Prediction of cation exchange capacity from soil index properties

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ABSTRACT: In many areas of geotechnical engineering it is necessary to have an estimate of the cation exchange capacity (CEC) of a soil in order to allow preliminary design estimates. Standard methods of CEC determination are time-consuming and involve several steps (e.g. displacement of the saturating cation requires several washings with alcohol). Therefore, a rapid method of CEC estimation would be very useful. During preliminary site investigations, the soil engineering parameters can be estimated from the considerable number of correlations available in the literature. In this study, relationships between CEC and various other soil engineering properties have been investigated, resulting in a quick method for estimating CEC.

Simple correlations were developed between CEC and specific surface area (SSA), soil organic matter (OM), clay fraction (CF), activity (A), Atterberg limits (liquid (LL), plastic (PL), and shrinkage (SL)), and modified free swell index (MFSI) of the soils. Strong correlations are observed between the CEC values and those for ethylene glycol monoethyl ether (EGME) uptake and methylene blue (MB) titration. However, no significant correlation was found between CEC and N\textsubscript{2}SSA. No unique relationship was seen between CEC and CF ($r^2 < 0.5$). No relationship was observed between CEC and OM in this study. The best correlation coefficient between the CEC and Atterberg limits exists between CEC and LL ($r^2 = 0.61$). No significant relationship was seen between CEC and PL or SL. The correlation coefficient between CEC and MFSI was 0.65. Multiple linear regression analyses were developed to investigate the contributions of different soil parameters to CEC. These analyses show that EGME\_SSA, in combination with LL, accounted for 91\% of the variation in CEC. Correlations between CEC and EGME\_SSA, MB\_SSA and LL appear to be sufficiently good to enable an indication of CEC to be estimated from these parameters.

KEYWORDS: cation exchange capacity, specific surface area, clay fraction, organic matter, Atterberg limits, swell index.

The quantity of the exchangeable cations needed to neutralize the negative charges in a clay mineral structure (at a given pH) is called the cation exchange capacity (CEC) and is expressed in milliequivalents (mEq) per 100 g of dried solid (or centimoles of charge of ion per kilogram, cmolc/kg). The CEC of a clayey soil originates primarily in the clay-sized fraction though a small portion of the silt-sized fraction also contributes to the soil’s ability to hold on to cations. For example, sand may have a CEC of 2 mEq/100 g, silt loam 25 mEq/100 g, and clay 50 mEq/100 g of dry soil.

In the literature it is well documented that the adsorption capacity of a soil is related to its CEC: the greater the CEC, the greater the adsorption capacity. It is also reported that CEC is related to the swelling potential of a clayey soil. In many areas of geotechnical engineering it is necessary to
predict the CEC of a soil for preliminary design estimates. However, methods for determining the CEC of soils are somewhat cumbersome and time-consuming (Manrique et al., 1991). Therefore, there is a need for an efficient and quick method for estimating the CEC of soils for practical engineering applications. In this respect, researchers use parameters that are easy to measure in order to predict parameters that are somewhat cumbersome to obtain. The CEC is one of the soil index parameters that the literature suggests can be estimated through other parameters such as specific surface area, clay fraction and Atterberg limits.

PREVIOUS STUDIES

Several researchers have correlated soil index properties with CEC and they have found that the CEC of a soil is closely related to its SSA (Churchman et al., 1991; Curtin & Smillie, 1976; Cihacek & Bremner, 1979; Tiller & Smith, 1990; Petersen et al., 1996). For example, Curtin and Smillie (1976) observed in Irish soils that the CEC of a soil was strongly correlated with its organic matter content and specific surface area but not with its clay content. They concluded that it might be possible to estimate the mineral component of CEC for a wide range of soils from their specific surface area rather than their clay content. Similarly, Farrar & Coleman (1967) found that the total surface area and CEC had correlation coefficients of 0.9 or greater for 19 British clayey soils. Farrar & Coleman (1967) concluded that that the coefficient of correlation was sufficiently high to correlate both total surface area and Atterberg limits with CEC. In addition to Farrar & Coleman’s (1967) findings, Newman (1983) observed that ethylene glycol and water sorption were strongly correlated with CEC.

