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ORIGINAL RESEARCH

Influence of gradation and proportion of sand on stress–strain behavior of clay–sand mixtures

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Abstract

To investigate the influence of proportion of sand as well as its gradation on the undrained strength behavior of soils, undrained tests on statically compacted specimens of clay–sand mixtures were carried, with two extreme clay minerals, namely commercially available kaolinite and bentonite mixed with specimens of three grades of sand fractions, and also varying their proportion from 10 to 80%. This work was extended to two natural soils, viz., Red earth (kaolinitic type) and B.C. soil (montmorillitic type) by using fractionized fine portion from these soils obtained by sedimentation process, and later mixed with different proportions and grades of sand fractions. Results from this experimental investigation reveals that, at optimum sand content in clay–sand mixtures, use of medium sand fractions is more beneficial to improve the undrained strength of the mixtures irrespective of the clay mineral type being present in the mixture. It thus implies that proper selection of grade of sand is also important along with the optimum content to obtain higher strength of a clay–sand mixture. This has practical implications in understanding the performance of embankments or any ground improvement applications involving strength of clayey natural soils for better load carrying capacity, stability, and good performance of the structure supported by soil. It is also very useful in the geo-environmental applications like proper selection of proper grade of clay–sand mixtures as liners for better performance.

Keywords: Compaction, Undrained strength, Embankments, Ground improvement, Clay liners

Background

When natural soils do not meet the field requirements of a specific geotechnical application, clay is blended with coarse aggregates like sand or gravel and made suitable for the intended purpose. To cite few examples of such applications are use of compacted clay-aggregate mixtures for cores of embankment dams [1–3]. For geo-environmental projects, it has become a current practice to employ a mixture of high plastic clay with aggregates as impervious blankets Lundgren [4–7].

Earlier, most of the engineering parameters for design of structures on soil have been developed for ideal soils such as pure sands or pure clays, though the reality is that these ideal soils are rarely found in nature. In a clay–sand mixture, the engineering behaviour is quite different as compared to pure clays or sands depending on the interactions of the sand and clay present in the matrix. To meet the various practical applications of soils, a need was felt for proper understanding of the interactions of clay and coarse fractions like sand or gravel present in the soil, and hence research focus changed from ideal soils to clay–sand mixtures. In this direction, many researchers have reported the findings of the interactions of clay-granular matrix and their influence on the engineering behaviour depending on the proportion of each component (sand/gravel or clay being present in the soil [8–10] to name a few). A review of the literature indicates that though various attempts have been made by various researchers to understand the interactions of granular aggregates with clay for different engineering applications like slope stability [9], for understanding the stability of foundations for offshore oil platforms and jack up rigs [8], for understanding of earth quake liquefaction [11] and the like, in most of the studies reported in the literature the focus was mainly on understanding the relative proportions of the clay and granular fractions on the strength behaviour without considering their gradation effect. Based on this, the proportions of the granular fractions or clay content for their predominance influence on the strength behaviour of the mixtures was brought out independently by various researchers.

However, in a clay-granular mixture, its behaviour depends not only on the proportion of coarse fractions, but also on its gradation. Additionally, the behaviour may also depend on the type and amount of clay mineral present in the clay. Natural soils do contain clay mixed with sand/gravel in different proportions, and also of different gradations. The type of clay mineral present in the natural soil may vary, and hence, its influence on the soil behaviour may vary. So, any research attempt being made to study the strength properties of clay–sand/gravel mixtures taking into consideration of the gradation effect of granular fractions and clay type would be useful in understanding their strength behaviour better. In this study, the coarse fraction was restricted to the use of three different grades of sand and two extreme type of clay minerals, namely, kaolinite and Montmorillonite, usually present in natural on-shore soils, to understand the influence gradation of sand in clay–sand mixtures on the strength of compacted clay–sand mixtures.

Experimental program

Materials

In this experimental program, two commercially available clays, namely kaolinite and montmorillonite representing two extreme clay mineral types, along with two natural soils, namely one red earth representing kaolinitic soil type, and one Black cotton soil representing montmorillonitic soil type were selected and used in this study.

Red earth

The principal clay mineral present in this soil is “kaolinite”. This natural soil was obtained from BMS College of Engineering, Bangalore district, Karnataka, India.

