The Mechanical Properties and Microstructure of Reticulated Red Clay-Sand Mixture Using X-Ray Diffraction

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Abstract. To assess the behavior of Reticulated Red Clay (RRC)-sand mixtures, a series of laboratory tests were performed on RRC-sand mixtures in which the weight ratio of sand ranging from 0% to 80%. Compaction test and direct shear test were conducted to evaluate the compactness of mixtures. The threshold sand content for the change of the mechanical properties of the mixture is 50%, and the mixture at this time has the densest structure. Oedometer test to the mixture indicate that the coefficient and compression modulus of it are only related to the ratio of its components. As the sand content in the mixture increases, the phenomena that the clay particles enclosing the sand particles and filling into the gaps of particles make the mixture denser. During the same time, there is a phenomenon of internal friction between sand particles caused by the inadequate wrapping of clay particles. Combined with the results of scanning electron microscopy and optical microscopy, the appearance of these phenomena and the transition process of the structure of the mixture from the clay structure to the sand structure were confirmed.

1. Introduction

Reticulated red clay, a special clay widespread in the middle and lower reaches of Yangtze River in China, has a distinct feature of red and white reticular formation. Complex and changeable fractions and mineral compositions of natural sedimentary soils were greatly affected by water content and historical conditions. (Chu et al., 2017) The RRC on the ground is generally uniform in texture and is composed of fine grains with uniform particle size distribution, high shear strength, poor compressibility and low porosity. However, the RRC under the ground turns out to be heterogeneous for the sand becomes the major constituent of the mixture. It is obviously unreasonable to name reticulated red clay in a large vertical span as the same kind when the site investigators carry out the naming of drilling and coring. The mixture of clay and sand, also named intermediate soil, boasts different mechanical properties as the mixing ratio varies. Therefore, the mechanical properties of the intermediate soil formed by mixing reticulated red clay with sand need to be tested.

Before this paper, many researchers have conducted studies upon mixed coarse- and fine-grained soil and clay-sand mixture. (Karim et al., 2017) found it was at 30% fine grain content that the mixture
changed its behaviors. (Vallejo and Mawby, 2000) affirmed that 40% and 75% were the thresholds that could lead to the mixture’s changes in mechanical properties. In Nagaraj’s assumption (Nagaraj, 2016), the mixture composed of kaolinite, bentonite and sand boasted the highest unconfined compression strength when the sample contained 40%–60% sand. By studying the mechanical properties of kaolinite clay-sand mixture, Simpson and Evans (Simpson and Evans 2016) held that the reason why the mixture changed from "sand-like" to "clay-like" was related to measuring conditions instead of being fixed. As to Cabalar et al. (Cabalar, 2010; Cabalar and Hasan, 2013; Cabalar and Waleed, 2015), they studied the mixture’s properties of liquid limit and undrained shear strength and proposed that the undrained shear strength of clay-sand mixture had nothing to do with sand grading. And Dafalla (Dafalla, 2013) proved that the shear strength of clay-sand mixture was affected by clay content, as its increases within a relative low level, for instance, 5% and 10%, would lead to the rise in cohesion; while its increases over 20% would decrease the cohesion. Since the former research results do not offer a universally applicable conclusion, it is necessary to do further study on the impacts of different sand contents upon the mechanical properties of clay-sand mixture.

The experimental procedures of this study are as follow: first, add sand into RRC with varying weight ratios of 0, 10, 20, 30, 40, 50, 60, 70 and 80%; second, measure grain sizes of RRC and sand through sieve analysis and laser grain-size analyzer; third, measure the liquid limit and plastic limit of RRC-sand mixture by liquid-plastic combine tester; fourth, measure the maximum dry density and the optimum moisture content of the mixture through compaction test; fifth, measure its shear strength by direct shear test; sixth, measure its coefficient and modulus of compressibility by standard oedometer test; seventh, through the analysis of the results of laboratory tests and engineering experience, four different particle contact forms and thresholds for the behavioral changes of the mixture in the adding sand process. Finally, the microstructure of the mixed soil was observed by optical microscopy and scanning electron microscopy, and the proposed conjecture was verified. All the laboratory tests are performed in accordance with “Standard for Soil Test Method (GB/T 50123-1999)”.

