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Comparisons of weathered lateritic, granitic and volcanic soils: compressibility and shear strength

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Abstract

Lateritic soil is rich in oxides of iron and aluminium (sesquioxide). The effects of these oxides on its mechanical behaviour are not well-understood. In this study, the compression and shear behaviour of lateritic (LAT) soil was tested and compared to those of two other chemically weathered granitic and volcanic soils for the first time within the critical state framework. The mineralogy, chemical compositions and microstructure of these three soils were also measured by x-ray diffraction (XRD), x-ray fluorescence (XRF) and scanning electron microscopy (SEM) respectively. It is found that only LAT contains goethite, while other minerals are similar in all the soils. The content of iron and aluminum oxides in LAT is about 40% higher than that in CDV and CDG soils. LAT is found to be less compressible than CDV and CDG by 18% and 36% respectively, even though the former has a higher clay content than the latter two soils. The low compressibility of LAT is mainly attributed to its high content of sesquioxide, which induces the formation of more aggregates. The LAT has more intra-aggregate pores and hence less inter-aggregate pores than CDV and CDG. A smaller volume of inter-aggregate pores of LAT results in a lower compressibility. It is found that the critical state friction angles of LAT, CDV and CDG are 42°, 33° and 38°, respectively. The highest friction angle of LAT is likely attributed to the content of large particles and presence of goethite. Due to the high sesquioxide contents of LAT, many clay fines also form large aggregates leading to a more granular microstructure. Consequently, the number of particle contacts is increased and therefore enhancing particle interlocking. Goethite mineral found in LAT could enhance inter-aggregate interlocking through its contiguous singly coordinated OH groups.

Keywords: Lateritic soil; goethite; sesquioxide; critical state

Introduction

Lateritic soils are chemically weathered materials, commonly formed and found in the hot and wet tropical areas. A good understanding of their mechanical behaviour, such as compressibility and shear strength, can improve the designs of civil engineering structures built on lateritic soils. Compared with other tropical soils, lateritic soils are rich in secondary oxides of iron and aluminum (sesquioxide) formed during the process of chemical weathering (Alexander and Cady, 1962). Up to now, however, there is no direct comparison among different tropical soils with considerations of their mineral compositions and mechanical behaviour.

Several previous studies investigated shear strength of saturated lateritic soils through experimental studies (Ogunsanwo, 1989; Adunoye, 2014; Fagundes and Rodrigues, 2015). Some researchers investigated the strength of tropical soils amended by SH-85 (a calcium-based powder), which is able to enhance the aggregation (Latifi et al., 2017; Rashid et al., 2017). It was found that soil strength was significantly improved because of the more significant aggregation. The reported shear strength parameters at the peak state are affected by many factors such as initial density and soil fabric (Wood, 1990). To understand the behaviour of lateritic soils more effectively, the critical state framework (Roscoe et al., 1958; Roscoe and Burland, 1968) should be a more useful approach for data interpretation. So far, critical state parameters of lateritic soils have been reported by limited researchers only.

In this study, the compressibility and shear behaviour of a lateritic soil are studied within the critical state framework. As far as the authors are aware, this is the first study to compare the compressibility and shear behaviour of different chemically weathered soils with various sesquioxide contents. Through the comparison, unique features of the lateritic soil with very high sesquioxide contents are highlighted.

Soil type

Three weathered soils are tested: a lateritic (LAT) soil, a completely decomposed volcanic (CDV) soil and a completely decomposed granitic (CDG) soil. Their physical properties were determined following the ASTM standard (ASTM, 2011) and summarized in Table 1. According to the unified soil classification system (ASTM, 2011), LAT, CDV and CDG are classified as sandy clay of low plasticity (CL), silty sand of low plasticity (ML) and well-graded gravely sand with little fines, respectively.

Figure 1 shows their grain size distributions (GSDs) determined following the ASTM D1140 procedures (ASTM, 2011). For each soil, GSDs were measured using both dry sieving method (sieving air-dried soil) and wet sieving method (sieving soil in water, with dispersant added to separate soil particles from aggregates). For each soil, there is a huge difference between the GSDs measured using the two methods. The difference is widely used to quantify the degree of aggregation using the following equation (e.g., Otalvaro, et al., 2015):

$$D_a = \frac{P_d - P_w}{P_w} \quad (1)$$

where D_a is the degree of aggregation, falling in the range of 0 to 1; P_d is the area below the GSD measured using the dry sieving method; P_d is the area below the GSD measured using the wet sieving method.

Using equation (1), the value of Da was 52%, 38%, 21% for LAT, CDV and CDG, respectively. This observation suggests that in LAT, many of the fine particles are strongly attached to form large aggregates, which may not be destroyed by ordinary mechanical remolding during specimen preparation. Otalvaro, et al. (2015) also reported a significant degree of aggregation for a lateritic soil using similar approach. The highest degree of aggregation of LAT is induced by some of its minerals not found in CDG and CDV. Details of this will be provided in later section.

