International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Estimation of Cation Exchange Capacity of Fine Grained Soil using AI Techniques

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DOI: https://doi.org/10.55248/gengpi.5.0524.1420

A B S T R A C T

Clay soils play a pivotal role in geotechnical and environmental contexts due to their unique mineral and chemical properties. The main characteristic property of these clay soils is cation exchange capacity (CEC) which is a crucial parameter influencing various soil processes, including nutrient accessibility, soil fertility, and geotechnical characteristics. Traditional laboratory methods for CEC determination are time-consuming and expensive. Recent advancements in artificial intelligence (AI) offer a promising alternative to streamline and enhance the accuracy of CEC predictions. This study explores the feasibility of estimating cation exchange capacity in clay soils by leveraging linear regression model and a comprehensive range of soil parameters, including Liquid Limit (LL), Plastic Limit (PL), Shrinkage Limit (SL) and Plasticity Index (PI). A dataset comprising about 200 data points from various research papers was compiled, and Linear regression model was trained using the dataset through orange data mining software to evaluate the correlation between cation exchange capacity and the Liquid Limit, Plastic Limit, Shrinkage Limit and Plasticity Index.

Keywords: Cation Exchange Capacity, Liquid Limit, Plastic limit, Shrinkage Limit, Plasticity Index

INTRODUCTION

The Cation exchange capacity (CEC), which is measured in milliequivalent (meq) per 100 g of dried solid (or centimoles of charge per kilogram, cmolc/kg),is the amount of exchangeable cations required to balance the negative charges in a clay mineral structure (at a specific pH) (Y Yukselen and Kaya, 2006a).

Cation exchange capacity in clays is a fundamental process in soil chemistry and geology, particularly in understanding how clays interact with positively charged ions (cations) in the soil (Brady and Weil, 2008). This negative charge is a result of isomorphous substitution, where some of the cations within the clay mineral lattice are replaced by smaller cations, leading to an excess of negative charges on the clay surface.

In 1850, Thomson and Way carried out the first known investigation on cation exchange in Rothamsted, England. They demonstrated how calcium sulfate was leached from the soil by running an ammonium sulfate solution through soil columns. The cation exchange in the soil has caused the major cation in the aqueous solution to shift from ammonium to calcium. Ammonium ions were maintained in an amount equivalent to the amount of calcium released, as demonstrated by Thomson and Way, and the exchange was extremely rapid and reversible.

Electrostatic forces cause soil clay minerals and organic matter, which have a tendency to be negatively charged, to draw positively charged ions (cations) to their surfaces. “However, they do not directly chemically bind to the surface; instead, they retain a shell of water molecules. The diffuse layer above the charged surface therefore contains exchangeable cations. It is quite easy for other cations from the surrounding solution to displace a cation away from the surface due to the weak interaction. Since the cation can be easily replaced by other cation so the term "cation exchange".

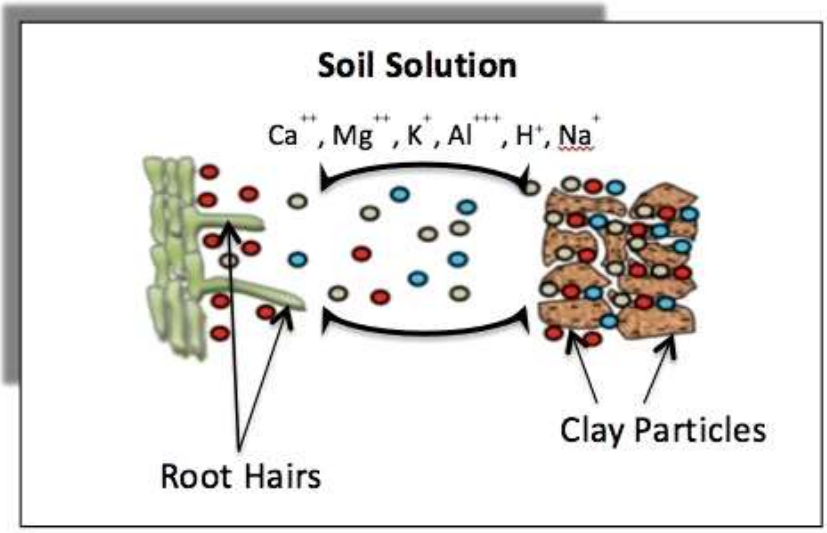

Figure 1: Ion Exchange between Clay particles and root hairs

In the diagram above, Na^+ cations are initially held on the negatively charged clay surface. When a solution containing Ca^{2+} cations is added, the Ca^{2+} cations are attracted to the clay surface. The Ca^{2+} cations displace some of the Na^+ cations from the clay surface. The displaced Na^+ cations move into the solution.

The main cations associated with cation exchange capacity (CEC) in soils are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+), commonly referred to as base cations (Rayment and Higginson, 1992).

IMPORTANCE

Cation exchange capacity is a very crucial feature in geotechnical engineering which can be used to find the the type of clay, Texture of clay and swelling of clay.

Arnepalli et al. (2008) provide the table below illustrating the range of CEC of various clays. If you know or calculate the CEC of the particular locality, you can easily determine the type of clay from it.

