Egypt. J. Soil Sci. 44, No. 1, pp.109 - 128 (2004)

Predicting Unsaturated Hydraulic Conductivity Using Pedotransfer Functions of Calcareous Soils in Egypt

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UNSATURATED hydraulic conductivity [K (θ)] was calculated using moisture retention curve data and the saturated hydraulic conductivity (Ksat) for different textures of the calcareous soils. The rate of change in K (θ) values differ according to the moisture content and / or the capillary pressure. The total and the active content of $CaCO_3$ associated by the soil texture affect the pore size distribution and pore continuity which in turn govern the rate of water movement. Pedotransfer functions were used to correlate the unsaturated hydraulic conductivity values with the basic soil properties including active carbonate content. The unsaturated K (θ) values obtained were affected mainly by the total $CaCO_3$%, the active $CaCO_3$ % and the quickly drainable pore % (QDP). It could be used in solving the dynamic model for water management of the calcareous soils.

Keywords: Unsaturated hydraulic conductivity pedotransfer functions, Water flow, Moisture retention, Total $CaCO_3$, Active $CaCO_3$.

Calcareous soil of the reclaimed area are recently put under agriculture use, however information about its physical and hydraulic properties are scare.

The $CaCO_3$ content, especially the active fraction affect the hydraulic properties of these soils (Gile *et al.*, 1998; Minhas *et al.*, 1998 and Senei & Morshed, 2000). Knowledge concerning the factors affecting the hydraulic properties in such soils are essential in desining of irrigation and drainage systems, to use the water resources as wisely and efficiently as possible and to optimize the soil water relationships.

The effect of $CaCO_3$ on moisture retention and / or movement seems to be more related to its effect on the formation of different structural units rather than to the ability of its surface to retain water (Massoud *et al.*, 1971).

Increasing the water holding pores and fine capillary pores of the loamy and sandy calcareous soils, leads to increase field capacity, available water capacity and wilting percentage. On the other hand, the saturated hydraulic conductivity decreased (Mohamed & Awad, 1998; Prosed *et al.*, 1996 and El-Sersawy, 1999).

Zaghloul (1977); Nasr (1989) and Negm *et al.* (1990) found that the moisture contents at each of wilting and field capacity percentage increased by increasing the amounts of active $CaCO_3$. They concluded that the high degree of $CaCO_3$ fineness causing an increase of contact points which held a larger amount of water.

Increasing the active $CaCO_3$ content leads to increase structure stability and the value of Ks increased (Gile *et al.*, 1998 and Minhas *et al.*, 1998). The observed relationship suggests that aggregates are formed by bonding of active groups of fulvic acids with exchangeable sodium and magnesium ions and that active $CaCO_3$ stabilize them by preventing their biodegradation. The dispersion and dis-aggregation of surface soil were the cause of reducing the hydraulic properties.

Reliable estimates of unsaturated hydraulic conductivity are especially difficult to obtain, partly because of its extensive variability in the field and partly because measuring this parameter is time consuming and expensive (Shawky and Warrick, 1985). Therefore several investigators have used model for calculating the unsaturated hydraulic conductivity from the more easily measured soil-water retention curve (Millington & Quirk, 1962; Jackson, 1972; Green & Corey, 1971; Mualem, 1978; Van Genuchetn, 1980 and Marion *et al.* 1994). On the mean time moisture retention curve determination takes a long time, compared to the simple laboratory techniques for characterizing the soil properties.

The term "pedotransfer functions" was used by Bouma (1989) to describe the quantitative relations between soil characteristics and other characteristics that are more readily available. In other words, pedotransfer functions (PTFs) is a term given to relation between the basic physical properties of soil (texture, structure,$CaCo_3$ ...) and other properties that are important to the soil management.

The objectives of this study were to i) calculate the K (θ) values using moisture retention curve data, ii) study the factors affecting K (θ) values and iii) achieve a mathematical relation between K (θ) at different water potentials and basic soil properties to simply obtain the unsaturated hydraulic conductivity values for the calcareous soils.

Material and Methods

Sixty soil profiles represent the calcareous soils from the Western Desert in Egypt were studied. One hundred and twenty soil layers were sampled (0-30 cm and 30-60 cm depth). These calcareous soils are cultivated and irrigated with the Nile water from El-Nubaria and El-Nasr canal. These soils have the same origin, and the calcite is the dominant type of carbonate minerals (Massoud *et al.*, 1971). In each layer particle size distribution analysis was determined, using sodium hexamete phosphate as dispersing agent, according to the method described by Gee and Bander (1986). The calcium carbonate distribution in particle sizes was determined by the difference in particle size distribution analysis without and with $CaCO_3$ removal in each fraction according to Yallon (1957).

Total $CaCO_3$ content was determined gasiometrically as cited by Nelson (1982). The active $CaCO_3$ content was determined as a percent of soil weight according to Yallon (1957).

The wet sieve analysis was performed for undisturbed soil samples and the water separates were determined by a wet sieving device as described by Kemper and Rosenau (1986).

Undisturbed soil samples were used for determing the moisture retention curves at applied pressures of 0, -10, -20, -33, -100, -300, -500 and –1500 KPa according to methods described by Klute (1986). Then the diameter of pores was calculated according the formula, : d = 0.30 /P, where "d" is the equivalent diameter of a cylindrical pore in mm and "P" is the pressure in Cm applied for the water retention.

The saturated hydraulic conductivity (Ks) was determined for each layer using undisturbed soil columns according to method described by Klute and Dirksen (1986).

