RELIABILITY OF MODELS ON SOIL WATER RETENTION CURVES BY USING CLAY

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Abstract
Geotechnical engineering community have long recognized that expansive soils may result in considerable distress and consequently cause severe damage to overlying structures, particularly to low-rise buildings and buried lifelines. Numerous reports of expansive and unsaturated soils problems and related damages have been documented in different countries.
Determinations of unsaturated soil parameters using experimental procedures are time consuming and difficult. In recent years, the soil water characteristic curve (SWRC) has become an important tool in the interpretation of the engineering behavior of unsaturated soils.
In this study, common mathematical functions used on the estimation of soil water retention curves (SWRC) given in the literature are presented, and reliability of them are investigated for Siran-I clay. For this purpose, three types of more soils that have different properties were formed by addition of various percentages (4%, 7%, and 11%) of lime to Siran-I clay. Each estimated SWRC by the mathematical functions for each type of soil is compared with each other by using regression analysis.

Key words: Soil water retention curve, SWRC models, Regression analysis, Unsaturated soils.

Introduction

Determinations of unsaturated soil parameters using experimental procedures are time consuming and difficult. In recent years, SWRC has become an important tool in the interpretation of the engineering behavior of unsaturated soils. A fundamental soil property SWRC has been employed for modeling water and solute movement in a soil mass. It shows the relationship between matric suction of soil and its volumetric water content. SWRC can also be described as the relationship between water and air as the soil de-saturated. Unsaturated soils consist of more than two phases so that the natural laws governing their behavior are changed. Specification of a soil water retention curve is necessary for most efforts at modeling soil water behavior [1-3].

SWRC is key information for unsaturated soils properties, was used in numerous investigations. Satisfactory predictions of shear strength functions can be made for the unsaturated soil after a reasonable estimate of SWRC is obtained [4-6].

Unsaturated hydraulic conductivity and moisture contents are determined by SWRC. A large number of theories have been developed to study the effect of spatial variability of what on flow and transport in unsaturated zones as well as saturated zones [7-19].

Many models have been proposed to estimate SWRCs of soils by a number of researchers. Each of these models requires several parameters of a soil such as air entry value, saturated water content, residual water content etc. Thus, some experiments are still needed to be performed since the parameters above must be known in order to use the models. Also, SWRC has been described by numerous mathematical functions [3, 20-35].

Soil water characteristic curve (SWCC) or soil water retention curves (SWRCs) that give useful information about unsaturated soils are estimated in different ways and by several equations. SWRCs play an essential role in characterizing soil's hydraulic behavior. These curves can be plotted by experimentally, and by empiric correlations. However, experimental approach is costly, time consuming, and difficult to perform. Thus, many researchers show intensive interest in mathematical models connected with SWRCs [2, 6, 10, 21, 22, 23].

Numerous mathematical functions have been explicitly developed for modeling the SWRCs. Each function used to generate SWRCs has its own advantages and disadvantages. These mathematical functions are called as estimation of SWRC models. These models can be grouped as two-parameter, three-parameter, and four-parameter models.

A-) Two-parameter model;

1-) Williams proposed a model in 1983. In the model, a relationship is established between matrix suction (ψ) and volumetric water content (θ_w) as seen Eq.1.

$$\ln(\psi) = a + b.\ln(\theta_w) \qquad \text{(Parameters: a, b)} \qquad (1)$$

B-) Three-parameter models;

1-) Gardner proposed an equation that seen in Eq.2.

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{1 + a.\psi^b} \qquad \text{(Parameters: } \theta_r \text{, a, b)} \qquad (2)$$

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{1 + (\frac{\psi}{a})^b} \qquad (3)$$

2-) Brooks-Corey has taken different parameters and gave two different types of their equations.

a-) $$\theta_w = \theta_r + (\theta_s - \theta_r).(\frac{a}{\psi})^b \qquad \text{(Parameters: a, b, } \theta_r \text{)} \qquad (4)$$

b-) $\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_a}{\psi}\right)^{\lambda}$ (Parameter: θ_r, ψ_a and λ) (5)

3-) Mckee and Bumb proposed two different equations that have same parameters in 1984 as seen Eq. 6 and 7.

a-) $\theta_w = \theta_r + (\theta_s - \theta_r).\exp(\frac{a-\psi}{b})$ (Parameters: θ_r, a, b) (6)

b-) $\theta_w = \theta_r + \frac{(\theta_s - \theta_r)}{1+\exp(\frac{\psi - a}{b})}$ (Parameters: θ_r, a, b) (7)

4-) Fredlund and Xing proposed the model given in Eq. 8.

