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Effect of stress induced anisotropy on the undrained behaviour of coal mine waste geo-materials (CMWGs)

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ABSTRACT: Recent research on coal mine waste geomaterials (CMWGs) has provided some insights into their susceptibility to liquefaction and instability, primarily due to their unique grain structures and potential for particle breakage. However, there is still limited knowledge on the effect of loading anisotropy on the undrained response of CMWGs. In this work, a series of triaxial compression and extension tests were conducted on isotopically and anisotropically consolidated CMWG samples from Tylorstown RH01 coal tip, in Wales, at different levels of consolidation pressure. The results show that both shearing mode and consolidation impact the undrained shear strength of the CMWG; furthermore, with certain degrees of change in the fabric, they also affect the pore water pressure response of the materials.

KEYWORDS: Coal mine waste, Liquefaction susceptibility.

1 INTRODUCTION

In light of the number and geographical distribution of at-risk coal tips across the UK (gov.uk, 2024), recent failures associated with heavy rainfall have raised increasing concern over the safety of nearby local communities and infrastructure. Despite significant post-Aberfan efforts to understand the mechanisms governing landslides in coal tips (Bentley & Siddle, 1996), the problem remains incompletely understood (Vo et al., 2022), particularly within advanced geotechnical frameworks such as critical state soil mechanics (CSSM). The CSSM framework offers a potentially effective means of identifying the underlying failure mechanisms and improving remedial measures (Dejaloud et al., 2024).

Coal mine waste geomaterials (CMWG) were historically tipped following the natural topography of the site. As is the case with most geomaterials in the field, it is therefore unrealistic to assume equal stress conditions in both the horizontal and vertical directions during consolidation. Within the failure plane of a slope, soils may experience different modes of shearing (i.e., extension or compression) and may exhibit varying initial principal effective stress ratios (Sadrekarimi, 2016). Laboratory studies have demonstrated the significant influence of loading-induced anisotropy on the undrained shear strength of soils (Fourie & Tshabalala, 2005; He et al., 2023; Fotovvat & Sadrekarimi, 2022), potentially increasing the level of reliability in the design and analysis of tips containing CMWG.

For saturated fine soils that are prone to undrained loading under certain drainage conditions, particle crushing, where it occurs, is an important factor influencing their mechanical response. The most dominant feature is, perhaps, the contractive response of the soil even when highly dense packing of the particles is achieved through compaction (Heitor et al., 2016; Taghavizade & Rezania, 2025). In addition to the shift in the position of the critical state line (CSL) in volumetric space (Bandini & Coop, 2011), potential breakage has been shown to impact the yielding characteristics of a crushable soil (Shahnazari & Rezvani, 2013; Heitor et al., 2016).

In this study, a series of triaxial experiments were conducted on CMWG samples to investigate the influence of shearing mode and consolidation path on their mechanical behaviour, with particular reference to the CSSM framework. This study aims to fill the knowledge gap in the field, as to the authors' knowledge, very limited experimental data exist for the behaviour of CMWG at different shearing modes and consolidation paths. The results are presented in terms of stress–strain response and stress paths and are discussed in some detail in the following sections.

2 MATERIAL AND METHOD

Fine colliery discards were obtained from RH01 at the Llanwonno Upper tip, located in the southern region of Wales, known as the Tylorstown coal mine waste (TT-CMW) tip. The procedures for initial treatment of the material, its mineral composition (Vo et al., 2025), triaxial sample preparation, equipment configuration, saturation, consolidation, and shearing are described in Taghavizade & Rezania (2025). To anisotropically consolidate the samples, isotropic consolidation was first carried out to the desired confining pressure, after which the axial stress was increased to achieve a principal effective stress ratio of $K = {\sigma'}_3 / {\sigma'}_1 = 0.84$. For consolidation at the coefficient of earth pressure (K_0), a computer-controlled feedback system was employed to maintain zero radial strain during consolidation until the target consolidation pressure was reached. In all cases, the rate of anisotropic consolidation was maintained at 5 kPa/h.

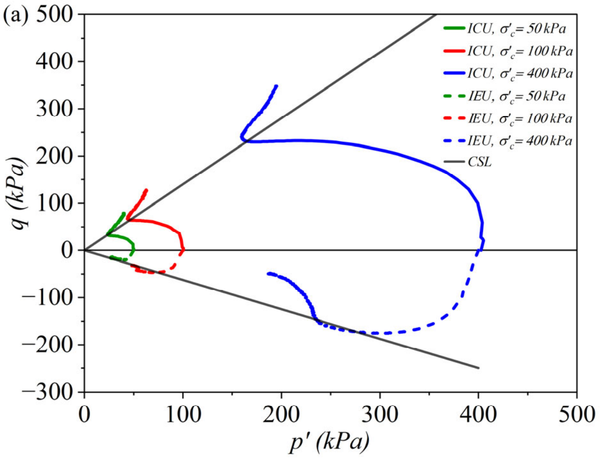
Three sets of triaxial experiments are presented in this study to provide further insight into the mechanical response of the TT-CMW under undrained loading conditions: (a) shearing of isotropically consolidated samples in compression, (b) shearing of isotropically consolidated samples in extension, and (c) shearing of anisotropically consolidated samples in compression. Results are reported for specimens with and without initial particle crushing, corresponding to breakage indices of $Br_0 = 0.13$ and 0, respectively, following the procedure outlined by Taghavizade & Rezania (2025). Unless otherwise stated, the discussion pertains to samples prepared without induced initial particle breakage.