The unsaturated hydraulic conductivity K (θ) was computed, as a function of both moisture retention curves and saturated hydraulic conductivity (Ks), using Millington & Quirk (1962) and Jackson (1972) approach. A computer program was elaborated in basic language for solving the formula according to Hillel (1980). Soluble salts (EC dS/m) were determined according to Rhoades (1982).

Result and Discussion

The calcareous soils under investigation are three main texture group (fine textured soils, medium textured soils, and coarse textured soils) non saline and non alkali soils. Data presented in Table 1 show the range, mean and standard deviation (Sd) of the important studied soil properties. The mean values of clay, total $CaCO_3$ active $CaCO_3$ content is 21.31, 27.83 and 11.18, respectively.

The unsaturated hydraulic conductivity of the different groups of textures and for the all groups, mean values are illustrated in Fig 1. In general the results show that the K (θ) values decreases with decreasing soil moisture content and / or increasing the pressure head (suction). The sharp decrease occurs from 0.1 atm. (suction) up to 0.33 atm., after words, the curve start to flatten with a minimum rate of change with decreasing soil moisture content.

TABLE 1. Range, mean and standard deviation (Sd) for the determined and calculated soil properties of soils under investigation.

Properties	Range	Mean	Sd
Saturated hydraulic Conductivity (cm/h)	2.1 – 54.96	12.90	11.64
Clay (%)	2.14 - 52.50	21.31	13.46
Silt (%)	2.15 – 39.16	15.86	8.93
F. Sand (%)	10.94 - 48.97	31.86	7.38
C. Sand (%)	3.03 - 69.71	31.02	18.47
Total CaCO3 (%)	3.60 - 62.50	27.83	14.01
Active CaCO3 (%)	0.33 - 34.10	11.18	8.13
Total aggregates (%)	23.94 - 61.77	40.73	8.80
5 – 2.0 mm aggregates (%)	0.79 - 9.22	3.03	1.69
2.0 – 1.0 mm agg. (%)	0.97 –16.10	4.88	2.91
1.0 – 0.5 mm agg. (%)	9.45 - 25.16	16.83	4.06
0.5 – 0.25 mm agg. (%)	7.25 - 29.25	15.98	4.75
Mean Weight diameter (mm)	0.22 - 0.58	0.37	0.08
Total porosity (%) (v/v)	35.16 - 55.49	45.72	5.45
Quickly drainable pores % (v/v)*	8.29 - 29.18	18.36	4.80
Slowly drainable pores % (v/v)	1.66 - 10.30	5.66	1.84
Water holding pores % (v/v)	3.12 - 21.82	10.64	3.55
Fine capillary pores % (v/v)	2.52- 23.03	11.07	5.24
Applied pressure KPa	Unsaturated hydraulic conductivity (cm/h)		
10	3.325 E-04 – 1.031 E-09	9.726 E-05	6.433 E-05
20	6.973 E-05 – 3.751 E-06	2.125 E-05	1.277 E-05
33	7.456 E-05 – 7.744 E-10	7.990 E-06	1.130 E-05
66	4.928 E-06 – 7.936 E-07	1.539 E-06	8.482 E-07
100	3.452 E-07 – 3.604 E-08	1.667 E-07	1.009 E-07
300	9.852 E-08 – 1.010 E-08	3.882 E-08	3.065 E-08
500	9.731 E-09 – 1.030 E-09	2.739 E-09	1.672 E-09
1500	3.590 E-09 – 3.952 E-11	7.994 E-10	7.569 E-10
Bulk density (g. Cm^{-3})	1.24- 1.72	1.49	0.13

* % of total porosity.

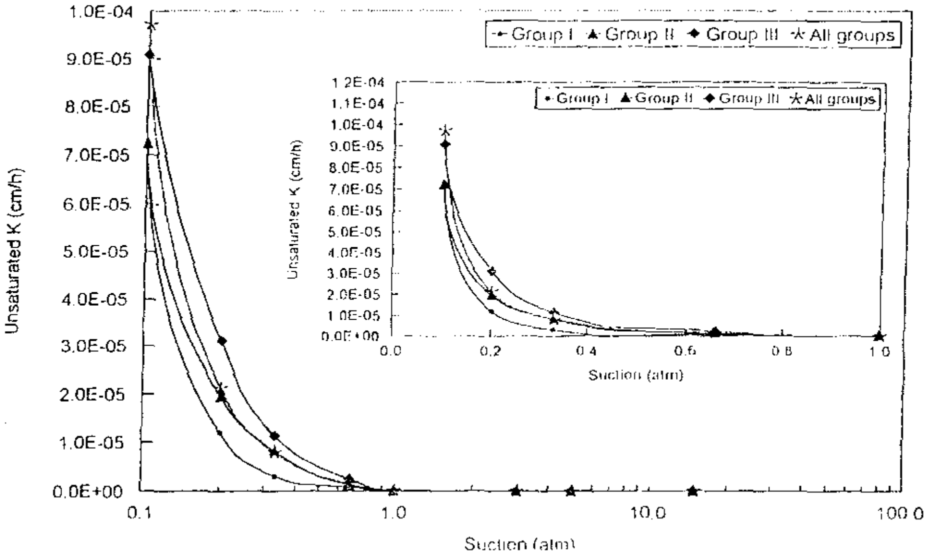

Fig. 1. Mean values of K- unsaturated ($cm.h^{-1}$) under different suctions level of the studied soil groups.

