THE DETERMINATION OF THE AIR-PERMEABILITY OF SOILS

A. R. P. JANSE and G. H. BOLT
Laboratory of soils and fertilizers, Agricultural State University, Wageningen, The Netherlands

SUMMARY

An improved apparatus for the determination of the air-permeability of soils at constant pressure gradient is described. Referring to existing literature the merits of this apparatus are discussed. As an example of the application of this determination to problems concerning the geometry of pore space some experimental results obtained with a sandy soil under different tillage conditions are given and commented upon.

INTRODUCTION

In comparison to the determination of the water permeability, the determination of the air-permeability of soils has received little attention in soil physical literature. The fact that gas-exchange in soils occurs predominantly by means of diffusion processes may have contributed to this neglect (4). As diffusion is in first approximation related to the fractional free space only, it appears that for soils with porosities of more than 10%, the effect of different air-permeabilities on the composition of soil air can be neglected (6). Nevertheless interesting information may be gained from this determination with regard to the geometrical build-up of soils (1, 7, 10).

Increasing interest for the determination of the air-permeability may be expected. The fluid is inert to the medium and the neglegeable disturbance of the sample allows many and repeated determinations, thus giving valuable data for statistical treatment. Aside from this merit the air-permeability together with waterpermeability may be used as an index of the stability of the geometrical arrangement of the solid phase (12). Finally the determination of air-permeability as a function of moisture content should yield information with regard to the problem of the so-called "blocked" pores (6).

The methods for determining the air-permeability of porous material, i.c. soils, can be divided into two main groups, viz.:

a. those methods in which a constant pressure drop over the sample is maintained during the period of measurement (2, 3, 8);

b. those methods in which a falling pressure-gradient is present during the period of measurement (9, 14). A discussion of the advantages of each of these methods from the point of accuracy is given by CARMAN (5) and BOLT (2). For very high permeabilities and measurements on samples with water retained at low suctions, the first method is preferable, because the determinations must be executed at corresponding low pressures to prevent a disturbance of the configuration of the liquid phase and to avoid turbulent flow. Though determinations in the field are very attractive, in most cases the upper layers of the soil profile are anisotropic and accordingly the mathematical interpretation is involved. Moreover the variability of the upper layers is usually large and anormally distributed; accordingly determinations in the field tend

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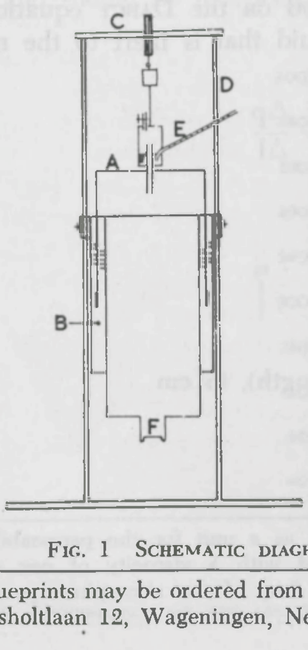
to be inconclusive and the investigation of isolated field samples in the laboratory should often be preferred.

With regard to the size of the samples the following considerations have to be taken into account. To obtain reproducible series of determinations and to acquire insight in the physical properties of different soils, a sample comprising several units of the soil structural pattern must be used. Depending on the tillage conditions of the soil these units can have rather large dimensions. For a sandy soil a sample of about 10 cm diameter and 6 cm length must be considered as a practical minimum.

Construction of the apparatus

The principal features of the apparatus [2]) are analogous to the equipment described by Grover (8), (see figure 1). As material galvanised iron, coated with a plastic varnish is used. It consists of a thin-walled cylinder with heavy rim, the float (A), closed at the top. This air chamber fits in an annular water reservoir (B). The use of a detergent (such as Rogypol), that diminishes the adhaerance of a waterfilm to the walls of the air chamber, can be recommended. In contrast with the apparatus of Grover the float is suspended to promote centration. The nylon suspension thread is connected to a counterweight via a pulley with ball bearing, thus minimizing frictional drag. The effective weight of the float may be varied by changing the counterweight. The constant pressure employed ranged from 0.3—10 cm water. In this manner a satisfactory sensitivity even for very loose structures and for soils at low suctions was attained.