3 RESULTS AND DISCUSSION

3.1 *CSL in compression and extension*

Stress paths and CSL obtained from both compression and extension shearing are illustrated in Figure 1. Movement of stress paths to the right side of the stress plane in Figure 1 (a) due to the generation of excess pore water pressure occurs in both compression and extension. A notable distinction, however, is the progressive strength gain in compression shearing even after reaching the CSL. In contrast, during extension shearing, the sample starts to lose strength before reaching the CSL and continues to do so afterwards. This may suggest that instability of the soil structure and susceptibility to collapse for the samples without initial crushing should be more of a concern in extension shearing than in compression. It is also worth noting that using data from both drained and undrained tests, the slope of the CSL in the stress plane is found to be 1.39 and -0.67 for compression and extension, respectively.

Similar to recent findings for other tailing materials (Fotovvat & Sadrekarimi 2022, Wagner et al. 2022), a distinct and non-unique CSL is found for compression and extension shearing. To obtain more accurate estimation of the CSL, data from the isotropically consolidated sample sheared in a drained condition are incorporated to obtain the corresponding CSLs in both compression and extension in Figure 1 (b). Given the equation for the CSL in the compression plane (i.e. $e = \Gamma - \lambda \ln p'$), the slope of the CSL (λ) and the intercept at p'= 1 kPa (Γ) in compression are found to be -0.176 and 1.59, respectively, while the respective values for extension shearing are obtained as -0.103 and 0.799. While results from Fotovvat and Sadrekarimi (2022) shows that the CSL for gold tailing in extension lies above that in compression, results from this study align more with the findings of Wagner et al. (2022) and De Bona Becker et al. (2023) on iron ore tailings, where the derived projection of the CSL for compression is located above that for extension in the compression plane.



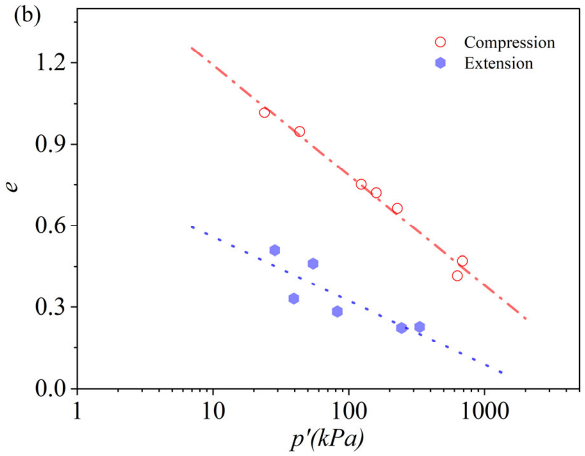
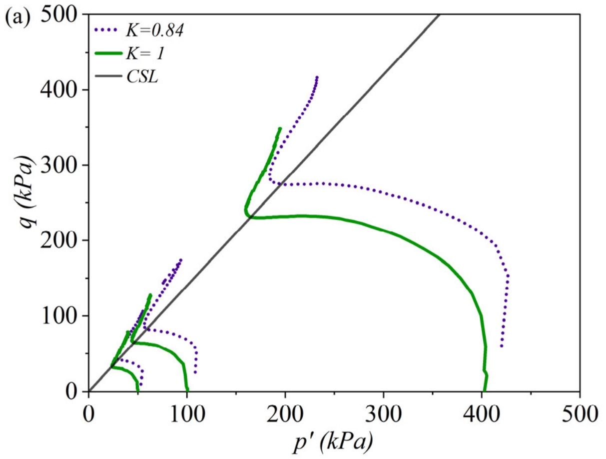


Figure 1. CSL of TT-CMW in compression and extension: (a) stress plane and (b) compression plane

