2012, Scienceline Publication

Journal of Civil Engineering and Urbanism

Volume 2, Issue 2: 56-62 (2012) (Received: December 17, 2011; Accepted: February 01, 2012; Published: March 30, 2012) ISSN-2252-0430

Study and Comparison the Efficiency of Mualem-Van Genuchten and Brooks-Corey Models in Predicting Unsaturated Hydraulic Conductivity in Compacted Soils

Hassan Abbaspour[1*], Mehdi Shorafa[2], Rasoul Daneshfaraz[3], Mohammad Hossein Mohammadi[4], Mehdi Rashtbari[5]

[1]*M.Sc. Student, Department of Soil Science Engineering, Campus of Agriculture and Natural Resources, Karaj, Tehran University, Iran*
[2]*Associate Professor, Department of Soil Sciences Engineering, Campus of Agriculture and Natural Resources, Karaj, Tehran University, Iran*
[3]*Assistant Professor, Department of Civil Engineering, Campus of Civil Engineering, University of Maragheh, Iran*
[4]*Assistant Professor, Department of Soil Sciences Engineering, Campus of Agriculture, Zanjan University, Iran*
[5]*M.Sc. Student, Department of Soil Science Engineering, Campus of Agriculture and Natural Resources, Karaj, Tehran University, Iran*

*Corresponding author's Email: abbaspour_hassan@yahoo.com

ABSTRACT: Soil hydraulic properties including soil water characteristics curve and hydraulic conductivity are two important properties to determination of water movement in soil. Hydraulic conductivity plays an important role in underground water movement, water flow to porous medium and pollutants transferring. Measuring these parameters in laboratory is costly and time-consuming. So, mathematical models were developed. Nowadays, numerous empirical models were presented to prediction of unsaturated hydraulic conductivity which of these models we can point out Gardner model, Campbell, Brooks-Corey and Mualem-Van Genuchten models. Present study was conducted on compacted soils in laboratory. Samples were collected from 0-10cm depth and Compaction created by proctor in six replication and four levels including C0 (control), C_1, C_2 and C_3 by increasing in soil bulk density with the ratio of 5, 10 and 15%, respectively. Unsaturated hydraulic conductivity for these treatments evaluated and compared using Mualem-Van Genuchten (VG) and Brooks-Corey (BC) models by RETC software and identified that unsaturated hydraulic conductivity increased due to increase in fine pores as compaction increased and amount of correlation coefficients between moisture content and unsaturated hydraulic conductivity in BC model for all compaction treatments was more than those for VG model.

Keywords: Brooks-Corey model, Mualem-Van Genuchten model, soil compaction, unsaturated hydraulic conductivity

ORIGINAL ARTICLE

1. INTRODUCTION

Soil compaction resulted from agricultural machinery traffic caused increasing in bulk density (BD), reduction in soil porosity, change in pore shapes and pore size distribution (Radford et al., 2000; Richard et al., 2001). Change in main properties changes soil moisture curve form and soil hydraulic properties which in turn will changes permeability and available water capacity and eventually soil compaction caused serious impacts on soil quality parameters, crop growth and environmental quality. Effects of soil compaction depends on compaction rate, soil type, moisture status, landscape status and cropping system (Radford et al., 2000; Miller et al., 2002; Green et al., 2003; Sillon et al., 2003; Tarawally et al., 2004). Hill and Sumner (1967) studied the soil moisture characteristic curve for artificially compacted soil at different bulk densities and found that soil compaction changed moisture curve form at different soil texture classes.

Compaction significantly increased soil bulk density and unsaturated hydraulic conductivity and reduced saturated hydraulic conductivity. Miller et al. (2002) reported that soil moisture characteristic curve had more sensitivity to compaction than soil moisture. Green et al. (2003) agricultural machinery traffic in farm had significant effects on soil compaction and its hydraulic conductivity at different soils and climates. Lipiec and Hatano (2003) stated that laboratory data related to compaction impacts on soil unsaturated flow is very limited.