Effect of soil texture on unsaturated hydraulic conductivity K (θ)

The mean values of K (θ) for the different soil profile groups are presented in Table 2 and Fig. 1. The data showed that group (3) which represents the coarse textured soils have a relatively higher K (θ) values compared to these of group (1) and group (2) at low suction range (0.1 to 0.66 atm.) but at higher suction, K (θ) values of clayey and loamy soils (group 1 and group 2) become higher than the coarse textured (group 3). This relationship is expected because at high soil moisture contents (low suction levels), K (θ) is more less directly related to soil structure, and increase as the texture becomes coarser (group 3). As the soil moisture content decreases, this relationship between K (θ) and texture is reversed, so that in dry conditions, heavy textured soils (group 1) and loamy textured soils (group 2) are likely to have higher K (θ) than coarse textured soils (group 3). This behavior is expected as the coarse textured soils have high percentage of macro pores, but fine and moderately textured soils have high percentage of micro pores governes the flow in unsaturated conditions. These results are in agreement with these of Ward (1967); Shawky and Wahdan (1977, 1986) and Wahdan *et al.* (2001).

TABLE 2. Maximum, minimum, mean and the standard deviation of the unsaturated hydraulic conductivity (cm .h^{-1}) under different suction levels of the studied soils.

Location (groups)		Total $CaCO_3$ (%)	Active $CaCO_3$ (%)	Unsaturated hydraulic conductivity (cm .h^{-1}) under different suction							
				0.1 atm.	0.2 atm.	0.33 atm	0.66 atm.	1.0 atm.	3.0 atm.	5.0 atm.	15.0 atm.
1 (30 samples)	Max.	62.50	34.10	3.325 E-04	2.040 E-05	5.659 E-06	3.019 E-06	3.145 E-07	9.513 E-08	9.731 E-09	3.590 E-09
	Min.	29.52	14.22	2.535 E-05	6.918 E-06	3.647 E-07	4.936 E-07	1.132 E-07	1.010 E-08	1.054 E-09	3.952 E-11
	Mean	42.34	21.41	7.285 E-05	1.203 E-05	3.089 E-06	8.864 E-07	1891 E-07	5.875 E-08	2.719 E-09	5.547 E-10
	S.d	8.03	4.43	8.226 E-05	3.353 E-06	1.131 E-06	4.470 E-07	5.036 E-08	2.762 E-08	2.765 E-09	8.214 E-10
2 (52 samples)	Max.	57.40	23.27	1.427 E-04	3.611 E-05	4.896 E-05	2.247 E-06	3.452 E-07	9.852 E-08	6.800 E-09	3.492 E-09
	Min.	14.60	4.35	1.031 E-09	8.417 E-06	2.274 E-06	5.908 E-07	3.787 E-08	1.014 E-08	1.030 E-09	5.062 E-11
	Mean	30.56	11.64	7.223 E-05	1.938 E-05	8.340 E-06	1.238 E-06	2.290 E-07	4.085 E-08	2.149 E-09	8.913 E-10
	S.d	9.65	4.79	2.783 E-05	6.092 E-06	1.050 E-05	3.481 E-07	9.232 E-08	3.524 E-08	8.527 E-10	9.330 E-10
3 (38 samples)	Max.	25.10	6.12	2.813 E-04	6.973 E-05	7.456 E-05	4.928 E-06	3.245 E-07	3.832 E-08	6.975 E-09	1.341 E-09
	Min.	3.60	0.33	7.679 E-05	3.751 E-06	7.744 E-	1.525 E-06	3.604 E-08	1.016 E-08	2.167 E-09	4.806 E-10
	Mean	12.66	2.49	1.508 E-04	3.108 E-05	010	2.467 E-06	6.369 E-08	2.030 E-08	3.560 E-09	8.669 E-10
	S.d	5.89	1.71	5.131 E-05	1.707 E-05	1.138 E-05	7.963 E-07	4.718 E-08	5.545 E-09	9.024 E-10	2.211 E-10
						1.503 E-05					
All soils (120 samples)	Max.	62.50	34.10	3.325 E-04	6.973 E-05	7.456 E-05	4.928 E-06	3.452 E-07	9.852 E-08	9.731 E-09	3.950 E-09
	Min.	3.60	0.33	1.031 E-09	3.751 E-06	7.744 E-10	4.936 E-07	3.604 E-08	1.010 E-08	1.030 E-09	3.952 E-11
	Mean	27.83	11.18	9.726 E-05	2.125 E-05	7.990 E-06	1.539 E-06	1.667 E-07	3.882 E-08	2.739 E-09	7.994 E-10
	S.d	14.01	8.13	6.433 E-05	1.277 E-05	1.130 E-05	8.482 E-07	1.009 E-07	3.065 E-08	1.672 E-09	7.569 E-10

Simple correlation coefficient between K (θ) and the particle size distribution is presented in Table 3. The data show a significant and negative correlation with clay and silt in the range from 0.1 to 0.66 atm. suction after that there is a significant and positive correlation in the high suctions range from 1.0 to 3.0 atm. suction. Then, the K (θ) values become not significantly changed with each of clay and silt content. The data show also a positive and significant correlation between K (θ) and either coarse sand or fine sand content within the range of 0.1 to 0.66 atm. suction. Within the range of 0.66 to 5.0 atm. suction, the correlation becames significant and negative one between K (θ) and either coarse sand or fine sand fractions. The change in the relation is mainly a porosity function, as with low suction levels, macro pores associated with presence of sand and / or inter-aggregate porosity lead to such decrease in the K(θ) values. Within high suction, micro pores and intra-aggregate porosity play the role giving the positive relation. At relatively very high suction above 5.0 atm., the very micro pores present has high tension reducing the conductivity without no big variation in reducing the K (θ) values. These findings are in agreement with Shawky & Wahdan (1977, 1986) and Wahdan *et al.* (2001).