$\frac{\theta_w}{\theta_s} = \frac{1}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c}$ (Parameters: a, b and c) (8)

C-) Four-parameter model

1-) Van Genuchten proposed a model in which a, n, m, θ_r parameters are used.

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + \left(\frac{\psi}{a}\right)^n\right]^m} \quad (9)$$

2-) Fredlund and Xing proposed Eqs.10 and 11 in which different parameters are used.

a-) $\theta_w = \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] . \frac{\theta_s}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c}$ (Parameters: a, b, c, ψ_r) (10)

b-) $\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c}$ (Parameters: θ_r, a, b, c) (11)

Where;

θ_r : Residual water content

θ_s : Saturated water content

θ_w : Volumetric water content

ψ : Matric suction

a : Air entry value

m, n : Shape factor

Materials and Methods

In this investigation, an expansive soil taken from village of Mertekli-Siran, Gumushane, Turkey called as Siran-I clay was used. Various percentages of lime were added to Siran-I clay so that new soils that have different properties were formed. These soils were created by addition of lime percentages of 4%, 7%, and 11%. Thus, four types of soils were available for filter paper tests to get SWRCs. Then, SWRCs of these four soils were plotted and compared with the SWRCs estimated by the equations given in literature by regression analyses.

The relationships between θ and ψ for Siran-I clay with no lime addition and with addition of various percentages (4%, 7%, and 11%) of lime were estimated by experimental data.

Results and Discussions

The results are compared with the results of equations given in the literature (Table 1-6). A regression equation for each sample was established for the given functions of SWRC models, and safety ranges were plotted for a level of significance of 0.05 (Figs.1-6). The coefficients of regression analyses were tested by t-test.

a-) Gardner proposed an empirical equation of $\theta_w = \theta_r + \frac{(\theta_s - \theta_r)}{1 + A.\psi^B}$ for SWRC function. Relationship between ψ-θ_w has been established for the soils used in this study. The constants of A, and B were estimated by a computer program after the parameters of θ_r, and θ_s were calculated from the relationship between ψ-θ_w. Table 1 shows coefficients of A, B, and the correlation coefficients between the results of experiments and results of Gardner's empirical equation. In this way, Gardner's empirical equation was tested. Regression equation was established, and confidence intervals were plotted for a level of significance of 0.05 (Fig.1)

Table 1. Coefficients for $\theta_w = \theta_r + \frac{(\theta_s - \theta_r)}{1 + A.\psi^B}$ equation

Sample name	A	B	Correlation Coefficients (r)	Determination Coefficients (r^2)
Siran-1 clay (no additive	$981*10^6$	0.747	0.876	0.767
%4 lime added Siran-1 clay	$160*10^6$	0.920	0.954	0.910
%7 lime added Siran-1 clay	$167*10^6$	0.886	0.974	0.949
%11lime added Siran-1 clay	$153*10^6$	0.857	0.984	0.968

