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ORIGINAL PAPER

Influence of Clay Content and Montmorillonite Content on Swelling Behavior of Expansive Soils

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Abstract
Swelling behavior of an expansive soil is principally governed by the contents of montmorillonite mineral and clay present in it. Studies attributing the swelling behavior to the presence of montmorillonite mineral are numerous, but defining an intricate relationship between clay and montmorillonite contents is almost nil. Thus, a comprehensive study is undertaken in this technical note that can aid in quantifying the exact influence of clay content (CC) and/or montmorillonite content in clay content (MC_{CC}) on the swelling behavior. Interrelating CC and MC_{CC} parameters is also another objective of the paper. Several numbers of different expansive soils were collected from different regions of India and experiments were conducted to quantify free swell index (FSI), CC, and MC_{CC}. The results demonstrate that it is not only CC, but also MC_{CC} has a remarkable influence on the swelling behavior. It has, particularly, been noticed from the interpretation of results that the role of mixed clay minerals, which is contrasting to a common belief that it is only MC_{CC} primarily contributes to the swelling phenomenon and is least attempted by research fraternity, cannot be subdued. The study finds that between MC_{CC} and CC, the former parameter seems to be more reliable for accurate prediction of swelling potential. The relationship between CC and MC_{CC} seems to be linear up to MC_{CC} of 40%. Beyond MC_{CC} of 40%, CC apparently clustered between 30 and 60% only. MC_{CC}, even though, found in minor quantity, exhibited significant influence on the FSI. The results presented in the study bear a practical significance for the safe design of foundation systems, buried pipelines, etc., in/on the expansive soils.

Keywords Expansive soils · Clay content · Montmorillonite content · Free swell index

Introduction

Clay soils, in general, are dominant with three major minerals: illite (mica), kaolinite (Kaolin) and montmorillonite (smectite), besides other mineral types. The swelling potential varies from soil to soil, however, depending upon its mineralogical compositions. But measurement of percent content of influential mineral, which would cause swelling phenomenon, is fundamentally more important than a mere identification of mineralogical compositions. In the case of soils prevalent with montmorillonite mineral, swelling is possible due to the formation of diffuse double layer and flocculation [1]. Mineralogical characteristics such as MC_{CC}, cation exchange capacity, specific surface area, etc., are the elemental properties that control the mechanical behavior of expansive soils [2]. Studies of Mehta and Sachan [2], Pandya and Sachan [3], Abdullah et al. [4], and Chittoori et al. [5] asserted that the expansive phenomenon was due to the presence of MC_{CC}. In a rudimentary way, Prakash and Sridharan [6] have stated that the swelling phenomenon is influenced by the clay minerals present in fine-grained soils. Further, Mehta and Sachan [2] reported that FSI has a linear relationship with water retention capacity, which is controlled by the quantity of mineral (e.g., montmorillonite). The above statements explicitly demonstrate that MC_{CC} has a significant influence on water retention capacity and thus, on the swelling behavior. In realization to the studies reported in the literature, it can be conferred that it is the montmorillonite mineral that is having a definite influence

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on the swelling behavior of expansive soils as compared to other minerals.

FSI, often referred to as free swell or differential free swell, is a simple method for identifying the swelling potential of expansive soils [7]. Studies by Skempton [8], Van Der Merwe [9], Mitchell [10], and Holtz and Kovacs [11] suggested that the swelling potential can be predicted indirectly from plasticity, clay size fraction and activity parameters. Conventional consolidation tests can also be used to measure the swelling potential of soils [12]. However, resorting to the consolidation tests is time consuming.

It is worth mentioning here the study by Prakash and Sridharan [6], who stated that it is difficult from the free swell ratio alone to decide the dominant clay mineral present in a soil. This is attributed to the fact that the diffuse double-layer repulsion effect due to the montmorillonite mineral may be balanced by the flocculation effect due to kaolinite mineral. It can be concluded from the literature that knowledge of clay mineralogy is very essential in investigating the swelling behavior of expansive soils. Mitchell and Soga [13] have stated that the type of clay minerals and phases present in a soil can be determined using X-ray diffraction (XRD), differential thermal analysis (DTA) and scanning electron microscope (SEM) techniques. Highly sophisticated in nature, non-availability of the facility and relatively complicacy involved in handling, most of the earlier researchers restrained to use these techniques, which has drawn the attention of the present study. Moreover, limited studies are available in the literature, which deal with the quantification of clay minerals and understanding their influence on the swelling behavior.

In the present study, an attempt is made to quantify the CC and MC_{CC} of soils collected from diverse regions across India, and their influence on swelling potential is investigated. Focus further was also made to relate CC with MC_{CC}, which can greatly aid in understanding the relative effect of these parameters on swelling behavior. The kind of information provided in this technical note is unique that it is essentially useful for all practical problems when dealing with the construction of important structures such as lightweight single storey buildings, pavements, retaining walls, etc., on/in the expansive soils. For all the practical scenarios, it is indispensable to have in-depth knowledge on expansive soils behavior linked with constituent CC and MC_{CC} to avoid/arrest the volume change-induced structural failure.