Specimen preparation

A total number of 12 specimens were prepared for the isotropic compression and undrained shearing tests. Each soil type has four specimens and all specimens were prepared using static compaction method. To ensure fair comparison, all the specimens were compacted at 19% water content. The dry density of all the specimens ranged from 70 to 74% of their proctor maximum. In order to ensure a uniform specimen is prepared, the under compaction method proposed by Ladd (1978) was adopted. Therefore, each specimen was compacted in 10 layers.

Test program

For each soil, two series of tests were designed and carried out using a triaxial apparatus. The first series is isotropic compression tests for investigating soil compressibility. The other series is consolidated undrained (CU) tests for studying shear strength, as summarized in Table 2. In CU tests on each soil, three different confining stresses (50, 100 and 200 kPa) were considered and used.

Moreover, mineralogy, chemical compositions and microstructure of all soils were investigated using X-ray diffraction (XRD), X-ray fluorescence (XRF) and scanning electron microscopy (SEM) tests, respectively. The results are used for interpreting experimental results of compression and shear tests.

Mineralogy and chemical analysis

Figure 2 shows the types of mineral identified in LAT, CDV and CDG by using the X-ray diffractometer. Some minerals such as quartz, hematite, and kaolinite are observed in all soils, while goethite and hematite are found only in LAT. Both goethite and hematite are secondary minerals formed during the chemical decomposition of parent rocks in relatively flat ground (Gidigasu, 1976). The goethite is a hydroxide of iron and contains pairs of contiguous singly coordinated OH groups, and the hematite is an oxide of iron. These two minerals enhance the formation and stability of soil aggregates which could influence soil behaviour (Schwertmann and Fitzpatrick, 1992; Larrahondo et. al., 2011). The influences of these two minerals led to more significant aggregation (see Figure 1).

Chemical oxides of the three soils are determined through the X-ray fluorescence tests (XRF) and summarized in Table 3. It is clear that the oxides of iron, aluminum and silicon dominate the three soils. At a quantitative level, LAT contains more iron oxide and aluminum oxide than CDV and CDG. This difference is due to the fact that the formation process of LAT involves the leaching of silica from the soil, leading to relative accumulation of iron and aluminum oxides content (Alexander and Cady, 1962). The oxides of iron and aluminum would provide cementation effects, alternatively described as cladding (Airey et al., 2012; Zhang et al, 2014). Due to cementation effects, LAT would have its fine particles aggregated. The result from XRD and XRF tests can be used to explain the degree of aggregation reported in Figure 1. The highest degree of aggregation in LAT can be attributed to the higher quantity of sesquioxide and the presence of Goethite mineral. More discussion on the minerals and chemical oxides is given later, while comparing the compressibility and shear strength of LAT, CDV and CDG.

SEM results

Figure 3(a) shows SEM photomicrograph of LAT. Fine clay particles are almost invisible, even though the clay content of LAT is up to 42%. This is mainly because clay particles have formed aggregates with much larger size. Moreover, the surface of aggregates appears very rough and the interlocking between aggregates is very significant.

The SEM photomicrograph of CDV is shown in Figure 3(b), where many fine clay particles can be identified. Compared with LAT, there are much fewer aggregates formed in CDV. This difference is mainly because the amount of sesquioxide is much lower in CDV than in LAT, as supported by the results of XRF tests. With fewer sesquioxide and less significant cementation effects, less fine clay particles tend to form aggregates.

In Figure 3(c) for CDG, no sign of aggregation is observed. This is due to the low quantity of sesquioxide in CDG. The above observations in Figure 3 suggest that the microstructure soils are closely related to mineral type and quantity of the sesquioxide.

Mechanical behaviour of LAT, CDV and CDG

Compressibility

Figure 4 shows the responses of LAT, CDV and CDG under isotropic compression. In the stress range considered, LAT and CDG exhibit a distinct yield point and a post yield normal compression line. The compressibility increases substantially after yielding. For CDV, however, the compressibility does not show obvious change during the loading process. The difference is likely because the initial void ratio of CDV is much larger than that of LAT and CDG, resulting in a much smaller yield stress (less than 20 kPa).

The slope of their NCL (usually denoted as λ) is 0.07, 0.09 and 0.11 for LAT, CDV and CDG, respectively. This implies that LAT is less compressible than CDV and CDG. It should be noted that compared with CDV and CDG, the clay content of LAT is much larger (see Table 1). The compressibility of these three soils seems contradictory with conventional understanding that a finer soil is generally more compressible than a coarser soil. The low compressibility of LAT is mainly attributed to its high content of sesquioxide (i.e., Iron and aluminium oxides). Iron and aluminium oxides enhance the formation and stability of soil aggregates, which control soil behaviour (Schwertmann and Fitzpatrick, 1992). In the current study, the LAT, CDV and CDG specimens have almost the same void ratio. The LAT specimen has more intra-aggregate pores but less inter-aggregate pores. Consequently, the compressibility associated with the rearrangement of soil aggregates is smaller. Another reason for low compressibility of LAT may be due to its goethite mineral (as evident by XRD tests), which is a hard material with a value of 5.5 on the Mohs scale of hardness (Mukherjee, 2012). Its existence in LAT likely stiffens soil skeleton and reduces soil compressibility. Moreover, few inter-aggregate pores and significant interlocking observed in the SEM micrograph of LAT would contribute to its low compressibility, as shown in Figure 2.