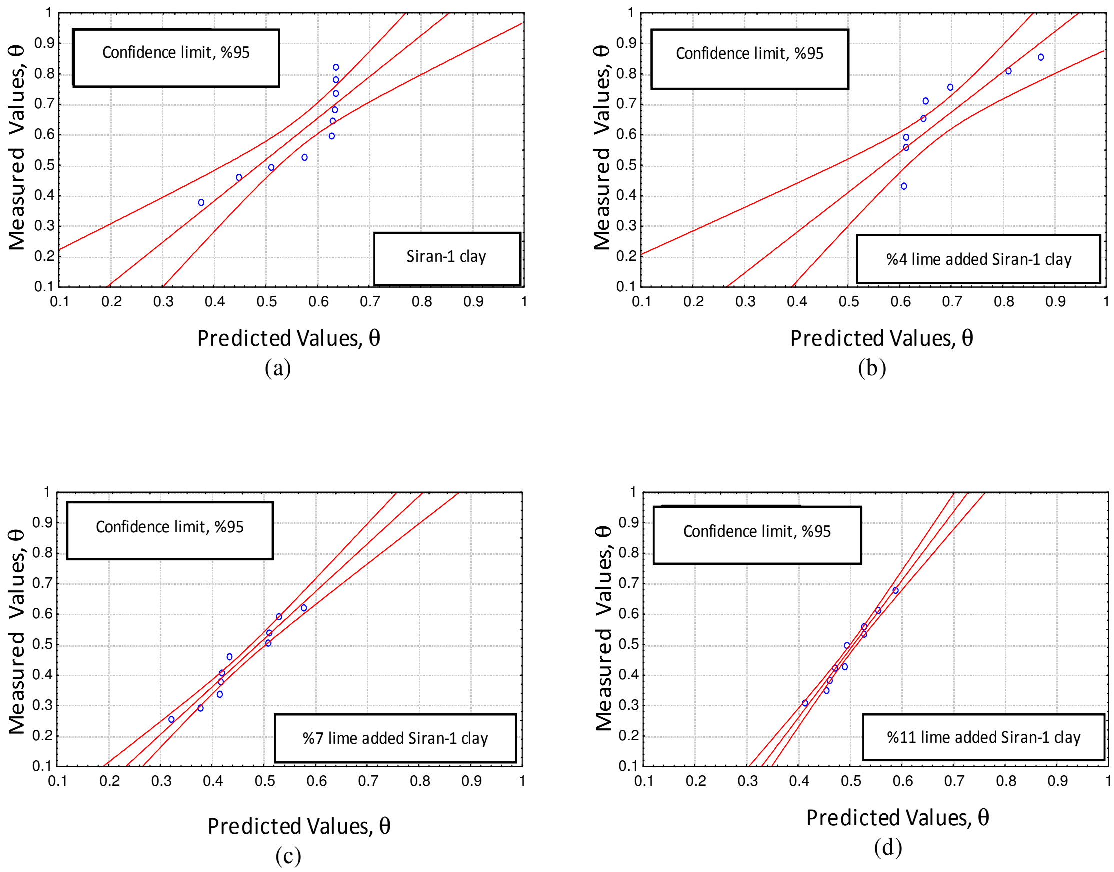
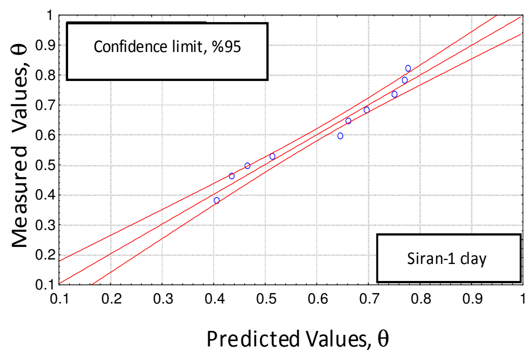


Figure 1. Comparisons between measured and predicted volumetric water contents for $\theta_w = \theta_r + \dfrac{(\theta_s - \theta_r)}{1 + A.\psi^B}$ equation

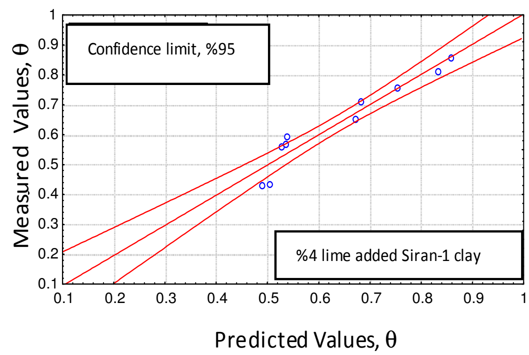
b-) Brooks-Corey proposed an equation of $\theta_w = \theta_r + (\theta_s - \theta_r).\left(\dfrac{A}{\psi}\right)^B$ as SWRC function. Previously established relationship between ψ-θ_w by laboratory experiments were used for the estimation of A and B. The constants of A and B are estimated by a computer program after the parameters of θ_r, and θ_s were calculated from the relationship between ψ-θ_w. Table 2 shows coefficients of A, B, and the correlation coefficients between the results of experiments and results of Brooks-Corey's equation. In this way, Brooks-Corey's equation was tested. Regression equation was established, and confidence intervals were plotted for a level of significance of 0.05 (Fig.2)

Table 2. Coefficients for $\theta_w = \theta_r + (\theta_s - \theta_r).\left(\frac{A}{\psi}\right)^B$ equation