Table 1: Exchange capacity of cation with respect to clay minerals

Clay minerals	CEC (meq/100 g)
Vermiculite	120-150
Montmorillonite	80-120
Illite	20-40
Chlorite	20-40
Kaolinite	1-10
Organic matter	100-300

(Kissel and Sonon, 2008) also gives range of CEC values for different soils at a buffer solution of PH 7

Table 2: Cation of various soil types, soil textures , and organic matter at PH 7.0 exchange capacities (Kissel and Sonon, 2008)

Soil and Soil Components Clay Type	CEC (meq/100 g)
Kaolinite	3-15
Illite	15-40
Montmorillonite	80-100

Soil Texture	
Sand	1-5
Fine Sandy Loam	5-10
Loam	5-15
Clay Loam	15-30
Clay	>30
Organic Matter	200-400

Novak et al. (2009) shows the relationship between the CEC of clay and its swelling potential. The below table shows that higher the CEC values higher will be the swelling potential.

Table 3: CEC values and swelling classification (Novak *et al.*, 2009).

Cation exchange capacity	swelling classification
<27	low swelling
27–37	medium swelling
37–55	high swelling
>55	very high swelling

Mengel (1993) gives the range of CEC values for different clays texture. By looking at the range of CEC you can determine the type of clay and the texture/color of clay

Table 4: Normal range of CEC values for Common Color/Texture soil groups (Mengel, 1993).

Soil groups	Examples	meg/100g
Light colored sands	Plainfield Bloomfield	• 3-5
Dark colored sands	Maumee Gilford	• 10-20
Light colored loams and silt loams	Clermont-Miami	• 10-20
Dark colored loams and silt loams	Sidell Gennesee	• 15-25
Dark colored silty clay loams and silty clays	Pewamo Hoytville	• 30-40
Organic soils	Carlisle muck	• 50-100

LITERATURE REVIEW

Cation Exchange Capacity (CEC) and Atterberg limit

Yukselen and Kaya (2006) suggested that Atterberg limits can provide important information regarding the behavior of soils. Atterberg limit tests provide information about characteristics linked to soil consistency.

The shrinkage limit (SL), liquid limits (LL), and plastic limit (PL) are all part of the Atterberg limit test. As illustrated in figure 2.14, soil transforms during watering from a solid to a semisolid, plastic, and finally a liquid state.

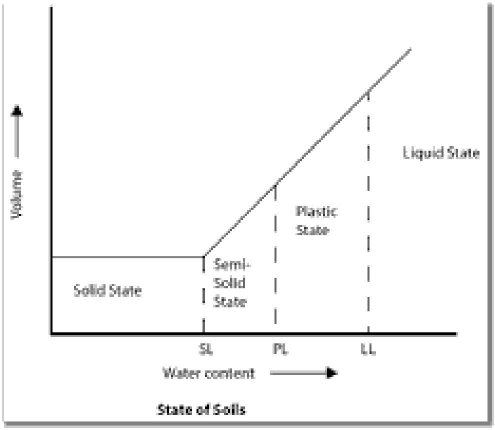

Figure 2: States of soils

CEC AND LIQUID LIMIT

The following linear regression equation has been created between the CEC (mEq/100 g) and LL (%) by (Y. Yukselen and Kaya, 2006)

CEC = 0.2027 LL + 16.231(R^2 = 0.61)

The correlation coefficients for the relationship between CEC and LL were given as R^2 = 0.72 by (Smith, 1985) and as R^2 = 0.62 by (El-Kasaby *et al.*, 2019)

CEC = 0.45 LL -5 (Farrar and Coleman, 1967)

CEC = 1.74 LL - 38.3 (Smith, 1985)

However, (Smith, 1985) and (Y. Yukselen and Kaya, 2006) offer estimates of the CEC that are quite ambiguous when LL is more than 300%.

(Farrar and Coleman, 1967) derived the linear regression equation for the relationship between LL and CEC, as stated by

$$CEC=0.45*LL-5 \ (R^2=0.9)$$

Yukselen and Kaya (2006) used linear regression to propose the relationship between LL and CEC given as

$$CEC= 0.2027*LL+16.231 \ (R^2=0.61)$$

CEC AND PLASTIC LIMIT

(Smith, 1985) derived the following linear regression equation between CEC and PL

$$CEC=3.57*PL-61.3 \ (R^2=0.56)$$

Yukselen and Kaya (2006) used linear regression to develop the relationship between CEC and PL as described as

$$CEC=2.3067*PL-40.3 \ (R^2=0.46)$$

CEC AND SHRINKAGE LIMIT

Yukselen and Kaya (2006) observed no evidence of a relationship between shrinkage limit and CEC, with the correlation coefficient between the two being R^2=0.2071 pertaining to the linear regression formula written as

$$CEC= -1.7643*SL+85.33 \ (R^2=0.3574)$$

CEC AND PLASTICTY INDEX

Yukselen and Kaya (2006) used linear regression to propose the relationship between PI and CEC given as

