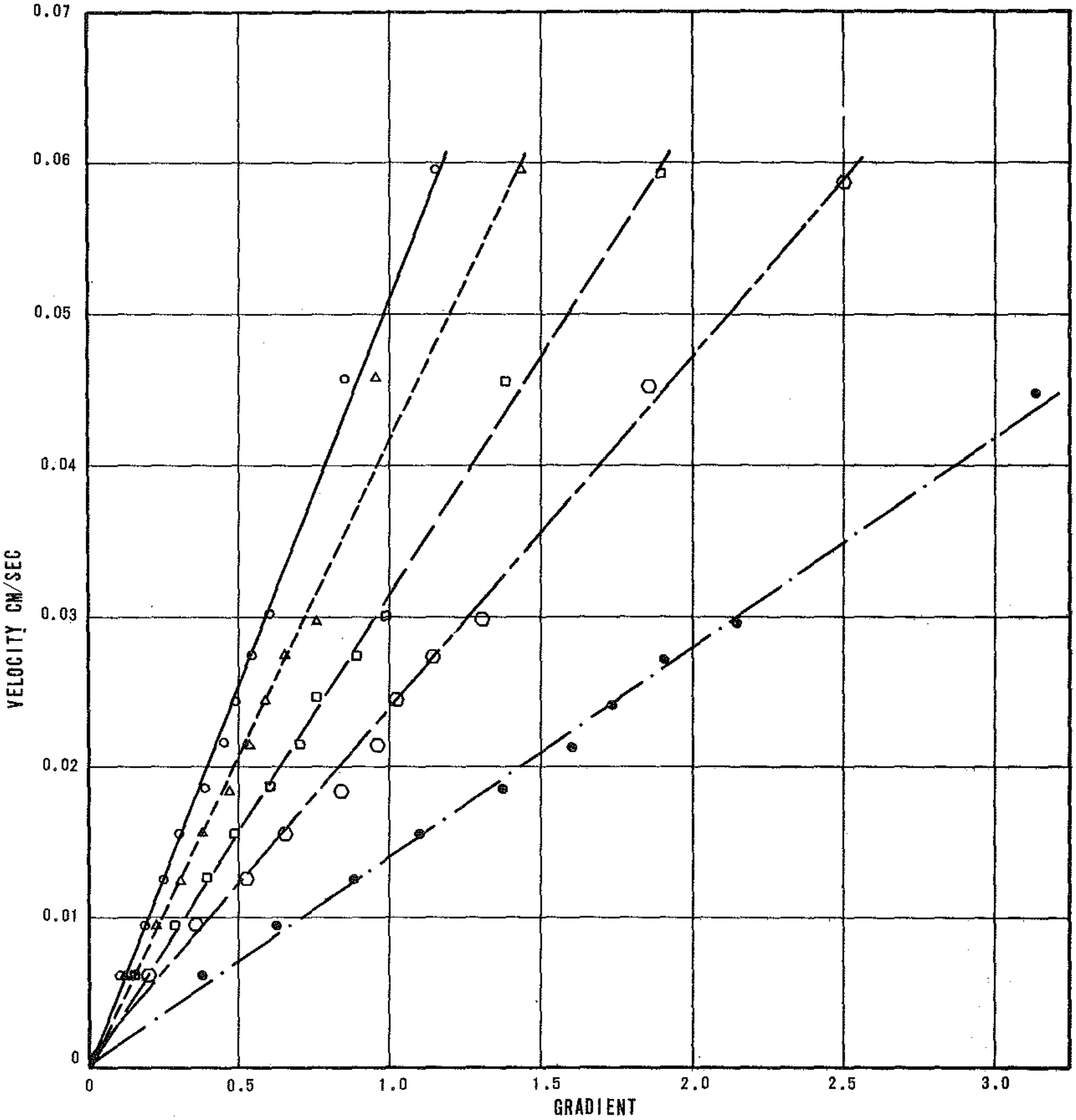
e = 0.657 △- - - -△ VEL = -0.0020 + 0.3806 GRAD, r = 0.998, F = 1969.3, $F_{.95(1,5)}$ = 6.61