So, in order to study this parameter, need to use mathematical models. Increasing in soil bulk density due to compaction, may affect many aspects of soil-water-plant-atmosphere system. Hydraulic conductivity coefficient in saturated medium reach to maximum and in unsaturated medium greatly decreased as volumetric moisture is reduced. Soil compaction caused change in moisture curve shape and reduction in pores and increasing in unsaturated hydraulic conductivity at all (Zhang et al., 2006). There are various methods to express

To cite this paper: Abbaspour H., Shorafa M., Daneshfaraz R., Mohammadi M.H., Rashtbari M. 2012. Study and Comparison the Efficiency of Mualem-Van Genuchten and Brooks-Corey Models in Predicting Unsaturated Hydraulic Conductivity in Compacted Soils. *Journal. Civil Eng. Urban.* 2(2): 56-62.
Journal homepage: http://www.ojceu.ir/main/

the soil's hydraulic properties. Field methods generally had limitations including number of replications, time consuming and uncertainty in soil sample boundaries, on the other hand, laboratory measuring mostly feasible near to saturated moistures and obtained results mostly related to disturbed soils (Klute and Dirksen, 1986).

Nowadays, soil scientists used various methods to determine soil hydraulic properties. Therefore, soil hydraulic properties could be explained by the simple sets of models. These equations give good estimation for the effects of compaction on hydraulic properties specially soil moisture curve and unsaturated hydraulic conductivity (Assouline, 2006). Numerous empirical models were presented to prediction of unsaturated hydraulic conductivity which of these models we can point out Gardner model (1958), Campbell (1974), Brooks-Corey model (1964) and Van-Genuchten model (1980).

In the present study unsaturated hydraulic conductivity using Brooks-Corey and Van-Genuchten model in compacted soils was evaluated. For this purpose RETC and SPSS software were used to estimation of unsaturated hydraulic conductivity and to compare the correlation coefficients, respectively.

2. METHOD AND MATERIALS

Studied soil samples randomly were collected from two different areas in Karaj; first Kordan due to having loamy sand texture and second area from research farm of College of Agriculture and Natural Resources of Tehran University due to having sandy loam texture. Samples were collected from 0-10cm depth. Soil samples analyzed for physical and chemical properties. Particle size distribution (PSD) was determined using hydrometer method (Gee and Bauder, 1986), bulk density by cylinder method and organic carbon measured by Walkley and Black method (1934).

Soil samples passed through 2mm sieve, and then were poured in standard steel cylinders (7.5 cm height and 7.5 cm diameter). Compaction created by proctor in six replication and four levels including C_0 (control), C_1, C_2 and C_3 by increasing in soil bulk density with the ratio of 5, 10 and 15%, respectively.

Saturated hydraulic conductivity was determined in laboratory for samples and saturated conductivity coefficient measured by constant load method according to equation (1) (Klute and Dirksen, 1986):

$K_s = Vl/hAt$ [1]

Where, K is saturated conductivity coefficient ($Cmhr^{-1}$), V the volume of collected water (Cm^3), l soil column height, h water load height (cm), A cylinder area (Cm^2) and t is time (hr).

In order to determine the moisture curves after compaction treatments, initially soil samples were saturated from below for different compaction treatments. Then, treatments moisture contents after reaching equilibrium by pressure plate were determined at 0, 0.33, 0.5, 1, 5, 10 and 15 bar suctions.

By using obtained points, unsaturated hydraulic conductivity using Mualem-Van Genuchten model (1980) and Brooks-Corey model (1964) was estimated by RETC software and unsaturated hydraulic conductivity for different treatments measured in laboratory. Mualem-Van Genuchten moisture curve model is as equation (2):

$\theta = \theta_r+(\theta_s - \theta_r)/[1+(\alpha h)n]m \quad m=1-1/n \quad n>1$ [2]

In which;

$S_e=\theta-\theta_r/\theta_s-\theta_r$ [3]

Which, S_e is relative saturation or efficient saturation, K_s saturated hydraulic conductivity (LT^{-1}), l empirical parameter related to soil pores continuity, θ_r residual moisture (L^3L^{-3}), θ_s saturation moisture and n and m are shape parameters.

