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Quantification of Clay Minerals and Its Correlation with Chemical and Index Properties of Soil

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ABSTRACT

Clay-mineral composition is one of the factors that determine the physical and engineering behaviours of fine-grained soils; however, it is usually ignored in soil investigations, because the determination of clay-mineral composition necessitates using sophisticated instruments which are time-consuming and require skilled personnel. Many correlations exist for faster prediction of soil engineering properties from its index properties, but correlations for quicker determination of the amount of clay mineral in the soil are still unexplored. This study focuses on determining the amount of clay mineral present in a soil sample rapidly by correlating clay-mineral percentages with soil index and chemical properties, which aids in selecting proper construction guidelines before undertaking construction work. Clay-soil samples collected from 20 different locations in Tamil Nadu state in India were subjected to chemical tests, like cation exchange capacity (CEC), specific surface area (SSA) and total potassium (TP), to quantify clay minerals such as kaolinite, illite and montmorillonite. Correlations were developed for kaolinite, illite and montmorillonite percentages in terms of chemical (CEC, SSA and TP) and index properties. It was observed that the montmorillonite percentage has shown a stronger correlation with soil index properties than illite and kaolinite percentages, because of its physico-chemical behaviour.

KEYWORDS: Correlation, Clay minerals, Quantification, CEC, SSA, Montmorillonite.

INTRODUCTION

Extensive damages occur in clay soils in spite of several soil investigations being undertaken. Soils containing high amounts of clay content possess higher plasticity, compressibility, shrinkage and swell potential and lower shear strength. Soil settlement under a structure takes a long time, due to the presence of higher clay content in the soil. The rate of settlement of clays containing expansive minerals, like montmorillonite, is very slow, but extensive. As a result, not only clay content, but also the type and amount of clay minerals present, influence the physical and engineering behaviours of clay soils.

Two clay soils with the same clay content may have varied soil properties, due to their mineralogical composition (Yukselen and Kaya, 2006b). According to Chittoori et al. (2009), two soil samples with the same plasticity index can have different mineral contents. The same stabilizer cannot effectively treat two soil types with the same plasticity index because of their varied mineralogical compositions. The importance of mineralogical studies in the effective treatment of soils was emphasized and hence the inclusion of clay mineralogy to be incorporated into the present PI-based stabiliser design was suggested (Chittoori et al., 2009). Hawari and Yaseen (2012) studied the origin of clay minerals in the mud flat area and investigated the effect of clay minerals on the basaltic rocks surrounding the area of Al-Azraq in Jordan. Beroya et al. (2009) investigated the influence of clay mineralogy on the cyclic behaviour of silt–clay mixes and found that soil's plasticity index does not accurately reflect the clay

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mineralogy effect on cyclic strength. The physical and chemical properties of individual grains determine the geo-technical properties of fine-grained soils (Santamarina et al., 2002). Clay mineralogy has an important role in the consolidation and permeability behaviors of soil and quantification is required to examine the impact of individual mineral composition on soil behaviour (Jayalekshmi and Elamathi, 2020). Hence, it is necessary to check the percentage of clay minerals contained in the soil sample, which helps in the selection of the appropriate construction standards prior to undertaking a building project.

The proportion of clay minerals in the sub-surface soil is difficult to measure, because assessing the clay mineralogy of soil is complex and time-consuming. Clay minerals can be directly identified and quantified using expensive and sophisticated instruments, such as an X-ray diffractometer, an infrared spectrometer and a scanning electron microscope, requiring skill-oriented personnel for operation. Few researchers had developed an indirect approach to predict the dominant clay mineral using a plasticity chart (Holtz and Kovacs, 1981), activity (Mitchell and Soga, 2005), FSR (Prakash and Sridharan, 2004) and using the liquid-limit cone penetration method (Prakash and Sridharan, 2004). The above-mentioned indirect methods predict the dominant clay mineral, but not the percentage of clay mineral present in the soil. Hence, the current study attempts to correlate the clay-mineral percentages with the chemical and index properties of soil to ease the procedures.

