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Influence of structure on the compression and shear behaviour of a saturated lateritic clay

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Abstract

Lateritic clay is well recognized to contain significant amount of iron and aluminum oxide (sesquioxide), which would affect soil structure greatly. The influence of the sesquioxide-dependent structure on the mechanical behaviour of soil is not well investigated. The influence of structure on the compressibility and shear behaviour of a lateritic clay sampled from a granitic parent rock has been studied. Tests including oedometer, isotropic compression and consolidated undrained shear tests were conducted on saturated intact, recompacted and reconstituted specimens. Additionally, mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) techniques were used to provide insight into the microstructure of the specimens. Results show that the compressibility of the recompacted and reconstituted lateritic specimen is about 90% larger than the intact specimen. The post-yield normal compression line of the three specimen continue to diverge and no sign of convergence was observed, different from soft clay. The peak shear strength of the intact specimen is about 100% higher than those of the reconstituted/recompacted specimen. Phase transformation was observed only in the intact specimen. The SEM results showed that the diameter of the aggregates is about 90% larger in the intact specimen than both reconstituted and recompacted specimen. The particle contacts involved in the load bearing are therefore larger in the intact specimen compared to the other specimen. Hence, the intact specimen becomes less compressible and showed higher dilative tendency than both recompacted and reconstituted specimens.

Keywords: Aggregates, sesquioxide, compressibility, phase transformation and critical state.

Introduction

Lateritic clays are weathered materials widely distributed in tropical areas and extensively used as construction materials in geotechnical projects. The lateritic clay often contains some secondary minerals that are rich in oxides of iron and aluminum oxides (sesquioxide) (Alexander and Cady, 1962). These minerals and sesquioxide are well recognized to possess cementing influences and enhance formation of soil aggregates (Schwertmann & Fitzpatrick, 1992; Zhang et al., 2016). Due to these aggregates, the lateritic clay may develop a complex structure in situ. However, it is not clear how the aggregated structure is affected by different method of preparation e.g. recompacting or reconstituting. The influence of the mineral and sesquioxide content in lateritic clays on its structure and mechanical behaviour are not well-understood.

Soil structure is a terminology commonly used to define the combination of the arrangement of the individual particles (fabric), and bonding /cementation between the particles that are not of a purely frictional nature (Mitchell & Soga, 2005). The structure of a soil is a function of the mode of weathering, deposition and specimen preparation technique. Every soil in any state, either intact, recompacted or reconstituted have a structure. According to Burland (1990), reconstituting a clay specimen at 1.5 times the liquid limit and consolidating under one dimensional conditions can bring a clay specimen to a fully de-structured state. This understanding is well-known and has been proven to be valid for several clay specimens with different form of deposition other than sedimentary (Xu & Coop, 2016; Gasparre & Coop, 2008;

Cai et al., 2018). Comparing the behaviour of the intact and recompacted specimen with the reconstituted behaviour can provide insights into the significance of soil structure on compressibility and shear strength of lateritic clay. However, such studies on lateritic clay has rarely been investigated by previous researchers.

Very few researchers have investigated the compressibility and shear strength of saturated intact and recompacted lateritic clay. Futai et al. (2004) studied the shear strength of a saturated intact and recompacted lateritic clay. The authors observed that there is no significant difference in the shear strength of the intact and recompacted specimen. On the contrary, Fagundes and Rodrigues (2015) studied the shear strength of a saturated intact and recompacted lateritic clay and observed higher shear strength in the recompacted specimen than the intact specimen. Presently, there is no clear understanding on how the behaviour of the intact lateritic specimen differ from that of the recompacted specimen. A good understanding of their mechanical behaviour, such as compressibility and shear strength, can aid in improving the designs of civil engineering structures built on lateritic soils.

Previous studies of lateritic clays have established that their behaviour was highly influenced by the parent rock and the presence of large-sized aggregates formed by the influence of sesquioxide content (Ng et al., 2019). It is still unclear how different specimen preparations affect the microstructure and consequently their mechanical behaviour. Moreover, there have been relatively few attempts to comprehensively understand the effects of structure in lateritic clays using similar techniques for other clays (e.g., Burland 1990). The composition and properties of lateritic clays is a function of location, parent rock, climatic condition and mineral types.

In this study, the influence of structure on the compressibility and shear strength of a lateritic clay (LAT) from a granitic parent rock was investigated. An intact, recompacted and reconstituted lateritic clay was tested at saturated condition using oedometer and triaxial apparatus. In addition, microstructural investigations were carried out using the mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) techniques. The frame work defined by Burland (1990) for natural clays was used to investigate, for the first time, the influence of structure on lateritic clay. Also, critical state framework, not commonly investigated in lateritic clays was adopted in interpreting the shear behaviour.

Soil properties

A lateritic material weathered from a granitic parent rock in South West Nigeria, Africa was studied. Both intact and disturbed samples were collected at 1.5m depth and the in-situ water content was 9%. Figure 1 shows the grain size distributions (GSD) determined following the ASTM procedures (ASTM, 2011). The GSD was measured using both dry sieving method (sieving air-dried soil) and wet sieving method. For the wet sieving, two analysis were conducted. The first analysis was sieving soil in water only whereas the second involves sieving the soil in water with dispersant added to separate soil particles from aggregates. It can be seen from the figure that there is a significant difference between the GSDs measured using the three methods. The difference in the GSDs suggests that most of the granular particles in the material were aggregates which can be separated easily using water or dispersant.

The physical properties of the studied soil determined from wet sieving without dispersant are summarized in Table 1. The results shows that the soil contains 42% sand, 16% silt and 42% clay fines with a plasticity index of 20%. According to the unified soil classification system (ASTM, 2011), the soil is classified as sandy lean clay.

The average quantity of chemical composition in the tested soil was measured using X-ray Fluorescence (XRF) tests. The quantity of iron oxide and aluminum oxide (sesquioxide) in the soil is estimated as 38%. Further details about the mineral types can be found in Ng et al., 2019.

Specimen preparation

Three different sample types were studied, namely intact, recompacted and reconstituted specimen. For each sample, four specimens were prepared to give a total of 12 specimens prepared in this study. The intact specimen was carefully trimmed vertically on a hand lathe to the required dimensions of 76 mm diameter and 152mm length (triaxial) and 76 mm diameter and 20mm length (oedometer). The initial void ratio was estimated using the dimensions of the specimen after trimming. The void ratio was validated by measuring the water content of the specimen after testing and by back calculating the measured volumetric strain. The variation in the value of void ratio between the two methods was found to be less than ±0.03. The initial dry density corresponds to about 95% of the maximum dry density (1.6 g/cm^3) and water content was 9%.

For the recompacted specimens, disturbed and dried specimen was compacted to the same dry density and water content of the intact specimen using the static compaction method. The under compaction method proposed by Ladd (1978) was adopted to prepare uniform specimen. The void ratio measurement was carried out following similar approach described earlier. The reconstituted specimen was prepared by mixing a dry soil with de-aired water to a gravimetric water content of 1·5 times the liquid limit. The essence of reconstituting is to completely destroy the structure (fabric and possible bonding) of the intact specimen. The mixture was poured in a one dimensional consolidometer and consolidated to the effective vertical stress of 100 kPa.

To investigate the microstructure, three specimens were prepared to represent each sample type and prepared in same manner as those described above. After preparation, each specimen was tested directly using MIP and SEM. Before the MIP and SEM tests, cubic specimens of about 5 mm dimensions were trimmed from each specimen and freeze-dried to remove the pore water.

