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Use of Commercially Available Bentonite Clay for Treatment of Micaceous Sand

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Abstract

Micaceous soils are considered to be detrimental due to low compactability, high compressibility and low shear strength behavior; which results in failures of pavements under traffic loading, earthen dams, embankments, cuts & excavations of retaining walls etc. Mica particles are platy, fragile and resilient in nature with inherent material anisotropy due to numerous intact mica flakes foliated over each other with low stiffness & hardness unlike spherical sand particles. As a result of resilient and fragile nature of mica particles, typical failures such as potholes, differential settlement, peeling of asphalt finish, warping of bituminous layer, subsidence and distortion are common feature in micaceous soils. The conventional stabilizing agents available are lime, cement, etc. but these techniques have a negative impact on the environment and ecosystem. In this study, bentonite was used as a stabilizing agent to treat micaceous sand due to its cohesive and eco-friendly nature. Different percentages of bentonite were used to increase the shear strength of micaceous sand. Also, conventional non ecofriendly lime stabilization was also used to conduct a comparative study on effective stabilization of micaceous sand with bentonite and lime in terms of improvement in shear strength, swelling-shrinkage characteristics, compressibility and overview on environmental impacts.

Keywords: Micaceous sand, Differential settlement, Stabilization, Bentonite, Lime

1. Introduction

Mica (muscovite) is found in igneous rock such as granite and disintegrated metamorphic rocks such as gneiss, schist, phyllite (Moore 1971; Frempong 1995; Seethalakshmi & Sachan 2018). Mica mineral is also a common constituent of sandstone and siltstone (Bokhtair et al. 2000; May 2006; Yasin & Tatsuoka 2007). Mica (muscovite) is a group of silicate and phyllosilicate mineral having chemical composition of $KAl2(Si3AlO10)(OH)2$ (Frempong 1994; Eze 2016). Mica particles are platy, fragile, and resilient in nature, which have less stiffness and hardness in comparison to spherical sand particles (Tate & Larew 1963; Bokhtair et al. 2000; Ekblad 2008). Mica particles are chemically inert and cohesionless. However, these particles have high water retention capacity as the water gets entrapped between the mica flakes (Eze 2016; Seethalakshmi & Sachan 2018). Micaceous soil shows low shear strength, low compactibility, and high compressibility (Moore 1971; Harris et al. 1984; Seethalakshmi & Sachan 2018). This is due to the geometrical arrangement of sand-mica particles as the void ratio increases with the increase in mica content due to its platy nature causing reduction in interparticle contacts. The geometrical arrangement of mica particles with sand particles varies according to the ratio of the length of mica particle (Lmica) to the diameter of sand particle (Dsand) (Lee et al. 2007). When Lmica/Dsand is less than unity, pore filling phenomena take place in which mica particles fill the voids of sand-sand particles. On the other hand, when Lmica/Dsand is greater than unity, bridging and ordering phenomena occurs. Bridging is the irregular arrangement of sand particles below the platy mica particles and ordering is the regular arrangement of sand particles above mica particles which creates void spaces between sand and mica particles. Due to these unique properties of mica, it is difficult to stabilize the micaceous sand in terms of improvement in shear strength, swelling-shrinkage characteristics and compressibility properties of soil.

Typical failures such as potholes, differential settlement, peeling of asphalt finish, warping of bituminous layer, subsidence and distortion on micaceous soil subgrade were seen in past (Mesida 1986; Meshida 2006). To eliminate these problems, it is previously recommended to stabilize micaceous soil using lime (Frempong 1994). Earlier, researchers have stabilized micaceous gravel, clay, and silt using cement, lime, sand, and vegetable waste (Frempong 1995; Mshali & Visser 2012; Mshali & Visser 2014; Eze 2016; Omar 2016) but stabilization of micaceous sand is not yet explored. Lime being the conventional method of stabilization has a negative impact on the environment. Another conventional treatment like cement is also unfavorable to the ecosystem. Considering the adverse effect of lime, cement, etc., it is needed to use some other alternative method of stabilization which is eco-friendly. Being cohesionless material, micaceous sand can be stabilized with the material having high cohesive property. In the current study, treatment of micaceous sand is conducted using bentonite as the stabilizing agent. Bentonite is eco-friendly, economical and easily available which makes it a suitable stabilizing agent to improve the shear strength of micaceous sand. The present study is focused on the effect of mica content on compactability and shear strength characteristics of micaceous sand at different mica content due to variation in sand-sand, sand-mica, and mica-mica matrix. The reduction in shear strength and negative impacts of mica particles in micaceous sand was rectified or minimized by the treatment of micaceous sand with non-conventional ecofriendly bentonite and conventional non ecofriendly lime stabilization. A comparative study on effective stabilization of micaceous sand at different mica content with bentonite and lime was conducted and these techniques were further examined in terms of improvement in shear strength, swelling and shrinkage characteristics, compressibility and overview on environmental impacts.