e = 0.616 □—— ——□ VEL = -0.0006 + 0.3273 GRAD, r = 0.998, F = 1408.9, $F_{.95(1,5)}$ = 6.61

e = 0.575 ⬡— — —⬡ VEL = -0.0004 + 0.2813 GRAD, r = 0.997, F = 822.2, $F_{.95(1,5)}$ = 6.61

e = 0.533 ●— · ——● VEL = 0.0003 + 0.2248 GRAD, r = 0.997, F = 907.8, $F_{.95(1,5)}$ = 6.61

FIGURE 9
VELOCITY vs GRADIENT FOR 20-30 OTTAWA SAND USING AIR




e = 0.523 (○——○) VEL = -0.0008 + 0.0519 GRAD, r = 0.997, F = 1945.2, $F_{.95(1,9)}$ = 5.12

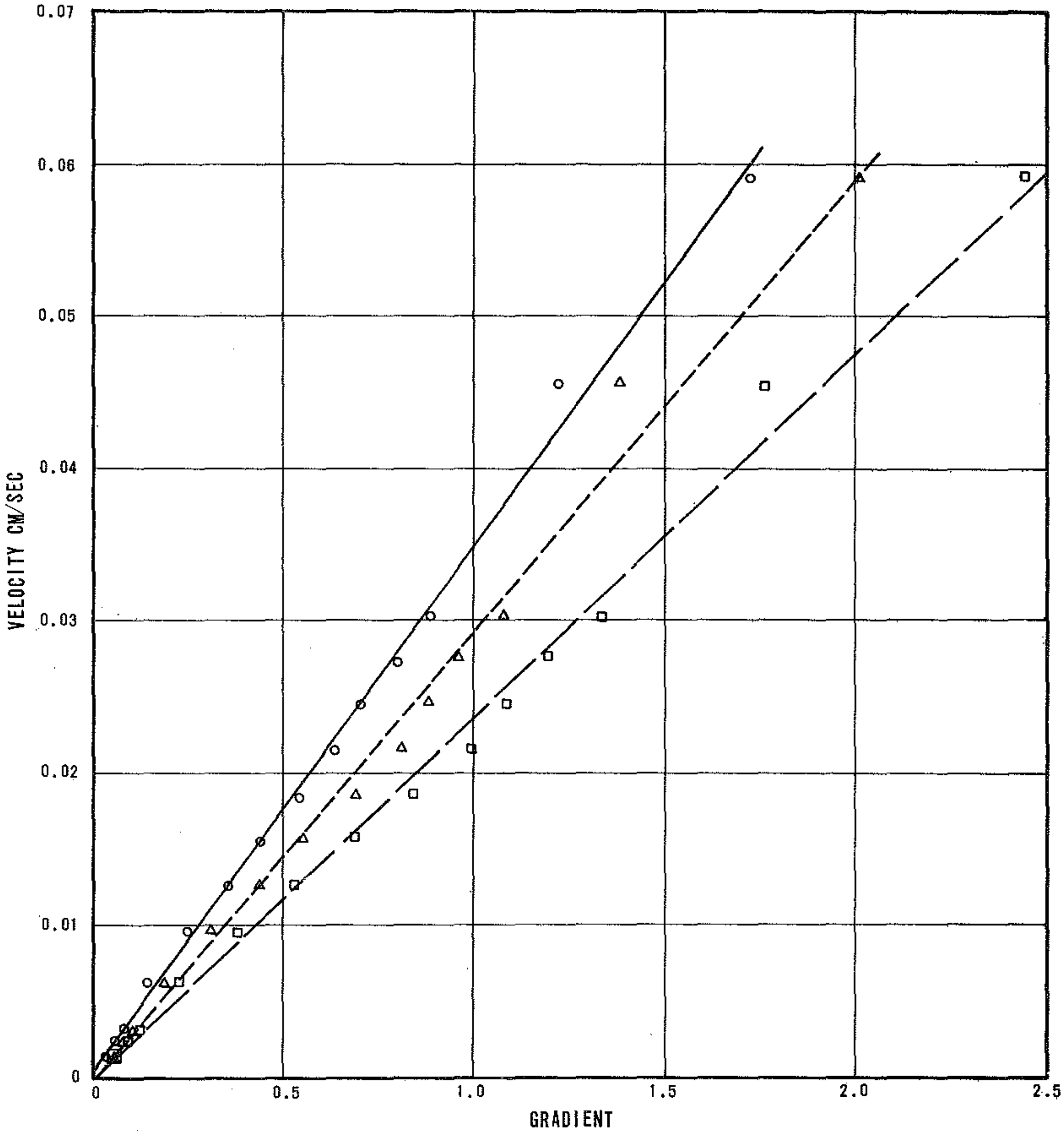
e = 0.494 (△- - -△) VEL = -0.0005 + 0.0425 GRAD, r = 0.992, F = 583.3, $F_{.95(1,9)}$ = 5.12