For the oedometer tests, all specimens were saturated in a desiccator de-aired water inside the oedometer chamber subjected vacuum conditions of about 80 kPa suction for 24 hours. The degree of saturation was confirmed by measuring the water content of each specimen and it was found that the specimens were fully saturated. In the triaxial tests, specimen were flushed with CO_2 before application of back pressure. The minimum back pressure used in all the test was 250kPa and minimum B value achieved for all the saturated specimen is 0.97.

Testing program

For each soil, two series of tests were designed and carried out using an oedometer and a triaxial apparatus. The first series is one dimensional and isotropic compression tests for investigating soil compressibility. The other series is consolidated undrained (CU) tests for studying shear strength. Details of the tests are summarized in Table2 and 3. In CU tests on each specimen, two confining stresses (50 and 200 kPa) were considered. Moreover, the microstructure of each specimen were investigated using mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) tests, respectively. The microstructure observation was used for interpreting experimental results of compression and shear tests.

Results and Discussion

One dimensional and isotropic compression behaviour

Figure 2a shows the results of oedometer compression test on intact, recompacted and reconstituted lateritic specimen. All the specimen shows a slight pre-yield behaviour before reaching a yield point. After yielding, the compressibility increases substantially and a post yield compression line can be determined. The slope of the post yield compression line (Cc) is

0.09, 0.18 and 0.25 for the intact, recompacted and reconstituted specimen respectively. The values of Cc imply that compressibility of the recompacted and reconstituted specimen is about 2 times larger than that of the intact specimen. The intact specimen is about 19% less compressible than a clean sand (Shipton & Coop, 2012). Figure 2b shows the isotropic compression test result of the intact, recompacted and reconstituted lateritic specimens. For the reconstituted specimen, no yield was observed as the specific volume continously decreased with increasing mean effective stress. On the other hand, the intact and recompacted specimen showed both pre-yield and post yield behaviour. A slight change in void ratio is first observed as the mean effective stress increases until a yield point is reached. On yielding, compressibility increases gradually. The values of the preconsolidation pressure was estimated to be 60kPa and 70kPa for the recompacted and intact specimen respectively. The slope of the post-yield normal compression line (λ) of each specimen was estimated as 0.043, 0.080 and 0.093 for the intact, recompacted and reconstituted specimen respectively. These values suggest that the reconstituted specimen is the most compressible among the three specimen. The trend of compressibility index of the three specimen is similar to the observation during the oedometer compression shown in Figure 2a. The compressibility of the reconstituted and recompacted specimen is about 2 times larger than that of the intact specimen. The values of the compressibility index and the preconsolidation pressure obtained in Figures 2a and 2b are summarized in Table 2.

Further inspection into both Figure 2a and 2b reveals that the compression curves of all the specimen seem to diverge as effective stress increases. No sign of convergence is observed as at 3MPa maximum vertical effective stress and 800kPa maximum mean effective stress in this study. The diverging compressibility of both intact and recompacted specimens from the reconstituted specimen suggests that structure effect is significant and that the yielding process was not yet complete. Otalvaro et al. (2015) observed converging compressibility during one dimensional compression test on a reconstituted and recompacted lateritic clay. The difference between the compression behaviour observed in this study and Otalvaro et al. (2015) may be due to the influence of the parent rock. While granite is the parent rock (igneous) of the lateritic clay in this study, Otalvaro et al. (2015) lateritic clay was from a Paranoa meta sedimentary rock. Since the sedimentary rock are formed from igneous rock, structure effect may be more pronounced on the lateritic clay from igneous rock than from a sedimentary rock.

Compared to another intact lateritic clay from 1m depth and a gneiss sedimentary parent rock (Futai & Almeida, 2005), the intact lateritic clay in this study is about 50% less compressible . The difference in compressibility may arise from the difference in parent rock. Granite is an intrusive igneous rock which has higher compressive strength than sedimentary rock (Mukherjee, 2012). As a result, the grains of the studied lateritic clay may be harder and more resistant to compressive forces, hence, low soil compressibility. Another possibility is the influence of degree of weathering which may arise from the difference in sampling depth. The depth of the intact lateritic clay in this study is at 1.5m while the lateritic clay in Futai & Almeida (2005) is from 1m depth. The difference suggest that the lateritic clay in this study is less weathered and may contain more features of the parent rock. As a result, the intact specimen in this study may have a stiffer structure which gives it a lower compressibility. More discussion about the compressibility of the lateritic clay is given later using microstructural evidences.

The influence of structure on the compressibility of lateritic clay

To better understand the influence of structure on the compressibility of intact lateritic specimen, the concept of void index (Iv) proposed in Burland (1990) is used as a normalizing parameter. The void index is calculated using eq. (1)

$$Iv = \frac{e - e*_{100}}{e*_{100} - e*_{1000}} \qquad (1)$$

where e^*_{100} and $e*_{1000}$ are the void ratios on the reconstituted specimen at 100 and 1000 kPa, respectively. Figure 3a shows the plot of void index (Iv) against vertical effective stress for the intact, recompacted and reconstituted lateritic specimen. The intrinsic compression line (ICL) and sedimentation compression lines (SCL) for natural clays defined by Burland (1990) are included in the figure to highlight the effect of structures. The ICL correspond to the compression line of reconstituted clays while the SCL corresponds to the in-situ compression line of normally consolidated natural clays (Burland, 1990). It can be seen that the reconstituted and recompacted specimens appear to agree with the ICL defined in Burland (1990). The slope of the ICL is similar to the slope of the reconstituted and recompacted specimen and it appears they may converge with the SCL at high stress not reached in this study. Even though the ICL was defined using sedimentary clays while the lateritic clay has a different mode of formation, it appears the ICL is not influenced by mode of deposition or mineralogy. Furthermore, it can be seen that the influence of structure is similar both in reconstituted and recompacted lateritic specimen. For the intact specimen, the compression line reach state outside the SCL defined in Burland (1990). The behaviour of the intact specimen indicates that the effect of structure is significant, which is attributed to the cementing influence of the sesquioxide in the lateritic specimen. Another possibility may be due to the mode of formation (chemical weathering) which is different from the sedimentary clay formation tested in Burland (1990).

Figure 3b shows the void index plot against mean effective stress for the three lateritic specimen studied. The limitation of the Burland void index is that it was defined only in terms of vertical stress for one-dimensional compression (Coop and Cotecchia, 1995). In this figure, the one dimensional ICL and SCL was converted to isotropic compression curve by using k_o value of 0.33. The determination of the critical state friction angle used in estimating k_o will be discussed during shearing. The resulting ICL and SCL is then compared with the void index obtained from the isotropic compression curve for each specimen. As seen in the figure, the void index from the isotropic compression data show similar trend with the one dimensional compression data shown in Figure 3a. For the reconstituted and recompacted specimen, their void index show tendency to converge with the ICL and SCL with increasing stress. The behaviour indicates structure effect not too significant compared to the intact specimen which extend outside the SCL. However, the slope of the void index for each specimen is similar at both oedometric and isotropic stress state. Similar to the observation in Figure 3a, the intact specimen showed no sign of convergence with the ICL and reached state outside the SCL. This behaviour indicates the significance of the influence of structure on the compressibility of the intact lateritic specimen.