Residual moisture (θ_r), α, n, m and air entry point suction (h_d) for control, 5, 10 and 15% compaction treatments were obtained. Suction amounts of air entry point obtained from equation (4):

$hd=1/\alpha$ [4]

Brooks-Corey model is as equation (5):

$\theta=\theta_r+(\theta_s-\theta_r)(\alpha h)^{-n} \quad \alpha h>1$ [5]

Which, α air entry point (L^{-1}), θ_r residual moisture (L^3L^{-3}), n is pore size distribution index and remaining factors are as Van Genuchten model.

Using SPSS software correlation rate between water content (WC) and different compaction treatments, and also standard deviation in each treatment were calculated. Different compaction treatments effects on unsaturated hydraulic conductivity curve graphed as a curve.

3. RESULTS AND DISCUSSION

Soil physical properties in different compaction treatments were presented in Table 1. Particle density of soils was assumed as 2.65 $g.cm^{-3}$.

Table 1. Physical properties in different compacted soil treatments

Site	Depth(cm)	Sand %	Silt %	Clay %	OM%	Compaction Level	$\rho_b(gcm^{-3})$
Kordan	0-10	65	16	19	0.28	control	1.61
						5%	1.69
						10%	1.77
						15%	1.85
Farm of Faculty	0-10	33	33	34	1.38	control	1.52
						5%	1.59
						10%	1.67
						15%	1.75

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Based on soil texture triangle (USDA), Kordan region soil texture and farm of University College were sandy loam and clay loam, respectively. Saturation volumetric moisture percent and saturated hydraulic conductivity for different compaction treatments were presented in Table 2.

As could be seen in Table 2, saturation volumetric moisture percent and saturated hydraulic conductivity decreased by increasing in compaction which is due to decreasing in soil total porosity as well as coarse and medium pores.

Based on Kay (1990) soil pores divided into three classes; coarse pores (larger than 30 µ), medium (0.2 to 30 µ) and small (smaller than 0.2µ). Based on this theory, by using moisture curve for both soils, changes in pores diameter in compaction treatments were obtained. Table 3 shows the results of analysis of variance for changes in pore diameters in compaction treatments.

Table2. Saturation volumetric moisture percent and saturated hydraulic conductivity for compaction treatments

Soil texture	Compaction level	Volumetric saturated Moisture (%)	saturated hydraulic conductivity ($cmhr^{-1}$)
Clay Loam	Control	39.24	1.637
	5%	36.22	1.013
	10%	33.20	0.425
	15%	30.18	0.215
Sandy Loam	Control	42.64	0.089
	5%	40.00	0.040
	10%	36.98	0.019
	15%	33.96	0.006

Table 3. Results of analysis of variance for changes in pore diameters in compaction treatments

Source of variance	df	Mean Squares					
		Sandy loam soil			Clay loam soil		
		30 µ <	0.2-30 µ	0.2 µ >	30 µ <	0.2-30 µ	0.2 µ >
Compaction	3	110.267**	3.271**	3.590**	8.742**	104.88**	16.39**
Error	20	0.010	0.010	0.007	0.003	0.010	0.008
Total	23						

**Significant at P <0.01

With respect to table 3 and figures 1 and 2, in both soils compaction has significant effects on studied diameters. Compaction decreased coarse and medium pores amounts in clay loam soil, while in sandy loam soil increasing in compaction declined coarse pores and medium pores in 5 and 10% compaction treatments had no significant difference but in 15% compaction decreased compared to control. Fine pores amounts in both soils increased due to compaction.

Tippkotter (1983) reported that compaction significantly reduced coarse pores in soil which affect air exchange and root developments in 100 to 200µ diameters. Radford et al. (2000) and Richard et al. (2001) showed that soil compaction resulted in increasing in bulk density, reduction in porosity and changes in pores shape and size distribution. Saturated hydraulic conductivity largely determined by coarse pores; its amount greatly reduced as bulk density increases (Hakansson and Lipiec, 2000).