e = 0.455 (□— —□) VEL = -0.0000 + 0.0314 GRAD, r = 0.998, F = 2362.4, $F_{.95(1,9)}$ = 5.12

e = 0.417 (⬡- - —⬡) VEL = 0.0001 + 0.0234 GRAD, r = 0.998, F = 3537.3, $F_{.95(1,9)}$ = 5.12

e = 0.358 (●- · —●) VEL = -0.0000 + 0.0140 GRAD, r = 0.998, F = 2112.4, $F_{.95(1,8)}$ = 5.32

FIGURE 10
VELOCITY vs GRADIENT FOR 2NS CONCRETE SAND USING AIR

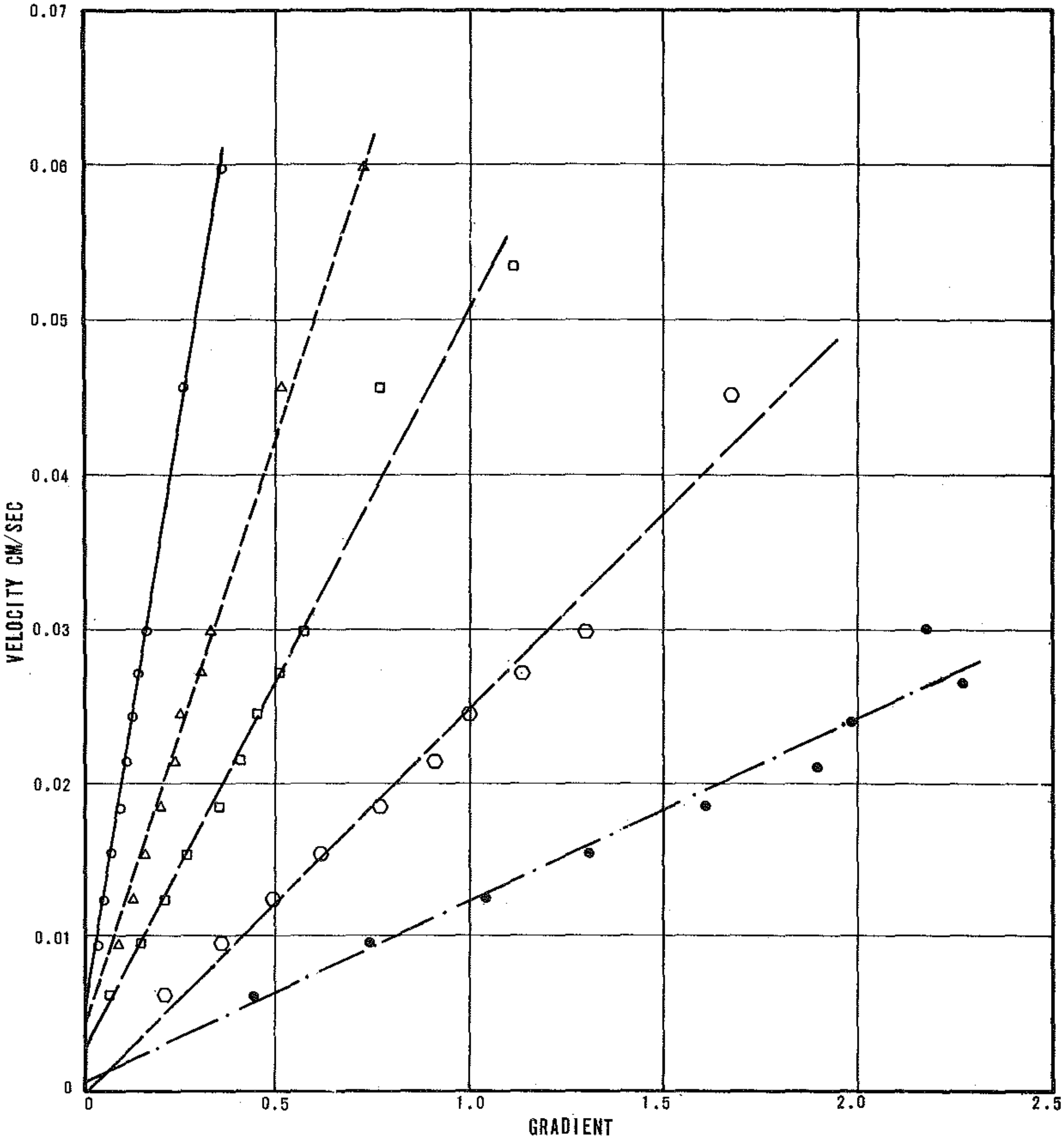



e = 0.822 ○———○ VEL = 0.0001 + 0.0346 GRAD, r = 0.998, F = 2926.0, $F_{.95(1,12)}$ = 4.75

e = 0.767 △- - - -△ VEL = -0.0005 + 0.0297 GRAD, r = 0.994, F = 1042.1, $F_{.95(1,12)}$ = 4.75

e = 0.724 □—— ——□ VEL = -0.0005 + 0.0241 GRAD, r = 0.996, F = 1562.5, $F_{.95(1,12)}$ = 4.75