Figure 4 shows the plot of void index against vertical effective stress for several intact fine-grained soils. The aim is to compare the influence of structure on their compression behaviour. As defined in Burland (1990), the soil type having their void index starting below 0 are from a deeper depth, hence denser and compact than those soil types starting above 0. It is important to state here that the influence of sampling depth was not considered in this comparison. According to Xu & Coop (2016), the effects of sampling depths influences only the pre consolidation pressure. It can be seen that all the soil types, except lateritic clay, plot close to the sedimentation compression line (SCL) and tend to converge with the ICL at high stress level. It is not commonly observed for intact clay specimen to reach state outside the SCL during compression. The observations from this figure further confirms that the effect of structure on the compression behaviour of intact lateritic specimen is highly significant. A very high stress level is required to fully de-structure the intact specimen to converge with the ICL and SCL. The mode of weathering and the influence of cementation by sesquioxide content might have given the lateritic specimen a stiff fabric. For the loess and the bothkennar clay, it can be seen that the compression line touches the SCL before tending to converge with the ICL. This imply that the effect of structure is also very significant in those soils, although, not as significant as in the lateritic clay. Both loess and bothkennar clay contain chlorite and calcite which also have cementing influence (Hight et al., 2003; Xu & Coop, 2016).

The influence of structure on the shear behaviour of lateritic clay

Stress-strain and pore water pressure relationship

Figure 5a shows the stress-strain relationship during undrained shearing of the three specimen at 50kPa and 200kPa confining stresses. At 50kPa, the reconstituted and recompacted specimen show brittle behaviour at both confining stress indicated by a peak and softening. On the other hand, the intact specimen shows a ductile (strain hardening) behaviour, although a slight evidence of softening was observed at low axial strain. Further inspection into the figure reveals that the peak shear strength of the intact specimen is 100% more than the peak shear strength of both reconstituted and recompacted specimens. The significant difference in peak strength highlights the significance of the effects of structure on the lateritic clay. The stress strain behaviour at 200 kPa is fairly the same as described at 50kPa. Although the difference between the peak shear strength of the intact and the recompacted/reconstituted specimen reduced to about 50%. The higher peak shear strength of the intact specimen is attributed to the low compressibility and stiffer structure as shown in Figure 2a and b.. Furthermore, it can also be observed the reconstituted and recompacted specimens are not significantly different in terms of shear behaviour. Bulging failure is observed in all specimen after the test. Compared to the shear behaviour of another intact lateritic clay sampled from similar 1.5m depth Fagundes & Rodrigues (2015), the shear strength of the recompacted specimen was found to be higher than the intact specimen. However, the author did not prepare the recompacted specimen to the same state as the intact specimen which might have influenced their result. Also, Futai et al. (2004) studied the shear behaviour of an intact lateritic clay sampled at 1.0m, they observe the peak shear strength is slightly higher in the intact specimen than recompacted specimen. The difference between the results in Futai et al., (2004) and this study can be attributed to the influence of degree of weathering. At 1.5m, the intact specimen is expected to be less weathered and stiffer than at 1m. Hence, the effects of structure on shear behaviour may be more significant.

The relationship between excess pore water pressure and axial strain generated during undrained shearing at 50kPa and 200kPa confining stresses is shown in Figure 5b. Positive excess pore water pressure was generated by all specimen. The positive build-up of excess pore water pressure indicates contractive tendency, which is consistent with the bulging failure observed in all specimen after shearing. The intact specimen appears to be less contractive than the recompacted and reconstituted specimen. As revealed by the isotropic compression curves

Figure 2b, the intact specimen is significantly less compressible and stiffer than the other two specimen. As a result, the intact specimen show lower contractive tendency.

Dilatancy

Figure 6 shows the stress paths of the three specimens under undrained shearing in the q – p′ plane. For the intact specimen, the effective mean stress initially reduces (showing a tendency of contraction), after reaching a turning point, phase transformation occurs. Under subsequent shearing, the effective mean stress increases (showing a tendency of dilation, accompanied by an increase in deviator stress) and soil state finally reaches the CSL. The behaviour of intact specimen is different from those reported by Futai et al. (2004) and Fagundes & Rodrigues (2015) on an intact lateritic clay. Both studies reported continuous contraction for an intact lateritic clay without observing any phase transformation. As for the recompacted and reconstituted specimen, all specimens continue to show tendency to contract until reaching the CSL. The difference between the intact specimen and recompacted/reconstituted specimen can be linked to their compressibility behaviour (Figure 2b). More discussion on the dilatancy is given later using the observations from MIP and SEM tests. The initial contraction is likely attributed to the collapse of large inter-aggregate pores. The subsequent dilative behaviour is due to rearrangement and interlocking of the large-sized aggregates.

Critical state shear strength

For each soil, the critical state line in q-p′ plane is shown in Fig. 6. It appears that the final state of all the specimen fall on single plane. The slope of the critical state line, M (commonly referred to as the stress ratio of the critical state) line, is estimated to be 1.73. The corresponding critical state angle of internal friction φ' is 42^o for intact, recompacted and reconstituted specimen. The high friction angle is due to the influence of large particles and aggregates in their microstructure. This finding imply that there is no effect of structure on the critical state friction angle. Similar finding was reported in Futai et al. (2004) on a recompacted and intact lateritic clay.

The critical state line in the v-ln p' compression plane is shown in Figure 7. A critical state line can be obtained for the intact, recompacted and reconstituted specimen after shearing. The slope of their CSL is approximately parallel to the slope of their NCL in the v-ln p plot. Although the CSL in the q-p' plane is identical for the three specimen, the opposite is the case in the v-ln p' plane. Each specimen appear to have its CSL in this plane and it is impossible to have a single CSL line for the three specimen. These observations demonstrate that the critical state line plane may not be unique in the v-ln p'. The non-unique CSL in the v-ln p' plane may be due to the difference in fabric each specimen due to different specimen preparation method. Similar findings have been reported in Nocilla et al. (2006) for soils having translational behaviour. Also, it can be observed that the distance between the NCL and CSL is significantly lower in the intact specimen compared to the other two specimen. This may be due to its significantly low compressibility than the recompacted and reconstituted specimen.

The influence of specimen preparation on microstructure of lateritic clay

Figure 8 presents the SEM micrograph of the intact, recompacted and reconstituted specimen at 10µm magnification. In Figure 8a, aggregates are clearly seen in the microstructure of the intact specimen. It is very difficult to see the inter-aggregate pores clearly as the aggregates appear to be strongly attached together. Although it is difficult to separate individual aggregates, an aggregate of about 60 µm is identified and shown in the figure for the purpose of comparing with other figures. The microstructure of the recompacted specimen is shown in Figure 8b. Again, aggregates are present but the inter-aggregate pores are more obvious compared to the intact specimen in Figure 8a. Since the recompacted specimen was prepared using the aggregates broken down from the intact specimen, it is reasonable to expect a more obvious inter-aggregate pores. About two different aggregate size of about 40 µm and 30 µm were chosen in the figure to show that the aggregate sizes are smaller compared to the intact specimen (see Figure 8a). At reconstituted state shown in Figure 8c, more inter aggregate pores are seen compared to Figures 8a and 8b. Also, it can be seen that the there is a significant reduction in the particle and aggregate sizes compared to figures 8a and 8b. The reduction in particle size is consistent with the observations from Figure 1 where a significant change in grain size distribution occur during wet sieving. An aggregate of about 35 µm could be seen in the figure, which appear to the largest diameter of aggregate in the figure.