Materials

Approximately, 46 different expansive soils from different locations across India were collected for the study purpose. Sampling and sample collection were done as per the guidelines of ASTM D4700-15 [14]. Each soil sample was grabbed from a depth of 0.5 m below the natural ground level to avoid the collection of unwanted materials like roots and debris. The samples were brought to the laboratory in a disturbed state and all necessary experimentation is carried out after processing them. In the laboratory, samples were first oven dried at 105 °C for 24 h [15], pulverized, and used for conducting grain size distribution and Atterberg's limit tests in accordance with the respective ASTM standards [16, 17]. Figure 1 presents the gradation curves of expansive soils belonging to different regions of the country. CC, percent fraction below 2 μm, in each soil is determined from the respective gradation curve. Table 1 summarizes the percent fractions, consistency limit values and classification done as per the Unified Soil Classification System (USCS), along with their respective IDs. From the plasticity chart as depicted in Fig. 2, it can be observed that all soils lie between A-line and U-line.

Free Swell Index Tests

These tests were conducted following the guidelines provided by IS (Indian Standard): 2720 Part XL [18], which mainly suggests monitoring the difference in volume of a soil when placed in two dissimilar liquids: water (dipolar liquid) and kerosene (non-polar liquid). 10 g of soil sample passing 425 μm and oven dried was used for testing purpose. Test begins by pouring 10 g of dry specimen into each 100-ml cylinder, filled one with water and kerosene of another. The contents were then stirred to ensure that particles are evenly spread within the solutions. The cylinders at perturbed condition were left on a flat surface to allow the particles to settle under self-weight. Monitoring of sediment height was continued until the sediment deposited at the bottom of the glass cylinder is noticed unchanged. For measuring the height of the sediment, cylinders were graduated along its height. After 24 h of stationary and undisturbed condition, the change in height of sediment in each cylinder was recorded. Multiplying the height with the cross-sectional area of a cylinder gives the volume of the soil in water, V_w, and in kerosene, V_k. The *FSI* can be computed using Eq. (1).

$$\mathrm{FSI} = \frac{V_w - V_k}{V_k} \times 100, \quad (1)$$

where, V_w is the volume of the soil in water, and V_k is the volume of soil in kerosene

Mineralogical Characteristics

The mineralogical compositions of soils used in the study were established with the help of D8 Advanced X-ray powder diffraction device (make, BRUKER, USA). Around

