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The use of air-filled porosity and intrinsic permeability to air to characterize structure of macropore space and saturated hydraulic conductivity of clay soils

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SUMMARY

Intrinsic permeability to air of macropore space (k_a) is related to macroporosity (ε) and organization of macropore space (O). Organization is defined as k_a/ε. The use of k_a for estimating saturated hydraulic conductivity (K_s) is also considered. The relationship between Log (O) and ε (O:ε characteristic) can be used to describe changes to the macropore space of clay soils by amelioration and compaction. The effects of dominant macropore shape can also be identified and calculated as an empirical index of the efficiency of the pore organization E ($E=\log(O)/\varepsilon$). Intrinsic permeability can then be related to E in a E:k_a characteristic. Intrinsic permeability is the parameter most sensitive to structural change and E is mainly influenced by the dominant shapes of the macropores. Thus, the E:k_a characteristic is suggested as a basis for studying differences in macropore space as may occur in response to external and internal stresses upon the soil and different systems of soil management, for example increases of packing pores by cultivation or of fissures by gypsum application and loss of packing pores by compaction. Empirical data indicate that K_s of the B horizons of Australian red-brown earths can be estimated from k_a of macropore space at a standard potential.

INTRODUCTION

The amount and organization of macropore space (the extent and organization of pores greater than 30 μm dimension) have been recognized as important to the behaviour of clay soils. The connectivity and dimensions of macropore space can influence water movement (Beven & German, 1982) and gas movement (Ball, 1981a). The macropore space of dense, clay-rich B horizons of Australian soils, owing to its very small volume and poor connectivity (McIntyre & Sleeman, 1982), can restrict water and air entry for crop growth. Exploration of the soil by roots can also be influenced by the extent and dimensions of the macropore space (Jakobsen & Dexter, 1988).

Major functions of the macropore space are fluid storage (proportional to macroporosity) and transmission or provision of pathways for exploration by biological organs (proportional to the connectivity and volume of the macropore space and reflected in the intrinsic permeability to air; permeability divided by viscosity and density). Volume and permeability of macropore space are

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highly correlated in sandy and granular soils, but can be more independent in structured clay soils. This has led to the use of indices of soil structure and the connectivity of the pore space. These indices are often ratios of volume and permeability of pores (Ball *et al.*, 1988), which are more sensitive to soil structural differences than other physical measurements. This paper attempts to develop further the use of such indices in the analysis of macropore space.

A numerical characterization using indices of the organization of the structure

Douglas (1986) and Groenevelt *et al.* (1984) showed that clay soils under different management systems need not have a unique relationship between macroporosity and intrinsic permeability. Ball (1981b) recognized similar varying relationships between relative diffusivity and macroporosity and proposed an index to express pore continuity and tortuosity (relative diffusivity/macroporosity). Groenevelt *et al.* (1984) and Ball *et al.* (1988) both derived indices of pore continuity from measurements of air-filled porosity and air permeability. They were able to use them to discriminate between the effects of different cultivation systems that could not be distinguished from measurements of bulk density. Indices based on permeability were more convenient to derive than those based on relative diffusivity as less expensive apparatus is required and measurements are often quicker.

In this paper we derive a similar index to Groenevelt *et al.* (1984) called 'organization' (O) from measurements of intrinsic permeability to air (k_a) (hereafter referred to as 'permeability') and macroporosity. Organization represents that part of permeability which is dependent on the arrangement and shape of the macropore space, rather than total volume and is defined as:

$$O = k_a/\varepsilon \qquad (1)$$

This is equivalent to K_2 of Groenevelt *et al.* (1984). Like k_a, the distribution of O is very skewed and a log-normal transformation should be used when calculating mean values of O.

By considering the permeability of some model pore systems, it is possible to see the factors by which O is likely to be influenced.

Granular systems. Marshall (1985) derived an equation for granular systems relating permeability to water (K) to porosity (ε), connectivity equal to ε and pore radii $r_1 \ldots r_n$ of n equal fractions of the total pore space:

$$K = \varepsilon^2 n^{-2} [r^2_1 + 3r^2_2 + 5r^2_3 \ldots + (2n-1)r_n^2]/8 \qquad (2)$$

If the air-filled macropores are considered as one class of mean radius r then:

$$k_a = \left[\frac{\varepsilon\, r^2}{8}\right].\varepsilon \qquad (3)$$

Channels. From a combination of Darcy's and Poiseuille's laws, permeability of a system of n tubes or channels of radius r and tortuosity T (length of channel/core length) in a core of radius r_s is given by Ball (1981a):

$$k_a = \frac{n\,\pi r^4}{8\,T\pi r_s^2} \qquad (4)$$

The porosity of the channels (ε_c) is:

$$\varepsilon_c = \frac{n\,T\pi r^2}{\pi r_s^2} \qquad (5)$$

Substituting into Equation 4:

$$k_a = \left[\frac{r^2}{8\,T^2}\right].\varepsilon_c \tag{6}$$

Fissures. For a system of fissures of length l in a cross-section normal to the direction of flow, width d and tortuosity T through a core of radius r_s, Douglas (1986) gives:

$$k_a = \frac{l\,d^3}{12\,T\,r_s^2} \tag{7}$$

The porosity of the fissure system (ε_f) is:

$$\varepsilon_f = \frac{l\,d}{\pi r_s^2} \tag{8}$$

Substituting into Equation 7:

$$k_a = \left[\frac{\pi d^2}{12\,T^2}\right].\varepsilon_f \tag{9}$$

From Equations (3), (6) and (9) permeability is a function of ε and of a resistivity term (in brackets), which is equivalent to O and depends on pore size, tortuosity and connectivity:

$$O = \frac{\varepsilon r^2}{8} \text{ for granular systems} \tag{10}$$

$$O = \frac{r^2}{8T^2} \text{ for channels} \tag{11}$$

$$O = \frac{\pi d^2}{12T^2} \text{ for fissures} \tag{12}$$

O and ε will have a degree of correlation because both are influenced by pore size (r or d) in the case of channels and fissures. In the case of granular systems the same is true because connectivity is taken as ε. The effects of changing the various pore parameters can be seen in Table 1 for a system of channels.

O can be calculated from measurements of k_a and ε and related on a graph of O *vs* ε (O:ε characteristic) where k_a isolines are hyperbolae. There is a skewed frequency distribution of O, due to the log-normal distribution of k_a; therefore, values of O are transformed to logarithms. Measurements from Douglas & Goss (1987) have been plotted in Fig. 1 to illustrate the variability of ε and O for a clay soil under three different management systems. Three key features of the macropore space can be identified. First are conditions of low permeability ($< 1\ \mu m^2$), low macroporosity and small values of O ($< 10\ \mu m^2$), associated with tillage pans in the ploughed and shallow tillage treatments. Second are conditions of moderate permeability, small macroporosity and large values of O ($> 100\ \mu m^2$), at 20–30 cm depths in the shallow-tilled and direct-drilled treatments where macropore space includes channels from earthworm burrowing. Third are conditions of similar permeability, but contrasting ε and O (20–25 cm direct drilled and 5–10 cm ploughed). The differences in ε and O reflect the proportion of the macropore space involved in fluid transmission. Ball (1981b) and Ball *et al.* (1988) also refer to such differences as a consequence of 'non-tubular' or 'blocked' pore space.

It is evident that volume, permeability and organization (O) of the macropore space are useful parameters for identifying large-scale attributes of the overall morphology.

Table 1. The variation of intrinsic permeability (k_a), porosity (ε) and organisation (O) for a system of n channels of radius r and tortuosity T. Core radius (r_s) is 50 mm

Tortuosity		1	2	4	1	2	4	1	2	4
r (mm)	n	k_a (μm^2)			ε ($cm^3 cm^{-3}$)			O (μm^2)		
0.1	10	0.05	0.025	0.013	0.004	0.008	0.016	1250	313	78
	20	0.1	0.05	0.025	0.008	0.016	0.032	1250	313	78
	40	0.2	0.1	0.05	0.016	0.032	0.064	1250	313	78
0.2	10	0.8	0.4	0.2	0.016	0.032	0.064	5000	1250	313
	20	1.6	0.8	0.4	0.032	0.064	0.128	5000	1250	313
	40	3.2	1.6	0.8	0.064	0.128	0.256	5000	1250	313
0.4	10	12.8	6.4	3.2	0.064	0.128	0.256	20000	5000	1250
	20	25.6	12.8	6.4	0.128	0.256	0.512	20000	5000	1250
	40	51.2	25.6	12.8	0.256	0.512	1.024	20000	5000	1250

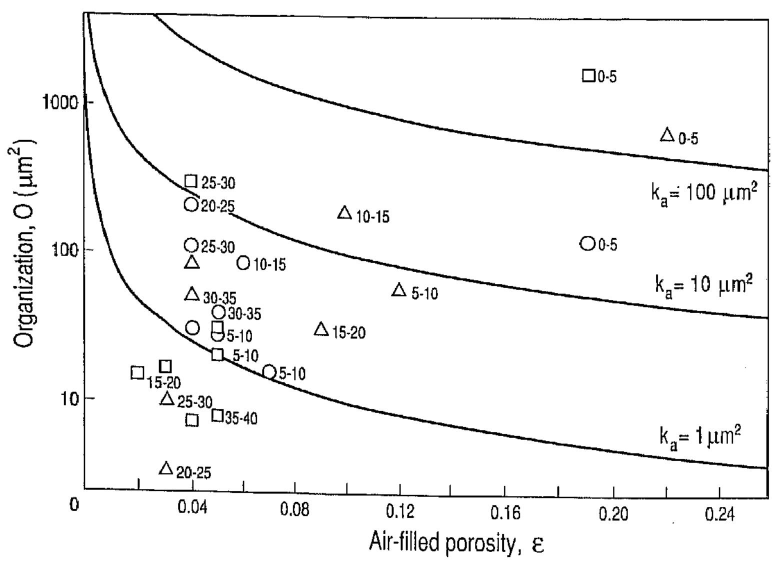

Fig. 1. Measurements of organization (O) and macroporosity (ε) of a clay soil under different management systems (from Douglas & Goss (1987), Table 6). The depths of some measurements are indicated in cm. (○ = Direct drilling; □ = shallow tillage; △ = ploughing). Intrinsic permeability (k_a) isolines are shown.