From Figure 8a, b and c, it can be confirmed that the largest aggregate size appear in the intact specimen. The intact aggregate is about than 50% and 80% larger in the diameter than recompacted and reconstituted aggregates respectively. Due to larger aggregate size in the intact specimen, it is reasonable to expect that fewer particle contacts in the specimen compared to the other two specimens. During compression, forces are transmitted through particle contacts, thereby generating a force chain network that leads to particle rearrangement and deformation. Since less particle contacts are present in the intact specimen, the particle contacts involved in load bearing/force chain are larger and lesser compared to the other two specimens. As a result, compressive forces is less significant in the intact specimen compared to both recompacted and reconstituted specimen. Hence, particle rearrangement would be lesser, resulting in low compressibility and higher dilative tendency in the intact (see Figure 2). Similar observations on low compressibility and high dilative tendency of soils having larger particles are also reported in Vallejo & Mawby (2000).

Figure 9 shows the differential pore volume of the intact, recompacted and reconstituted specimen. It is important to state here that the un-intruded pores are 40% in the intact specimen and about 20% in both recompacted and reconstituted specimen. These unintruded pores are attributed to the presence of large pores above 100 μm diameter which is beyond the working range of the MIP equipment used. The presence of larger pores is reasonable to assume considering the highly aggregated structure of the lateritic clay as observed in the SEM images (Figures 8a, b and c). For the intruded pores shown in the figure, it can be seen that all the specimen exhibit dual-porosity structure indicated by the two major peaks. Since all the specimen have similar distribution up to 0.8µm, the boundary between the inter-aggregate pore and intra-aggregate pore is therefore placed at 0.8 µm. Although the reconstituted specimen has slightly higher pore volume which is attributed to the slightly higher void ratio. The highest peak is found within the intra-aggregate zone at a pore diameter of 0.025µm. Within the inter-aggregate zone, two major peaks can be identified at 10 µm and 100 µm. pore diameter. At 10 µm, the highest peak belong to the reconstituted specimen. The observation at 10 µm is consistent with the SEM image shown in Figure 8 a, b and c. Meanwhile, the highest peak at 100 µm belong to the recompacted specimen. The peak of the intact specimen is not seen but it is reasonable to expect it would be above 100 µm considering the large size of its aggregates. Details of the MIP result are summarized in Table 4.

For the reconstituted specimen, the peak of the inter-aggregate pores at 10 µm is consistent with the SEM image in figure 8c. Compared to the intact and recompacted specimen, it has the lowest diameter of inter-aggregate pores which is due to the decrease in particle size as suggested by wet sieving result in figure 1. Generally, unimodal pore size distribution is often observed in reconstituted specimen because most of the inter-aggregate porosity are almost entirely erased due to the high water content of reconstituted specimen (Tarantino, 2011). The bimodal structure observed in the reconstituted lateritic specimen suggests that the inter-aggregates pores did not collapse significantly. The difference may be due to the influence of the 38% sesquioxide content in the lateritic specimen. The sesquioxide content is able to enhance the stability of the aggregates at high water content (Zhang et al., 2016).

Even though, the intact specimen is expected to have the largest diameter of inter-aggregate pores which could not be intruded, yet it has the lowest compressibility. The low compressibility suggests that most of the inter-aggregate pores in the intact specimen could not be compressed significantly. As explained earlier, fewer particle contacts are present in the intact specimen due to its large aggregate size. The distribution of the force chain is majorly within the few contact areas of the large aggregates while most of the smaller size aggregates would occupy the large inter-aggregate pores. As a result, it becomes more difficult to compress the inter-aggregate pores due few contact areas and large aggregates. Consequently, the specimen shows lower compressibility and higher dilative tendency. Unlike the recompacted and reconstituted specimen, a more significant distribution of force chain is present owing to smaller particle sizes and more particle contacts. Therefore a higher compressibility is observed and a more contractive tendency during shearing.

Conclusions

The tested lateritic specimen is classified as a sandy lean clay. It contains about 38% sesquioxide content. The influence of structure on the compression and shear behaviour was studied. Data from the oedometer, isotropic compression and consolidated undrained shearing tests were provided and interpreted using the critical state framework for saturated soils.

Microstructural evidences were used to explain the differences in behaviour. The key findings are summarized as follows:

(a) The post yield compressibility behaviour of the intact, recompacted and reconstituted specimens continue to diverge as the effective stress increases. Unlike other intact clays such as loess and bothkennar, the intact lateritic specimen reach state outside the sedimentation compression line and no sign of convergence was observed. This indicates significant effect of structures on the compressibility of lateritic clay. The behaviour of the intact specimen is attributed to the influence of sesquioxide cementation which likely stiffen its structure.

(b) The compressibility of the recompacted and reconstituted lateritic specimen is about 90% larger than the intact specimen. As suggested by the SEM results, the aggregate size is about 50% larger in the intact specimen than both reconstituted and recompacted specimen. As a result, less particle contact is established in the intact specimen which helps the large aggregates to bear a larger percentage of the compressive force chain. Hence, the large inter-aggregate pores could not be compressed significantly within the stress range studied, resulting in low compressibility. Unlike the reconstituted/recompacted specimens, more aggregates participated in the load bearing which increases their compressibility. If the significant difference in the compressibility of intact and recompacted lateritic clay is considered in design, a more economical serviceability limit state design can be achieved in lateritic clays.

(c) Phase transformation behaviour was observed only in the intact specimen during shearing. The recompacted and reconstituted specimen show overall contractive tendency throughout the shearing. The behaviour of the intact specimen suggest the specimen exhibit tendency to dilate. The dilation tendency of the intact specimen is due to its larger aggregate size which have more significant particle contact forces. As a result, its contractive tendency of the intact skeleton is suppressed and the tendency to undergo particle rearrangement and dilation is enhanced.

(d) During undrained shearing, the peak shear strength of the intact specimen is about 100% higher than the peak shear strength of reconstituted/ recompacted specimen. The difference reduces with increasing confining stress. The difference in the peak shear strength is due to the higher dilation tendency of the intact specimen than both reconstituted and recompacted specimen. Moreover, the intact specimen generated the lowest excess pore water pressure. It can be concluded that the shear strength behaviour of the lateritic clay is governed by the aggregate size rather than the inter-aggregate porosity. A similar critical state friction angle was estimated for the three specimens despite different specimen preparation.

