

Influence of Strain Rate on the Shear Strength Properties of Lateritic Soils from Six Local Government Areas of Ibadan Metropolis, Southwestern Nigeria

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Abstract- Laboratory shear strength parameters of lateritic soils are routinely measured at a single, arbitrarily selected displacement rate, although field loading rates span several orders of magnitude. This study examined whether strain rate influences the Mohr–Coulomb shear strength of lateritic soils from six Local Government Areas (LGAs) of Ibadan metropolis, southwestern Nigeria: Akinyele, Egbeda, Ido, Lagelu, Oluyole and Ona-Ara. Disturbed samples were taken from one borrow pit per LGA at 1.0–1.5 m depth and characterised by natural moisture content, bulk and dry density, specific gravity, particle-size distribution and Atterberg limits. Consolidated direct shear tests (ASTM D3080) were then carried out at normal stresses of 50, 100 and 150 kPa and at two displacement rates, 0.5 and 1.0 mm/min. The soils are predominantly sandy (fines content 1.2–9.1%) with plasticity indices of 4.3–10.9%; the Ido soil is non-plastic. Fitted friction angles ranged from 19.5° to 38.7° ($R^2 = 0.81–1.00$), whereas cohesion intercepts were small and frequently negative, an artefact of fitting three-point envelopes that makes them indicative only. Doubling the displacement rate increased mean cohesion by 6.2 kPa and mean friction angle by 1.1°, but neither change was statistically significant across the six LGAs (paired *t*-test, $p = 0.584$ and 0.766) and the direction of change was inconsistent between LGAs. At LGA level, only Egbeda showed a significant increase in peak shear stress (mean +27.8 kPa, $p = 0.0018$). Over the 0.5–1.0 mm/min range, results obtained at either rate can be used interchangeably for preliminary design in five of the six LGAs, whereas Egbeda warrants site-specific multi-rate testing. Wider rate ranges, more normal stress levels and replicate specimens are needed to confirm and explain the localised response.

Keywords: lateritic soil; strain rate; direct shear test; Mohr–Coulomb criterion; rate sensitivity; Ibadan

I. INTRODUCTION

Lateritic soils are the dominant geomaterial across tropical West Africa and cover roughly 70% of the land area of Nigeria (Ola, 1983). They form the

subgrade of most of the country's road network, the founding stratum for a large share of its buildings, and a common source of fill and embankment material. Their formation through prolonged, intense tropical weathering concentrates iron and aluminium oxides and depletes silica, producing residual soils whose grading, plasticity, cementation and mineralogy vary strongly with parent rock, climate and degree of lateritisation (Buchanan, 1807; Gidigas, 1976; Ola, 1983). Reliable knowledge of their shear strength is therefore central to the safe and economical design of foundations, slopes, embankments, retaining structures and pavements.

Shear strength is conventionally expressed through the Mohr–Coulomb criterion, in which the limiting shear stress on a plane is a linear function of the normal stress, defined by a cohesion intercept (c) and an angle of internal friction (ϕ) (Coulomb, 1776; Terzaghi, 1943). These parameters are usually obtained from direct shear or triaxial compression tests. In both, the rate at which shear deformation is imposed is a controllable but often overlooked test variable. Strain rate influences the measured response through viscous and viscoplastic interparticle resistance, through the rate-dependent generation and dissipation of pore pressure, and through the time-dependent behaviour of cemented bonds (Vaid & Campanella, 1977; Leroueil & Marques, 1996; Mitchell & Soga, 2005). Field loading rates range from the very slow consolidation of fill beneath a building to the rapid pulses imposed by heavy traffic, pile driving and vibrating machinery, so laboratory strength obtained at one arbitrary rate may be conservative or unconservative relative to the loading that a structure actually experiences.

In Nigerian university and commercial laboratories the displacement rate for direct shear and triaxial tests is

frequently chosen by convention or convenience, sometimes defaulting to about 1.25 mm/min without systematic justification, and it is often not reported alongside the strength parameters (Amadi et al., 2012). Consequently, published shear strength data for lateritic soils cannot be compared confidently across studies, and the sensitivity of these soils to loading rate remains largely unquantified.

The problem is compounded by geological heterogeneity. Ibadan lies within the Precambrian Basement Complex of southwestern Nigeria, where migmatite-gneiss, granite and schist among other rocks weather to residual soils of contrasting character (Rahaman, 1988; Oguike & Akpokodje, 2011). Six local government areas (LGAs) make up the core of the metropolis: Akinyele, Egbeda, Ido, Lagelu, Oluyole and Ona-Ara. Because these areas differ in parent rock and in the resulting soil properties, strength data borrowed from a different site can carry substantial uncertainty into design calculations. In a rapidly urbanising city, where new roads, housing estates, bridges and drainage works are built directly on these soils, both sources of uncertainty (loading rate and location) are consequential.

This paper reports a controlled laboratory investigation of the influence of strain rate on the shear strength of lateritic soils from the six LGAs. The specific objectives were: (i) to characterise the index properties (natural moisture content, density, specific gravity, grain-size distribution and Atterberg limits) of the soils from each LGA; (ii) to determine the Mohr–Coulomb parameters c and ϕ of each soil in direct shear at two displacement rates, 0.5 mm/min (slow) and 1.0 mm/min (fast); and (iii) to compare the shear behaviour at the two rates, at both metropolitan and individual-LGA level, and thereby identify where, if anywhere, the soils are rate-sensitive.

II. BACKGROUND AND RELATED WORK

2.1 Geology and lateritic soils of Ibadan

Ibadan is underlain by the Precambrian Basement Complex, whose dominant lithologies include migmatite-gneiss, porphyritic granite, schist belts, quartzite and meta-sedimentary sequences (Rahaman, 1988). Intense tropical weathering of these rocks has

produced lateritic profiles that differ from zone to zone in clay mineralogy, particle-size distribution and plasticity (Oguike & Akpokodje, 2011). Adeyemi (1995) found that plasticity indices of soils from different parts of the metropolis ranged from 9 to 26% and that California Bearing Ratio values at optimum moisture content ranged from 8 to 34%, underlining the need for zone-specific characterisation. Lateritic profiles range from less than a metre thick on steep, well-drained slopes to more than 10 m in valley bottoms, and the upper metre or so, which is the depth of interest here, is the layer most directly affected by seasonal moisture change, construction disturbance and surface loading.