2. Material Properties and Specimen Preparation

The present study was carried out on soil collected from Sabarmati river basin situated in Gujarat, India. Soil consisted of 89% sand of medium & fine size (2.0 mm to 75 μm) and 11% silt content. Silt content was removed and pure sand was used throughout the experimental study. Commercially available mica (muscovite) powder procured from National Chemicals Pvt. Ltd, Vadodara in Gujarat (India) was used throughout this research. The particle size of mica particles were ranging from 0.5mm to 0.3μm. Micaceous sand specimens of different mica content (0%, 5%, 10%, 15%, 20%, 25%, and 30% mica) were prepared by mixing the pure Sabarmati sand particles with mica powder at dry state by weight until the attainment of uniform conditions. Such micaceous sand specimens with 0%, 5%, 10%, 15%, 20%, 25%, and 30% mica were denoted as 0MS, 5MS, 10MS, 15MS, 20MS, 25MS and 30MS respectively throughout this study. The specific gravity of pure sand (0MS) and pure mica were obtained to be 2.64 and 2.75 respectively, and hence the specific gravity of micaceous sand was also increased with the increment in percentage of mica (Table 1). Figure 1 shows the grain size distribution curves of micaceous sand with different percentage of mica. It was observed that the percentage of fines (<75μm) increased significantly with the increase in mica content from 0% to 30%. The rate of increment in percentage of fines was noticed to be higher at lower mica contents (upto 15%) and it was gradual at higher percentage of mica (from 20% to 30%). The SEM (Scanning Electron Microscope) images of micaceous sand at different mica content signified that the continuous sand-sand matrix in pure sand (0% mica), sand-sand matrix with mica particles in pores (5% mica), sand-mica matrix with gradual change of dominancy from sand to mica particles (10% mica, 15% mica and 20% mica), continuous mica-mica matrix with sand particles embedded in it (25% mica, 30% mica) (Seethalakshmi & Sachan 2018).

Specimens of untreated micaceous sand with different mica content were prepared at their corresponding maximum dry density (γdmax) and optimum moisture content (w) as mentioned in Table 1 as it simulates the in-situ conditions for road pavements and embankment construction. All samples were prepared using moist tamping method for all the experimental investigations as it would decrease the segregation of flaky mica particles from spherical sand particles. Cuboidal specimens of size 60mm*60mm*25mm were prepared in three layers by altering the compacting efforts to be applied per layer in order to achieve the required dry density (γdmax) and were being used for the study of shear strength characteristics of micaceous sand using direct shear test. The treatment of micaceous sand was conducted using bentonite clay as well as lime at different percentages by weight in order to improve the mechanical behavior of micaceous sand at different mica content. The percentage of bentonite and lime added to micaceous sand for its treatment was varied from 0% to 8%. The commercially available bentonite clay and lime (calcium oxide) were procured from Pinal Corporation and Finar Ltd., Ahmedabad, Gujarat respectively. The specific gravity of bentonite clay was 2.8 whose particle size was less than 2μm, while the specific gravity of lime was 3.37 according to the CASR no. 1305-78-8. The chemical composition of lime being used in the current study was as follows: Calcium oxide assay min. 95.0%. The readily available micaceous sand with different percentage of mica was taken and bentonite clay was added and mixed at dry state until the uniform state was attained. Such micaceous sand specimens with different percentage of bentonite (2%, 4%, 6%, 8%) at a given mica content was then used to prepare cuboidal specimens at their corresponding maximum dry density and optimum moisture content obtained at untreated state for understanding the shear strength behavior of treated micaceous sand with bentonite clay. All prepared specimens in split mold were kept inside air-tight desiccator for 24 hours in order to ensure uniform distribution of water molecules among sand-mica-bentonite soil matrix without altering the dry density and water content of the specimen. This might improve the mechanical behavior of soil with bentonite in terms of shrinkage, swelling, redistribution of contact forces, etc. Similarly, micaceous sand at varying mica content were treated with different percentage of lime (2%, 4%, 6%, 8%) by weight at dry state until the achievement of uniform state as similar to that of bentonite clay. The readily mixed micaceous sand of given mica content at varying lime percentage were then used to prepare direct shear test specimens at their corresponding maximum dry density obtained at untreated state. The water content was used slightly higher than optimum moisture content of untreated soil in order to overcome the heat of hydration process during the curing period during which the calcium oxide would be converted into calcium hydroxide. The prepared cuboidal specimens of micaceous sand in split mould at different lime percentage was kept inside desiccator for 7 days curing period without disturbing the density of the specimen. The loss of water content due to heat of hydration would be accounted with higher water content during specimen preparation such that all specimens would attain water content equivalent to optimum moisture content at the end of curing period. The minimum curing period of 7 days was selected such that the successful completion of hydration process was ensured along with the gain of reasonable shear strength (Locat et al., 1990; Abdi and Wild, 1993; Mallela et al., 2004; Jawad et al., 2014).

