Montmorillonite Content of Expansive Soils and Its Relationship with Swelling and Consistency Properties

P. Sreekanth Reddy, Bijayananda Mohanty, and B. Hanumantha Rao

1 Introduction

Mineral quantification plays a vital role when dealing with expansive soils, as they grossly account for the consistency and swelling behavior. However, the quantification of clay minerals is a challenging issue due to their complex chemical compositions and effect of particle orientations [1, 2]. Compared to all associated minerals in expansive soils, montmorillonite is having a high surface and high cation exchange capacity. Considering it, several studies also report that mineral content can be identified indirectly from cation exchange capacity [3] and chemical balance method [4], where the latter method was successful up to the mark. On the other hand, Chittoori [5] developed a new regression model for the quantification of clay minerals based on chemical soil properties such as cation exchange capacity (CEC), total potassium, and specific surface area (SSA). Analytically, X-ray diffraction (XRD), transmission electron microscopy (TEM), infrared analysis (IR), and differential thermal analysis (DTA) are in use for the identification of clay minerals in soils [6], which are expensive and available at a limited number of laboratories [4]. Nevertheless, XRD is the only technique that in practice for the quantification of minerals from early 1960s.

Needless to state, the enormity in consistency limits of expansive soils largely depends on different parameters relevant to physical, chemical, and mineralogy [7]. But, undoubtedly, not much attention was paid to comprehend the exact influence of MMC on geotechnical properties, in particular on consistency limits. This paper is themed to address important points related to the quantification of montmorillonite content for understanding its impact on swelling behavior and consistency limits. For

P. Sreekanth Reddy (✉) · B. Mohanty · B. Hanumantha Rao
Department of Civil Engineering, NIT Mizoram, Aizawl, Mizoram 796012, India
e-mail: psreddy.civil.phd@nitmz.ac.in

B. Hanumantha Rao
School of Infrastructure, IIT Bhubaneswar, Khordha, Odisha 752050, India

S. Saha et al. (eds.), *Recent Advances in Materials, Mechanics and Structures*,
Lecture Notes in Civil Engineering 269,
https://doi.org/10.1007/978-981-19-3371-4_2

the study purpose, expansive soil samples were collected from nine different regions across India. MMC, and consistency limits of these soils were determined, and appropriate interrelations were developed. The compilation of data was prompted to develop separate sets of correlations for bentonite soils (BS), having extreme consistency values, and natural expansive soils (NES), having low to very high consistency values, and the same was accomplished in the study.

2 Materials and Testing Methodology

Experimental investigations were conducted on expansive soil samples collected from different regions across India. The clay content of the soil samples was determined by hydrometer analysis (<75 μm) (ASTM D7928-17) [8], and consistency limits (liquid limit, w_L, plastic limit, w_P, plasticity index, w_{PI}, shrinkage limit, w_{SL} and shrinkage index, w_{SI}) were determined as per the ASTM D4318-00 [9] and ASTM D427–98 [10] standards. The swelling potential of the samples was determined as per the guidelines of ASTM D2435–04 [11]. The physical properties of soil samples used in the current study are listed in Table 1.

2.1 XRD Analysis

The mineralogy of soil samples used in the current study is analyzed by employing to D8 Advanced X-ray powder diffraction device (make, BRUKER, USA). For testing purpose, the clay content of the soil samples was separated by following the procedure

Table 1 Physical properties of soil samples used in the current study

Location	Soil properties							Classification
	Particle size distribution (%)			Consistency limits (%)			Mineralogy	
	Clay	Silt	Sand	w_L	w_P	w_{SL}	MMC (%)	USCS
Bhopal	51	43	6	68	27.52	8.5	35.61	CH
Guntur	58	31	11	93	36	8.85	19.06	CH
Kakinada	49	46	5	82	31	12	17.24	CH
Nagpur	41	43	14	61	21.92	10.62	31.59	CH
Raipur	45	39	15	76.7	25.39	9.89	31.03	CH
Vijayawada	55	33	12	92	34.32	8.65	43.97	CH
Warangal	42	30	26	70	26	15.32	33.18	CH
Mysore	53	26	21	72	28.35	8.97	28.66	CH
Kendrapara	43	38	15	60	28.29	9.85	12.19	CH

of Rao et al. [12]. The obtained samples were placed in the equipment and scanned with a voltage of 40 kV and a current of 40 mA. Further, the 2θ in the range of 5–80°, step size of 0.025°, and time interval of 0.5 s are maintained, and a copper X-ray tube (i.e., Cu-Kα radiation) was used. The presence of different minerals, especially targeting montmorillonite content (MMC) in the soil samples, was analyzed with the help of software DIFFRAC. EVA, which is already equipped with the equipment. Further, the quantity of MMC is identified by using the software TOPAS 4.2, which performs a whole pattern followed by Rietveld analysis. The MMC of soil samples determined from the analysis is listed in Table 1. The detailed procedure for the quantification of minerals can be found in Rao et al. [12].

