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Influence of clay fraction and particle mineralogy on the residual strength of iron and bauxite tailings.

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ABSTRACT: Currently, there is a need for a better understanding of the effects of mineralogy on the differences in frictional behavior at the critical and residual states of tailings. Previous studies indicate that changes in clay fraction in some plastic soils may cause multiple drops in the friction angle at both states. Consequently, it is important to understand how these changes in frictional behavior could impact stability of TSFs with existing slip surfaces particularly those having experienced excessive movements. In this study, the influence of clay fraction and particle mineralogy on critical and residual behaviors were examined using iron ore and bauxite tailings. To assess the effect of mineralogy on the frictional behavior of clayey tailings, the critical friction ratio measured using triaxial compression tests was compared with the residual friction angle measured using a constant pressure ring shear device. The results showed that the mobilised friction angle in iron ore tailings was reduced when critical states were compared with residual states. However, in bauxite tailings, the residual friction behaviour was equivalent to critical friction behaviour. Preliminary findings indicate that particle mineralogy and clay fraction influence the frictional behaviour at both critical and residual states of tailings. Discussions are provided on how these findings may better inform TSF design.

KEYWORDS: Residual strength, tailings, particle mineralogy, ring shear, residual friction angle.

1 INTRODUCTION

The rising global demand for minerals, driven by decarbonization, infrastructure development and technological advancements, has significantly increased mining activities. Inevitably, mine ore extractions have significantly increased generation of the waste by-products referred to as “tailings/residues”, which consist of fine to coarse grained solids that are stored in tailings storage facilities (TSFs). Geotechnical failures of TSFs have led to environmental pollution, fatalities and distortion of financial markets (e.g. Lumbroso et al. 2021). As a result, it remains vital to prevent failure of TSFs through understanding of lower bound limits of strength, often referred to as residual strength (e.g. Skempton 1985, Mmbando et al. 2022)

Geotechnical stability of TSFs with existing slip surfaces, particularly those that have experienced excessive deformations is dependent on the drained residual strength of tailings (Stark and Hussain 2010a), which is governed by frictional behavior of tailings. TSF failures often occur when the mobilized shear stress exceeds the residual strength of the material, as evidenced by the 1985 Stava dam failure in Italy (Gens and Alonso 2006). Current frameworks of critical state soil mechanics used to model shear behavior of tailings define the strength envelope using a reference stress ratio at failure, referred to as “critical friction stress ratio (M_{tc}) for triaxial compression tests, which is related to the critical friction angle (ϕ_{tc}) (Shuttle and Jefferies 2010, Jefferies and Been 2016). Existing literature also highlights that understanding of progressive failure of slopes (Skempton 1964, Stark and Hussain 2010a), requires estimating the lower bound friction angle, (Bishop A 1967, Skempton 1985), which is often less than ϕ_{tc}, the latter being referred to as the residual friction angle (ϕ_r). Current geotechnical practice correlates ϕ_r with soil plasticity and clay fraction (Lupini et al. 1981, U.S. Department of Defense 2012, Carter and Bentley 2016) with relatively good agreement in many soils. However, such correlations are often variable and inconsistent for some soils, as their applicability depends not only on plasticity and clay fraction but also mineralogy (Tiwari and Marui 2005, Wesley 2010, Blight and Leong 2012).

Increase in clay fraction and plasticity in soils has been shown to reduce ϕ_r measured using ring shear tests (Lupini et al. 1981, Skempton 1985, Tiwari and Marui 2005), with a higher reduction in soils with high plasticity (Toyota et al. 2009). Similar trends were reported in triaxial tests when comparing peak and critical frictional behaviour (Zhu and Yin 2000). However, variations in mineralogy, including the presence of smectite minerals have shown an influence on residual behaviour (Stark and Eid 1994, Tiwari and Marui 2005). Moreover, substantial scatter in correlations relating plasticity with ϕ_r (e.g.Carter and Bentley 2016), have indicated an influence of mineralogy. Given that mineralogy of most tailings differs significantly from typical researched soils, such as London clay, it remains important to assess and compare the validity of such correlations to tailings, which often have distinctly different geochemistry, such as bauxite residue (BR) and iron ore tailings (IOT).