Reported shear strength parameters for Nigerian lateritic soils are correspondingly variable. Cohesion of compacted lateritic soils is commonly reported between 5 and 60 kPa and the friction angle between 18° and 38° , depending on soil type, compaction state, moisture content and test procedure (Ola, 1983; Adeyemi, 1995; Iyeke et al., 2016). For Ibadan specifically, Adeyemi (1995) reported cohesion of 8–42 kPa and friction angles of 12° – 30° . That work, like most of the Nigerian literature, was conducted at a single, unstated displacement rate. Water content is a further first-order control on the strength of these soils (Onyelowe, 2013), which reinforces the need to standardise specimen preparation when comparing test series.

2.2 Shear strength theory

Coulomb's (1776) failure criterion, integrated with the effective-stress principle by Terzaghi (1943), can be written in total-stress form as

$$\tau = c + \sigma \tan \phi \quad (1)$$

where τ is the shear stress at failure, σ is the normal stress on the failure plane, c is the cohesion intercept and ϕ is the angle of internal friction. In effective-stress terms, $\tau = c' + (\sigma - u) \tan \phi'$, where u is the pore-water pressure (Bishop & Henkel, 1957). The effective-stress form is the more fundamental description of interparticle forces, whereas total-stress parameters depend on drainage conditions during loading. The friction angle reflects particle-surface friction and dilatancy, and, in lateritic soils, is also

influenced by particle shape, grading and the presence of cemented concretions (Das, 2010). The direct shear test permits close control of the horizontal displacement rate but does not allow pore pressure to be measured, so parameters derived from it are total-stress values that cannot be compared directly with effective-stress parameters from triaxial tests (Bishop & Henkel, 1957; Nazir et al., 2020).

2.3 Strain-rate effects in soils

Rate dependence of soil strength has been recognised since the mid twentieth century (Casagrande & Shannon, 1948; Bishop & Henkel, 1957). Leroueil and Marques (1996) identified three principal mechanisms in cohesive soils: viscous drag from adsorbed water films between clay particles, rate-dependent generation of excess pore pressure under undrained or partially drained conditions, and creep and relaxation of cemented bonds at slow rates. Vaid and Campanella (1977) showed that the undrained strength of sensitive clay increases almost linearly with the logarithm of strain rate, by roughly 10% per log cycle, a relationship since embedded in many design guidelines. Subsequent work has shown that the magnitude of this effect varies with soil type, mineralogy, plasticity and stress history (Sheahan et al., 1996; Lunne & Andersen, 2007). It is often expressed by a rate-sensitivity coefficient μ , the fractional change in strength per tenfold change in strain rate. Typical μ for soft natural clays is 0.05–0.20, and for stiffer, overconsolidated clays and tropical residual soils it is commonly 0.03–0.12 (Leroueil & Marques, 1996).

For cohesionless soils drained under modest stress, rate effects are generally small because the granular skeleton adjusts to changes in loading without viscous delay. They can, however, emerge where excess pore pressure cannot dissipate, at high normal stresses, or where fine particles introduce viscous resistance (Gebrenegus et al., 2017; Wang et al., 2025). In lateritic soils, cementation by goethite and hematite bridges is expected to stiffen interparticle contacts and reduce rate sensitivity, whereas kaolinitic, moderately plastic laterites may behave more like other tropical clays, because kaolinite platelets with thin adsorbed water films can still offer viscous resistance at engineering strain rates (Mitchell & Soga, 2005).

Tamassoki et al. (2022) further showed that specimen preparation and compaction degree strongly affect the apparent rate sensitivity of lateritic soil, so that in-situ density should be reproduced and preparation standardised when rate effects are compared between materials.

Constitutive models built on viscoplasticity, beginning with Perzyna's (1966) overstress framework and extended for soils by Adachi and Oka (1982) and Yin and Graham (1999), allow rate effects to be represented in numerical analyses of embankments, piles and traffic loading. Such models must be calibrated against laboratory rate-sensitivity data, and in practice simple correction factors that scale laboratory strengths to the expected field loading rate offer a route to incorporating rate effects in routine design without replacing Mohr–Coulomb methods (Lunne & Andersen, 2007).

2.4 Recent experimental evidence and the research gap
Recent studies confirm that strain-rate effects are widespread but soil-specific. He et al. (2024) sheared soft coastal soil in direct shear at rates from 0.2 to 8.0 mm/min and found that peak and residual strength rose systematically with rate, with peak strength increasing by about 15% over the range. Zhang et al. (2024) reported that in loess the rate effect on cohesion exceeded that on friction angle, attributing it to pore-pressure and viscous mechanisms rather than to particle interlocking. Yan et al. (2024) found a modest increase in the residual friction angle of expansive soil with shear rate, consistent with residual strength being governed largely by particle rearrangement and friction. Liu et al. (2024) observed that stiffness and peak deviator stress of saturated soft soil rose with strain rate over two orders of magnitude, stiffness proportionally more than strength; Guo et al. (2025) showed that strain rate matters under cyclic loading of silty clay; and Chen et al. (2025) examined the undrained response of nonplastic soils. For lateritic soil specifically, Nazir et al. (2020) found that higher strain rates were associated with greater peak undrained strength and more brittle post-peak behaviour in a laterite from a geologically similar setting, but cautioned against extrapolating to soils with different mineralogy and iron-oxide content.

Against this background, no published study has quantified the effect of strain rate on the shear strength of lateritic soils from the distinct geological sub-zones of Ibadan. Nigerian investigations of lateritic soil strength (Adeyemi, 1995; Iyeke et al., 2016; Adunoye et al., 2018) have used standard tests without varying the rate, and the broad index-property databases of Amadi et al. (2012) and Bello et al. (2019) do not address rate sensitivity. Whether rate effects reported for tropical residual soils elsewhere apply to these materials, and whether they vary across the six LGAs, is therefore unknown. The present work addresses this gap with a rate-controlled, standardised programme applied uniformly to all six LGAs.

III. MATERIALS AND METHODS

3.1 Study area and soil sampling

Ibadan, the capital of Oyo State, lies at approximately $7^{\circ}22'-7^{\circ}30'N$ and $3^{\circ}50'-4^{\circ}00'E$ on a dissected upland plateau at about 150–275 m above sea level. The climate is humid tropical, with mean annual rainfall of 1,200–1,400 mm in two rainy seasons (March–July and September–November) and a mean annual temperature of about 26 °C, conditions that favour intense chemical weathering. The study covered the six LGAs forming the core of the metropolis: Akinyele (north), Lagelu (northeast), Egbeda (east), Ona-Ara (southeast), Oluyole (south) and Ido (west). The dominant parent rock at each sampling location is listed in Table 1.