Assessment of saturated permeability to water

If water is used to measure saturated hydraulic conductivity (K_s) soil structure can be affected by the interaction between the amount of electrolyte in the water and the exchangeable cations in the soil (Quirk, 1986). In the extreme case of a sodic clay and water with very low electrolyte concentration, clay dispersion can preclude any measurement of K_s. Encapsulated air can also influence measurements of saturated hydraulic conductivity (Collis-George & Yates, 1985; Ball *et al.*, 1988). The amount of air encapsulation depends on the method of wetting the soil, and may not resemble field conditions. Clay dispersion can be prevented by a suitable ionic strength of permeating solution and air encapsulation can be prevented by replacement of air by carbon dioxide before wetting (Constanz *et al.*, 1988).

K_s may be estimated (without air occlusion) from the intrinsic permeability, calculated from measurements of air permeability after drainage to a suitable suction, if both fluids are using the same pore space (Klinkenberg, 1941). Therefore, for structured clay soils measurement of permeability to gas (i.e. air) flow offers the following advantages over that to water for the estimation of K_s: more rapid measurement; no reaction with the colloid; no encapsulation of the other fluid; convenient integration with desorption techniques and selected use of 'transmission' pores emptied at appropriate water potentials (e.g. -1 to -10 kPa).

The principal problem in measurement of air permeability appears to be shrinkage of soil away from the walls of rigid sleeves. Many sufficiently undisturbed, or previously compacted clay soils can have sufficient fabric strength to resist deformation by mechanical stresses from small water potentials which will empty the macropores, e.g. -5 kPa (McIntyre *et al.*, 1982). More recently disturbed and weaker soils can shrink under such small effective stresses. Therefore, it would be useful to know if K_s can be predicted from k_a at a 'standard' potential to which the soil is drained and whether it can also be estimated from k_a at other potentials.

Choice of Methods

The most accurate measurement of volume and permeability of macropore space may be *in situ* methods, instantaneous profile analysis (Talsma, 1985) or large encased monoliths (Murphy *et al.*, 1981). Sleeved cores offer the advantages over *in situ* methods of convenient isolation of soil from small zones in the profile and less effort per unit measurement in the field. Douglas *et al.* (1986) have used combined measurements of air-filled porosity and air permeability at different water potentials to identify differences in macrostructure in a silt loam caused by different management practices.

Some shortcomings of sleeved cores for clay soils are:

1. The need to cut the cores from field soil in a moist state, during a drainage phase from near-saturation;
2. The need to avoid suction steps in the laboratory which cause shrinkage from the sleeve and artificial pathways for air movement;
3. Removal of the overburden load, which may also create complications if the soil changes volume and the macrostructure changes.

Fewer, but complementary, measurements of the macrostructure by the more time-consuming methods in the field and laboratory may help to compensate for these problems with sleeved cores. Despite these limitations, sleeved cores were chosen for this study.

Objectives

Our objectives were:

1. To use a quantitative index (O) to describe the change of macropore space of clay soils during amelioration or compaction;
2. Derivation of another quantitative index influenced mainly by the shape of macropores:
3. Estimation of saturated hydraulic conductivity from air permeability at a standard water potential.

METHODS AND MATERIALS

Sampling

The methods were adapted from Loveday (1974). The metal (brass) sleeves for the soil cores ranged from 50 to 100 mm outside diameter and 30 or 75 mm length, with 1.6 mm wall thickness and an angle of about 7 degrees at the cutting edge. Wherever possible the larger sizes were used, but the sampling of some features, such as rip zones and gypsum-enriched slots, required smaller diameters.

The sleeves were lubricated with sunflower oil and pushed into field soil when the water potential was approximately 0 to -5 kPa, either during wet winter periods or after irrigation and a few days drainage. Various methods of inserting the sleeves were used, most commonly by a drop hammer or by jacking against a metal beam kept in place by legs at each end and by the weight of a tractor