FIGURE 11
VELOCITY vs GRADIENT FOR DUNE SAND USING AIR




e = 0.462 (○———○) VEL = 0.0042 + 0.1545 GRAD, r = 0.999, F = 3887.5, $F_{.95(1,8)}$ = 5.32

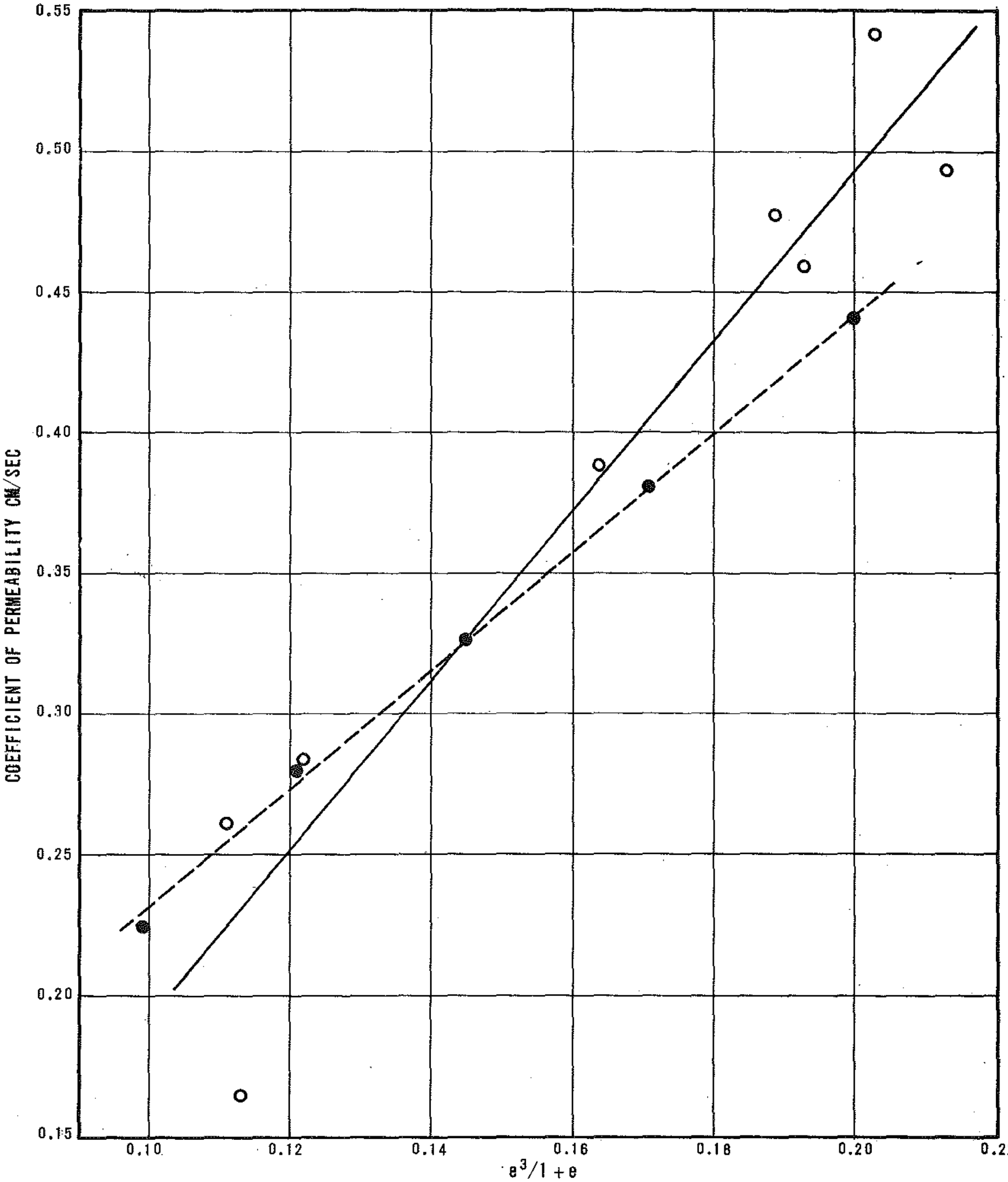
e = 0.407 (△- - -△) VEL = 0.0032 + 0.0790 GRAD, r = 0.997, F = 1604.5, $F_{.95(1,8)}$ = 5.32

