COMPACTION EFFECTS ON MINELAND SOIL QUALITY[1]

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Abstract. Management of water is vital to sustenance of biomass production and environmental quality of reconstructed minelands in semi-arid North Dakota. Since water resides and moves through soil pores, quantification of soil pore characteristics is a key to evaluate soil quality for reclamation success. We measured field saturated hydraulic conductivity (K) by double-ring ponded infiltration method on 26 premine and postmine profiles. The same profiles, each installed with a neutron probe access tube and a set of five tensiometers, were used to monitor post-infiltration redistribution of water by measuring volumetric water contents and matric potentials with time. An empirical equation was fitted to the soil water retention data to derive proportional distribution of various sizes of pores, maximum water capacity, median pore size, and a depth weighted pore index (Ω) to compare efficiency of each profile to transmit and retain water. The undisturbed premine soils showed high Ω's and high proportion of effective pores (ε) with radii > 5 µm. The reclaimed mineland profiles show low Ω and general deficiency of pores effective in transporting water to deeper depths. The pooled data from the premine and postmine soil profiles included in this study show that K increased linearly with Ω and ε^2. We recommend that the K - ε relationship be further evaluated by measuring infiltration and pore size distribution from various locations under different management conditions. If feasible, the easily measurable, profile scale, K - ε relationship provides a quantitative tool to evaluate soil quality of premine and reclaimed soils.

Additional Key Words: Land Reclamation, Soil Structure, Soil Hydrology

Introduction

About 800 - 1000 hectares of prairie landscapes in western North Dakota are annually disturbed for surface mining of lignite coal. Following the Surface Mine Control and Reclamation Act (U. S. Congress, 1977) guidelines, federal and state regulations on surface mining mandate that the disturbed lands be reconstructed to a level of productivity and environmental quality equal to or better than before mining. To achieve this goal, previously stripped non-sodic subsoil (original lower B and upper C) and topsoil (original A and upper B) materials are respread over reshaped spoil. The depth of respreading depends upon the physical and chemical properties of the spoil. Scrappers are generally used to respread the materials at about 15-cm increments until the desired depths of subsoil and topsoils are achieved (Halvorson et al., 1986). Vegetation is reestablished and, following the SMCRA guidelines, the quality of reclaimed soils are assessed on the basis of respread soil depth and biomass yield.

In the undisturbed Mollisols of western North Dakota, the natural prairie vegetation and associated granular soil structure supports rapid movement of water through well-developed inter-aggregate voids and biologically created macropores. When these soils are mined, the existing network of soil pores is destroyed.

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During land reclamation after surface mining, the frequent and heavy vehicular traffic used in spreading and leveling operations cause compaction resulting an abundance of fine sized inter-aggregate pores. As a result, reclaimed soils lack the effective pore volume and continuity needed for adequate distribution of water and roots (Chong et al., 1986). Potter et al. (1988) compared pore volumes of constructed mine soils of 4 and 11 years after reclamation with undisturbed soils. They observed that mesopore volume (pore radii > 15 μm) of reclaimed soils and associated hydraulic conductivities, especially of the subsoil layer, were significantly lower than the undisturbed soils.

Soil quality relates to the ability of soil to function as medium for plant growth, as partitioner and regulator of water, energy, and solute fluxes in the landscape and biosphere, and as filter and buffer for inorganic and organic pollutants (Larson and Pierce, 1994). A good quality soil sustains onsite productivity, efficiently utilizes available water and nutrients, and minimizes offsite damages to water and air quality. By replacing suitable soil material to specified depths, the current reclamation mitigation package seeks to reconstruct the rootzone and achieve reference area biomass productivity. However, it ignores the role of the root zone pore space to harvest precipitation water for maximum plant growth. While the current technology tries surficial control of overland flow and effluents to minimize onsite and offsite damages, it fails to stress the role of the reconstructed root zone pore structure to achieve hydrologic balance in the watershed.

Larson and Pierce (1994) favor the use of a dynamic systems approach to assess soil quality by evaluating a management system in terms of its actual performance in the watershed rather than an output comparison with other systems. A systematic observation of changes in soil quality parameters and their behavioral indications in energy, water, sediment, and solute fluxes in the watershed should be the proper approach to monitor the success of reclamation. Since water is the key integrator of these fluxes and water resides and moves through soil pores, we propose that characterization of pore structural aspects of root zone soil quality is fundamental to the restoration and sustenance of agricultural productivity and environmental quality of restored ecosystems

To understand the effect of root zone soil characteristics on distribution of water on reclaimed lands vis-à-vis that of premine lands and pre-law abandoned minelands, we measured infiltration, water retention and seasonal variability of soil water contents on surface coal minelands of North Dakota from 1989 to 1993. The data on seasonal distribution of soil water (Sharma et al., 1993) and infiltration experiments (Sharma et al., 1994) were presented elsewhere. In this paper, we report on water retention characteristics and infer the profile scale pore structural attributes of soil quality.