The compressibility of some other chemically weathered soils is summarized in Table 4 for comparison, including a lateritic gravel and a sandy clay from Singapore (Toll and Ong, 2003). It is clear that the LAT studied in this study is less compressible than the other two lateritic soils. The difference of the two lateritic soils can be explained from their parent rock types. The LAT is decomposed from a granitic rock (intrusive igneous rock), the lateritic gravel from a Basalt (extrusive igneous rock). Compared with extrusive rocks, Intrusive rock have larger crystals/grain texture due to slower cooling of magma below the earth surface which encourages growth of larger crystals causing reduced pore size, thereby affecting compressibility (Loughnan, 1969).

Stress-strain relationship during shearing

Figure 5 shows the stress strain relationship for the specimen sheared at undrained condition. For the LAT and CDV sheared at 50 kPa, the deviator stress increases monotonically with the axial strain and no sign of softening was observed till the end of the test. The observation for LAT and CDV indicates both soil exhibits a strain hardening behavior. For the CDG specimens sheared at all confining stresses, the deviator stress reach a peak value at an axial strain of about 5% and then decrease towards a steady state. The contrasting behaviour of CDG from LAT and CDV is explained later by using the stress path. For other specimen sheared at 100 and 200 kPa effective confining stresses, their behaviour is similar to the response described earlier at 50 kPa for each soil type.

Soil dilatancy

Figure 6 shows the stress paths of LAT, CDV and CDG under undrained shearing in the q - *p'* plane. For LAT, the effective mean stress initially reduces (showing a tendency of contraction) since soil state lies on the 'wet' side of the critical state line (CSL) before shearing. 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. These results are different from those reported by Toll (1990), where a lateritic gravel exhibits a continuous dilation tendency during the shearing. Futai et al. (2004) reported continuous contraction for a lateritic soil without observing any phase transformation.

CDV specimens also shows initial tendency to contract, followed by phase transformation to dilative behaviour. As for CDG, all specimens continue to show tendency to contract until reaching the CSL. Due to the significant contraction, a reduction of mean confining stress and thus deviator stress was observed in the strain range of 5% to 25% (see Figure 5). Similar results of CDG were reported by Wang and Yan (2006) and Junaideen, et. al., (2010). On the other hand, the difference between CDG and LAT/CDV may be because there are large-size aggregates in LAT and CDV, but not in CDG, as illustrated in Figure 2. The initial contraction of the LAT and the CDV 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 stress state in q-p' plane is determined as shown in Figure 6. The stress ratio of the critical state line M is 1.73, 1.32 and 1.55 for LAT, CDV and CDG, respectively. The corresponding critical state angle of internal friction φ' is 42°, 33°, and 38°

for the LAT, CDV and CDG respectively. The differences in shear strength of LAT, CDV and CDG are likely attributed to the content of large particles and some other factors such as mineralogy and sesquioxide composition. As shown in Figure 1, the particle size of LAT is larger than that of CDV and CDG using the dry sieving method. The SEM images (see Figure 3) illustrate that the large particles in LAT are embedded in a matrix of smaller particles. Moreover, the influence of large particles on shear strength was investigated by some previous studies by testing soil-rock mixtures (Vallejo and Zhou, 1994; Vallejo 2001; Verma, et al., 2016) and clay-sand mixtures (Vallejo and Mawby, 2000). It was found that the presence of large particles increased shear strength, probably because the large particles could increase the number of particle contacts and therefore enhance particle interlocking. The influence of large particles on shear strength does not occur completely in the CDV and CDG samples. Consequently, the large particles in LAT are likely to result in a higher friction angle. In addition, it should be noted that if the wet sieve method is used, the content of the large particles in LAT is reduced significantly (see Figure 1). This is mainly because by adding Sodium Hexametaphosphate in the wet sieve method (ASTM, 2011), the large aggregates breakdown. On the other hand, the high friction angle of LAT is also likely attributed to the presence of goethite (iron hydroxide) which affects the surface texture of particles through its surface hydroxyl configuration (Barron and Torrent, 1996) and hematite (iron oxide), which increases the particle sizes through aggregation of the fines. The goethite was also described by Airey et al. (2012) as a needle like material capable of increasing interlocking between soil particles.

In order to show how the goethite mineral and sesquioxide compositions of the lateritic soils influence their friction angle, it is compared with some other chemically weathered soils in the tropics as shown in Table 4. It is found that the lateritic soil studied has the highest friction angle. The difference between LAT and the lateritic gravel (Toll, 1990) may be attributed to the contributions from their parent rock. The soil particle surface from intrusive granitic rock (LAT) is rough and harder compared to the extrusive rocks already exposed to the earth surface Loughnan (1969).