3. Experimental Program

The compactability behavior of untreated micaceous sand specimens were studied using a series of standard proctor compaction tests as per IS: 2720, Part VII (1980) with increment of water content at the rate of 2% starting until the dry density

Table 1: Effect of mica content on geotechnical properties of micaceous sand

Type of soil	Name of soil	G_s	MDD	OMC	ϕ_u
			g/cm^3	%	degrees
0%Mica	0MS	2.64	1.77	8.0	38.4
5%Mica	5MS	2.65	1.80	12.0	37.2
10%Mica	10MS	2.67	1.77	12.8	36.1
15%Mica	15MS	2.67	1.76	12.9	35.9
20%Mica	20MS	2.73	1.71	13.3	34.4
25%Mica	25MS	2.73	1.65	16.0	35.3
30%Mica	30MS	2.74	1.64	16.0	33.3

decreased after achieving maximum dry density. The shear strength behavior of all micaceous sand specimens under untreated conditions, treated with bentonite, and treated with lime were studied separately by conducting several series of direct shear tests as per IS: 2720, Part-13 (1986). All untreated micaceous sand specimens were transferred to the shear box set up of the direct shear apparatus immediately after the specimen preparation in split mould and tested for the shear strength characteristics. However, the bentonite treated micaceous sand specimens were stored for 24 hours and the lime treated micaceous sand specimens were stored in desiccator for 7 days curing period. Such samples were further shifted to the shear box set up without disturbing the soil structure by gradual application of uniformly distributed pressure on the split mould which was then subjected to shear deformation. All the tests were conducted on the compacted – partially saturated specimens under undrained conditions. Each type of specimens were subjected to undrained shear deformation under three different normal stresses such as 50kPa, 100kPa and 150kPa simulating the overburden pressure on a typical subgrade soil layer in order to determine the undrained shear strength parameters such as cohesion (c_u) and angle of internal friction (ϕ_u) using Mohr-Coulomb Failure criteria. All tests were conducted at a constant deformation rate of 0.25 mm per minute and the tests were continued until the specimen achieved its maximum shear stress or it achieved cumulative horizontal displacement equivalent to 10% of length of the specimen whichever occurred earlier. The shear resistance offered by the soil specimen was measured using proving ring of 2KN capacity with respect to horizontal displacement while the vertical displacement of the sample was measured with respect to time during shear deformation. The vertical displacement directly depicted the volumetric response of the soil as the lateral deformation of the sample was restrained with rigid boundary condition in the shear box set up during undrained shear deformation.

4. Results and Discussion

Reconstituted specimens of micaceous Kutch soil at different water contents were prepared by using moist tamping method. The specimens were prepared in shear box (60 mm x 60 mm x 25 mm) by providing 25 blows each layer in three uniform layers (wt of compactor=50 gm). Shear strength parameters of micaceous Kutch soil at water content of 0%, 0.28%, 1%, 3.4%, 5.4%, 7.8%, 11.3%, 15.1%, 18%, 20% and 23.5% were obtained. Shear strength tests for chosen water content were performed at normal stresses, 50 kPa, 100 kPa, 150 kPa and 200 kPa. No Wet condition was allowed during all the direct shear tests performed in the current study. Strain rate of 0.25 mm/min was kept throughout the test, and Failure was defined at the point of maximum shear stress. All the specimens used in shear strength tests were prepared at dry density of 1.42 g/cc (90% of maximum dry density) with varying water content. Maximum water content was kept 23.5% because of the difficulty in specimen preparation for water content more than 23.5%. The water molecules (for water content more than 23.5%) would have departed from the specimen due to the tamping action during specimen preparation for direct shear test. The reason could be attributed that the inter-space between thin flakes of mica particles (14% mica) were completely saturated with water at 23.5 % water content; thus additional water molecules (for water content more than 23.5%) would go into the pore space of soil mass. During the process of specimen preparation for direct shear test, the tamping action caused the water to depart from the saturated inter-space of mica particles leading to the significant decrease in water content of prepared specimen.

4. 1. *Compactability and shear strength behavior of micaceous sand at varying mica content*

The compactability behavior of micaceous sand at varying mica content was shown in Figure 2. It was observed that the maximum dry density of pure sand (0MS) was higher than all micaceous sand specimens except 5MS. The maximum dry density was noticed to decrease with the increase in percentage of mica upto 30% whereas the optimum moisture content was increased with increment in mica content from 0% to 30%. The reduction in dry density could be due to the change of soil matrix from continuous stable sand-sand matrix in 0MS to vulnerable/metastable sand-mica matrix in 5MS to 20MS specimens. The increased unstable soil structure with larger non-uniform void spaces caused by bridging and ordering mechanisms resulted into achieving reduced dry density of micaceous sand at higher mica content. The soil matrix was further changed to continuous mica-mica matrix in 25MS and 30MS with relatively uniform soil structure having the sand particles embedded within them. However, the resilient nature of overlapped mica particles might restrict the closer configuration of soil particles under densification which resulted into further decrement of maximum dry density at larger percentage of mica. The increased optimum water content could be due to the higher water retention capacity of mica particles as compared to sand particles. The water molecules which get entrapped amongst the foliated mica flakes of individual mica particles would enhance the adsorption capacity of micaceous sand. This might further build up the resilient nature of mica particles leading to undulated and inconsistent compactability nature of micaceous sand at increased percentage of mica.