2. Experimental

2.1. Materials

RRC samples came from the south foot of Yuelu Mountain in Changsha, Hunan Province, while sand samples came from the river sand of Xiangjiang River (Li et al. 2018a, 2018b). To identify the elemental mineral composition of RRC samples, the author conducted an X-ray diffraction analysis, the result of which (shown in Fig. 1) indicating the undisturbed soil was composed of 52% illite, 19% montmorillonite, 18% chlorite and 11% kaolinite.

![Figure 1. XRD Results of RRC](image-url)
2.2. Sample Preparation
The particle size distribution of sand and RRC after 2-mm sieve analysis and laser grain-size analysis was presented in Fig. 2. And grain gradation indexes as effective diameter d10, constrained diameter d60, nonuniform coefficient Cu, curvature coefficientCc and elemental mechanical properties of RRC and sand samples summarized from Fig. 2 were presented in Table 1 and Table 2, by which shown that the RRC samples were uniform soil and sand samples were well-graded. (When soil has its Cu under 5, it is called uniform soil and poorly graded; while when soil has its Cu over 10, it is called well-graded. For sandy soil, it can be called well-graded when its Cc is 1~3 and Cu ≥5.) To get 9 experimental groups, the author added sand into RRC with varying weight ratios of 0, 10, 20, 30, 40, 50, 60, 70 and 80% and put the samples into sealing bags to make them well-distributed by continuously stirring and shaking. Taking dry density of 1.6g/cm³ as the control standard, the author made the samples for direct shear test and oedometer test by layer-by-layer compaction and then cutting the samples with φ61.8mm-cutting ring after 1-day vacuum saturation.

| Reticulated red clay | Water content (%) | 24.7 |
|----------------------|-------------------|------|
|                      | Plastic limit (%) | 23.8 |
|                      | Liquid limit (%)  | 43.9 |
|                      | Specific gravity  | 2.71 |
|                      | Density (g/cm³)   | 1.90 |
|                      | Cohesion (kPa)    | 70   |
|                      | Friction angle (°) | 23   |

| Sand            | Specific gravity | 2.63 |
|-----------------|------------------|------|
|                 | Density (g/cm³)  | 1.62 |

Figure 2. The Grain Grading Curves of RRC and Sand
2.3. Compaction Test
This test was to measure the mixture samples’ maximum dry density and optimum moisture content. The compaction energy per unit volume of proctor compaction test was 592.2 kJ/m$^3$. The specifications of the compaction test apparatus’ main components include: a) Hammer bottom diameter was 51mm. b) Hammer mass was 2.5 kg. c) Hammer drop height was 305 mm. d) Inner diameter of compact cylinder was 102 mm. e) Height of compact cylinder was 116 mm.

**Table 2. The Particle Size Distribution.**

| Reticulated red clay | $d_{10}$ (mm) | 0.0018 |
|----------------------|---------------|--------|
|                      | $d_{30}$ (mm) | 0.0032 |
|                      | $d_{60}$ (mm) | 0.007  |
|                      | $C_U$         | 3.89   |
|                      | $C_C$         | 0.81   |

| Sand | $d_{10}$ (mm) | 0.075 |
|------|---------------|-------|
|      | $d_{30}$ (mm) | 0.22  |
|      | $d_{60}$ (mm) | 0.76  |
|      | $C_U$         | 10.4  |
|      | $C_C$         | 0.84  |

2.4. Direct Shear Test
This test was to measure the cohesion and internal friction angle. Put four prepared samples into unconsolidated-undrained quick shear equipment respectively at vertical pressures of 100, 200, 300, 400 kPa, with the equipment’s shear rate at 0.8 mm/min, and kept shearing until the appearance of peak value or the shear deformation of samples reaching 6mm.

2.5. Oedometer Test
This test was to measure the mixtures’ compressibility indexes, including compressibility coefficient ($a_v$), compressibility modulus ($E_s$), and porosity ($e$). With a leverage ratio of 1:12, the author put 30 cm$^2$ prepared sample into the consolidometer and respectively applied upper loads of 12.5, 25, 50, 100, 200, 400 kPa on the sample, each for 24 hours. As there was no need for the measurement of settling rate, the reading of every 24 h displacement meter was taken as the final settling amount.

