Soil Phys. Cond. Plant Growth, Jpn.
土壌の物理性
No. 81, p. 5～14 (1999)

Response of Soil Hydraulic Conductivity to Prewetting Rates and Water Quality

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Abstract

Physical disintegration of aggregates as a response to externally imposed disruptive forces to soil or the physico-chemical dispersion and swelling of soil clays (soil intrinsic behavior) are often reported to cause deterioration in the hydraulic properties of soils. The joint effect of these two mechanisms on column hydraulic conductivity (HC) of different soils was studied. Three prewetting rates (PWR) of 1, 6 and 30 mm/hr and a water quality characterized by sodium adsorption ratio (SAR) 10 and total electrolyte concentration (TEC) of 0.5, 0.05, 0.01 $\mathrm{Mol_c\,L^{-1}}$ and distilled water (DW) were used. The results showed that absolute values of HC and its relative changes over time depended on the type of soil, the PWR, the TEC, and the aggregate size. HC decreased with an increase in the silt and clay content, with an increase in the PWR, and with a decrease in the TEC of the percolating solution. Soils that slaked into microaggregates under the effect of fast PWR, showed a substantial decrease in HC with an increase in the PWR. In structurally unstable soils, fast PWR caused more slaking and physical disintegration of aggregates that restricted water flow leading to low HC. HC of the columns that sustained greater slaking also deteriorated more under the effect of dilute solutions. The larger the aggregate size fraction, the more pronounced was the PWR effect on HC apparently due to greater pore throttling by the slakes. Development of cohesive forces between clay structural units with time (aging) was suggested to counteract HC deterioration as observed for smaller aggregate size fraction of this soil. HC of less aggregated or structurally stable soils were less affected by the PWR. The study also indicated that PWR effects on soil HC could be satisfactorily predicted from soil aggregate stability tests.

Key words : Prewetting rate, hydraulic conductivity, slaking, dispersion, swelling

1. Introduction

Saturated hydraulic conductivity (HC) is an important soil hydraulic parameter as it establishes a limit on the rate of water and solute or pollutant transmission through the soil. It is also an important variable in design of drainage systems and estimation of runoff from either a rainfall catchment or irrigated areas. HC is known to be a combined property of the soil and the quality of the water flowing through it.

On irrigated or cultivated soils, changes in HC in general and its deterioration with time in particular is often attributed to either of the following two mechanisms : (I) Physical disintegration and swelling of soil aggregates due to disruptive forces of soil wetting process leading to the formation of low-permeable layer ; or, (II) Physico-chemical dispersion and swelling of soil clays, which clog and narrow water-conducting pores in the soil. The processes involved in influencing soil hydraulic properties under mechanism (I) are mechanical in nature and are determined primarily by analysis of forces generated due to kinetic energy of water droplets (Moldenhauer & Kemper, 1969) or surface flowing water (Kemper *et al.*, 1985) in relation to impacts induced on the stability of soil aggregates. Influences due to mechanism (II), however, are controlled mainly by the concentration and composition of cations in the soil and/or in the solution flowing through it (Agassi *et al.*, 1981). The effects due to the latter mechanism have been well studied and can be predicted satisfactorily from basic mineralogical and chemical properties of the soil (Shainberg & Levy, 1992) and the quality of the percolating water. However, the role of the former mechanism in influencing the hydraulic properties of soils is relatively more complex to be defined yet. The dependence of the processes involved on intrinsic soil properties as well as extrinsic factors accounts for the complexity. Moreover, the interaction of these two mechanisms in influencing the HC of soils has been paid less attention and thus less knowledge or information is available despite its practical significance.

The intrinsic soil behaviors upon which soil aggregate stability largely depend include organic matter, clay and oxide contents (Kemper & Koch, 1966), which are known to be cementing agents that keep soil particles together in an aggregate. However, factors like initial water content, rate of wetting, aggregate size fraction, as well as the method of determination of aggregate stability influence aggregate stability index of soils (Kemper & Rosenau, 1986). In the same report, they indicated that soil wetting could be a highly disruptive process and if a dry soil aggregate is wetted quickly, the wetted portion can swell appreciably compared to the dry portion, and the nonuniform swelling can break many of the cohesive bonds that hold the particles into aggregates. Furthermore, quick wetting was reported to give rise to escape of entrapped compressed air that ultimately cause slaking (spontaneous breakdown of aggregates into microaggregates). Conversely, slower wetting avoids entrapment of air, and reduces spatial swelling differences leaving a larger portion of the particles cohering in the aggregates.