One borrow pit was selected in each LGA. Borrow pits were preferred to road cuttings or natural slopes because they expose fresh, representative material from the upper horizon that governs subgrade and shallow-foundation performance. Sites were chosen using published geological maps (Rahaman, 1988; Oguike & Akpokodje, 2011), field reconnaissance and local geotechnical advice against four criteria: proximity to the dominant parent-rock formation of the LGA; accessibility to the sampling team; absence of recent grading or filling; and freedom from permanent waterlogging. Locations were recorded with a handheld GPS unit and photographed.

Disturbed samples were recovered from 1.0–1.5 m depth using a hand auger and shovel, below the topsoil

horizon affected by organic matter, cultivation and seasonal moisture variation. Handling followed the recommendations of Bello et al. (2019) for lateritic soils in southwestern Nigeria: each sample was sealed in a labelled heavy-duty polythene bag to prevent moisture exchange, placed in a rigid plastic container to limit mechanical disturbance, and labelled with LGA, pit identifier, depth, date and visually assessed field moisture condition. All laboratory work was carried out at the Soil Mechanics Laboratory of the University of Ibadan.

3.2 Sample preparation

Air-dried samples were disaggregated by hand with a rubber mallet, taking care not to crush individual particles, and passed through a 4.75 mm BS test sieve. The fraction passing was used for subsequent tests and the retained fraction was weighed and recorded as gravel. Specimens for direct shear were compacted directly into the 60 mm × 60 mm shear box in three equal layers, each receiving the standard compactive effort (ASTM D698), at the target density and moisture content.

3.3 Index property tests

Natural moisture content was determined by oven drying at 105 °C to constant mass (ASTM D2216; BS 1377, 1990) as $w = (W_2 - W_3)/(W_3 - W_1) \times 100$, where W_1 , W_2 and W_3 are the masses of the empty can, can with wet soil and can with dry soil. Bulk density was determined from the mass of soil in a mould of known volume, in three trials for each LGA and each rate series, and dry density was calculated as $\rho_d = \rho_b/(1 + w)$. Specific gravity was measured by the density-bottle (pycnometer) method (ASTM D854; BS 1377, 1990) as $G_s = (W_2 - W_3)/[(W_4 - W_1) - (W_3 - W_2)]$, in which W_1 is the mass of the empty bottle, W_2 bottle plus dry soil, W_3 bottle plus soil and water, and W_4 bottle plus water. From dry density and specific gravity, the solids volume fraction $V_s = (\rho_d/G_s) \times 100$ and the void volume $V_v = 100 - V_s$ (both as percentages of total volume) were calculated.

Grain-size distribution was determined by washing 100 g of oven-dried soil over a 75 µm sieve after 24 h of soaking, then dry sieving the retained material through the standard sieve set from 4.75 mm to 0.075 mm (BS 1377, 1990). The effective size D_{10} , the

intermediate size D_{30} and the size D_{60} were read from the distribution curves, and the coefficients of uniformity ($C_u = D_{60}/D_{10}$) and curvature ($C_c = D_{30}^2/(D_{10}D_{60})$) were computed. Liquid limit was determined with the Casagrande apparatus from three points of moisture content versus number of blows, plastic limit by rolling 3 mm threads, and the plasticity index as $PI = LL - PL$ (ASTM D4318). The Ido soil could not be rolled to a thread and was recorded as non-plastic.

3.4 Direct shear testing

Consolidated direct shear tests followed ASTM D3080 in a 60 mm × 60 mm shear box with porous stones top and bottom. Each specimen was consolidated under its normal stress for at least 24 h before shearing. Normal stresses of 50, 100 and 150 kPa were applied to represent the stress range typical of road subgrades and shallow foundations in Ibadan. Specimens were sheared at two constant displacement rates, 0.5 mm/min (slow) and 1.0 mm/min (fast), a 2:1 ratio bracketing the range commonly used in routine testing (about 0.8–1.25 mm/min). One shear series of three normal stresses was therefore performed for each LGA at each rate, twelve series in all. Shear force, horizontal displacement and vertical displacement of the top platen were logged electronically at one-second intervals, and shearing continued to 10 mm horizontal displacement or until a stable post-peak plateau was reached, whichever came first.

3.5 Control of strain rate and test conditions

Because strain rate was the single independent variable, all other conditions were held constant: the same equipment and technician were used throughout, specimens were prepared by the same procedure, and room temperature was kept within 22–28 °C. The motorised drive was calibrated against a displacement transducer before testing, and the achieved displacement rate was checked against elapsed time at the start of each test. Any test deviating from the target rate by more than ±5% was repeated. Calibration was repeated at two-weekly intervals or after the equipment was moved or serviced.

3.6 Data reduction and statistical analysis

Shear stress was computed as $\tau = F/A$, where F is the horizontal shear force and $A = A_0(1 - \delta/L)$ is the

contact area corrected for horizontal displacement δ (A_0 is the initial area and L the initial specimen length). Normal stress was the applied normal force divided by the corrected area. Peak shear stress was taken as the maximum of the shear stress–displacement curve, or the value at 10 mm displacement where no distinct peak occurred (ASTM D3080).

For each LGA and rate, the Mohr–Coulomb envelope $\tau = c + \sigma \tan \phi$ was fitted to the three peak shear stresses by least-squares regression, with ϕ obtained as the arctangent of the slope and the coefficient of determination R^2 used to judge fit. The effect of rate on the fitted friction angle was expressed as a rate sensitivity index,

$$RSI_\phi = [(\phi_{1.0} - \phi_{0.5})/\phi_{0.5}] \times 100 \quad (2)$$

and the effect on cohesion as the absolute change $\Delta c = c_{1.0} - c_{0.5}$, since a percentage measure is unstable when the cohesion intercept is close to zero. Two paired comparisons were made at the 95% confidence level. First, a metropolitan-level paired t -test treated the six LGAs as matched pairs ($n = 6$) of fitted c and of ϕ at the two rates. Second, within each LGA, the peak shear stresses at the two rates were paired by normal stress ($n = 3$ per LGA, $df = 2$) and compared with a paired t -test on τ itself. This second analysis avoids the instability of the fitted parameters but has limited power, and its results are treated as indicative.