Chitoori and Puppala (2011) proposed simple and inexpensive test procedures to determine the dominating clay minerals and mineralogical proportions from chemical properties of soil, such as cation-exchange capacity (CEC), specific surface area (SSA) and total potassium (TP). This method was an extension of the formulation given by Mitchell and Soga (2005). SSA and CEC are essential soil parameters used in conjunction with clay fraction to characterize the mineralogy of fine-grained soils. The grain-size distribution and clay mineralogy control the surface area of soil; hence, it can be called an "intrinsic" soil component. Montmorillonite, an expansive mineral has SSA ranging from 600 to 810 m^2/g. Kaolinite, a non-expansive mineral, has SSA ranging from 10 to 40 m^2 /g. As a result, the kind of clay mineral present in the soil plays a critical role in defining the impact of specific surface area on soil parameters. A high CEC (80–150 meq/100g) shows the existence of an expansive mineral, such as montmorillonite, while a low CEC (1-6 meq/100g) shows the existence of a non-expansive mineral, such as kaolinite. Potassium is encountered in the interlayer of illite; hence, the TP value (0-6%) indicates the presence of illite mineral.

Researchers (Yukselen and Kaya, 2006b; Smith et al., 1985; Farrar and Coleman, 1967; Yilmaz, 2004) have focused on developing correlations between CEC and index properties. Few studies have presented correlative equations for SSA in terms of index properties (Petersen et al.,1996; Hammel et al., 1983; Yukselen and Kaya, 2006a; Smith et al., 1985). Since CEC and SSA are considered direct indications of the presence of clay minerals, researchers have not focused on correlating the clay mineralogy with soil-index properties. Hence, the present study attempts to correlate clay mineralogy with soil-index properties for predicting the amounts of clay minerals in the soil directly. Based on Chitoori and Puppala (2011) approach, the amounts of stable mineral forms, like kaolinite, illite and montmorillonite, are only quantified in this study. Because highly compressible soil (say W_L>50%) will definitely have montmorillonite mineral in dominance, the soil is considered problematic. Precautions will be taken prior to construction. But the quantification is required for soils with lower W_L containing a mixture of kaolinite, illite and montmorillonite. So, the study considered soil samples containing a mixture of kaolinite, illite and montmorillonite.

The current study examines the test findings of chemical characteristics of soils (CEC, SSA and TP) of twenty natural soils to determine the composition of montmorillonite, kaolinite and illite, as well as the dominant clay mineral present in the soil. The dominant clay mineral determined from the soil chemical properties of the current study is verified with the dominant mineral predicted using the free swell ratio (FSR) approach and X-Ray diffraction. Multiple-regression analysis was conducted between mineral percentages and soil chemical properties and correlations between mineral percentages and chemical variables, such as CEC, SSA and TP were generated. This study also attempts to derive correlations, taking into account the clay mineralogy and index properties.

The correlations developed using chemical and index properties can be used to determine the amounts of clay minerals present in the soil sample without using sophisticated instruments.

Test Materials and Methodology

Clay-soil samples for the study were collected from twenty different locations in the state of Tamil Nadu in India using the test-pit method. The locations of all 20 soil samples collected from various places of Tamil Nadu are shown in Figure 1. Bulk and disturbed samples are taken from test pits dug to depths of 1 to 1.5 meters. Atterberg-limit tests were performed on all the twenty soil samples to determine the index properties of the soil. To calculate the FSR of all the soil samples, free-swell index tests were performed. X-ray diffraction was used to predict the types of clay minerals present in all 20 soil samples as part of the experimental program. The twenty soil samples were also subjected to chemical tests, such as CEC, SSA and TP, which help in the quantification of clay minerals.

