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MODELING OF SATURATED HYDRAULIC CONDUCTIVITY AND MEAN SOIL PORE DIAMETER IN AN ALLUVIAL LOAMY SOIL

Hammad, S. A.; T. M. El - Zehery and Enas M. Soliman
Soils Dept., Fac. Agric., Mansoura Univ., Mansoura, Egypt

ABSTRACT

The effects of anion types and concentrations on hydraulic properties should be understood in order to model mean soil pore diameter in reactive soils subsequently develop guidelines as an indicator of soil structural stability for sustainable land application of wastewater. Thus, a laboratory experiment was carried out during 2011 in Soils Dept., Faculty of Agric., Mansoura Univ., Egypt, by using an alluvial loamy soil to study the relationship between saturated hydraulic conductivity *Ks* and mean soil pore diameter (MPD) under three types of sodium salts [0, NaCl, $(Na)_2SO_4$] and three rates of nitrogen fertilizer as ammonium sulfate (ASF) [0, 100, 150 Kg fed^{-1}].

The obtained results illustrated that the structural degradation is a function of electrolyte concentration, sodicity and the combined anion of sodium salts. According to that, all the treatments caused a decreasing in MPD subsequently decreasing in the saturated *Ks*. Correlation coefficients and regression equations were developed to study the dependence of *Ks* on some physical parameters (MPD and ρb) in studied soil. The mixed NaCl and ASF treatments were the most effective on decreasing MPD and *Ks* as compared to control, as a result to the specific effect of chloride anion.

Keywords: Sodium salts, Mean soil pore diameter, Saturated hydraulic conductivity, Ammonium sulfate fertilizer, Structural degradation.

INTRODUCTION

One of the major concerns in irrigated agriculture is the maintenance of sufficiently high soil permeability for salinity control. The indices of soil permeability are hydraulic conductivity and infiltration rate. Soil water movement is always from points of higher potential energy to points of lower potential energy. The rate of movement is controlled by both the potential energy gradient (the ratio of the change in total potential over distance), that exists and by the hydraulic conductivity of the soil. The hydraulic conductivity at any point is a function of the soil's pores, particle size distribution, mean pore diameter, arrangement of the pores, total porosity and degree of saturation.

In addition, soil hydraulic conductivity depends on composition of the exchangeable and soluble cations and concentration of the electrolytes in the soil solution (Quirk and Schofield, 1955). *Ks* decreases exponentially when the degree of saturation decreases from 100%. This phenomenon occurs because those pores continuing to contain water contribute to flow. According to the law of capillarity, large pores will be the first to drain, the large, interconnected pore spaces are responsible for majority of a soil's hydraulic conductivity. In soils with a pore-size distribution that is skewed towards the larger pore diameters (e.g. sandy soils), the *Ks* drops very quickly when subjected to a small capillary tension. A soil with the same porosity, but dominated by micropores (e.g. clay soils), have a higher relative conductivity at that capillary tension, since the majority of its pores will resist desorption until a much higher tension is experienced. Soils midway between these two extreme often exhibit high values of both saturated and unsaturated hydraulic conductivity. Also, the *Ks* decrease with the increase of ESP, SAR (McIntyre, 1979) and the decrease of total electrolyte concentration (TEC) of the soil solution. This reduction in *Ks* has been attributed mainly to swelling and dispersion of the soil clays (Quirk and Schofield, 1955; Suarez *et al*. 2006 and Bardhan *et al*. 2007. NaCl salt solution in soil caused a decrease in *Ks* with decreasing salt concentration. These decreases could be attributed to decrease in diffuse double thickness as described by Mishra *et al*. 2006.

Pores can be defined as a function of the aggregate structure organization (Libardi, 2005) and classified as: (a) cryptopores or residual pores related to the intra-aggregate arrangement and particle type (clay, oxides), where hygroscopic water is highly bound by molecular attraction (sorption) (pore diameter d < 0.2 µm), (b) micropores where capillarity forces are predominant (0.2 < d < 50 µm) and (c) macropores where the water flow occurs by convection due to gravitational forces (d > 50 µm); micropores and macropores depend on the inter-aggregate arrangement. Soil pore volume as well as pore size, shape, type, continuity and lateral drainage of water by gravitational forces occur through the large non-capillary soil pores, but redistribution and upward movement of water occur through the capillary soil pores. (Abdel-Monem *et al*. 2009). In addition, Gonçalves *et al*. 2010. illustrated that the irrigation with treated wastewater (sodic waters) modifies the soil pore size distribution and pore mean diameter by slightly increasing macroporosity (pore diameter higher than 50 µm) and decreasing microporosity (0.2-50 µm). The cryptoporosity (< 0.2 µm) increased due to the high Na^+ concentration in small pores that causing expansion of microaggregates. This indicates that the study of mean soil pore diameter may be a reasonable approach to detect changes in the soil physical properties.