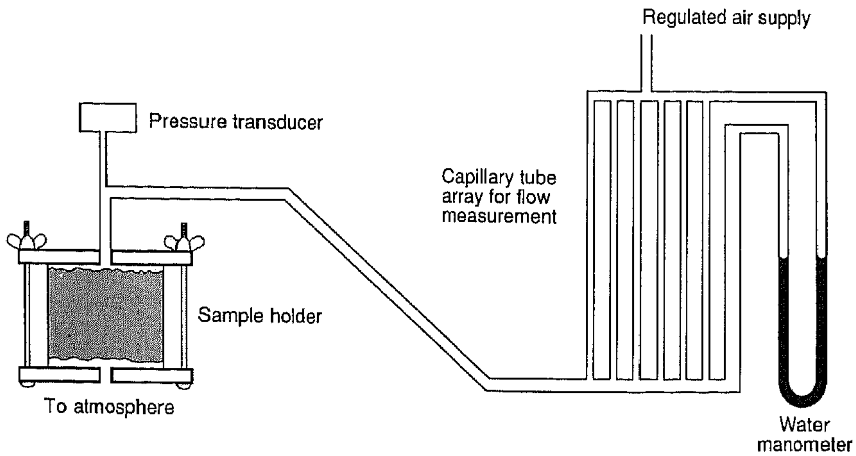

Fig. 2. Schematic diagram of the apparatus used for measurement of air permeability (not to scale).

transferred onto its centre by the arm of a back-hoe, in a similar fashion to the methods of Douglas & Goss (1987). A mechanical, worm-drive jack was used to insert the sleeves at a constant rate in order to avoid pauses when static friction can induce extra tearing ('biscuiting') of the core near the sleeve.

Macroporosity

The volume of macropores was measured from the air-filled volume calculated from wet bulk density and average particle density after drainage to -1, -5 or -10 kPa matric potential on ceramic plates in a constant-temperature room (22°C).

Air permeability

Air permeability was measured after picking away a few millimetres of soil from each end of the core to expose all available pores. The sample was clamped in a holder with two rubber-faced plates, so that sleeves of different diameters could be accomodated. The apparatus allowed both the air flow through the sample and the pressure drop across it to be measured at constant flow rates at the same temperature used for drainage on the ceramic plates (Fig. 2). The flow rate was measured by a capillary tube flowmeter (British Standard 4359, 1971). The flow rate was increased up to about 9 $cm^3 s^{-1}$ in six equal steps by a fine regulator and the pressure difference across the sample measured using a pressure transducer at each step. The influence of turbulent flow on the calculation of permeability was minimized by choosing sections of the pressure/flow rate graph which remained linear at the lower flow rates (Ball *et al.*, 1981). Calculation of intrinsic permeability used the same equation as Groenevelt & Lemoine (1987) for measurement of flow upstream of a sample at differential pressures less than 0.2 m of water. The apparatus is easier to use if downstream measurements of flow are made. We found it useful to check periodically the performance of the equipment by measuring the permeability of a standard length of capillary tubing and comparing it to the theoretical value calculated for the same tube.

Pore shape

The shapes of coarse pores (larger axes >2 mm) were estimated by eye as vughs or channels. Estimation of the occurrence of fissures was assisted by a low power (× 10) hand lens.

Saturated hydraulic conductivity

This was measured by the constant head method described by McIntyre & Loveday (1974) using 0.01 M $CaCl_2$ and pre-flushing the core with carbon dioxide for 60 min at a pressure of 5 to 10 cm of water.

SOILS AND SUBJECT AREAS

The soil cores were taken from the B horizon (or equivalent depths after deep cultivation and amelioration with gypsum) of red-brown earths from the riverine plains of South Eastern Australia. These soils have a marked texture contrast between A and B horizons and are often poorly suited to irrigated cropping, owing to a 'throttle' in the B horizon—a layer of lower permeability which restricts infiltration (McIntyre *et al.*, 1982). Some morphological, physical and chemical properties of these soils before amelioration are shown in Table 2, as well as their geographical location. The amelioration techniques include treatments using deep ripping and slotting, with application of gypsum. Blackwell *et al.* (1987) and Jayawardane *et al.* (1988) describe some of the equipment used.

Data presented in this paper are geometric (k_a) or arithemetric (ε) means of six to 10 cores that have been collected from a variety of field experiments constituting parts of other research reported separately. Each is described below.

Amelioration of macropore space by deep ripping and gypsum application

Field experiments at Whitton (Mundiwa clay loam), Tatura (Lemnos loam) and Trangie (Trangie-Cowal silty loam) which included treatments using deep ripping and gypsum application were sampled after one winter cereal crop had been grown. Agricultural traffic had been avoided by using bed cultivation systems.

Deterioration af ameliorated macropore space by compaction

For one of the ameliorated soils (Trangie-Cowal silty loam), which had the largest macroporosity and permeability after amelioration, 30 mm long cores were collected from the upper 15 cm of beds formed after deep ripping. The cores were subjected to uniaxial compression for 1 s at a soil water potential of -10 kPa. Uniaxial stresses of 0, 50, 75, 100, 150 and 250 kPa were used. Macroporosity and permeability were measured after compression. In addition, the soil in ripping troughs in Mundiwa clay loam was compressed in the field by wheeling. The full details of this experiment, which included measurements of stresses, is given in Blackwell *et al.* (1989). Measurements of maximum vertical stress and macrostructure at 20 cm depth before and after wheeling are used here.