3 Results and Discussion

Consistency limits are the mostly used parameters for identifying the presence of clay minerals in fine-grained soils. Among them, liquid limit, w_L and plasticity index, w_{PI} are the best for approximation of mineralogy of fine-grained soils [7, 13]. With this in mind, an attempt was made to deduce the relationship between consistency limits and montmorillonite content, MMC as depicted in Fig. 1a, b. The maximum values of w_L and w_{PI} of the soils used in the study are measured as 93 and 57%. In order to validate the present results, the related data have been collected from the literature and superimposed on Fig. 1.

As depicted in Fig. 1a, b, both w_L and w_{PI} increased linearly with an increase in MC. As MMC increases so does w_L and w_{PI}. Prominently, the data of Fig. 1a, b reflect both NES and BS. It is observed that the values of w_L and w_{PI} of BS are considerably higher vis-à-vis with those of NES. It is seen from Fig. 1a, b that the value of w_L as high as 993% and w_{PI} up to 950% have been reported, especially, for BS. It is, in general, seen from Fig. 1a, b that MMC in BS is reported significantly high (>50%) vis-à-vis with those of NES, for which MMC is measured below 50%. Consequently, it is prudent to make an inference that soils rich in MMC of above 50% can exhibit an average w_L of above 100% and w_{PI} of above 60%, respectively. These observations well corroborate with the results of Croft [14], who has reported that soils with w_L of greater than 60% and w_{PI} of greater than 25% evidently consist of expansive clay minerals such as montmorillonite.

As such, a linear fit model was employed to mathematically correlate w_L and w_{PI} with MMC. The empirical equations derived based on fitting functions are also printed in the same graph, alongside the values of constants. Incidentally, the values of regression coefficients, R^2, pertinent to w_L are 0.78 and 0.82 for w_{PI}. It is obvious from the trends shown in Fig. 1a, b that when MMC is extrapolated to zero, soils yet exhibited w_L of 32% and w_{PI} of 19%. Based on these observations, it can be theorized that soils without comprising of expansive minerals like montmorillonite, they still exhibit consistency behavior. This may be attributed to the fact that soils in addition to possessing minerals, like montmorillonite, might also constitute with mixed layer minerals such as illite–smectite, which would cause soils to exhibit

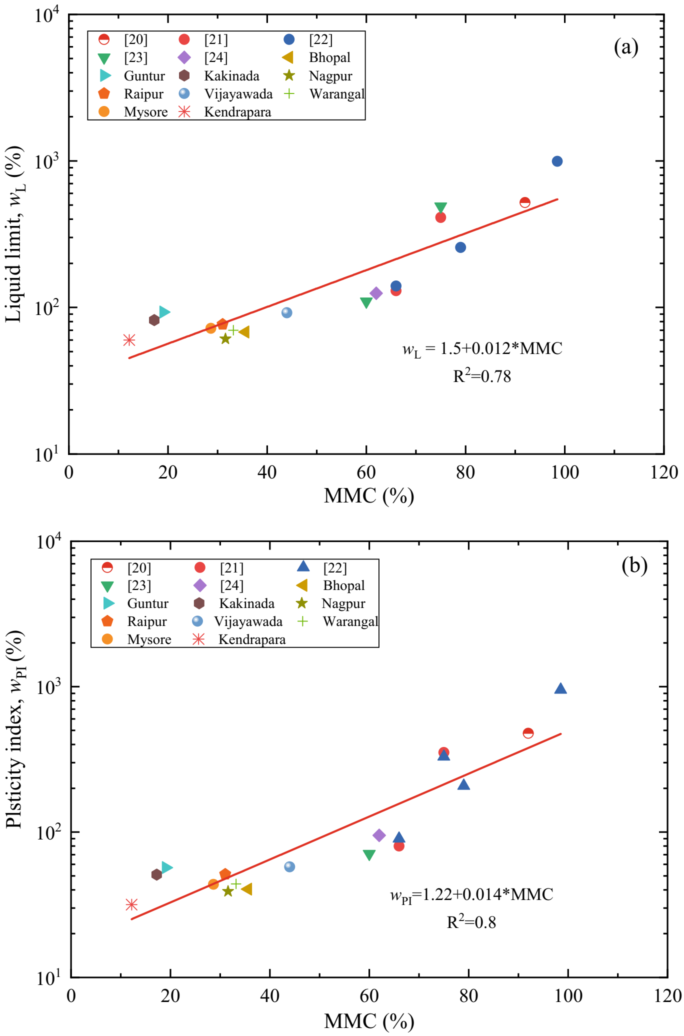

Fig. 1 Influence of MMC on liquid limit and plasticity index of soils used in the study

consistency behavior. The findings of studies by Prakash and Sridharan [13] and Reddy et al. [2], who reported that the mixed layer minerals could induce swelling to the expansive soils, excellently validate this statement.