3.2 *Impact of stress-induced anisotropy*

The comparison of the stress paths in the stress plane for isotropically and anisotropically consolidated TT-CMW samples, for the range of the studied effective confining pressures (σ_c'= 50 – 400 kPa), is shown in Figure 2. As shown in Figure 2 (a), pre-shearing of the TTCMW samples in terms of anisotropic consolidation results in strength gain and higher structural stability. This is observed through a lower rate of excess pore water pressure (EPWP) development and higher shear strength compared to the isotropically consolidated samples. Figure 2 (b) compares the stress paths of the sample sheared at σ_c' = 100 kPa and consolidated at different principal effective stress ratios. The obtained plots confirm an apparent reverse relationship between K and the stability of the TT-CMW sample. The K_0 consolidated sample clearly demonstrates the stiffest response with generation of negative EPWP during initial stages of shearing accompanied by higher undrained shear strength. Further observation shows an apparent increase in the critical state stress ratio (M) with reduction of K, where phase transformation (i.e. elbow in the stress path) occurs at higher stress ratio for K_0 and K= 0.84 compared to the isotropic sample.



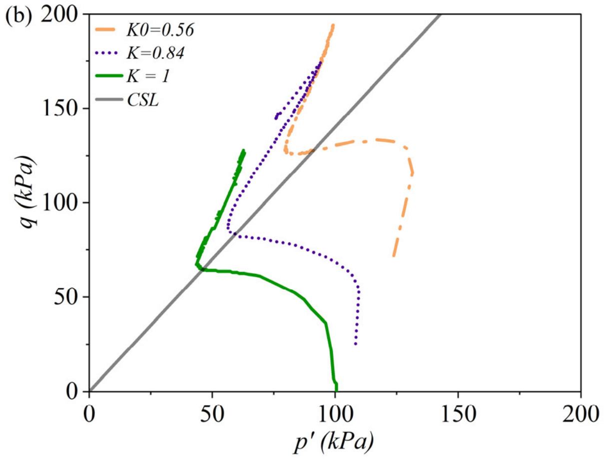
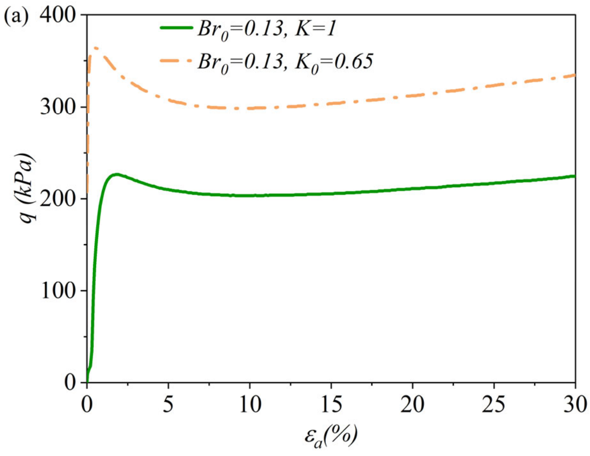


Figure 2. Effect of stress-induced on TT-CMW stress paths; (a) K = 0.8 in the range of effective stress (b) Different Ks at σ_c'=100 kPa

3.3 *Initial particle breakage and stress induced anisotropy*

A previous study (Taghavizade & Rezania, 2025) demonstrated the impact of initial particle crushing for CMWG, in particular through compaction, on the liquefaction susceptibility and stability of soil structure across a range of confining pressures. The findings of the study revealed that compacted samples tend to become instable and even liquefy, especially at lower confining pressures, while showing similar undrained shear strengths. In other words, reduction in breakage potential, or higher initial breakage, transforms the behavioural regime from strain hardening to softening, and hence facilitates instability.

Figure 3. compares the behaviour of samples with initial particle breakage of Br_0 = 0.13, where Br_0 denotes the quantitative amount of particle crushing introduced to the sample during compaction using the Hardin method (Hardin, 1980). One sample was isotropically consolidated while the other was consolidated under the K_0 path and both were sheared at σ_c' = 400 kPa. Stress-strain behaviour in Figure 3. (a) indicates a stiff response of the anisotropically consolidated sample. As particle crushing during consolidation increases with the level of consolidation pressure, together with gradual fabric rearrangement during K_0, such a stiff response at low levels of axial strains and higher undrained shear strength can be readily explained. Yet, low capacity for particle crushing limits the opportunity for strength gain, which may increase the potential for instability (Figure 3. (b)).



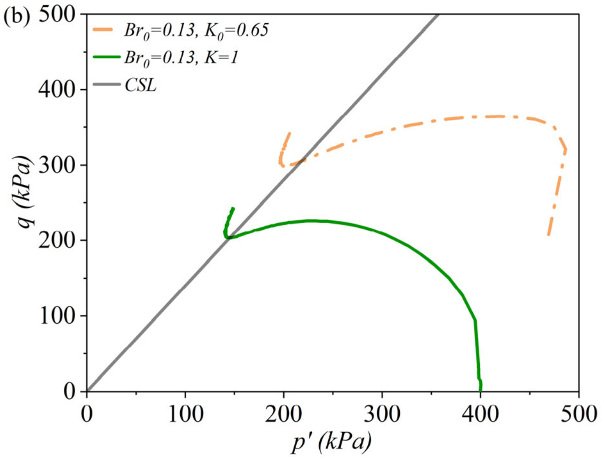


Figure 3. Comparison of isotropically and K_0 consolidated samples with initial particle breakage at σ_c' = 400 kPa