Hence, this investigation was conducted to study the changes in hydraulic conductivity as a function of mean soil pore diameter of alluvial loamy soil under mixed sodium salts and rates of ammonium sulfate fertilizer.

MATERIALS AND METHODS

This experiment was conducted at laboratory of Soils Dept., Faculty of Agric., Mansoura Univ. There were nine treatments, replicated twice, involved three types of sodium salts (S) [0, NaCl, $(Na)_2SO_4$] at 0.4% concentration and three rates of nitrogen fertilizer as ammonium sulfate [$(NH_4)_2SO_4$, 20.6 N%] (F) (0, 100, 150 Kg fed^{-1}), as the following S_0F_0, S_0F_1, S_0F_2, S_1F_0, S_2F_0, S_1F_1, S_1F_2, S_2F_1 and S_2F_2, recommended doses of P and K were added to each treatment.

Potassium sulfate fertilizers (40% K) and calcium super phosphate (7% P) were added as a recommended dose for corn crop with rates of 41.5 kg K fed^{-1} and 30.5 kg P fed^{-1}. The studied soil was air dried, grinded and passed through 2 mm sieve. Some physical and chemical properties of the experimental soil are presented in Table 1.

Table 1. Some physical and chemical properties of the studied soil.

Physical properties	Value	Chemical properties	Value
Mechanical analysis		pH (in soil paste)	7.98
Coarse sand%	13.00	EC dsm^{-1} (in soil paste extract)	2.85
Fine sand%	20.00	$CaCO_3$%	1.00
Silt%	29.00	OM%	1.10
Clay%	38.00	**Soluble cations (meq L^{-1})**	
Texture class	Loamy	Ca^{++}	7.60
θm%	5.46	Mg^{++}	5.90
θV%	7.75	K^{+}	5.70
SP (saturation %)	56.00	Na^{+}	8.50
FC%	28.00	**Soluble anions (meq L^{-1})**	
WP%	14.00	CO_3^{--}	0.00
AW%	14.00	HCO_3^{-}	7.22
Ks (m s^{-1})	$5x10^{-5}$	Cl^{-}	11.98
ρb (Mg m^{-3})	1.14	SO_4^{--}	8.90
ρs (Mg m^{-3})	2.19	**Available nutrients (ppm)**	
Total porosity%	48.00	N-NH_4^{+}	10.60
Air porosity (Ea%)	40.25	N-NO_3^{-}	20.50
Void ratio (e)	0.923	Phosphorus (P)	8.30
MPD (μ)	2.63	Potassium (K)	35.00

The analyses of studied soil before applying any treatments and after the experiment were done as the following determinations: Particle size distribution and total carbonate ($CaCO_3$%) were determined as described by (Piper, 1950). Saturation percentage (SP) and field capacity (FC), soil pH and total soluble salts were determined by (Richards, 1954). Bulk density was determined by (Dewis and Freitas, 1970) while, particle density was determined according to (Black *et al*. 1965). Porosity (E%) was calculated according to (Hillel, 1980). Organic matter content, amounts of the soil soluble ions and soil available potassium determined by according to (Hesse, 1971). Ammonium nitrogen (NH_4^{+}) and nitrate nitrogen (NO_3^{-}) were measured according to (Bremner and Keeney, 1966). Soil available phosphorus was determined colorimetrically using ascorbic acid as described by (Van Schouwenburg and Walinge, 1967). Saturated hydraulic conductivity of soil columns was determined using the constant head premeater in disturbed soil (Singh, 1980).

$$K = \frac{QL}{HAT}$$

Where; K: hydraulic conductivity coefficient in cms^{-1}, Q: volume of water being passed through the soil column at time (T) in cm^3, L: length of soil column in cm, H: hydraulic head in cm, A: cross section area in cm^2.