Conclusions

This study compared the compressibility and shear behaviour of three weathered soil; LAT (sandy clay), CDV (silty sand) and CDG (gravelly sand). Of the three soil types LAT has about 40% higher content of iron and aluminium oxides than those of CDG and CDV. These two oxides cause much more significant aggregation in LAT, as evident by its dry and wet grain size distribution and SEM microphotographs. On the other hand, only LAT among these three soils contains goethite (a hydroxide of iron), which is formed during the decomposition of apparent rocks. The goethite contains pairs of contiguous singly coordinated OH groups, which are involved in surface adsorption and are capable of enhancing inter-aggregate interlocking. It is found that the critical state friction angles of LAT, CDV and CDG are 42°, 33° and 38°, respectively. The highest friction angle of LAT is likely attributed to the content of large particles and presence of goethite. Due to the large particles, the number of particle contacts is increased and therefore enhancing particle interlocking. The goethite mineral found in LAT could enhance inter-aggregate interlocking through its contiguous singly coordinated OH groups.

The compressibility of LAT is found to be lower than that of CDV and CDG by 18% and 36% respectively, even though LAT has a higher clay content than the other two soils. The low compressibility of LAT is mainly attributed to its high content of sesquioxide, which induces the formation of more aggregates. The aggregates rather than clay particles control the compressibility. Moreover, given the same void ratio, the LAT has more intra-aggregate pores and hence less inter-aggregate pores than CDV and CDG. A smaller volume of inter-aggregate pores of LAT results in a lower compressibility.

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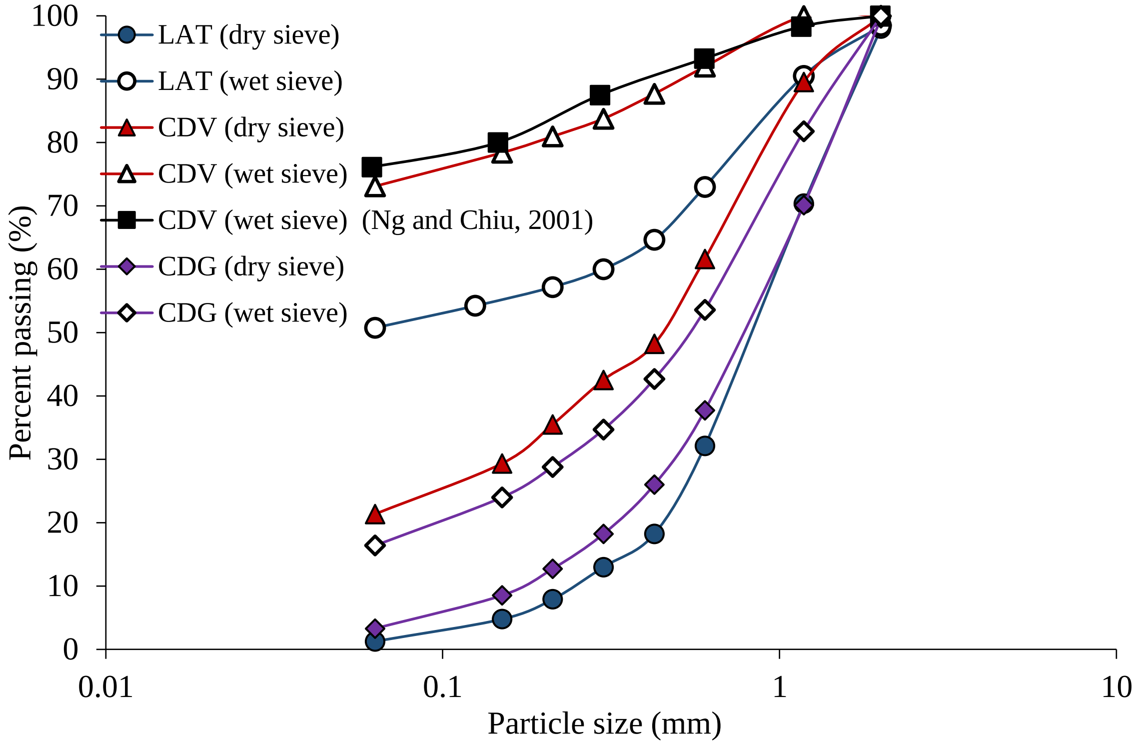
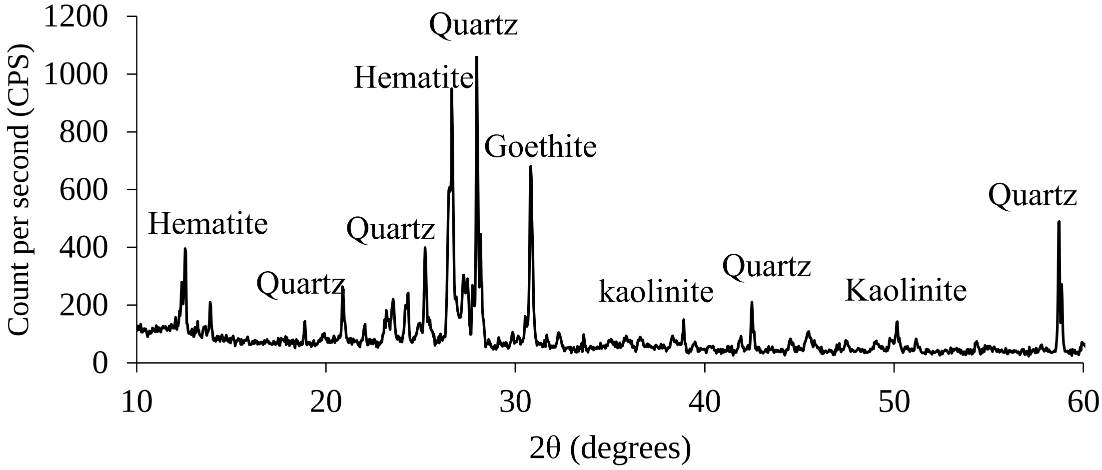