Effect of soil structure on the unsaturated hydraulic conductivity K (θ)

The data presented in Table 3 show the simple correlation coefficient between K (θ) and the soil structure parameters (water stable separates and pore size distribution). The data revealed a negative correlation with each of water stable separates 5-2 mm and 2-1 mm with the suction range from 0.1 to 0.2 atm., and a positive correlation at suction range from 0.66 to 3.0 atm., at suction greater than 3.0 atm., the correlation was not significant. On the other hand, the correlation was positive and significant between K (θ) and each of 1.0 – 0.5 mm and 0.5 – 0.25 mm water stable separates. The mean weight diameter (MWD), showed a positive and significant correlation with K (θ) for suction range from 0.1 to 0.66 atm., after that the correlation coefficient became negative for the suction range from 1.0 to 3.0 atm.

The data show a positive and significant correlations between K (θ) and quickly drainable pores (QDP) and a negative and significant correlations with each of water holding pores (WHP), slowly drainable pores (SDP), fine capillary pores (FCP) and the total porosity within the range from 0.1 to 0.66 atm. after that the correlation between the above mentioned pore size distribution and K (θ) was positive when the suction increased from 0.66 to 3.0 atm. The above mentioned findings can be explained according to the findings of Ward (1967); Shawky & Wahdan (1977, 1986) and Wahdan *et al.* (2001). They concluded that the effect of moisture on the variation of K(θ) must be considered in association with the pore size distribution of the soil. At high soil moisture content, the K(θ) increased by increasing coarse fraction because water will obviously be transmitted easily through large water filled pores than through small pores. As the moisture content decreases, and the suction increases the K(θ) increases by increasing fine soil fraction, since the finer soils will have more water filled pores than the coarser soils due to the increasing micro pore water pathways by increasing fine fraction (clay, silt and active $CaCO_3$ content). also by increasing the water pathways.

The impact of $CaCO_3$ content on the unsaturated hydraulic conductivity K(θ)

The data presented in Table 3 show the simple correlation coefficient between K(θ) and each of total and active $CaCO_3$ at different suction levels. The data revealed a negative and significant correlation between each of total and active $CaCO_3$ and K(θ) under the suction range from 0.1 to 0.66 atm., afterwards a positive and significant correlation was found at the suction range from 1.0 to 3.0 atm. After suction 3.0 atm., the effect of total and / or active $CaCO_3$ % was significant within K(θ) at the range from 5.0 to 15.0 atm.

These results are in agreement with those of Shawky & Wahdan (1986); El-Amir (1987) and Nasr (1989). They pointed out that the highly calcareous soils have the highest amount of active CaCO3 (> 20%), highest amount of fine capillary pores and the lowest amounts of drainage pores. Therefore the values of K(θ) decreased with decreasing soil water content and both of active and total $CaCO_3$ content.

Considering the effect of total and active $CaCO_3$ content as an important parameters in calcareous soils, the relationship between K(θ) at different water potential levels and each of total and active $CaCO_3$ content were quantitatively calculated through a linear, logarithmic, exponential, quadratic and polynomial equations. The best fitting equation types which have the highest correlation coefficients (r) between K(θ) and each of total and active $CaCO_3$ are presented in Table 4 and illustrated in Fig.2 , 3 and 4. These equations show that the K(θ) decreased by increasing each of total or active $CaCO_3$ content under suction levels of 0.10, 0.20 and 0.66 atm. On the other hand, the K(θ) increased by increasing each of total and active $CaCO_3$ content under suction levels of 1.0 and 3.0 atm. This relationship is expected as at high soil moisture contents at suction 0.1 and 0.20 atm., the K(θ) is more or less directly related to soil texture and decreases as the texture becomes finer by increasing total $CaCO_3$ and subsequently active $CaCO_3$. As the moisture content decreasesd by increasing suction at 1.0 and 3.0 atm., the K(θ) increased by increasing active $CaCO_3$, (Fig. 3 and 4). This relationship is expected, since the texture becomes finer and subsequently the finer soils will have more water filled pores due to increasing micro pores, therefore a large cross-sectional area through which flow can take place.

TABLE .3. Simple correlation coefficient (r) between unsaturated hydraulic conductivity [K(θ)] and some soil parameters of the studied soils.

Soil properties	K (θ)							
	0.1 atm.	0.2 atm.	0.33 atm	0.66 atm.	1.0 atm.	3.0 atm.	5.0 atm.	15.0 atm.
$CaCO_3$ (%):								
Total $CaCO_3$	-0.451*	-0.611**	-0.614**	-0.669**	0.507**	0.433*	-0.189	-0.172
Active $CaCO_3$	-0.444*	-0.578**	-0.198*	-0.198*	0.467**	0.415*	-0.084	-0.190
Particle size distribution (%):								
Clay	-0.451*	-0.607**	-0.237*	0.698**	0.425**	0.390*	-0.094	-0.134
Silt	-0.444*	0.443*	-0.144	0.587**	0.476**	0.328*	-0.114	-0.092
Fine sand	-0.056	0.040	0.248*	0.152	-0.262*	-0.044	-0.105	-0.101
Coarse sand	-0.517**	0.637**	0.142	0.727**	-0.436	-0.457**	-0.111	0.106
Water stable aggregates distribution (%):								
Aggregates 5-2 mm	-0.253*	-0.393*	0.124	0.489**	0.191	0.127	0.089	-0.102
Aggregates 2-1 mm	-0.311*	0.411**	0.139	0.468**	0.203*	0.285*	0.102	0.176
Aggregates 1-0.5 mm	0.503	0.627**	0.223*	0.769**	0.571**	0.393*	-0.171	-0.119
Aggregates 0.5-0.25 mm	0.536**	0.639**	0.194*	0.371*	0.517**	0.427**	0.182	-0.134
Mean weight diameter (MWD)	0.453**	0.614**	0.190*	0.402**	-0.447**	-0.387*	-0.170	-0.189
Pore size distribution (%):								
QDP	0.367*	0.548**	0.184	0.539**	-0.329*	-0.223*	0.106	0.198
SDP	-0.437*	-0.385*	-0.256*	-0.516**	0.487**	0.116	-0.282*	0.052
WHP	-0.377	-0.556**	-0.137	-0.526**	0.356*	0.268*	-0.151	-0.161
FCP	-0.471*	-0.611**	-0.219*	-0.686**	0.410*	0.392*	-0.126	-0.141
Total porosity	-0.521**	-0.596**	-0.224*	-0.699**	0.499**	0.394*	-0.223	0.093