Materials and Methods

Constant head, ponded infiltration was measured by double ring method (Bouwer, 1986) on premine lands, abandoned minelands, and reclaimed mineland profiles at Indian Head (T144N R89W sec. 24 and 25) and Velva (T152N R81W Sec. 27,28, 33 and 34) mines in west-central North Dakota. Prior to water application, a neutron probe access tube was installed at the center of the inner ring using a hydraulically driven core sampler of equivalent diameter to the access tube. Additionally, side walls of the access tube hole was carefully repacked by pouring loose soil material around the tube and tamping with a small metal rod. Marriotte bottles were used to supply constant head of water in the rings and infiltration measured for 2 to 3 hours. The infiltration volume vs. time data were fitted with infiltration equations to evaluate the parameters of sorptivity and field saturated hydraulic conductivity (Sharma et al., 1994).

After about 15-22 days of the first infiltration run, tensiometers were installed inside the inner ring on 26 of a total of 40 profiles used for infiltration. The tensiometers were fitted with high flow (air-entry pressure = 100 kPa) porous ceramic cups and installed at depths of 15, 30, 46, 61, and 76 cm. Before installation, each tensiometer tubing was plastered with wet bentonite, and installation, the space around the tensiometer tubing was back filled soil and repacked to prevent preferential flow.

The tensiometers were filled with deaired, distilled water and closed with rubber septa. The hydraulic potential was measured with a transducer readout system by inserting a hypodermic needle through the septum (Marthaler et al., 1983). A second infiltration run was conducted until the deepest tensiometer indicated a steady state reading. Water supply was then stopped, and the profile covered with mulch and heavy plastic to prevent evaporation. After about 30 days of redistribution, the mulch and the plastic were removed to allow free evaporation.

During the redistribution process, measurements of neutron probe and tensiometers were recorded at short time intervals in the beginning then daily, and weekly, at later times. The measurements were discontinued when the top two tensiometers stopped functioning due to air-entry into the ceramic cups. At the end of the experiment of about 45 to 60 days, disturbed samples taken at the approximate depth of the tensiometer locations were used to determine 1500 kPa water contents in the laboratory using a pressure membrane apparatus (Klute, 1986).

The relationship between the volumetric water contents and the corresponding matric suctions at each tensiometer depth is represented by the following two parameter closed form equation (van Genuchten, 1980):

$$\Theta = (\theta - \theta_r)/(\theta_s - \theta_r) = [(1 + (\alpha h)^n]^{(1/n-1)} \quad (1)$$

In the above equation, Θ is relative saturation; θ is water content, m^3/m^3; θ_r is residual water content, m^3/m^3, θ_s is near saturation water content, m^3/m^3; and h is matric suction in kPa. For this analysis, we used θ_r equal to the laboratory measured 1500 kPa water content and θ_s equal to 85% of the total porosity (calculated from bulk density of the samples) to approximate incomplete satiation under field conditions. The θ_s and θ_r only represent the upper and lower limits of the fitted curve, and hence, do not have a physical meaning. The curve shape parameters, α and n are derived by nonlinear curve fitting of Eq. [1] to the measured data. For freely draining undisturbed and abandoned mineland profiles, Eq. [1] fitted the data fairly well with nonlinear regression coefficients > 0.95. For tensiometers at deeper depths of reclaimed soils and at highly sodic-clay profiles, the fitting of data was erratic with nonlinear $R^2 > 0.70$.

From Eq. [1], the rate of water desorption ($d\theta/dh$), defined as the water capacity (ϕ, 1/ kPa) is calculated as (Horton and Chung, 1991):

$$\phi = (n-1)\,(\theta - \theta_r)\,[1 - \Theta^{\{n/(n-1)\}}]\,/h \quad (2)$$

The matric suction (h) at which the ϕ is maximum (ϕ_{max}) is converted to corresponding median pore size (η, μm) by dividing 150 with h. The constant of 150 comes from the capillary equation between matric suction (kPa) and capillary radius (μm) at 20° C (Gupta et al., 1989). The median pore size is assumed to represents the size of pore at which most of the water at the point of measurement will be released due to forces of gravity, root extraction, or upward flux due to evaporative demand of the surface (Hillel, 1980). From N tensiometer measurements at the various depths, a depth weighted pore index (Ω) of the profile is calculated by cumulating the product of η and ϕ_{max} for each depth of measurement:

$$\Omega = 100/z \sum_{T=1}^{N} \eta\, \phi_{max} \quad (3)$$

Here, T is the count of tensiometers and z is the depth of the deepest tensiometer, cm. The factor of 100/z is used to extrapolate the Ω value to a meter of root zone depth. The Ω index is used to assess the relative depth integrated capacity of the various profiles to desorb water. Hence it is a measure of profile scale soil pore structure.

From the soil water retention data measured at each tensiometer depth, we derive pore size distribution using the following pore classification scheme (Table 1).