Black cotton soil

The principal clay mineral present in this soil is “montmorollinite”. This soil was obtained from Belgaum district, Karnataka, India.

Sand

Locally available sand confirming to zone II was used for the present study. It was sun dried and sieved to separate the fractions into three types as listed below:

- Fine sand fractions (<425 μm)
- Medium sand fractions (425 μm–2 mm)
- Coarse sand fractions (>2 mm)

These three fractions of sand were used in varying proportions along with commercially available clay and fractionized fines from two natural soils to understand the gradation effect of sand on stress–strain behaviour of clay–sand mixtures.

Methods

All the soils used in this study including the two pure clay minerals were characterized for their physical properties using the standard procedures as specified by SP 36 [12] (Table 1). The particle size distribution of all the soils (except bentonite, which was 100% clay) and sand used in this study has been presented in Fig. 1. It can be seen that bentonite and B.C soil have higher value of Free Swell Ratio (FSR), indicating the presence of montorillonite clay mineral [13]. Compaction test at Proctor energy level for the selected soils was done by using mini compactor developed by Sridharan and Sivapullaiah [14].

Though triaxial shear test is frequently used because of the laterally restrained soil conditions in most geotechnical applications, but still the unconfined compression test is useful for laterally exposed conditions and applicable to fine-grained soils under undrained loading, UCC test requires a short testing time, is easy to conduct data analysis. There are many practical situations like open cuts being done in natural soils (which may be mixtures of clay–sand) which are laterally exposed for short duration and whose strength determination is needed under undrained conditions. This test is also used to get strength parameters to be used in the design of road embankments, shallow footings, and retaining walls [15]. Hence, in this study UCC test was used to determine the strength characteristics of statistically compacted sand-clay mixtures.

Unconfined compression test on statically remoulded samples was carried out as per IS: 2720-part 10 [16]. The cylindrical samples were 76 mm in height and 38 mm in diameter, thus having a height to diameter ratio of 2. This confirmed the minimum specimen diameter of 38 mm and height to diameter ratio of 2 as per the Bureau of Indian standards mentioned above.

Experimental program

Preparation of clay–sand series

In order to understand the effect of gradation of sand, and also the mineral type present in the clay on shear strength of clay–sand mixtures, the experimental program was carried out in two stages. In the first stage, pure clay minerals, namely, commercially available Bentonite and Kaolinite were used in the study. Artificial clay–sand mixtures were prepared by adding sand with pure clay in varying proportion from 10 to 80%. Three grades of sand were mixed separately with the selected clay to form six commercial clay–sand series.

Table 1 Physical properties of soils used in the present study

S. No	Soil description	Specific gravity, G_s	Liquid limit, w_L	Plastic limit, w_P	Sediment volume (cc)		Free swell ratio (FSR)[a]	Grain size distribution				I.S classification
					V_D	V_{CC14}		Gravel	Sand	Silt (size)	Clay (size)	
1	Kaolinite	2.65	50.1	28.2	12.0	31.0	0.38	0	0	45	55	MH-CH
2	Bentonite	2.72	335.0	36.2	83.0	19.5	4.25	0	0	0	100	CH
3	Red earth	2.68	42.2	22.8	12.0	10.0	1.2	1	60	31	8	SM
4	B.C Soil	2.70	82.5	58.0	17.5	9.5	1.87	0	24	41	35	MH

[a] Free Swell Ratio, FSR is defined as the ratio of equilibrium sediment volume of 10 g oven dried soil passing a 425 μm sieve in distilled water (V_D) to that in carbon tetrachloride (V_{CCL4})

