

Modeling of Soil Cation Exchange Capacity Based on Soil Colloidal Matrix

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Abstract: There are instances in which it is desirable to determine relationships among soil physical and chemical properties. For example, soil Cation Exchange Capacity (CEC) are often determined using laborious and time consuming laboratory tests, but it may be more suitable and economical to develop a method which uses some soil physical and chemical properties. In this study, five linear regression models for predicting soil CEC from some soil physical and chemical properties i.e. Sand (Sa), Silt (Si), Clay (C), Organic Carbon (OC) and pH (pH) of soil were suggested. Statistical results of the study indicated that organic carbon is the most important factor, which affects soil CEC and in order to predict soil CEC the linear regression soil CEC model $CEC = 7.93 + 8.72 OC$ with $R^2 = 0.74$ can be recommended.

Key words: Cation exchange capacity · modeling · organic carbon · prediction

INTRODUCTION

Soil Cation Exchange Capacity (CEC) is the total of the exchangeable cations that a soil can hold at a specified pH. Soil components known to contribute to soil CEC are clay and organic matter and to a lesser extent, silt [1, 2].

The exchange sites can be either permanent or pH-dependent. Mineral soils have an exchange capacity that is a combination of permanent and pH-dependent exchange sites, while that of organic soils is predominantly pH-dependent. In any given soil, the number of exchange sites is dependent on the soil pH, size, amount and type of clay minerals as well as the amount and source of the organic material [3-6].

The relationship between clay content (% by weight) and CEC can be highly variable because different clay minerals have very different CEC values. In addition, the relative proportion of pH-dependant and permanent CEC varies among clay minerals [6]. Several researchers have attempted to predict CEC from clay and organic carbon contents alone, using multiple regression. Results show that greater than 50% of the variation in CEC could be explained by the variation in clay and organic carbon content for several types in; New Jersey [7], Florida [8], Philippine [9] and Mexico [10]. Only a small improvement

was obtained by adding pH to the model for four Mexican soils [10]. In B horizons of a toposequence, the amount of fine clay (particle size $< 0.2 \mu\text{m}$) was shown to explain a larger percent of the variation in CEC than the total clay content [11]. In gleyed subsoil horizons of lowland soils in Quebec, surface area of the colloidal matrix i.e. organic matter and clay gave a better prediction of CEC than did total clay [1]. Martel *et al.* [1] also showed that the variations in mineralogical composition, although small, were sufficient to explain nearly 50% of the variation in CEC. Similarly, Miller [6] found that the type of clay alone could explain up to 50% of the variation in CEC.

Many of the above predictive models are specific to a region or area and confined to only a few soil types. Many attempts have been made to predict CEC indirectly from some easily available soil physical and chemical properties. MacDonald [12] developed two equations $CEC = 2.0 (\text{organic carbon}) + 0.5 (\text{clay})$ and $CEC = 3.8 (\text{organic carbon}) + 0.5 (\text{clay})$ for Quebec and Alberta soil state in Canada, respectively. Bell and van Keulen [10] studied Mexico soils and proposed an equation to predict soil CEC by some independent variables such as clay, organic carbon and pH. In their equation, 96% of soil CEC variations were explained by clay, organic carbon and pH. Also, Krogh *et al.* [13] suggested an equation based on silt, clay, organic carbon and pH which explained 90% of

soil CEC variation. Asadu and Akamigbo [14] predicted soil CEC from organic matter and clay content grouped by taxonomic order (Inceptisols, Alfisols, Ultisols and Oxisols).

Despite the considerable amount of research done, which shows the relationship between soil CEC and soil physical and chemical properties, very limited work has been conducted to model soil CEC based on some soil physical and chemical properties. Therefore, the specific objectives of this study were to determine soil CEC model and to verify the model by comparing its results with those of the laboratory tests.

MATERIALS AND METHODS

Experimental procedure: Seventy-five soil samples were taken at random from different fields of experimental site of Varamin, Iran. The site is located at latitude of 35°-19'N and longitude of 51°-39'E and is 1000 m above mean sea level, in arid climate in the center of Iran. The soil of the experimental site was a fine, mixed, thermic, Typic Haplocambids clay-loam soil.

In order to obtain required parameters for determining soil CEC model, particle size distribution i.e. sand, silt, clay and some chemical properties such as organic carbon content (% by weight) and pH of the soil samples were measured using laboratory tests as described by the Soil Survey Staff [15]. Physical and chemical properties of the seventy-five soil samples used to determine soil CEC model are shown in Table 1.

Also, in order to verify soil CEC model by comparing its results with those of the laboratory tests, fifteen soil samples were taken at random from different fields of the experimental site. Again, sand, silt, clay and organic carbon content (% by weight) and pH of these soil samples were measured using laboratory tests as described by the Soil Survey Staff [15]. Physical and chemical properties of the fifteen soil samples used to verify soil CEC model are shown in Table 2.