Fig. 1. Grain size distribution of the studied soils


Count per second (CPS)
2θ (degrees)
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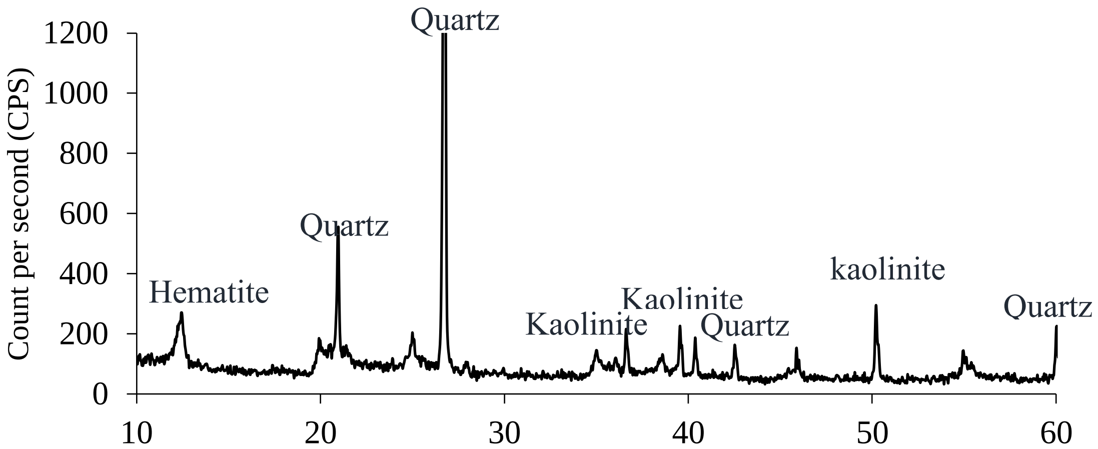
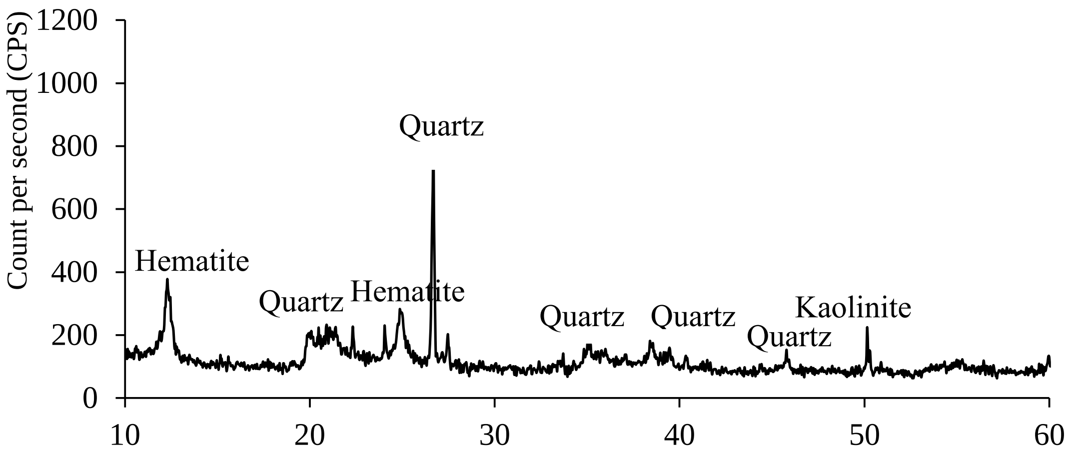
Quartz
Quartz
Hematite
Quartz
Goethite
kaolinite
Quartz
Kaolinite
Quartz

(a)