Influence of some macropore shapes

Cores from three sources were used to show effect of macropore shape. The first was a long-term rotation experiment on ameliorated Lemnos loam, which has been reported by Mason *et al.* (1984). The experiment had run for 4 years after deep ripping and gypsum application. One treatment which included a previous crop of lucerne was used. The second was a similar experiment on Lemnos loam at Tatura Research station, which was also used to show the effect of deep ripping. The third was the B horizon of Mundiwa clay loam in the spring after amelioration by surface application of 4 t ha^{-1} of gypsum followed by a crop of winter wheat.

Estimation of saturated hydraulic conductivity

Cores were collected from a field experiment on Mundiwa clay loam (at Whitton, NSW.) comparing different methods of gypsum-enriched slotting with other amelioration techniques. Cores were taken from 20 cm depth either within or between the slots into which either the equivalent of 4 or 8 t ha^{-1} of gypsum had been incorporated. Other cores were collected from the unameliorated soil from the upper part of the B horizon to 55 cm depth.

RESULTS AND DISCUSSION

Amelioration of macropore space by deep ripping and gypsum application

The unameliorated B horizons, where a 'throttle' had been recognized from other measurements (Lemnos loam and Mundiwa clay loam), had similar low macropore volumes and permeabilities (Fig 3), typically $\varepsilon < 0{\cdot}08$ and k_a at -10 kPa $< 2{\cdot}0\ \mu m^2$. The soil with no evidence of a 'throttle' (Trangie-Cowal silty loam) had larger macroporosity and permeability.

Amelioration increased k_a of the Lemnos loam and Mundiwa clay loam to that of the unameliorated Trangie-Cowal silty loam, where k_a also increased with amelioration. However, the increase in

Table 2. Some physical and chemical properties of the unameliorated soils

Soil type (location) [US classification (Soil Survey Staff, 1975)] (Northcote (1971) key)	Horizon (depth, mm)	Density (approx.) ($t\ m^{-3}$)	Primary particles* clay (%)	silt (%)	sand (%)	CEC ($mmol_c\ kg^{-1}$)	ESP	OM %w/w	Dominant clay minerals
Mundiwa clay loam (Whitton, NSW) [Natric Palexeralf] (Dr 2.33)	A1 (0–100)	—	17	24	60	140	2.0	1.0	kaolinite
	B1 (200–300)	1.5	62	14	26	300	4.7	0.7	kaolinite
Lemnos loam (Tatura, Kyabram, VIC) [Typic Haplustalf] (Dr 2.13)	A1 (0–100)	—	24	40	35	150	4.8	2.6	illite
	B1 (200–300)	1.6	47	30	22	210	4.8	0.7	illite and kaolinite
Trangie-Cowal silty loam (Trangie, NSW) [Rhodic Paleustalf] (Dr 2.23)	A1 (0–200)	—	17	27	56	100	2.6	1.9	illite and kaolinite
	B1 (300–600)	1.6	35	20	45	160	4.3	0.7	illite, kaolinite and randomly interstratified minerals

*Silt size is 2 to 20 μm

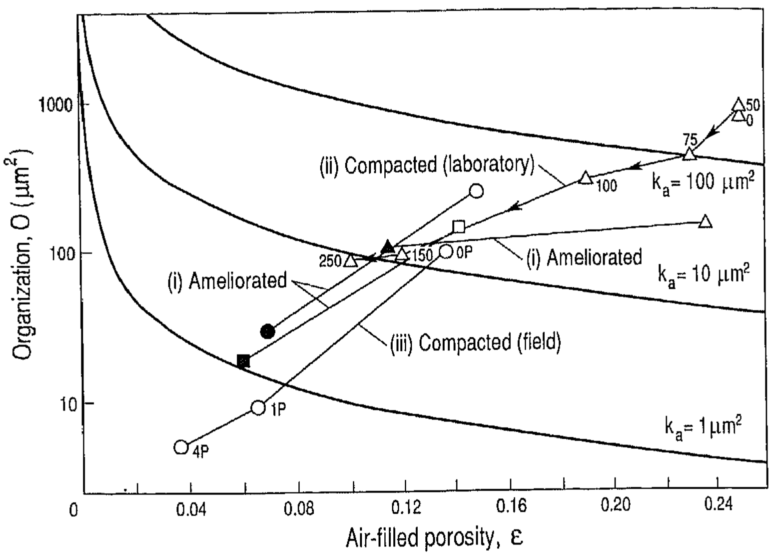

Fig. 3. The effects of amelioration and compaction on the macropore space of some clay soils as described by changes in the O:ε characteristic. (i) Effect of amelioration by deep ripping and gypsum application on B horizons of Trangie-Cowal silty loam (▲); Lemnos loam (■) and Mundiwa clay loam (●). Closed symbols: unameliorated; open symbols: 1 year after amelioration and without traffic. (ii) Effect of uniaxial loading for 1 s on surface soil of ameliorated Trangie-Cowal silty loam. Numbers indicate load in kPa. (iii) Effect of wheelings by the rear wheel of a tractor with a 4 t load on ameliorated Mundiwa clay loam at soil water contents near the lower plastic limit from Blackwell *et al.* (1989). Samples were from 20 cm depth in ripping troughs. OP: Unwheeled; 1P: one pass; 4P: four passes. Intrinsic permeability (k_a) isolines are also shown.