Sample name	A	B	Correlation Coefficients (r)	Determination Coefficients (r^2)
Siran-1 clay (no additive material)	66.606	0.0914	0.979	0.958
%4 lime added Siran-1 clay	332.305	0.145	0.960	0.922
%7 lime added Siran-1 clay	464.245	0.164	0.823	0.677
%11lime added Siran-1 clay	2876.613	0.386	0.950	0.903



(a)



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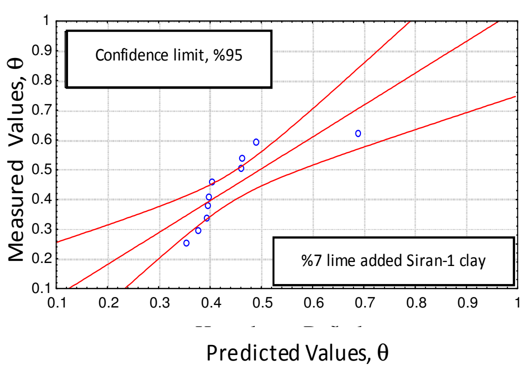

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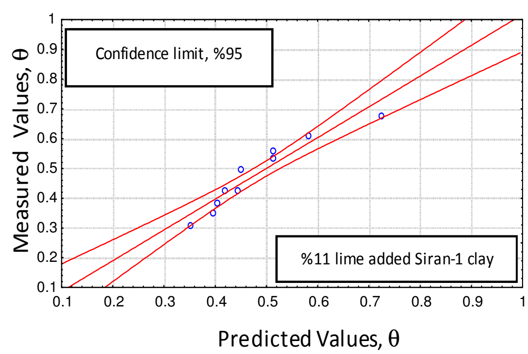

(d)

Figure 2. Comparisons between measured and predicted volumetric water contents for $\theta_w = \theta_r + (\theta_s - \theta_r).\left(\frac{A}{\psi}\right)^B$ equation

c-) Fredlund and Xing proposed an equation of $\theta_w = \dfrac{\theta_s}{\left\{ \ln\left[e + \left(\dfrac{\psi}{A} \right)^B \right] \right\}^C}$ as SWRC function. Previously established relationship between ψ-θ_w by laboratory experiments were used for the estimation of A, B, and C. The constants of A, B, and C are estimated by a computer program after the parameters of θ_r, and θ_s were calculated from the relationship between ψ-θ_w. Table 3 shows coefficients of A, B, and the correlation coefficients between the results of experiments and results of Fredlund's equation. In this way, Fredlund's equation was tested. Regression equation was established, and confidence intervals were plotted for a level of significance of 0.05 (Fig.3)

Table 3. Coefficients for $\dfrac{\theta_w}{\theta_s} = \dfrac{1}{\left\{ \ln\left[e + \left(\dfrac{\psi}{a} \right)^b \right] \right\}^c}$ equation

Sample name	A	B	C	Correlation Coefficients	Determination Coefficients (r^2)
Siran-1 clay (no additive material)	364.538	1.390	0.293	0.893	0.797
%4 lime added Siran-1 clay	2516.115	7.816	0.238	0.900	0.810
%7 lime added Siran-1 clay	5362.056	1.927	0.854	0.973	0.947
%11lime added Siran-1 clay	5665.283	3.295	0.569	0.983	0.966