Shrinkage index, w_{SI} of soil can be defined as the difference between plastic limit, w_{PI} and shrinkage limit, $w_{SL.}$ A close observation of Fig. 2a, b shows that w_{SL} and w_{SI} decreases with an increase in MMC. These observations are contrary to the results of Fig. 1. The maximum and minimum values of w_{SL} and w_{SI} of soils are measured as 8.5–15.32% and 46.81–110.15%, respectively. Based on the measured w_{SL} values, the volume change behavior of soils used in the study can be categorized

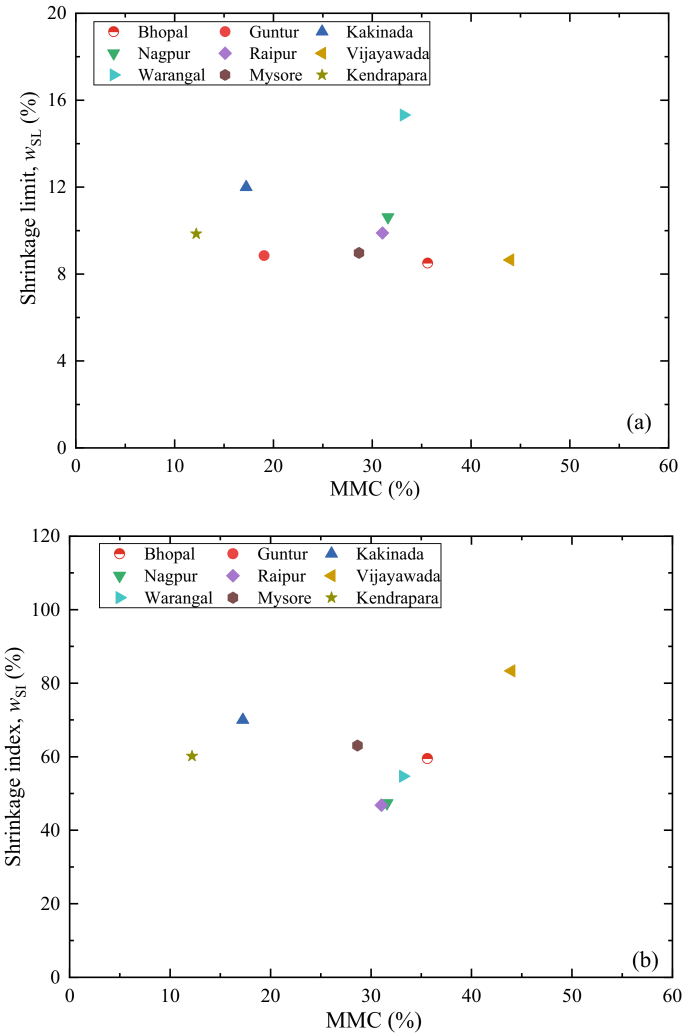

Fig. 2 Influence of MMC on shrinkage limit and shrinkage index of soils used in the study

as: non-critical to critical [15]. Furthermore, as per IS 1498 that classifies the soil based on w_{SI}, soils used in the study exhibited high to very high swell potential [16]. Many studies report that w_{SL} and w_{SI} may not be better parameters for predicting the swelling behavior of expansive or fine-grained soils. It is because these properties are not considered as plasticity characteristics, and the mechanism behind these properties is different from swelling. The swelling is due to the expansion of clay mineral lattice, whereas, in the case of $w_{SL,}$ it is chiefly managed by the relative grain size distribution of expansive or fine-grained soils [17].

