

Geoenvironment 2000, Specialty Conference sponsored by the Geotechnical and Environmental Divisions of ASCE, pp. 815-828. February 24-26, New Orleans, Louisiana. 1995

Effect of Degree of Saturation on the Adsorption Characteristics of Inorganic Chemical in Unsaturated Soils

P.C. Lim¹, S.L. Barbour² and D.G. Fredlund³

Abstract: Adsorption is an important mechanism in determining the fate and transport of a contaminant. Adsorption characteristics of saturated soil have been extensively studied while little is known for an unsaturated soil. This paper describes a laboratory investigation of the effect of the degree of saturation on the adsorption characteristics of unsaturated soils. A series of laboratory experiments of one-dimensional diffusive transport of inorganic chemicals on sandy and silty soils have been conducted, at various degree of saturation. Potassium was used as the adsorbing contaminant for this study.

Results for a silt showed that the degree of saturation has little effect on the adsorption characteristics from 100 percent saturation to near the residual degree of saturation. Adsorption at or near residual degree of saturation was only 7% of the value measured at 100 percent saturation. In the case of sand, the results showed a definite trend of decreasing adsorption as the degree of saturation decreases. The decrease in adsorption is most significant as the water content approaches the residual degree of saturation. At or near the residual degree of saturation, adsorption was 50% of the value measured at 100 percent saturation. The decrease in the adsorption characteristics is attributed to a decrease in the active soil mass participating in the adsorption reaction. The factor causing the decrease in adsorption may be related to a discontinuity in the liquid phase which isolates a fraction of the soil mass from the diffusive pathways.

¹Graduate student, Dept. of Civil Engineering, University of Saskatchewan, College Drive, Saskatoon, Saskatchewan, S7N 0W0

²Professor, Dept. of Civil Engineering, University of Saskatchewan, Saskatoon, Sask.

³Professor, Dept of Civil Engineering, University of Saskatchewan, Saskatoon, Sask.

INTRODUCTION

The processes governing the transport of inorganic chemicals through saturated soils are also relevant for unsaturated soils; however, a key difference between the saturated and unsaturated cases lies in the definition of the transport parameters. The effect of the degree of saturation on the hydraulic conductivity has been well defined. The effect of the degree of saturation on the diffusion coefficient has also been studied by Porter et al., (1960), Barraclough and Tinker, (1982) and others; however, the effect of the degree of saturation on adsorption characteristics is not known. Characterization of the adsorption phenomenon is essential as it is an important mechanism by which contaminants can be removed from the pore fluid.

This paper describes a laboratory investigation of the effect of the degree of saturation on adsorption characteristics of unsaturated soils. A series of laboratory experiments simulating one-dimensional diffusive transport of inorganic chemicals have been conducted on sand and silt, at various degrees of saturation. Potassium was used as the adsorbing contaminant for this study. The degree of saturation in the soil was established by drainage of the pore-water through the use of the axis-translation principle. The objectives of this study are to evaluate the effect of desaturation on the adsorption characteristics of an unsaturated soil and to characterize the functional relationship between adsorption and degree of saturation.

BACKGROUND

Adsorption is the phenomenon by which a portion of the mass of a dissolved substance (e.g., inorganic or organic contaminants) can be held on the solid at a fluid-solid interface (Bear, 1987). The mechanism of adsorption can be categorized into physical adsorption and chemical adsorption, depending on the form of interaction. The adsorption of cations or cation-exchange by physical adsorption is governed by electrostatic forces of attraction. It involves only a surface interaction in which the solutes accumulate on the solid surfaces without penetrating the structure of the solid phase. Such interaction is a result of a net negative charge on the soil particles. The negative charge on soil particles may be the result of isomorphous substitution within the lattice structures of clay minerals, broken bonds at the edges and external surfaces of clay minerals, or a terminal layer of metal oxides. Other sources of variable charges in soil include dissociation of acidic functional groups in organic compounds and the preferential chemisorption of certain ions on the particle surfaces (Rhoades, 1982).

Laboratory studies on the adsorption characteristics of soil components are usually conducted under saturated conditions using batch testing techniques in accordance to the ASTM D4646-87. The solution to solid ratio of 20:1, as specified in these methods, is unrealistically high when compared to that normally encountered under *in situ* conditions. The use of excess water and aggressive mixing would disperse the soil solids and thereby ensure that all the exchange/reactive sites are available for adsorption.

Laboratory studies on the adsorption characteristics of unsaturated soils are limited. Back-analysis of the adsorption parameter from transient-type diffusion tests is impossible because the soil solution concentration is unknown. The theoretical model for unsaturated soil using the concept of mobile and immobile water (van Genuchten and Wierenga, 1976) assumes that all the sites are completely accessible. The difference between equilibrium and non-equilibrium models is that the rate of reaction or access to the reactive sites are not instantaneous. No consideration has been given to the possibility of a discontinuous liquid phase and its effect on the accessibility to the reactive sites.

Bohn et al. (1985) has attributed the rate-limiting step to ion diffusion to or from the colloid surface (i.e., film diffusion), and the movement of ions through tortuous or relatively thick, stagnant water films on the surfaces of soil colloids in order to reach the exchange/reactive site. For this reason, samples in the batch test are normally shaken to speed up ion movement and to minimize the thickness of the stagnant water layers on the soil particle surfaces. The physical model described by Bohn et al. deserves greater attention, particularly in regard to the role of the degree of saturation on the adsorption characteristics of an unsaturated soil. It may be that the adsorption reaction is not dependent on the amount of water present but rather, the distribution of water at various soil suctions may have a significant impact on the extent of adsorption. The effect of water can be seen primarily in its role in providing the pathways to the reactive sites on the soil particles.