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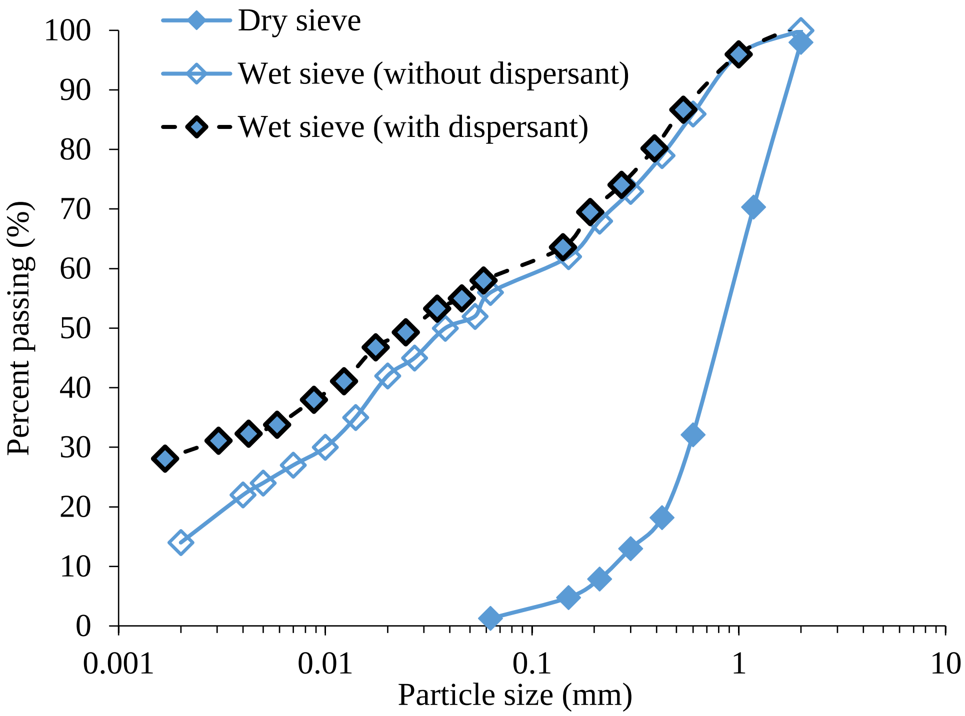
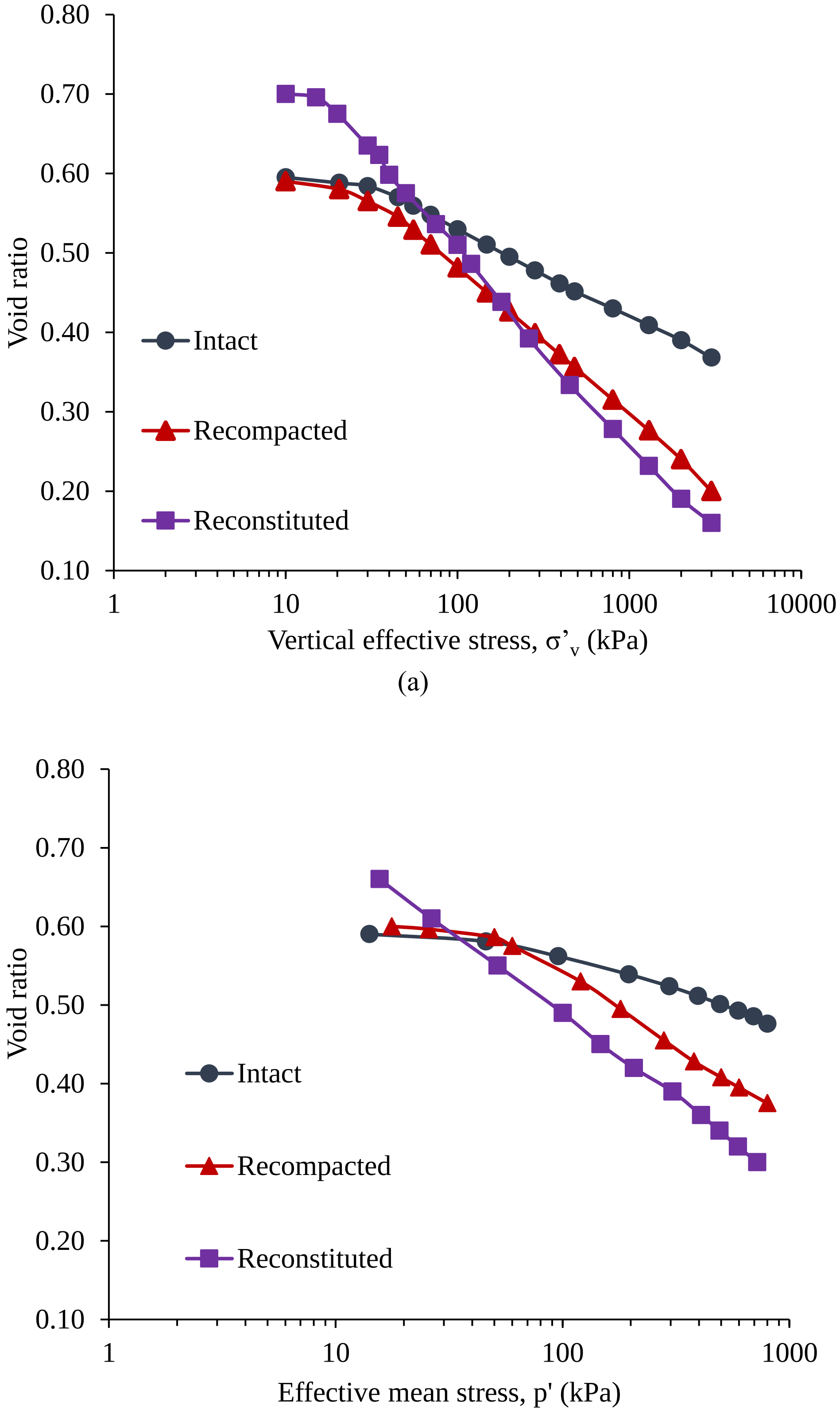


Fig. 1. Grain size distribution of the tested LAT



(a)

(b)

Fig. 2. Compression behaviour of the intact, recompacted and reconstituted LAT specimens under a) one dimensional and b) isotropic stress states