Table 1: Classification of pore sizes

Pressure head (kPa)	Pore radii (μm)	Pore class
< 3	> 50	Macropores
3 - 30	5 - 50	Mesopores
30 - 1500	0.1 - 5	Micropores
> 1500	< 0.1	Residual pores

Note: The proportion of macropores and meso-pores (volume of pores with radii > 5 μm) are collectively called effective pores. Traditionally, the volume of water held in the effective pores is defined as drainable water, and that in the micropores is called available water.

Results and Discussion

To demonstrate the effect of compaction on water retention and water capacity curves, we purposefully chose six typical premine and postmine profiles from the data set. Table 2 lists the location, major characteristics, hydraulic conductivity (K), and depth averaged median pore size (η) and weighted pore index (Ω) of the six profiles. The undisturbed (Z215I, V116) and the compacted (Z511, Z004) premine soils mainly consist of the Flaxton - Williams association (Typic haploborolls) with wind and water deposited sediments overlying glacial tills. The root zone texture ranges from sandy loam to clay loam with undisturbed profiles having a well developed aggregated structure due to dominance of natural prairie vegetation. The topsoil and subsoil layers of the reclaimed profile at Indian Head (Z503), consisting of sandy loam to loam materials, are underlain by loam to silty clay, sodic minespoil materials. The profile at Velva (V102) shows a typical pre-SMCRA characteristics with haphazard respreading of overburden materials.

Table 2: Site characteristics and pore structural indices of six representative premine and reclaimed soil profiles.

Mineland Type	Location	Dominant Characteristics	η[†] (μm)	Ω[‡] (μm/kPa)	K[§] (cm/h)
Premine undisturbed	Z 215I	sandy loam, natural prairie	30 (12.7)	5.42	26.33
	V116	clay loam, natural prairie	46 (8.0)	7.91	11.82
Premine compacted	Z511	vehicle traffic, hay	26 (6.9)	0.85	1.54
	Z004	vehicle traffic, grazing	24 (11.8)	0.73	0.50
Postmine reclaimed	Z503	post-SMCRA, hay	21 (14.4)	0.93	1.64
	V102	pre-SMCRA, grazing	14 (3.3)	0.08	1.82

[†] Median pore size, [‡] Weighted pore index, [§] Satiated hydraulic conductivity. The numbers in parenthesis are standard deviations.

Representative Water Retention Curves

Figure 1 shows the soil water retention characteristics with depth of the two undisturbed prairie soils from the Indian Head (Z215I) and Velva mine (V116). The sigmoid-shaped curves show the fitted water content versus pressure head relationships (Eq. [1]), and the bell shaped curves represent the derived specific water capacity versus pore size relationships (Eq. [2]) with depth. The curve shapes are more pronounced on the well aggregated clay loam profile (V116) than the sandy loam profile (Z215I). Table 2 shows that the depth weighted pore index (Ω) and hydraulic conductivity of these two profiles are significantly higher than those of premine compacted and reclaimed soils.

Examples of water retention and specific water capacity curves of compacted premine soils in the vicinity of minelands are shown in Fig. 2. These profiles were subjected to heavy vehicular traffic during mining in the 1970's. After mining was completed in the early 1980's, profile Z511 was managed with alfalfa hay while the profile Z004 was used for intensive grazing. Compared to the undisturbed profiles (Fig. 1), the retention and specific water capacity curves of the compacted profiles (Fig. 2) are flatter. Compaction has decreased the total pore volume at the cost of inter-aggregate effective pores and increased the volume of intra-aggregate residual pores. Compared to the undisturbed profiles shown in Fig. 1, the weighted pore indices (Ω) of these two compacted profiles were < 1.0.

Figure 3 shows the soil water retention characteristics and specific water capacity curves of the reclaimed profiles listed in Table 2. The Z503 profile at the Indian Head mine was reclaimed under the SMCRA guidelines in the early 1980's and restored with grass-legume hay crop. The bulged shape of the 15-cm water capacity curve indicates that the topsoil of Z503 has an improved pore structure than subsoils at deeper depths. Compared to those of the undisturbed profiles which show pronounced curve shapes throughout the depth (Fig. 1), the deeper depths of this reclaimed profile has flatter shapes indicating poor structure development. The Z503 profile has a Ω index of 0.93 which is comparable with the compacted premine profiles (Table 2).

The profile at Velva (V102) was not reclaimed as per the SMCRA guidelines, and since the vegetation reestablishment, the land is used for grazing. This overgrazed, reclaimed profile at Velva (V102) shows a severe lack of porosity with depth. Despite overnight saturation, the deeper tensiometers in this profile did not show any response during infiltration and during subsequent redistribution process. The Ω index of 0.082 calculated from the three remaining tensiometers weighted for 1.0 m of root zone depth (Eq.[3]) indicates a massive structure.