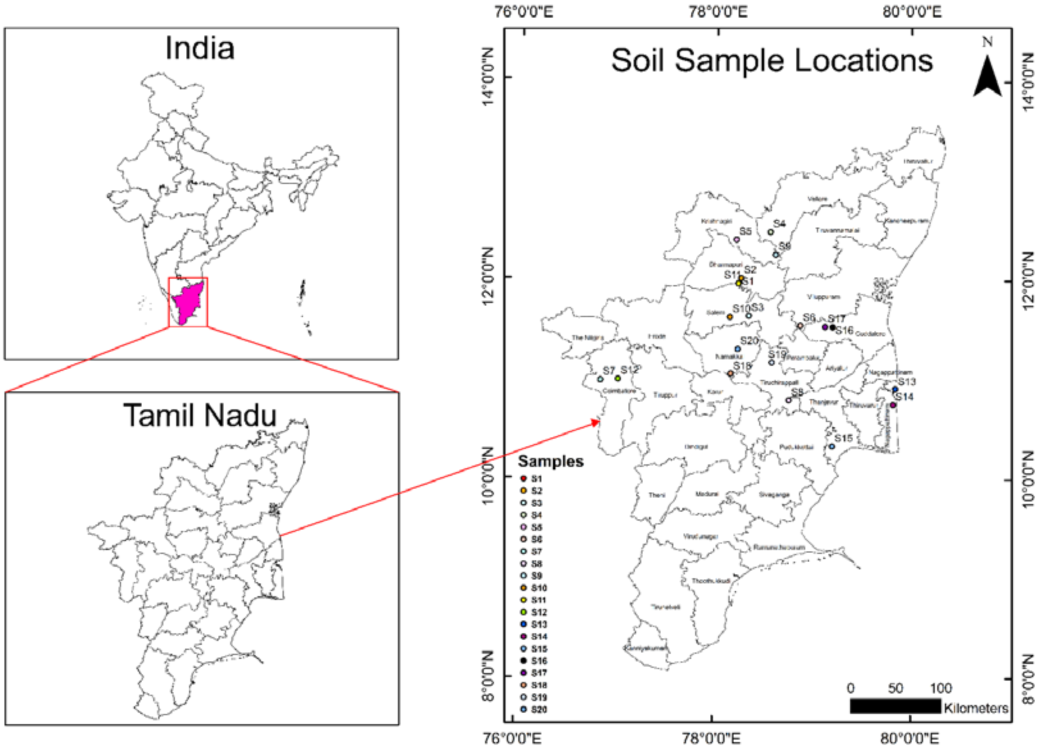

Figure (1): Map showing the locations of the 20 soil samples collected for the current study

Cation-exchange Capacity

Clay minerals carry negative charges at their surfaces which attract cations to neutralize those negative charges (Chapman, 1965; Camberato, 2001). These cations are exchangeable and can be exchanged without affecting the mineral structure. Cation-exchange capacity (CEC) is the amount of exchangeable cations necessary to neutralize negative charges and it is measured in milliequivalent electric charges per 100 gram (meq/100g). The approach described by Chapman (1965) was employed in this investigation, due to its ease of implementation. Air-dried soil sample passing through 2-mm sieve is used for this test. The method involves leaching of soil sample with ammonium acetate (NH_4OAc) several times. Again, the soil is leached with potassium chloride to remove all the adsorbed ammonium (NH_4^+) ions in the soil. The spectrophotometer is used to determine the concentration of NH_4 in the final leachate. CEC of soil is then calculated from the NH_4 concentration value using Eq.1.

$$\mathrm{CEC(meq/100g)} = \frac{\mathrm{NH_4{-}N_{(extract)}}}{18} \tag{1}$$

Specific Surface Area

The specific surface area of a soil sample is the total surface area contained in a unit mass of soil. Soils rich in clay minerals have much greater specific surface areas and soils with a large specific surface area may hold more amounts of water. Various methods for detecting soil SSA were reviewed and concluded that the Ethylene Glycol Monoethyl Ether (EGME) method (Carter et al., 1986) provides the best reliable results and is inexpensive, though time-consuming (Arnepalli et al., 2008; Yukselen and Kaya, 2006a). The EGME approach is simple and can be used on soils having a wide range of minerals with specific surface areas ranging from 15 to 800 m^2/g (Cerato and Lutenegger, 2002). As a result, the EGME approach is utilized to determine SSA. The procedure includes adding EGME to 1.1g of oven-dried soil sample and stirring thoroughly to produce a slurry. The slurry samples were kept in a desiccator, over a desiccant (EGME-$CaCl_2$ solvate). The sample is weighed every two hours until there is no further decrease in weight. The specific surface area is calculated from the weight of EGME retained by the sample, as in Eq. 2.

$$A = \frac{W_a}{W_s * 0.000286}\,\mathrm{m}^2/\mathrm{g} \qquad (2)$$

where, W_a = weight of EGME retained by the sample.

W_s = weight of dried soil sample.

Weight of EGME required to form a mono-molecular layer on a square meter of surface = 0.000286 g/m^2.

Total Potassium

Illite is the only clay mineral in which potassium exists as an interlayer cation. As a result, the presence of illite mineral in the soil is reflected by the amount of potassium ions present. The method of determination of TP (Knudsen et al., 1982) uses the (Jackson, 1958) double-acid (HF-$HClO_4$) digesting process adopted in this study. Perchloric acid ($HClO_4$) decomposes the organic matter in the soil sample, whereas hydrofluoric acid (HF) decomposes the silicate material. Potassium ions are collected from the soil sample after decomposition and their concentration is evaluated using a spectro-photometer. The decomposition is required to keep the potassium ions in the soil sample and avoid interference during spectro-photometric potassium analysis. Using Eq. 3, the total potassium from the potassium concentration value is computed.

$$\mathrm{TP} = \text{Concentration of } \mathrm{K}^{+} \times 0.05 \qquad (3)$$

where, TP = % of total potassium.