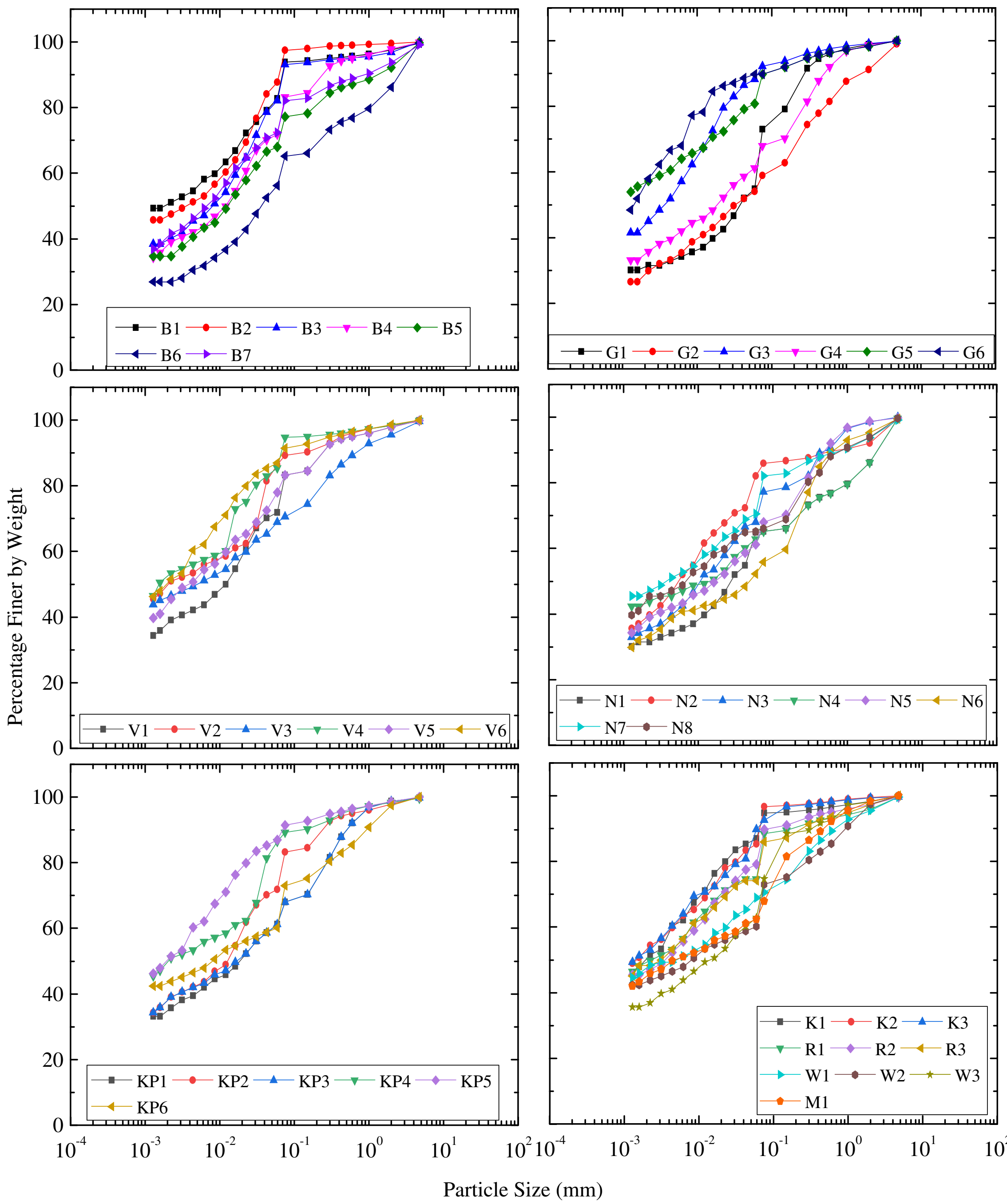

Fig. 1 Grain size distribution curves of soil samples collected from different regions across India

2–3 g of oven-dry soil passing sieve size of 75 µm was used for the analysis. The sample preparation involves uniformly spreading powder on the sample holder and then mounting it on a resting platform. The test samples are scanned for reflections with a voltage and current of 40 kV and 40 mA, respectively, 2θ ranging from 5° to 80° at a step size of 0.025° and with a time interval 0.5 s for each step using a copper X-ray tube (i.e., Cu-Kα radiation). The presence of different minerals in each soil was identified with the help of DIFFRAC.SUITE EVA software. The software does an automatic search on raw data, which has been background subtracted automatically, and on the peak, list to identify the most appropriate mineral phase.

Attempts were also made to determine the MC_{CC} in each soil with the help of TOPAS 4.2 software. As such, quantitative clay mineralogy by most of the XRD techniques requires mineral standards with XRD properties similar to those of the mineral phases in unknown samples [19]. For

Table 1 Physical properties of soil samples used in the study

State/region	Sample ID	% Fraction				Consistency limits (%)					G	MC_{CC} (%)	FSI (%)	USCS
		Gravel (> 4.75 mm)	Sand (4.75 mm –75 μm)	Silt (75 μm–2 μm)	Clay (< 2 μm)	w_L	w_P	w_{PI}	w_{SL}	w_{SI}				
Bhopal	B1	–	6	43	51	68	27.52	40.48	8.5	59.5	2.57	69.83	73	CH
	B2	–	6	50	44	57.5	23.54	33.96	10.1	47.4	2.59	67.56	55	
	B3	–	3	51	46	62	27	35	10.56	51.44	2.64	26.65	73	
	B4	–	7	53	40	63.9	21.42	42.48	13	50.9	2.56	59.31	73	
	B5	–	17	44	39	43	19.25	23.75	11.78	31.22	2.56	15.54	50	CL
	B6	1	23	43	33	48	18.52	29.48	12	36	2.62	48.19	60	
	B7	1	21	42	36	46	16.9	29.1	12.3	33.7	2.64	32.18	52	
	B8	1	17	40	42	50.8	23.5	27.3	9.98	40.82	2.67	32.18	50	
Guntur	G1	–	11	31	58	93	36	57	8.85	110.15	2.62	32.87	80	CH
	G2	–	26	37	37	78	25.78	52.22	9.2	68.8	2.64	35.39	58	
	G3	1	40	29	30	43	19.35	23.65	10.43	34.57	2.73	23	48	CL
	G4	–	8	47	45	68	24	44	11.56	56.44	2.53	45.05	60	CH
	G5	–	32	32	36	44.83	21.23	23.6	9.56	35.27	2.52	11	50	CL
	G7	–	10	33	57	80	29.53	50.47	9.78	65.22	2.7	51	62	CH
	G8	–	13	28	59	88	27.63	60.37	10.67	105.33	2.56	69.05	73	
Kakinada	K1	–	5	46	49	82	31	51	12	70	2.54	53.29	66	CH
	K2	–	3	42	55	73.6	29.78	43.82	8.85	64.75	2.65	29.94	79	
	K3	–	4	40	56	70.2	27.65	42.55	10.45	59.75	2.62	61.07	67	
Nagpur	N1	2	14	43	41	61	21.92	39.08	10.62	47.38	2.68	77.05	64	CH
	N2	4	16	38	42	58	23	35	8.9	49.1	2.8	56.34	84	
	N3	3	26	38	33	48	20.85	27.15	9.5	38.5	2.53	58.57	55	CL
	N4	1	22	30	53	57.7	22.52	35.18	12.86	44.84	2.59	77.2	90	CH
	N5	3	19	29	51	69	24.68	44.32	10.12	58.88	2.62	52.36	82	
	N6	2	21	28	49	61.9	29.76	32.14	11.89	50	2.58	54.58	105	
	N7	1	14	32	53	74	27.24	46.76	11.35	62.65	2.67	47.54	90	
	N8	3	13	30	54	66	27.16	38.84	10.45	55.55	2.58	32.18	73	
Raipur	R1	1	15	39	45	76.7	25.39	51.31	9.89	46.81	2.7	68.97	80	CH
	R2	–	10	43	47	62	23	39	10.25	41.75	2.62	74.57	56	
	R3	–	14	38	48	57	25.54	31.56	11.75	58.25	2.6	57	64	