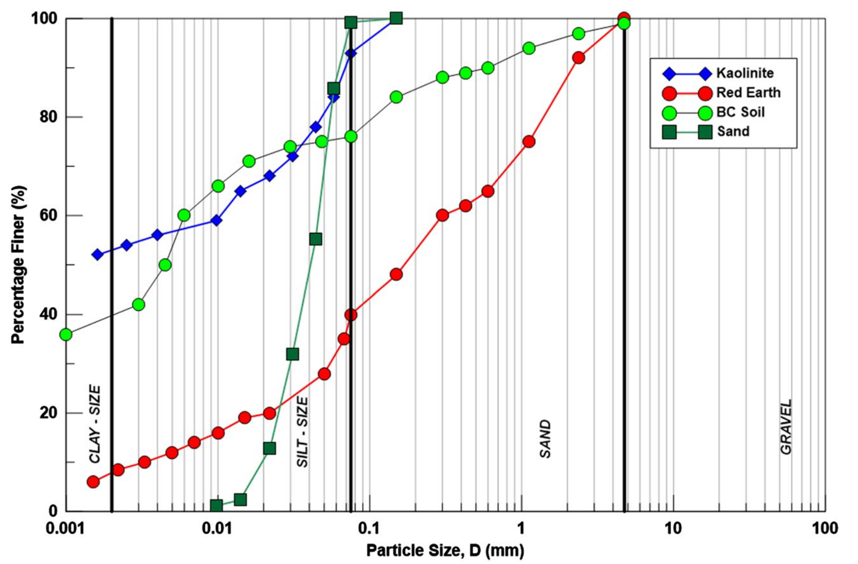

Fig. 1 Particle size distribution curves of kaolinite, *red* earth, B.C. soil and sand used in the present study

Further, in order to extend this study to natural soils, two natural soils, namely one Red earth representing kaolinitic clay type, and one B.C. soil, representing montmorillonitic clay type were used to fractionize the fines content from them (procedure is given in the following sub-section). This fine content was later used to form natural clay–sand mixtures by mixing the fractionized clay portion with sand in varying proportions in increments of 10% up to 80% by weight. Three grades of sand were mixed separately with the fractionized clays to form six sets of natural clay–sand series.

In the second stage of the experimental program, all the twelve clay–sand series were tested for evaluating their compaction (Table 2) and stress–strain properties.

Procedure of fractionization of fines from natural soils

The two natural soils were soaked with water in plastic containers (drums), and the mixture was uniformly mixed using hand for 15–20 min and allowed for some time for the coarse fractions to settle. Then the top portion of the slurry was collected and transferred to a separate tray. This process was repeated for every half a day taking care to separate fines from the soil. The collected slurry containing only fines was allowed to sediment to obtain the fines. Later, the water was decanted, and the remaining slurry containing fines portion was air dried for sufficient time to obtain flakes of fines (clay

Table 2 Compaction characteristics of soils used in the study

S. No	Soil description	Compaction characteristics	
		Maximum dry unit weight (kN/m^3)	OMC (%)
1	Red earth	14.52	29.05
2	Kaolinite	13.14	33.89
3	B.C soil	12.46	40.00
4	Bentonite	12.36	38.92

and silt). This was powdered to get a uniform mixture of fines, which was used along with the sand in varying proportions as mentioned earlier.

Sample preparation

For evaluating the unconfined compression strength for each clay–sand mixture (both for artificial and natural clay–sand mixtures) from the twelve series as explained earlier, 38 mm diameter cylindrical samples with a height to diameter ratio of 2 were prepared using a static compactor at their respective optimum moisture obtained from the compaction test.

Unconfined compression test

All the samples prepared as explained above were tested in a UUC test apparatus adopting a strain rate of 0.25 mm/min. The load reading were recorded at regular intervals of axial strain till the sample reached a peak value and started showing receeding values of load. All the samples failed within 20% of strain except for samples with bentonite and BC soil, wherein the failure load was reckoned at 20% axial strain. The UCC strengths were calculated based on the angle of failure plane obtained from the failed specimens.

Results and discussion

Figures 1, 2, 3, 4 and 5 are plots of UCC strength versus sand content respectively for the Kaolinite-sand series, Bentonite–sand series, Red earth-sand series, and B.C. soil-sand series. It can be observed from all the figures that, in general, there is an increase in the UCC strength with an increase in sand content up to 40 or 50%, and further increase in sand content has lead to decrease in the strength. The When the proportion of fine particles (i.e. clay) is more, the coarse particles (i.e. sand) float inside the matrix of fine particles, and hence, the fines dominate the mechanical behavior of the clay–sand mixture,