* Significant at 5% ** Significant at 1 %

TABLE 4. Best fitting equation for the relationship between unsaturated hydraulic conductivity in cm.h^{-1} (Y) under different suctions levels and each of total $CaCO_3$ (X1) and active $CaCO_3$ (X2) for all the studied soils.

Suction (atm.)	Total $CaCO_3$ (%) (X_1)	r	Active $CaCO_3$ (%) (X_2)	r
0.1	$Y = 0.0004466\ X_1^{-0.6583}$	-0.307*	$Y = 0.000144\ X_2^{-0.336704}$	-0.616**
0.2	$Y = 0.00008783\ X_1^{-0.9059}$	-0.542**	$Y = 0.00003154\ X_2^{-0.2908}$	-0.741**
0.33	$Y = [11.459-0.112X_1.0.00036X_1^2]^*\ 10^{-6}$	0.195*	$Y = [10.447-0.1134X_2.0.0063X_2^2]^*\ 10^{-6}$	0.202*
0.66	$Y = 0.0000481-0.0000013\ \mathrm{Ln}\ X_1$	-0.689**	$Y = 0.0000027-0.000006\ \mathrm{Ln}\ X_2$	-0.675**
1.0	$Y = 0.000000016\ X_1^{0.6643}$	-0.406**	$Y = 0.000000061\ X_2^{0.38503}$	-0.467**
3.0	$Y = 0.000000073\ e^{0.0214X_1}$	0.433**	$Y = 0.0000000104-0.0000000184\ \mathrm{Ln}\ X_2$	0.451**
5.0	$Y = [0.00516-0.00018\ X_1-2.77^*10^{-6}\ X_1^2]^*10^{-6}$	0.401**	$Y = [0.0043-0.00384\ X_2+1.0411^*10^{-5}\ X_2^2]^*10^{-6}$	0.575
15.0	$Y = [0.000987-2.916^*10^{-6}X_1-1.11^*10^{-7}X_1^2]*10^{-6}$	0.175	$Y = [0.000896+8.533^*10^{-6}X_2-1.0097^*10^{-6}X_2^2]*10^{-6}$	0.202*

* Significant at 5%   ** Significant at 1 %

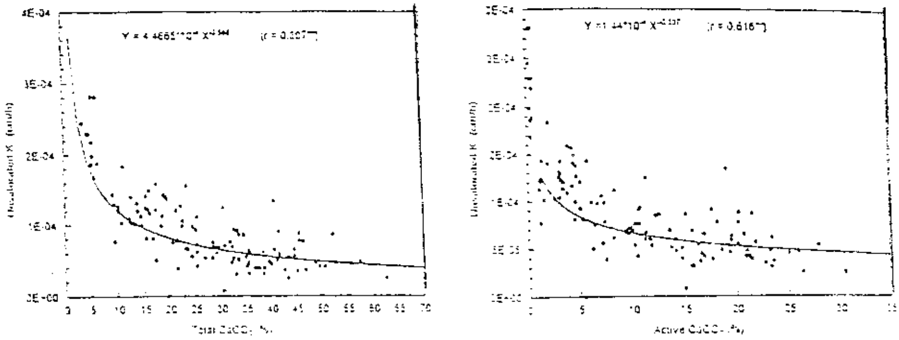

Fig.2a. The relationship between total $CaCO_3$,active $CaCO_3$ and unsaturated hydraulic conductivity under 0.1 atm.

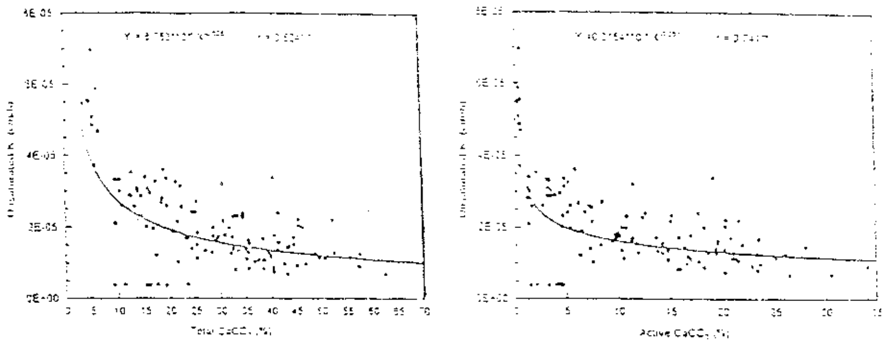

Fig.2b. The relationship between total $CaCO_3$,active $CaCO_3$ and unsaturated hydraulic conductivity at 0.2 atm.