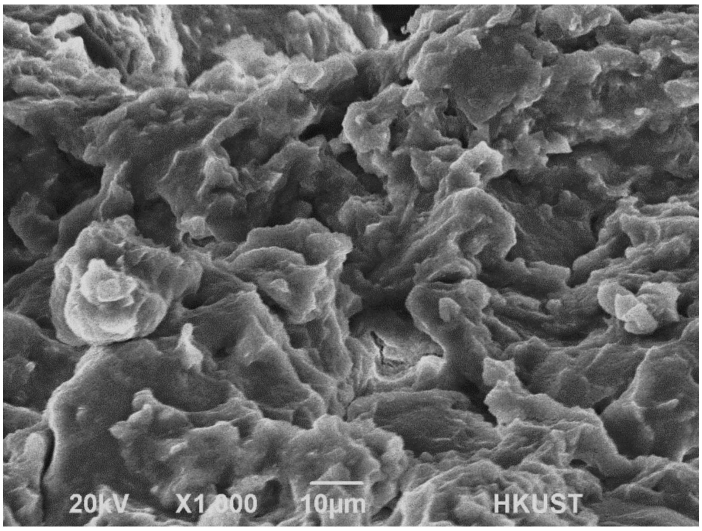

Count per second (CPS)
Quartz
Quartz
Hematite
Kaolinite
Kaolinite
Quartz
kaolinite
Quartz

(b)

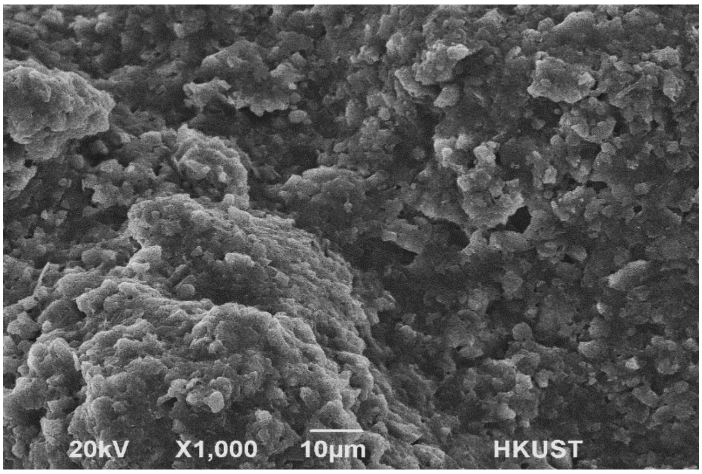

Count per second (CPS)
Quartz
Hematite
Quartz
Hematite
Quartz
Quartz
Quartz
Kaolinite

(c)

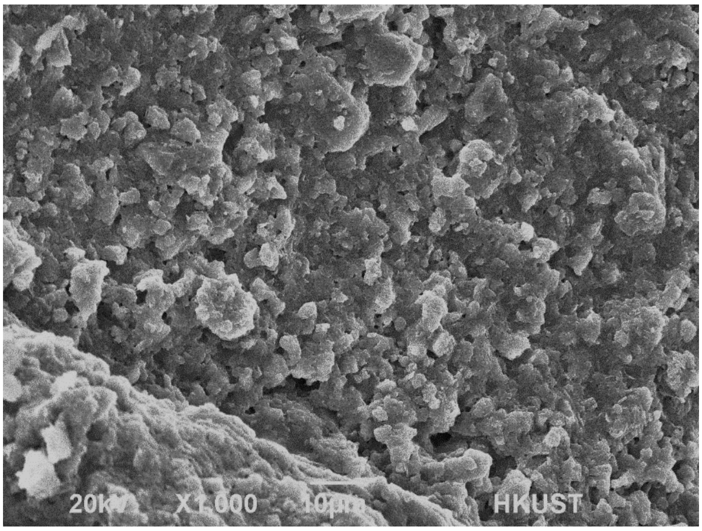
Fig. 2. Result of X-ray diffractometer and types of minerals in (a) LAT (b) CDV and (c) CDG



(a)



(b)



(c)