Pore Size Distribution

The depth averaged pore size distribution of the 26 different profiles for which soil water retention characteristics were measured in the field are shown by bar diagram in Fig. 4. The number at the bottom of each bar represents the average total pore volume of which the proportion of macropores, mesopores, micropores, and residual pores are shown in shades. The number at the top of each bar denotes the weighted pore index (Ω) of each profile.

In general, the six undisturbed premine profiles and the two non-sodic profiles (Z213, Z214) in the abandoned minelands show higher pore volumes. In these profiles, macropores and mesopores (effective pores) constitute about 50% of total pore space. The comparatively higher Ω index of these profiles signify a pore structure with potential to efficiently transport and store precipitation and runon water.

Compared to the well structured soils, the total pore volumes and Ω indices of the four premine compacted soils and the six reclaimed soils are smaller in magnitude. The decrease in total pore volume due to compaction is mainly due to a decrease in the proportion of macropores and mesopores. Only about 25% of the total pore volume is occupied by effective pores. Of the four premine compacted soils shown in Fig. 4, Z511 is the farthest from the mine area with a Ω index of 2.45. The Ω indices of other premine compacted and reclaimed profiles are < 1.0. The abandoned minelands, on the other hand, show high total pore volume and a wide range of Ω values. Though not compacted, the ability of abandoned mineland profiles to transport and retain water, as signified by the Ω index, is limited by the location of sodic clay materials in the root zone. The three sodic spoil profiles (Z211, Z703, V205) have the lowest Ω and hydraulic conductivities.

Hydraulic Conductivity vs. Pore Indices

The structural signature of a soil profile is typified by its pore characteristics defined by the number and size of pores, their continuity, tortuosity and stability. The entry and rate of movement of water and its retention in soil are dependent upon the depth integrated pore characteristics of the profile. While effective porosity is a measure of the volume of large size pores, the hydraulic conductivity is a measure of the continuity and tortuosity of these pores. A relationship between the two parameters is an indicator of relative pore structure of various premine and postmine soils with respect to their ability to transport water.

We regressed the hydraulic conductivity (K) calculated from ponded infiltration experiments (Sharma et al., 1994) against the volume of effective pores (ε) and the weighted pore index (Ω) derived from water retention experiments. The K-ε relationship was derived by nonlinear curve fitting of the form $y=ax^b$, of which, the exponent 'b' was 2.02. For clarity of interpretation, we refitted the data with $K=a\varepsilon^2$. The K-Ω relationship was derived by linear regression.

Figure 5 shows that even for data from various heterogeneous premine and postmine soil profiles, K increased with ε^2 and the Ω index. Also shown in Fig. 5 inset, the best estimates for K (cm/h) for the data set included in this study are as follows:

$$K = 1.276 \times 10^{-4}\,\varepsilon^2 \qquad (r^2 = 0.86) \qquad [4]$$

$$K = 1.243 + 1.302\,\Omega \qquad (r^2 = 0.81) \qquad [5]$$

The intercept in Eq. [5] is not significantly different from 0. Of the 26 field measurements included in this regression, there were three outlier data from infiltration into coarse textured undisturbed and nonsodic abandoned mineland profiles. These profiles contained big desiccation cracks and numerous colonies of ants; in comparison to their effective porosities, these profiles had excessive infiltration rates.

Figure 5 demonstrates how a generalized profile scale K- ε or K- Ω type relationship is useful in comparing the pore structural qualities of premine and postmine profiles. For simplicity of measurement, we recommend that the K-ε relationship methodology be further evaluated with measurements on additional premine and postmine soils from different locations and under various management systems. As K can be easily measured from the steady state infiltration rate, ε can be calculated from the measurement of volumetric water content at 30 kPa (near field capacity) from undisturbed samples in the laboratory. On the other hand, development of the K-Ω relationship requires expert knowledge; it is time consuming, and the data is highly dependent upon precision and robustness of tensiometric instrumentation used under field environments.

Conclusions

The data, in general, show that the undisturbed soils have high effective porosities and associated hydraulic conductivities. The pore structural attributes of abandoned minelands show the widest range of variability depending upon the location of sodic spoil material in the profile. The post-SMCRA reclaimed profiles with subsoil and topsoil replacements show improved pore structure than when the sodic spoil materials are respread alone. However, the structural quality of these reclaimed profiles was only comparable to compacted premine soils and at a level significantly lower than that of the undisturbed premine profiles.

The data in this study and previous studies on soil structure of reclaimed soils in North Dakota and elsewhere indicate that soil structure regeneration due to natural processes of wetting-drying and freezing-thawing is extremely slow to nonexistent. With the current land reclamation technology and grass-legume hay crop as postmine land use for a decade or more seems to have improved the pore structure to a depth of about 0.3 m. The studies also point out that the deeper depths of reclaimed subsoil show a severe lack of pore space and pore continuity. The repercussion of this lack of adequate pore space in the subsoil results in a restricted root zone with lack of available water during drought and oxygen during floods. For sustained productivity of reclaimed soils, it is recommended that respreading technology, post-reclamation land management, and reclamation evaluation guidelines need to focus on increasing the effective porosity of the entire root zone.