Differences in particle orientation during shearing of soils has been reported to influence the friction resistance at the residual state, including that the residual strength is dependent on the degree of particle orientation, and the clay fraction (Lupini et al. 1981, Skempton 1985). Where smectite minerals are present, a considerable influence of particle orientation on the residual strength has been observed at stresses lower than 100 kPa (Gibo et al. 1987). It has been reported that reduced clay fraction in sandy clays results in minimal orientation of particles, which results in ϕ_{cv} being equivalent to ϕ_r (Skempton 1985). The classification of different particle orientations during shearing with increasing clay fraction, such as rolling, sliding and transitional, indicates that particle orientation is likely in soils with clay fraction higher than 20-25% (Skempton 1985, Stark et al. 2005, Stark and Hussain 2010b). However, it remains unclear whether this applies to bauxite and iron ore tailings.

Studies indicate that mineralogy and weathering of parent rock influences the residual behaviour of soils, including variations in cementation, and presence of halloysite, mica and feldspar content in clayey soils (Vaughan 1988, Rigo et al. 2006). Different correlations between residual strength behavior, clay fraction and plasticity in some soils have been reported (Wesley 1977, 2010). Additionally, it remains unclear whether conventional correlations applied to estimate ϕ_r in montmorillonite and kaolinite mixtures, and montmorillonite and quartz mixtures (e.g. Lupini et al. 1981) are applicable to bauxite and iron tailings, noting that tailings may constitute crystalline minerals and amorphous states (Mmbando 2024, Mmbando et al. 2024).

This study examines the frictional behaviour of bauxite and iron tailings at critical and residual states, using materials previously characterized by Mmbando (2024). Triaxial and ring shear results are combined to assess the effect of mineralogy on the residual friction of bauxite and iron ore tailings, providing insights that build upon Skempton's work.

2 MATERIALS

The material properties of BR and IOT have been described intensively in previous work (e.g. Mmbando et al., 2023, Mmbando et al., 2024). The properties of BR and IOT used in this study are summarized here. The liquid limit (LL), plastic limit (PL), plasticity index (PI) and clay fraction of BR and IOT were 63, 37, 25, 33% and 39, 21, 18 and 38% respectively.

X-ray diffraction (XRD) was undertaken to evaluate the mineralogy of both tailings. The XRD results of BR were also part of results presented by Mmbando et al. (2024). Table 1 and Figure 1a and b shows the relative mineralogical composition and colloidal activity, respectively for both tailings. IOT tailings showed a higher proportion of hematite and kaolinite, while BR composed more of muscovite and quartz, behaving similar to illite clays.

Table 1. Mineral phase of BR and IOT

BR		IOT	
Crystalline mineral phase	Concentration (%)	Crystalline mineral phase	Concentration (%)
Muscovite-Illites	41.93	Hematite	44.2
Quartz	12.97	Kaolinite	34.4
Goethite	11.80	Muscovite	8.1
Calcite	8.87	Quartz	7.9
Bohmite	6.83	Goethite	3.5
Hematite	5.75	Clinochlore, ferroan	1.9
Gibbsite	5.36		
Grossular	2.05		
Nosean	1.85		
Armophous	2.50		