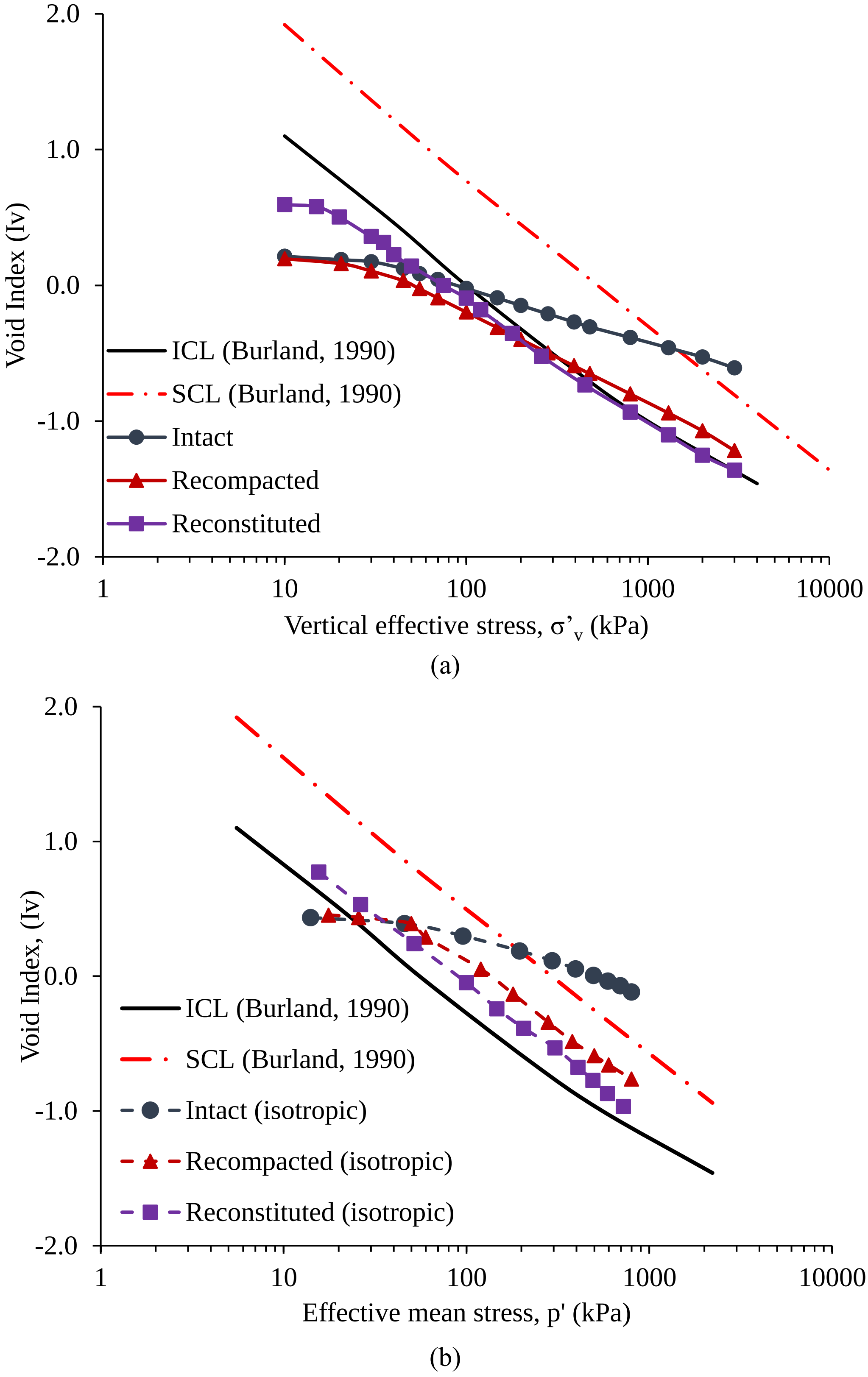


Fig. 3. Variation of void ratio index Iv of the intact, recompacted and reconstituted LAT specimens under (a) one dimensional and (b) isotropic compression

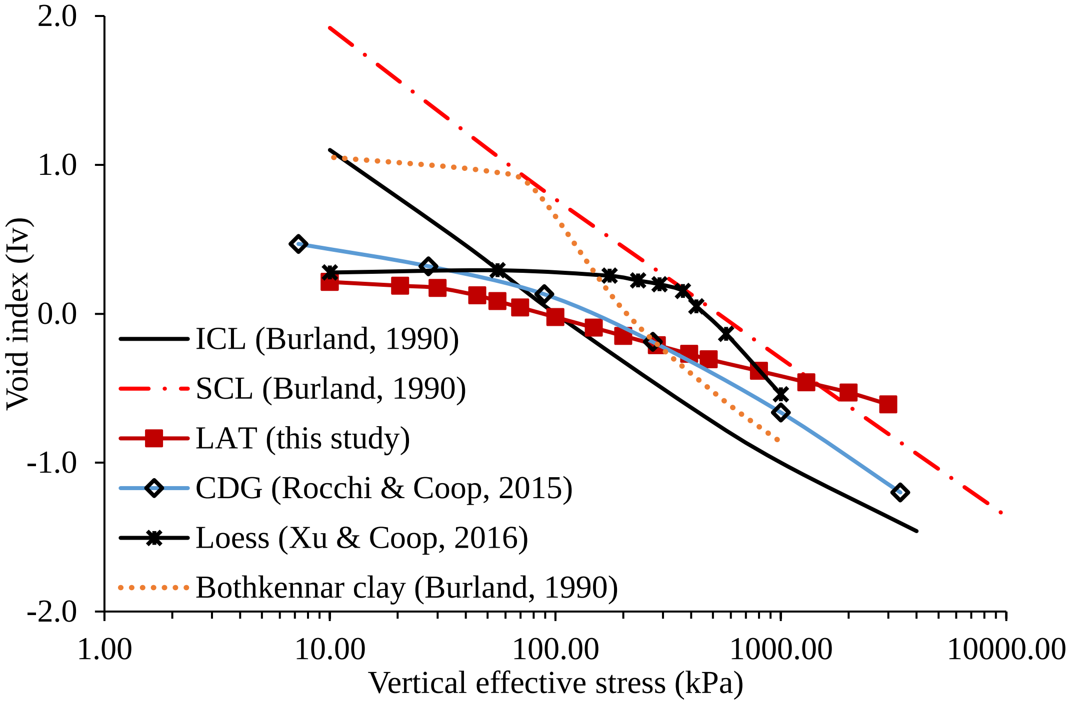
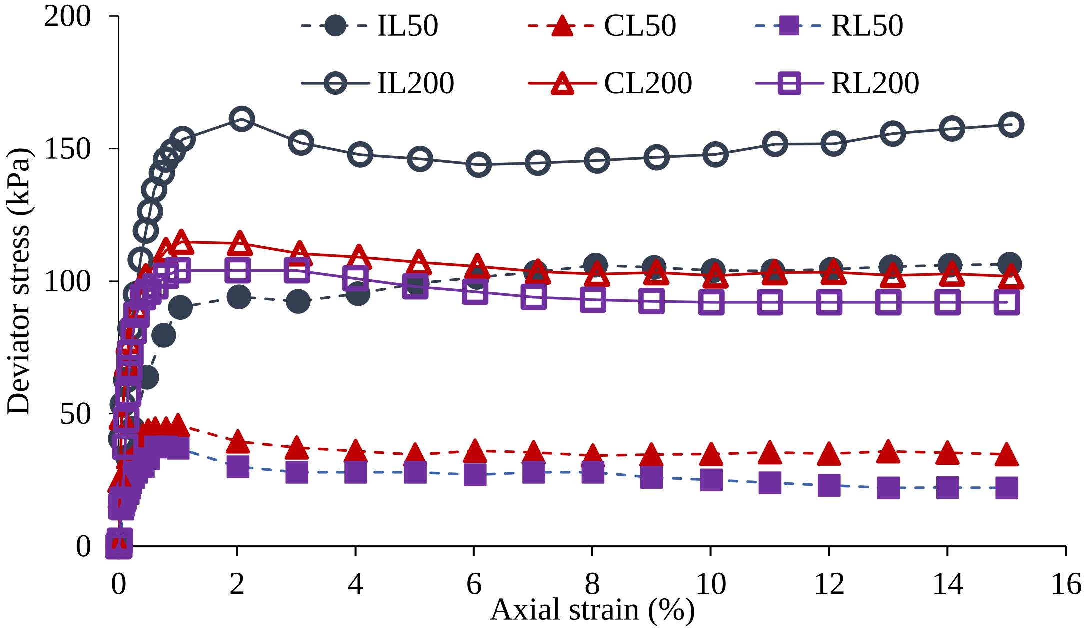
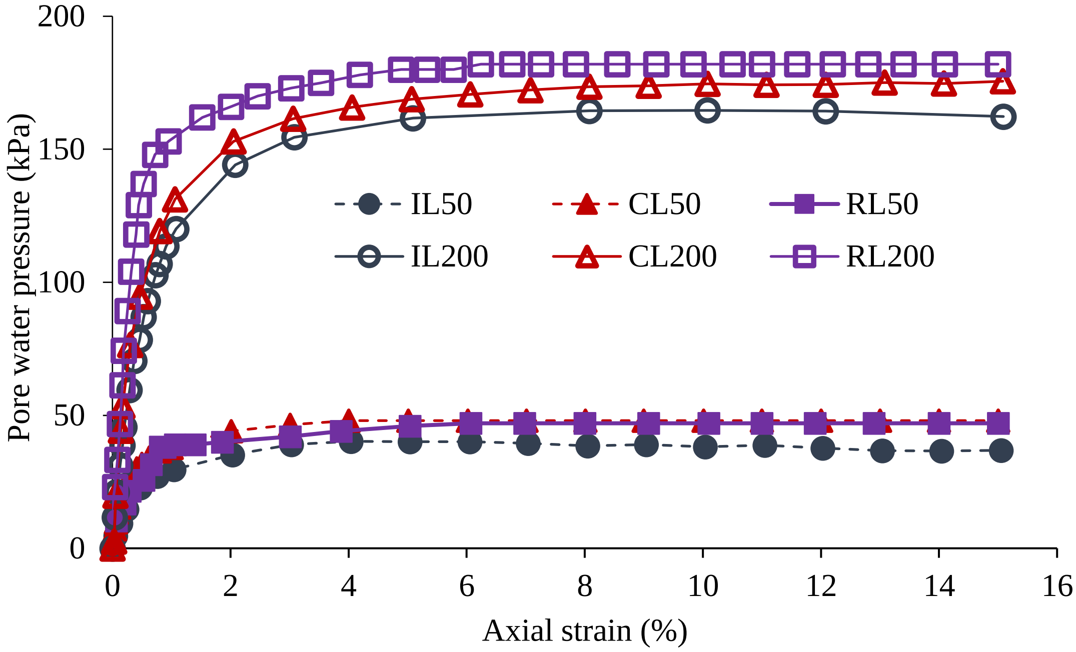