Ishaq et al. (2001) showed that compacted treatments decreased bulk density, total porosity and air filled porosity by 16, 27 and 63%, respectively. Tarawally et al. (2004) reported that compaction significantly reduced pores volume larger than 50µ diameter. Zhang et al. (2006) and Assouline et al. (2006) studied the effects of different compaction levels on soil hydraulic properties and showed that soil compaction could affect soil hydraulic properties in several ways.

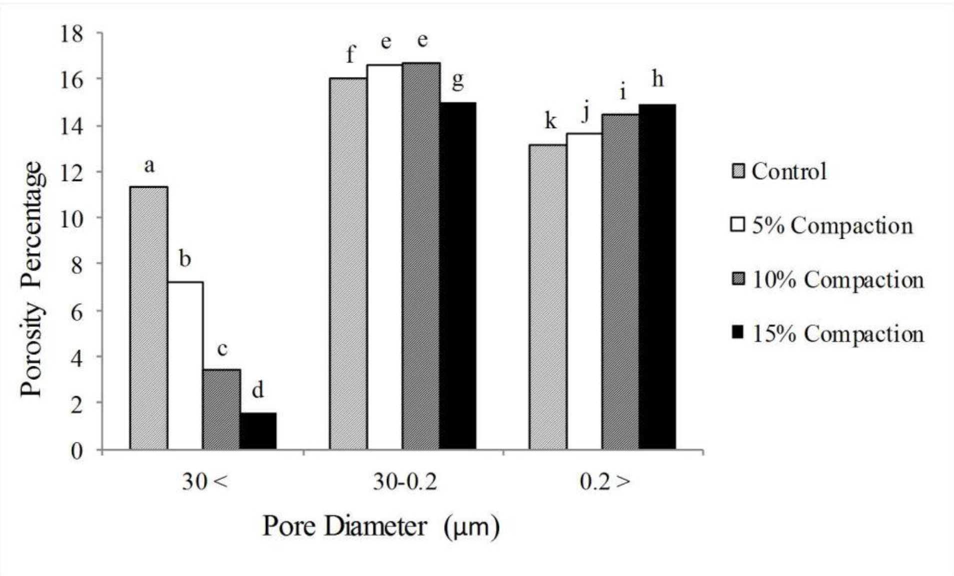

Figure 1. Effect of compaction treatments on pore size distribution in sandy loam soil

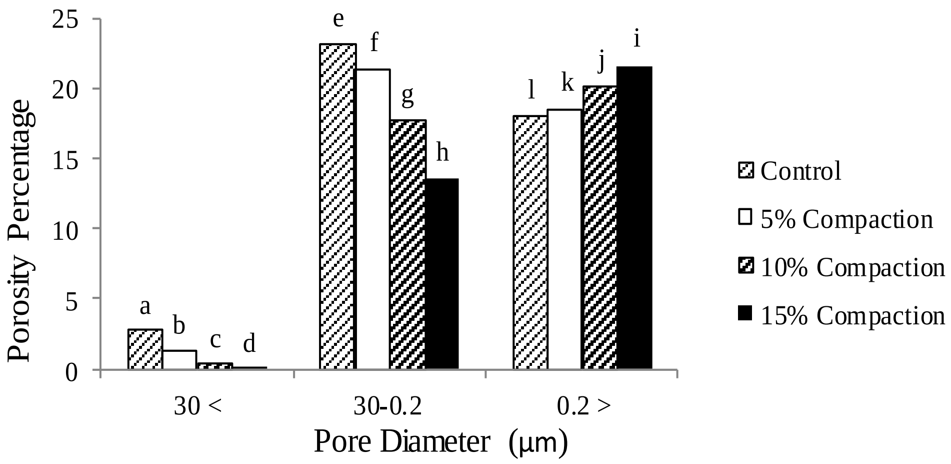

Figure 2. Effect of compaction treatments on pore size distribution in clay loam soil

Assouline (2006) and Hill and Sumner (1967) reported that compaction made aggregates smaller and eventually increased soil fine pores.