Lemnos loam and Mundiwa clay loam was caused by increases in both O and ε, whereas in Trangie-Cowal silty loam it was caused solely by an increase in ε.

Deteriation of ameliorated macropore space by compaction

As the uniaxial load applied to the loosened Trangie-Cowal silty loam was increased, the volume and permeability of the macropores declined (Fig. 3).

The response of macropore space of deep ripped Mundiwa clay loam to wheeling (Fig. 3) is similar to the Trangie-Cowal silty loam. One pass, with a maximum vertical stress of 100 kPa, returned the macropore space to a condition similar to that before amelioration. Three more passes caused further deterioration.

Influence of some macropore shapes

The dominant shape of the larger macropores can influence the O:ε characteristic. Macropore shape can be considered as either fissures, channels or packing pores/vughs. Vughs are more poorly connected than packing pores (Ringrose-Voase & Bullock, 1984). Visual observation of cores from the recently deep-ripped Lemnos loam revealed that some cores contained coarse vughs (2–5 mm diameter). Others, in which lucerne had previously been grown, contained coarse channels (3–8 mm diameter) with fibrous remains of roots. The effects of these pores on the O:ε characteristic can be seen in Fig. 4. The samples with channels had lower macroporosity than those without channels, yet had a similar permeability. Conversely samples with vughs had relatively large macroporosities compared to others with similar permeabilities.

The soil ameliorated by only surface application of gypsum had low porosity but a permeability of about 40 μm² (Fig. 4). This structure included many fine fissures. The replacement of exchangeable sodium by calcium probably restricted the swelling of the soil during the winter causing more fissures to be retained on wetting than in the unameliorated control.

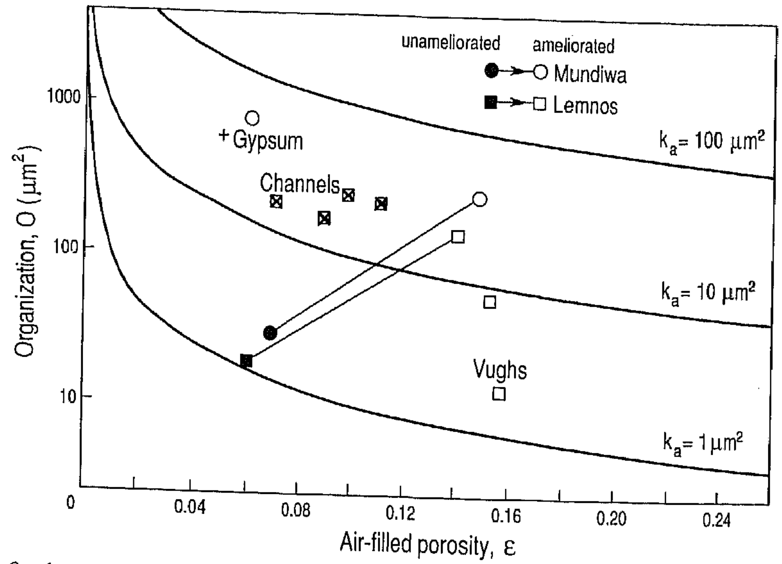

Fig. 4. The O:ε characteristic for individual samples of ameliorated Lemnos loam with channels from old lucerne roots (⊠) or many coarse occluded vughs (□) and for Mundiwa clay loam B horizon ameliorated only by surface gypsum applications (+gypsum). Mean values (from Fig. 3) for Lemnos loam and Mundiwa clay loam of unameliorated soil and ameliorated soil without large channels or vughs are also shown together with intrinsic permeability (k_a) isolines.

These results indicate that fissures and channels are better organized for fluid transmission, in terms of permeability/unit volume (O) than poorly connected vughs.

The upper limits of k_a for a specific ε can be defined for granular structures, channels and fissures using Equations (3), (6) and (9). The lower limits are more difficult to define because large volumes of pore space may be occluded from fluid flow, e.g. chambers excavated by soil fauna, then partly collapsed to seal the entrance.

An index (E) to estimate the effect of shape in the macropore space

From Figs 1, 3 and 4 it is evident that intrinsic permeability (and hence saturated hydraulic conductivity) is more sensitive to changes of macropore space than macroporosity or organization. It has been recognized that measurements of air permeability and hydraulic conductivity can reveal extremely small changes of soil conditions caused by compaction (Soane *et al.*, 1980; Ball *et al.*, 1988). Therefore, it is useful to characterize the macrostructure in terms of intrinsic permeability and another parameter that is influenced mainly by morphology of the macropore space.