Table 1 (continued)

State/region	Sample ID	% Fraction				Consistency limits (%)					G	MC_{CC} (%)	FSI (%)	USCS
		Gravel (> 4.75 mm)	Sand (4.75 mm –75 μm)	Silt (75 μm–2 μm)	Clay (< 2 μm)	w_L	w_P	w_{PI}	w_{SL}	w_{SI}				
Vijayawada	V1	–	12	33	55	92	34.32	57.68	8.65	83.35	2.69	79.95	40	CH
	V2	2	18	35	45	43	22	21	13.23	29.77	2.74	32.18	78	CL
	V3	2	20	32	46	46	17.7	28.3	10.58	35.42	2.66	0.27	68	
	V4	3	22	33	42	46.1	18.93	27.15	11.85	34.25	2.62	46.06	50	
	V5	1	17	39	43	52	15.54	36.46	10.12	41.88	2.58	27.37	64	CH
	V6	–	9	40	47	82.8	26.43	56.37	9.38	73.42	2.59	78.55	70	
	V7	–	11	39	50	79.8	26.20	53.6	9.1	70.7	2.67	61.6	60	
Warangal	W1	2	26	30	42	70	26	44	15.32	54.68	2.58	79	79	CH
	W2	–	27	29	44	51.5	23.27	28.23	11.89	39.61	2.62	57	67	
	W3	1	43	28	28	53.45	22.89	30.56	12.12	41.33	2.58	68	95	
Mysore	M1	–	21	26	53	72	28.35	43.65	8.97	63.03	2.57	54.08	73	CH
Kendrapara	KP1	4	15	38	43	60	28.25	31.71	9.85	60.15	2.6	28.36	36	CH
	KP2	3	17	33	47	53	29.54	33.46	10.2	62.8	2.59	20.64	33	
	KP3	2	18	29	51	70	32	38	8.97	61.03	2.65	40.53	63	
	KP4	3	21	31	45	42.5	19.5	23.5	9.53	62.97	2.62	28.35	50	
	KP5	4	20	29	47	51	23.73	27.73	11.2	59.8	2.57	28.67	38	
	KP6	2	19	35	44	68	22.87	47.81	10.35	57.65	2.55	28.64	64	

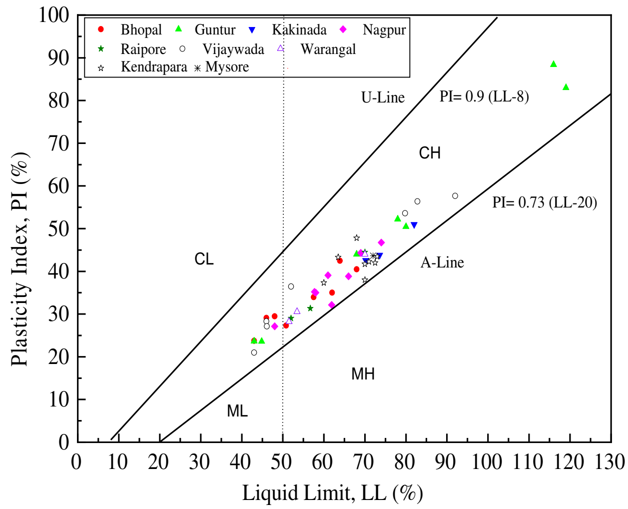

Fig. 2 Plasticity chart classifying the expansive soils used in the study

this purpose, Inorganic Crystal Structure Database (ICSD) reference patterns were used to match the measured patterns. TOPAS 4.2 is graphics-based profile analysis program; it integrates various types of X-ray and neutron diffraction analyses by supporting all profile fit methods currently employed in powder diffractometry. The software applies the Rietveld technique to compute the mineral compositions quantitative analysis of different phases (e.g., montmorillonite mineral in the present study) in a soil mass. Quantitative phase analysis relies on the estimation of full powder pattern from the crystal structure database, and hence, it does not need calibration curves.