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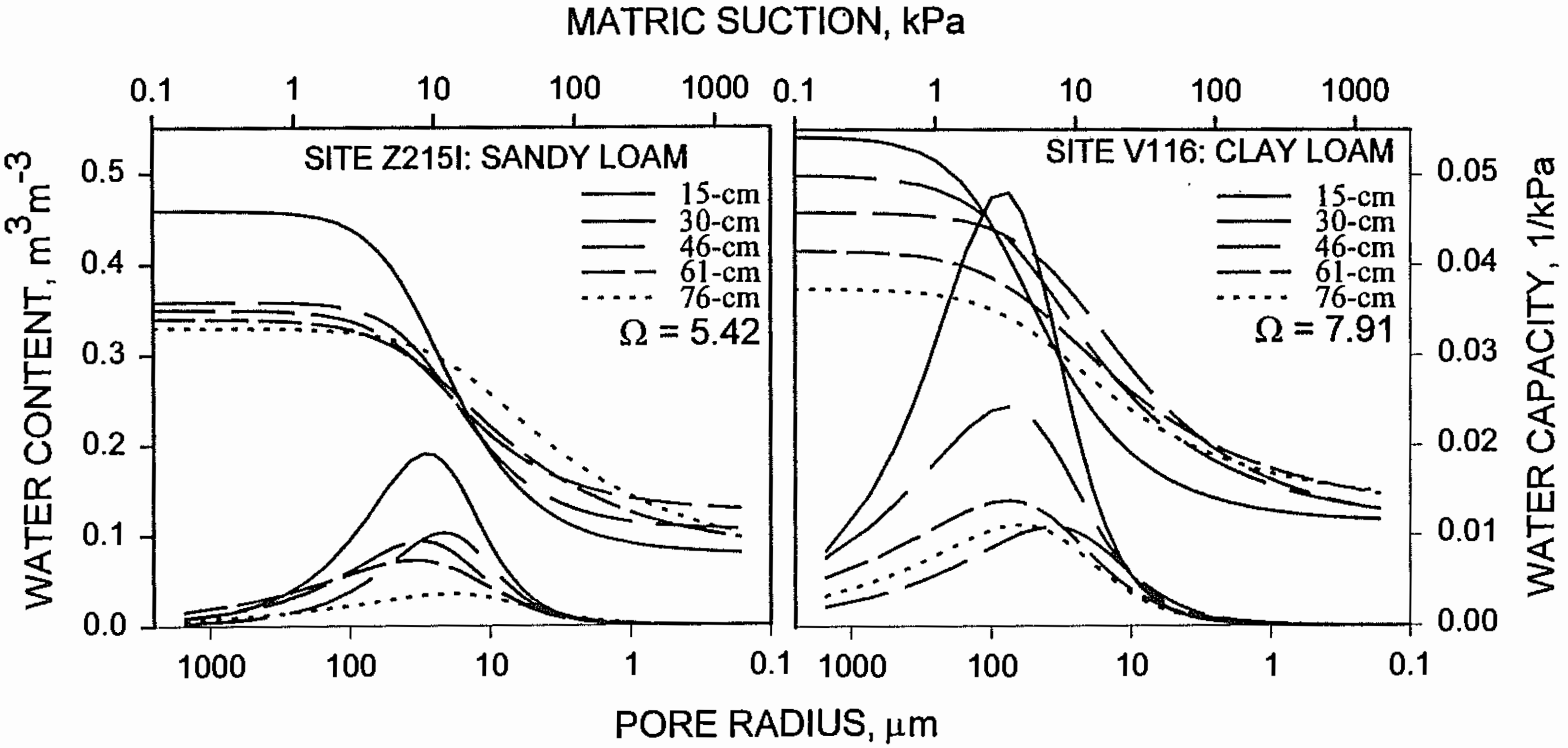

Fig.1: Fitted soil water retention and water capacity curves for two premine undisturbed profiles.