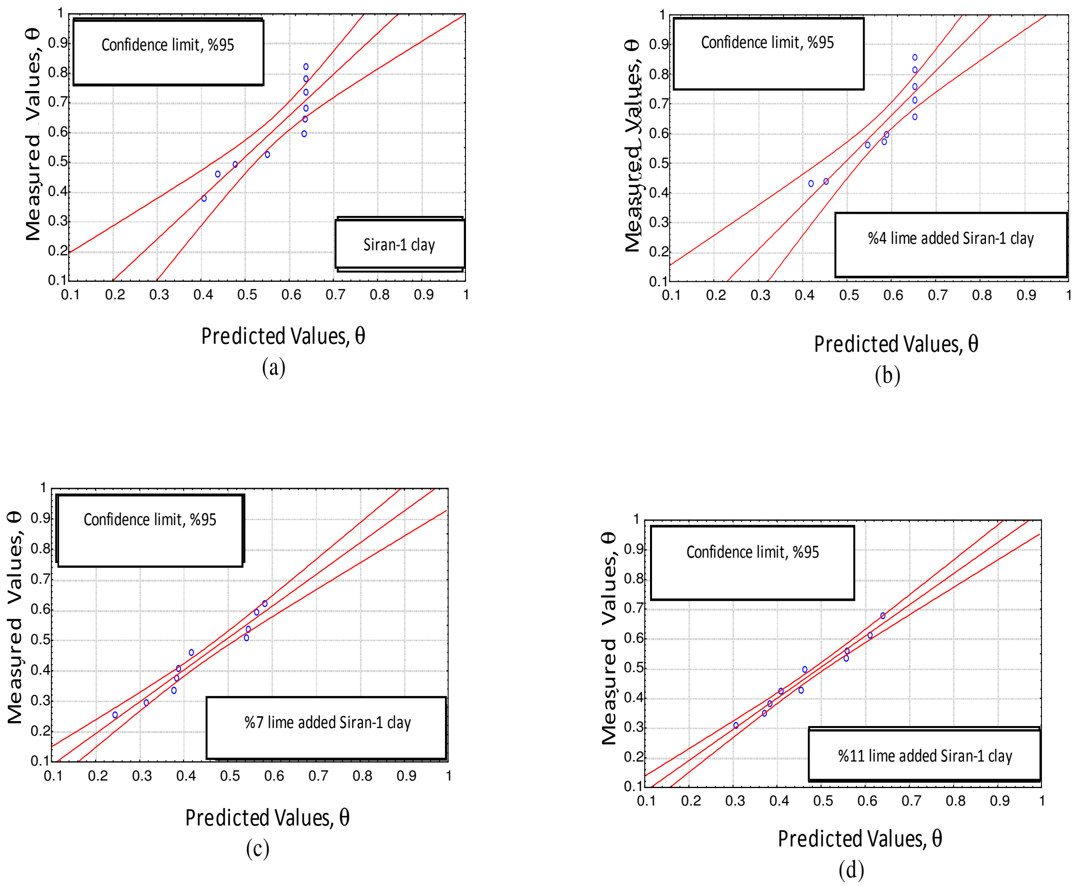

Figure 3. Comparisons between measured and predicted volumetric water contents for $\frac{\theta_w}{\theta_s} = \frac{1}{\left\{ \ln\left[e + \left(\frac{\psi}{a} \right)^b \right] \right\}^c}$ equation

d-) Van Genuchten proposed an equation of $\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + A.\psi^B\right)^C}$ as SWRC function. Previously established relationship between ψ-θ_w by laboratory experiments were used for the estimation of A, B, and C. The constants of A, B, and C are estimated by a computer program after the parameters of θ_r, and θ_s were calculated from the relationship between ψ-θ_w. Table 4 shows coefficients of A, B, and the correlation coefficients between the results of experiments and results of van Genuchten's equation. In this way, van Genuchten's equation was tested. Regression equation was established, and confidence intervals were plotted for a level of significance of 0.05 (Fig.4)

Table 4. Coefficients for $\theta_w = \theta_r + \dfrac{\theta_s - \theta_r}{\left(1 + A.\psi^B\right)^C}$ equation

Sample name	A	B	C	Correlation Coefficients (r)	Determination Coefficients (r^2)
Siran-1 clay (no additive material)	$21.8*10^{-5}$	1.560	0.096	0.897	0.804
%4 lime added Siran-1 clay	$12*10^{-5}$	1.101	0.398	0.951	0.904
%7 lime added Siran-1 clay	$16.9*10^{-5}$	0.841	1.680	0.973	0.947
%11lime added Siran-1 clay	$20.1*10^{-5}$	0.837	1.100	0.985	0.970