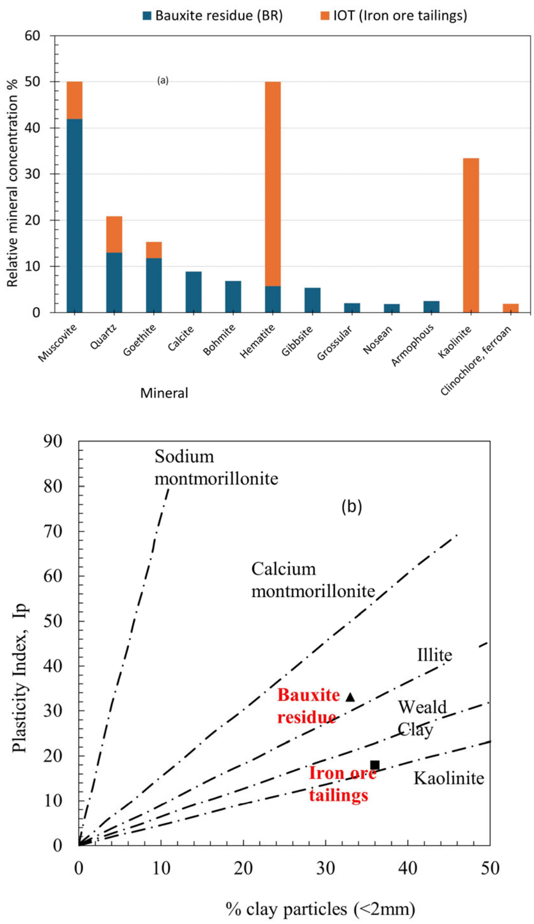


Figure 1. Relative mineralogical composition of BR and IOT (b) Colloidal activity of BR and IOT

3 EXPERIMENTAL METHODS

Drained triaxial tests were carried out to evaluate the mobilized friction ratio at critical state (M_{tc}) using loosely reconstituted samples of BR and IOT. Moist tamped (MT) (Ladd 1978), slurry reconstituted (SC) (Sheeran and Krizek 1971) and undisturbed trimmed (TR) samples were back pressure saturated to B values higher than 0.95, isotropically consolidated to different mean effective stresses (p') and sheared to critical state based on the triaxial testing methods suggested by (Jefferies and Been 2016, Lade 2016). Table 2 shows the summary of triaxial tests of IOT and BR presented by Mmbando (2023, 2024),) with their respective friction angles.

Constant pressure ring shear (CPRS) tests were carried out to determine the mobilized friction angle at residual conditions (ϕ_r) using saturated samples (e.g. Stark and Vettel 1992, Mmbando et al. 2022). Samples of IOT and BR were normally consolidated at different vertical effective stresses (σ'_{vo}) and then sheared at varying rates ranging between 0.1 and 0.0024 deg/s as presented in Table 3. Ring shear test procedures such as load friction corrections followed the same methods presented by Mmbando et al. (2022).

Table 2. List of Triaxial tests

	Test	p'_c kPa	e_c	p'_{cs} kPa	q_{cs} kPa	ψ	ϕ_{tc}	M_{tc}
BR	MT-L3	151	1.32	284	398	0.049	35	1.4
	MT-L4	301	1.26	537	712	-0.003	33	1.3

	SC2	100	1.49	197	287	0.068	36	1.5
	SC3	203	1.39	383	542	0.072	35	1.4
	TR5	400	1.15	682	844	-0.026	31	1.2
IOT	MT3	101	0.91	155	164	-0.001	27	1.1
	MT4	299	0.81	455	439	0.001	25	1.0
	SD1	503	0.91	790	858	0.15	27	1.1
	SD2	403	0.92	629	689	0.14	28	1.1

Note: e_{cs} – critical void ratio, e_c - void ratio after consolidation, p'_c - consolidated mean effective stress, p'_{cs} - critical mean effective stress, q_{cs} - critical deviatoric stress, ψ-state parameter.

Table 3. List of ring shear tests

Material	Test	σ'_{vo} kPa	Shear rate (deg/s)	ϕ_r	*M*
BR	B6	800	0.1	34	0.67
	B7	400	0.003	33	0.65
	B8	300	0.003	33	0.66
	B9	200	0.003	33	0.65
	B10	100	0.003	34	0.67
IOT	R4	800	0.0024	23	0.43
	R5	500	0.0024	24	0.44
	R6	300	0.0024	23	0.43

3.1 *Methods of calculating mobilized friction ratio (M)*

M at critical state and residual state were determined using methods outlined by Jefferies and Been (2016), as summarized below.

a) M_{tc} was measured as the stress ratio ($\eta = q/p'$) at maximum axial strains (ε_a) of drained triaxial tests. BR and IOT triaxial samples were sheared to maximum limit of triaxial compression apparatus. At critical state, where q and p' remained constant with negligible change in volumetric strain, the corresponding η was taken as *M*. φ_{tc} was determined using equation *(1)*

$$M_{tc} = \frac{6 \sin \phi_{tc}}{(3 - \sin \phi_{tc})} \qquad (1)$$

b) M_{tc} in drained triaxial tests was calculated as the slope of change in η with plastic dilatancy(D^p) , similar to the stress dilatancy approach described by Ghafghazi and Shuttle (2006).