Soil mean pores diameter was calculated using the equation described by **Dielman and De Ridder (1972)**.

$$d = 6.177637\ \sqrt{K}\ \text{(for water at 20°C)}$$

Where; d: soil mean pores diameter in microns, K: hydraulic conductivity in m day^{-1}.

RESULTS AND DISCUSSION

1. The Bulk Density and Mean Soil Pore Diameter

The influence of mixed sodium salts and ASF on the bulk density (*ρb*) and mean soil pore diameter (MPD) of the studied soil are given in Table 2 and Figs. 1, 2 and 3. It is evident that the mixed [NaCl, ASF] and ASF without salts causes a pronounce decrease in MPD as compared to control (S_0F_0). These decreases recorded 8.38, 32.87 and 33.92% for mixed [NaCl, ASF], 12.32 and 22.18% for ASF without salts. In contrast with mixed [$(Na)_2SO_4$, ASF] records a decrease followed by an increase in MPD with the increasing of fertilizer rate, but still lower than the control. These rates of decreases were 33.00, 18.75 and 11.99%. Also, all the treatments cause a slight decrease in *ρb* as compared with control (S_0F_0).

Table 2. Some physical parameters of the studied soil as affected by adding salts and ammonium sulfate application on studied soil.

Treat.	Mean Values		
	Ks **(m day^{-1})**	**d (µ)**	***ρb*** **(Mg m^{-3})**
NaCl + ASF			
S_0F_0	0.181	2.63	1.14
S_1F_0	0.152	2.41	1.14
S_1F_1	0.081	1.76	1.10
S_1F_2	0.079	1.74	1.10
$(Na)_2SO_4$ + ASF			
S_0F_0	0.181	2.63	1.14
S_2F_0	0.081	1.76	1.10
S_2F_1	0.119	2.13	1.10
S_2F_2	0.140	2.31	1.10
ASF			
S_0F_0	0.181	2.63	1.14
S_0F_1	0.139	2.30	1.14
S_0F_2	0.109	2.04	1.05

2. The hydraulic conductivity

The hydraulic conductivity depends jointly on the attributes of the soil (i.e. total porosity, pore sizes distribution, tortuosity and soil's pore geometry) and of the fluid (i.e. density and viscosity). Thus, the differences in composition or concentration of soil solutes can greatly affect the hydraulic conductivity. The saturated *Ks* data of the studied soil as affected by addition mixed sodium salts and ASF are given in (Table 2. and Fig. 1, 2 and 3).

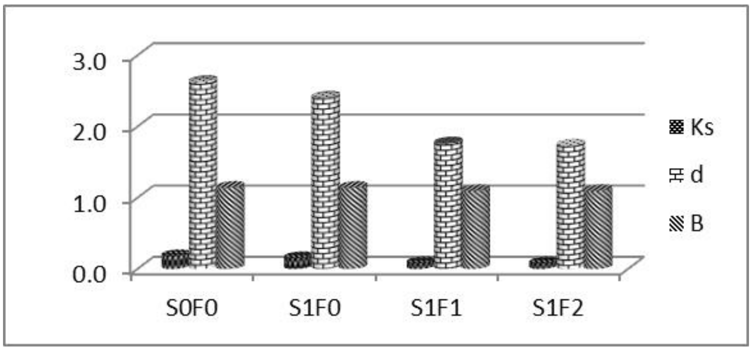

Fig. 1: Some physical parameters of alluvial soil as affected by NaCl and ammonium sulfate application.

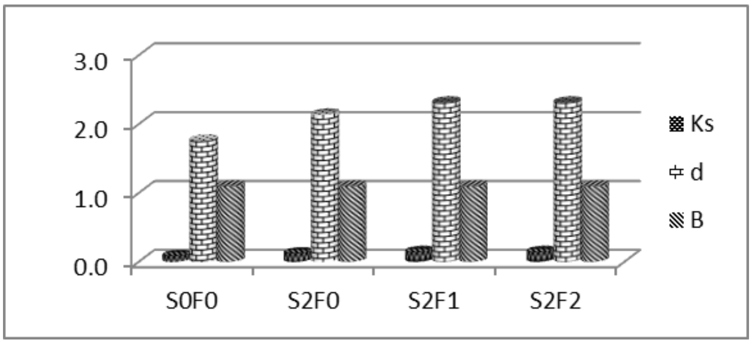

Fig. 2:Some physical parameters of alluvial soil as affected by $(Na)_2SO_4$ and ammonium sulfate application.