K^+ = Potassium ions.

RESULTS AND DISCUSSION

CuKα X-ray Diffractometer with 2θ range of 5° to 80° was used to perform X-ray diffraction studies on all samples collected from the state of Tamil Nadu. Figure 2 shows a typical XRD plot of soil collected for the current study. Xpert HighScore software was used to analyse the XRD results of all the 20 soil samples. It compared the extracted diffractogram with International Center for Diffraction Data (ICDD) and indicated the presence of clay minerals, like kaolinite, illite and montmorillonite and quartz as a non-clay mineral in all the soil samples. CEC, SSA and TP were measured for all the 20 soil samples. All the three chemical tests were repeated three times to check the reliability of the data. The mean of the three trials is taken as the measured value of corresponding chemical properties. The highest standard deviations of CEC, SSA and TP observed in the tested soils are 3.5 meq/100g for soil S18, 5.3 m^2 /g for soil S6 and 0.04 % for soil S19, respectively. These values are small in magnitude compared with original magnitudes of corresponding chemical properties and hence, this indicates that repeatable measurements made the data more reliable. Table 1 provides the results of index properties of soil, like liquid limit W_L, shrinkage limit W_S, plasticity index I_P, shrinkage index I_S, activity Act, clay fraction CF and chemical properties of soil.

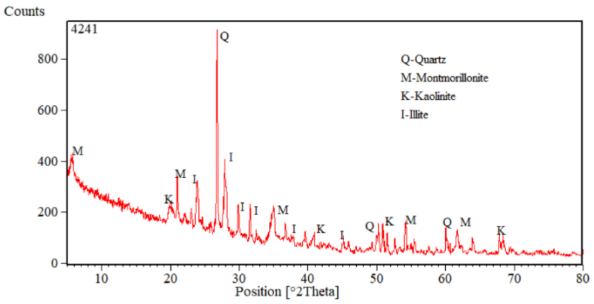

Figure (2): Typical XRD pattern of the soil sample (S3) used in the study

Table 1. Index properties and chemical properties of soil

Sample No.	Index properties						Chemical properties		
	CF	WL	WS	IP	IS	Act	CEC (meq/100g)	SSA (m^2/g)	TP %
S1	32	30	18.5	8.7	11.5	0.27	60.2	196.2	1.86
S2	55	62	13.2	35.8	48.8	0.65	104.4	400	0.66
S3	49	49	13.6	29.8	35.4	0.61	129.9	416.4	1.02
S4	10	25	19.3	3.4	5.7	0.3	39.2	89	1.68
S5	50	61	15.2	33.5	45.8	0.67	100.2	381.3	0.3
S6	64	60	10.1	36.8	50.9	0.58	111.3	432.7	0.42
S7	49	44	16.2	23.2	27.8	0.47	76.3	270.4	1.26
S8	52	46	15.2	22.7	30.8	0.43	81.8	355.1	1.62
S9	53	42	16.6	22.2	25.4	0.42	92.3	315.7	2.34
S10	43	29	16	10.8	13	0.25	80.2	245.4	3.48
S11	51	37	14.5	16.9	22.5	0.33	81.4	239.5	2.58
S12	50	46	14.5	24.3	31.5	0.48	126.6	389.7	1.74
S13	44	40	17.3	16.3	22.7	0.37	71.6	191.2	2.52
S14	28	30	20	6.8	10	0.24	44.8	148.8	1.56
S15	36	32	17.7	12.5	14.3	0.34	62.3	191.6	3.72
S16	50	40	18.3	19.6	21.7	0.39	74.8	243.1	3.3
S17	37	32	18.4	10.7	13.6	0.28	55.6	162.2	2.04
S18	45	50	11.2	28.2	38.8	0.62	122.3	420.1	0.36
S19	59	58	13.3	35.5	44.7	0.60	100.8	378.4	0.84
S20	61	55	17.6	30.7	37.4	0.50	97.5	353.2	1.68

CF-Clay Fraction, W_L- Liquid Limit, W_S- Shrinkage Limit, I_P – Plasticity Index, I_S – Shrinkage Index, Act -Activity, CEC- Cation-exchange Capacity, SSA- Specific Surface Area, TP – Total Potassium.