Several studies have also related the swelling potential of a clay to its CEC. For example, Kariuki & Meer (2004) reported a strong relationship between the CEC and percent volume change (PVC), which portrayed CEC as a very useful parameter for estimating the swelling behaviour of soils. They suggested a unified swelling potential index for expansive soils based on the CEC of clayey soils. Following Kariuki & Meer (2004), Yilmaz (2006) offered a classification for swelling soils derived using the liquid limit (LL) and the CEC of soils.

Yet these classifications were not without their difficulties. The main source of problems cited here and elsewhere is that the parameters used for these classifications are interrelated. For example, the LL of a clayey soil is a function of its CEC. In addition, the parameters that are used in such classifications are method dependent. Specific surface area is a primary example of a parameter strongly dependent on the measuring method. However, CEC is linearly dependent on SSA in the following manner:

$$\text{CEC} = \sigma \times \text{SSA}$$

where \( \sigma \) is surface charge density of clay particles.

Thus, for accurate utilization of soil index properties to estimate geotechnical soil properties, it is necessary to determine the factors affecting the measurement of soil index properties. Moreover, it is necessary to clarify the previously suggested correlation of CEC of soils with other soil index properties. Because of this, we decided to determine the SSA of our samples using three different methods (BET_N\textsubscript{2} adsorption, ethylene glycol monoethyl ether (EGME) uptake, and methylene blue (MB) titration), and the CEC, Atterberg index, and modified free swell index (MFSI) of a set of clayey soils of different origins and with different compositions. After having established the soil index parameters, we investigated correlations between: (1) CEC and SSA of soils using the different methods; (2) CEC and Atterberg limit indexes; (3) CEC and clay fraction (CF); (4) CEC and organic matter (OM); and (5) CEC and modified free swell index.

MATERIALS AND METHODS

Sixteen soils with different origins and characteristics were selected. All samples were obtained from different parts of Turkey, except Soil 4 which was a Georgia kaolin (KGa1b) obtained from the Source Clays Repository of The Clay Minerals Society, located at Purdue University, Indiana. The soils showed variations in mineralogy, CEC, liquid limit and SSA. The CECs ranged from 2 to 132.3 mEq/100 g. The dominant minerals in the tested soils were kaolinite (K), halloysite (H), zeolite (clinoptilolite) (Z), chlorite (C), mixed-layer mineral (montmorillonite-illite) (ML), illite (I), and montmorillonite (M). The powder X-ray diffraction (XRD) patterns were obtained using a Philips diffractometer and Cu-K\alpha radiation. The dominant minerals in the soils and their clay fractions are listed in Table 1. All soil samples were oven-dried
(80°C for 48 h), crushed, and sieved through a 75 μm mesh. Specific gravity, CEC, and soil OM of the samples were determined according to ASTM D-854-92, the Na method (Chapman, 1965), and ASTM D-2974-87, respectively. The clay fraction of the samples was determined according to the ASTM D-422 standard, which requires a hydrometer test on 50 g of oven-dried soil in a 1000 ml cylinder. The soil was mixed in a 40 g/l solution of sodium hexametaphosphate and distilled water and was allowed to soak overnight. The solution was agitated with a mixer and then transferred to the cylinder. The solution was mixed for 1 min by hand, was inverted and then returned upright. Immediately after having set the cylinder down, the stopwatch was started. Hydrometer readings were taken at various elapsed times. The results of these tests are given in Table 1. Liquid, plastic and shrinkage limits were determined according to British Standard BSI 190, ASTM D-4318-98, and ASTM D-427-93, respectively.