The practical significance of soil aggregate stability has been well appreciated in studies on erosion. Nijhawan & Olmstead (1947) noticed that aggregates at high water contents were more resistant to slaking forces than air dried aggregates. Cernuda *et al.* (1954) reported that aggregate stability results were meaningful only when the initial soil moisture condition was clearly defined. Lyles *et al.* (1974) found that more than twice as much soil was detached from large dry aggregates by raindrop impact as from aggregates which had been moistened prior to the rainfall event.

The diverse conclusions and suggestions of the various researchers above apparently demonstrate that soil aggregate disintegration and the changes in soil HC are dynamic processes which depend on soil conditions. The objective of this work was to study the effect of prewetting rate (PWR) on the hydraulic conductivity of different soils and to investigate the interaction of the physical and physicochemical mechanisms in influencing the same soil hydraulic parameter. PWR, herein is defined as the rate at which water is applied to an initially dry soil (to saturate) prior to subjecting it to a constant head device for HC measurement. The paper discusses HC results obtained from tests conducted on laboratory column studies.

2. Materials and Methods

Two soil samples from A- and B-horizons of Lower Syr-Darya Plain (Kzyl-Orda, Kazakhstan), hereafter referred to as A- and B-horizon samples, and a Paddy soil from the Agricultural Experiment Station of Tottori Prefecture (Japan) were used in this study. Some properties of these samples are given in Table 1. Oven-dry (at 105℃) samples were crushed to pass through 2 mm sieve size and stored in a room (20℃) where the experiment was conducted. Then 120 g each of the samples stud-

Table 1 Some properties of the samples studied

Item	Soil type		
	A-horizon	B-horizon	Paddy
Sand (%)	65.9	12.1	48.3
Silt (%)	18.1	49.0	29.3
Clay (%)	16.0	38.9	22.1
Mineralogy	smectite, chlorite, vermiculite	smectite, chlorite, vermiculite	halloycite, kaollinite, illite
CEC (cmol$_c$/kg)	7.7	14.3	13.5
Gypsum (%)	1.6	3.4	—
Organic matter (%)	0.7	0.5	2.5

ied were packed into 50 mm diameter plastic columns. The packing was done slightly to reproducible dry bulk densities given in Table 2. The length of the soil columns ranged between 4.3 and 5.5 cm corresponding to bulk densities of 1.42 and 1.11 g/cm^3, respectively. Bottom support for the soil columns was provided by a rubber stopper with a hole that lead the outflow to a fraction collector set to desired times. Cheesecloth covered with a 5 mm layer of sand served as a filter. Initially the columns were prewetted (to saturation) from bottom with a 0.5 mol$_c$ L^{-1} solution of sodium adsorption ratio (SAR) 10 at three PWR of 30, 6, and 1 mm/hr, applied by a peristaltic pump. The beaker from which the saturating solution withdrawn was placed on an electric balance to monitor weight/volume changes against cumulative pump flows. Once saturated, the columns were leached from the top with the same solution long enough for the exchangeable sodium percentage (ESP) of the column soils to be in equilibrium with the SAR of the percolating solution (U.S. Salinity Laboratory Staff, 1954).

Effect of water quality was evaluated by measuring HCs of each of the soil columns by successively displacing leaching solutions having total electrolyte concentration (TEC) of 0.5, 0.05, 0.01 Mol$_c$ L^{-1} and finally distilled water (DW) using a constant head device. The columns were subjected to a hydraulic heads of either 20- or 100 cm depending on the rate of flow. For each of the solutions, HC measurement was continued until steady state flow was attained and the corresponding effluent composition in terms of electrical conductivity (EC) is given in Table 2. Each treatment was, at least duplicated. Same procedure was repeated for the B-horizon sample segregated into 0~1 and 1~2 mm size fractions to look into the effect of aggregate sizes. Samples of the three soils were wet-sieved for stability test using Yoder (1936) method. Samples of the soils at three initial conditions, dry, prewetted at rates of 30 and 1 mm/hr were placed on the top sieve of each nest, and the nest was lowered to the point where the soil sample in the top screen was just covered with water. A motor and a mechanical arrangement lowered and raised the nest of sieves through a distance of 3.18 cm at a rate of 30 cycles/min for 0.5 hr. The amount of soil retained on the nest of sieves (>0.1 mm in size) for each of the soils' conditions at placement were determined by drying and weighing. Size fractions < 0.1 mm in diameter were determined by sedimentation, decanting, drying and weighing.