Quantification of Clay Minerals from Soil Chemical Properties

The measured CEC, SSA and TP values are used to quantify clay minerals: montmorillonite, kaolinite and illite in all the samples by solving the simultaneous equations given by Chittoori and Puppala (2011).

$$\%M\times CEC_M+\%K\times CEC_K+\%I\times CEC_I=CEC_{Soil} \tag{4}$$

$$\%M\times SSA_M+\%K\times SSA_K+\%I\times SSA_I=SSA_{Soil} \tag{5}$$

$$\%M\times TP_M+\%K\times TP_K+\%I\times TP_I=TP_{Soil} \tag{6}$$

where %M, %K and %I denote the percentages of the minerals: montmorillonite, kaolinite and illite present in the soil sample, respectively. CEC, SSA and TP with subscripts M, K and I in the equations indicate CEC, SSA and TP values of pure montmorillonite, kaolinite and illite, as given in Table 2. CEC_{soil}, SSA_{soil} and TP_{soil} are the values of the chemical properties CEC, SSA and TP of the soil sample, respectively.

Solver function of Microsoft Excel program was used to solve these simultaneous equations (Chitoori and Puppala, 2011). This tool makes use of the "what-if" analysis function, which enables finding the best result for a formula used in one cell, known as the target cell, by changing the values in another cell, known as the changing cell. The detailed procedure was given by (Chitoori and Puppala, 2011) and Chitoori (2008). Table 3 provides the percentages of montmorillonite, kaolinite and illite quantified from chemical properties. The main limitation of the study is that this approach could only predict three stable types of clay minerals; however, soil may also contain other types of clay minerals and non-clay minerals that were not considered in this study, because montmorillonite, kaolinite and illite have more impact on the volume-change behaviour of soil than the other types of clay minerals.

Dominant Clay Mineral Prediction from Chemical Properties of Soil, FSR and XRD

Prakash and Sridharan (2004) classified soils based on the FSR method and predicted the dominant clay mineral in the fine-grained soil as kaolinitic (non-expanding type) and montmorillonittic (expanding type) in the soil using FSR (FSR = V_d/V_k), where the volume of soil in the graduated cylinder containing distilled water is V_d and the volume of soil specimen in the graduated cylinder containing kerosene is V_k, as given in Table 4. The dominating clay mineral determined from chemical properties of soil is compared with the dominating clay mineral found using FSR and XRD methods and the findings are shown in Table 5.

Table 2. Range of values for CEC, SSA and TP of pure minerals (Mitchell and Soga, 2005)

Mineral Type	CEC (meq/100 g)	SSA (m^2/g)	TP (%)
Kaolinite	1–6	5–55	0
Illite	15–50	80–120	6
Montmorillonite	80–150	600–800	0

CEC- Cation Exchange Capacity, SSA- Specific Surface Area, TP – Total Potassium.

Table 3. Percentage of clay minerals quantified from the chemical properties of soil

Sample No.	%K	% I	%M
S1	41	31	28
S2	24	11	65
S3	13	17	70
S4	61	28	11
S5	32	5	63
S6	22	7	71
S7	37	21	42
S8	20	27	53
S9	14	39	47
S10	9	58	33
S11	22	43	35
S12	7	29	64
S13	31	42	27
S14	53	26	21
S15	15	62	23
S16	12	55	33
S17	43	34	23
S18	23	6	71
S19	25	14	61
S20	17	28	55

%K- Kaolinite percentage, %I – Illite percentage, %M -Montmorillonite percentage.

Table 4. Prediction of dominant clay mineral based on FSR.
(Prakash and Sridharan, 2004)

Free-swell ratio	Clay type	Dominant clay-mineral type
≤1.0	Nonswelling	Kaolinitic
1.0-1.5	Mixture of swelling and non-swelling	Kaolinitic and Montmorillonitic
1.5–2.0	Swelling	Montmorillonitic
2.0–4.0	Swelling	Montmorillonitic
>4.0	Swelling	Montmorillonitic

Table 5. Comparison of dominant clay minerals predicted from chemical properties, XRD and FSR