e = 0.361 (□— —□) VEL = 0.0026 + 0.0482 GRAD, r = 0.990, F = 441.2, $F_{.95(1,9)}$ = 5.12

e = 0.300 (⬡— - —⬡) VEL = -0.0003 + 0.0252 GRAD, r = 0.990, F = 386.0, $F_{.95(1,8)}$ = 5.32

e = 0.245 (●— · —●) VEL = 0.0000 + 0.0121 GRAD, r = 0.978, F = 156.7, $F_{.95(1,7)}$ = 5.59

FIGURE 12
VELOCITY vs GRADIENT FOR 22A GRAVEL USING AIR

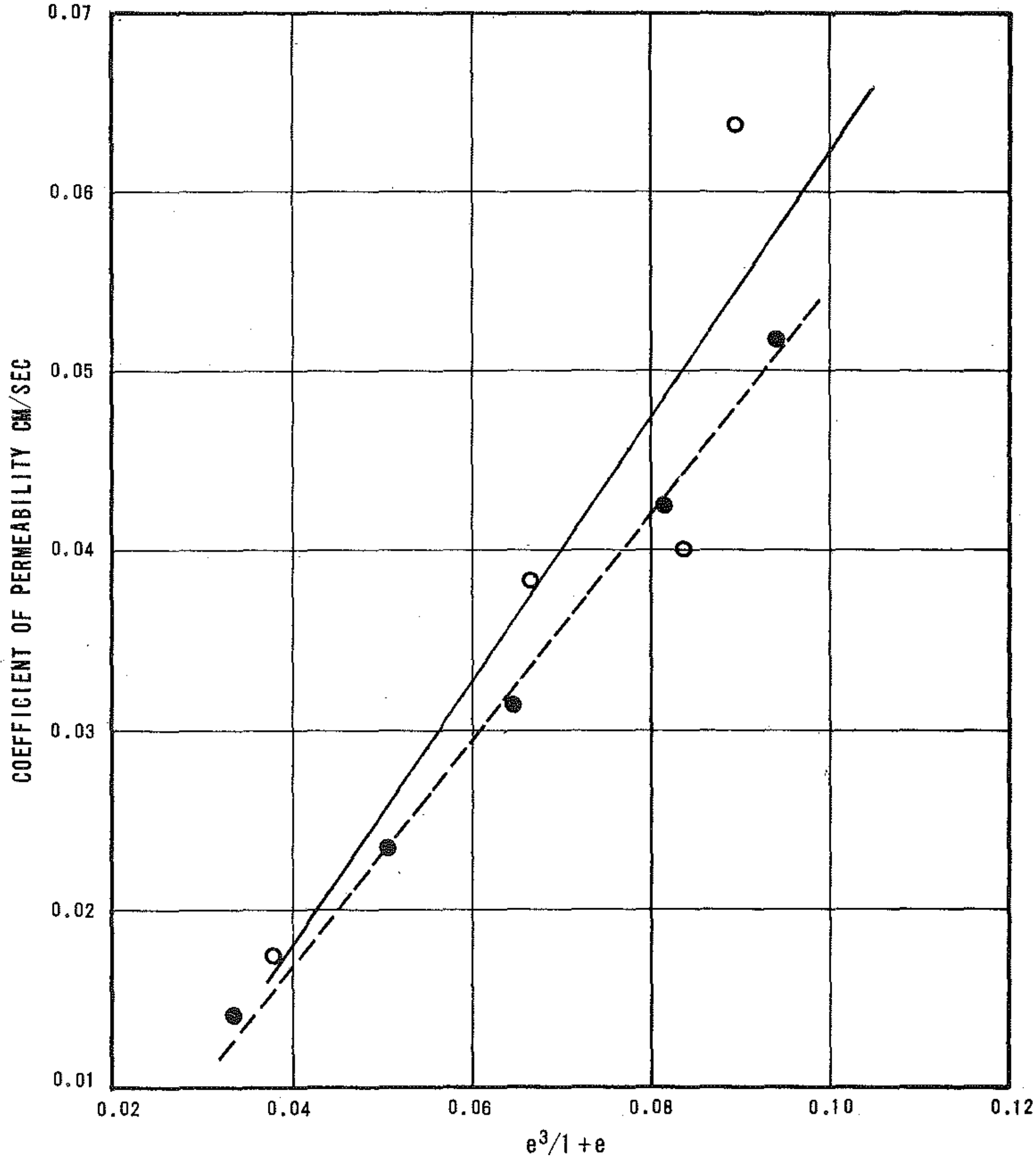



USING WATER: $k = -0.1069 + 3.0051\ e^3/1+e$, $r = 0.958$, $F = 67.3$, $F_{.95(1,6)} = 5.99$

USING AIR: $k = 0.0226 + 2.0972\ e^3/1+e$, $r = 0.998$, $F = 1207.2$, $F_{.95(1,3)} = 10.13$