All untreated micaceous sand specimens were subjected to a series of direct shear test in order to understand the shear strength characteristics at varying mica content. The stress-strain response of untreated micaceous sand with different mica content at three different normal stresses (50kPa, 100kPa, 150kPa) is shown in Figure 3. It was observed that the stress-strain response of micaceous sand from 0% to 20% mica (0MS to 20MS) showed deteriorating trend with decreased peak shear stress which was reversed and showed an improved response at 25% and 30% mica (25MS & 30MS) with increased peak shear stresses at lower normal stress of 50kPa. The volumetric response of untreated micaceous sand with different mica content at three different normal stresses (50kPa, 100kPa, 150kPa) during undrained shear deformation is shown in Figure 4. The volumetric response was in accordance with the stress-strain response of untreated micaceous sand. At 50kPa normal stress, 0MS specimen showed greater dilative response which was further decreased and changed to contractive response with increase in mica content upto 30MS. This could be due to the change of soil matrix from sand-sand with larger stable interparticle contacts resulting into higher peak strength. However, the change of soil matrix to metastable and weaker sand-mica matrix with decreased interparticle contacts and larger non uniform void spaces due to enhanced bridging and ordering could be responsible for decreased shear strength upto 30MS. Similarly, the stronger sand-sand matrix in 0MS would tend to make the particle roll over each other making it highly dilative while the addition of mica particles among sand would tend to shear the specimen most likely by sliding over other rather than rolling over each other. Additionally, the weaker mica particles would bend among stronger sand particles resulting into larger contractive response from 5MS to 30MS. The resilient nature of overlapped mica particles in continuous water filled mica-mica matrix with improved interparticle contacts, in spite of being weaker than sand particles, would be the reason for reverse nature of shear strength response at lower normal stress (50kPa). However, the reverse response was gradually diminished with increase in normal stresses such as 100kPa and 150kPa. The peak shear stress was observed to decrease continuously with increase in percentage of mica rom 0% to 30% (0MS to 30MS) at higher normal stresses unlike 50kPa and no reverse pattern was observed in stress-strain response of untreated micaceous sand specimens. The possible reason could be due to the replacement of stronger sand particles with weaker mica particles to considerable extent. The resilient nature would be suppressed at larger normal stresses due to expulsion of water molecules from within the flakes of individual mica particle which in turn increase the probability of sliding over each other making it further weaker specimens with lower shear strength at larger mica contents. It was further noticed that the undrained shear strength parameter (ϕu) of untreated micaceous sand using Mohr Coulomb failure criteria with zero cohesion (cu) decreased significantly from 38 degrees to 33 degrees. The shear strength (τ) of soil was determined using the formula, $\tau = c_u + (\sigma * \tan \phi_u)$ where cu is the undrained cohesion, ϕu is the angle of internal friction and σ is the normal stress applied during shearing. The reduction in shear strength of untreated micaceous sand was also compared with that of pure sand (0MS) at 50kPa normal stress. There was a gradual and consistent reduction of shear strength with increase in percentage of mica content due to suppressed resilient nature at higher normal stresses and hence, micaceous sand with 30% mica (30MS) exhibited the highest reduction in shear strength (17%) with reference to that of pure sand (0MS) in spite of having improved peak shear stress at lower normal stress as observed in Table 2.

In addition to decreased shear strength, micaceous sand specimens have various severe challenges with respect to resilient nature, crushing nature, compactability issues and non-uniform metastable interparticle contacts caused by bridging, ordering and pore filling phenomena to be used in earthen construction especially as subgrade material for pavements and embankments. Hence an attempt was made to rectify or minimize the above mentioned vulnerabilities to the considerable extent by treatment of micaceous sand with two different components such as non-conventional ecofriendly bentonite clay and conventional non ecofriendly lime stabilization. The optimum percentage of bentonite clay and lime for micaceous sand with different percentage of mica was determined with reference to the shear strength of pure sand (0MS). The percentage of bentonite clay or lime was considered to be optimum in the current study when the shear strength of treated soil specimen was at least 20% greater than the shear strength of pure sand (0MS) at the given normal stress of 50kPa. The normal stress of 50kPa was chosen over higher normal stresses (100kPa and 150kPa) to better understand the stress-strain and volumetric response of treated micaceous sand in comparison to the untreated soil with respect to the variation in enhanced resilient nature as observed in Figures 3a and 4a.