Montmorillonite Content in Clay Content (MC_{CC})

Many researchers have reported that the failure of structures built on expansive soil is due to the presence of montmorillonite mineral and its quantity [20]. Among different minerals, montmorillonite is the primary mineral responsible for the swelling behavior. This is dominant in shale and residual soils derived from volcanic ash [21]. Generally, the quantity of montmorillonite mineral content is more in bentonite than in natural soils.

Many researchers report that MC_{CC}, in natural soils [2–5, 22, 23] and bentonite [24–26], can be determined by a variety of techniques (Table 2). As such, Mehta and Sachan [2] have illustrated that the rate of swelling depends on the quantity of MC_{CC} present in a soil. Incidentally, most of the works remain confined to the quantification of montmorillonite, only, but failed to relate it to geotechnical properties of soils. It is also evident from Table 2 that the researchers have considered a small number of soil samples and mostly restricted for a particular location. Because of narrow data range and conservatism, a specific effort is not devoted to propose a relationship between MC_{CC} and swelling property of expansive soils. It is also a known fact that the gradation and mineralogy vary with the origin of the soils [22]. It can also be noticed from the literature survey that there is no concrete study defining the exact quantity at which the influence of MC_{CC} is more. The MC_{CC} in the present study refers to the quantity of montmorillonite present in the clay fraction only.

Results and Discussion

A series of grain size distribution, *FSI*, and XRD tests were conducted on 46 different soil samples (8 each from Bhopal and Nagpur, 7 each from Vijayawada and Guntur, 3 each from Raipur, Warangal, and Kakinada, 1 from Mysore, and 6 from Kendrapara) collected from multiple locations across the country. Table 1 presents the values of consistency limits (viz., liquid limit, w_L, plastic limit, w_P, plasticity index, w_{PI}, shrinkage limit, w_{SL}, and shrinkage index, w_{SI}), MC_{CC}, FSI, and CC of these samples with their respective IDs. It is seen that the majority of the soils fall under the category of 'Inorganic clays of high plasticity (CH)', while a few classified under 'Inorganic clays of low plasticity (CL)'. It is also seen that, except for a few samples, almost all samples exhibited a significantly high to very high value of w_L (43–93%) and shrinkage index, w_{SI} (31.22–110.15%). This is in conformation with the classification scheme proposed by Chen [27] for w_L (high 40–60% and very high > 60%) and IS 1498 [28] for w_{SI} (high 30–60% and very high > 60%). The very high values of shrinkage index indicate that these soils may experience unpredictable volume change behavior. As such, the measured large values of w_L and w_{SI} may be linked to the presence of MC_{CC}, which has an inherent characteristic of retaining a substantial amount of water upon wetting [29].

It can be observed from the results in Table 1 that the CC varies from 28 to 59%, illustrating its dominance. Chen [30] and Holtz and Gibbs [7] have reported that the soils possessing large CC are generally prone to exhibit swelling behavior. Similarly, a study by Reddy et al. [31] have illustrated that swelling characteristics of expansive soils are influenced by the particle mean diameter (i.e., clay fraction). As such, the results presented in Table 1 well corroborate with the literature statements. For a better understanding on the influence of CC on swelling behavior, a plot between these parameters is developed as depicted in Fig. 3. Further, similar data from the literature were assimilated and superimposed on Fig. 3. A perfect fit of present data with literature data evidently validates the results obtained by the present study. It can be seen from Fig. 3 that as the CC increases, so is the FSI. As such, the relationship between CC and FSI appears to be linear in nature. However, due to

Table 2 The value of montmorillonite content, free swell index and clay content of data collected from the literature for comparison with the present study