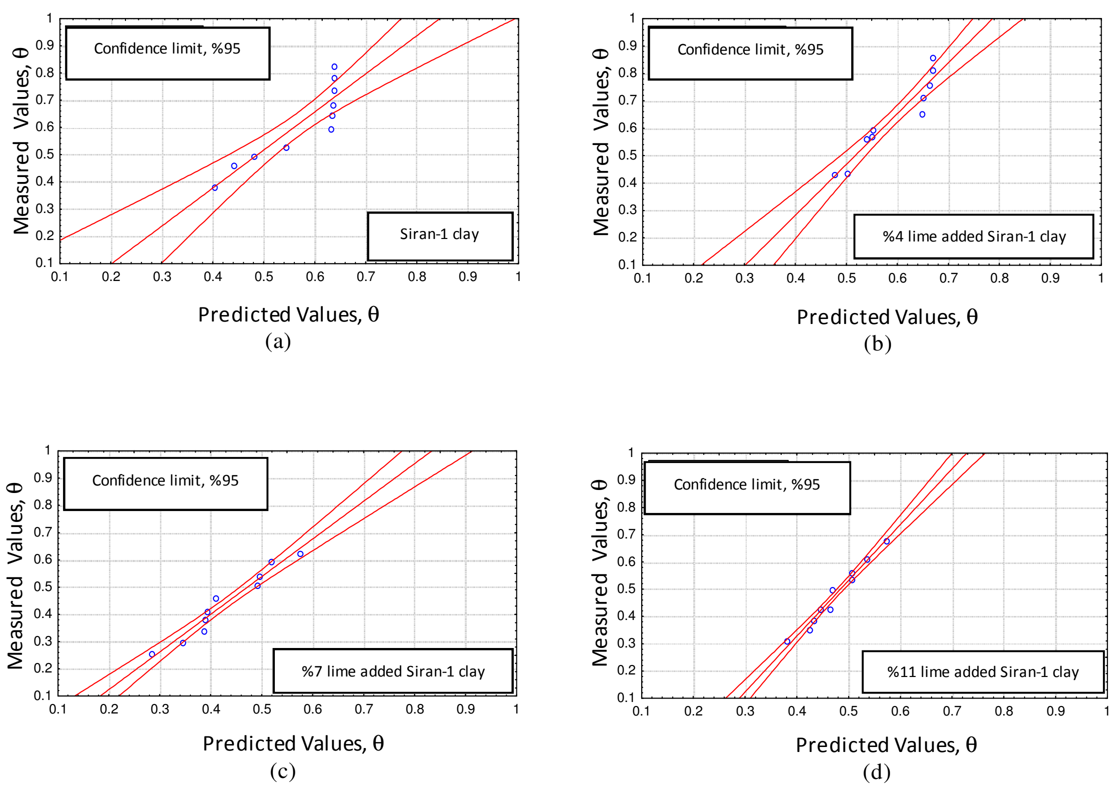

Figure 4. Comparisons between measured and predicted volumetric water contents for $\theta_w = \theta_r + \dfrac{\theta_s - \theta_r}{\left(1 + A.\psi^B\right)^C}$ equation

e-) Fredlund and Xing proposed an equation of $\theta_w = \left[1 - \ln\left(1 + \psi/\psi_r\right)/\ln\left(1 + 1000000/\psi_r\right)\right] * \left(\theta_s / \left\{\ln\left[e + \left(\psi/a\right)^b\right]\right\}^c\right)$ as SWRC function. Previously established relationship between ψ-θ_w by laboratory experiments were used for the estimation of a, b, and c. The constants of a, b, and c are estimated by a computer program after the parameters of θ_r, θ_s, and ψ_r were calculated from the relationship between ψ-θ_w. Table 5 shows coefficients of A, B,C and the correlation coefficients between the results of experiments and results of Fredlund's equation. In this way, Fredlund's equation was tested. Regression equation was established, and confidence intervals were plotted for a level of significance of 0.05 (Fig.5)

Table 5. Coefficients for $\theta_w = [1 - \ln(1+\psi/\psi_r)/\ln(1+1000000/\psi_r)] * \left(\theta_s / \{\ln[e + (\psi/a)^b]\}^c\right)$ equation

Sample name	A	B	C	Correlation Coefficients (r)	Determination Coefficients (r^2)
Siran-1 clay (no additive material)	48.49	7.606	0.077	0.928	0.861
%4 lime added Siran-1 clay	5318.93	1.614	0.936	0.975	0.950
%7 lime added Siran-1 clay	6281.67	15.314	0.275	0.967	0.935
%11lime added Siran-1 clay	5703.77	3.501	0.508	0.982	0.964