4. 2. Treatment of micaceous sand with non-conventional ecofriendly bentonite

The shear strength parameters such as undrained cohesion (cu) and angle of internal friction (ϕu) were determined using Mohr Coulomb failure envelope criteria. The addition of bentonite clay significantly increased the cohesion and drastically reduced the friction angle of micaceous sand as expected. The gain of cohesion with increase in bentonite content was substantial at lower mica content (5MS and 10MS), however the reduction in friction angle was also observed to be higher at all mica contents with increment in percentage of bentonite. The larger gain of cohesion could be attributed due to the stronger bonding of clay with sand-sand matrix in 5MS and 10MS, while the loss of sand-sand matrix by replacement of sand-clay interaction however decreased the friction angle significantly. The gradual and lower gain of cohesion in 15MS and 20MS even at higher bentonite content would be attributed due to the dominancy of sand-mica matrix. The interparticle interaction among mica and clay particles might be weaker than that of sand and clay particles due to flaky sliding nature as well as bridging, ordering and pore filling phenomena. While, the reduction of friction angle was noticed to be higher in 15MS and 20MS which could be resulting from both weaker sand-mica matrix and weaker mica-clay matrix as compared to stronger sand-sand and sand-clay matrix. Hence the weaker sand-mica-clay interactions would be responsible for lower gain of strength in 15MS and 20MS specimens in comparison to 5MS and 10MS specimens. However, the gain of cohesion with increment of bentonite was not substantial in 25MS and 30MS beyond certain percentage of bentonite (4%) but with the continuous reduction in friction angle which might be due to sliding nature of the weakest mica-mica matrix and poor bonding nature of flaky mica-clay matrix. The non-uniform distribution of clay minerals among mica particles with no considerable contribution from embedded sand particles might be responsible for deteriorating behavior beyond certain percentage of bentonite (4%). Hence an attempt was made to identify the optimum percentage of bentonite to be added in micaceous and specimens with different mica content. The percentage of bentonite was considered to be optimum when the shear strength of treated micaceous sand was at least equivalent to ($\approx$) 20% greater than that of pure sand (0MS), which could however be suitable to consider the equivalent strength of 0MS, in order to incorporate the experimental and manual errors and deviations during the testing conditions. The gain of shear strength was noticed to be larger and continued to increase with increase in bentonite content in 5MS, while the strength gain in 10MS, 15MS and 20MS was decreased over narrow range with increment of bentonite percentage. However, the gain of strength was not significant beyond 4% bentonite in case of 25MS and 30MS micaceous sand specimens. It was observed that 2% bentonite (low bentonite content) would be sufficient for 5MS, 4% bentonite would be adequate for all other micaceous sand specimens (10MS to 30MS) for achieving the shear strength equivalent to 20% higher than that of 0MS specimens.

4. 3. Treatment of micaceous sand with conventional non-ecofriendly lime

The shear strength parameter such as angle of internal friction (ϕu) was determined using Mohr Coulomb failure envelope criteria with the assumption of zero undrained cohesion (cu). The development of cohesion was not noticed to be substantial (⩽ 20kPa) even at higher percentage of lime at all percentages of mica. At the same time, the cohesion developed during sample preparation might not be long lasted after curing which might be reduced with increase in curing time causing higher brittle nature. Hence, it was assumed to be zero and the variation in shear strength was assumed to be contributed only from the development of angle of internal friction. The increment in friction angle was observed to be significantly higher for 5MS and 10MS upto 60% larger than that of pure sand (0MS) with gradual increment of lime from 2% to 8%. Hence the optimum percentage of lime was assumed to be the achievement of shear strength in treated micaceous sand equivalent to 20% more than that of pure sand (0MS). This criterion led to the optimum percentage of lime as 6% and 4% for 5MS and 10MS micaceous sand specimens respectively. However, the gain of frictional angle in 15MS to 30MS with lime treatment was not significant as well as inconsistent due to development of extensive non-uniformity in samples during curing which would make the specimen vulnerable to distort the soil structure even under undisturbed condition maintained inside desiccator due to higher resilient nature of mica particles. In addition to that, larger influence of resilient nature of overlapped mica particle interaction along with very least contribution of lime in developing the frictional resistance among mica particles. This would lead to higher brittle nature of sample during shearing and resulted in providing varying shear strength characteristics of lime treated micaceous sand specimens at higher mica content. Hence the optimum percentage of lime was not achieved at higher mica content (15% to 30%) due to the predominant influence of bridging, ordering and resilient nature of mica particles which could not be rectified or minimized by the addition of lime. However, the marginal achievement of shear strength equivalent to at least 10% more than the shear strength of pure sand (0MS) was achieved at 6%, 4%, 8% and 6% lime by micaceous and specimens with 15%, 20%, 25% and 30% mica content (15MS, 20MS, 25MS and 30MS) respectively (Table 3). These results were in accordance with the previous literature reviews where in the presence of more than 10% mica content in micaceous sand were considered not suitable for construction of earthen structures such as subgrade of pavements, embankments, retaining walls and earthen dams due to the undesirable geotechnical characteristics of micaceous soil. Such vulnerable behavior of micaceous sand with higher percentage of mica (>10%) could not be rectified by treatment of such soils with conventional stabilizing materials such as lime, cement and sand.

4. 4. Comparative analysis on treatment of micaceous sand using bentonite and lime

The shear strength of bentonite treated micaceous sand was contributed significantly by both consistent cohesion and angle of internal friction which also showed gradual steady state of strength gain with increase in percentage of bentonite at all mica contents. The non-compatible and metastable sand-mica matrix with bridging and ordering might have transformed to stable soil structure due to strong cohesive forces among sand-mica-clay particles which not only would reduce the non-uniform void spaces but also reduce the rebound nature of overlapped mica particles to considerable extent making the bentonite treated micaceous sand highly stable.