FIGURE 13

COEFFICIENT OF PERMEABILITY vs $e^3/1+e$ FOR 20-30 OTTAWA SAND




USING WATER: $k = -0.0121 + 0.7452\ e^3/1+e$

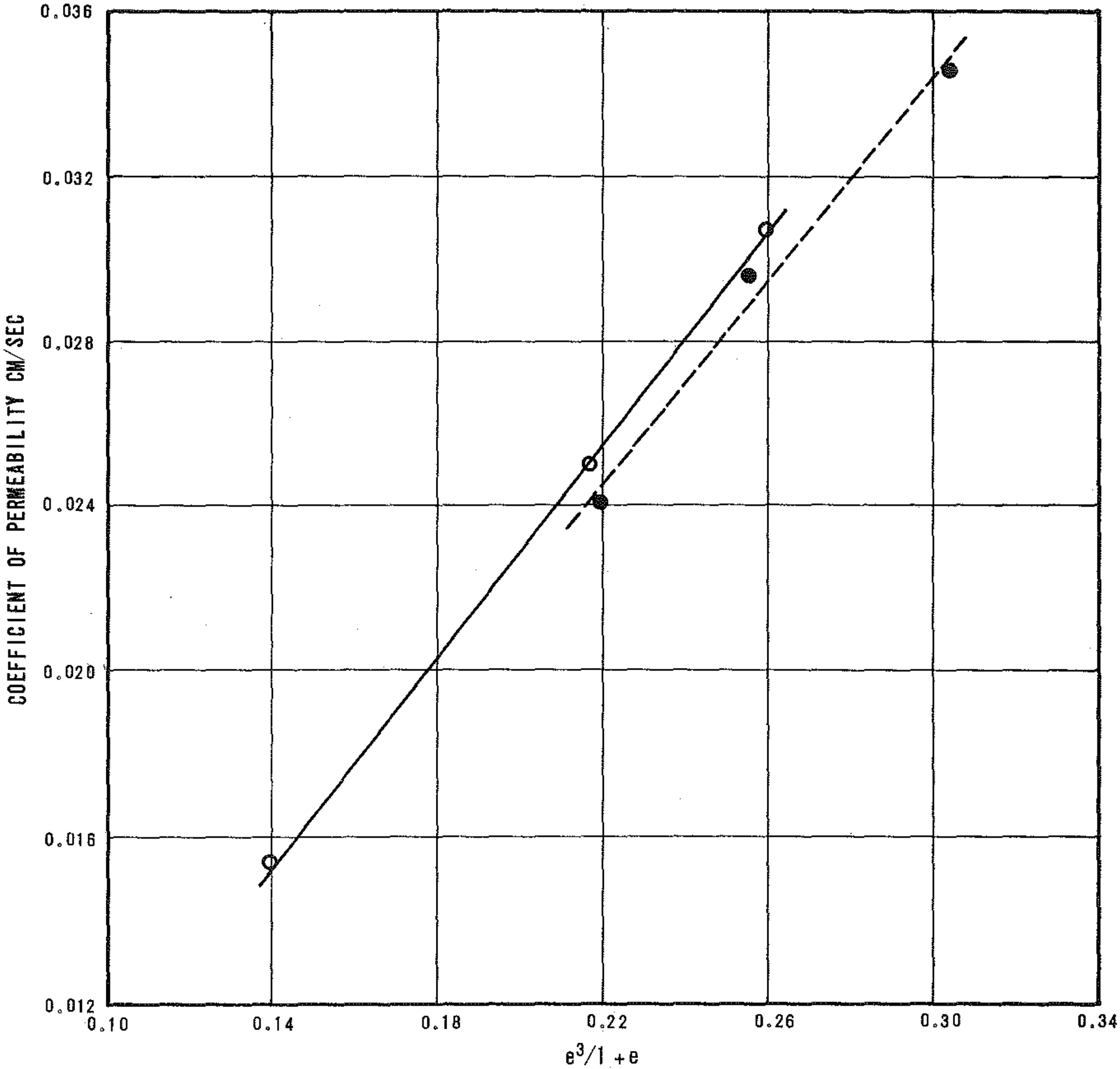
$r = 0.907,\ F = 9.3,\ F_{.95(1,2)} = 18.51$