The SSA values of the samples were determined by three different procedures: BET_N\textsuperscript{2} adsorption, EGME uptake and the MB titration method. The BET_N\textsuperscript{2} SSA was determined by nitrogen adsorption at 77 K using a Quantachrome Monosorb device. Monosorb operation is based on the theoretical BET (Brunauer et al., 1938) equation. Surface area was determined by the BET equation. Following the EGME method (Cerato & Lutenegger, 2002), approximately 3 ml of laboratory-grade EGME were added to 1 g of oven-dried soil and gently mixed by hand with a swirling motion to create uniform slurry. The tare, which had plexiglass lids on top, was placed in a glass sealed-vacuum desiccator. Excess EGME was removed by applying vacuum (640 mm Hg) continually until a gravimetric measurement of the tare did not vary by >0.001 g. The SSA of the sample was calculated from the EGME retained on the soil.

In the MB titration method (Santamarina et al., 2002), the MB solution of known concentration was added to 2 g of oven-dried soil specimen and 200 ml of deionized water soil slurry and shaken for 2 h and allowed to settle overnight. After centrifugation of the suspended material, the MB concentration in the supernatant solution was measured at a wavelength of 655 nm by a NovaSpec II spectrophotometer. The SSA was computed from the amount of adsorbed methylene blue (MB). Further details of the testing procedures can be found in previously cited references and in Yukselen & Kaya (2006).

| Soil sample | Clay fraction (wt.% <2 μm) | Specific gravity | Cation exchange capacity (mEq/100 g) | Soil organic matter (%) | Specific surface area (m\textsuperscript{2}g\textsuperscript{-1}) N\textsubscript{2} | EGME | MB titration | Activity PI/CF | Dominant mineral |
|-------------|---------------------------|-----------------|-------------------------------------|-------------------------|---------------------------------------------|-----|---------------|----------------|----------------|
| S-1         | 32.5                      | 2.50            | 25.1                                | 10.4                    | 56.4                                        | 105.7 | 48.9          | 0.43           | K              |
| S-2         | 44                        | 2.63            | 2.9                                 | 2.3                     | 6.9                                         | 29.8 | 6.1           | –              | K              |
| S-3         | 38                        | 2.52            | 6.8                                 | 1.9                     | 20.8                                        | 37.1 | 12.2          | 0.26           | K              |
| S-4         | 42                        | 2.63            | 2.0                                 | 2.7                     | 10.1                                        | 25.5 | 12.2          | 0.53           | K              |
| S-5         | 28                        | 2.48            | 24.0                                | 10.5                    | 93.5                                        | 135.1 | 61.0          | 0.83           | H              |
| S-6         | 35.5                      | 2.39            | 60.5                                | 5.6                     | 34.3                                        | 149.0 | 122.1         | 0.32           | Z              |
| S-7         | 32                        | 2.36            | 57.2                                | 4.8                     | 32.0                                        | 69.8 | 47.1          | 0.19           | Z              |
| S-8         | 21                        | 2.75            | 5.9                                 | 1.8                     | 5.3                                         | 34.9 | 18.3          | 0.31           | C              |
| S-9         | 77                        | 2.76            | 26.2                                | 4.4                     | 25.3                                        | 94.8 | 84.9          | 0.49           | ML             |
| S-10        | 46                        | 2.63            | 10.7                                | 1.5                     | 15.5                                        | 62.4 | 73.4          | 0.94           | I              |
| S-11        | 82                        | 2.50            | 83.7                                | 7.0                     | 56.7                                        | 299.1 | 244.1         | 0.65           | M              |
| S-12        | 75                        | 2.64            | 38.4                                | 5.2                     | 36.4                                        | 104.3 | 158.3         | 0.54           | M              |
| S-13        | 90                        | 2.76            | 86.1                                | 2.4                     | 51.9                                        | 578.1 | 850.9         | 4.63           | M              |
| S-14        | 56.8                      | 2.37            | 132.3                               | 5.0                     | 11.2                                        | 393.4 | 704.6         | 1.23           | M              |
| S-15        | 80                        | 2.76            | 67.1                                | 2.2                     | 28.7                                        | 442.0 | 777.5         | 3.51           | M              |
| S-16        | 90                        | 2.72            | 127.9                               | 2.3                     | 21.5                                        | 582.3 | 948.8         | 3.82           | M              |