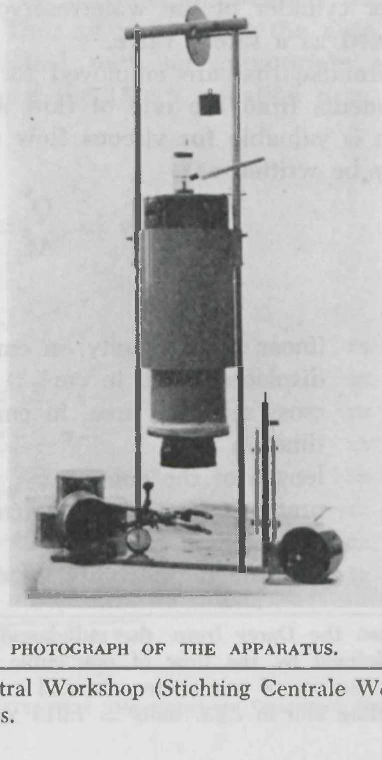


Fig. 1 Schematic diagram and photograph of the apparatus.

[2]) Blueprints may be ordered from the Central Workshop (Stichting Centrale Werkplaats), Dr. Mansholtlaan 12, Wageningen, Netherlands.

The vertical displacement of the float can be read on a scale (D), attached to one of the supporting rods, with an accuracy of 0.5 mm. The maximum displacement amounts to 27 cm, corresponding to an air volume of 5.4 liter. The pressure can be read on a water manometer (E). Better is a filling with *o*-di-iso-amyl-phthalate. One of the legs of the manometer is inclined permitting a more accurate measurement of the pressure (up to 0.15 mm).

The samples to be measured are sealed hermetically to the bottom opening (F) of the apparatus by means of a rubber band (inner tubing of a bicycle tire). By simple exchange of the different sample-holders, cylinders of 3, 5, 9 and 16 cm diameter may be used. The larger sizes of sampling cylinders are clamped to one of the legs of the apparatus. Direct field measurements, are also possible (cf. GROVER, 8).

METHOD OF MEASUREMENT

The downward movement of the float is started by gradually loosing the counterweight. The resulting increase of the pressure in the air chamber will initially cause a periodic movement of the menisci. The damping of this vibration of the menisci in the legs of the water manometer may be improved by selecting an appropriate mass of the fluid in the manometer. After a few seconds the pressure reading should be practically constant. As a result of the immersion of the wall of the float in the annular reservoir the pressure decreases slightly during descent of the float. For the calculation the mean pressure during the period of descent is taken.

In practice the measuring time can be limited to about 3 minutes, by a suitable choice of the counterweight. One has to keep in mind that the pressure deficit during the lifting of the float may not exceed the free height of the inner cylinder of the waterreservoir. For that purpose the manometer is constructed as a safety valve.

All formulae that are employed for the calculation of the permeability of porous media from the rate of flow are based on the DARCY equation. This equation is valuable for viscous flow of a fluid that is inert to the medium, and may be written as:

$$v = \frac{Q}{At} = -\frac{k_i}{\eta}\frac{\Delta p}{\Delta l} \qquad (1)$$

where:

v = linear flow velocity, in cm sec^{-1}
Q = displaced fluid, in cm^3
A = cross sectional area, in cm^2
t = time, in sec
Δl = length of the column ($\neq$ path length), in cm
Δp = pressure drop, in dynes cm^{-2}
η = viscocity, in poise
k_i = intrinsic permeability, in cm^2 [3]).

[3]) Often the Darcy (resp. the millidarcy) is used as a unit for the permeability. This unit is defined by the flow of one cubic cm fluid with a viscocity of one centipoise through a surface of one square cm, and a pressure drop of one atmosphere per cm. The corresponding unit in c.g.s. units = 1.013×10^8 darcy.