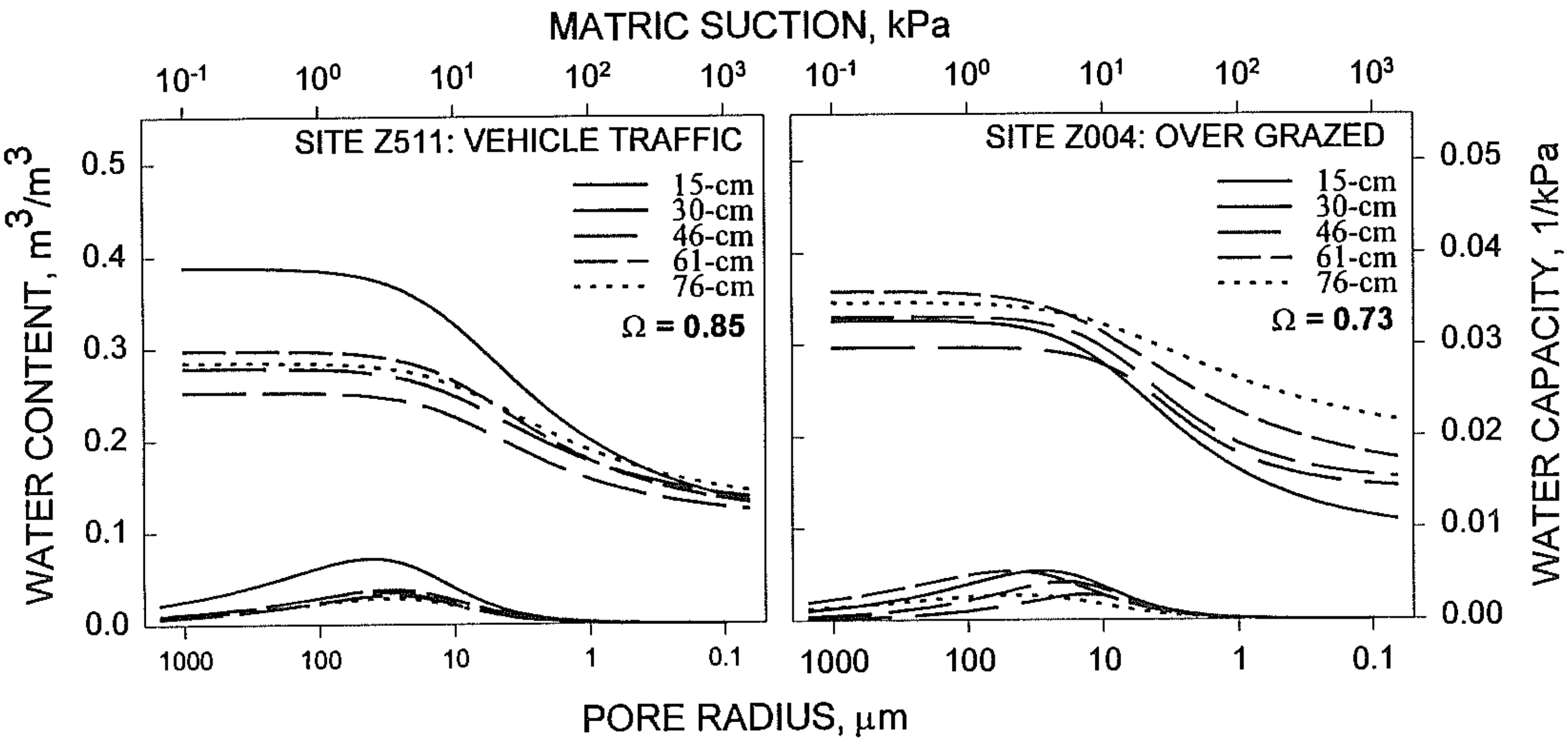

Fig. 2: Fitted soil water retention and water capacity curves for two premine compacted profiles.