Regression model: A typical linear regression model is shown in Eq. 1:

$$Y = k_0 + k_1X \tag{1}$$

Where:

- Y = Dependent variable, for example soil CEC
- X = Independent variable, e.g. sand, silt, clay, organic carbon and pH of each soil
- k_0, k_1 = Regression coefficients

Table 1: The mean values, Standard Deviation (S.D.) and Coefficient of Variation (C.V.) of some soil physical and chemical properties of the seventy-five soil samples used to determine soil CEC model

Parameter	Minimum	Maximum	Mean	S.D.	C.V. (%)
Sand (%)	14.00	44.00	33.10	6.31	19.10
Silt (%)	30.00	56.00	45.30	4.13	9.12
Clay (%)	9.00	50.00	22.00	6.65	30.20
OC (%)	0.15	1.90	0.68	0.32	47.10
pH	7.00	8.10	7.50	0.27	3.60
CEC (cmol kg ⁻¹)	7.00	23.00	13.90	3.25	23.40

Table 2: The mean values, Standard Deviation (S.D.) and Coefficient of Variation (C.V.) of soil physical and chemical properties of the fifteen soil samples used to verify soil CEC model

Parameter	Minimum	Maximum	Mean	S.D.	C.V. (%)
Sand (%)	10.00	34.00	24.10	5.87	24.40
Silt (%)	40.00	56.00	48.20	4.40	9.13
Clay (%)	18.00	50.00	28.20	7.90	28.00
OC (%)	0.36	2.00	0.83	0.39	47.00
pH	7.00	8.00	7.31	0.33	4.51
CEC (cmol kg ⁻¹)	8.00	25.00	15.20	3.72	24.50

Table 3: Linear regression models

Model No.	Model
1	CEC = $k_0 + k_1 Sa$
2	CEC = $k_0 + k_2 Si$
3	CEC = $k_0 + k_3 C$
4	CEC = $k_0 + k_4 OC$
5	CEC = $k_0 + k_5 pH$

In order to predict soil CEC from some soil physical and chemical properties i.e. Sand (Sa), Silt (Si), Clay (C), Organic Carbon (OC) and pH (pH), five linear regression models were suggested (Table 3).

Statistical analysis: A paired samples t-test and the mean difference confidence interval approach were used to compare the soil CEC values predicted using model with the soil CEC values measured by laboratory tests. The Bland-Altman approach [16] was also used to plot the agreement between the soil CEC values measured by laboratory tests with the soil CEC values predicted using model. The statistical analyses were performed using Microsoft Excel (Version 2003).

RESULTS

The p-value of the independent variable, coefficient of determination (R^2) and Coefficient of Variation (C.V.) of

Table 4: The p-value of independent variable, coefficient of determination (R²) and Coefficient of Variation (C.V.) of all the models

Model No.	Independent variable	p-value of independent variable	R ²	C.V. (%)
1	Sand	3.41E-06	0.26	20.3
2	Silt	0.559616	0.01	23.5
3	Clay	1.20E-04	0.19	21.2
4	OC	7.04E-23	0.74	12.1
5	pH	3.82E-05	0.21	20.9

all the models are shown in Table 4. Among the models, models No. 1, 2, 3 and 5 were judged unacceptable based on the statistical results. On the other hand, model No. 4 where organic carbon was considered as independent variable was judged acceptable due to statistical results. The R² value and C.V. of model No. 4 were 0.74 and 12.1%, respectively. Model No. 4 is given in Eq. 2.

$$CEC = 7.93 + 8.72 OC \quad (2)$$

DISCUSSION

A paired samples t-test and the mean difference confidence interval approach were used to compare the soil CEC values predicted using the linear regression model No. 4 with the soil CEC values measured by laboratory tests. The Bland-Altman approach [16] was also used to plot the agreement between the soil CEC values measured by laboratory tests with the soil CEC values predicted using the linear regression model No. 4.