In Fig. 4 the dominant shapes of macropores are associated with different efficiencies of macropore space for fluid flow (fissures and channels are very efficient and vughs/packing pores are very inefficient). These differences of efficiency are reflected in deviation of O from the common trend between O and ε. Efficiency for fluid flow (E) can be defined empirically as the magnitude of the slope:

$$E = \log(O)/\varepsilon \qquad (13)$$

The E:k_a characteristic is shown in Fig. 5, with porosity isolines superimposed. The same data used in Figs 3 and 4 are included in Fig. 5. Samples dominated by vughs tend to have values of E less than 12 μm² and those dominated by channels or fissures have values greater than 20–25 μm². Granular structures dominated by packing pores have values between these two limits.

Conditions restricting root growth and water movement in swollen clay horizons can be considered by reference to lines of isoporosity in Fig. 5. The upper limit of permeability for a throttle ($k_a = 2.0$ μm²) approximates to $\varepsilon = 0.075$ for these Australian soils. Research on plant and root

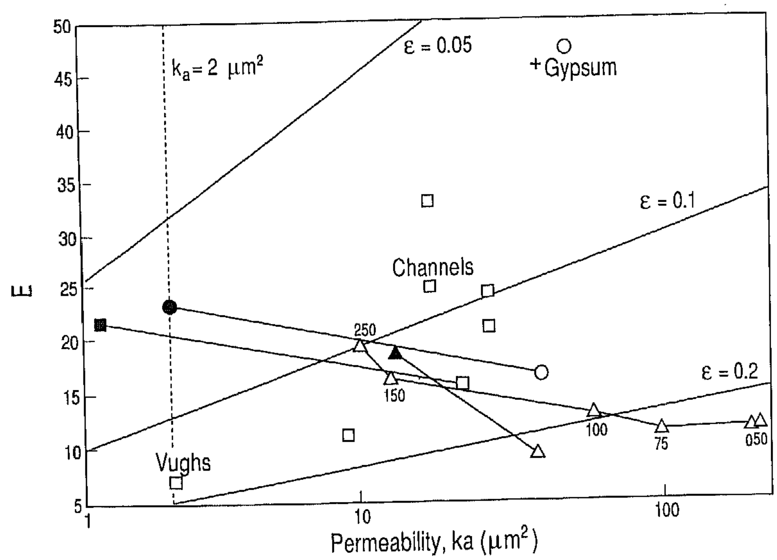

Fig. 5. The E:k_a characteristic relating intrinsic permeability to the efficiency of the organization of the pore space (E). Data from Figs 3 and 4 are shown with the same symbols. The upper limit of throttle condition ($k_a = 2.0$ μm²) is included. Isoporosity lines are also shown.

growth on the same soils (Jayawardane *et al.*, 1987) has also found 0.08 to be the lower limit of air-filled porosity for root growth unrestricted by oxygen supply. For larger values of E and similar low values of k_a, root growth has been noted along channels and fissures when $\varepsilon < 0.08$ (Douglas & Goss, 1987). Thus, the limits for root growth also may be defined in terms of a limiting value of intrinsic permeability.

This characterization of the macrostructure in terms of most sensitive property to change (permeability) and a single parameter related mainly to macropore shape (E) can be used as a basis for the comparison of responses of clay soil to external and internal forces and, in a more qualitative manner, to different management systems. However, it is no general substitute for more time-consuming direct morphological investigations, e.g. the same value of E may be derived from a granular structure, or a structure with a few coarse channels and many vughs. Thus, the O:ε and E:k_a characteristics are valuable compliments to direct morphological examination.

The use of intrinsic permeability to estimate saturated hydraulic conductivity

Intrinsic permeability to air (k_a) of macropores drained to -5 kPa was compared with intrinsic permeability to water (k_w) calculated from saturated hydraulic conductivity (K_s) ($K_s \cdot \eta/\rho$, where η is the viscosity and ρ the density of water). Fig. 6 shows the relationship between k_w and k_a for ameliorated and unameliorated Mundiwa clay loam. The common linear model was:

$$k_w = 0.772\,(\pm 0.022)\,k_a + 0.147\,(\pm 0.607)\ \mu\text{m}^2 \qquad r^2 = 0.955,\ n = 60 \tag{14}$$

The slope was significantly different ($P < 0.05$) from 1 and deviation from the model was greater for the ameliorated soil.

For the unameliorated soil alone there was a relationship with a different slope which was also significantly different from 1.

$$k_w = 1.164\,(\pm 0.079)\,k_a - 0.098\,(\pm 0.122)\ \mu\text{m}^2 \qquad r^2 = 0.859\ n = 38 \tag{15}$$

Neither linear regression had an intercept that was significantly different from zero.