References	Sample ID	MC_{CC} (%)	FSI (%)	CC (%)
Shi et al. [22]	Ia	10.5	85	26
	Ib	46	91	56
	IIa	12	53.5	33
	IIb	45	69.5	40
	III	5.5	43	19
	IV	11	80	45
Mehta and Sachan [2]	S1	50	100	50
	S2	48	97	50
	S3	37	68	37
	S4	37	67	44
	S5	30	58	38
	S6	28	55	28
	S7	28	54	34
	S8	25	52	25
	S9	18	23	18
	S10	21	29	21
Pandya and Sachan [3]	S1	55	134	67
	S2	40	104	59
	S3	34	70	60
	S4	12	30	32
Samingan [24]	Bentonite	60.5	–	40
Sun et al. [25]	Na Bentonite	75.4	160	–
	Ca Bentonite	77	115	–
Komine [26]	Bentonite A (Kunigel-V1)	48	–	65
	Bentonite B (Volclay)	69	–	92
	Bentonite C (Kunibond)	80	–	18.5
	Bentonite D (Neokunibond)	76	–	71.5
Sudjianto et al. [23]	KarangJati Clay	76.10	–	95.60
Chu et al. [47]	Bentonite	–	800	40.3
	Kaolinite	–	27	22.2
Sridharan and Prakash [32]	Shimoga (Kaolinite)	–	−48.21	22
	Hassan (Chlorite)	–	−11.53	7
	Bangalore	–	−26.32	20
	Mangalore	–	2.94	21
	Bangalore	–	20	36
	Bangalore	–	31.03	36
	Korapet	–	42.31	30
	Chitradurga	–	96	50
	Dharwar	–	90.9	37
	Bijapur	–	109.52	31
	Dharwar	–	214.28	42
	Chittor	–	627.27	39
	Kolar (Bentonite)	–	1240	100
Tahasildar et al. [35]	S1	–	230	52
	S2	–	67	46
	S3	–	46	40
	S4	–	265	46
	S5	–	48	46
	S6	–	350	51

Table 2 (continued)

References	Sample ID	MC_{CC} (%)	FSI (%)	CC (%)
	S7	–	283	53
	S8	–	404	54
	S9	–	25	40
	S10	–	39	38
	S11	–	21	39
	S12	–	13	46
	S13	–	25	40
	S14	–	383	48
Rao et al. [46]	A	–	230	52
	B	–	67	46
	C	–	46	40
	D	–	265	46
	E	–	48	46
	F	–	350	51
	G	–	283	53
	H	–	404	54
	I	–	25	40
	J	–	39	38
	K	–	21	39
	L	–	13	46
	M	–	25	40
	N	–	383	48
Abdullah et al. [4]	EI Mokattam 1	83.93	25	6.68
	3	72.91	88	95.1
	4	74.16	100	58.5
	5	70.05	30	15
	EI Qattamiya 7	75.38	135	27.9
	9	69.54	290	95.2
	11	85.04	140	99.5
	12	75.52	10	4.8
	14	71.43	60	8.63
	EI Obour 16	71.67	80	10.3
	19	77.48	119	52.6
	20	73.6	138	50.6
	EI Sherouq 23	70.99	150	59.7
	24	62.68	125	35.9
	25	74.54	180	57.3
Chittoori et al. [5]	Austin	53	–	57
	Bryan	37	–	47
	EI Paso	23	–	21
	Fort Worth	60	–	52
	Keller	20	–	37
	Paris	70	–	46
	Pharr-A	48	–	59
	Pharr-B	18	–	42