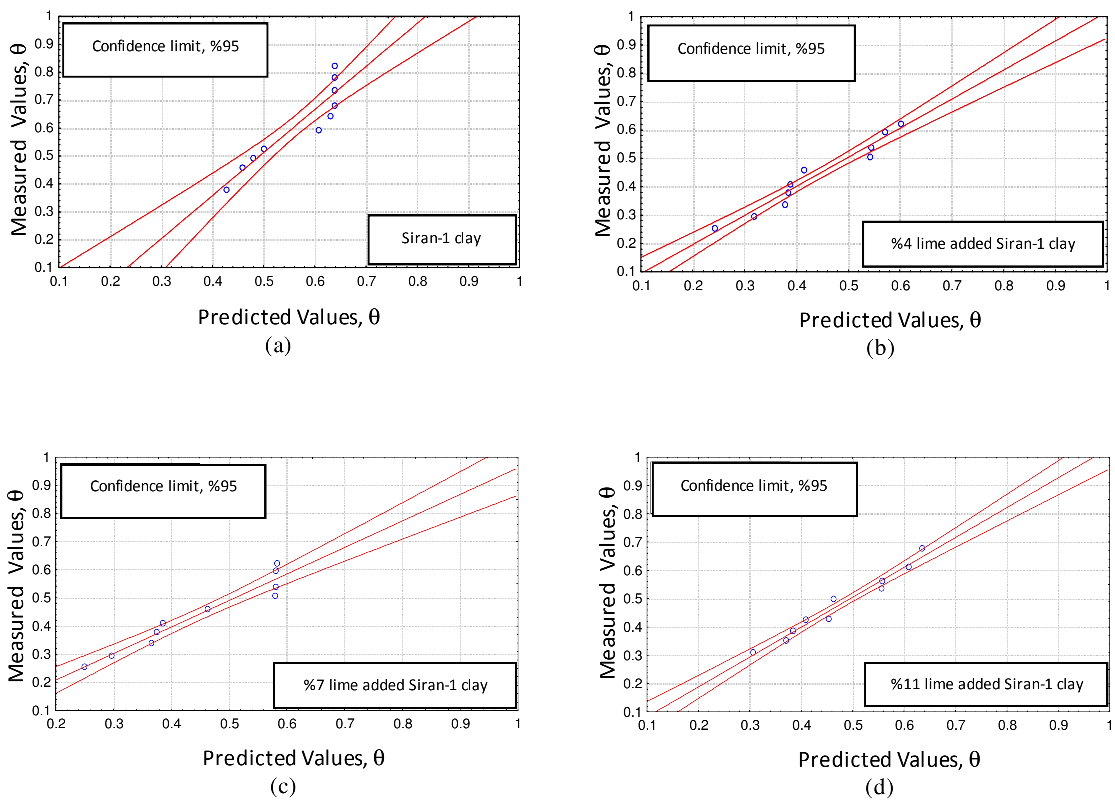

Figure 5. Comparisons between measured and predicted volumetric water contents for $\theta_w = [1 - \ln(1+\psi/\psi_r)/\ln(1+1000000/\psi_r)] * \left(\theta_s / \{\ln[e + (\psi/a)^b]\}^c\right)$ equation

f-) Fredlund and Xing proposed an equation of $\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\{\ln[e + (\psi/A)^B]\}^C}$ as SWRC function. Previously established relationship between ψ-θ_w by laboratory experiments were used for the estimation of A, B, and C. The constants of A, B, and C are estimated by a computer program after the parameters of θ_r, θ_s, and ψ_r were calculated from the relationship between ψ-θ_w. Table 6 shows coefficients of A, B, and the correlation coefficients between the results of experiments and results of Fredlund's equation. In this way, Fredlund's equation was tested. Regression equation was established, and confidence intervals were plotted for a level of significance of 0.05 (Fig.6)

Table 6. Coefficients for $\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\{\ln[e + (\psi/A)^B]\}^C}$ equation

Sample name	A	B	C	Correlation Coefficients (r)	Determination Coefficients (r^2)
Siran-1 clay (no additive material)	389.20	1.374	0.372	0.893	0.797
%4 lime added Siran-1 clay	2412.51	6.975	0.296	0.904	0.817
%7 lime added Siran-1 clay	6138.74	1.890	1.237	0.973	0.946
%11lime added Siran-1 clay	5824.38	3.246	0.668	0.983	0.966