Fig. 4. Comparisons of structure effects on the compressibility of some fine grained intact soils;



(a)



(b)

Fig. 5. Shear behaviour from undrained tests at confining stress of 50kPa and 200kPa for the intact, recompacted and reconstituted LAT specimens (a) stress- strain and (b) pore water pressure response

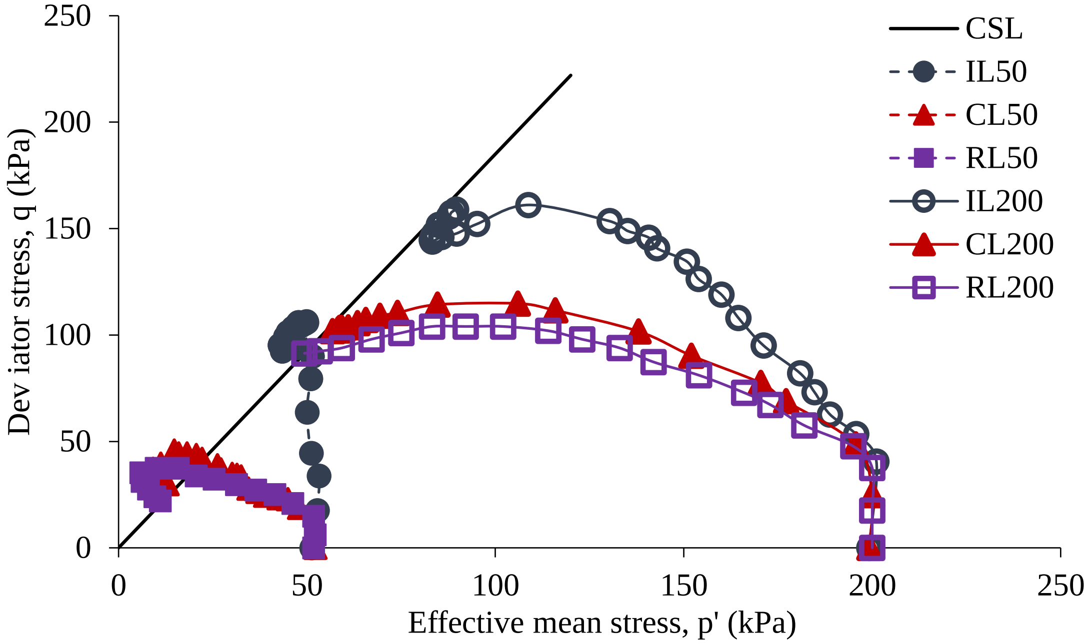


Fig. 6. Stress paths of the intact, recompacted and reconstituted LAT specimens in q - *p*’ plane

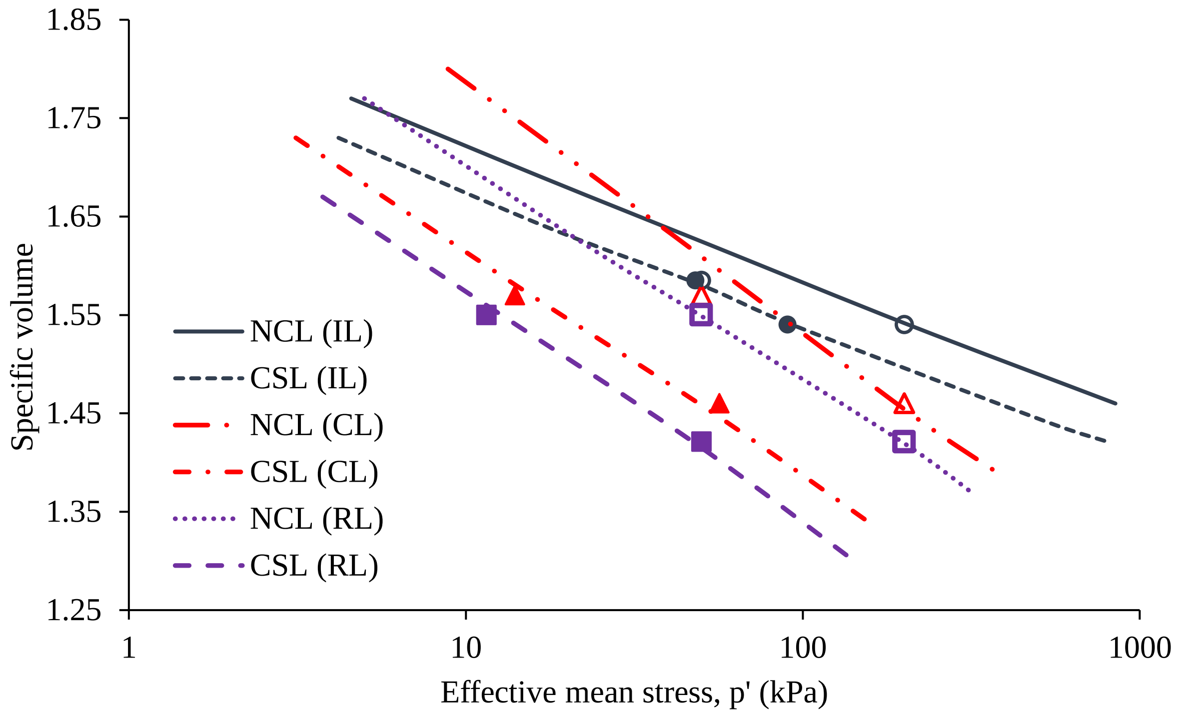
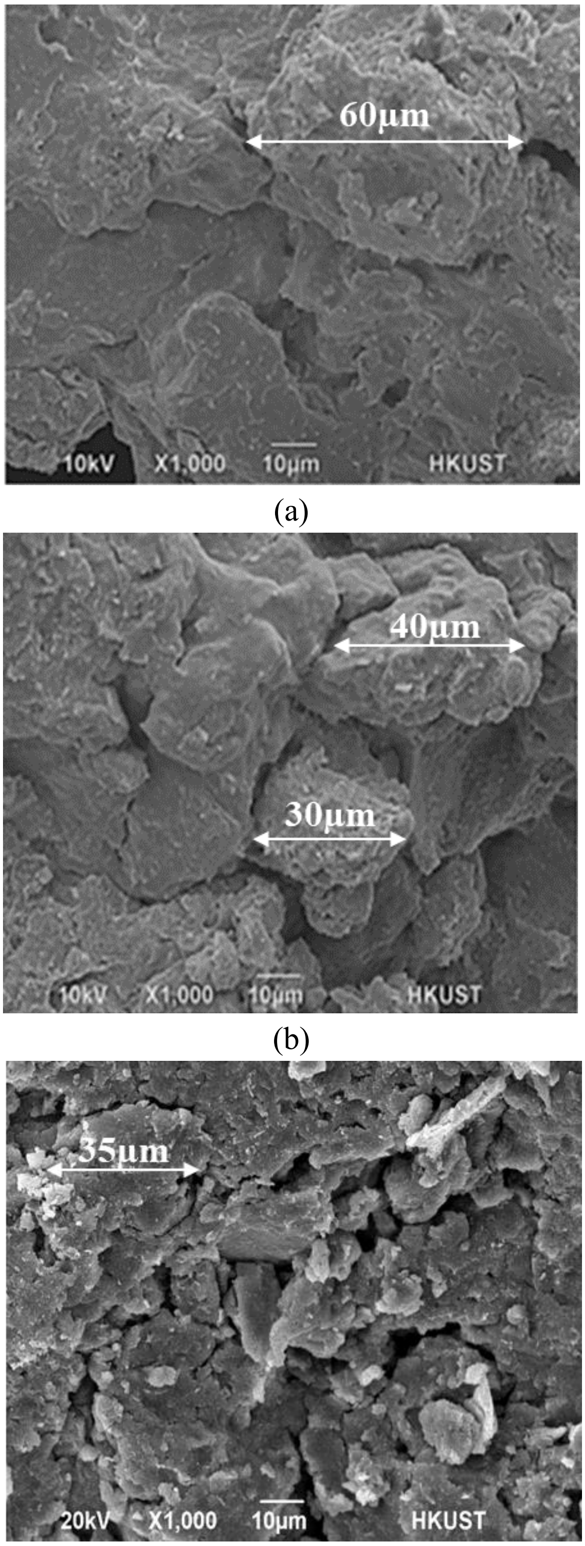