With regard to the viscocity of the fluid BUEHRER (3) has demonstrated, that the viscocity of air is strongly dependent upon relative humidity; the effects of changing pressure and temperature are under practical conditions neglegeable. To eliminate the differences caused by changes in viscocity under actual experimental conditions a standard sample was used (e.g. sponge-plastic). Before and after each series of determinations the permeability of this sample is measured and the experimental data are corrected accordingly.

EXPERIMENTAL DATA

In this section two examples are given of the use of the described apparatus for different purposes. These examples are by no means a thorough investigation of the problems stated, but merely serve to illustrate some possibilities for the application of the apparatus.

1. Check of the validity of the DARCY equation. The formula (1) given above suggests a linear dependence of the velocity upon the named factors. The experimental results which BUEHRER obtained for sandy soils, were checked with the described apparatus. With a constant pressure drop the proportionality between volume rate and cross section of the sample could be verified. For samples with very coarse textures a correction for wall effects must be applied.

Partially in contradiction with the results, given by BUEHRER, some difficulties were encountered when the applied pressure was varied, as is demonstrated in figure 2. In this figure the product of the mean pressure gradient and the time, t, necessary to pass a certain volume of air through a series of standard dimensions is plotted against the mean pressure gradient. It is obvious that for samples of standard dimensions the pressure gradient is proportional to the excess pressure in the air chamber, p. whereas the velocity of flow is inversely proportional to t. Thus pt is in effect the ratio of pressure gradient and flow velocity multiplied with an appropriate apparatus factor, and should be independant of p if the DARCY equation is to hold. As

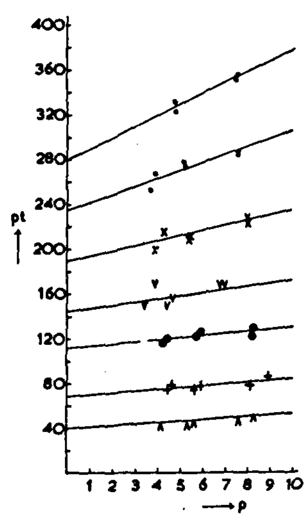


FIG. 2 DEPENDENCE OF THE AIR-PERMEABILITY UPON THE PRESSURE GRADIENT (SEE TEXT).

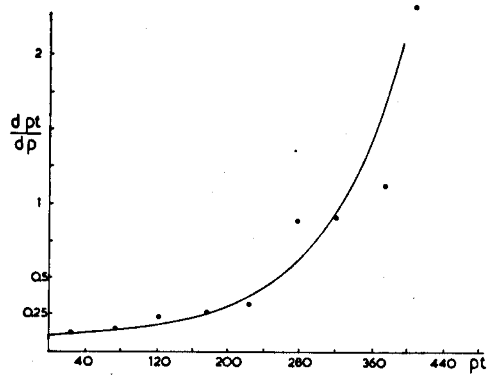


FIG. 3 SLOPE OF THE LINES OF FIGURE 2 AS A FUNCTION OF THE AIR-PERMEABILITY (SEE TEXT).

is illustrated in figure 2 this is approximately true for highly permeable structures, but does not hold at all for the lesser permeable ones. It is noteworthy that the deviation from constancy, for which the slope of the lines, d pt/dp, is a measure, increases continually with decreasing permeability (figure 3). Since deviations from DARCY's law caused by the beginning of turbulent flow (which could conceivably be the case for these systems) would increase with the permeability, figure 3 indicates that some other disturbing effect us present.

2. Investigation of the pore geometry. The investigation of the relationships between air permeability and certain other soil properties is of interest. These properties are in the first place the total volume and size distribution of air filled pores. Because the air-filled pore space of a given configuration of solids depends on the moisture content, the latter will also influence the air permeability.