Considering the impact of particle breakage and fabric rearrangement/reorientation during anisotropic consolidation on the CSL projection in the compression plane, data from the discussed experiments are extracted and combined with data from Taghavizade & Rezania (2025) to plot Figure 4. As expected, the extracted points show a correlation with the established lines from isotropically consolidated tests. The highest correlation with isotropic data found for the sample with initial particle crushing of Br_0 = 0.13, where the CS point lies exactly on the established line for Br_0 = 0.13, while higher scatter appears for Br_0 = 0 highlighting the significance of the "molding effect" (Velten et al. 2022) for TT-CMW materials.

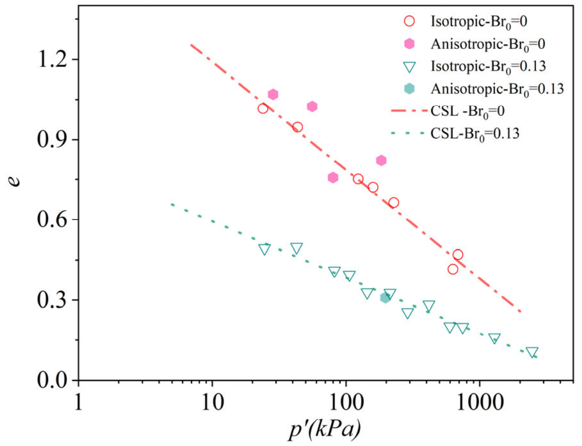


Figure 4. Representation of critical state data from compression test considering initial particle breakage and anisotropic consolidation

3.4 *Undrained shear strength assesment*

Due to the strain hardening behavioural regime of TT-CMW at Br_0 = 0, and the relative impact of anisotropic loading/consolidation on the stress-strain behaviour, it is difficult to adopt the brittleness index (Bishop, 1973) to assess the strength loss in both isotropic and anisotropic samples. Here, the undrained yield strength (S_u), which is the same as the undrained peak shear strength, is used to make a comparison between isotropically and anisotropically consolidated sample. Variation of normalised undrained shear strength with the state parameter (i.e. $\psi = e - e_{cs}$) (Been & Jefferies 1985, Dejaloud et al., 2024) is illustrated in Figure 5. Reduction in the normalised shear strength values with an increase in the state parameter is a general trend for tailing materials and the values of normalised shear strength obtained for both isotropic and anisotropic TT-CMW samples fall within the range of other tailing geomaterials (Fotovvat & Sadrekarimi, 2022). As previously shown, higher normalised shear strength is observed for anisotropically consolidated samples compared to isotropically consolidated samples. This can be attributed to higher particle interlocking and more shear-oriented fabric during the consolidation process, potentially leading to higher undrained strength of anisotropically consolidated samples.

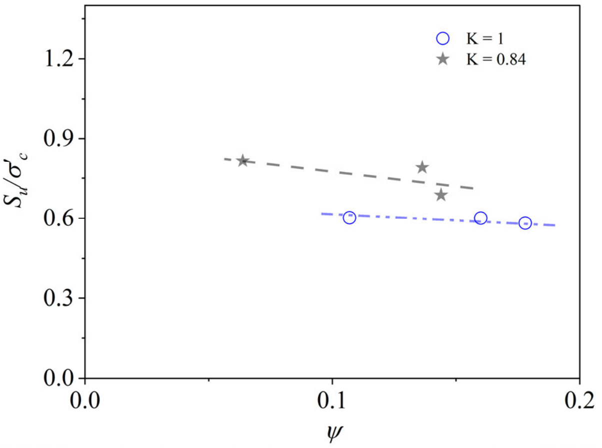


Figure 5. Variation of normalised undrained shear strength (S_u/σ'_c) with state parameter, ψ.

4 CONCLUSIONS

Results from triaxial tests on pre-crushed and uncrushed TT-CMW samples are presented to examine the influence of shearing mode and stress-induced anisotropy on their mechanical behaviour within the CSSM framework. The findings indicate that the CSL in the $e-\ln p'$space differs between compression and extension shearings. In contrast, the influence of anisotropic consolidation on the CSL projection in this space appears to be subtle, allowing determination of a unique CSL for both isotropically and anisotropically consolidated samples, irrespective of initial particle crushing. Anisotropically consolidated samples exhibited greater undrained strength and enhanced stability compared with isotropically consolidated samples. A negative correlation between the consolidation stress ratio (K) and undrained shear strength was also observed.

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