3. Results and Discussion

3.1 Prewetting Rate (PWR) Effect on Soil Hydraulic Conductivity

Table 2 presents the properties of the soil columns studied. The reference HC (Table 2), hereafter referred to as HCo is the absolute value of the respective column's HC taken at

Table 2 Results of the columns studied

Soil Column	PWR (mm/hr)	HCo (mm/hr)	Pore volume (cm^3)	Density at 0.5M* (g/cm^3)	RHC (Ratio to HCo)			EC (dS/m)		
					0.05M*	0.01M*	DW	0.05M*	0.01M*	DW
A-horizon (0～2 mm)	1	38.12	38.2	1.42	0.97	0.91	0.55	5.70	2.70	1.90
	6	38.12		1.42	0.93	0.86	0.52	6.00	2.70	1.80
	30	32.87		1.42	0.92	0.84	0.59	6.00	3.40	2.00
B-horizon (0～2 mm)	1	9.91	43.0	1.36	1.00	0.55	0.28	5.70	2.70	1.90
	6	5.18		1.36	0.75	0.55	0.26	6.00	3.00	2.00
	30	1.34		1.22	0.84	0.68	0.07	6.00	3.00	2.00
B-horizon (1～2 mm)	1	201.78	60.9	1.13	1.00	1.00	0.71	5.20	1.00	0.35
	6	80.71		1.13	1.00	1.00	0.36	5.20	1.20	0.45
	30	14.68		1.02	1.00	1.00	0.04	5.50	1.30	0.58
B-horizon (0～1 mm)	1	4.28	36.9	1.46	3.50	2.00	1.25	7.10	1.50	0.90
	30	1.07		1.46	1.00	1.00	1.88	7.00	2.40	1.00
Paddy (0～2 mm)	1	5.21	52.4	1.11	1.00	1.00	0.38	4.60	1.10	0.08
	30	4.88		1.11	1.00	1.00	0.43	4.55	1.10	0.08

*M stands for M Cl^-

the 0.5M Cl^- solution. The relative HC (RHC) is the ratio of the steady state HC values obtained for a given leaching solution to its HCo.

Generally, the HCo depended on the type of soil texture and for a given soil, it depended on the PWR and the aggregate size fraction. For the fast PWR (30 mm/hr) the HCo of the soil depended on the texture of the soil, thus the higher the clay and silt contents (Table 1), the lower the HCo was. The HCo of the slow PWR (1 mm/hr) column also depended on aggregate size such that the 1～2 mm aggregate size of the B-soil (Table 2) had the highest value.

For all the columns, the HCo increased (Table 2) with a decrease in the PWR. However, the extent of increase in the HCo with a decrease in the PWR were different for the various soils. The increase in the HCo due to the slow PWR (1 mm/hr) relative to the fast (30 mm/hr) for the B-horizon soil was 7.39 fold (Table 2), while the A-horizon and the Paddy soil samples increased only 1.16 and 1.06 fold, respectively. The HCo of the 6 mm/hr PWR were intermediate to those of the 1 and 30 mm/hr PWRs.

Intrinsic soil behaviors were partially responsible for the differences in the HCo and the responses of the soils to the PWR. The decrease in the HCo with increase in the PWR for a given soil column, however, was attributed to the disruptive forces associated with the fast wetting process that caused slaking of the soil, leading to the disintegration of the aggregates into microaggregates and primary particles. This gave rise to a narrower average pore size, and a more tortuous water-conducting pores that caused lower HCo. Differential swelling and entrapped compressed air explosion was apparently higher for a soil with a better aggregation (possibly due to a higher clay content) as was the case for the B-horizon. The decreased bulk density (Table 2) for the 30 mm/hr PWR of the 0-2- and 1-2 mm aggregate sizes of B-horizon implied an increased in length of the soil columns during wetting. In all other columns, no increase in soil column length was observed and bulk densities values given were essentially the same before and after saturation. Irrespective of the PWR, it however was observed that, the columns were saturated with about 1 (one) pore volume (% pore volume=100-(bulk density)/(particle density)*100), wherein a particle density was taken as 2.65 g/cm^3.