Table 2: Shear strength of treated micaceous sand using Bentonite

Type of soil	**Bentonite content**	**c_u** (kPa)	**ϕ_u** (degree)
5%Mica	0 %	0.0	37.2
	2 %	**14.6**	**34.6**
	4 %	24.2	31.5
	6 %	33.0	27.8
	8 %	48.1	22.5
5%Mica	0 %	0.0	36.1
	2 %	6.3	34.6
	4 %	**15.6**	**32.5**
	6 %	21.4	32.5
	8 %	35.6	28.1
15%Mica	0 %	0.0	35.9
	2 %	17.3	30.8
	4 %	**18.6**	**32.3**
	6 %	33.8	26.4
	8 %	38.1	22.9
20%Mica	0 %	0.0	34.4
	2 %	6.5	33.1
	4 %	**20.8**	**29.7**
	6 %	29.5	28.4
	8 %	32.9	29.3
25%Mica	0 %	0.0	35.3
	2 %	16.6	29.0
	4 %	**19.5**	**29.0**
	6 %	30.9	26.4
	8 %	27.9	27.8
30%Mica	0 %	0.0	33.3
	2 %	12.9	29.2
	4 %	**19.5**	**28.9**
	6 %	19.6	28.9
	8 %	32.8	23.8

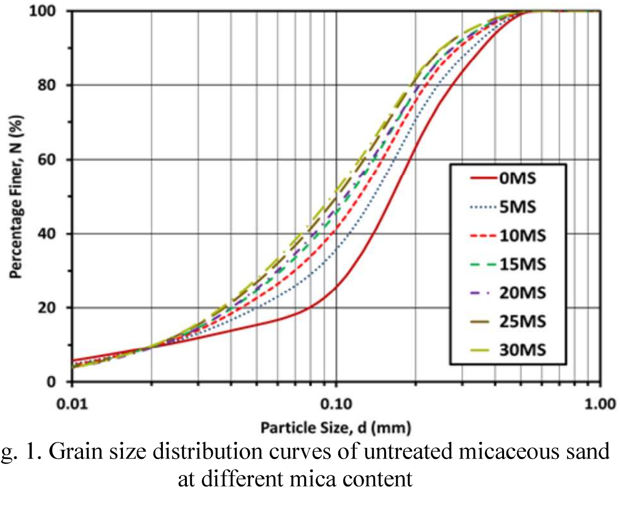

Fig. 1. Grain size distribution curves of untreated micaceous sand at different mica content

However, the shear strength of lime treated micaceous sand contributed only through friction angle was obtained to be reliable for lower mica content (upto 10%) and the influence of lime was drastically reduced at higher percentage of mica content due to enhanced resilient nature.

Bentonite clay, which is being highly expansive in nature, would typically expand upto saturation. Addition of bentonite to micaceous sand upto 8% typically showed swell pressure upto a maximum value of 50kPa. While the bentonite treated micaceous sand with varying mica content at optimum percentages of bentonite were subjected to series of Terzaghi's 1D consolidation test as per IS: 2720, Part-15 (1986) as mentioned in Table 4. The swell pressure was measured indirectly through consolidation test during saturation of the specimens at constant seating pressure of 5kPa. The consolidation loading was started only after the vertical deformation achieved a steady constant state under seating pressure. The swell pressure developed in bentonite treated specimens at optimum percentages as mentioned in Table 4 showed very negligible value of less than 10kPa which was considerably less and under acceptable range for design analysis of earthen structures. The response of change in void ratio vs. vertical effective stress of bentonite treated micaceous sand at optimum percentage during consolidation is shown in Figure 5. The compression index values were obtained to be very less and were equivalent to that of the conventional sand specimens (Table 4) signifying the achievement of closer, uniform, and stable soil configuration with bentonite clay which was also within the permissible limits of settlement analysis. The recompression index values were also observed to be significantly less signifying the reduction in resilient nature of mica particles in presence of bentonite clay due to the counter balanced mechanism of cohesive nature of bentonite with rebound nature of mica. The cohesive bentonite clay would tend to hold back the mica particles against rebounding upon unloading making it highly favorable for stabilization of micaceous sand with higher mica content upto 30%.

The addition of lime might induce the liberation of heat during hydration mechanism which would need to be mixed thoroughly to avoid non-uniformity in soil structure. The environmental conditions should be maintained for proper curing process in order to develop the proper bonding among particles. The duration of curing period might also be a disadvantage for lime treatment as compared to bentonite which could be compacted immediately after mixing in proper proportions. The brittle nature of lime treated specimens might result in unreliable geotechnical behavior of micaceous and with higher mica content. The chemical reaction of lime with soil minerals might deteriorate the performance characteristics of soil mass in long term stability analysis. However, the non-conventional ecofriendly bentonite is generally a typical clay mineral, which is being part of soil mass, would not be chemically harmful to the agricultural environment in long term serviceability criterion. The true cohesion developed among soil mass would not be degraded unlike lime and hence, the use of bentonite over larger area would also be cheaper as compared to lime. This would make the treatment of micaceous sand with bentonite more economical and efficient over lime for stabilizing micaceous sand with larger percentage of mica even upto 30% in comparison to lime which was effective only upto 10% mica content.