There was a close relationship between k_a and K_w despite using cores with widely differing macropore space, including dense clay with few pores and many fissures and loose soil from slots

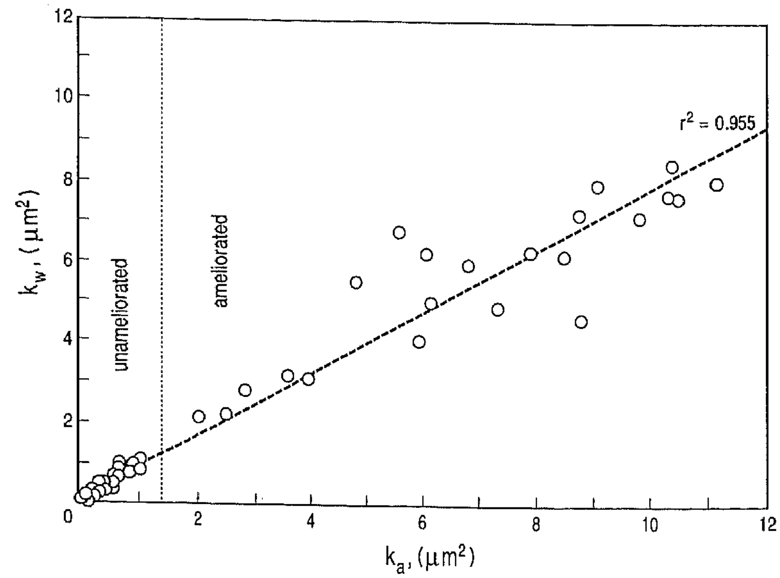

Fig. 6. Relationship between intrinsic permeability to water (k_w) and intrinsic permeability to air at −5 kPa (k_a) for unameliorated Mundiwa clay loam from 10–55 cm depth and ameliorated soil from 10–20 cm depth with the linear regression lines superimposed.

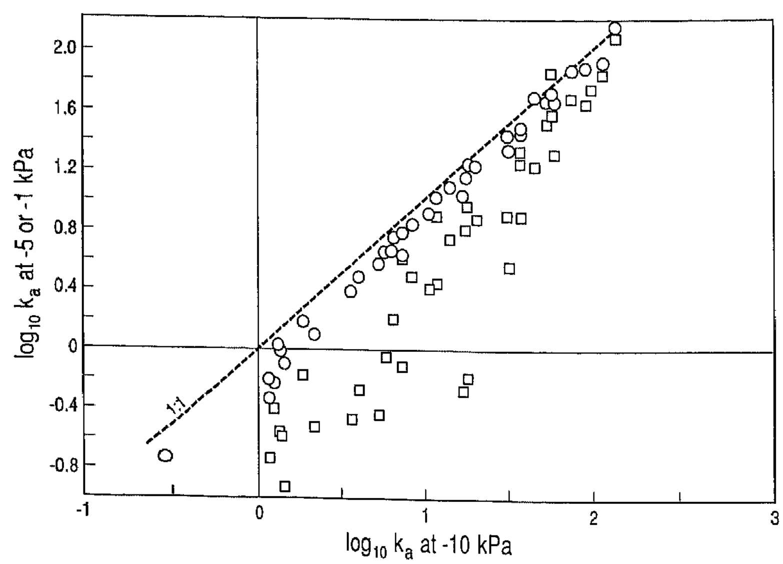

Fig. 7. The relationship between intrinsic permeability to air (k_a) at −5 kPa (○) or −1 kPa (□) matric potential and k_a at −10 kPa. The line for equal values is shown.

with high porosity and many vughs. Intrinsic permeability to water tended to be underestimated in the ameliorated soil. This can be explained by larger amounts of water flowing through pores water-filled at −5 kPa in the more permeable ameliorated soil than in the unameliorated soil.

Intrinsic permeability to air when drained to −10 kPa was related to, but slightly greater than k_a at −5 kPa (Fig 7). In this case the diffence between these measurements is small and k_a at −5 or −10 kPa can be considered as equivalent, especially at larger permeabilities. Therefore, if it is not convenient to drain cores of these soils to -10 kPa e.g. owing to shrinkage of loose soil, it is feasible to make the measurement at -5 kPa and estimate the equivalent k_a at -10 kPa. The larger variation in the relationship between k_a at -1 kPa and -10 kPa (Fig. 7) could be explained by varying degrees of occlusion of smaller macropores at the higher matric potential. These smaller macropores presumably allowed most of the air flow at -10 kPa in some of the cores.

CONCLUSION

1. A characteristic relationship between macroporosity and organization ($O = k_a/\varepsilon$, where k_a is intrinsic permeability to air and ε is macroporosity) can be derived for the macropore space of clay soils. This O:ε characteristic can be used to identify changes caused by soil management practices and biological activity.
2. The dominant shape of macropores in macropore space influences the efficiency for fluid flow and can be expressed as efficiency ($E = \log(O)/\varepsilon$). An E:k_a characteristic can identify influences on both intrinsic permeability of macropore space and dominant shapes of macropores and can be used in conjunction with observations of soil morphology.
3. Saturated hydraulic conductivity of clay soils with minimum air occlusion can be estimated from measurements of intrinsic permeability to air of the drained macrostructure using matric potentials of -5 or -10 kPa, provided dispersion is inhibited.

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