IV. RESULTS

4.1 Physical and index properties

Table 1 summarises the density, moisture and specific-gravity results. Mean wet bulk density of the compacted specimens ranged from 1.555 g/cm³ (Ona-Ara) to 1.875 g/cm³ (Akinyele), with Egbeda (1.865 g/cm³) and Lagelu (1.775 g/cm³) also above 1.75 g/cm³ and Ido (1.705 g/cm³) and Oluyole (1.635 g/cm³) in between. Natural moisture content fell into two groups: Oluyole (22.39%) and Akinyele (20.72%) were markedly wetter than the other four soils, which lay between 9.55% (Egbeda) and 11.43% (Ona-Ara). Dry density was lowest at Oluyole (1.336 g/cm³) and highest at Egbeda (1.702 g/cm³). Specific gravity ranged from 1.65 (Oluyole) to 2.51 (Egbeda); all six values lie below the 2.60–2.80 typical of quartz-

dominated soils, and the Oluyole value is unusually low. The calculated void volume was smallest at Oluyole (19.04%) and largest at Ona-Ara (38.39%).

Table 1 Physical properties of the six lateritic soils

LGA	Parent rock	ρ_b (g/cm ³)	w (%)	G_s	ρ_d (g/cm ³)	V_v (%)
Akinyele	Migmatite-gneiss	1.875	20.72	2.26	1.553	31.28
Egbeda	Granite	1.865	9.55	2.51	1.702	32.17
Ido	Migmatite-gneiss	1.705	10.55	2.25	1.542	31.45
Lagelu	Schist	1.775	10.80	2.14	1.602	24.97
Oluyole	Granite	1.635	22.39	1.65	1.336	19.04
Ona-Ara	Granite	1.555	11.43	2.27	1.395	38.39

Note. ρ_b = mean wet bulk density of compacted specimens (mean of the two rate series); w = natural moisture content; G_s = specific gravity; ρ_d = dry density; V_v = void volume as a percentage of total volume. V_v was computed from unrounded G_s .

Bulk density also differed slightly between the two rate series prepared for each LGA: the mean difference was 0.09 g/cm³ at Akinyele, 0.07 at Oluyole, 0.05 at Ona-Ara, and 0.03 at each of Egbeda, Ido and Lagelu. Trial-to-trial scatter was smallest at Akinyele (range 0.21 g/cm³) and largest at Egbeda (range 0.61 g/cm³), where one specimen in the 1.0 mm/min series recorded

2.22 g/cm³ against otherwise consistent values of 1.6–1.9 g/cm³.

The grain-size curves (Figure 1, Table 2) show that all six soils are predominantly coarse-grained: sand accounts for 66.4–89.0% of each sample and the fraction passing the 0.075 mm sieve is only 1.2–9.1%. Egbeda is the coarsest, with 32.4% gravel and 1.2% fines, whereas Akinyele has the most fines (9.1%). On the tabulated diameters, Oluyole, Egbeda and Ona-Ara satisfy the coefficient criteria for a well-graded sand ($C_u > 6$ and $1 \leq C_c \leq 3$), Ido lies at the boundary ($C_c = 0.98$), and Akinyele and Lagelu are poorly graded ($C_c < 1$).

Figure 1 Particle-size distribution curves of the soils from the six LGAs

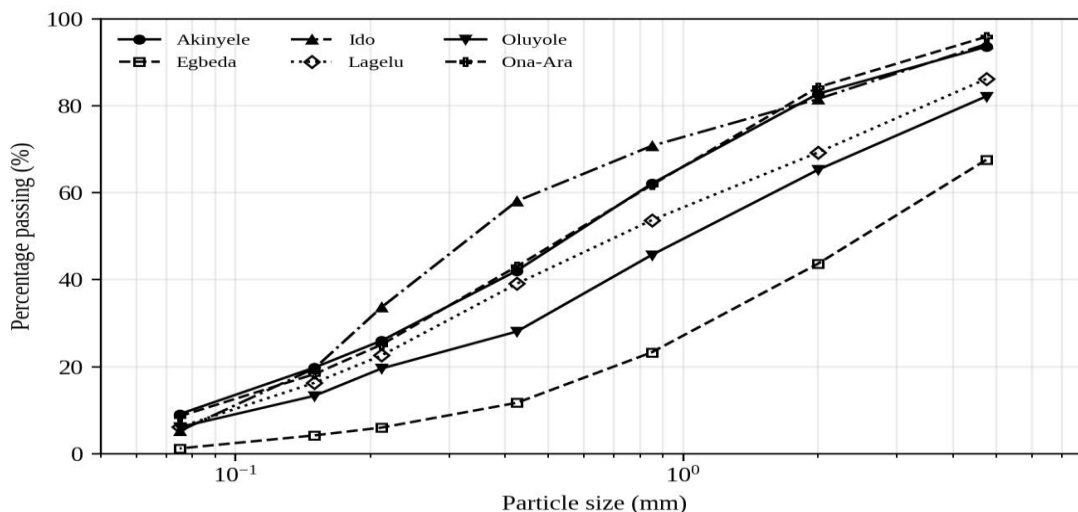


Table 2 Grain-size and Atterberg-limit results

LGA	Gravel (%)	Sand (%)	Fines (%)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	LL (%)	PL (%)	PI (%)
Akinyele	6.4	84.5	9.1	0.08	0.20	0.85	10.6	0.59	45.16	40.83	4.34
Egbeda	32.4	66.4	1.2	0.35	1.17	2.92	8.3	1.34	40.57	29.67	10.90
Ido	5.8	89.0	5.2	0.09	0.22	0.55	6.1	0.98	NP	NP	NP
Lagelu	13.8	80.1	6.1	0.10	0.28	1.20	12.0	0.65	45.32	40.47	4.85
Oluyole	17.8	76.1	6.1	0.12	0.47	1.60	13.3	1.16	53.65	43.06	10.59
Ona-Ara	4.1	87.3	8.6	0.11	0.30	0.81	7.4	1.01	53.97	47.22	6.75

Note. Fines = percentage passing the 0.075 mm sieve. C_u and C_c were computed from the tabulated D -values. LL = liquid limit; PL = plastic limit; PI = plasticity index; NP = non-plastic.