Table 3: Shear strength of treated micaceous sand using Lime

Type of soil	**Lime content**	**c_u** (kPa)	**ϕ_u** (degree)
5%Mica	0 %	0.0	37.2
	2 %	0.0	41.8
	4 %	0.0	40.8
	6 %	**0.0**	**43.2**
	8 %	0.0	52.1
5%Mica	0 %	0.0	36.1
	2 %	0.0	40.5
	4 %	**0.0**	**43.8**
	6 %	0.0	45.7
	8 %	0.0	52.4
15%Mica	0 %	0.0	35.9
	2 %	0.0	40.8
	4 %	**0.0**	**41.7**
	6 %	0.0	41.6
	8 %	0.0	41.5
20%Mica	0 %	0.0	34.4
	2 %	0.0	40.1
	4 %	**0.0**	**41.5**
	6 %	0.0	36.0
	8 %	0.0	41.0
25%Mica	0 %	0.0	35.3
	2 %	0.0	39.2
	4 %	0.0	36.5
	6 %	0.0	36.8
	8 %	**0.0**	**40.4**
30%Mica	0 %	0.0	33.3
	2 %	0.0	36.2
	4 %	0.0	36.9
	6 %	**0.0**	**40.0**
	8 %	0.0	38.6

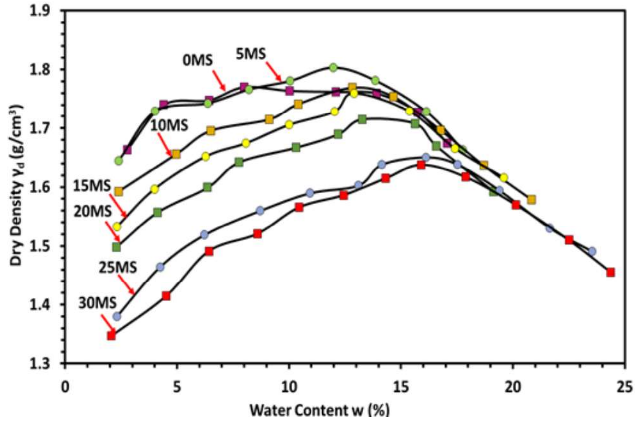

Fig.2. Compactability behavior of untreated micaceous sand at different mica content

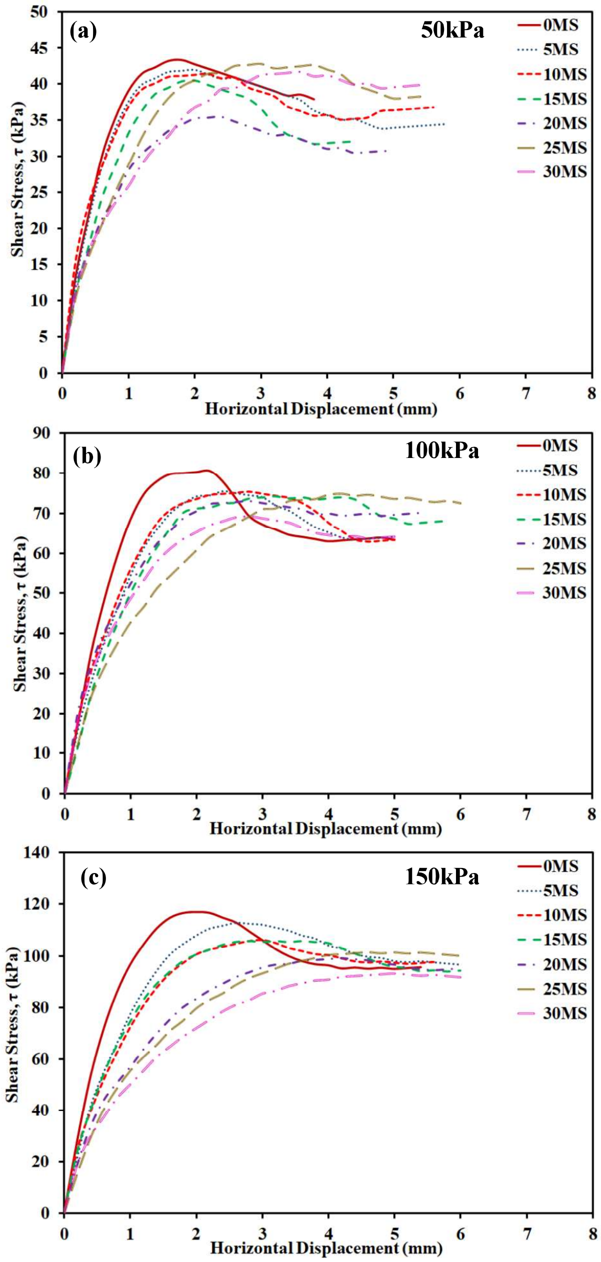

Fig.3. Stress-strain of micaceous sand at different mica content at different normal stress. (a) 50kPa, (b) 100kPa, (c) 150kPa