Laboratory data indicating the effects of bulk density on unsaturated hydraulic conductivity is limited. There are few methods to estimating or predicting unsaturated hydraulic conductivity in compacted soils using hydraulic conductivity functions (HCFs) (Mualem, 1986). Increase in fine pores due to compaction, caused significant increase in unsaturated hydraulic conductivity in both soils. In order to estimate the amounts of unsaturated hydraulic conductivity in compaction treatments, Mualem Van Genuchten and Brooks-Corey models were used. Output parameters obtained for both models by RETC software.

In table 4, constant coefficients amounts in Mualem Van Genuchten (VG) and Brooks-Corey (BC) models were presented. Shape parameters (n and α) more affected moisture curve shape and unsaturated hydraulic conductivity. These parameters often caused displacement of moisture characteristics in vertical direction (up and down), While, θ_s and θ_r caused horizontal displacement (left and right). Suction in air entry point (h_d) increased by compaction in both models, but its amount in VG was more than BC model. The amount of α inversely related to suction in air entry point (h_d). Saturation volumetric moisture (θ_s) decreased as compaction increased but residual moisture (θ_r) in both models was constant since residual moisture for any soil texture has constant amount and not affected by compaction.

Table 4. Constant coefficients amounts in Mualem Van Genuchten (VG) and Brooks-Corey (BC) models

Texture	treatment	n		θ_r		α		h_d	
		VG	BC	VG	BC	VG	BC	VG	BC
Sandy loam	control	1.41	0.35	0.12	0.11	0.28	0.05	3.55	16.86
	5%	1.72	0.58	0.12	0.11	0.03	0.05	28.98	19.64
	10%	1.56	0.27	0.12	0.11	0.02	0.04	42.01	20.08
	15%	1.75	0.31	0.12	0.11	0.01	0.03	57.14	25.31
Clay loam	control	1.79	0.73	0.15	0.13	0.01	0.01	99.10	73.69
	5%	1.39	0.34	0.15	0.13	0.006	0.01	102.14	79.05
	10%	1.33	0.27	0.15	0.13	0.007	0.01	136.79	96.99
	15%	1.39	0.31	0.15	0.13	0.009	0.007	157.47	131.75

In figure 3, relationship between unsaturated hydraulic conductivity and volumetric moisture of sandy loam soil in VG and BC models were compared. As seen in Figure 3A and 3B, unsaturated hydraulic conductivity increased with increase in compaction. In BC model this trend in control, 5% and 10% treatments was very close, but in 15% compaction reducing in moisture and soil drying, curve was separated from other three curves and its unsaturated hydraulic conductivity considerably increased (Figure 3A). But for VG model (Figure 3B), unsaturated hydraulic conductivity for all treatments was very close and in 10 and 15% compaction treatments, relevant curves had overlapping.

Figure 4 shows the comparison of relationship between unsaturated hydraulic conductivity and volumetric moisture of clay loam soil in VG and BC models.

In Figure 4, changes in unsaturated hydraulic conductivity in both models (VG and BC) were similar. So that these changes in control, 5 and 10% compaction treatments were very close but in 15% compaction, curve was separated from other three curves.

Compaction normally affected unsaturated hydraulic conductivity under moist conditions (Horton et al., 1994). But in different compaction levels and low moisture, compaction significantly increased unsaturated hydraulic conductivity (Lipiec and Hatano, 2003).