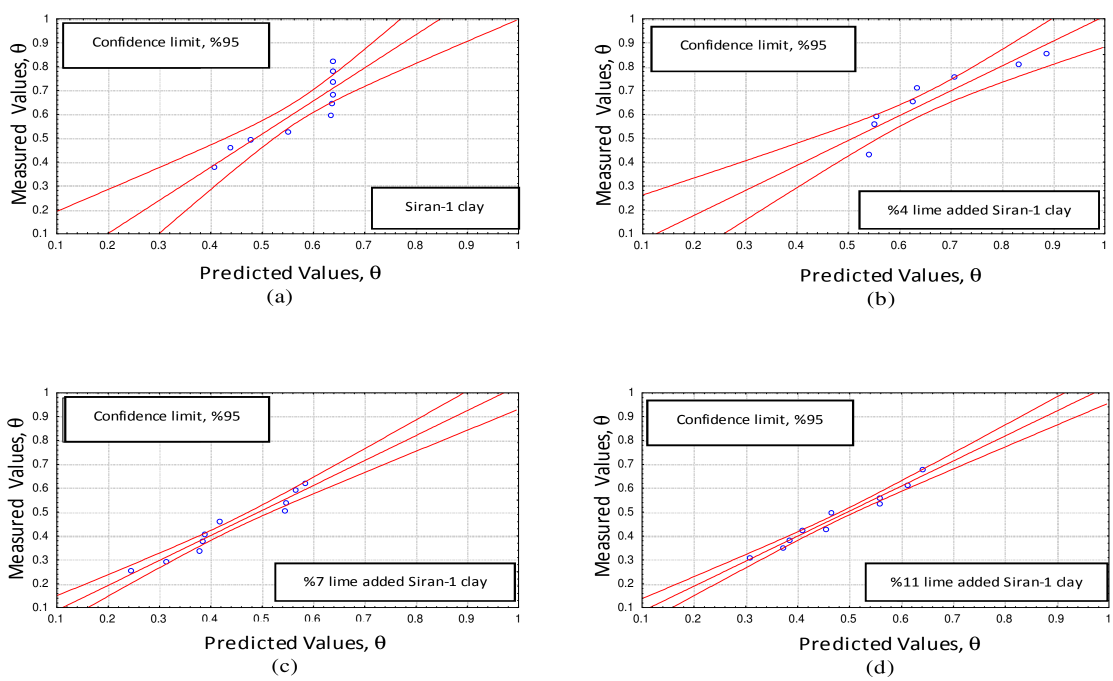

Figure 6. Comparisons between measured and predicted volumetric water contents for $\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\{\ln[e + (\psi/A)^B]\}^C}$ equation

Conclusions

The equations of SWRC models have been tested for their compatibility with experimental observations on all of the samples used in this study. The correlation coefficients were tested by t-test, and it has been ended up with a decision that the relationship between θ-ψ is very strong on the level of significance of 0.05 (Table 7).

Table 7. Goodness of fit of the SWRC equations to test results for various ratios of additive

Sample name	**Gardner (2)equation**		**Brooks-Corey (4) equation**		**Fredlund and Xing (7) equation**		**Van Genuchten (8) equation**		**Fredlund and Xing (9) equation**		**Fredlund and Xing (10) equation**	
	r	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**	**r**	**r^2**
Siran-1 clay (no additive material)	0.876	0.767	0.979	(A)* **0.958**	0.893	0.797	0.897	(C) **0.804**	0.928	(B) **0.861**	0.893	0.797
%4 lime added Siran-1 clay	0.954	(C) **0.910**	0.960	(B) **0.922**	0.900	0.810	0.951	0.904	0.975	(A) **0.950**	0.904	0.817
%7 lime added Siran-1 clay	0.974	(A) **0.949**	0.823	0.677	0.973	(B) **0.947**	0.973	(B) **0.947**	0.967	0.935	0.973	(C) **0.946**
%11lime added Siran-1 clay	0.984	(B) **0.968**	0.950	0.903	0.983	(C) **0.966**	0.985	(A) **0.970**	0.982	0.964	0.983	(C) **0.966**

*Goodness of fit of the equations by determination coefficient: (A) the best, (B) good, and (C) fair.

The strongest relation with a determination coefficient of r^2 =0.958 has been gotten by Brooks-Corey equation (Eq.4) for Siran-1 clay with no additives. The equation given by Fredlund-Xing (Eq. 9) had a determination coefficient of r^2=0.861, on the other hand the equation given by van Genuchten (Eq. 8) had a determination coefficient of r^2 =0.804. The strongest relations for lime added specimens are varied among the equations depending upon the dosage of lime added to the soil. The best determination coefficients for 4%, 7%, and 11% lime dosages have been gotten by Fredlund-Xing (equation 9), Gardner (equation 2) and van Genuchten (equation 8), respectively.

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