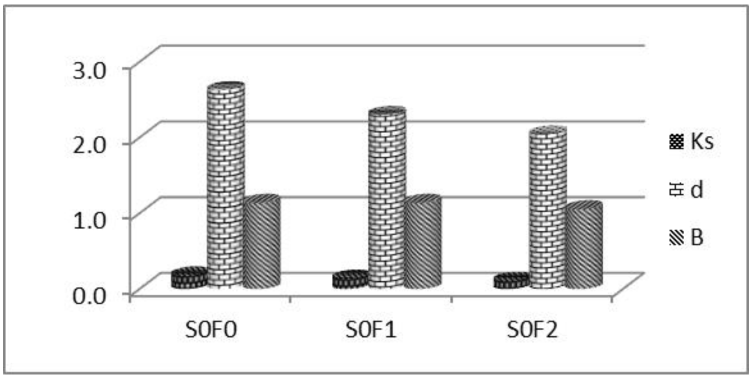

Fig. 3: Some physical parameters of alluvial soil as affected by ammonium sulfate application.

It revealed that the mixed [NaCl, ASF] decrease the *Ks* as compared to control. These decreases were 16.1, 54.9 and 56.3% lower than the control (S_0F_0), while, the application of mixed [$(Na)_2SO_4$, ASF] causes a decrease followed by an increase in *Ks*. These decreases recorded 55.1, 34.0 and 22.5% lower than the control (S_0F_0). On the other hand, the effect of using ASF without salts causes a decreasing in *Ks* values with rates 23.1 and 39.4% lower than the control (S_0F_0). It was noticed that the single effect of ASF on *Ks* values was higher than in mixed sodium salts and ASF.

Although, the addition of mixed salts and ASF caused a highly increasing in total electrolyte concentration, a decrease in *Ks* was recorded, this is attributed to the presence of Na^+ ions which decrease the permeability of soil through the swelling and dispersion of clays and the slaking of the aggregates. This result is confirmed with the work of Hanson *et al*. 1999 and Levy *et al*. 1999. They found that the sodic soils are associated with structural changes that principally affect permeability of soils. If the level of Na^+ in the soil is high, the colloidal fraction behavior will be affected, and caused losses of structure which reduces the hydraulic conductivity.

The differences in the behavior of mixed sodium salts and ASF could be attributed to the associated anions in studied salt. The chloride (Cl^-) is more hazard than sulfate (SO_4^{-2}). Thus, the NaCl caused a very high decreasing in Ks values more than $(Na)_2SO_4$.

The linear regression analyses were used to describe effect of the relation between the bulk density and mean soil pore diameter on hydraulic conductivity. The correlation coefficients and simple regression equations between some studied physical parameters as affected by addition of sodium salts and rates of ASF presented in Table 3. The obtained data were positively correlated and significant for all the treatments. The correlation coefficients between *Ks* and MPD were in the descending order ASF > (NaCl + ASF) > (Na_2SO_4 + ASF) while, the correlation coefficients between *Ks* and *ρb* were in the descending order (NaCl + ASF) > ASF > (Na_2SO_4 + ASF). In addition, the correlation coefficients between d and *ρb* was (NaCl + ASF) > ASF > (Na_2SO_4 + ASF).

It is very clear that, there is a decrease in saturated *Ks* values as a result to the decrease in MPD and *ρb*. These decreases might be attributed to the increase of sodium salinity types. These results are in a harmony with those of (Park and O'connor, 1980 and Gouda *et al*. 1989). They proved that sodium salinity types decreased the volume drainable pores (quickly and slowly). This might be due to the dispersion effect of Na^+ ions on soil aggregation and the companied of arrangement of the soil pores. Omer, 1984 stated that the sodic clay soil is poor in pores > 8.62 µ, and rich in pores < 8.62 µ. This indicates that mean soil pore diameter is not only depend on saturated hydraulic conductivity and bulk density, but also on soil properties i.e. dispersion, swelling behavior, and soluble and exchangeable sodium percentage of the soil.