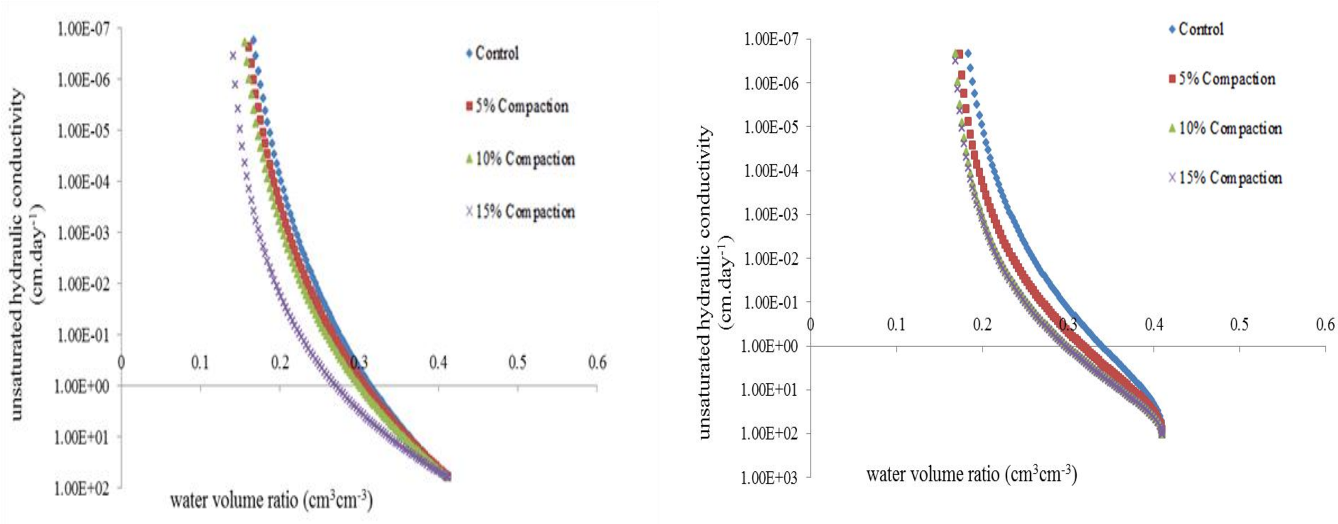

Figure 3. Unsaturated hydraulic conductivity in sandy loam soil estimated by Brooks- Corey's model and Mualem - van Genuchten model . Left panel is BC models and right panel is VG model

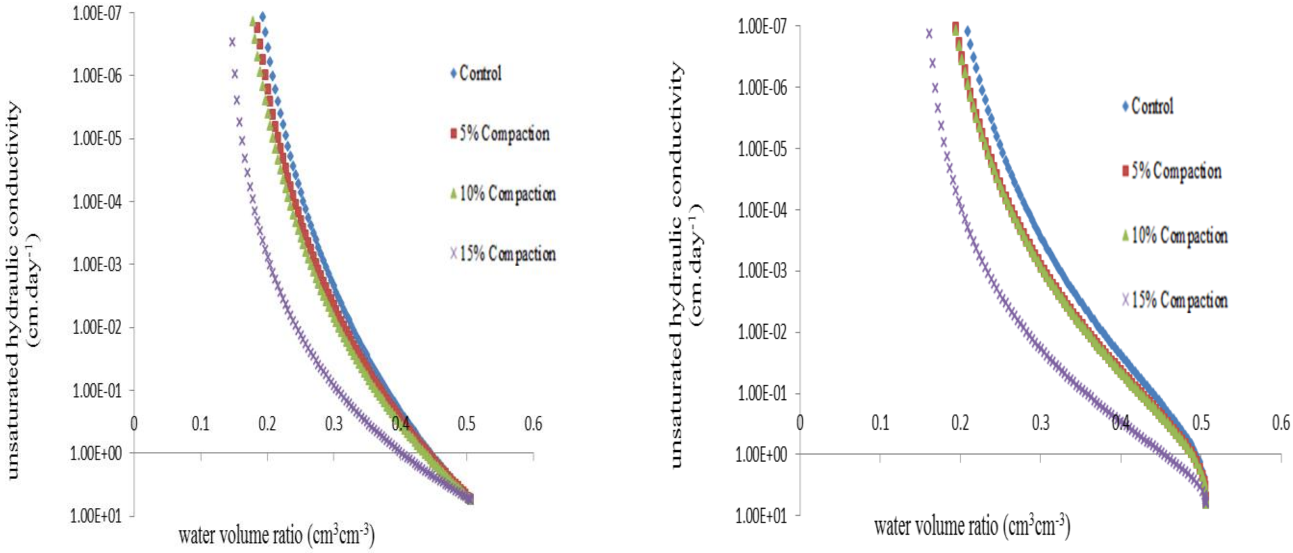

Figure 4. Unsaturated hydraulic conductivity in clay loam soil estimated by Brooks- Corey's model and Mualem - van Genuchten model. Left panel is BC models and right panel is VG model