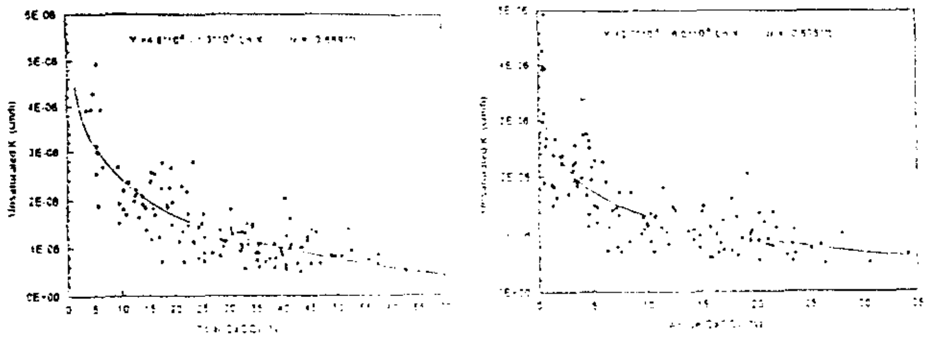

Fig.3a. The relationship between total $CaCO_3$,active $CaCO_3$ and unsaturated hydraulic conductivity at 0.66 atm.

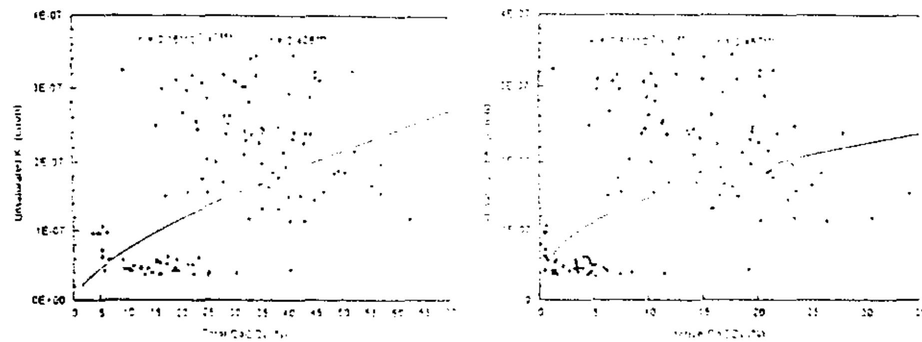

Fig.3b. The relationship between active $CaCO_3$ and unsaturated hydraulic conductivity at 0.66 atm.

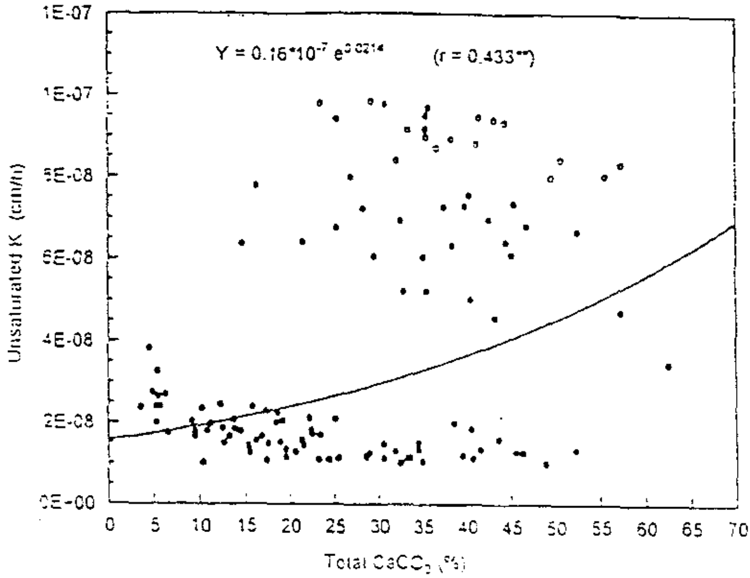

Fig.4a. The relationship between total $CaCO_3$ and unsaturated hydraulic conductivity at 1.0 atm.

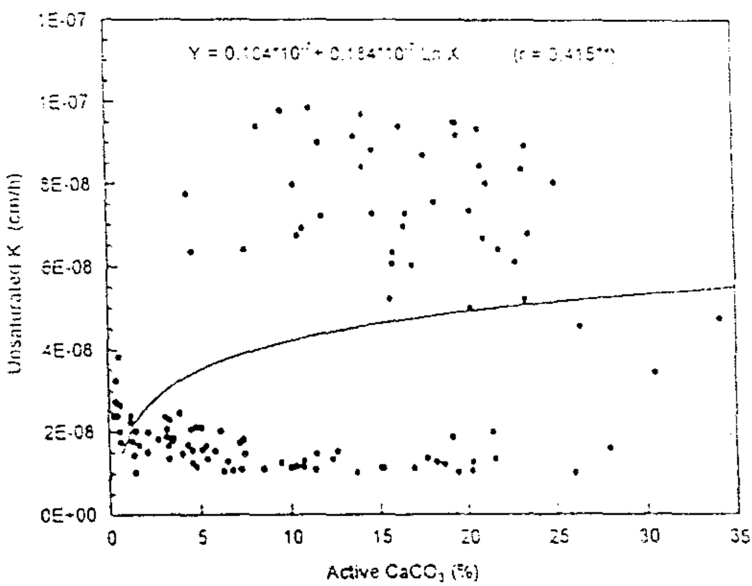

Fig.4b. The relationship between active $CaCO_3$ and unsaturated hydraulic conductivity at 1.0 atm.

Pedotrans for functions can be used to predict hydraulic properties of soils from basic soil properties. (Van Gonuchten *et al*,1992 and Schaap *et al.*, 1998).