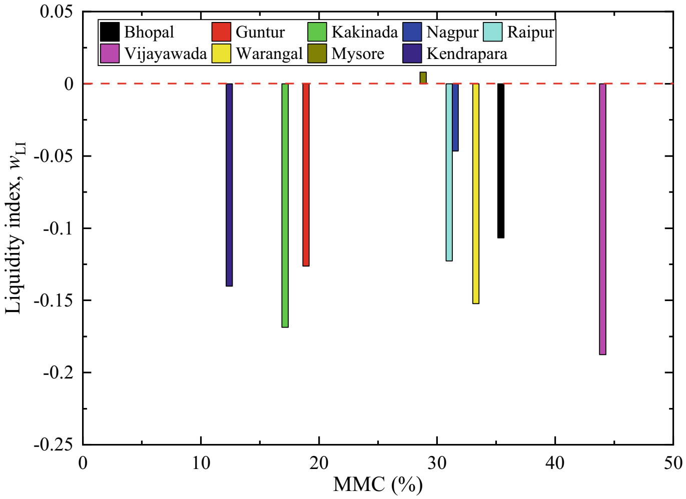

Fig. 3 Variation of liquidity index with MMC of soils used in the study

Liquidity index (w_{LI}) merely indicates the moisture condition of a soil. It becomes negative when the natural moisture content of soils lies below w_{PI}, which generally happens for overconsolidated clays or semi-plastic solids. Figure 3 depicts the relationship for w_{LI} versus MMC of respective soil samples. Observance of both +ve and –ve values is possible from Fig. 3. A close examination of Fig. 3, in general, reveals that w_{LI} could predominantly be –ve for expansive type soils. It is clearly seen that most of the data fall below zero (i.e., –ve), but a few data points are even +ve (i.e., above zero). This highlights the variability in consistency of expansive soils used in the present study. These statements well corroborate with the observation of Chen [18], who reported that expansive soils exhibit w_{LI} of –ve. It is seen from Fig. 3 that w_{LI} decreased with an increase in MMC. As such, the results presented in Fig. 3 are found to matching excellently with those reported by Shi et al. [19].

Many studies confirmed that MMC and its associated minerals, such as illite–smectite, kaolinite-smectite, which are categorized as mixed layer minerals, inherently govern the swelling behavior of expansive soils [2]. With this in mind, an attempt is made to correlate MMC with swelling potential, S_a. From Fig. 4, it can be observed that S_a increased linearly with an increase in MMC in the expansive soils. It is obvious that as MMC increases so does S_a. In order to validate the present results, the relevant data have been collected from the literature, and the same is used to validate the data produced by the present study. Additionally, a linear fit is employed, and empirical equation along with values of constants is printed in the figure. The regression coefficient, R^2, value of 0.58 was obtained for MMC versus S_a. The following observations can further be made from the results presented in Fig. 4: (a) the maximum MMC measured in NES is 42%; (b) the maximum S_a measured of these soils is 15%; (c) S_a consistently increased with MMC, for its whole measured range from 0 to 42%, and (d) MMC has a significant effect on S_a of expansive soils.

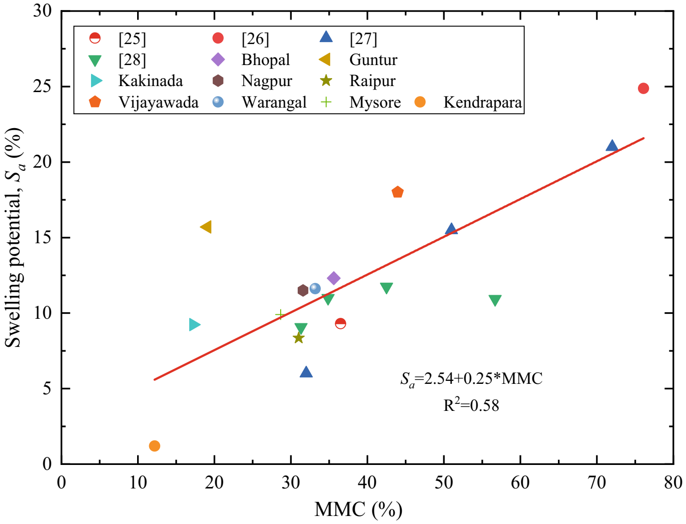

Fig. 4 Variation of swelling potential with MMC of soils used in the study

The similarity in trends of Figs. 1a, b and 4 reveals that there exists a relationship between these parameters.

4 Conclusions

In this study, different expansive soil samples were collected from different regions across India and were characterized for montmorillonite content. From the extensive experimental data, several correlations separately for natural expansive soils and mineral-rich bentonite soils were developed, and the same were validated with the literature data. Based on the correlations and further interpretations of the results, the following conclusions were derived:

1. Demonstrably, it is the montmorillonite mineral and its content is a prime controlling factor prompting consistency and swelling behavior in expansive soils.
2. Interpretation of the results evidently manifests that variability in the data of montmorillonite content, consistency limits, and swelling potential is intrinsic, in particular, pertinent to expansive soils.
3. The maximum values of MMC, w_L, w_{PI}, w_{SL}, w_{SI}, w_{LI} , and S_a of expansive soils used in the study are measured as: 44%, 93%, 57.68%, 15.32%, 110.15%, −0.05, and 18%, respectively.