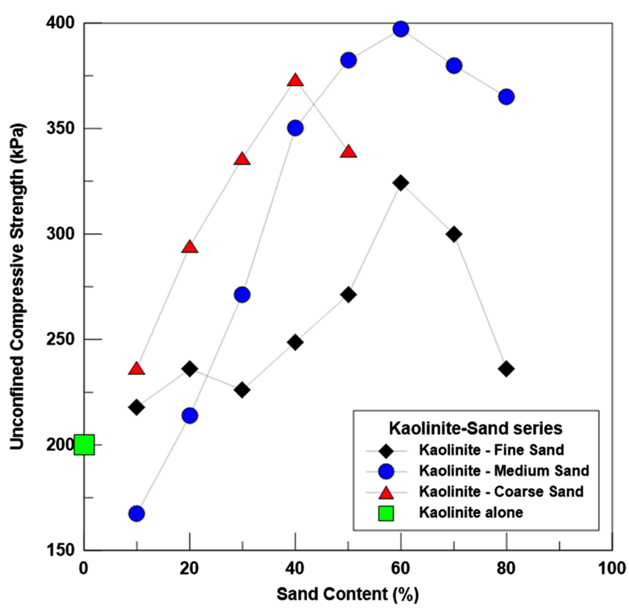

Fig. 2 UCC strength versus sand content for kaolinite-sand series with different grades of sand

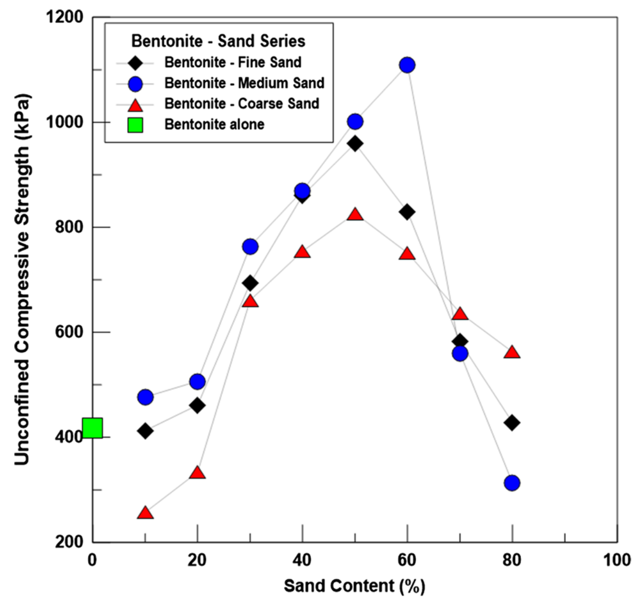

Fig. 3 UCC strength versus sand content for bentonite–sand series with different grades of sand

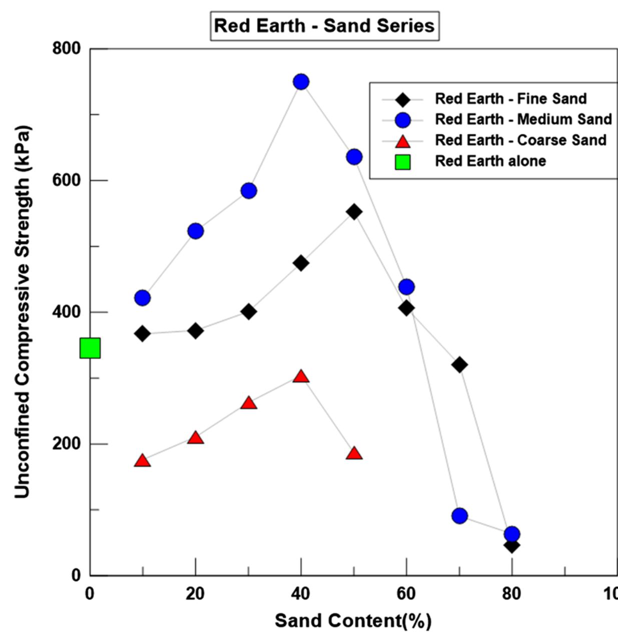

Fig. 4 UCC strength versus sand content for *red* earth–sand series with different grades of sand

and the coarse grains may or may not contribute to shear resistance as a reinforcing element. The threshold value for the soil mixture to reach this condition depends on the specific mixture, but is usually in the range of 25–45% fines in most cases [8, 10, 11, 15, 17, 18]. Similar influencing behavior of clay in the soil mixtures containing coarse particles mixed with clay in varying proportions has been reported by other researchers