The effect of water content on cation exchange in soils of differing textures has been studied by Brown (1953). The soil samples were pre-wetted to various water contents extending from saturation to the wilting point (i.e., the water content corresponding to 15-atmosphere suction). Synthetic cation-exchange resin membranes presaturated with hydrogen ions were used to measure the variations in cation exchange capacity for soils at different water contents. The membrane was buried in 100 grams of moistened soil and a 96 hour exchange period was established for each treatment. Typical results for sandy loam, silt loam and clay are presented in Fig. 1. The results showed that the total amount of cations exchanged decreased with decreasing water content, from 100 percent saturation to the wilting point for sandy and silt loam. In the case of a clayey soil, the decrease in the amount of cations exchanged was small up to the wilting point, followed by a rapid decrease thereafter.

The main factor controlling the decrease in the amount of cation exchanged with decreasing water content is attributed to the thickness and continuity of the water films within the pore system of the soil (Brown, 1953). As the water content approaches the wilting point, the water films exist primarily as thin, isolated wedges. At this stage, the exchange is confined to the layer of soil adjacent to the membrane while the exchange of cations from more distant points in the soil will be severely limited due to the lack of continuous water films.

The findings of the above study; however, may not be conclusive for several reasons. First, chemical equilibrium has not been attained. Second, at different water contents the soil samples have different diffusion coefficients (Porter et al., 1960). The observed decrease in the amount of cations exchanged with decreasing water content over the same exchange period may be due to a decrease in the rate of

diffusive flux rather than a decrease in the exchange capacity of the soil. For this reason, experimental studies were undertaken to quantify the effect of degree of saturation on the adsorption characteristics of unsaturated soils in controlled diffusion tests.

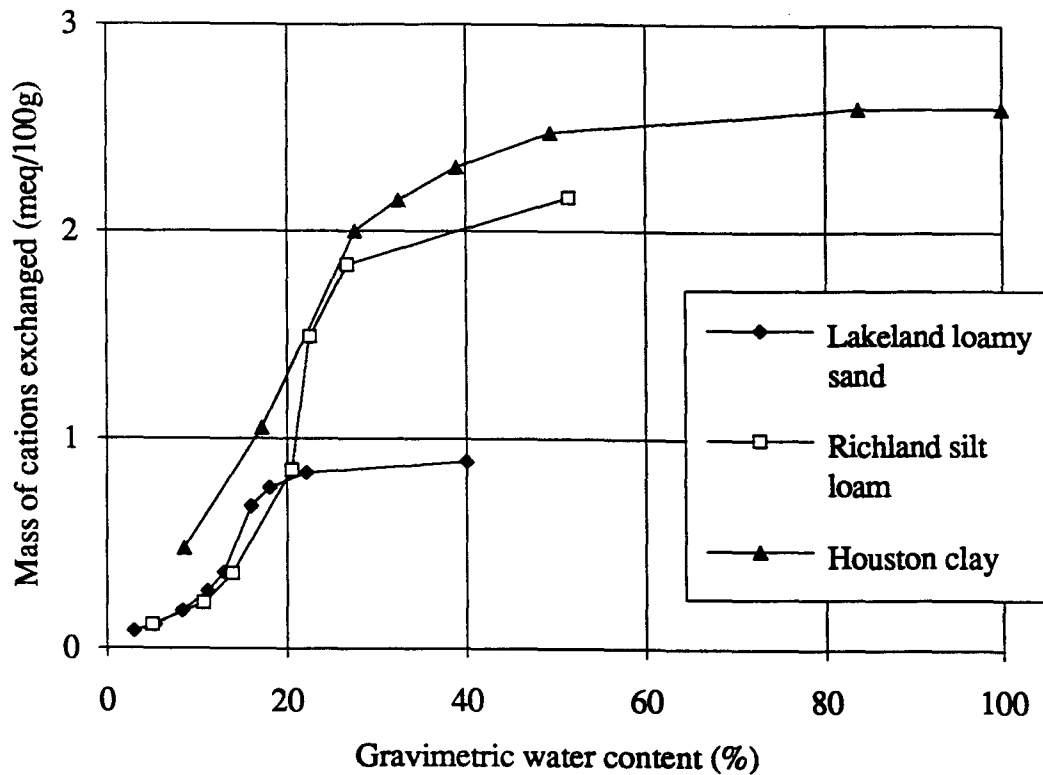


Fig. 1 The Effect of Water Content on the Amount of Cations Exchanged in Soils of Differing Textures as obtained from Brown, (1953).