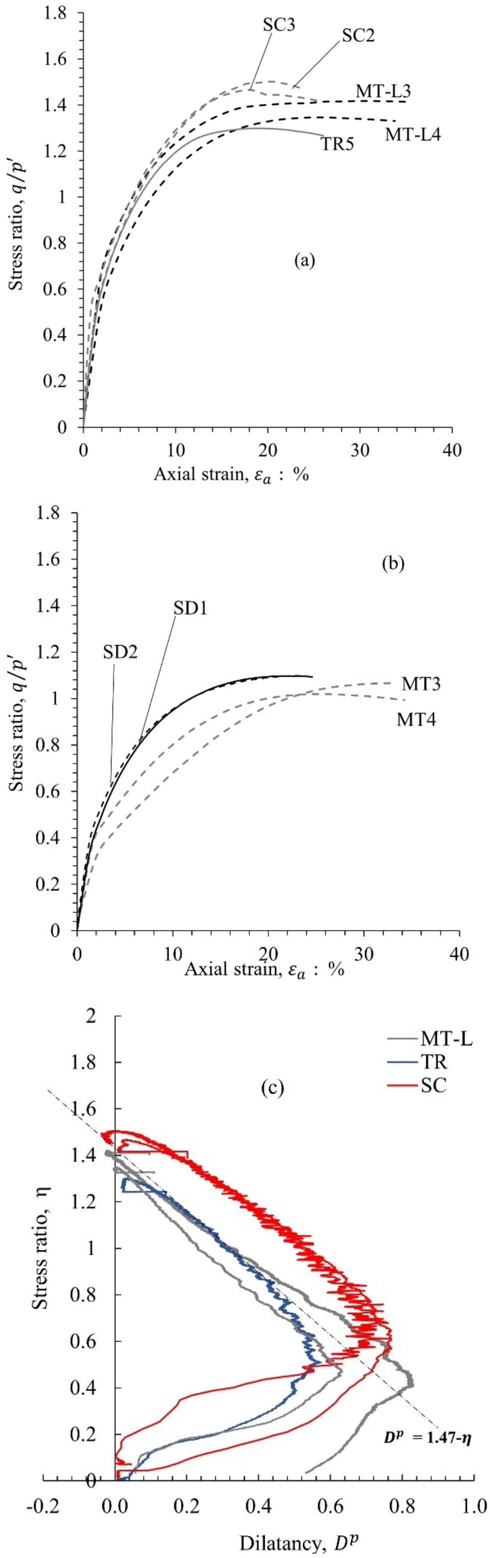
c) Estimation of *M* in the ring shear device neglected the inclination of principal stress (α) (Toyota et al. 2009, Sadrekarimi and Olson 2011) and assumed that horizontal failure plane is equivalent to the maximum shear stress (Roscoe 1967, Holtz et al. 1981). The angle of shear resistance at residual state (ϕ_r) was determined using equation *(2)*.

$$\phi_r = \tan^{-1}[\tau/\sigma'_{vo}] \qquad (2)$$

4 RESULTS

4.1 *Triaxial compression behavior*

Figure 2a and b show the change in η with axial strain (ε_a) in drained tests of BR and IOT. The variations in e_o between dense and loose triaxial samples resulted in a variation of η, e.g., looser samples showed slightly lower η than medium dense samples. The η measured at higher strains was considered as the M_{tc}. The M_{tc} of BR and IOT averaged 1.45 and 1.1respectively. Figure 2c and d show the stress dilatancy results of BR and IOT, respectively. The stress dilatancy behaviour was assessed using changes in η with D^p. The slope of the stress dilatancy curve at the point of maximum D^p to the point of zero dilatancy was taken as the M_{tc}. In this work, loose and medium dense samples were used for analysis. The M_{tc} calculated from stress dilatancy result was found to be 1.47 and 1.15 in BR and IOT respectively.