2.6. Observation
Firstly, use optical microscope to observe the sample’s macrostructure by taking low-magnification photographs. Secondly, cut the prepared sample into rectangular sections of 5mm$^2$ large and 1mm thick and make them conductive by spraying the vacuum sections after being quick frozen by liquid nitrogen and sublimated. Thirdly, use scanning electron microscope to observe the sample’s microstructure.

3. Results and discussion

3.1. Compaction Test
Given the results of compaction test presented by Table 3, the process of adding sand into RRC had made huge impacts on the compaction characteristics of the mixtures. As the sand content increases, the maximum dry density of the mixture would increase, while its optimum moisture content, liquid limit
and plastic limit all decreased. When the sand content was relatively low, all compaction test indexes changed fast, while the changing rate slowed down with the rise of sand content. Therefore, the conclusion could be drawn that the sand content had a positive correlation with compactness to a certain extent and had a negative correlation with water retention characteristic, which corresponded to the former research finding, that is, the liquid limit decreased linearly with clay content (Nagaraj et al.,1987; Tan et al.,1994; Boutin et al.,2011).

| Sand content (%) | Plastic limit (%) | Liquid limit (%) | Optimum moisture content (%) | Maximum dry density (g/cm³) | Specific gravity |
|------------------|-------------------|-----------------|-------------------------------|-----------------------------|-----------------|
| 0                | 23.5              | 40.7            | 20.2                          | 1.54                        | 2.71            |
| 10               | 24.1              | 41.8            | 20.5                          | 1.57                        | 2.70            |
| 20               | 23.9              | 40.9            | 19.9                          | 1.63                        | 2.69            |
| 30               | 22.1              | 38.2            | 20.1                          | 1.68                        | 2.69            |
| 40               | 20.8              | 35.4            | 16.8                          | 1.72                        | 2.68            |
| 50               | 20.1              | 34.3            | 16.8                          | 1.76                        | 2.67            |
| 60               | 19.2              | 32.4            | 16.1                          | 1.73                        | 2.66            |
| 70               | 18.8              | 31.7            | 15.7                          | 1.70                        | 2.65            |
| 80               | 18.3              | 30.8            | 15.4                          | 1.68                        | 2.65            |

### 3.2. Direct Shear Test

The cohesion and internal friction angle of the mixtures of different sand contents measured by the test were presented in Fig.3, in which the internal friction angle rarely changed when the sand content varies between 0-10%, while when the sand content varied between 10-60%, the internal friction angle increased in a faster rate and it would increase even faster when the sand content was over 60%. As to cohesion, it decreased from 75 kPa to about 60 kPa when the sand content increased from 0% to 20%. But when the sand content was over 20%, the cohesion gradually increased and reached its peak when the sand content increased to 50%. And when the sand content exceeded 50%, the cohesion would drop sharply. Since the mixture had its maximum dry density reaching the peak at the same time when boasting the highest shear strength, the author held that the sand content of 50% should be identified as the point when RRC and sand were in the tightest combination. However, this conclusion differed from 40% proposed by Vallejo LE et al. (2000) as well as 30% proposed by Karim et al. (2017), which might be explained by different choices of experimental materials, as this study chose RRC composed of illite, montmorillonite, chlorite and so on instead of pure clay taken by other researchers. For RRC-sand mixture, it should be 50% sand content that served as the threshold changing the mixture’s macroscopic mechanical properties. The process of adding sand would increase the mixture’s cohesion and the internal friction of grains as long as the sand content
remaining under 50%; while this process could also dramatically decrease the mixture’s cohesion and greatly enhance the internal friction of grains as long as the sand content exceeded 50%

![Figure 3. Internal Friction Angle and Cohesion of Mixture](image)

3.3. Oedometer Test
The result of this test presented by Fig.4 shown that the mixture’s void ratio was correlated to sand content as the porosity of RRC-sand mixture was less than that of pure clay. With the increase of sand content, the value of void ratio would decrease and reach its minimum value at 50% sand content and gradually rose when the sand content exceeded 50%. And Fig.5 indicated the correlation between the mixture’s porosity and vertical stress under different sand contents. When the vertical stress was 100-200 kPa, the slope of the curve represented the mixture’s compressibility coefficient, while the mixture’s compressibility modulus should be

\[
E_s = \left(1+e_0\right)/a_v
\]

(1)

![Figure 4. Pore Ratio of RRC-Sand Mixture](image)