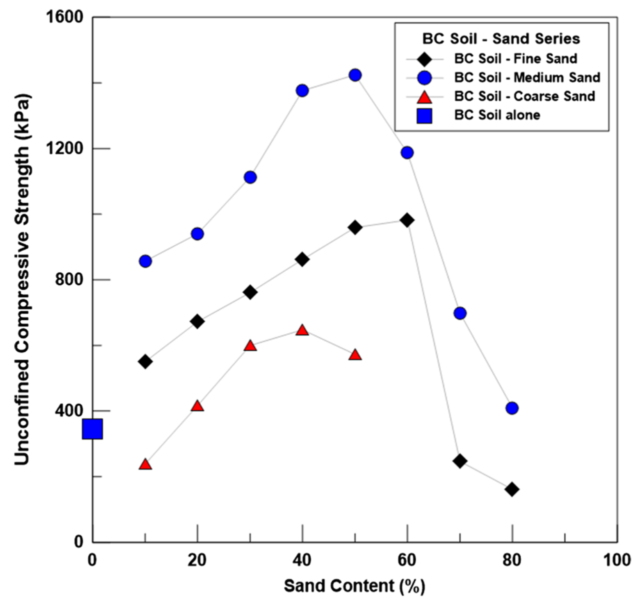

Fig. 5 UCC strength versus sand content for B.C. soil–sand series with different grades of sand

[19–23]. Prakasha and Chandrasekaran [8] reported that inclusion of sand grains in a clay matrix leads to an increase in pore pressure resulting in a decrease in undrained shear strength. Khan et al. [15] opined that because of increased material heterogeneity and loss of sand grains from the sides during shearing there was a reduction of strength with an increase in proportion of sand beyond a certain optimum. However, the author feels to add that when sand content is optimum in the clay–sand matrix, the interaction between the sand and clay may be more, leading to maximum mobilization of strength from clay in the form of cohesion, and in the form of friction from sand. This combined contribution towards mobilization of strength will be less with further increase in sand content. It can be further seen that, when the clay is montmorillonitic type, which is more plastic clay, the strength mobilized is higher than that of kaolinitic type clay. This is because Montmorillonite clay which is having more plasticity would have contributed to more cohesion than kaolinite clay which is having relatively less plasticity.

Now coming to the effect of gradation of sand on the strength, it can be seen for any type of clay used in this study, the gradation of sand has shown a significant influence on the strength of clay–sand mixture at any percentage of sand. The gradation effect is prominently seen with natural clay–sand series rather than artificial clay–sand series. It can be further observed from the figures that maximum strength at the optimum level of clay–sand combination, clay-medium sand mixtures have shown to have maximum strength, followed by clay-fine sand and clay-coarse sand mixtures. An exception to this behavior is only kaolinite-sand series, where clay–coarse sand series has shown higher strength when compared to medium and fine sand series. This may be explained based on the observations reported by Prakasha and Chandrasekaran [8], that inclusion of sand grains in a clay matrix leads to an increase in pore pressure resulting in a decrease in undrained shear strength. Probably, in the presence of lesser quantity coarse sand fractions in pure kaolinite clay, the pore pressures developed may be less compared that of medium sand and fine sand. However, at optimum sand content, kaolinite- medium sand has shown to have higher strength than kaolinite clay-coarse sand. More detailed studies may throw light on this aspect of clay–sand interactions with different grades of sand. Further, it was observed that, it was not possible to prepare clay-coarse sand specimens when the sand content was above 60%, except in the case of bentonite-coarse sand series. Hence, the results could not be obtained for those percentages of sand i.e., 70 and 80% sand. It is to be noted that, since this was a preliminary attempt to understand the effect of gradation of sand clearly, this study was restricted to use of individual grades of sand and not in combination.

Conclusions

Results from this experimental investigation reveals that, at some optimum content of sand along with clay, use of medium sand fractions is more beneficial to improve the undrained strength of clay–sand mixtures irrespective of the clay mineral type being present in the mixture, thus implying that proper selection of grade of sand is also important along with the optimum content to obtain higher strength of a clay–sand mixture. This has practical implications in the design of embankments or any ground improvement applications involving strength of clayey soils for better load carrying capacity, stability, and good performance of the structure supported by soil.

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Competing interests
The author declares that he has no conflict of interest.

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