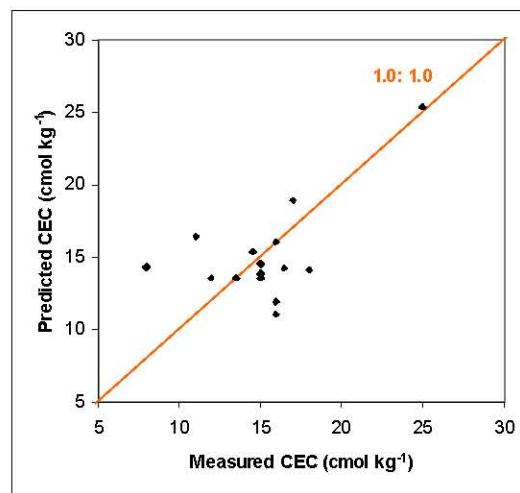


Fig. 1: Measured CEC and predicted CEC using model No. 4 with the line of equality (1.0: 1.0)

The soil CEC values predicted by model No. 4 were compared with the soil CEC values determined by laboratory tests and are shown in Table 5. A plot of the soil CEC values determined by model No. 4 and laboratory tests with the line of equality (1.0: 1.0) is shown in Fig. 1. The mean soil CEC difference between two methods was 0.09 cmol kg⁻¹ (95% confidence interval: -1.67 and 1.85 cmol kg⁻¹; P = 0.911). The standard deviation of the soil CEC differences was 3.18 cmol kg⁻¹. The paired samples t-test results showed that the soil CEC values predicted with model No. 4 were not significantly different than the soil CEC measured with laboratory tests (Table 6). The soil

Table 5: Physical and chemical properties of soil samples used in evaluating soil CEC model No. 4

Sample No.	Soil physical and chemical properties					CEC (cmol kg ⁻¹)	
	Sand (%)	Silt (%)	Clay (%)	OC (%)	pH	Laboratory test	Model No. 4
1	18	45	37	0.65	7.8	12.0	13.6
2	21	53	26	0.98	7.9	11.0	16.5
3	28	48	24	1.26	7.0	17.0	18.9
4	34	48	18	0.86	7.3	14.5	15.4
5	22	48	30	0.76	7.2	15.0	14.6
6	10	40	50	0.36	7.4	16.0	11.1
7	17	47	36	0.71	7.0	18.0	14.1
8	27	43	30	0.46	7.1	16.0	11.9
9	24	55	21	0.73	8.0	8.00	14.3
10	24	52	24	2.00	7.0	25.0	25.4
11	26	48	26	0.93	7.3	16.0	16.0
12	29	49	22	0.56	7.2	13.5	13.6
13	27	47	26	0.65	7.1	15.0	13.6
14	28	44	28	0.72	7.3	16.5	14.2
15	27	48	25	0.68	7.0	15.0	13.9

Table 6: Paired samples t-test analyses on comparing soil CEC determination methods

Determination methods	Average difference (cmol kg ⁻¹)	Standard deviation of difference (cmol kg ⁻¹)	p-value	95% confidence intervals for the difference in means (cmol kg ⁻¹)
Model No. 4 and laboratory test	0.09	3.18	0.911	-1.67, 1.85

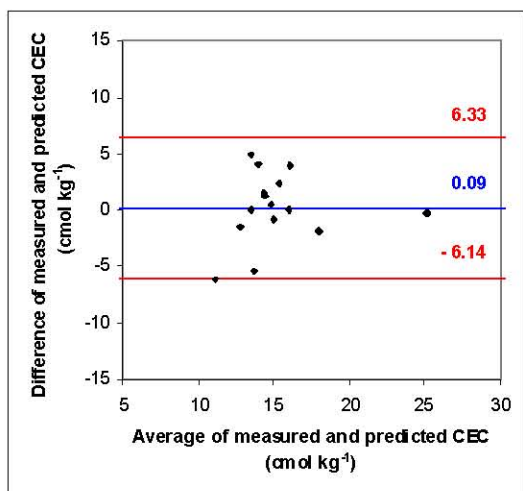


Fig. 2: Bland-Altman plot for the comparison of measured CEC and predicted CEC using model No. 4 [the outer lines indicate the 95% limits of agreement (-6.14, 6.33) and the center line shows the average difference (0.09)]

CEC differences between these two methods were normally distributed and 95% of the soil CEC differences were expected to lie between $\mu+1.96\sigma$ and $\mu-1.96\sigma$, known as 95% limits of agreement [16]. The 95% limits of agreement for comparison of soil CEC determined with laboratory test and model No. 4 were calculated at -6.14 and 6.33 cmol kg⁻¹ (Fig. 2). Thus, soil CEC predicted by model No. 4 may be 6.14 cmol kg⁻¹ lower or 6.33 cmol kg⁻¹ higher than soil CEC measured by laboratory test. The average percentage differences for soil CEC prediction using model No. 4 and laboratory test was 18.2%.

CONCLUSIONS

Linear regression model based on soil organic carbon was used to predict soil CEC. The soil CEC values predicted using the model was compared to the soil CEC values measured by laboratory tests. The paired sample t-test results indicated that the difference between the soil CEC values predicted by the model and measured by laboratory tests were not statistically significant ($P>0.05$). Therefore, the linear regression soil CEC model can provide an easy, economic and brief methodology to

estimate soil CEC. Statistical results of the study also indicate that organic carbon is the most important factor which affects soil CEC.

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