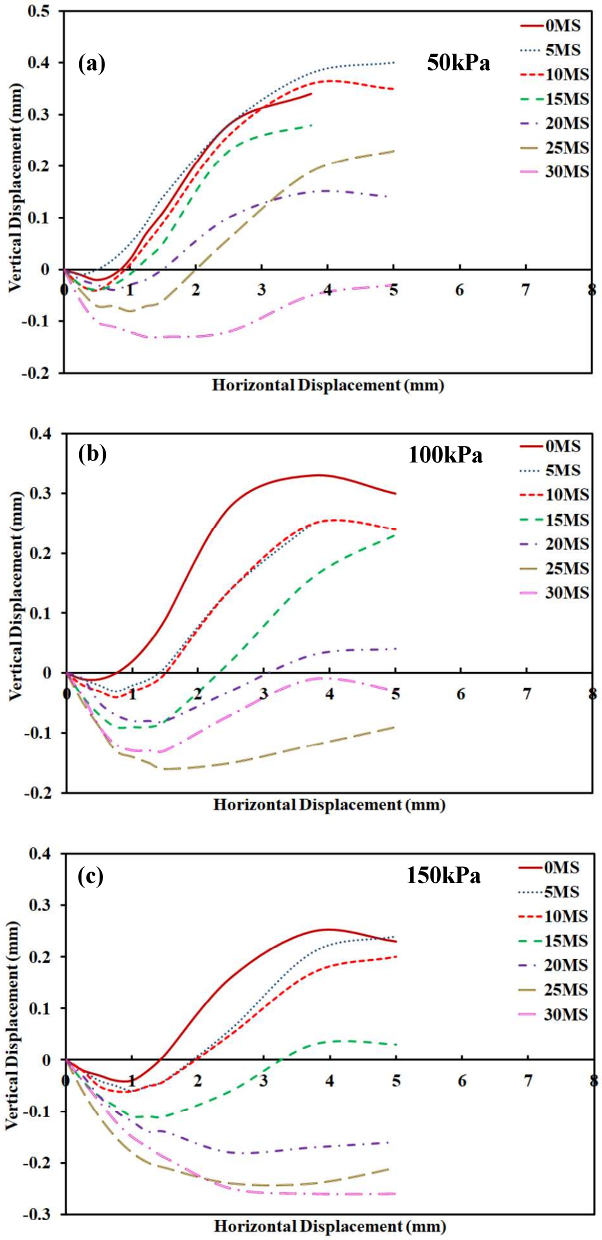

Fig. 4. Volumetric response of micaceous sand at different mica content at normal stress. (a) 50kPa, (b) 100kPa, (c) 150kPa

Table 4: Optimum percentage of bentonite and lime for treatment of micaceous sand varying with different mica content

Type of soil	**% Bentonite** Optimum	**% Lime** Optimum	**Swell pressure** kPa
5%Mica	2	-	0
10%Mica	4	-	0
15%Mica	4	-	1
20%Mica	4	-	0
25%Mica	4	-	2
30%Mica	4	-	5
5%Mica	-	6	-
10%Mica	-	4	-
15%Mica	-	6	-
20%Mica	-	4	-
25%Mica	-	8	-
30%Mica	-	6	-

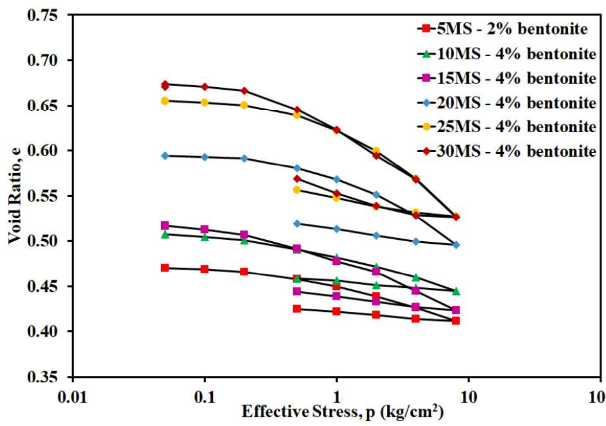

Fig.5. Effect of optimum percentage of bentonite on compressibility behavior of micaceous sand

5. Conclusions

The current study was conducted to evaluate the effect of mica content on compactability and shear strength characteristics of untreated micaceous sand. The shear strength characteristics of treated micaceous sand with non-conventional ecofriendly bentonite clay as well as with conventional non-ecofriendly lime was studied and comparative study on effectiveness of bentonite over lime for treatment of micaceous and at different mica content was summarized. Key observations are summarized as follows:

1.The shear strength of micaceous sand was degraded and compactability behavior was also decreased with increase in percentage of mica due to bridging & ordering of metastable sand-mica matrix and resilient nature of mica particles.

2. Treatment of micaceous sand with bentonite showed significant increase in shear strength due to development of true cohesion along with angle of internal friction which would suppress the deteriorated behavior of mica particles in sand-mica and mica-mica particle interactions even at higher percentage of mica upto 30%.

3. Treatment of micaceous sand with lime was considerably good only upto 10% mica beyond which the lime stabilization was not observed to be appropriate for micaceous sand.
4. Considering the environmental factors, utilization process, cost effectiveness and economical background, stabilization of bentonite would be considered to be appropriate solution in comparison to that of lime.

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Notations

0MS = Micaceous sand with 0% mica content
5MS = Micaceous sand with 5% mica content
10MS = Micaceous sand with 10% mica content
15MS = Micaceous sand with 15% mica content
20MS = Micaceous sand with 20% mica content
25MS = Micaceous sand with 25% mica content
30MS = Micaceous sand with 30% mica content
c_u = Undrained cohesion
d = Particle size
D_{10} = Diameter at which 10% of particles are finer
D_{50} = Diameter at which 50% of particles are finer
D_{90} = Diameter at which 90% of particles are finer
e = Void ratio
G_s = Specific Gravity
GSD = Grain size distribution
MDD = Maximum Dry Density
N = Percentage fines
OMC = Optimum Moisture Content
ϕ_u = Undrained Angle of internal friction
p = Effective Stress
σ = Normal Stress
τ = Shear Stress
w = Water content
γ_d = Dry Density
γ_{dmax} = Maximum Dry Density

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