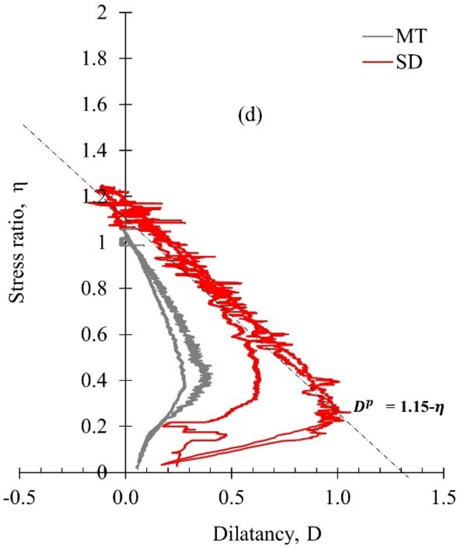
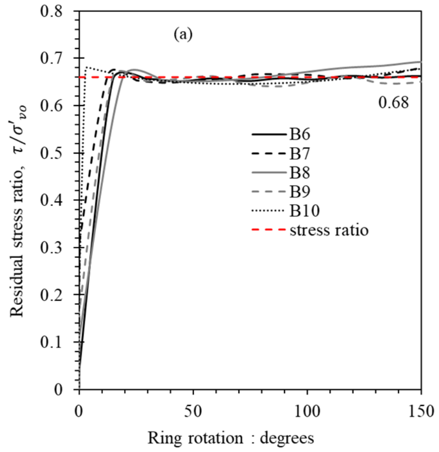
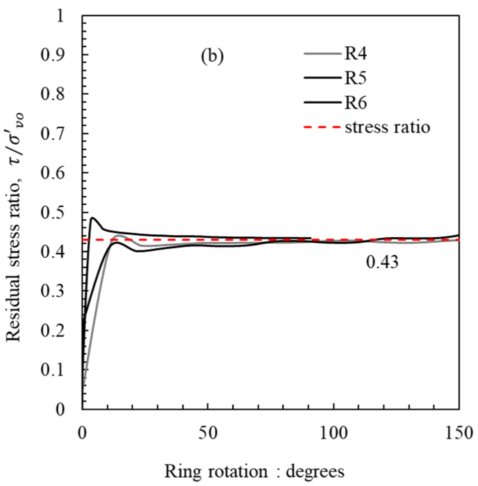


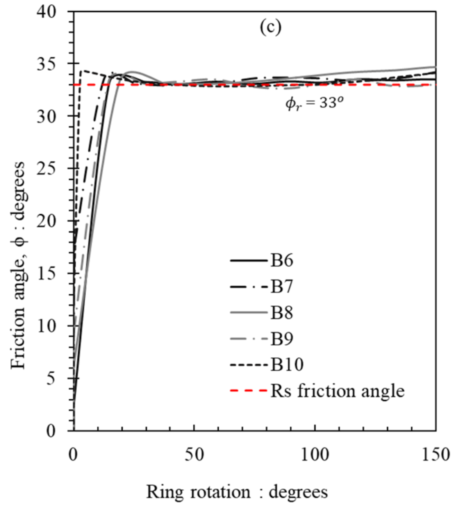
Figure 2. Stress ratio vs axial strain (a) BR (b) IOT, Stress dilatancy behavior (c) BR (d) IOT

4.2 *Residual drained behaviour*

The ratio of τ with σ'_{vo} during constant pressure ring shear tests was used to calculate the residual stress ratio (τ/σ'_{vo}). Figure 3a and b show the change in τ/σ'_{vo} with ring rotation of BR and IOT respectively. Figure 3c and d show the changes in φ_r of BR and IOT respectively.