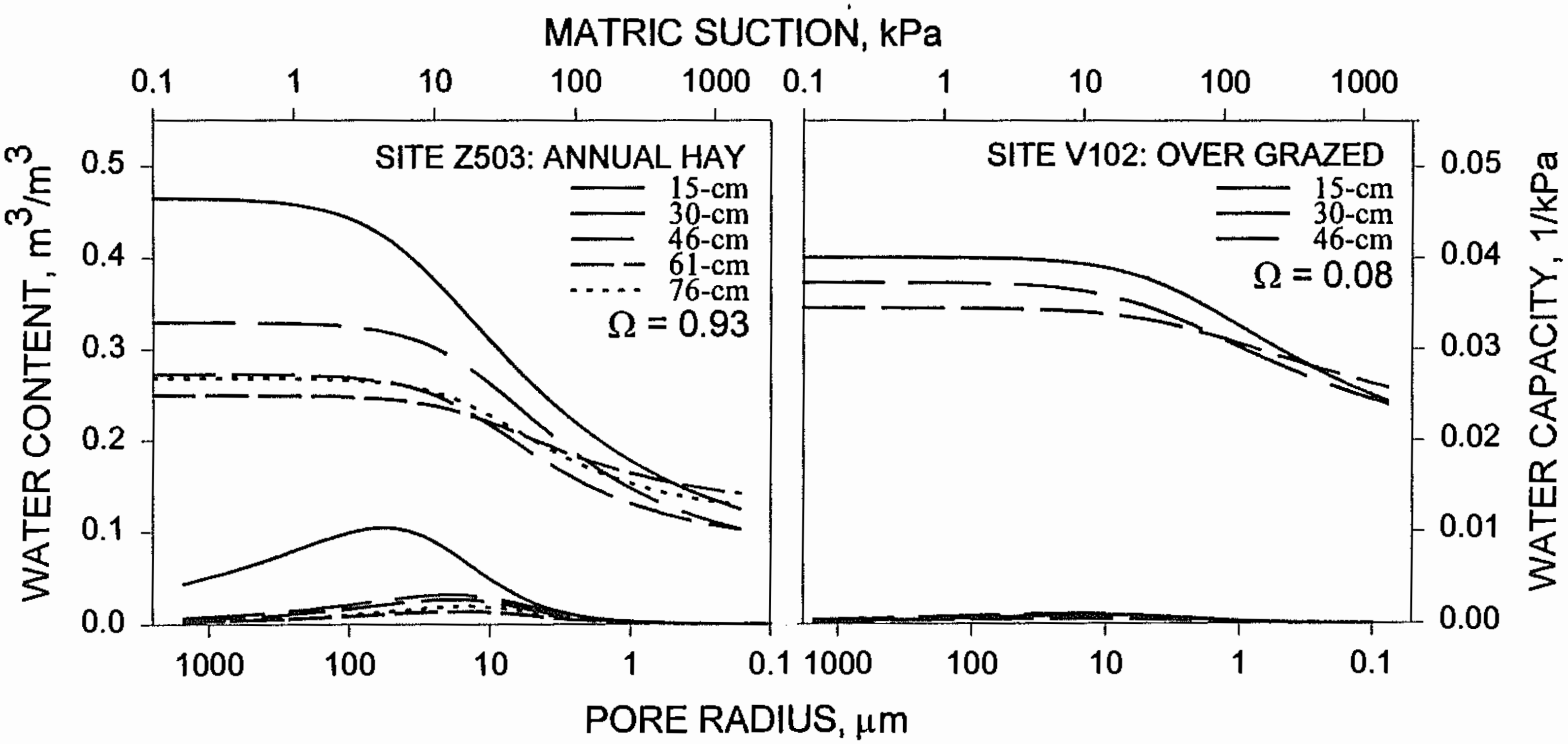

Fig. 3: Fitted soil water retention and specific water capacity curves for two reclaimed profiles.