Numerically, the *Ks* was low for the saline loamy soil but variability was very high. This is consistent with the results of Khan and Afzal (1989**)**, who showed that *Ks* was positively correlated with pores 1 to 33 KPa and was adversely affected by high electrical conductivity and SAR. The effect of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity was studied by Frenkel *et al*. (1978). They found that plugging of pores by dispersed clay particles is the major cause in reduced hydraulic conductivity of montmorillonitic, vermiculitic and kaolinitic soils of SAR's of 10 to 30 and salt concentration of 0 to 10 meqL^{-1}.

Table 3. Correlation coefficients (r) and regression equation between the studied physical parameter as affected by adding salts and ASF of studied soil.

Regression equations	R^2	R
NaCl + ASF		
Ks = 0.1129 **d** - 0.1177	0.9988	0.999**
Ks = 1.9728 ***ρb*** - 2.0816	0.9455	0.973*
ρb = 0.0546 **d** + 1.0012	0.9595	0.980*
$(Na)_2SO_4$ + ASF		
Ks = 0.1146 **d** - 0.1228	0.9957	0.998**
Ks = 1.5344 ***ρb*** - 1.5676	0.6553	0.811
ρb = 0.0468 **d** + 1.0033	0.5953	0.776
ASF		
Ks = 0.1226 **d** - 0.142	0.9988	1.000*
Ks = 0.5969 ***ρb*** - 0.5203	0.6597	0.814
ρb = 0.139 **d** + 0.7882	0.6927	0.830

*** Correlation is significant at the 0.05 level (2-tailed).**
**** Correlation is significant at the 0.01 level (2-tailed).**

CONCLUSION

It could conclude that the structural degradation is a function of both salinity (i.e. electrolyte concentration) and sodicity of the mixed sodium salts and ammonium sulfate fertilizers. Also, it will deduce possible methodologies for determining the electrolyte threshold in soils, preventing the application of wrong saline and sodic water qualities.

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مودل العلاقة بين التوصيل الهيدروليكي المشبع و متوسط أقطار المسام في تربة رسوبية طميية

سامي عبد الحميد حماد، طارق محمد الزهيري وإيناس مصطفي سليمان
قسم الأراضي - كلية الزراعة - جامعة المنصورة – مصر

يمكن الاستدلال علي ثبات البناء الأرضي من خلال فهم تأثير الأنيونات سواء نوعها أو تركيزها علي الصفات الهيدروليكية للتربة بدلالة متوسط أقطار المسام وبالتالي يمكن تطوير منهجية إضافة الماء الغير صالح بالأراضي الملائمة له. لذلك أجريت تجربة معملية عام 2011 بمعمل قسم الأراضي بكلية الزراعة - جامعه المنصورة لدراسة العلاقة بين التوصيل الهيدروليكي المشبع و متوسط أقطار المسام باستخدام ثلاثة أنواع من أملاح الصوديوم (صفر, كلوريد الصوديوم, كبريتات الصوديوم) وثلاث معدلات من سماد سلفات الأمونيوم تحت ظروف الأراضي الرسوبية الطميية.

أوضحت النتائج المتحصل عليها أن تدهور البناء يعتبر دالة لعاملين هما تركيز الأملاح ونوع الأنيون المرافق لعنصر الصوديوم. وطبقا لذلك أظهرت جميع المعاملات انخفاضًا ملحوظًا في متوسط أقطار المسام وبالتالي التوصيل الهيدروليكي المشبع. كذلك استخدم معامل الارتباط ومعادلات الانحدار لدراسة مدي اعتماد تقدير التوصيل الهيدروليكي المشبع علي تقدير بعض خواص التربة الطبيعية والممثلة هنا بمتوسط أقطار مسام التربة والكثافة الظاهرية. وكانت أكثر المعاملات تأثيرًا علي خفض قيم متوسط قطر المسام هي الناتجة من مخلوط ملح كلوريد الصوديوم مع سماد سلفات الأمونيوم بمعدلاته كنتيجة للتأثير النوعي لأنيون الكلوريد.

قام بتحكيم البحث

ا.د./ زكريا مسعد الصيرفي	**كلية الزراعة - جامعة المنصورة**
ا.د./ شوقي محمد متولي أحمد	**كلية التكنولوجيا والتنمية - جامعة الزقازيق**