K: kaolinite, H: halloysite, Z: zeolite (clinoptilolite), ML: montmorillonite-illite mixed-layer mineral, I: illite and M: montmorillonite
The modified free swell index (MFSI) determination method was adapted from ASTM D-5890 and Sivapullaiah et al. (1987). In this adapted swell index method, 10 g of oven-dried soil were used with a No. 40 filter. However, for expansive soils, like montmorillonite, 2 g of soil were used in the experiments. 90 ml of distilled water were transferred to the 100 ml graduated cylinder. Approximately 0.1 g increments of a sample were dusted over the entire water surface in the graduated cylinder over a period of ~20 s. Sample hydration and settlement were allowed for a minimum of 5 min. After the final increment had settled, the water volume was raised to 100 ml by rinsing the adhering particles from the sides of the cylinder. After 2 h, the hydrating clay column was inspected for trapped air. After the 24 h hydration period, the volume (ml) was recorded at the top of the settled sample.

RESULTS AND DISCUSSIONS

CEC and SSA

The SSA and CEC results are presented in Fig. 1. As can be seen, the relationship between CEC and SSA is dependent on the method used to determine SSA. For example, correlations between CEC and EGME_SSA and MB_SSA are significantly better than those of N₂_SSA. It appears that the best correlation is between CEC and EGME_SSA ($r^2 = 0.83$). The poor correlation between CEC and the N₂_SSA method is probably an inevitable result of using gas adsorption methods with dry specimens. Under dry conditions, the layers of the clay minerals are tightly bound. The molecules of the N₂ gas cannot penetrate the interlayer surfaces of potentially expandable layer silicates such as montmorillonite and only measure the external surface areas of these soils.

Phelps & Harris (1968) reported that CEC of kaolinite appears to be a straight-line function of its nitrogen adsorption specific surface. However, they observed that such a relation did not exist for montmorillonite, which implies that application of the N₂ gas adsorption method to montmorillonite-type minerals has limitations.

Both the EGME and MB methods are applied under wet conditions. Ions or water can easily intercalate between these clay mineral layers. The results indicated that (unlike the situation with N₂ sorption) the CEC of the soils can be estimated from the correlations with SSA obtained using either EGME or MB testing procedures. De Jong (1999) observed similar findings. He found correlation coefficients between the CEC and EGME_SSA and N₂_SSA to be 0.66 and 0.13, respectively. Petersen et al. (1996) and Cihacek & Bremner

Fig. 1. Relationship between the CEC and three different SSAs (N₂_SSA, EGME_SSA and MB_SSA) of the soils.
(1979) found correlations between the EGME_SSA and CEC to be $r^2 = 0.66$ and $r^2 = 0.59$. Petersen et al. (1996) concluded that CEC was better predicted from SSA than from clay or OM content. Churchman & Burke (1991) observed the correlation between CEC and EGME retention to be $r^2 = 0.86$, while the correlation between CEC and N$_2$SSA was only $r^2 = 0.31$. Cerato (2001) observed the relationship between CEC and EGME SSA for alluvial deposits as $r^2 = 0.96$.

Figure 2 shows the relationships observed between the estimated and measured CEC of soils from this study and those reported by Farrar & Coleman (1967) and by Churchman & Burke (1991). It is seen from Figure 2 that as the SSA of soil increases, the differences between the calculated and measured values also increase. In other words, the prediction of CEC of highly plastic soils using SSA correlations is poor, which can be attributed to the difficulty of measuring the internal surface area (interlayer space) of these soils.