Zhang et al. (2006) studied the unsaturated hydraulic conductivity in two soil depths at different compaction treatments in silty loam soils and concluded that compaction had no much effect on unsaturated hydraulic conductivity and its curves close to each other.

In present study, in all compaction treatments significant difference was observed, but in 15% compaction this difference was more clear (Table 5).

Table 5 present the comparison of correlation coefficients between moisture content (WC) and compaction treatments in VG and BC models.

As could be seen in table, relationship between WC and compaction treatment, generally, has increasingly trend. In means that increase in soil compaction, increased unsaturated hydraulic conductivity, too, which was due to increase in fine pores during compaction, as determined by measuring pore size distribution before and after of compaction. Also, Table 5 compared the VG and BC models. Correlation rate between WC and unsaturated hydraulic conductivity in BC model was more than VG model. It means that prediction of unsaturated hydraulic conductivity for all treatments by BC model was better than VG model. Should be noted that VG model also was significant in prediction of unsaturated hydraulic conductivity but results of Table 5 confirmed that BC was more efficient. Zhang et al. (2007) estimated the unsaturated hydraulic conductivity by internal drainage method using soil moisture curve in laboratory and concluded that among fitted models, BC model estimated unsaturated hydraulic conductivity very close to laboratory method.

CONCLUSION

Increase in bulk density could affect many aspects of soil-water-air system and eventually plant growth. Considering that modeling and predicting results from bulk density and unsaturated hydraulic conductivity very limited, present study evaluate the unsaturated hydraulic conductivity in compaction treatments using Mualem Van Genuchten and Brooks-Corey models. unsaturated hydraulic conductivity increased by increasing in compaction, so that curves for control, 5 and 10% compaction treatments very close to each other. These results are in agreement with Zhang et al. (2006). But in 15% compaction unsaturated hydraulic conductivity increased so that its curve considerably separated from other curves. This is in consistent with Lipiec and Hatano (2003). Increase in unsaturated hydraulic conductivity is associated with increase in fine pores in compaction treatments. Also, the results of the present study showed that using both models (VG and BC) to estimate the unsaturated hydraulic conductivity was satisfactory but amount of correlation coefficients in BC model for all compaction treatments was more than those for VG model which in agreement with Zhang et al. (2007). So, Brooks-Corey model is recommended for estimating unsaturated hydraulic conductivity in compacted soils.

Table 5. Correlation coefficients between moisture content (WC) and compaction treatments in VG and BC models

Soil and model type	correlation	(wc)	control	5%	10%	15%
(BC) model In Sandy Loam soil	(wc)	1				
	control	0.694**	1			
	5%	0.713**	0.999**	1		
	10%	0.728**	0.998**	0.999**	1	
	15%	0.793**	0.979**	0.986**	0.991**	1
(VG) model In Sandy Loam soil	(wc)	1				
	control	0.530**	1			
	5%	0.599**	0.990**	1		
	10%	0.651**	0.971**	0.995**	1	
	15%	0.659**	0.967**	0.993**	1**	1
(BC) model In Clay Loam soil	(wc)	1				
	control	0.694**	1			
	5%	0.713**	0.999**	1		
	10%	0.725**	0.998**	1**	1	
	15%	0.819**	0.968**	0.976**	0.981**	1
(VG) model In Clay Loam soil	(wc)	1				
	control	0.486**	1			
	5%	0.521**	0.997**	1		
	10%	0.522**	0.997**	1**	1	
	15%	0.670**	0.932**	0.956**	0.957**	1

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