According to the previous findings and to clarify the idea of selecting the simple soil physical properties to correlate it with the K (θ) values instead of its calculation from the moisture curve, stepwise statistical method was used. The method based on the selection of the most effective factors that govern the K (θ) values under the prevailing conditions. The presented models are selected from the statistical analysis carried out according to their significant level, as to be the highest, also the equations included the most effective soil physical properties that affect the K (θ) values. These equations could be summarized as follows :

1) For water potential at – 10 KPa

$$K(\theta)_{10} = (80.996) \times 10^{-6} + (1.751\ X_1) \times 10^{-6} - (7.743\ X_5) \times 10^{-6} + (3.306 X_{13}) \times 10^{-6} - (1.404\ X_{11}) \times 10^{-6} + (0.615 X_3) \times 10^{-6} \qquad (\text{adj } r = 0.595^{**}).$$

2) For water potential at – 20 KPa

$$K(\theta)_{20} = (13.012) \times 10^{-6} + (0.437\ X_1) \times 10^{-6} - (1.351\ X_5) \times 10^{-6} + (0.476 X_3) \times 10^{-6} - (0.312\ X_{13}) \times 10^{-6} \qquad (\text{adj } r = 0.705^{**}).$$

3) For water potential at – 33 KPa

$$K(\theta)_{33} = (5.523) \times 10^{-6} + (0.314\ X_2) \times 10^{-6} - (1.329\ X_{10}) \times 10^{-6} + (0.184 X_3) \times 10^{-6} - (0.016\ X_{13}) \times 10^{-6} \qquad (\text{adj } r = 0.329^{**}).$$

4) For water potential at – 66 KPa

$$K(\theta)_{66} = (1.316) \times 10^{-6} + (0.139\ X_6) \times 10^{-6} + (0.021\ X_1) \times 10^{-6} + (0.086 X_{12}) \times 10^{-6} - (0.242\ X_8) \times 10^{-6} \qquad (\text{adj } r = 0.817^{**}).$$

5) For water potential at – 100 KPa

$$K(\theta)_{100} = (0.1313) \times 10^{-6} + (0.015\ X_6) \times 10^{-6} - (0.013\ X_7) \times 10^{-6} - (0.0027 X_2) \times 10^{-6} + (0.006\ X_5) \times 10^{-6} - (0.0029\ X_{11}) \times 10^{-6} + (0.0014\ X_{13}) \times 10^{-6} - (0.00064\ X_4) \times 10^{-6} + (0.00038\ X_9) \times 10^{-6} \quad (\text{adj } r = 0.622^{**})$$

6) For water potential at – 300 KPa

$$K(\theta)_{300} = (0.188) \times 10^{-6} + (0.001\ X_1) \times 10^{-6} - (0.001\ X_3) \times 10^{-6} + (0.004 X_9) \times 10^{-6} - (0.004\ X_{11}) \times 10^{-6} - (0.015\ X_8) \times 10^{-6} + (0.0025\ X_7) \times 10^{-6} \qquad (\text{adj } r = 0.605^{**}).$$

7) For water potential at – 500 KPa

$$K(\theta)_{500} = (0.0573) \times 10^{-6} - (0.000185\ X_5) \times 10^{-6} + (0.00029\ X_7) \times 10^{-6} - (0.0000357\ X_2) \times 10^{-6} - (0.00019\ X_6) \times 10^{-6} + (0.000077\ X_{13}) \times 10^{-6} - (0.000066\ X_{12}) \times 10^{-6} - (0.00000132\ X_4) \times 10^{-6} \quad (\text{adj } r = 0.483^{**}).$$

8) For water potential at – 1500 KPa

$$K(\theta)_{1500} = -(0.001) \times 10^{-6} - (0.0037\ X_8) \times 10^{-6} + (0.000067\ X_9) \times 10^{-6} + (0.0000275\ X_4) \times 10^{-6} + (0.0000099\ X_2) \times 10^{-6} + (0.000075\ X_{11}) \times 10^{-6} - (0.000034\ X_5) \times 10^{-6} - (0.0000181\ X_{13}) \times 10^{-6} \quad (\text{adj } r = 0.347^{**}).$$

Where:

$K(\theta)$	is unsaturated hydraulic conductivity ($cm.h^{-1}$) at different water potential levels.
X_1	is coarse sand (%).
X_2	is fine sand (%).
X_3	is silt (%).
X_4	is clay (%).
X_5	is water stable separates 0.5 – 0.25 mm (%) .
X_6	is water stable separates 1.0 – 0.5 mm (%) .
X_7	is water stable separates 2.0 – 1.0 mm (%) .
X_8	is water stable separates 5.0 – 2.0 mm (%) .
X_9	is quickly drainable pores (O.D.P % of total).
X_{10}	is slowly drainable pores (S.D.P % of total) .
X_{11}	is fine capillary pores (F.C.P % of total) .
X_{12}	is water Holding pores (W.H.P % of total) .
X_{13}	is Active $CaCO_3$ (% of soil).

The total contribution percent of these factors to the $K(\theta)$ values were statistically calculated and presented in Table 5.

TABLE 5. Contribution percent of the main factors affecting unsaturated hydraulic conductivity $K(\theta)$ at different suction levels for the studied soils.