$$CEC=0.1873*PI+33.13 \ (R^2=0.2071)$$

METHODOLOGY

The study collect Training dataset of about 200 points of Liquid Limit, Plastic Limit, Shrinkage Limit, Plasticity Index and cation exchange capacity from different researcher papers including (Kadali *et al.*, 2016), (Tian, Wei and Tan, 2019a), (Yukselen-Aksoy, Kaya and Ören, 2008), , (Y Yukselen and Kaya, 2006b), (Arnepalli *et al.*, 2008b), (Fernandez *et al.*, 2017),(Lutenegger, Cerato and Harrington, 2003), (Mahmoudi, Srasra and Zargouni, 2016a), (Bayat *et al.*, 2015), (Cerato *et al.*, 2011), (Tadza *et al.*, 2019), (Nambiar, Remya and Varghese, 2020), (Mahmoudi, Srasra and Zargouni, 2016b), (Lu and Dong, 2017), (Tian, Wei and Tan, 2019b), (Ngun *et al.*, 2011), (Kozlowski and Nartowska, 2013).

Then the study use the data mining software orange to visualize and analyze the model using the Linear regression model which is illustrated in below figure.

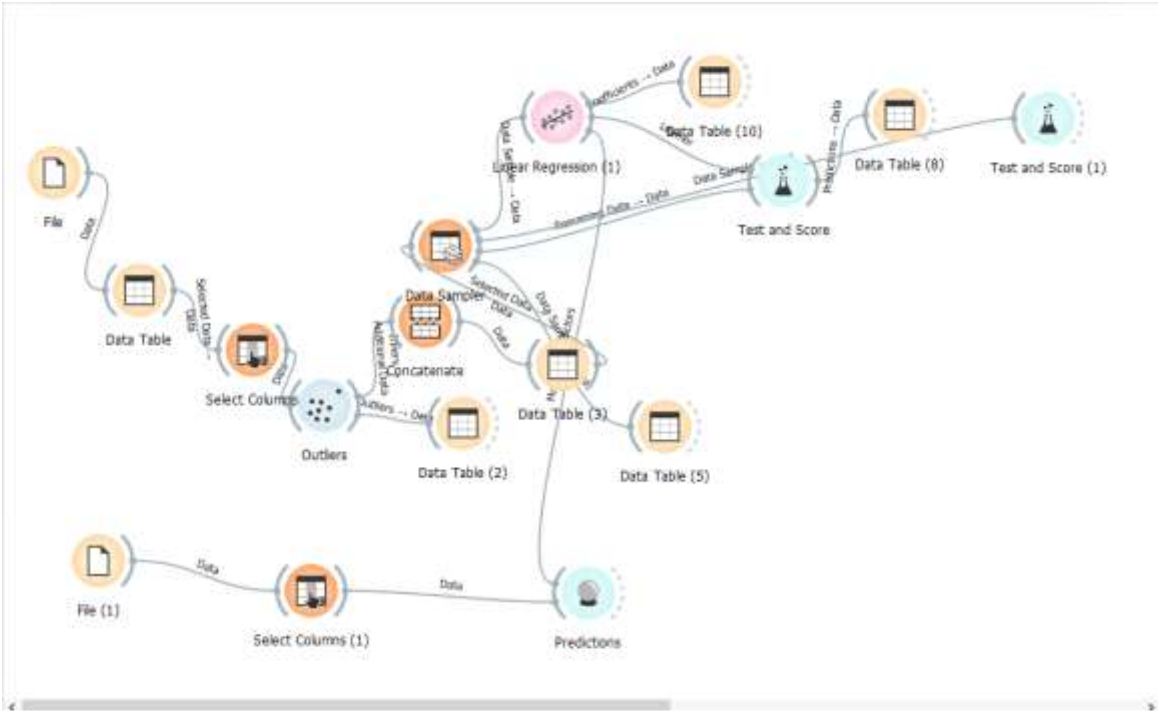

Figure 4: Linear regression workflow diagram

RESULTS AND DISCUSSION

Table 5: Regression parameter results

PARAMATER	R^2
Liquid limit	0.9288
Plastic limit	0.7756
Plasticity index	0.8801
Shrinkage limit	0.657

The study found a strong correlation between the Cation Exchange Capacity and Liquid limit with a R^2 value of 0.9288 that means that there is a strong relationship ship between Cation Exchange Capacity and Liquid limit. The study also found a strong correlation between the Cation Exchange Capacity and Plastic limit, Plasticity index with a R^2 value of 0.7756, 0.8801. On the other hand the study found no correlation between Cation Exchange Capacity and Shrinkage limit with a low R^2 value of 0.657.

CONCLUSION

- The study found strong correlation between Cation Exchange Capacity and Liquid limit, Plastic Limit and Plasticity Index.
- The study found no correlation between Cation Exchange Capacity and Shrinkage limit

ACKNOWLEDGEMENTS (optional)

I would like to express my sincere gratitude to my MS Supervisor Prof. Dr. Irfan Jamil for his technical guidance, moral support & continuous motivation throughout this research. I'm much obliged to him for his valuable suggestions in spite of his busy schedule. I also appreciate the assistance provided to me by my colleagues Engr. Asad Jamil & Engr. Samiullah.

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