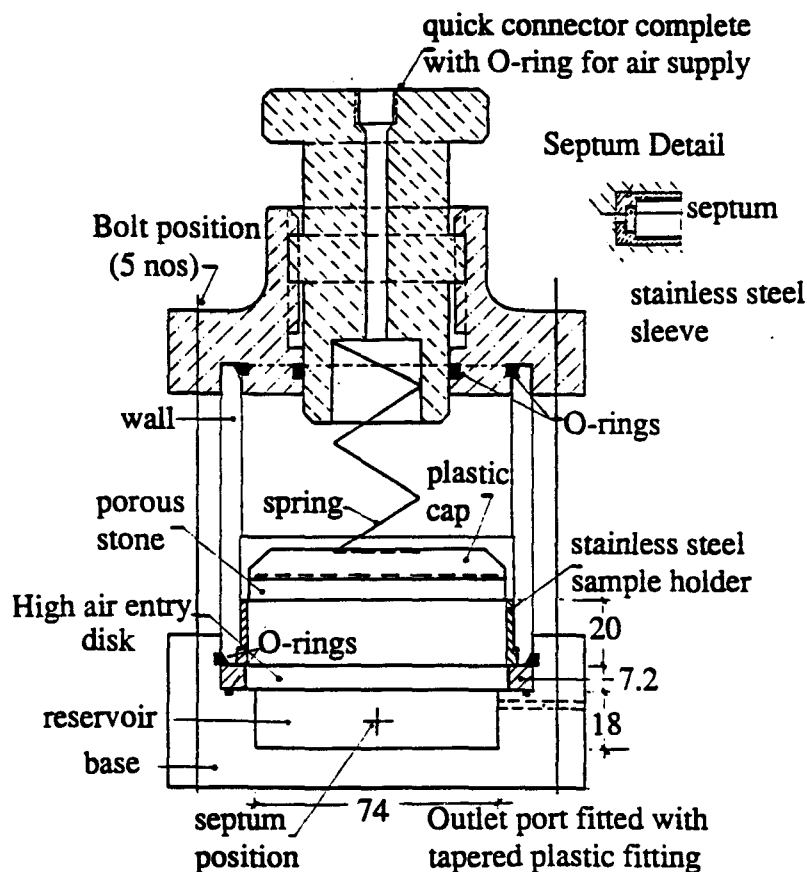
METHOD OF STUDY

The method used to measure the adsorption characteristics of an unsaturated soil has been described in an earlier paper (Lim et al., 1994). The tests were conducted using an apparatus which integrates the single column reservoir method for diffusion testing of saturated soils and the axis-translation principle for controlling the degree of saturation of the soil. The desired matric suction was maintained constant throughout the test duration. The apparatus as shown in Fig. 2 consists of a base which holds a source reservoir of known volume, a saturated air-entry disk located between the reservoir and the soil sample, a stainless steel sample holder for soil sample, a brass porous stone to ensure uniform distribution of the air pressure, a plastic cap and spring for preloading the soil sample, a top with a quick connection to an air supply, complete with O-rings at critical locations to provide a seal against

leakage of air, water vapor and water. The size of the soil sample is 7.9 cm in diameter and approximately 1.5 cm in thickness.

This approach allows the calculation of both the diffusion and adsorption coefficients from a single test. The principal of this concept is that the system can be left to attain chemical equilibrium after which, the mass absorbed by the soil can be calculated by accounting for the mass of the chemical species in the system. The attainment of chemical equilibrium is monitored by sampling a small volume of 0.7 ml of the solution in the reservoir.

At the end of the test, the soil sample is extruded and sectioned into smaller segments of approximately 4 to 5 mm in thickness, for water content determinations. The soil is then left to air dry and upon drying, the total mass of potassium adsorbed by the soil is extracted using an ion replacement method. The replacement method involves equilibrating the soil samples with 0.1 N Barium chloride solution with three repeated washings. The mass adsorbed by the soil is then calculated by subtracting the mass in the soil solution and the background mass if any, from the total mass extracted from the soil.



All dimensions are in millimeters.

Fig. 2 A Cross-Section of the Apparatus for Diffusion Testing of Unsaturated Soil.

The adsorption characteristics of soils at full saturation was measured by a diffusion-type batch test using Potassium chloride at a solid to solution of 1:1 by weight. The isotherms for both sand and silt were found to be non-linear over range of 50 mg/l to 600 mg/l of K⁺. Adsorption characteristics of the air-entry disk was measured separately in duplicates. The adsorption of K⁺ by the disk varies from 0.033 to 0.051 mg/g at the respective concentration of 350 to 550 mg/l. The equilibrium isotherm for the disk was approximately linear over this range of concentration.

The key disadvantage of the test relates to the long testing duration required for attaining chemical equilibrium. For example, in cases approaching the residual water content, a test duration of at least 100 days is required for the system to achieve equilibrium. For this reason, tests at water contents close to the residual water content have to be terminated prior to attaining chemical equilibrium in order to reduce the waiting time. This creates some difficulties in the back-analysis of the parameters. However, back-analysis of the adsorption data for the non-equilibrium cases can still be evaluated. The method of analysis is described in the next section.

METHOD OF ANALYSIS

The method of analysing the absorption characteristics of the soil can be grouped into two distinct cases. First, cases in which the system has attained chemical equilibrium. Second, cases which fall short of chemical equilibrium.

Cases with chemical equilibrium

The mass adsorbed by the soil is calculated by simply accounting for the mass in the system at the start and end of the test. The method of calculation is illustrated in the following:

$$M_{ads} = M_i - M_{sa} - M_{sol} - M_{add} \quad (1a)$$

and,

$$M_i = C_o V_r \quad (1b)$$

$$M_{sol} = C_f V_{sol} \quad (1c)$$

$$M_{add} = K_d M_d C_f \quad (1d)$$

$$M_{sa} = C_i V_s \quad (1e)$$

where, M_{ads} = mass of chemical species adsorbed by soil (mg)

M_i = initial mass of chemical species at the start of test (mg)

M_{sa} = mass removed from the reservoir during sampling (mg)

M_{sol} = mass of chemical species in solution at equilibrium (mg)

M_{add} = mass of chemical species adsorbed by the air-entry disk (mg)
 C_o = initial solution concentration in the reservoir(mg/l)
 C_f = final or equilibrium solution concentration(mg/l)
 C_i = reservoir concentration at time i (mg/l)
 V_r = volume of reservoir (l)
 V_s = volume of sample (l)
 V_{sol} = total volume of solution in the system (l)
 M_d = mass of the air-entry disk (g)
 K_d = distribution coefficient of the air-entry disk (ml/g)

Cases with no chemical equilibrium

For cases in which chemical equilibrium was not attained, the concentration of the soil solution is not uniform. As a result, the mass absorbed by the soil cannot be computed by the simple mass balance approach. This problem can be resolved by adjusting the diffusion and the modified adsorption coefficients systematically until a best fit is obtained for both the concentration-time profile of the reservoir, and the concentration versus depth profile in the soil column. The theoretical solution of the concentration versus time and concentration versus depth profiles was obtained using CTRANW (1992). CTRANW is a proprietary computer software distributed by Geo-Slope International Ltd., Calgary, Alberta Canada. It is a finite element program for solving the contaminant transport problem.