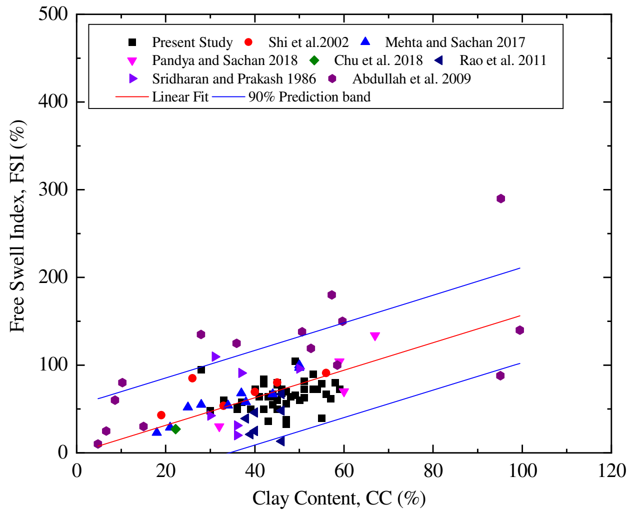

Fig. 3 Influence of CC on the FSI

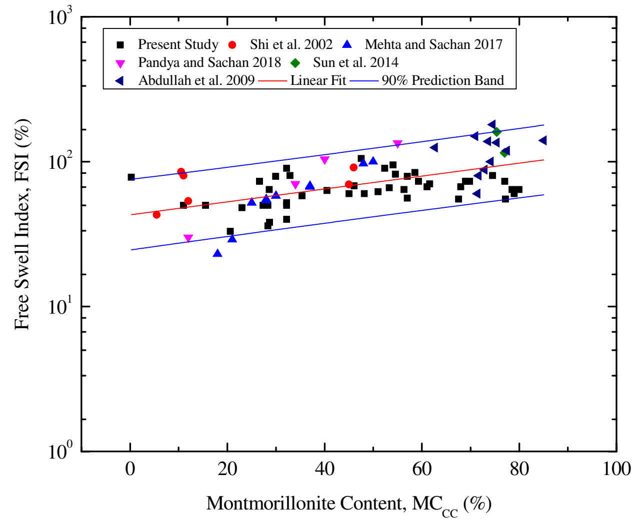

Fig. 4 Influence of MC_{CC} on the FSI

the large scatter and substantial variation in the data that is exceeding 50%, R^2 obtained is very poor. Thus, no linear equation was fit to relate these parameters. Nevertheless, to verify the reliability of data, prediction bands were fit, which reveal that all the soil samples used in the present study well established within 90% of the previous studies. From Fig. 3, it can be noticed that for same CC, soils exhibited substantial difference in degree of swelling potential; for a few soils even exceeding 100%. Another interesting point is that even though a few soils comprise of less CC (28%), they still exhibited an FSI of 95%. This can be linked to swelling causing mineral and its quantity in a given soil. This observation well corroborates with the findings of Abdullah et al. [4], who reported that soils consisting of a minor quantity of MC_{CC} can exhibit considerably greater FSI. In Fig. 3, when extrapolated the linear line, it passes through the origin, indicating a fact that FSI becomes zero, if CC is zero. The statement is well justified in a sense that no CC means that the expansive soil does not comprise any clay fraction.

Many researchers report that MC_{CC} is the prime reason for the swelling behavior [2, 3, 5]. To confirm the above statement as well as to arrive at the logical conclusion, MC_{CC} of 46 different expansive soils was quantified (Table 1) by employing the established diffraction patterns. Using the data of MC_{CC} listed in Table 1, a correlation is plotted between MC_{CC} and FSI, as depicted in Fig. 4. To further verify sanctity of results produced by the present study, similar data were collected from the literature and superimposed in the graph. From Table 1 and Fig. 4, it is obvious that MC_{CC} varies in the range from 10 to 80% irrespective of clay content. It is seen from Fig. 4 that FSI increased linearly with an increase in MC_{CC}, in its whole range. Alike the response of FSI to CC (Fig. 3), for a given MC_{CC}, FSI varied over a wide range. Interestingly, soils still exhibited significantly high FSI of above 50%, even though the percent content of MC_{CC} is trivial. As such, the relationship between FSI and MC_{CC} seems to be linear in nature. However, no linear fit equation is employed due to considerable scatter and significant variability in the data, which has yielded poor R^2 value. To establish the reliability of data, prediction bands (10%) are plotted, as depicted in Fig. 4. As such, 10% of prediction bands reveal that the results well match within 90% of the previous studies. When extrapolated the linear line on to the ordinate, which represents MC_{CC} of zero percent, FSI of above 20% can be obtained. This observation, in fact, contrasted with the results of Fig. 3. It is to be noted that the swelling is not only caused by MC_{CC}, but also by the mixed-layer minerals such as montmorillonite–illite/montmorillonite–kaolinite, which are sensitive to water content and, thus, undergo swelling when hydrated [32–35]. This may be a reason behind FSI of above 20%, although MC_{CC} is zero in the expansive soils. Further, from Fig. 4, for a low and high MC_{CC}, FSI of the same value can be noticed. This can be attributed to interference of MC_{CC} with other non-expansive or mixed-layer-type minerals [36, 37].

The results discussed herein, prima facie, affirm two crucially important points. First, the CC has definite and considerable influence on the FSI of expansive soils. Second, it appears that it is not only CC that is the basic reason for swelling phenomenon, but also the role of mineralogy, especially MC_{CC} which would cause swelling, should be accounted for. Further, a close observation of Figs. 3 and 4 elucidates more scatter in the data of CC versus FSI, in comparison to MC_{CC} versus FSI. The reason for the variance is that CC, a representative of individual particles, is a physical parameter, which is basically constituted with minerals such as montmorillonite, kaolinite, illite, quartz, etc. Furthermore, these minerals are of expansive type or non-expansive type, exhibiting no influence or interfering with expansive-type minerals causing it to scatter in the data. On the other hand, montmorillonite is a very soft phyllosilicate group of minerals with an exceptional affinity to water adsorption. It is also appreciated that for the same value of CC, MC_{CC} can vary from 0 to 100% and vice versa may not be possible. Thus, it can be inferred based on the above observations that MC_{CC} could be a more reliable parameter to predict FSI, as compared with CC. It is also worth mentioning here based on Figs. 3 and 4 that CC varied over a wider range from 3 to 100%, while MC_{CC} variation confined to in the range from 10 to 80%. It can be noted that the data points of CC above 90% predominantly belong to bentonite clay.