### CEC and clay fraction

In general, it is expected that as the clay fraction increases, so would the CEC of the soil. Based on this expectation, researchers have proposed simple linear regressions between CF (<2 μm) and CEC. However, our data, as seen in Table 2, indicate that there is no significant relationship between CEC and CF. This is because CEC is dependent more on the type of clay than on its amount. This is shown well in the results given in Table 2. The reason for the poor correlation between CEC and CF is that two soils may have the same CF; yet their CF may have very different chemical and mineralogical

| Soil property | Regression coefficients ($R^2$) |
|---------------|-------------------------------|
| CEC          | EGME_SSA (m$^2$ g$^{-1}$) | MB_SSA titration (m$^2$ g$^{-1}$) | N$_2$SSA (m$^2$ g$^{-1}$) | CF (<2 μm) | OM (%) | Activity |
|               | 0.83                         | 0.81                          | 0.41*                      | 0.37        | 0.002   | 0.36     |

* Soil 5 is not included
compositions. Thus, it is not unusual to observe a better correlation between CEC and SSA than between CEC and CF (Uehara, 1982). The present study's poor correlations are similar to those found in the literature (Curtin & Smillie, 1976; Locat et al., 1984; Smith et al., 1985; Nettleton et al. 1983; Manrique et al., 1991).

**CEC and organic matter**

No relationship has been observed between CEC and OM for the soils tested in this study ($r^2 = 0.002$). The contribution of OM to the CEC of soils is difficult to evaluate. The OM may have CEC values between 100 and 300 mEq/100 g at a pH of 7. The net effect of organic matter is usually to increase the CEC and SSA of the soil. Tan & Dowling (1984) observed that in soils with mixed mineralogy, destruction of organic matter resulted in a decrease in CEC (permanent charges). Thompson et al. (1989) observed that, on average, organic matter contributes 49% of the CEC of the fractioned materials. Curtin & Smillie (1976), Thompson et al. (1989), and Manrique et al. (1991) and Ohtsubo et al. (1983) found the correlation between CEC and OM as $r^2 = 0.5$, $r^2 = 0.74$, $r^2 = 0.12$ and $r^2 = 0.27$ respectively. However, estimated net contributions of organic matter to the CEC and SSA of fractioned materials are also difficult to compare with reports in the literature due to differences in methodology.

**CEC and activity**

The Skempton activity, $A$, relates plasticity (PI) to the clay size fraction, $A = PI/CF$. The particle size of montmorillonite is small: particles are only a few nm thick. Since surface activity is related inversely to particle size, montmorillonite is more active than kaolinite. The CEC is another useful indicator of clay activity because it is the product of two fundamental properties of clay, namely the specific surface area per unit mass of clay, and the surface charge density or number of charges (milliequivalents) per unit area. However, as can be seen in Fig. 4, there is no significant relationship between the CEC and activity of the soils tested ($r^2 = 0.36$, Table 2). Similar to these findings, literature data also show that there is no general correlation between activity and CEC (see Fig. 3).

**CEC and Atterberg Limits**

Atterberg limits can yield significant information about the behaviour of soils. Atterberg limits are water contents at boundaries that show characteristic engineering behaviours. Liquid, plastic and shrinkage limits of the samples are shown in Table 3, and the relationships with CEC are shown in Figure 4.

The liquid limit is the water content at which a soil passes from a plastic state to an almost liquid condition. A linear regression equation has been

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**Fig. 3. Relationship between the CEC and activity.**
developed between the CEC (mEq/100 g) and LL (%): 

\[ \text{CEC} = 0.2027 \times \text{LL} + 16.231 \quad R^2 = 0.61 \quad (2) \]

Smith et al. (1985) and Ohtsubo et al. (1983) gave correlation coefficients of the relation between CEC and LL as \( R^2 = 0.72 \) and \( R^2 = 0.62 \), respectively. Some authors have developed the following linear regression equations between CEC and LL (%):

\[ \text{CEC} = 0.45 \times \text{LL} \]  
Farrar & Coleman (1967) (3)

\[ \text{CEC} = 1.74 \times \text{LL} - 38.3 \]  
Smith et al. (1985) (4)

Figure 5 shows the measured and estimated CEC using the relationships suggested in equations 2, 3 and 4, for the soils of the present study. All three equations give good estimates for CEC. However, the present study (equation 2) and Smith et al. (1985) (equation 4) give estimates of the CEC with large uncertainty when LL > 300%.
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TABLE 3. Atterberg limits and modified free swell index (MFSI) of the soils.