$K(\theta)$ at	Main parameters	Contribution (%)
0.1 atm.	Coarse sand	54.7
	Water stable separates 0.5-0.25 mm	2.4
	Active $CaCO_3$	2.1
	Fine capillary pores (FCP)	0.2
	Silt	0.2
	Total	59.5
0.2 atm.	Coarse sand	65.7
	Water stable separates 0.5-0.25 mm	2.7
	Silt	1.5
	Active $CaCO_3$	0.6
	Total	70.6
0.33 atm.	Find sand	27.4
	Slowly drainable pores (SDP)	4.6
	Silt	0.55
	Active $CaCO_3$	0.5
	Total	32.9
0.66 atm.	Water stable separates 1.0-0.5 mm	77.0
	Coarse sand	1.5
	Water holding pores (WHP)	1.9
	Water stable separates 5-2 mm	1.3
	Total	81.7

TABLE . 5 Contd .

K(θ) at	Main parameters	Contribution (%)
1.0 atm.	Water stable separates 1.0-0.5 mm	57.1
	Water stable separates 2-1 mm	1.5
	Fine sand	2.4
	Water stable separates 0.5-0.25 mm	0.7
	Fine capillary pore (FCP)	0.3
	Active $CaCO_3$	0.1
	Clay	0.2
	Quickly drainable pore (QDP)	0.2
	Total	62.6
3.0 atm.	Coarse sand	45.0
	Silt	5.4
	Quickly drainable pore (QDP)	5.4
	Fine capillary pore (FCP)	1.4
	Water stable separates 5-2 mm	2.9
	Water stable separates 2-1 mm	0.4
	Total	60.5
5.0	Water stable separates 0.5-0.25 mm	28.2
	Water stable separates 2-1 mm	12.0
	Fine sand	2.5
	Water stable separates 1-0.5 mm	3.1
	Active $CaCO_3$	1.8
	Water holding pores (WHP)	0.6
	Total	28.2
15.0 atm.	Water stable separates 5-2 mm	20.2
	Quickly drainable pore (QDP)	2.9
	Clay	6.1
	Fine sand	1.4
	Fine capillary pore (FCP)	1.2
	Water stable separates 1-0.5 mm	1.2
	Active $CaCO_3$	0.7
	Total	34.7

The above mentioned relations indicate the following:

1.The sand fraction content followed by the aggregate sizes play an important role in determining the K (θ) values obtained at all levels of water potential. That is due to the high variation exist of sand fraction and aggregates.

2.Within the suction range between 0.1 and 0.33 atm. The factors affecting the K (θ) value vary, indicating that the sand content is the main factor contributing to the variation in K (θ) values at these water potential range. The relations indicate that the sand content increases the K (θ) values at water potentials of 0.1, 0.2 and 0.33 atm, after that the relation is reversed at 1.0, 5.0 and 15.0 atm. Suction. This is expected, since at higher soil moisture content (low water potentials) the increasing of sand fraction leads to an increasing of macro-pores which are the main pathway of water movement at high soil moisture content. At lower soil moisture content, this behaviour is reversed, since the K (θ) values increase by increasing micro-pores which are the main pathways of water movement at high water potential levels.

3.Within the suction at 0.66, 1.0 , 5 and 15 atm, the aggregate sizes become the main factors affecting the K (θ) values. The aggregate size effect on K (θ) values fluctuates between positive and negative effect within the different water potential levels, it seems that the fluctuation of K (θ) values depend on the intera and inter aggregates porosity and its continuity which govern the water movement in the unsaturated condition in the calcareous soils.

4. The presented relations indicate that, the pore sizes are not the main factors affecting the K (θ) values at any suction level, it seems that the pore diameter itself is not of that importance as compared with the paths present and their continuity. Also, it seems under field condition, that is difficult to obtain higher contribution values for all the contributing parameter at the K (θ) as multi factors interfere in the relations tested.

In conclusion, the $CaCO_3$ contents, soil texture and soil structure are important parameters affecting the unsaturated water movement in the calcareous soils as the sand content, and aggregate sizes distribution are the main factors contributing at the K (θ) values. The aggregate sizes and pore geometry, consequently are responsible for creating the paths that govern the water movement in the unsaturated conditions. The pore diameter itself is not of that importance as compared to the paths present and their continuity. This fact was realized as the pore size distributions were not the main contributing factor of K (θ) values at any suction levels under the prevailing conditions when it was tested. Finally prediction of the K (θ) values in the studied calcareous soils through determing the more contribution soil physical parameter is a good task for studying the unsaturated flow in such soils.

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Recevied 10/2002

التنبؤ بمعامل التوصيل الهيدروليكى الغير مشبع بإستخدام النماذج الرياضية للأراضى الجيرية المصرية

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تم حساب معامل التوصيل الهيدروليكى غير المشبع K (θ) بإستخدام منحنيات الشد الرطوبى ومعامل التوصيل الهيدروليكى المشبع (Ksat) للأراضى الجيرية بقوامات مختلفة. وتشير النتائج إلى تأثر قيم K (θ) بعدة عوامل أهمها النسبة الكلية لكربونات الكالسيوم ، نسبة كربونات الكالسيوم النشطة ونسبة مسام الصرف السريعة.

أختلف معدل التغير فى K (θ) تبعاً لإختلاف المحتوى الرطوبى للتربة أو الضغط الشعرى وبوجه عام فإن المحتوى الكلى والمحتوى النشط لكربونات الكالسيوم والمرتبط بقوام التربة يؤثر على قيم التوزيع الحجمى للمسام وإستمراريتها وبالتالى على قيم التوصيل الهيدروليكى غير المشبع المتحصل عليها.

وقد تم إشتقاق عدة نماذج يمكن منها حساب قيم التوصيل الهيدروليكى غير المشبع ، وذلك بإستخدام خصائص التربة التى تسهل تقديرها معملياً ، ويمكن الإستفادة من ذلك فى رسم برامج للإدارة المائية للأراضى الجيرية.