Sample No.	FSR	Dominant clay mineral identified using		
		FSR	XRD	Chemical properties
S1	1.2	Kaolinite, Montmorillonite	Kaolinite, Illite	Kaolinite
S2	1.9	Montmorillonite	Montmorillonite	Montmorillonite
S3	2.0	Montmorillonite	Montmorillonite	Montmorillonite
S4	1.1	Kaolinite, Montmorillonite	Kaolinite	Kaolinite
S5	2.2	Montmorillonite	Montmorillonite	Montmorillonite
S6	2.0	Montmorillonite	Montmorillonite	Montmorillonite
S7	1.6	Montmorillonite	Montmorillonite,	Montmorillonite
S8	1.6	Montmorillonite	Montmorillonite	Montmorillonite
S9	1.6	Montmorillonite	Montmorillonite	Montmorillonite
S10	1.3	Kaolinite, Montmorillonite	Illite	Illite
S11	1.5	Kaolinite, Montmorillonite	Illite, Montmorillonite	Illite
S12	1.9	Montmorillonite	Montmorillonite	Montmorillonite
S13	1.5	Kaolinite, Montmorillonite	Illite	Illite
S14	1.1	Kaolinite, Montmorillonite	Kaolinite	Kaolinite
S15	1.2	Kaolinite, Montmorillonite	Illite	Illite
S16	1.4	Kaolinite, Montmorillonite	Illite	Illite
S17	1.4	Kaolinite, Montmorillonite	Kaolinite	Kaolinite
S18	2.3	Montmorillonite	Montmorillonite	Montmorillonite
S19	2.0	Montmorillonite	Montmorillonite	Montmorillonite
S20	1.9	Montmorillonite	Montmorillonite	Montmorillonite

FSR-Free-swell ratio, XRD- X-ray diffractogram.

Prakash and Sridharan (2004) and Prakash et al. (2009) predicted the dominant clay mineral of soils as kaolinite or montmorillonite or a mixture of kaolinite and montmorillonite using the FSR method, as given in Table 4, but the method has not considered illite mineral. However, illite is also a dominating mineral for some soil samples in the current study, as shown in Table 5. The predicted dominant clay mineral from the FSR method matches well with the results from XRD and chemical properties, except for the illite-dominated soils (S10, S11, S13, S15, S16). As a result, the FSR approach is used only to qualitatively predict the clay mineral as kaolinite or montmorillonite, but not quantitatively and more studies can be carried out on illite-dominated samples as well.

Relationship between Clay Mineralogy and Soil Chemical Properties

Multiple linear-regression analysis was performed between the mineral percentages and soil chemical properties to derive correlations. Table 6 provides the correlation for predicting the amounts of montmorillonite, kaolinite and illite in terms of chemical properties CEC, SSA and TP as single and multiple parameters. If CEC, SSA and TP are known for a soil, the regression equations can be used for predicting the proportions of kaolinite, illite and montmorillonite in a soil. Correlations with R^2 value greater than 0.8 are only considered in Table 6.

Table 6. Correlations for % kaoinite (%K), % illite (%I) and % montmorillonite (%M), using CEC, SSA and TP as single and multiple parameters

Parameters	Correlation	R^2-value
%K = f (SSA, TP)	$\%K = -0.16 \times SSA - 14.4 \times TP + 100.6$	0.99
%K = f (CEC, SSA, TP)	$\%K = -0.135 \times CEC - 0.135 \times SSA - 14.5 \times TP + 101.5$	0.96
%I = f (TP)	$\%I = 16.67 \times TP$	1
%I = f (SSA, TP)	$\%I = 3.15E^{-17} \times SSA + 16.67 \times TP - 1.1E^{-14}$	1
%I = f (CEC, TP)	$\%I = -6.4E^{-17} \times CEC + 16.67 \times TP - 5.6E^{-15}$	1
%I = f (CEC, SSA, TP)	$\%I = -5.8E^{-16} \times CEC + 3.15E^{-17} \times SSA + 16.67 \times TP - 1.1E^{-14}$	1
%M = f (CEC)	$\%M = 0.703 \times CEC - 15.48$	0.89
%M = f (SSA)	$\%M = 0.18 \times SSA - 8.32$	0.98
%M= f (CEC, SSA)	$\%M = 0.058 \times CEC + 0.169 \times SSA - 9.5$	0.98
%M = f (SSA, TP)	$\%K = 0.169 \times SSA - 2.22 \times TP - 0.59$	0.99
%M= f (CEC, TP)	$\%M = -0.59 \times CEC - 5.33 \times TP + 2.89$	0.95
%M = f (CEC, SSA, TP)	$\%M = 0.135 \times CEC + 0.135 \times SSA - 2.66 \times TP - 1.48$	0.98

CEC- Cation-exchange Capacity, SSA- Specific Surface Area, TP – Total Potassium, %K- Kaolinite percentage, %I – Illite percentage, %M -Montmorillonite percentage.