Liquid limits of the five plastic soils lie between 40.57% and 53.97% and plasticity indices between 4.34% and 10.90%, that is, low to medium plasticity, with Egbeda (10.90%) and Oluyole (10.59%) the most plastic and Akinyele (4.34%) the least. The Ido soil was non-plastic. Egbeda thus combines the lowest

fines content with the highest plasticity index of the group.

4.2 Shear stress–displacement behaviour and peak strength

In every test, shear stress rose with horizontal displacement to a peak or plateau and increased with normal stress. Table 3 lists the peak shear stresses. Mean peak shear stress across the three normal stresses ranged from 36.43 kPa (Lagelu, 0.5 mm/min) to 87.48 kPa (Egbeda, 1.0 mm/min). Raising the rate from 0.5 to 1.0 mm/min increased mean peak shear stress at four LGAs (Egbeda +27.80 kPa, Akinyele +15.35 kPa, Lagelu +9.63 kPa, Oluyole +8.99 kPa) and reduced it at two (Ona-Ara –7.53 kPa, Ido –6.45 kPa).

Table 3 Peak shear stress (kPa) at each normal stress and displacement rate

LGA	Rate (mm/min)	$\sigma = 50$ kPa	$\sigma = 100$ kPa	$\sigma = 150$ kPa	Mean	Rate ratio
Akinyele	0.5 / 1.0	14.72 / 32.70	34.88 / 60.23	73.85 / 76.58	41.15 / 56.50	1.37
Egbeda	0.5 / 1.0	29.98 / 59.68	59.95 / 88.02	89.11 / 114.74	59.68 / 87.48	1.47
Ido	0.5 / 1.0	34.88 / 20.71	66.50 / 43.33	70.31 / 88.29	57.23 / 50.78	0.89
Lagelu	0.5 / 1.0	11.72 / 25.89	47.14 / 40.60	50.42 / 71.68	36.43 / 46.06	1.26
Oluyole	0.5 / 1.0	20.44 / 12.81	32.70 / 65.13	70.85 / 73.03	41.33 / 50.32	1.22
Ona-Ara	0.5 / 1.0	24.80 / 23.71	59.40 / 58.05	104.90 / 84.75	63.03 / 55.50	0.88

Note. Each cell gives the value at 0.5 mm/min / 1.0 mm/min. Rate ratio = mean peak shear stress at 1.0 mm/min divided by that at 0.5 mm/min.

4.3 Mohr–Coulomb parameters

The fitted failure envelopes are shown in Figure 2 and the parameters in Table 4. The linear model fitted all twelve LGA–rate combinations well ($R^2 = 0.813$ –

1.000), with the envelopes for Egbeda at both rates essentially exact ($R^2 = 1.000$). Friction angles ranged from 19.51° (Ido, 0.5 mm/min) to 38.69° (Ona-Ara, 0.5 mm/min). Eleven of the twelve values fall within the 18°–38° range reported for compacted Nigerian lateritic soils (Ola, 1983; Adeyemi, 1995; Iyeke et al., 2016), and six exceed the 12°–30° range reported for

Ibadan by Adeyemi (1995), which may partly reflect the coarse grading of the present soils.

Figure 2 Peak shear stress versus normal stress and fitted Mohr–Coulomb envelopes at 0.5 mm/min (filled markers, solid lines) and 1.0 mm/min (open markers, dashed lines)

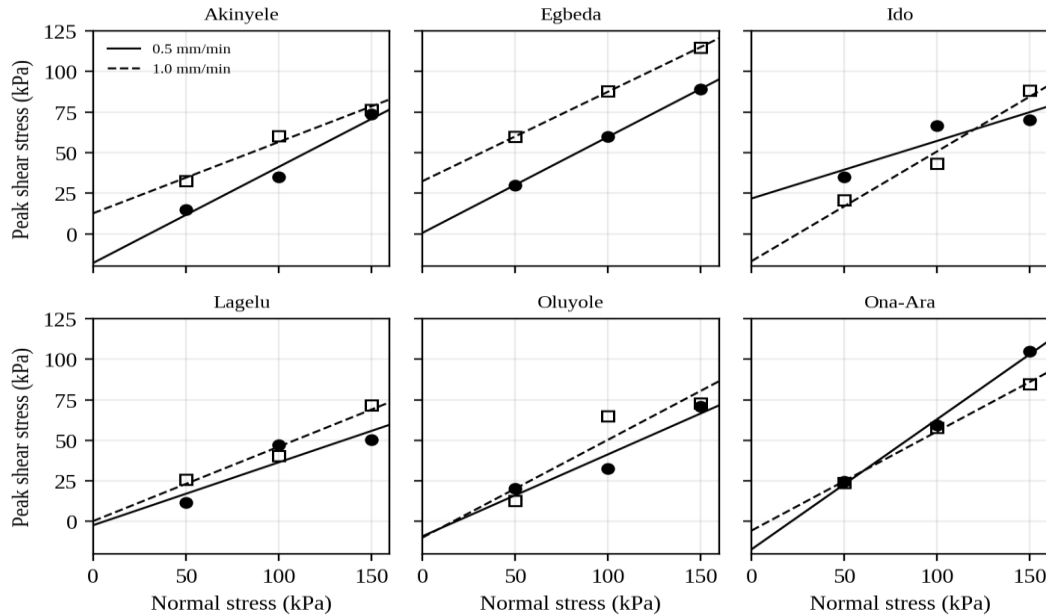


Table 4 Mohr–Coulomb parameters derived from peak shear stresses

LGA	c (kPa) 0.5	c (kPa) 1.0	ϕ (°) 0.5	ϕ (°) 1.0	R^2 0.5	R^2 1.0
Akinyele	-17.98	12.62	30.60	23.69	0.967	0.979
Egbeda	0.55	32.42	30.60	28.84	1.000	1.000
Ido	21.80	-16.80	19.51	34.05	0.830	0.965
Lagelu	-2.27	0.27	21.16	24.60	0.813	0.959
Oluyole	-9.08	-9.90	26.75	31.06	0.919	0.846
Ona-Ara	-17.07	-5.54	38.69	31.40	0.994	0.995

Note. Column labels 0.5 and 1.0 denote the displacement rate in mm/min. Parameters are total-stress values from three-point regressions.