For the A-horizon and the Paddy soil samples, differences in the HCo with PWR treatments were not as pronounced as those for the B-horizon sample (Table 2). The results suggest that the structure in the A-horizon sample was inherently less stable and even slow PWR was enough to disintegrate the aggregates. Thus, the disruptive forces of fast prewetting had no further influence on the structure of soils with weak structure. The low clay content also suggests that the A-horizon sample was less aggregated.

3.2 Effect of Prewetting Rate on Aggregate Stability

Soil aggregate is a group of particles and microaggregates that cohere to each other, and aggregate stability is an index as to how the cohesive forces withstand disruptive forces.

The wet-sieving results, the percentage of soil retained on the nest of sieves with mesh opening$\geq$0.1 mm and taken as the aggregate stability of the studied soils as a function of PWR is given in Fig. 1.

Direct immersion of dry soil into water resulted in more breakdown of aggregates for each of the soils compared to respective slow prewetted ones, indicating the disruptive effect of fast prewetting on soil aggregate stability.

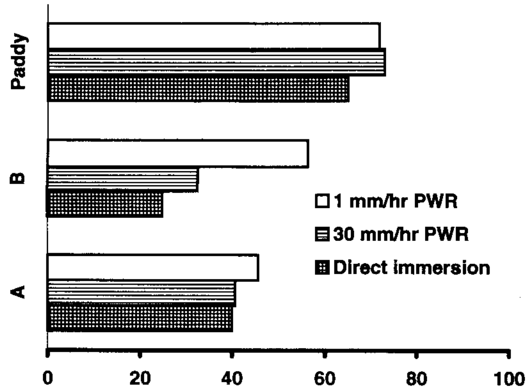

Fig. 1 Aggregate stability of the samples (wet-sieving) as a function of soil conditions at placement.

Amounts of soils left on the sieves for slow PWR were 2.27, 1.14 and 1.11 times greater than those for direct immersion for the B-horizon, A-horizon and Paddy samples, respectively. The effect of PWR on aggregate stability was similar to that of PWR on HCo of the soil columns, and confirmed that stability of the aggregate as affected by PWR could be determined by both the wet-sieving and HCo data.

The A-horizon sample had low clay content and thus was less aggregated. The Paddy soil, however, contained 22.1% clay and the wet-sieving results also suggested that the soil was well aggregated (higher percentage of aggregates left on the nest of sieves). Despite, the PWR had negligible effect on the HCo of this soil. It seemed that the Paddy soil was very stable. The organic matter (Table 1) and other cementing oxides, possibly Al or Fe, could be responsible for the stability of the soil structure. The aggregates were so stable that even direct immersion into water did not disintegrate the aggregates and thus PWR had negligible effect on its HCo.

3.3 Effect of Water Quality

The effect of the interaction of PWR and water quality on HC of A- and B-horizon samples is given in Fig. 2 and RHC (Table 2). HC values given as an intercept (time=0) were the steady state values obtained for the displaced solutions. It can be noted that irrespective of the PWR (values in brackets) and soil type (A & B), HC decreased with a decrease in the concentration of the percolating solution. However, both the magnitude and the relative decline in HC with a dilution of the leaching solution (as a function of time) depended on the PWR.

A decline in soil HC as salt concentration levels of the percolating solutions decrease was attributed to clay dispersion and/or clay swelling (Quirk & Schofield, 1955). Both dispersion and swelling mechanisms have the potential to partially or wholly block water-conducting pores in the soil. However, their significance is closely related to the behavior of the soil