Generally, the dominance of montmorillonite mineral in a clay designates that expansion behavior prevails in such soils [38, 39]. It is important to recognize that the quantity of CC present in a soil does not matter very much, because the presence of even trivial quantity (5–10%) of montmorillonite can turn the soil to sensitive clay [33]. It is also worth here to mention that not a single attempt was made by earlier studies to verify the possible linkage between the CC of a given soil with the constituent amount of montmorillonite in it. With this in mind, an attempt is made to relate CC with MC_{CC}, as depicted in Fig. 5. To further validate the interrelationship, data from the literature were collated and superimposed on the graph. It is obvious from Fig. 5 that the CC in soils used for the study just varied over a narrow range from 28 to 59%. Contrary to it, there is a wider variation of MC_{CC} from as low as 10% to as high as 80% can be seen. Evidently, the relationship between CC and MC_{CC} seems to be linear up to MC_{CC} of 40%. Beyond MC_{CC} of 40%, CC apparently clustered between 30 and 60% only. It is also obvious from the graph that for a given CC, there is a remarkable change in MC_{CC}. For example, corresponding to CC of 40%, MC_{CC} varied from 10 to 80%. This observation further endorses that MC_{CC} is the more reliable parameter for accurate determination of the swelling potential over the CC. An appreciable scatter with notable variations in the data, which has yielded poor R^2 value, corresponding to both CC and MC_{CC} can be noticed from Fig. 5 and hence, no equation is employed to relate these parameters. The scatter in the data of Fig. 5 may be attributed to differences in methodologies such as Reference Intensity Ratio (RIR) [40], Mineral Intensity Factor (MIF) [41], External Standard Method [42], No-standard Method [43], Rietveld method [44], and Full Pattern Summation Method [45] employed for quantifying the MC_{CC}. The differences in MC_{CC} may also be linked to variability in diffraction patterns influenced by absorption coefficients, particle orientations, crystallinity, etc [13].

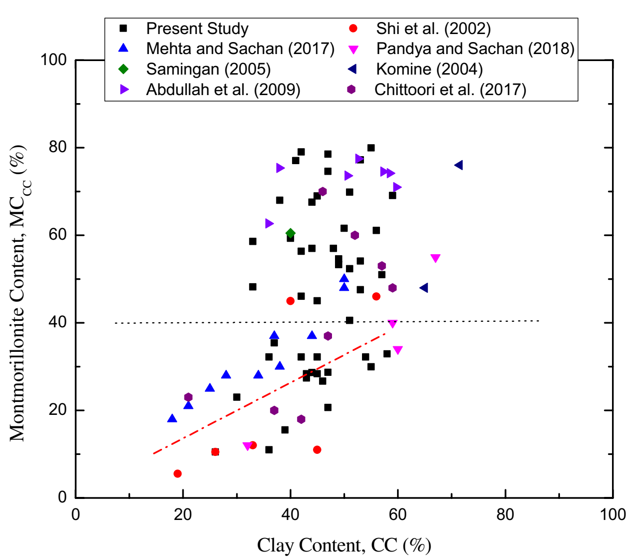

Fig. 5 Variation of MC_{CC} with CC of expansive soils

The distinctions in percent proportions between CC and MC_{CC} parameters demonstrate that there exists an inherent linkage between them. This is why any two expansive soils, although contain similar proportions of clay content, yet exhibit a significant contrast in consistency and swelling behavior. In this connection, the statement made by Terzaghi [38] is worth to be mentioned herein. Terzaghi [38] stated that two samples of the same clay at the same initial state (i.e., moisture content and void ratio) might exhibit different swelling potential due to the differences in their particle arrangements. Although, Terzaghi [38] had made this statement in the context of microstructure of soils, it is equally valid for the present study because mineralogical compositions are a part of the microstructure of a soil. Regardless of the percentage of "fines" in a particular sample, a significant presence of clay minerals in a sample can indicate a possible expansive soil problem. The results presented herein undoubtedly draw the attention to the necessity and importance to be paid for the mineralogical compositions and their phase quantity in understanding as well as assessing the geotechnical behavior of expansive soils.

Concluding Remarks

In the present study, 46 different expansive soils were collected from different locations across India. CC and MC_{CC} of these soils were quantified and their relative influence on swelling behavior is demonstrated. Based on the obtained results and interpretations made, the following conclusions are derived:

1. The very high liquid limit and free swell index values together with the presence of montmorillonite content

clearly indicate that all soils used in the study are expansive in nature.

2. It has been perceived that both CC and MC_{CC} have a definite influence from marginal to a significant on the swelling behavior. However, the effect of the latter parameter, as its percent content is although less and yet exhibited FSI of above 50%, found to be superior over the former one.
3. A discrepancy in the MC_{CC} has been comprehended from the analysis of the spectrum of diffraction patterns, even though, the CC is invariable, substantiating a fact that MC_{CC} does not depend on the clay content.
4. The relationship between CC and MC_{CC} has been found to be linear in nature. Up to 40% of MC_{CC}, it varied linearly with CC and beyond 40% of MC_{CC}, CC found to be clustered between 30 and 60%.
5. The various correlations endorse that MC_{CC} is a more reliable parameter for predicting FSI, than the CC.

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