A Freundlich equation for the adsorption isotherm was used in the numerical simulation. The adsorption coefficient for an unsaturated soil has a slightly different definition from that for saturated soil. A correction factor has been incorporated into the adsorption isotherm to reflect the effect of the degree of saturation on the adsorption coefficient. The modified adsorption isotherm for an unsaturated soil is as given in Eq. 2. The terms K_f and m are constants for the Freundlich equation for the equilibrium isotherm for saturated soil.

$$Q = \frac{AA}{PA} K_f C^m \quad (2)$$

where, Q = mass adsorbed by soil per unit mass of solids (mg/g)
 AA/PA = ratio of the actual adsorption to the potential adsorption which is equivalent to the ratio of the active mass to total mass of soil.
 K_f = a partition coefficient (ml/g)^m
 m = a power constant in the Freundlich equation.

MATERIALS

A sand and silt were selected for the study of the effect of degree of saturation on the adsorption characteristics. The choice of these soil types was based on the consideration of soil texture, pore structure and the soil-water retention characteristics of the soil. These factors may have a significant role in providing an

understanding of the influence of the degree of saturation on the adsorption characteristics in relation to the distribution of water at various matric suctions. The soil-water drying characteristic curve for the sand and silt are given in Fig. 3. The distribution of the pore size for these soils is very uniform as illustrated by the slope of the drying curve. The main differences between the two soil types are the pore size and its water holding characteristics. The sand has a much larger pore diameter than the silt. The silt is able to maintain higher water content than sand as the residual water content is approached.

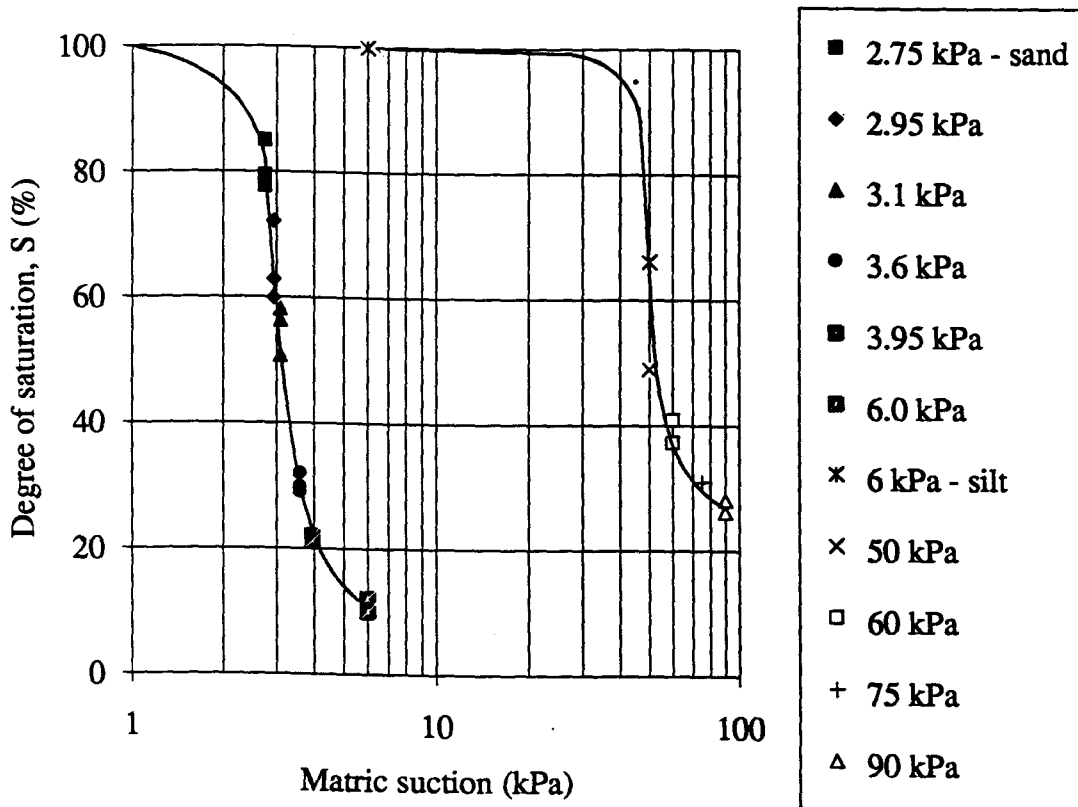


Fig. 3 Soil-Water Drying Characteristic Curve for Sand and Silt.

The physical properties of sand and silt are also as given in Table 1. These properties were evaluated from the soil samples at the end of the test. The void ratio and the dry density were controlled so as to minimize possible differences in the pore structure. The water content distribution expressed as either by the volumetric water content or the degree of saturation was fairly uniform across the soil sample in most cases.

Table 1. Physical properties of sand and silt.

Soil type	Matric suction (kPa)	Void ratio	Dry density (kg/m ³)	*Final volumetric water content	*Final degree of saturation (%)
Sand n=0.39	0.00	0.64	1620	n = 0.393	100
	2.75	0.61	1645	0.300/0.315/0.300	79/81/80
	2.95	0.62	1645	0.274/0.240/0.229	72/63/60
	3.10	0.62	1650	0.215/0.221/0.194	56/58/51
	3.60	0.61	1650	0.121/0.109/0.113	32/29/30
	3.95	0.61	1650	0.080/0.083/0.080	21/22/21
	6.00	0.62	1645	0.046/0.039/0.038	**12/10/10
Silt n=0.35	6.00	0.54	1726	n = 0.348	100
	50.00	0.54	1723	0.231/0.172	66/49
	60.00	0.54	1720	0.143/0.133	41/38
	75.00	0.54	1726	0.107/0.108	31/31
	90.00	0.54	1725	0.091/0.099	**26/28

* The three values are values measured in each sublayer of the soil sample from bottom to top.

** These values are close to the residual degree of saturation.

SAMPLE PREPARATION

Prior to the placement of the soil sample, a saturated high air-entry disk was first assembled into the cell and then cleaned by flushing numerous pore volumes of deaired, deionized, distilled, water through the disk. After flushing the disk, the cell was then disassembled leaving the disk in-place and a sample ring was placed over the disk. The ring was partially filled with some water and a known quantity of air-dried soil was then slurried into the water in small quantity. This is to ensure complete saturation and also to minimize entrapped air bubbles. The soil was placed at a water content near the liquid limit. Once the soil has been placed, the cell was assembled and a small preload of 5 kPa was then applied to consolidate the soil sample and to ensure good contact between the soil and the disk. In the case of sand, the preload was applied instantaneously while in the case of silt, the load was gradually applied in steps. After consolidation, the cell was then connected to a regulated air supply which drains the pore water to the desired matric suction. Upon moisture equilibrium, the reservoir was spiked with approximately 5 ml of 384 meq/l of Potassium chloride solution.