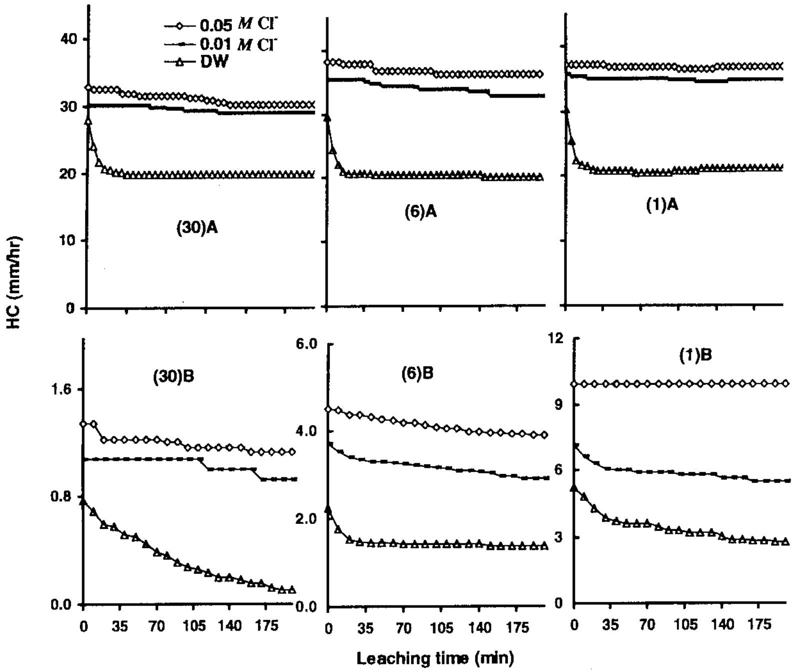

Fig. 2 Hydraulic conductivity for the A- and B-horizons at different prewetting rates (values in brackets) and the leaching solutions as a function of leaching time.

clays and the electrolyte concentration of the percolating solutions (Melkamu *et al.*, 1997). Dispersion occurs at very low salt concentration levels less than the critical flocculation concentration of the soil clays. Swelling, however, does gradually but continuously increase with a decrease in electrolyte concentration. It is accepted that variation in salt content of the water can cause changes in the cation exchange mechanism between the percolating water and the soil clay surfaces and hence stability of soils. In this study, results were compared and interpreted for soil columns subjected to similar set of electrolyte conditions, but exposed to different PWRs used to bring initially dry soil to saturation.

Table 1 and EC values (Table 2) suggest that the A- and B-horizon soils were essentially the same with regard to inherent constituents and behaviors. The difference in HC between the two samples was attributed to the difference in texture and porosity. The soils contained gypsum (Table 1) and its dissolution maintained EC values of the effluents (Table 2) higher than that of the inflow solutions. The 0.05-, 0.01M Cl^- and DW inflow solutions had EC values close to 5, 1 and 0 dS/m, respectively. Gypsum dissolution (that increased with the dilution of the inflow solution) prevented clay dispersion even when leached with DW and restricted a further drop in HC. Yet, HC showed a moderate decline with dilution of the leaching solution with little or no differences between PWR treatments for the A-horizon soil (Fig. 2).

The response of the B-horizon sample to both PWR and water quality was remarkable. In spite of the prevented dispersion, the HC of the columns sharply declined with a dilution of the leaching solution (Fig. 2). Moreover, the decrease in HC depended to a greater degree on the PWR, with RHC in DW of 0.07, 0.26, and 0.28 for the 30, 6, and 1 mm/hr PWRs, respectively. These correspond to absolute HC values (after physical and chemical mechanisms for HC decline were accounted for) of 0.09, 1.35, and 2.77 mm/hr in the same order. It is important to note that the low HCo for the 30 mm/hr PWR coupled with the greater decline (RHC=0.07) meant that the column was nearly clogged. The fact that the final HC in DW of the 1 mm/hr PWR was double the HCo of the 30 mm/hr marks how stabilized soil aggregates (by slow prewetting) maintained favorable water movement in the soil.

With no dispersion for the A- and B-horizon columns, the deterioration in HCs with a dilution of the leaching solution was solely attributed to clay swelling. The results of B-horizon columns, however, further suggested that ; (I) fast PWR caused slaking of aggregates and reduced average sizes of water-conducting pores which resulted in lower column HCo even at high salt concentrations of the leaching solution, compared to HCo obtained for slow PWR at the same salt concentration level, (II) slaking exposed more clay surfaces to swell that increased with dilution of the leaching solution, leading to a greater deterioration in the soil HC as dilute solutions displaced concentrated ones. This, in turn, indicated to us that the activity of the physico-chemical mechanisms responsible for HC deterioration to have been enhanced by increased physical disintegration of aggregates in structurally unstable soils.