Seven of the twelve cohesion intercepts are negative, and only three lie within the published ranges of 5–60 kPa and 8–42 kPa. Shear stress increased with normal stress in every test, but the three-point envelopes are not perfectly linear (convex in five tests, concave in seven), so the fitted intercept is highly sensitive to the reading at 50 kPa. The negative intercepts therefore

reflect the limitation of fitting a two-parameter model to three stress levels, not a genuine absence of cohesive strength or an error in the data. Cohesion is accordingly treated here as indicative only. The Ido results illustrate the point: the fitted parameters swing from $c = 21.80$ kPa, $\phi = 19.51^\circ$ at 0.5 mm/min to $c = -16.80$ kPa, $\phi = 34.05^\circ$ at 1.0 mm/min, while mean peak shear stress changed by only -11%.

Table 5 gives the change in the fitted parameters between the two rates. Cohesion increased at four

LGAs and decreased at two, while the friction angle increased at three and decreased at three. The largest RSI ϕ values (+74.5% at Ido, -22.6% at Akinyele) belong to the LGAs with the least stable intercepts, and

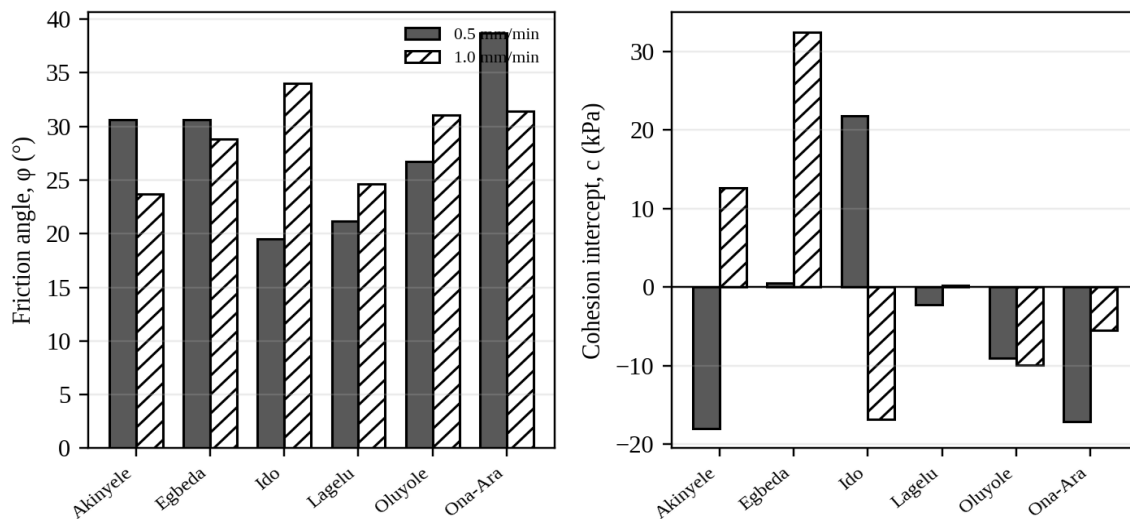
the sign of the change in ϕ is generally opposite to that in c (Figure 3), as expected when the intercept and slope of a short regression trade off against each other.

Table 5 Change in fitted Mohr–Coulomb parameters when displacement rate increased from 0.5 to 1.0 mm/min

LGA	Δc (kPa)	$\Delta \phi$ (°)	RSI ϕ (%)
Akinyele	+30.60	-6.91	-22.6
Egbeda	+31.87	-1.76	-5.7
Ido	-38.60	+14.54	+74.5
Lagelu	+2.54	+3.44	+16.3
Oluyole	-0.82	+4.31	+16.1
Ona-Ara	+11.53	-7.29	-18.9
Mean	+6.19	+1.06	—

Note. $\Delta c = c_{1.0} - c_{0.5}$; $\Delta \phi = \phi_{1.0} - \phi_{0.5}$; $RSI\phi = \Delta \phi / \phi_{0.5} \times 100$.

Figure 3 Fitted friction angle (left) and cohesion intercept (right) by LGA and displacement rate



4.4 Metropolitan-level comparison

Paired t-tests across the six LGAs (Table 6) showed no significant effect of rate on either parameter. Mean cohesion rose from -4.01 to 2.18 kPa (mean difference 6.19 kPa; $t(5) = 0.585$, $p = 0.584$) and mean friction angle from 27.88° to 28.94° (difference 1.06°; $t(5) = 0.314$, $p = 0.766$). Both differences are small relative

to the LGA-to-LGA variability: the standard deviations of the paired differences are 25.90 kPa for c and 8.24° for ϕ , giving 95% confidence intervals for the mean difference of -21.0 to +33.4 kPa and -7.6° to +9.7°, respectively.

Table 6 Paired t-test of fitted shear strength parameters at 0.5 and 1.0 mm/min (n = 6 LGAs)

Parameter	Mean at 0.5	Mean at 1.0	Mean difference	t (df = 5)	p
Cohesion, <i>c</i> (kPa)	-4.01	2.18	6.19	0.585	0.584
Friction angle, ϕ (°)	27.88	28.94	1.06	0.314	0.766

Note. Neither difference is significant at the 95% confidence level.

4.5 Per-LGA comparison of peak shear stress

Because each LGA–rate combination yields a single regression-derived pair of parameters, the metropolitan test cannot show whether the rate effect is uniform across LGAs. Peak shear stresses were therefore paired by normal stress within each LGA and compared directly (Table 7, Figure 4). Five LGAs showed no significant difference between rates ($p = 0.148$ – 0.657). Egbeda was the exception: peak shear stress was higher at 1.0 mm/min at every normal stress