| Soil sample | LL* (%) | PL* (%) | SL* (%) | PI* (%) | MFSI |
|-------------|---------|---------|---------|---------|------|
| S-1         | 58.0    | 440     | 38.8    | 14.1    | 2.75 |
| S-2         | 30.1    | NP      | 20.4    | NP      | 1.49 |
| S-3         | 51.7    | 41.9    | 34.8    | 9.8     | 3.10 |
| S-4         | 42.0    | 26.0    | 26.0    | 16.0    | 2.89 |
| S-5         | 58.4    | 35.1    | 27.9    | 23.3    | 1.83 |
| S-6         | 61.6    | 50.1    | 39.3    | 11.4    | 2.34 |
| S-7         | 44.9    | 38.7    | 35.9    | 6.2     | 2.02 |
| S-8         | 24.5    | 18.1    | 16.1    | 6.5     | 1.33 |
| S-9         | 72.2    | 34.7    | 17.3    | 37.5    | 3.61 |
| S-10        | 60.9    | 17.7    | 16.8    | 43.2    | 3.52 |
| S-11        | 113.6   | 60.7    | 19.8    | 52.9    | 7.99 |
| S-12        | 70.0    | 29.8    | 16.8    | 40.2    | 3.75 |
| S-13        | 464.8   | 48.2    | 10.4    | 416.6   | 60.37|
| S-14        | 111.5   | 41.6    | 5.8     | 69.9    | 6.10 |
| S-15        | 330.7   | 49.9    | 7.1     | 280.8   | 23.88|
| S-16        | 395.8   | 52.4    | 11.7    | 343.4   | 53.67|

* LL: liquid limit, PL: plastic limit, SL: shrinkage limit, PI: plasticity index, NP: non-plastic

Plastic limit (PL) is another important index property for identifying soil behaviour. The PL is defined as the water content at which a thread of soil just crumbles when it is carefully rolled out to a diameter of 3 mm (Holtz & Kovacs, 1981). Generally, the correlation coefficients between CEC and PL are found to be less than the corresponding coefficients for liquid limit correlations. The lower correlation with PL is possibly due to inaccuracies in the test (Farrar & Coleman, 1967). The correlation coefficient of the CEC and PL relationship was found to be 0.46 (excluding Soil 2 (non-plastic)). Smith et al. (1985) found the coefficient of correlation between the CEC and PL to be $r^2 = 0.56$.

The Plasticity Index (PI) is numerically equal to the difference between the LL and the PL (PI = LL − PL). Many engineering properties have been found to empirically correlate to PI. The correlation between CEC and PI is less than with either PL or LL (Table 3). Such correlations show that the CEC cannot be estimated from PI data.

Shrinkage limit (SL) is governed by the amount of water absorbed and desorbed from soil surfaces. However, no significant correlations were observed between SL and CEC. This may be due to the uncertainty in the shrinkage limit test itself.

CEC and modified free swell index (MFSI)

A regression analysis was developed between CEC and the MFSI of the soils. When a linear relationship was used, the correlation coefficient was 0.58; however, when the best-fitted logarithmic relationship was used (Fig. 6), the regression coefficient between CEC and MFSI increased to 0.65. Kariuki & Meer (2004) found this regression coefficient in their study to be $r = 0.84$. The difference can be attributed to the different soils used in the studies. This is because Kariuki & Meer (2004) used only expansive soils while in the

![Fig. 5. Relationship between the CEC and modified free swell index (MFSI).](image-url)
Multiple linear regressions

Multiple regression analysis is a useful method which can be used to evaluate the contributions of several physical and chemical soil properties to CEC. In this study, multiple linear regression analysis shows that SSA in combination with OM has accounted for 77% of the variation in CEC, whereas OM and CF has only accounted for 40% of the variation. As mentioned before, there is no relationship between the CEC and OM ($r^2 = 0.002$). However, the correlation coefficient between the CEC and EGME_SSA is 0.83. When the multiple linear correlation was conducted between the CEC and EGME_SSA with OM, the correlation coefficient decreases to 0.77 which indicates the negative effect of OM on prediction of CEC (equations 6 and 7). Specific surface and organic matter are clearly superior to clay fraction and organic matter for the prediction of the CEC. The multiple linear equations are as follows:

$$\text{CEC} = 2.84 \text{OM} + 1.16 \text{CF} - 28.02 \quad (r^2 = 0.40) \quad (5)$$
$$\text{CEC} = 2.12 \text{OM} + 0.19 \text{SSA} + 0.38 \quad (r^2 = 0.77) \quad (6)$$
$$\text{CEC} = 0.1135 \text{(EGME}_\text{SSA})^{1.1371} \quad (r^2 = 0.83) \quad (7)$$

Similar observations were also reported by previous researchers. For example, Curtin & Smillie (1976) and Thompson et al. (1989) reported that OM combined with SSA accounted for 97% and 89% of variation, respectively. The LL and SSA could explain ~91% of the variability in CEC by the following equation:

$$\text{CEC} = -0.33 \text{LL} + 0.4 \text{EGME}_\text{SSA} + 8.8 \quad (r^2 = 0.91) \quad (8)$$

The correlation coefficient increases to 0.91, with multiple linear regression of LL and EGME_SSA. Clearly, LL and SSA are the most important factors affecting the CEC of the soils.

CONCLUSIONS

In many areas of geotechnical engineering it is necessary to have an estimate of the CEC of a soil to allow preliminary design estimates. Standard methods of CEC determination are time-consuming and involve several steps (e.g. displacement of the saturating cation requires several washings with alcohol). Therefore, a rapid method of CEC estimation would be useful. During preliminary site investigations, the soil engineering parameters can be estimated from the considerable number of correlations available in the literature. In this study, relationships between CEC and various soil engineering properties have been investigated, giving a speedy method for estimation of CEC.

Strong correlations exist between CEC and both EGME_SSA and MB_SSA, but not with N$_2$_SSA. The N$_2$ adsorption method only measures external surfaces; therefore predictions from N$_2$_SSA cannot estimate CEC, especially for swelling soils. EGME_SSA and the CEC of soils are well correlated ($r^2 = 0.83$). Also, there is a strong
relationship between the MB_SSA and CEC. No significant correlation is observed between CEC and CF or OM. It is usually assumed that as CF increases, the CEC of the soils increases as well. However, the poor correlation found between CEC and CF shows that this assumption is untrue. The specific mineralogy is more important than the total CF. It has also been reported that an increase in organic matter increases the CEC of the soils. However, no such correlation is observed in this study.

Simple linear correlations between CEC and Atterberg limits show that there is a relationship between CEC and LL; however, no significant relationship was found between CEC and PL, PI or SL (Table 4). It is believed that the LL and the CEC are both factors that control the swelling characteristics of soils. However, the correlation coefficient between the CEC and the modified free swell index was 0.65.

Multiple linear regression analyses show the contributions made by different physical and chemical properties to CEC. SSA and OM explain ~77% of the variability in CEC. The results of this study indicate that specific surface area and liquid limit are the most important factors that affect the CEC of the soils. The parameters most closely related to CEC, i.e. LL and EGME_SSA, account for 91% of the variability. However, the relationship between the SSA and CEC is greater than that between LL and CEC. If the LL or SSA values of the soil are known, the CEC can be estimated by regression equations. However, the N\textsubscript{2} SSA value cannot be used for highly swelling soils, because the N\textsubscript{2} method cannot measure the highly sorbing interlayer surfaces of these soils.

Significant correlation coefficients indicate that the CEC of soils can be estimated readily and accurately using LL with either EGME_SSA or MB_SSA of soils.

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**TABLE 4. Correlations between the CEC and liquid, plastic and shrinkage limits and modified free swell index (MFSI).**

|        | LL  | PL  | PI  | SL  | MFSI |
|--------|-----|-----|-----|-----|------|
| CEC    | 0.61| 0.46| 0.36| 0.21| 0.65*|

LL: liquid limit, PL: plastic limit, SL: shrinkage limit, PI: plasticity index

* Soil 14 is not included
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