Fig. 3 presents HC for the Paddy soil column in DW leaching. For this sample no change in HC was observed over the range of solution concentrations above 0.01 M inclusive and hence the plots were not presented. In DW leaching, the HC decreased to nearly same RHC values for both the fast (30) and slow (1 mm/hr) PWRs. EC of the effluent (Table 2) has dropped to very low values, values that are low enough for clay dispersion to occur and, indeed, the dispersed clay also appeared in the effluent collected.

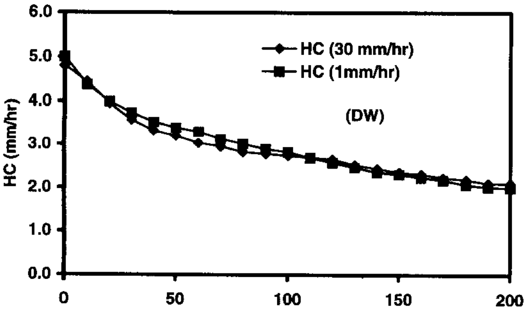

Fig. 3 Hydraulic conductivity for the Paddy sample for two prewetting rates in distilled water leaching.

The decrease in HC, though not independently quantified, was attributed to a combined effects of swelling and dispersion of the soil clays. The absence of marked difference in HCo and RHC values between the PWR treatments indicates that for the Paddy soil sample, PWR does not appear to influence aggregate breakdown despite higher clay content and well aggregation of this sample.

3.4 Effect of Aggregate Size

The response of different aggregate sizes to the PWR treatments and subsequent response to water quality in terms of influences on HC was investigated by segregating the B-horizon sample into fractions constituting 0~1 and 1~2 mm sizes. The results showed that the effect of PWR on HC of B-horizon sample also depended on the aggregate size fraction.

Fig. 4 presents the HC for the B-horizon, 1~2 mm aggregate fraction leached with DW. Despite evidence of greater slaking with an increase in PWR, no change in HC (RHC=1.0) of the 1 ~2 mm aggregates was observed in TEC above 0.01 M Cl^- leaching solutions for this aggregate size fraction (Table 2).

Upon displacing the 0.01 M Cl^- solution by DW, HC deteriorated to RHC values of 0.71, 0.36, and 0.04 for the 1, 6, and 30 mm/hr PWRs, respectively. The slow PWR (1 mm/hr) for columns of the 1~2 mm aggregate size fraction brought about a 14 fold increase in the HCo (Table 2), compared to the same size fraction wetted at fast (30 mm/hr) PWR, signifying greater slaking to have taken place. The corresponding values for the 0~2 and 0~1 mm aggregate size columns were 7.4 and 4.0, respectively. HCo as well as final HCs given as RHC values (Table 2 and Fig. 4) were substantially

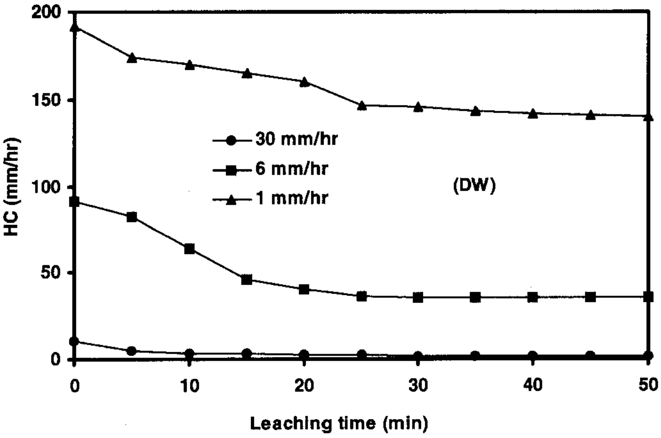

Fig. 4 Hydraulic conductivity for the B-horizon 1～2 mm aggregate size at different prewetting rates in distilled water leaching.

higher for columns of the 1～2 mm aggregate fraction compared to that of the whole (0～2 mm) soil. This was attributed to the big water-conducting pores (no deposition of fine particles<1 mm) between the 1～2 mm aggregates. The high HCo (1 ～2 mm) for the 1 mm/hr PWR indicates that the big conducting pores were retained by the slow PWR. Disintegration and slaking of aggregates due to the wetting process increased as the PWR and the associated disruptive forces increased. Conversely, high HC was maintained by slow wetting that stabilized soil aggregates or caused less slaking.