In the equation, \(E_s\) represents the modulus of compressibility, MPa; \(a_v\) represents the coefficient of compressibility, MPa-1; \(e_0\) represents the initial void ratio.
Figure 5. Variation of Pore Ratio under Different Vertical Stress

Fig 6. The Corresponding Compression Coefficient and Compression Modulus when the Vertical Stress is 100-200kPa

Fig.6 indicated the coefficient and modulus of compressibility of each sample. With the increase of sand content, the mixture’s compressibility modulus would increase and the mixture’s compressibility coefficient would decrease, the maximum and minimum values of which would gradually approach the values of pure sand and pure clay. Therefore, the mixture’s coefficient and modulus of compressibility were correlated to nothing but the ratio of its constituents.

3.4. Scanning Electron Microscope
The prepared samples of various sand contents of 0, 10, 20, 30, 40, 50, 60, 70 and 80% were observed by scanning electron microscope and optical microscope, the results of which presented by Fig.7 and Fig.8 had confirmed the author’s assumptions. By Fig. 7(b). and Fig.7(c)., it could be seen clearly how the clay grains wrapped the sand grains to form larger grains and how the small clay grains filled into the gaps of large grains. Fig. 7(a). shown that how the inadequate wrapping of clay grains led to
the increase of internal friction among grains by enlarging the contact area among sand grains. In Fig. 8(a) and Fig. 8(b), the RRC’s platy structures had become increasingly compacted. And Fig. 8(c) indicated that the mixture boasted the highest density at 50% sand content as the filling of grains made the mixture’s pores much smaller. However, the rising of sand content, as presented in Fig. 8(d) and Fig. 8(e), would produce larger gaps since the inadequate wrapping of clay grains enlarged the contact area among sand grains.

Figure 7. Optical Microscope Observation Results of RRC-Sand Mixture: (a) Sand content 0%, (b) Sand content 20%, (c) Sand content 50%, (d) Sand content 80%

Figure 8. SEM Observation Results of RRC-Sand Mixture (left:500×, right:2000×): (a) Sand content 0%, (b) Sand content 20%, (c) Sand content 50%, (d) Sand content 60%, (e) Sand content 80%
3.5. Discuss
Based on the results of former tests, several assumptions were made. When the sand content is relatively low, that is, 0%~20%, the mixture, basically belonging to clay-structure, has its mechanical properties enhanced for the formation of bigger grains, firstly by the clay grains enclosing the sand grains and then by the formed bigger grains being combined together by the clay’s cements. When the sand content increases from 20% to 50%, the mixture is gradually evolving from clay-structure to sand-structure, as the smaller grains filling into the gaps of bigger grains to make the mixture denser and its structure more stable. When the sand content is over 50%, the mixture’s cohesion would decrease for coarse and rough sand grains bear most of the external forces with gradual formation of clay-skeleton. This conclusion also applies to the articles of Hong, Z.S. et al.; Tripathi, K.K. et al.; Watabe, Y. et al. and Wang, Q. et al.

4. Conclusion
To study the impacts of various sand contents upon the mixture’s mechanical properties, this research has made 9 groups of RRC-sand mixture by adding common river sand into RRC with varying weight ratios of 0, 10, 20, 30, 40, 50, 60, 70 and 80%. After several tests, the conclusions are drawn as follow:

1) The mechanical properties of reticulated laterite with different proportions of sand are quite different, which can be reflected in the parameters of maximum dry density, internal friction angle and cohesion. Therefore, the logging personnel at the project site need to roughly describe the particle size of the sample taken from the borehole to prevent engineering accidents caused by recording problems during the investigation.

2) Compaction test shows that the RRC-sand mixture’s maximum dry density is closely correlated to sand content and it is at 50% sand content that the value reaches its peak.

3) When sand content is less than 50%, the mixture would have a structure that is more stable and can bear more external forces because of the wrapping and filling of clay grains. While when sand content is more than 50%, the inadequate wrapping of clay grains enlarges the contact area among sand grains and thus leads to the increase of internal friction angle.

4) During the process of adding sand, the phenomena that the clay particles enclosing the sand particles and filling into the gaps of particles make the mixture denser. The phenomenon of internal friction between sand particles caused by the inadequate wrapping of clay particles Increase the internal friction angle of the mixture. In the process of adding sand, the structure of the mixture changes from clay structure to sand structure.

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