RESULTS AND DISCUSSION

In all the experimental studies, Potassium was used as the inorganic chemical tracer. The initial concentration of K⁺ in the reservoir was approximately 870 mg/l and 1000 mg/l for sand and silt, respectively. The effect of the degree of saturation on adsorption was based on the fate of the potassium ions (K⁺). The changes in the concentration of K⁺ in the reservoir with time for sand and silt are shown in Figs. 4 and 5.

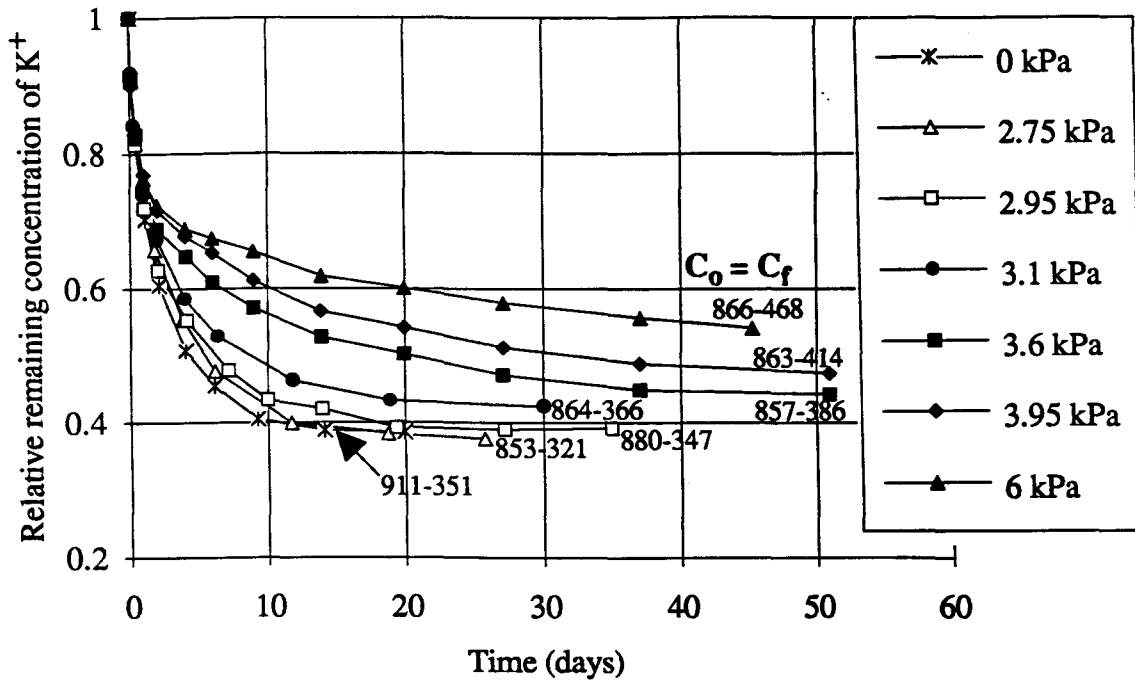


Fig. 4 Relative Remaining Concentration of K^+ in Reservoir versus Time for Sand.

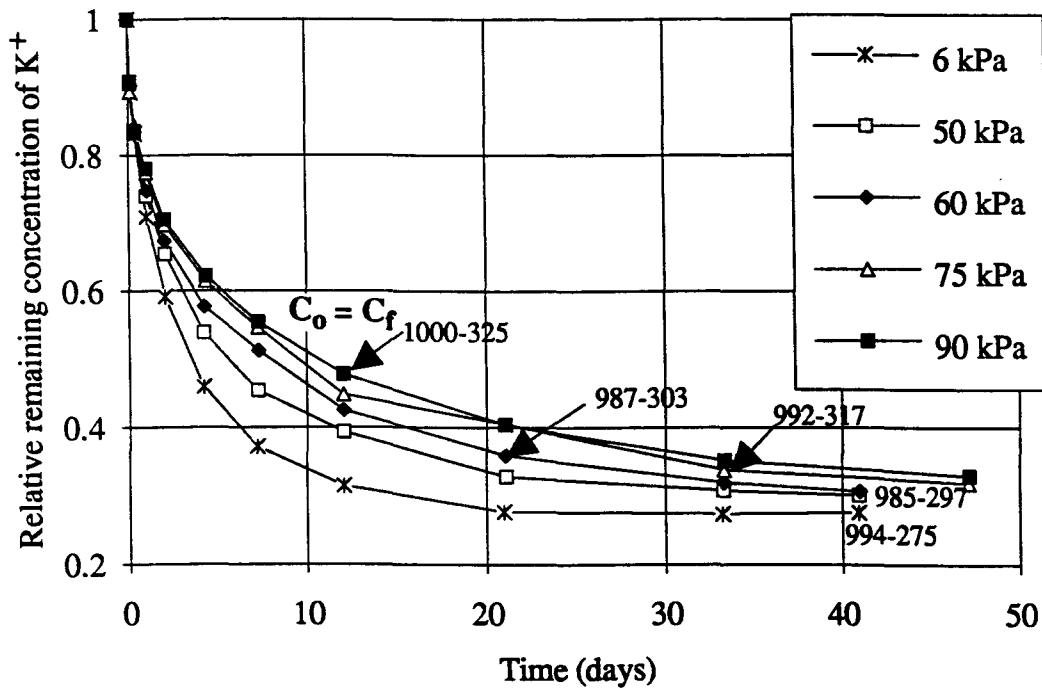


Fig. 5 Relative Remaining Concentration of K^+ in the Reservoir versus Time for Silt.