Fig. 7. Stress paths of the intact, recompacted and reconstituted LAT specimens in v – ln *p*’ plane



(a)

(b)

(c)

Fig. 8. Scanning electron micrographs of (a) intact, (b) recompacted and (c) reconstituted specimen at 10 μm magnification

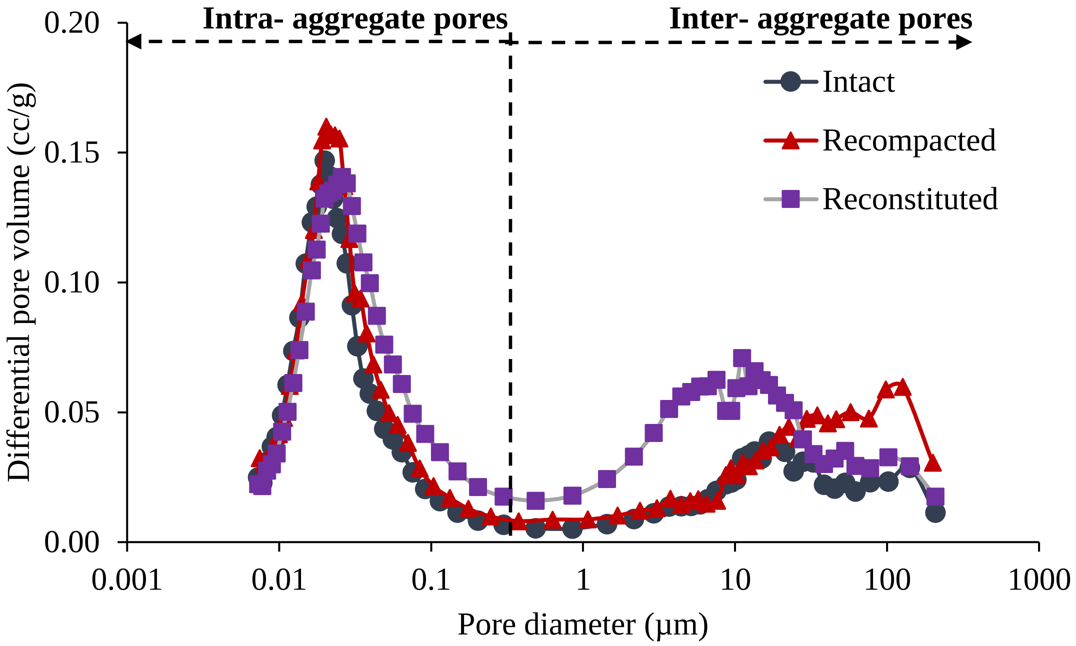


Fig. 9. Pore size distribution of the intact, recompacted and reconstituted LAT specimens

Table 1. Classification and mineral composition of LAT tested in this study

Index test	Lateritic soil
Standard compaction Test	
Maximum dry density: kg/m^3	1696
Optimum water content: %	20
Grain size distribution	
Percentage of sand: %	42
Percentage of silt: %	16
Percentage of clay: %	42
Coefficient of uniformity	35
Coefficient of gradation	1.6
Atterberg limits	
Liquid limit: %	44
Plastic limit: %	24
Plasticity index: %	20
Specific gravity	2.67
Soil classification based on USCS (ASTM,2011)	CL (sandy lean clay)
Chemical composition (%)	
Silicon oxide (SiO_2)	60
Iron oxide (Fe_2O_3)	10
Aluminum oxide (Al_2O_3)	28
Sesquioxide ($Fe_2O_3 + Al_2O_3$) content	38%

Table 2. Details of one dimensional and isotropic compression tests

Specimen ID*	Specimen preparation method	Initial void ratio	Effective preconsolidation pressure, Pc (kPa)	Cc	λ
IL-O	Intact	0.59	40	0.09	-
IL-T		0.58	70	-	0.043
CL-O	Recompacted	0.62	35	0.18	-
CL-T		0.58	60	-	0.080
RL-O	Reconstituted	0.70	N/A	0.25	-
RL-T		0.70		-	0.093

Note: * O- Oedometer, T- Triaxial, IL- Intact lateritic, CL – Recompacted lateritic, RL – Reconstituted lateritic

Table 3. Details of triaxial shear tests

Specimen ID	Confining stress (kPa)	Initial void ratio	Void ratio after consolidation	Ψ after consolidation*
IL50	50	0.59	0.58	0.02
CL50		0.60	0.57	0.12
RL 50		0.70	0.55	0.14
IL200	200	0.58	0.54	0.05
CL200		0.59	0.46	0.15
RL200		0.70	0.43	0.16

Note: * Ψ is the state parameter defined by Been and Jefferies (1985) as the difference in current and critical state void ratios.

Table 4. Details of MIP results

Specimen ID	Initial void ratio	e_{MIP}*	Intra-aggregate void ratio	Inter-aggregate void ratio	Un-intruded pores (%)
IL	0.59	0.35	0.23	0.12	40
CL	0.60	0.46	0.26	0.20	21
RL	0.70	0.54	0.30	0.24	23

Note: *e_{MIP} is the total void ratio intruded by the mercury during the MIP test.