USING AIR: $k = -0.0083 + 0.6308\ e^3/1+e$

$r = 0.998,\ F = 804.2,\ F_{.95(1,3)} = 10.13$

FIGURE 14

COEFFICIENT OF PERMEABILITY vs $e^3/1+e$ FOR 2NS CONCRETE SAND




O———O USING WATER: $k = -0.0025 + 0.1271\ e^3/1+e$

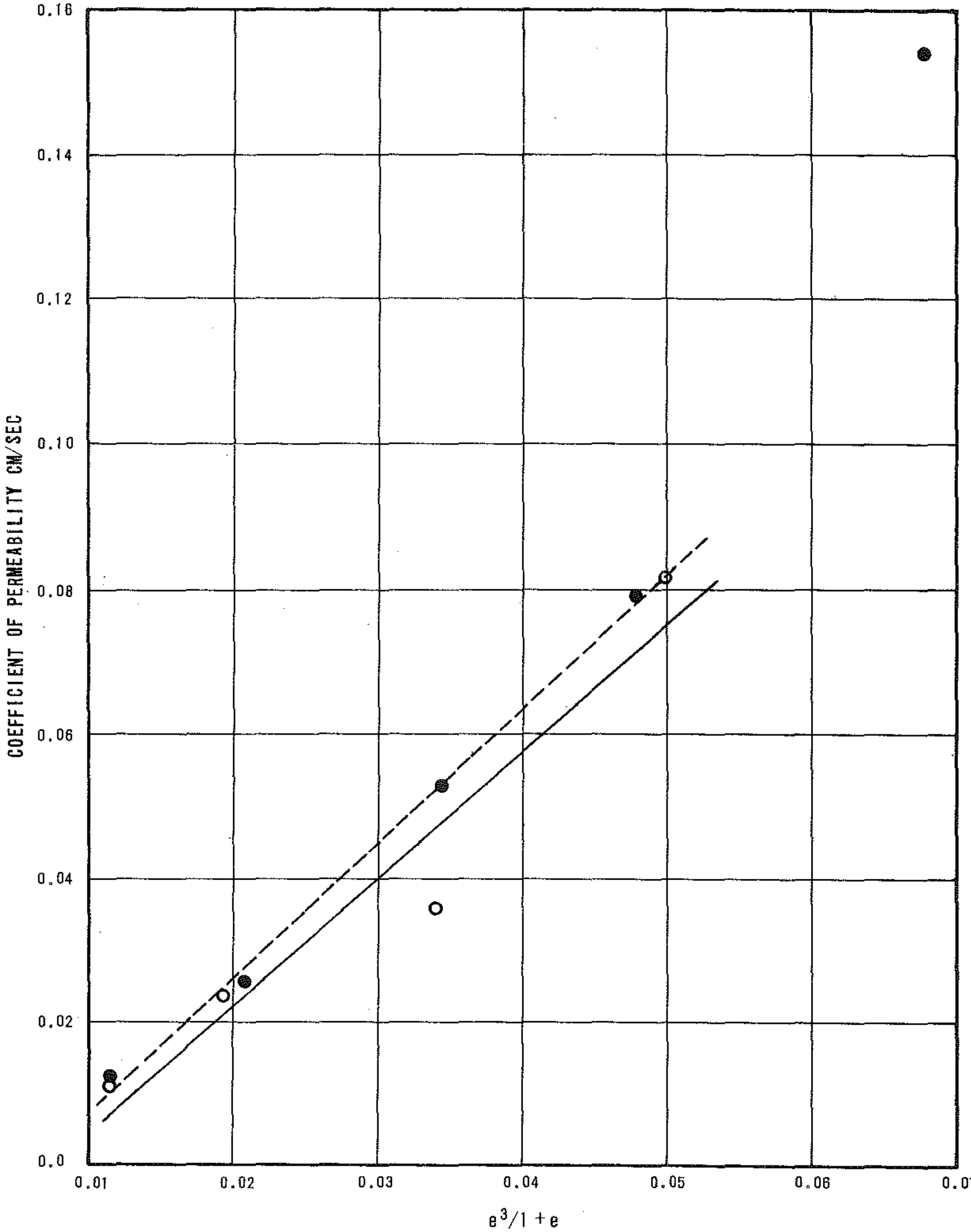
$r = 0.999,\ F = 1271.8,\ F_{.95(1,1)} = 161.4$

●- - -● USING AIR: $k = -0.0022 + 0.1217\ e^3/1+e$

$r = 0.991,\ F = 54.9,\ F_{.95(1,1)} = 161.4$

FIGURE 15

COEFFICIENT OF PERMEABILITY vs $e^3/1+e$ FOR DUNE SAND




USING WATER: $k = -0.0127 + 1.7597\ e^3/1+e$, $r = 0.965$, $F = 27.0$, $F_{.95(1,2)} = 18.51$

USING AIR: $k = -0.0119 + 1.8810\ e^3/1+e$, $r = 0.998$, $F = 604.9$, $F_{.95(1,2)} = 18.51$

FIGURE 16

COEFFICIENT OF PERMEABILITY vs $e^3/1+e$ FOR 22A GRAVEL