In the initial time from zero to 10 hours, the results showed that the rate of change of the remaining relative concentration of K^+ was identical for all the cases, regardless of the differences in the matric suction. This is attributed to the presence of the air-entry disk beneath the soil which dominates the rate of diffusion and hence the concentration change at initial time. The effect of matric suction on the change in the concentration only becomes evident at larger times as the chemical species diffuse into the soil.

The results for the sand showed that chemical equilibrium was established for all but two cases near or at the residual water content. The case with a matric suction of 3.9 kPa is seen to be approaching chemical equilibrium whereas the case at 6.0 kPa is still quite a long way from equilibrium. Nearly all the cases involving a silt soil have attained chemical equilibrium, except for the case at 90 kPa which is approaching equilibrium. The final concentration of K^+ for sand ranged from 350 mg/l to 468 mg/l and 275 mg/l to 325 mg/l for silt as the at 100% saturation to residual degree of saturation.

The adsorption characteristics of sand and silt at various suction levels are shown in Figs. 6 and 7, respectively. The adsorption data is expressed as the ratio of the mass of K^+ adsorbed by the soil to total dry mass of soil and is plotted against the soil solution concentration at the end of test. At equilibrium, the soil solution concentration is the same as the reservoir concentration. For cases in which chemical equilibrium was not attained, the concentration of the soil solution was obtained from the numerical simulation as described in the method of analysis. This simulated soil solution concentration was then compared with the calculated concentration based on the measured total mass of K^+ in the soil and the AA/PA used in the numerical solution. The goodness of the fit to both the concentration-time and concentration-depth profiles were estimated by the eye.

The results for sand (Fig. 6) show that the mass of K^+ adsorbed by the soil per total dry mass of soil at the various suction levels falls below the equilibrium isotherm for saturated soil (i.e., potential adsorption). The equilibrium isotherm for the saturated soil was obtained by a diffusion-type batch test method. Even for the case with the lowest matric suction of 2.75 kPa, the actual adsorption is smaller than the potential adsorption. The air-entry value of sand occurs at 2.5 kPa, and consequently, drainage of water from the largest pores has resulted in a decrease in the mass adsorbed by the soil.

The results for silt are shown in Fig. 7. The data points for matric suctions at 6, 50 and 60 kPa matric suctions lie close to the equilibrium isotherm for saturated soil; therefore, the effect of matric suction does not seem to change the adsorption characteristics as the soil desaturates. As the water content approaches the residual degree of saturation (i.e., cases at 75 and 90 kPa), the mass of K^+ adsorbed by the soil per total dry mass of soil falls below the equilibrium isotherm. The departure from the equilibrium isotherm for saturated silt is relatively small in comparison to sand.

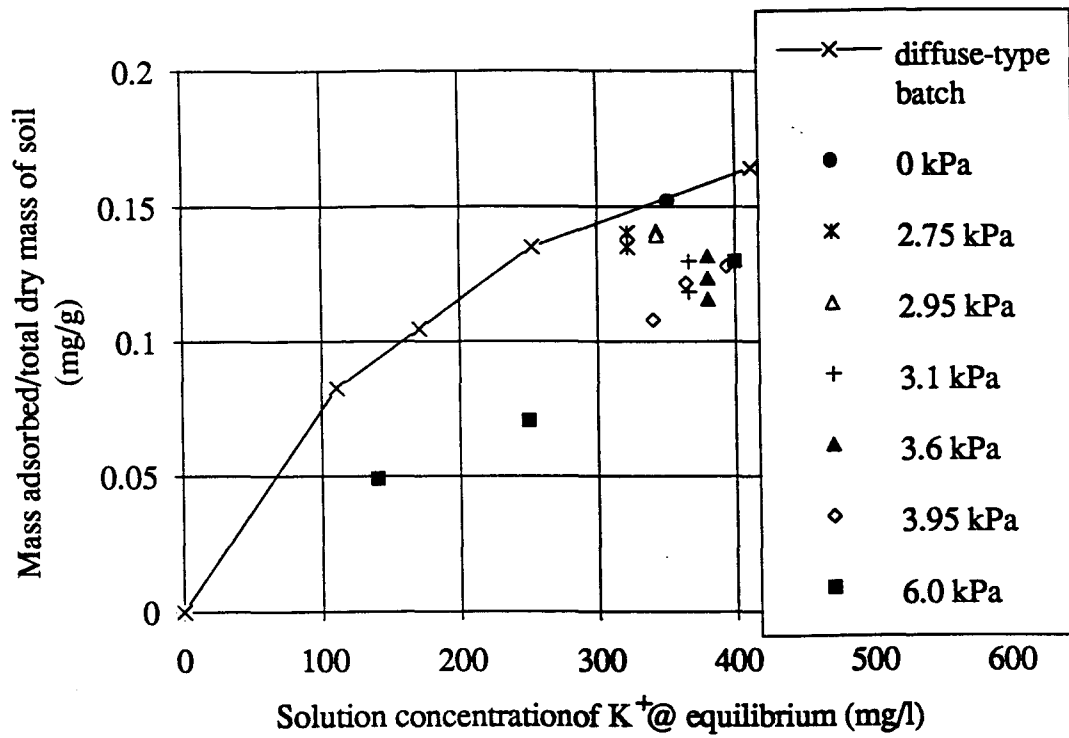


Fig. 6 Relationship between the Mass of K⁺ adsorbed by Soil per Total Dry Mass of Soil and the Equilibrium Concentration for Sand.