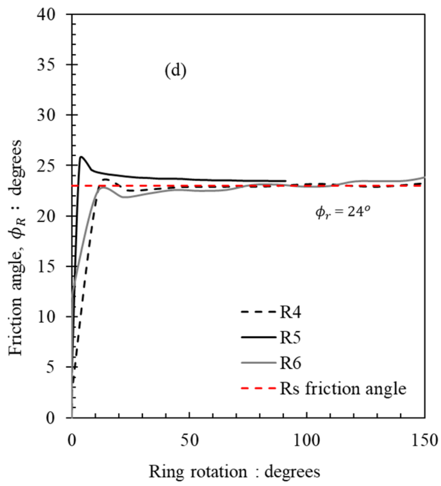


Figure 3. Residual change in stress ration vs ring rotation (a) BR (b) IOT; Residual angle of friction vs ring rotation (c) BR (d) IOT

The τ/σ'_{vo} was higher in BR than IOT. φ_r was selected at higher ring rotations near 150 degree of rotation. During shearing, the alignment of soil particles in one direction at large strains allowed estimation of a constant φ_r. The φ_r of BR was more than that measured in the IOT, e.g., 33^0 and 24^0 in BR and IOT respectively.

4.3 *Comparison of residual and critical state conditions*

To evaluate the differences in frictional behavior at critical state and residual state, the ϕ_{tc} was compared with the ϕ_r. Figure 4 shows the comparison of ϕ_{tc} with ϕ_r of granular materials reported by Negussey et al. (1988), IOT and BR. The results for IOT and BR followed the trend of granular materials reported by Negussey et al. (1988). It is also noted that ϕ_{tc} was similar to ϕ_r in BR, in contrast to IOT which showed a reduction in ϕ_r. The frictional softening in IOT suggests a different residual behaviour to that of BR, which was interpreted to be an inherent effect of particle mineralogy and not plasticity. Previous literature (e.g. Gibson 1953, Carter and Bentley 2016) indicate that an increase in plasticity of clayey-like soils corresponds to a drop in friction angle, which is contrary to the results in this study. These differences indicates that plasticity is not the only factor influencing residual behaviour of tailings. Additional modifications of the framework proposed by Negussey et al. (1988) is provided in Figure 4, based on insights provided by Lupini et al. (1981) to indicate that it is likely for soils with high clay fraction (e.g London Clay) to mobilise residual strength at lower stress ratios (resulting in sliding shear behaviour) than soils and tailings with low clay fraction, resulting in rolling and transitional shear modes.

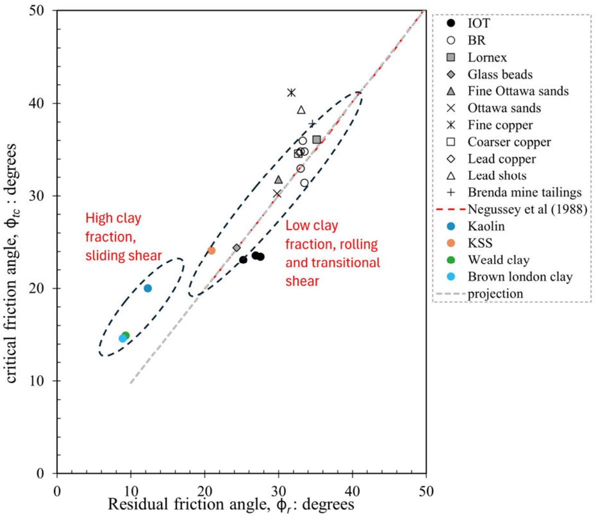


Figure 4. Critical state vs residual friction behavior, an overlay from Negussey et al. (1988)

4.4 *Influence of Mineralogy*

To determine the effect of mineralogy on residual behavior, ϕr was compared with increase in clay fraction, given that previous works considered an increase in clay fraction changes with mineralogy (Skempton 1985, Iverson et al. 1997, Tiwari and Marui 2005). The change in ϕr with clay fraction of BR and IOT were superimposed on results presented by Skempton (1964) in Figure 5.