References

1. Srodon J (2002) Quantitative mineralogy of sedimentary rocks with emphasis on clays and with applications to K-Ar dating. Mineral Mag 66(5):677–687
2. Reddy PS, Mohanty B, Rao BH (2020) Influence of clay content and montmorillonite content on swelling behavior of expansive soils. Int J Geosynth Ground Eng 6(1):1
3. Kaufhold S, Dohrmann RB, Ufer K, Meyer FM (2002) Comparison of methods for the quantification of montmorillonite in bentonites. Appl Clay Sci 22(3):145–151
4. Hao L, Wei Q, Zhao Y, Lu J, Zhao X (2015) Optimization method for quantitative calculation of clay minerals in soil. J Earth Syst Sci 124(3):675–680
5. Chittoori BCS (2008) Clay mineralogy effects on long-term performance of chemically treated expansive clays. Ph.D thesis, University of Texas at Arlington
6. Mitchell JK, Soga K (2005) Fundamentals of soil behavior. John Wiley and Sons, New York
7. Sridharan A, Rao SM, Murthy NS (1986) Liquid limit of montmorillonite soils. Geotech Test J 9(3):156–159
8. ASTM D7928–17 (2017) Standard test method for particle-size distribution (gradation) of fine-grained soils using the sedimentation (hydrometer) analysis. ASTM International, West Conshohocken PA, USA
9. ASTM D4318 (2010) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken PA, USA
10. ASTM D427–98 (1998) Test method for shrinkage factors of soils by the mercury method. ASTM International, West Conshohocken PA, USA
11. ASTM D2435–04 (2004) Standard test methods for one-dimensional consolidation properties of soils using incremental loading. ASTM International, West Conshohocken PA, USA
12. Rao BH, Reddy PS, Mohanty B, Reddy KR (2021) Combined effect of mineralogical and chemical parameters on swelling behaviour of expansive soils. Sci Rep 11:16562
13. Prakash K, Sridharan A (2004) Free swell ratio and clay mineralogy of fine-grained soils. Geotech Test J 27(2):220–225
14. Croft JB (1986) The problem in predicting the suitability of soils for cementitious stabilization. Eng Geol 2(6):397–424
15. Altmeyer WT (1956) Discussion. Transit ASCE 121:666–669
16. IS 1498 (1987) Indian standard classification and identification of soils for general engineering purposes. BIS, New Delhi
17. Sridharan A, Prakash K (1998) Mechanism controlling the shrinkage limit of soils. Geotech Test J 21(3):240–250
18. Chen FH (1975) Foundations on expansive soils. Elsevier Science, Amsterdam, The Netherland
19. Shi B, Jiang H, Liu Z, Fang HY (2002) Engineering geological characteristics of expansive soils in China. Eng Geol 67(1–2):63–67
20. Wang Q, Tang AM, Cui YJ, Delage P, Gatmiri B (2012) Experimental study on the swelling behaviour of bentonite/claystone mixture. Eng Geol 124:59–66
21. Tripathy S, Sridharan A, Schanz T (2004) Swelling pressures of compacted bentonites from diffuse double layer theory. Can Geotech J 41(3):437–450
22. JNC TN 2000 H12 (2000) Project to establish the scientific and technical basis for HLW disposal in Japan. (JNC TN1410 2000–003)
23. Schanz T, Nguyen-Tuan L, Datcheva M (2013) A column experiment to study the thermo-hydro-mechanical behaviour of expansive soils. Rock Mech Rock Eng 46(6):1287–1301
24. Zhang G, Germaine JT, Whittle AJ, Ladd CC (2004) Index properties of a highly weathered old alluvium. Géotechnique 54(7):441–451
25. Lin B, Cerato AB (2012) Prediction of expansive soil swelling based on four micro-scale properties. Bull Eng Geol Environ 71(1):71–78

26. Sudjianto AT, Cakrawala M, Aditya C (2012) The effects of water contents on free swelling of expansive soil. Int J Civ Environ Eng 12:13–17
27. Basma AA, Al-Homoud AS, Malkawi AI, Al-Bashabsheh MA (1996) Swelling-shrinkage behavior of natural expansive clays. Appl Clay Sci 11(2–4):211–227
28. Puppala AJ, Manosuthikij T, Chittoori BC (2004) Swell and shrinkage strain prediction models for expansive clays. Eng Geol 168:1–8