Fig. 3. Scanning electron micrographs of (a) LAT; (b) CDV and (c) CDG

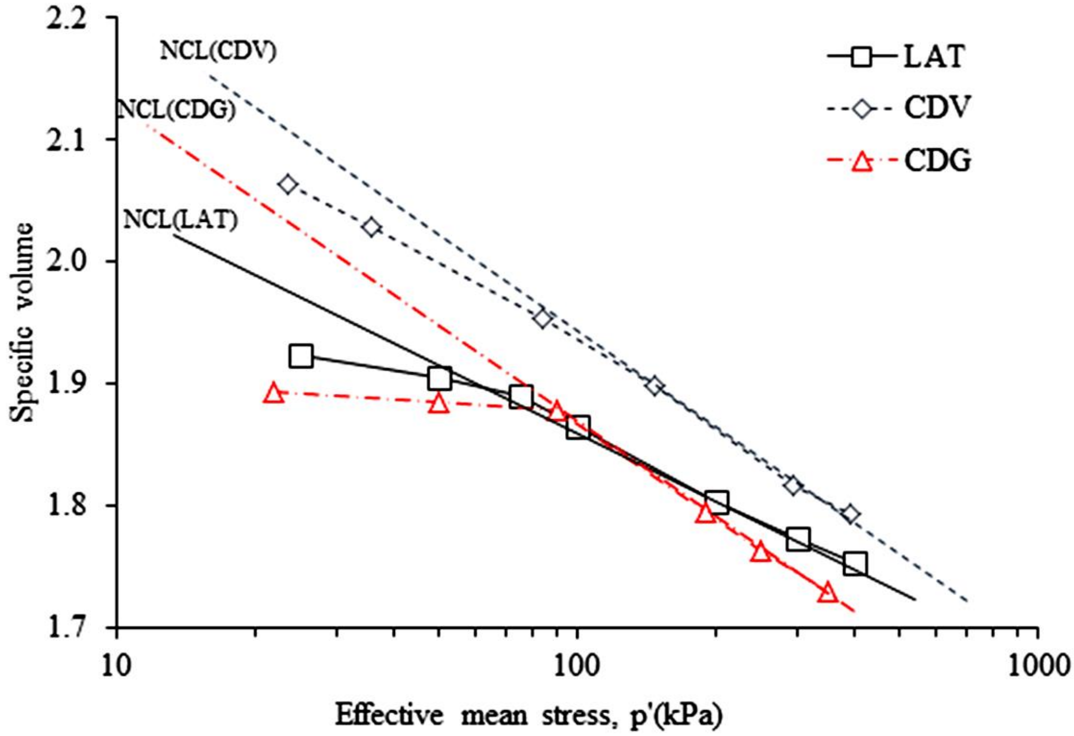


Fig. 4. Isotropic compression behaviour of LAT, CDV and CDG

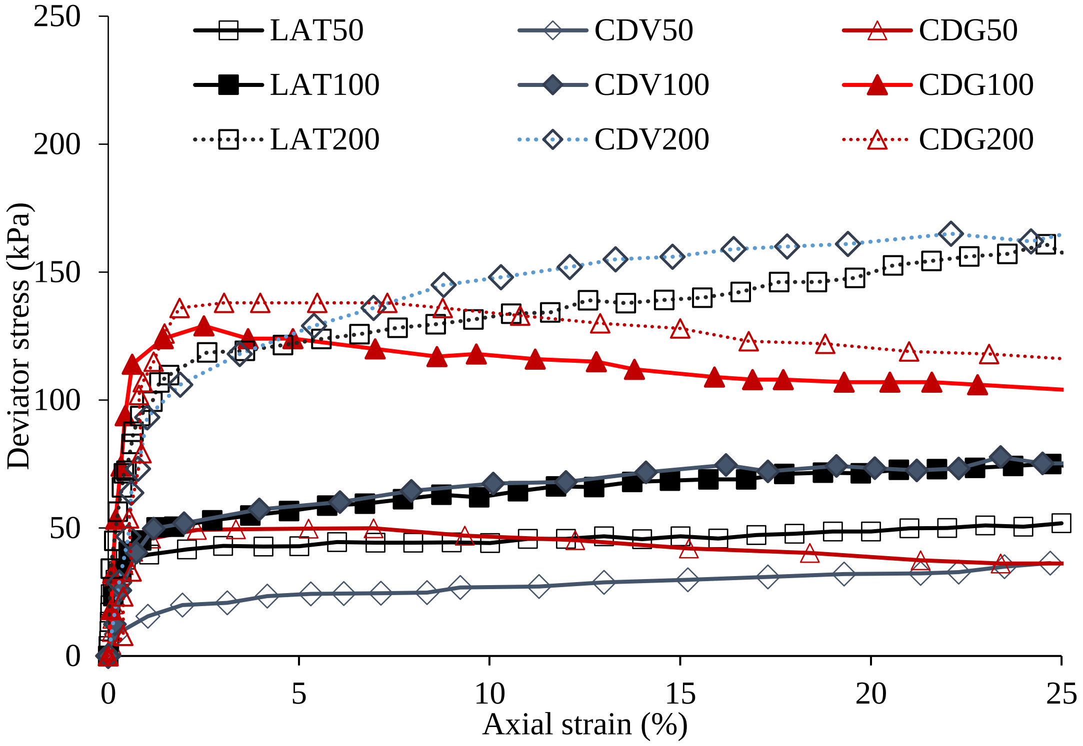


Fig. 5 Triaxial stress strain responses from undrained tests at confining stress of 50, 100 and 200kPa for all specimen.