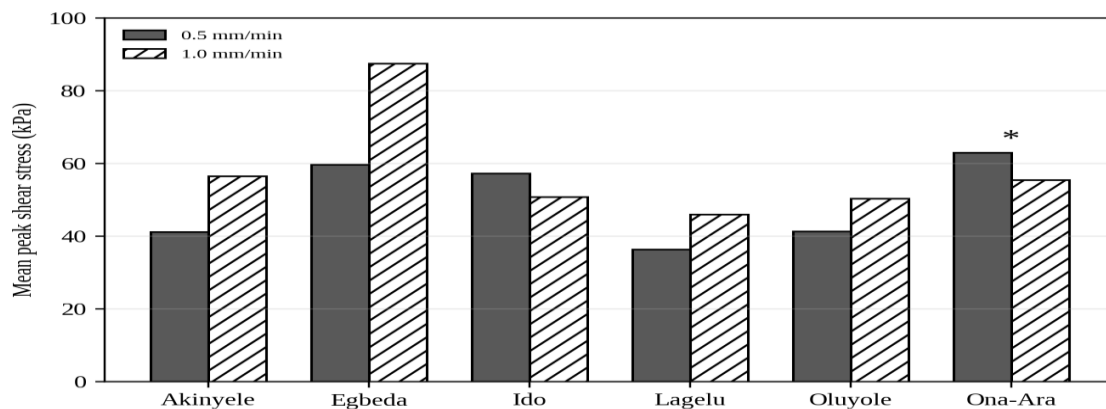
(by 29.70, 28.07 and 25.63 kPa at 50, 100 and 150 kPa), a mean increase of 27.80 kPa ($t(2) = 23.507$, $p = 0.0018$). This result remains significant after a Bonferroni adjustment for six comparisons (adjusted threshold $p < 0.0083$). With only three pairs per LGA ($df = 2$), the tests have low power, so the non-significant results should be read as an absence of demonstrated effect, not as proof of none.

Table 7 Per-LGA paired t-test on peak shear stress at 0.5 and 1.0 mm/min (n = 3 normal stresses per LGA)

LGA	Mean τ at 0.5 (kPa)	Mean τ at 1.0 (kPa)	Mean difference (kPa)	t (df = 2)	p	Significant ($\alpha = 0.05$)
Akinyele	41.15	56.50	+15.35	2.305	0.1476	No
Egbeda	59.68	87.48	+27.80	23.507	0.0018	Yes
Ido	57.23	50.78	-6.45	-0.517	0.6568	No
Lagelu	36.43	46.06	+9.63	1.155	0.3676	No
Oluyole	41.33	50.32	+8.99	0.746	0.5334	No
Ona-Ara	63.03	55.50	-7.53	-1.193	0.3551	No

Note. τ = peak shear stress averaged over the three normal stresses. The bold row marks the only LGA with a significant rate effect.

Figure 4 Mean peak shear stress by LGA and displacement rate (asterisk: significant difference, $p < 0.05$)



V. DISCUSSION

5.1 Overall insensitivity to rate over the range tested
Taken as a group, the lateritic soils of Ibadan showed no statistically significant dependence of Mohr–Coulomb parameters on displacement rate between 0.5 and 1.0 mm/min. The direction of change was inconsistent, and variation between LGAs was much larger than the mean rate effect. This is consistent with the composition of the soils. They are dominated by sand and gravel, with fines below 10%, and the literature indicates that rate effects in drained granular soils are small because the skeleton adjusts rapidly to changes in loading, becoming appreciable mainly at high normal stresses or when fines introduce viscous resistance (Gebrenegus et al., 2017; Leroueil & Marques, 1996). The normal stresses used here (50–150 kPa) are modest, and the specimens were consolidated for 24 h, so excess pore pressures were probably small at these shearing rates. Cementation of lateritic particles by iron oxides may also stiffen the contacts and reduce viscous contributions (Mitchell & Soga, 2005).

It is important not to over-read the null result. Over a two-fold change in rate (0.30 of a log cycle), coefficients of 0.03–0.12 per log cycle typical of stiffer clays and tropical residual soils (Leroueil & Marques, 1996) would imply strength changes of only about 1–4%. Such changes are far smaller than the scatter in the present data, and even the 95% confidence intervals for the mean differences (-7.6° to $+9.7^\circ$ for ϕ) are wide. The experiment could therefore detect only a large rate effect. What it can support is a practical conclusion: across most of Ibadan, the choice between 0.5 and 1.0 mm/min in routine direct shear testing does not, by itself, produce a measurable difference in strength; it cannot establish that the soils are rate-insensitive over the orders-of-magnitude range that separates laboratory from seismic or impact loading.

5.2 Egbeda as a localised exception

Egbeda showed a consistent and statistically significant increase in strength with rate, and the pattern is notable in its form. The envelopes at both rates are near-perfectly linear ($R^2 = 1.000$), and the difference in peak shear stress is nearly constant across the three normal stresses (25.6–29.7 kPa). A near-constant offset corresponds to an upward shift of the envelope, a change in the intercept rather than in the slope, and the fitted cohesion increased by 31.87 kPa while the friction angle changed by only -1.76° . This resembles the finding of Zhang et al. (2024) that rate effects in loess act more on cohesion than on friction, which those authors attributed to viscous and pore-pressure mechanisms rather than to particle interlocking. Because the intercept is the least reliable quantity in three-point fits, this reading is suggestive, but here the regression is exact and the shift is present at every stress level.

Index properties offer partial clues. Egbeda has the highest plasticity index (10.90%), the lowest fines content (1.2%), the highest specific gravity (2.51) and the highest dry density (1.702 g/cm³) of the six soils, and it also has the lowest natural moisture content (9.55%). A plastic fraction that is concentrated within the fine sand and silt sizes (the Atterberg limits are determined on the material finer than 0.425 mm, which is 11.7% of the Egbeda sample) could provide viscous resistance despite the low fines content in the strict sense. Plasticity alone, however, does not explain the result. Oluyole is also derived from granite and has a comparable plasticity index (10.59%), yet showed no significant rate effect (mean strength ratio 1.22 against 1.47 for Egbeda; Table 8). The response at Egbeda therefore presumably reflects a combination of factors, such as density, cementation, the plastic fines and moisture, not any single index property.

Table 8 Parent rock, index properties and strain-rate response of the six LGAs

LGA	Parent rock	PI (%)	Fines (%)	Mean $\Delta\tau$ (kPa)	Rate ratio	p	Significant
Akinyele	Migmatite-gneiss	4.34	9.1	+15.35	1.37	0.1476	No
Egbeda	Granite	10.90	1.2	+27.80	1.47	0.0018	Yes
Ido	Migmatite-gneiss	NP	5.2	-6.45	0.89	0.6568	No

LGA	Parent rock	PI (%)	Fines (%)	Mean $\Delta\tau$ (kPa)	Rate ratio	p	Significant
Lagelu	Schist	4.85	6.1	+9.63	1.26	0.3676	No
Oluyole	Granite	10.59	6.1	+8.99	1.22	0.5334	No
Ona-Ara	Granite	6.75	8.6	-7.53	0.88	0.3551	No

Note. $\Delta\tau$ = change in mean peak shear stress from 0.5 to 1.0 mm/min; rate ratio = mean τ at 1.0 mm/min divided by mean τ at 0.5 mm/min; NP = non-plastic.