The proportion of montmorillonite correlates better with SSA (R^2 =0.98) than with CEC (R^2 = 0.89). R^2 value for percent illite predicted is 1.0, since it is directly obtained by dividing the TP value from the chemical test by the TP value for pure Illite, which is six. It has been found that SSA has a greater impact on montmorillonite mineral than CEC. This could be due to water adsorption and desorption, which are dependent on surface area (Ross, 1978). Soils with high specific surface areas can have high water holding capacities (Carter et al., 1986). Cerato and Lutenegger (2002) reported that the type of clay mineral present in the soil had a greater impact on SSA.

Relationship between Clay-mineral Content and Soil-index Properties

Correlations between mineral percentage and index properties to study the relationship between montmorillonite content and index properties are given in Table 7, aiming at determining the amount of montmorillonite present in the soil quickly. It was observed that when the liquid limit, shrinkage index, activity and clay content increase, the quantity of montmorillonite in the soil increases, but the amount of montmorillonite in the soil decreases as the shrinkage limit increases. The diffused double-layer mechanism of montmorillonite determines the liquid limit of the soil (Sridharan and Prakash, 2000). Similarly, there is a significant relationship between montmorillonite % and liquid limit (R^2=0.8). The concentration of smectite is a determining factor of activity (Ohtsubo et al., 2000). The proportion of montmorillonite and activity had a strong correlation (R^2=0.82) in this research. There is no correlation between CF and CEC, since CEC is influenced more by the type of clay than by its quantity (Yukselen and Kaya, 2006b). Clay content is responsible for only a small portion of the variation in CEC (Manrique et al., 1991). The current study found a lower R^2 value of 0.58 between montmorillonite content and clay fraction, indicating that the percentage of montmorillonite in soil cannot be determined by the quantity of clay fraction in it. The SSA and free-swell index (FSI) were shown to have a strong correlation, indicating that SSA is more dependent on shrink-swell potential than on clay content (Ross, 1978). In the current study, it was found that FSR has a good association with R^2 = 0.87. As a result, the swelling behaviour of soil cannot be predicted only by its clay content, which is decided entirely by its mineralogical composition. The amount of water adsorbed and desorbed from soil surfaces governs the shrinkage limit. It is evident from Table 7 that the shrinkage limit and shrinkage index vary linearly with montmorillonite percentage with higher R^2-values.

Table 7. Correlations for montmorillonite percentage (%M) in terms of index properties

S.No.	Correlations	R^2-value
1	$\%\mathrm{M} = 1.486\mathrm{W_L} - 19.705$	0.8
2	$\%\mathrm{M} = 1.726\mathrm{sI_p} + 7.868$	0.86
3	$\%\mathrm{M} = -5.899W_s + 137.92$	0.72
4	$\%\mathrm{M} = 1.298\mathrm{I_s} + 8.94$	0.85
5	$\%\mathrm{M} = 123.97\mathrm{ACT} - 10.37$	0.82
6	$\%\mathrm{M} = 50.07\ \mathrm{FSR} - 36.83$	0.87
7	$\%\mathrm{M} = 1.1861\ \mathrm{CF} - 36.83$	0.58

%M -Montmorillonite percentage, W_L- Liquid Limit, I_P – Plasticity Index, W_S- Shrinkage Limit, I_S – Shrinkage Index, Act -Activity, FSR- Free-swell Ratio, CF-Clay Fraction.

It was observed that an increase in the montmorillonite content increases liquid limit, plasticity index, shrinkage index, activity, free-swell ratio and clay fraction and decreases shrinkage limit, showing that the percentage of montmorillonite has a greater impact on the engineering behaviour of the soil. Montmorillonite has a better correlation with index properties due to its physico-chemical behaviour. Table 7 provides the correlations for montmorillonite percentage in terms of index properties. These correlations can be used for natural-clay soil samples containing kaolinite, illite and montmorillonite with W_L less than 62%.

Illite and kaolinite have shown similar behaviour, but opposite to montmorillonite. This might be due to the mechanical behaviour of kaolinite and illite and the physio-chemical behaviour of montmorillonite, influencing the index properties. Soils dominated by kaolinite and illite showed similar consolidation and swelling behaviour (Tiwari and Ajmera, 2011). It can be seen from Table 8 that when illite percentage is correlated with index properties, the lowest R^2 value of 0.49 is found with liquid limit and the highest R^2 value of 0.58 is found with activity, whereas kaolinite percentage has the lowest R^2 value of 0.09 with activity and the highest R^2 value of 0.17 with shrinkage index.