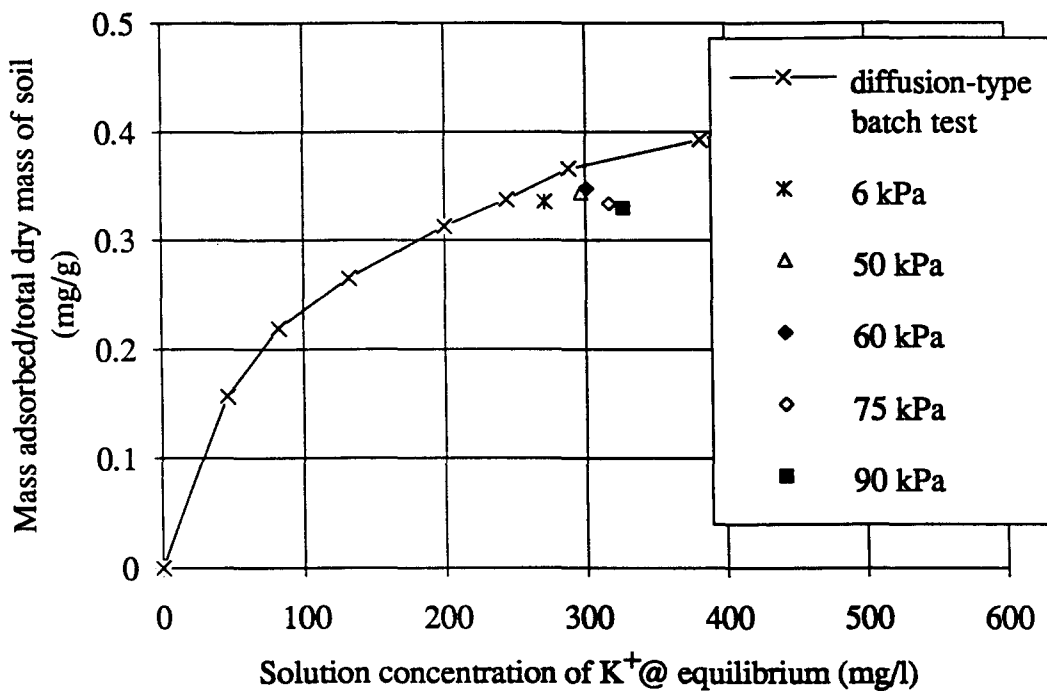


Fig. 7 Relationship between the Mass of K⁺ adsorbed by Soil per Total Dry Mass of Soil and the Equilibrium Concentration for Silt.

Two probable explanations for the observed decrease in the adsorption characteristics with increasing matric suction (i.e., decreasing water content) are postulated. First, the decrease in the adsorbed mass at decreasing degrees of saturation could be due to a decrease in the partitioning coefficient. The decrease in the partitioning coefficient could be related to the changes in the solid to solution ratio. The solid to solution ratio at 100 percent saturation and at near residual degree of saturation were 1:1 and 1:0.85, respectively. The variation of the solid to solution ratio from 100 percent saturation to near residual saturation was small. As long as the activity of the chemical species remains unchanged; the manner in which the chemical species partition between the solid and the liquid phases should not be affected by the water content. Second, the decrease in the adsorbed mass could be attributed to a loss of reactive surfaces due to discontinuity of the liquid phase. This breakage in the liquid phase may isolate a certain fraction of the soil mass from the continuous liquid phase. Physical access by diffusion to those disconnected adsorption/reactive sites would be impossible and this results in a loss of adsorption/reactive sites (i.e., a loss of active soil mass).

The interpretation of the adsorption characteristics for these unsaturated soils was based on the premise that the water content does not affect the activity of the chemical species. The partitioning coefficient at a given concentration would remain unchanged, regardless of the degree of saturation. The decrease in the adsorption characteristics with decreasing degree of saturation is attributed to a loss of active mass of soil. The loss of active mass of soil can be related to the presence of isolated soil pockets caused by the development of a discontinuous liquid phase. The fraction of the active mass of soil participating in the adsorption phenomenon is given by the ratio of the actual mass of K^+ adsorbed per total dry mass of soil to the potential mass of K^+ adsorbed per total dry mass soil. The potential mass of K^+ adsorbed by the soil is defined by the equilibrium isotherm for the saturated soil at the corresponding equilibrium concentration.

The influence of the degree of saturation on the adsorption characteristics of an unsaturated soil is expressed in terms of a functional relationship between the ratio of the active mass of soil to the total dry mass of soil and the degree of saturation. The functional relationship for the adsorption phenomenon for unsaturated sand and silt are shown in Fig. 8.

The results show that for silt, almost all of the soil particles remain active from 100 percent saturation to near the residual degree of saturation. Near the residual degree of saturation, such as case of matric suctions of 75 kPa and 90 kPa, the decrease in the soil mass that is active in adsorption was only 7% of the total dry mass of soil. This appears to suggest that the liquid films are sufficiently thick and are almost completely continuous even at or near the residual degree of saturation.

The functional relationship for sand showed a definite trend in which the active soil mass decreased with decreasing degree of saturation. The decrease in the active soil mass varied from zero to 25% of the total dry mass of soil as the degree of saturation decreased from 100% to 20%, respectively. At the residual degree of saturation, the active soil mass was only 50% of the total dry mass of soil. The decrease in the active soil mass was quite gradual but, it decreased rapidly as the

degree of saturation approached the residual value. The shape of the functional seems to take on the form of a step function. The decrease in the fraction of active soil mass was constant over a certain sector of the degree of saturation but dropped fairly sharply at specific degrees of saturation. This observed trend may be attributed to the very uniform distribution of pores where drainage of the pore-water occurs rather abruptly. The sudden emptying of the pore-water may isolate a portion of the soil mass in the vicinity of these empty pores which results in the incremental loss of active soil mass.