Two cautions apply. First, the size of the Egbeda effect, a 47% increase in strength for a 0.30 log-cycle increase in rate, corresponds to roughly 1.5 per log cycle, an order of magnitude above the coefficients of 0.03–0.20 reported for clays and tropical residual soils (Leroueil & Marques, 1996). A purely viscous mechanism is therefore an unlikely sole explanation. Differences in specimen density or fabric between the two series are a plausible contributor, given that Egbeda also had the greatest trial-to-trial spread in bulk density (including one specimen at 2.22 g/cm³) and that compaction state is known to modulate apparent rate sensitivity (Tamassoki et al., 2022). Second, the Egbeda finding rests on one borrow pit and three stress levels. It should be treated as a well-supported observation requiring confirmation, not as an established property of the Egbeda soils.

5.3 Reliability of the fitted parameters

The prevalence of negative cohesion intercepts (seven of twelve) and the large parameter swings at Ido and Akinyele show that two-parameter Mohr–Coulomb fits to three normal stresses are too unstable to support conclusions about rate effects on c and ϕ separately. Comparing shear stress at fixed normal stress, as in the per-LGA analysis, is more robust, and the near-zero or opposite-signed changes in ϕ and c at several LGAs are best regarded as compensating errors in the regression rather than physical change. The friction angles obtained (19.5°–38.7°) are physically reasonable for coarse-grained lateritic soils, and eleven of twelve fall within the range in the Nigerian literature, though six exceed the range Adeyemi (1995) reported for Ibadan. Because direct shear does not measure pore pressure, all parameters are total-stress values and should not be compared directly with effective-stress parameters from triaxial tests (Bishop & Henkel, 1957).

Some of the index results also merit verification. The specific gravity of the Oluyole soil (1.65) is far below the range expected for mineral soil grains and might indicate porous, partially weathered concretions or incomplete de-airing of the pycnometer. Moreover, the liquid limits of 40–54% combined with plasticity indices of only 4–11% place the plastic soils well below the A-line of the plasticity chart, behaviour often seen in soils with microaggregated iron-oxide and kaolinitic or halloysitic fines. That such plasticity occurs alongside fines contents below 10% is a reminder that the sub-0.425 mm fraction, which carries the Atterberg limits, may be a larger share of the soil than the sub-0.075 mm fraction. This does not affect the direct shear comparison, which is between rates on the same soil, but it bears on the interpretation of the index data.

5.4 Implications for geotechnical practice

For five of the six LGAs (Akinyele, Ido, Lagelu, Oluyole and Ona-Ara), direct shear results obtained at 0.5 or 1.0 mm/min can be used interchangeably for preliminary design of road subgrades and shallow foundations under normal stresses of 50–150 kPa, since no statistically detectable difference was found. This should not be extended to Egbeda, where site-specific multi-rate testing is advisable. Because a rate effect could not be demonstrated outside Egbeda, this study does not propose general rate-correction factors; the descriptive strength ratios in Table 8 (0.88–1.47) are not statistically supported for that purpose. A further practical consequence follows from Section 4.3. Laboratories reporting Mohr–Coulomb parameters from three-point envelopes should add normal stress levels, and should state the displacement rate with every reported result so that data can be compared across studies (Amadi et al., 2012).

5.5 Limitations

Several limitations qualify the findings. Only two rates differing by a factor of two were used, so nothing can be said about rates several orders of magnitude apart,

such as those in dynamic or seismic loading; cyclic and dynamic effects (cf. Guo et al., 2025; Wang et al., 2025) were beyond the scope of the equipment. One borrow pit represented each LGA, so within-LGA variability is not captured. Each LGA–rate combination comprised one specimen at each of three normal stresses, so the per-LGA tests rest on three pairs and cannot separate specimen-to-specimen variability from rate effects. Bulk density of the paired specimens differed by up to 0.09 g/cm³ (Akinyele), and no specimen-level density control beyond the standard compactive effort was applied. Tests were on disturbed, recompacted material, so natural fabric and structure are not represented, and all parameters are total-stress values from a drained-consolidated test with no pore-pressure measurement. Finally, only peak strength was analysed; residual strength, which may respond differently to rate (Yan et al., 2024), was not examined.

VI. CONCLUSIONS

Lateritic soils from six LGAs of Ibadan metropolis were characterised and tested in direct shear at 0.5 and 1.0 mm/min to assess the influence of strain rate on their Mohr–Coulomb shear strength. The main conclusions are as follows.

(i) The soils are predominantly sandy, with fines of 1.2–9.1%, natural moisture contents of 9.55–22.39%, specific gravities of 1.65–2.51, and low to medium plasticity (PI 4.34–10.90%, Ido non-plastic). Index properties vary measurably between LGAs, confirming the value of zone-specific characterisation.

(ii) Friction angles of 19.5°–38.7° were obtained with good linear fits ($R^2 = 0.81$ –1.00). Seven of the twelve cohesion intercepts were negative, an artefact of three-point regression, so cohesion values are indicative only and comparison of shear stress at fixed normal stress is preferable.

(iii) Doubling the displacement rate increased mean cohesion by 6.19 kPa and mean friction angle by 1.06°, but neither change was significant ($p = 0.584$ and 0.766) and the direction of change was not consistent across LGAs.

(iv) At LGA level, five LGAs (Akinyele, Ido, Lagelu, Oluyole, Ona-Ara) showed no significant change in peak shear stress with rate, whereas Egbeda showed a consistent and significant increase (mean +27.80 kPa, $p = 0.0018$). Rate sensitivity in the study area is thus localised, not regional, over the range examined, although the magnitude of the Egbeda effect is larger than viscous mechanisms alone would suggest and requires confirmation.

6.1 Recommendations

For routine direct shear testing of Ibadan lateritic soils, results at either 0.5 or 1.0 mm/min may be used for preliminary design in Akinyele, Ido, Lagelu, Oluyole and Ona-Ara, but multi-rate testing should be specified for Egbeda. Laboratories should report the strain rate with every strength result and use more than three normal stress levels where practicable. Further work should extend the rate range, include replicate specimens and additional sampling points per LGA, use triaxial tests with pore-pressure measurement, and investigate the cause of the Egbeda response through density control and mineralogical analysis of the fine fraction.

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Data availability

The shear stress–displacement records and index test data supporting this study are available from the corresponding author on reasonable request.

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