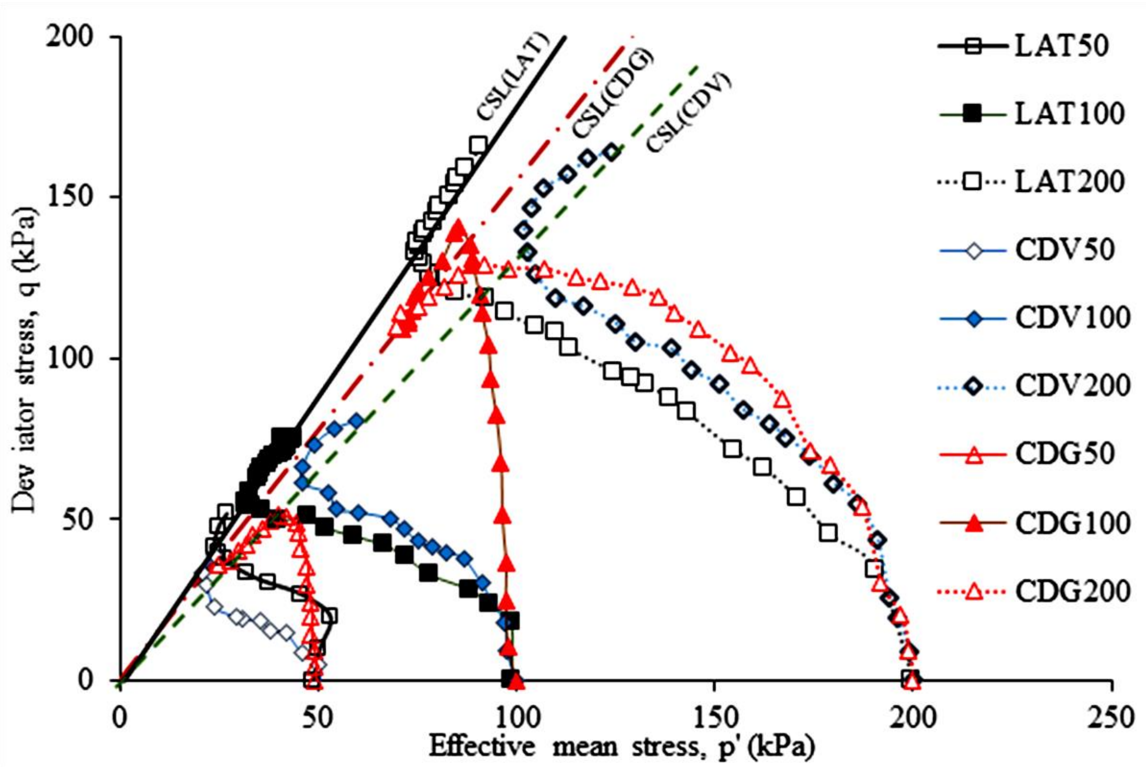


Fig. 6. Stress paths of LAT, CDV and CDG in q - *p*’ space

Table 1. Physical properties of LAT, CDV and CDG

Index Test	LAT (this study)	CDV (Ng & Chiu, 2001)	CDG (Ng & Chiu, 2003)
Standard compaction Test			
Maximum dry density: kg/m^3	1696	1540	1670
Optimum water content: %	20	21	20
Grain size distribution			
Percentage of sand: %	42	25	53
Percentage of silt: %	16	65	12
Percentage of clay: %	42	10	14
Specific gravity	2.67	2.66	2.61
Atterberg limits			
Liquid limit: %	44	48	N.A.
Plastic limit: %	24	35	N.A.
Plasticity index: %	20	13	N.A.
Soil classification based on USCS (ASTM, 2011)	sandy clay (CL)	silty sand (ML)	gravelly sand (SW)

Table 2. Details of test program

Series	Soil type	Specimen ID	Confining stress (kPa)	Initial void ratio	Void ratio after consolidation	Ψ after consolidation*
I	LAT	LAT50	50	1.011	0.942	0.05
	CDV	CDV50		1.101	1.005	0.062
	CDG	CDG50		1.080	0.961	0.059
II	LAT	LAT100	100	0.942	0.897	0.06
	CDV	CDV100		1.099	0.945	0.062
	CDG	CDG100		0.918	0.872	0.046
III	LAT	LAT200	200	1.013	0.859	0.07
	CDV	CDV200		1.145	0.882	0.06
	CDG	CDG200		1.083	0.857	0.107

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

Table 3. Major chemical oxides present in the LAT, CDG and CDV (X-Ray Fluorescence test)

Oxide	LAT	CDV	CDG
Iron II oxide (Fe_2O_3)	10%	4%	2%
Aluminum oxide (Al_2O_3)	28%	23%	17%
Silicon oxide (SiO_2)	60%	70%	72%

Table 4. Comparison of compression and friction angles of LAT, CDG and CDV

Soil types*	λ	ϕ'_{cs}
LAT (this study)	0.07	42
CDV (Ng and Chiu, 2001)	0.09	33
CDG (Ng and Chiu, 2003)	0.11	38
Residual sandy clay (Toll & Ong, 2003)	0.08	31
Lateritic gravel (Toll, 1990)	0.11	38

Note: *All the soils are decomposed materials with similar degree of weathering