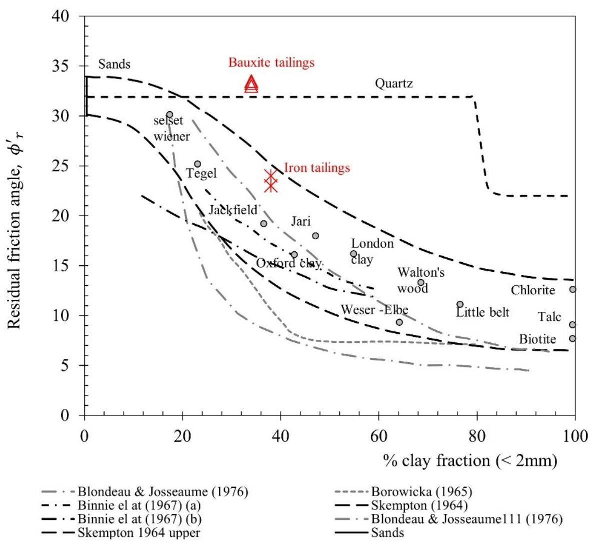


Figure 5. Residual friction angle vs clay fraction

A high clay fraction dominated by high kaolinite-haematite (Figure 1) enhanced frictional softening behaviour in IOT, agreeing with the upper bound of Skempton (1964). Unlike BR with high muscovite (illite- like mineral) (Mitchell and Soga 2005, Mmbando et al. 2024), the residual behaviour was similar to that of sandy soils. The discrepancy between BR residual behaviour and Skempton's findings is attributed to be an intrinsic effect of particle mineralogy, such that high muscovite-illite and substantial quartz content is likely to influence friction behaviour, resulting in higher stress ratios and no frictional softening.

5 DISCUSSION

The outcomes of this work showed that frictional softening of IOT was consistent with existing correlations for estimating the residual friction angle. However, the residual behavior of BR did not align with the data presented in existing literature, which is attributed to its mineralogy. These findings suggest that applications of existing correlations for residual frictional behavior based on soil consistency limits need to consider mineralogy and be applied with caution during TSF designs, as such correlations may not be applicable to all types of tailings. As illustrated in the results, the residual frictional behavior of clayey-like bauxite tailings was similar to sandy soils.

The effects of particle mineralogy highlight that some tailings may not behave like typical sandy and clayey soils but instead behave like "residual soils". Consequently, existing correlations of estimating residual friction angle for conventional soils may not be applicable to some tailings, such as bauxite residue. Residual soils are known to behave differently from classical soils due to their formation processes (Wesley 2010). In this context, the Bayer process, which is used to chemically digest and clarify bauxite, modifies the mineralogy and physical properties of bauxite (Gräfe et al. 2011), resulting in a residue mainly composed of high proportions of muscovite and quartz, which form the later mineral sequence of residual soils (Bowen 1928, Blight and Leong 2012). In contrast, the beneficiation process that generated IOT, resulted in mainly crystalline clay minerals such as kaolinite and hematite (weathered kaolinite (Mitchell and Soga 2005)) and low quartz content, with its residual friction behavior falling near the upper bound proposed by Skempton (1964). Given that some tailings are likely to behave like residual soils, it is important to consider the effect of particle mineralogy when correlating the residual strength of tailings with plasticity. Moreover, in TSFs with pre-existing slip surfaces and slope movements, appropriate measurement of residual friction angle of tailings is important, as it can significantly impact remediation costs.

Inconsistencies in existing correlations are not limited to variations in the mineralogy of solid crystalline phases; there remains a need to further assess the effect of substantial amorphous content in tailings on residual behavior. In some cases, increased amorphous content has resulted in a reduction of friction angle (Wan and Kwong 2002). However, in this study, the low amorphous content in bauxite tailings did not result in a reduction of the residual friction angle.

6 CONCLUSIONS

This study compared the frictional behaviour of iron ore and bauxite tailings at critical state and residual state using drained triaxial tests and constant pressure ring shear tests. The key results were as follows

- Unlike bauxite tailings, iron ore tailings exhibited significant variations in the frictional behaviour between critical and residual conditions.
- The residual frictional behaviour of iron ore tailings can be correlated with plasticity and clay fraction relationships applicable to typical soils.
- The results suggest that the behaviour of bauxite residue resembles that of residual soils

- The differences in frictional behaviour between both materials are attributed to be differences in mineralogy.

Therefore, residual behaviour correlations must consider tailings mineralogy, as neglecting this risks mischaracterizing the behaviour of TSFs if only empirical correlations are used.

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