Relatively lower final EC values for the 1～2 mm (Table 2) compared to that of the 0～2 and 0～1 mm aggregate sizes were attributed to the high rate of flow rather than a progressive leaching, as one would expect, from the displacement of concentrated solutions by a dilute ones. This meant the inflow solution could flow out faster than gypsum could dissolute and influence the EC value.

Fig. 5 presents the HC for the 0～1 mm aggregate fraction of the B-horizon sample. The HCo increased as the PWR decreased, as is the case for the 0～2 and 1～2 mm aggregate size fractions. However, results for successive leaching solutions differed from both the 0～2 and 1～2 mm aggregate size fractions. Whereas, the HC of the 0～2 and 1～2 mm size fractions was either constant or decreased with the dilution of the solutions (Fig. 2 & Fig. 4), that of the 0～1 mm size fraction increased or decreased in unexpected way (Fig. 5). Also, while the HC of the 30 mm/hr PWR slightly increased only in DW, that of the 1 mm/hr column increased or decreased at all solution concentration levels with RHC>1.00 throughout.

Moutier *et al.* (1998) reported that the processes responsible for HC decrease have been effectively counterbalanced by the development of cohesion forces (with aging or longer leaching time) between clay fabric structural units (domains) and micro-aggregates, which resulted in an increase in a column HC.

It is highly probable that the increase in HC for the 1 mm/hr (Fig. 5) was due to the development of intra-aggregate cohesive forces over time (～30 hr of prewetting and conditioning), which according to Moutier *et al.* (1998) leads to a reorientation and reorganization of clay structural units, effectively increasing the average size of water transmission pores. It also appears that these less disrupted aggregates were subject to compression (hydraulic head = 100 cm) by water layers surrounding them. These two conditions were believed to have contributed to an increase in pore size and

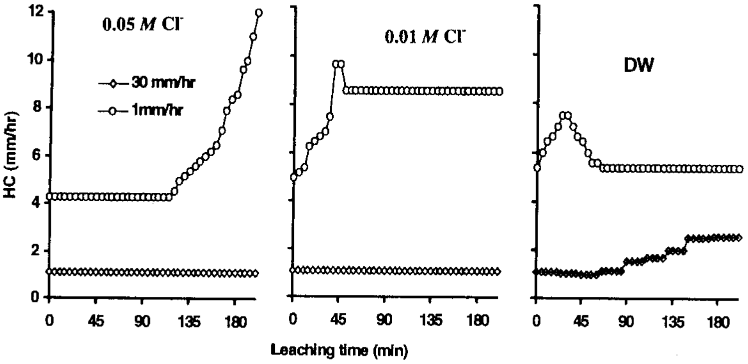

Fig. 5 Hydraulic conductivity for the B-horizon 0~1 mm aggregate size at different prewetting rates and leaching solutions.

hence the HC increased. A relative decline and more stable trend of the HC with the dilution of the solutions is attributed to clay swelling as an expense of the pore sizes. For the 30 mm/hr PWR the time was not long enough (less than 5 hours of prewetting and conditioning) for the cohesive bonds to reform for the level of aggregate disruption. The slight increase in HC of this column in DW, however, suggested an increase in pore size due to eventual development of cohesive bonds with leaching time. For this aggregate fraction, the processes of deterioration of HC as illustrated were effectively counterbalanced by time dependent changes in the soil. However, further research is needed to fully describe this phenomenon.

4. Conclusion

In all irrigation water application techniques, the rate at which water is applied to soils, somehow, is a manageable factor. The results of this study indicated the effects of disruptive forces of wetting on the HC of different soils. The extent to which soil hydraulic conductivity is affected due to PWR depends on the stability of the soil. Soil HC obtained in the laboratory for arbitrary aggregate sizes could also be misleading. The results of this study suggested that changes in HC as caused by the effects of extrinsic factors as well as time dependent variables could also be aggregate size specific.

Irrigation water quality can vary widely between very low salinity and sodicity to high salinity and sodicity within short distances or times. Understanding soil responses to these conditions is essential for better management of soils and water. How soils respond to forces of prewetting in terms of changes in hydraulic properties, in practice, determines the amount of soil loss by erosion and also the effectiveness of replenishing soil moisture during irrigation events.

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Manuscript received 24 Aug. 1998,
accepted 21 Dec. 1998.