Table 8. R^2-values for kaolinite and illite for various soil index properties

S.No.	Parameter	R^2-value	
		Illite	Kaolinite
1	Liquid limit W_L	0.51	0.14
2	Shrinkage limit W_S	0.42	0.24
3	Plasticity index I_P	0.35	0.23
4	shrinkage index I_S	0.54	0.17
5	Activity Act	0.61	0.13
6	Clay fraction CF	0.5	0.11
7	Free-swell ratio	0.53	0.15

Table 8 shows that kaolinite has a much lower correlation with soil-index properties than illite and it is clear that kaolinite has no significant relationship with soil-index properties. As a result, the quantity of kaolinite in a soil sample cannot be determined using index properties. Illite, on the other hand, shows a moderate correlation compared to kaolinite. It is inferred that illite has a greater impact on soil-index properties compared to kaolinite. A strong relation exists between illite and mechanical properties, whereas kaolinite remains neutral (Supandi et al., 2019). Mechanical properties of the soil are increased with decrease in illite content and a lower amount of illite content contributed to a lower settlement of soil and a high factor of safety (Supandi et al., 2019). More research should be carried out to see how the percentage of illite affects the geo-technical behaviour of soil.

Mechanical factors (short-range particle interaction) govern the behaviour of minerals including kaolinite, illite and powdered quartz, whereas physico-chemical factors control the behaviour of montmorillonite (diffused double-layer mechanism) (Robinson and Allam, 1998). It is observed that the proportion of montmorillonite, a physico-chemical component, has an impact on the soil-index properties, but not kaolinite or illite, which are influenced by mechanical factors. As a result, it is inferred that soil-index properties are physico-chemical properties and not physical properties. Sridharan (2002) studied the impact of clay mineralogy on the physical and engineering behaviours of clays and brought out that the physical and engineering behaviours of kaolinite and montmorillonite clays are different.

Because of the physico-chemical behaviour of montmorillonite, index properties of soil can be used to estimate the exact percentage of montmorillonite in the soil better than illite and kaolinite. It is well known that a larger proportion of montmorillonite has a stronger influence on the engineering behaviour of soil. As a result, this study recommends utilizing the index properties to determine the montmorillonite composition of soil before undertaking any construction activities on clay soil, which aids in selecting suitable construction guidelines.

CONCLUSIONS

The engineering behaviour of clay-containing soil depends on the mineralogical composition present in the soil. To identify the type and amount of minerals present in the soil, quantification is necessary. But, clay minerals are quantified using expensive instruments, like X-Ray diffractometer, infrared spectroscope and scanning electron microscope. Since chemical properties, like CEC and SSA, give direct indication of clay minerals present in the soil, CEC, SSA and TP were used for quantification following Chitoori and Puppala (2011). Since potassium is an interlayer cation in the illite mineral, the amount of illite is determined directly from the total potassium in the soil. Chemical properties of soil were used to determine the amount of stable clay minerals, such as kaolinite, illite and montmorillonite, present in the soil. Some of the study's significant conclusions are as follows:

1. Dominant mineral present in the soil found from soil chemical properties matches well with XRD method and FSR approach. FSR can be preferred over XRD, since it is the simplest way of determining dominant minerals. However, chemical properties can be preferred over XRD for the quantification of clay minerals.
2. Correlations were developed for clay-mineral percentages in terms of CEC, SSA and TP as single

and multiple parameters using multiple linear-regression analysis and these correlations can be used for direct determination of the amounts of kaolinite, illite and montmorillonite present in the soil sample. The percentage of montmorillonite has a greater correlation with SSA (R^2 =0.98) than with CEC (R^2 = 0.89).

3. Montmorillonite has a stronger relationship with index properties than illite and kaolinite, because of its physico-chemical behaviour (diffused double-layer mechanism). Since the amount of montmorillonite present in the soil determines the expansiveness of the soil, it can be predicted directly from the correlative equations.
4. Correlation between clay fraction and montmorillonite has given a lower R^2 value of 0.58 compared to other index properties ($R^2 > 0.7$), because clay fraction based on the size of the soil is less than 2 µ. Clay soil may contain different clay minerals. The physico-chemical behaviour, which is based on the type of clay mineral, influences the index properties. Since montmorillonite exhibits higher physio-chemical behavior, it has given a higher correlation for index properties compared to clay fraction.
5. There is no significant relationship between index properties and kaolinite or illite. Illite, on the other hand, has a notable correlation than kaolinite. Hence, more research should be carried out to check the effects of the proportion of illite on the index and engineering properties of soil.
6. As a result, it can be concluded that the index properties of soil are controlled by the amount of montmorillonite (physico-chemical behaviour), but not by kaolinite and illite (mechanical behaviour). It has been inferred that the index properties of fine-grained soil are physico-chemical properties rather than physical properties.

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