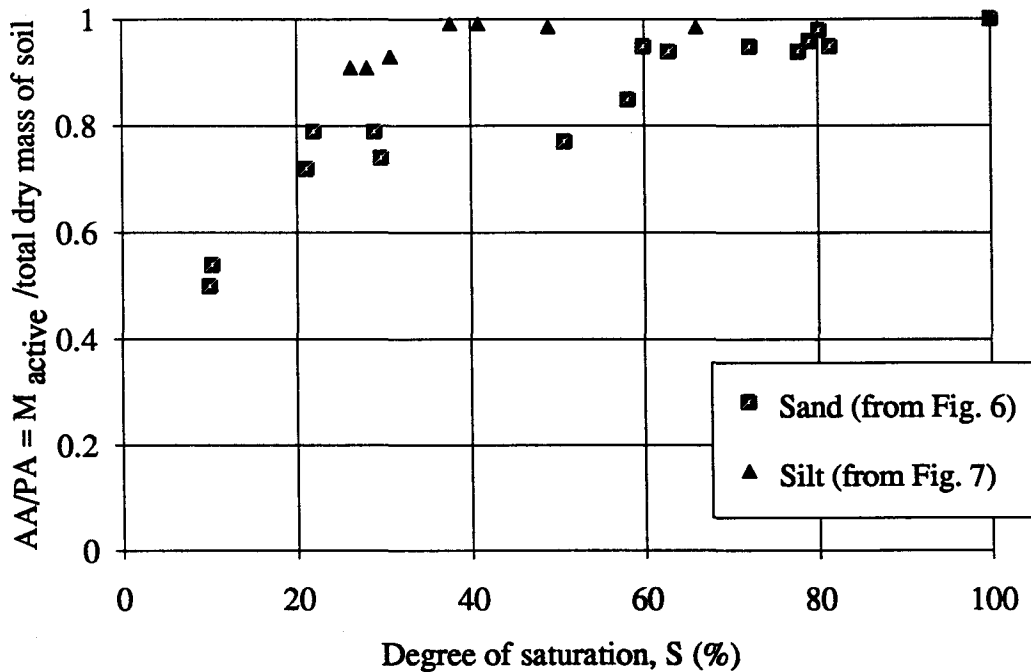


Fig. 8 Functional Relationship between the Ratio of the Active Mass of Soil to the Total Dry Mass of Soil and the Degree of Saturation for Sand and Silt.

The results appear to show that the fraction of the active mass is significantly affected by the continuity of the liquid films. Near the residual degree of saturation, a large fraction of the total soil mass may still remain active as long as the liquid films are interconnected and continuous. However, once breakage of liquid films occurs, the active soil mass would decrease rapidly. The extent of the decrease of the active soil mass differs for soils of differing textures. The decrease in the active soil mass is higher in the case of a sandy soil than for a silty soil and it is also more significant near the residual degree of saturation. Also, as long as the adsorption sites are accessible by the chemical species, the manner in which the chemical species partition between the solid and the liquid phases is the same, regardless of the degree of saturation.

CONCLUSIONS

Experimental studies on the effect of the degree of saturation on the adsorption characteristics for an unsaturated soil have been investigated using two soils of different textures. The types of soil used for this study were a sand and a silt. The results showed that the sand and silt exhibit different adsorption characteristics as the degree of saturation decreases from 100 percent saturation to residual degree of saturation.

In the case of a sand, the adsorption at different matric suctions (i.e., different water content) was smaller than the potential adsorption as measured by the diffusion-type batch test method. Results for the silt showed that the adsorption only decreases as the water content approaches the residual degree of saturation. Near the residual degree saturation which includes matric suctions at 75 kPa and 90 kPa, the decrease in adsorption was small. The decrease in adsorption as observed in silt was significantly smaller than for sand.

One probable explanation for the decrease in the adsorption characteristics of the soil components at decreasing degree of saturation, can be attributed to a loss of reactive surfaces. The factor causing this loss of reactive surfaces may be related to the discontinuity of the liquid phase. The fraction of the active mass of soil at decreasing degree of saturation is given by the ratio of the actual adsorption to the potential adsorption at the corresponding equilibrium concentration.

The functional relationship between the ratio of the active mass of soil to the total dry mass of soil and the degree of saturation for sand showed that the active soil mass decreased gradually from zero to 25% of the total dry mass of soil as the degree of saturation decreased from 100% to 20%, respectively. The active soil mass decreased to approximately 50% of the total dry mass of soil at near the residual degree of saturation. The functional relationship for silt showed all the soil mass remains active from 100 percent saturation to near the residual degree of saturation. Near the residual degree of saturation, the decrease in the active mass was only 7% of the total dry mass of soil.

REFERENCES

- Barracough, P.B., and Tinker, P.B. (1982). "The determination of ionic diffusion coefficients in field soils. I. Diffusion coefficients in sieved soils in relation to water content and bulk density." *Journal of Soil Science*, 32, 225-236.
- Bear, J., and Verruijt, A. (1987). "Modeling groundwater flow and pollution." Dordrecht; Boston: D Reide Pub. Co., chap 6, 414 pp.
- Bohn, H.L., McNeal, B.L., and O'Connor, G.A. (1985). "Soil chemistry - Cation retention." A Wiley-Interscience Publication, 2nd ed., 341 pp.
- Brown, D.A. (1953). "Cation exchange in soils through the moisture range, saturation to the wilting percentage." *Proc., Soil Sci. Soc. of Amer.*, 17, 92-96.

D4646-87, "Test method for 24-hour batch-type measurement of contaminant sorption by soils and sediments." Annual Book of ASTM Standards.

International Congress on Environmental Geotechnics, Edmonton, Alberta, Canada, 319-324.

Porter, L.K., Kemper, W.D., Jackson, R.D., and Stewart, B.A. (1960). "Chloride diffusion in soils as influenced by moisture content." Proc. Soil Sci. Soc. of Amer., 24, 460-463.

Rhoades, J.D. (1982). "Cation exchange capacity." Method of soil analysis, Part 2, chemical and microbiological properties - Agronomy Monograph, 2nd ed., 9, 149-157.

van Genuchten, M. Th., and Wierenga, P.J. (1976). "Mass transfer studies in sorbing porous media, 1, Analytical solutions." Soil Sci. Soc. of Amer. J., 40, 473-480.

Key Words: Unsaturated soil, Degree of saturation, Adsorption characteristics, Inorganic chemical species.