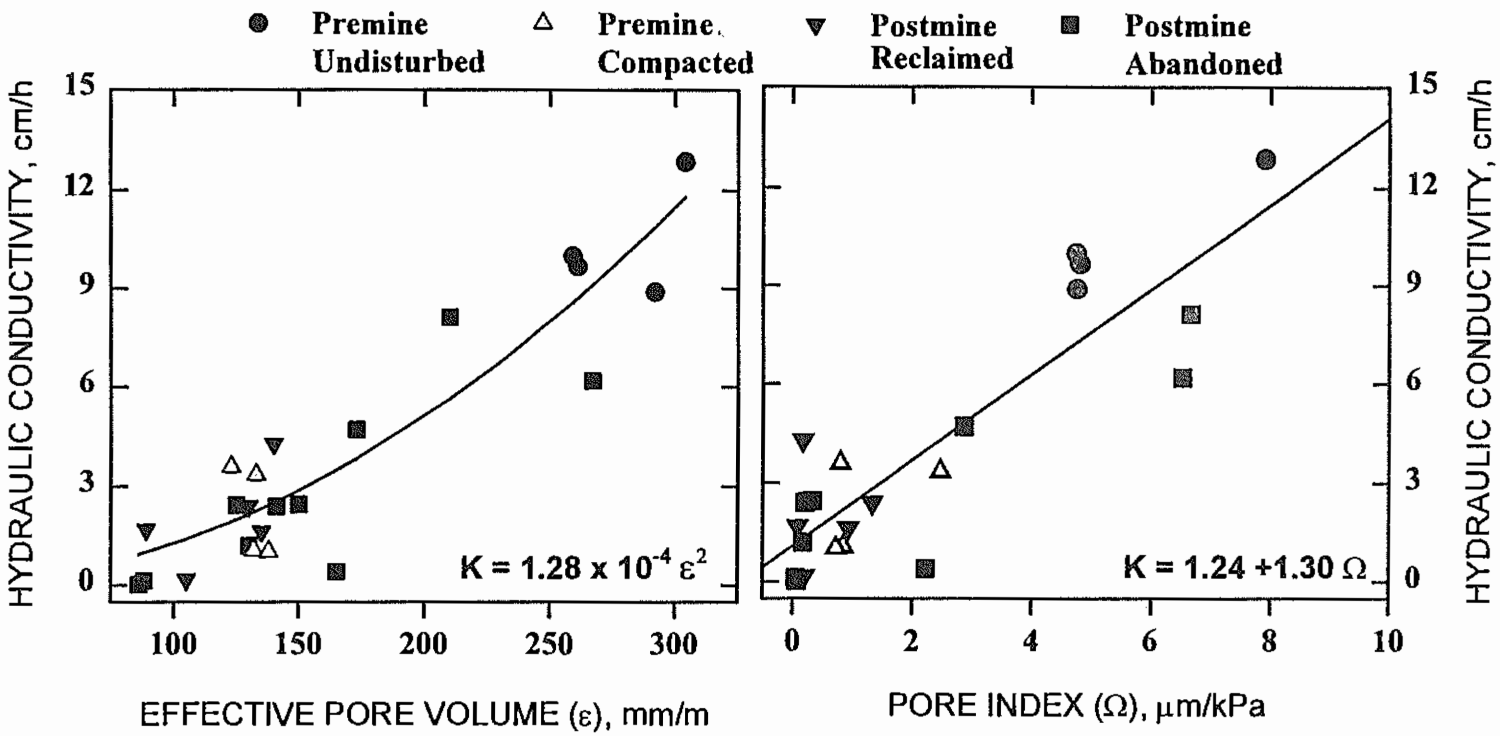

Fig. 5: Field saturated hydraulic conductivity(K) as a function of average volume of effective pores (ε) and weighted pore index (Ω) of premine and postmine soil profiles.

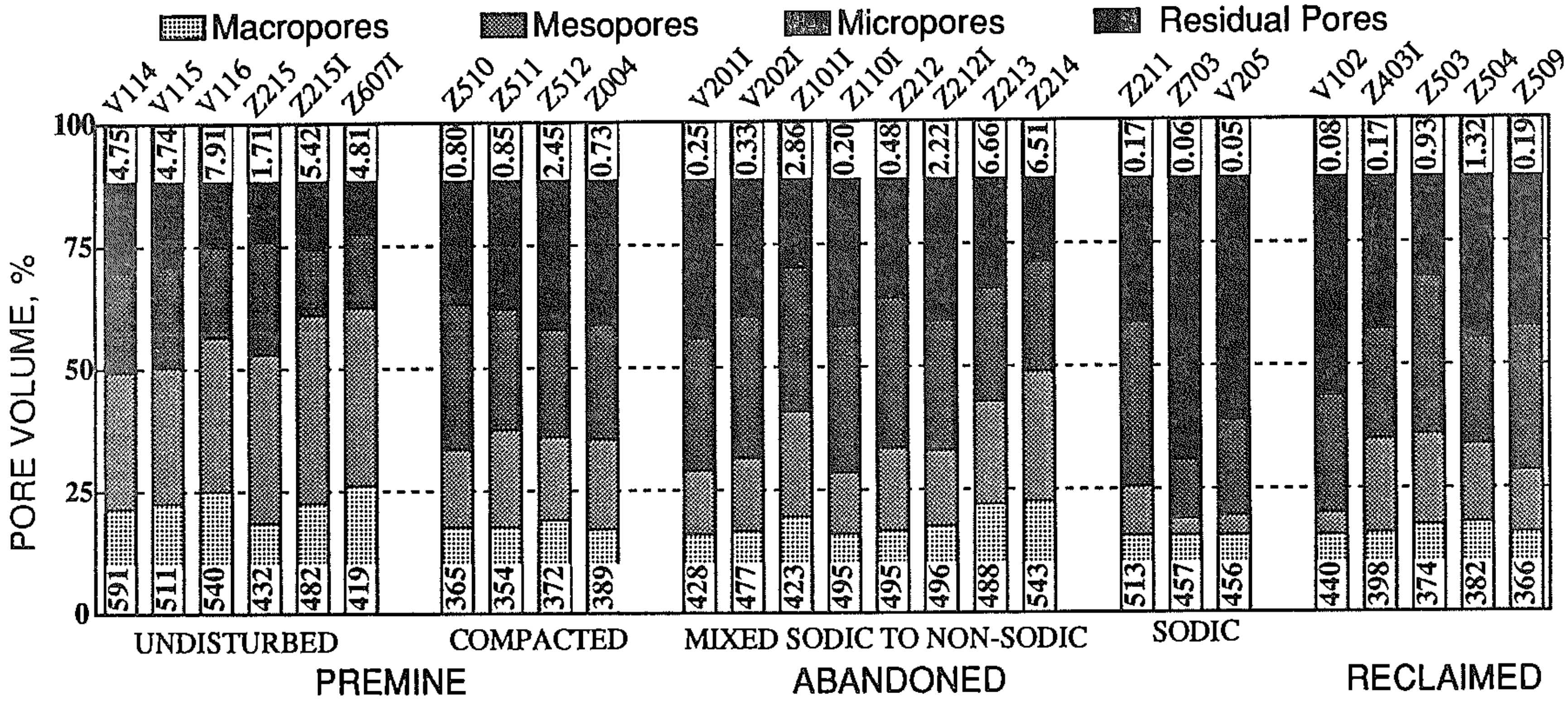

Fig. 4: Depth averaged pore size distribution of 26 pre- and post-mine soil profiles. The numbers at the bottom of each bar represent average total pore volume (mm/m), and those at the top represent the weighted pore index (Ω) of each profile.