For dry granular materials equations have been described in the literature, as reviewed by CARMAN (5) and SCHEIDEGGER (13), which relate k_{air} to the porosity and a size parameter, as e.g. the specific surface area. These equations are obviously of limited significance for natural soils, because of the composite structure and the presence of water. Even if the porosity were replaced by the volume of the air-filled pores, complications arise because of the presence of occluded air-filled voids. Thus k_{air} should be related to an "effective" volume of air-filled pores. This effective volume is hardly accessible for direct determination, because the porosimeter will measure at least part of the occluded pore volume. Possibly some information could be gained from the dilution of a known volume of foreign gas (e.g. labeled with radio-active tracer) brought in contact with a given soil sample. Although the ratio of the air-permeability of wet and dry samples of the same soil should contain information with regard to the presence of occluded pores, another independent measurement will be necessary to extract this information, since the moisture occupies the smallest pores. Thus the "size parameter" is different for wet and dry samples. Furthermore it should be kept in mind that during drying the pore geometry might also change.

An interesting aspect is the variation of k_{air} induced by different types of tillage operations on a given soil. For this purpose a small tillage experiment was set up on a sandy soil (5% of fraction $< 2\,\mu$, 1,5% organic material) comparing the effect of plowing, hand-digging and rotary tillage on a number of plots. From these plots samples were taken in five consecutive months. Sampling depth was 15 cm, and the samples (4 per plot, 9 cm diameter, 6 cm height) were taken both in vertical and horizontal direction. After weighing of the sample k_{air} was determined twice at three different values of p. The value of k interpolated at p = 6 was taken as a characteristic value for the wet sample (k^w). After careful drying of the samples the weight and permeability were determined again yielding the value of k for the dry sample (k_d).

Table 1 Phase distribution and air-permeability under different tillage conditions.

Treatment	Vertical samples					Horizontal samples				
	solids vol. %	water vol. %	air vol. %	k_w 10^{-8} cm²	k_d	solids vol. %	water vol. %	air vol. %	k_w 10^{-8} cm²	k_d
Untreated	57.6	14.2	28.2	50	55	60.2	16.0	23.8	30	40
Hand-digging . . .	50.8	14.5	34.7	141	230	55.8	16.6	27.6	73	100
Rotary-cultivation .	52.5	14.1	33.4	130	163	55.4	16.1	28.5	60	73
Plowing	46.9	14.8	38.3	172	193	50.5	16.2	33.3	96	135

In table 1 the mean values of a series of determinations at a certain date are given. Other series proved to be analoguous. The standard deviation was of the order of magnitude of 6 for the k_w values, and of 3 for the k_d values. From this table the following conclusions may be drawn.

a. The small increase in air space caused by the different tillage operations is accompanied by substantial increases in the permeability.

b. The observed differences in pore space of the vertical and horizontal samples indicate that compression of the samples occurred during sampling. Apparently compression in the vertical samples (if present) was always less

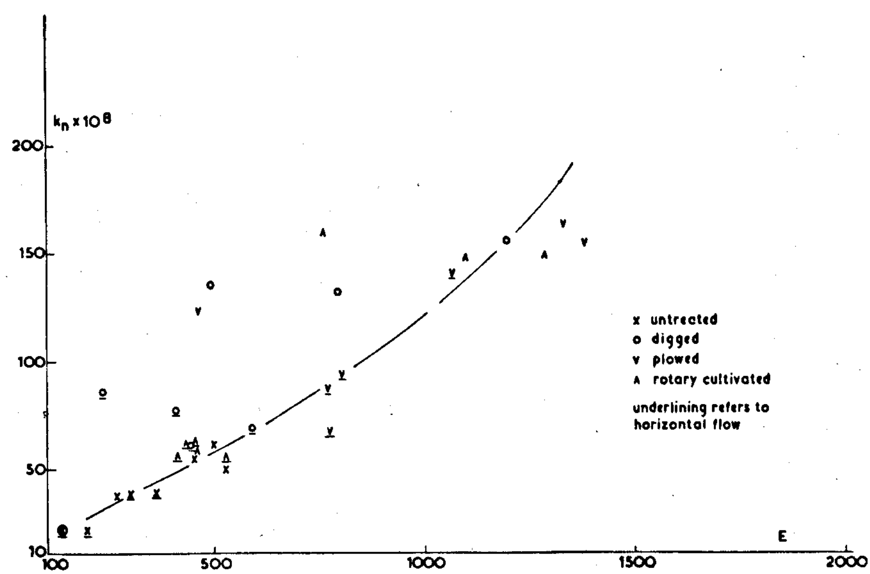


FIG. 4 THE AIR-PERMEABILITY OF WET SAMPLES AS A FUNCTION OF THE KOZENY-FACTOR.

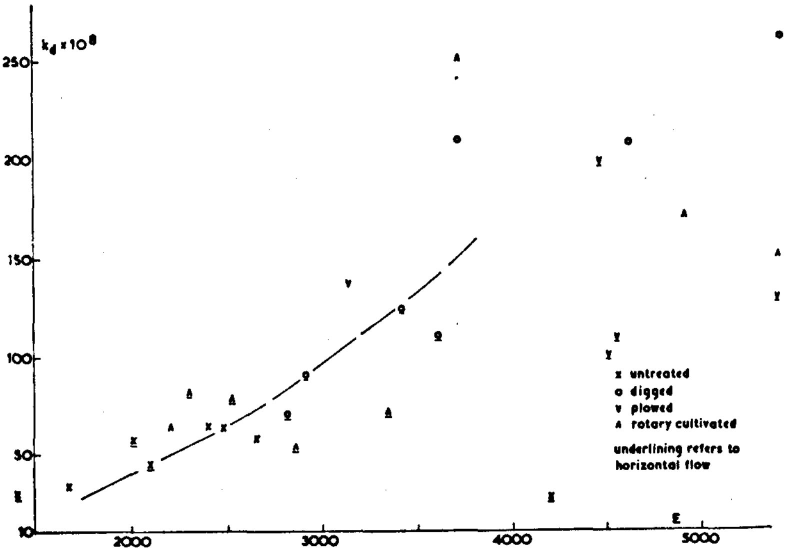


FIG. 5 THE AIR-PERMEABILITY OF DRY SAMPLES AS A FUNCTION OF THE KOZENY-FACTOR.

than in the horizontal samples. The relative degree of compression for the horizontal samples was about equal for all treatments. The differences in geometry of horizontal and vertical samples is substantiated by corresponding differences between the permeability of the samples.

c. With respect to the interpretation of the differences between k_w and k_d it is advisable to relate these values to the volume of air-filled pores. Although the different equations relating the permeability to the porosity and a size parameter cannot be expected to hold for the composite arrangement of solids in an ordinary soil, it is nevertheless interesting to plot the k value against the KOZENY factor E $\left(= \frac{\Sigma^3}{(1-\Sigma)^2}\right.$, with Σ = air-filled pore space). The slope of the line relating these two quantities is then a measure of the size-parameter and of the occurrence of blocked pores. In figures 4 and 5 k_w and k_d as observed for one series are plotted in this manner. The lines were hand-drawn through the values belonging to the horizontal samples. Although the points are fairly widely scattered it is remarkable that the KOZENY relationship (assuming a constant size parameter) is still obeyed to this extent. The larger slope of the line for the wet samples (note difference in axis calibration) should be expected because the water will occupy the smallest pores, thus changing the size distribution of the air-filled pores. On the other hand the presence of blocked pores should decrease the slope of the line. Without other information it can only be concluded that in the samples studied the effect of pore blocking was, if present, completely overshadowed by the increase in effective pore size.

Summarizing it may be stated that the determination of the air-permeability of soils constitutes a simple and sensitive method to help characterize the pore geometry of soils. Although difficult to interpret quantitatively by itself, the air-permeability should yield valuable information if used in conjunction with other methods available for the investigation of pore geometry.

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