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Statistical Variability of Soil Parameters within the Copper Belt Region of the Democratic Republic of the Congo

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***Abstract*—**The accurate determination of the engineering parameters of soil is necessary for the design of geotechnical structures, such as Tailings Storage Facilities. The shear strength and saturated permeability of soil and tailings samples obtained from 14 sites located in the copper belt in the Democratic Republic of the Congo have been tested at six commercial soil laboratories in South Africa. This study compiles a database of the test results proved by the soil laboratories. The samples have been categorised into clay, silt, and sand, based on the Unified Soil Classification System, with tailings kept separate. The effective friction angle (Φ') and cohesion (c') were interpreted from the stress paths, in s':t space, obtained from triaxial tests. The minimum, lower quartile, median, upper quartile, and maximum values for Φ',c', and saturated hydraulic conductivity (k) have been determined for the soil sample. The objective is to provide statistics of the measured values of the engineering properties for the Tailings Storage Facilities (TSFs) borrow material, foundation soils and tailings of this region.

***Keywords*—**Democratic Republic of the Congo, laboratory test work, soil engineering parameter variation, tailings storage facilities.

I. Introduction

Numerous Tailings Storage Facilities (TSFs) have been developed in the copper-cobalt-rich region in the south of the Democratic Republic of the Congo (DRC). As part of any TSF design, a geotechnical site investigation is completed to ascertain, amongst other aspects, the engineering parameters of the embankment borrow material, foundation soils and the tailings it shall store. The preparatory works of a TSF typically include an earth-fill embankment, constructed from borrow material. Tailings are the by-product of mining and are stored in the basin of the TSF. Depending on the construction method employed [1], it can be used to form the outer competent shell, provided that the material is deposited at a rate that allows consolidation to take place so that the tailings can gain adequate shear strength.

The accurate determination of the engineering parameters of the foundation soil and tailings forms a critical part of the design of geotechnical structures such as TSFs. The consequence of failure of TSFs requires designs that are based on reliable engineering parameters derived from test results.

For this study, Epoch Resources (Pty) Ltd made available the soil laboratory test results from 14 TSF sites, located within the Copper Belt Region of the DRC. The test results form part of various geotechnical investigations undertaken for the knowledge bases of the TSFs. Soil samples, representing the earth embankments, foundation and tailings of the respective TSF sites have been collected over 13 years, dating back to 2011, by professional engineering geologists and tested at accredited commercial soil laboratories in South Africa. This paper reports the distribution of soil parameters obtained from the laboratory tests which included triaxial tests, shear box tests, flexible wall permeability tests and falling head permeability tests as per BS 1377. The test methods through which these parameters were determined are also discussed.

II. Regional Geology

The Central African Copperbelt is notable for its extensive Neoproterozoic rock formations, which are essential in hosting sediment-hosted copper-cobalt (Cu-Co) deposits, primarily located within the Katanga Supergroup. This geological formation straddles the border between the DRC and Zambia, regions. The geology of the area is shaped by a history of continental thinning and extension, which facilitated the formation of rift basins during the early Neoproterozoic era, setting the stage for the deposition of various lithostratigraphic units. These include the RAT, Mines, Dipeta, and Mwashya Subgroups, each characterised by unique sedimentary features such as dolomitic shales, siltstones, and carbonates (refer to Fig. 1).

The geological landscape is further dominated by two main formations: the Nguba and Kundelungu Groups, interspersed with formations from both the Post-Katanga cover and the Roan Group [3].

The residual soils formed in this region are described as Ferrallitic and Ferruginous soils in [4]. These soils occur in tropical and subtropical climates. Often a transported soil layer had been identified in test pits and boreholes where it overlies the residual soil horizon. It is expected that soils weathered in high-rainfall regions shall exhibit consistent engineering properties, although, it is acknowledged that local variations may arise due to factors such as topography, climate variations, and specific geological features.

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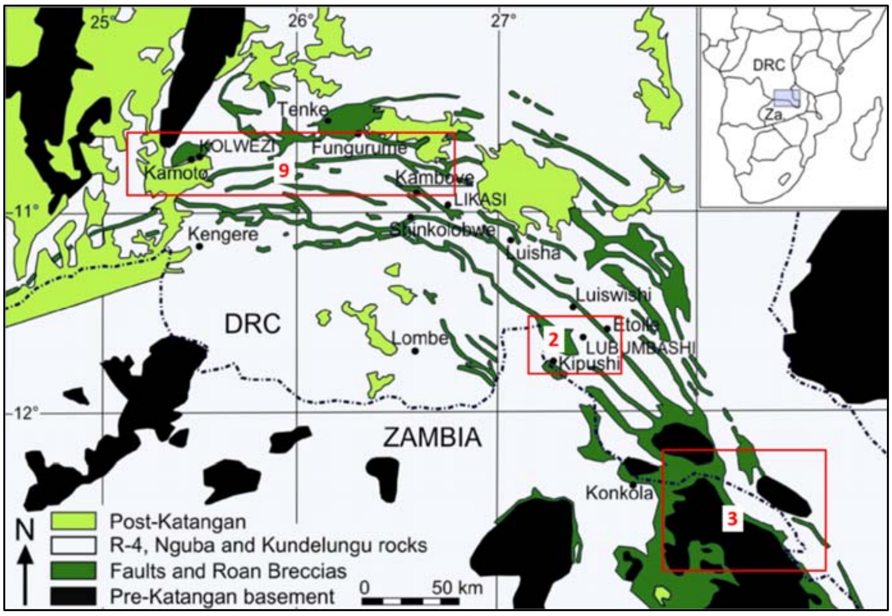

Fig. 1 Map of the Central African Copperbelt through Zambia and the DRC including distribution of TSF sites, adapted from [2]

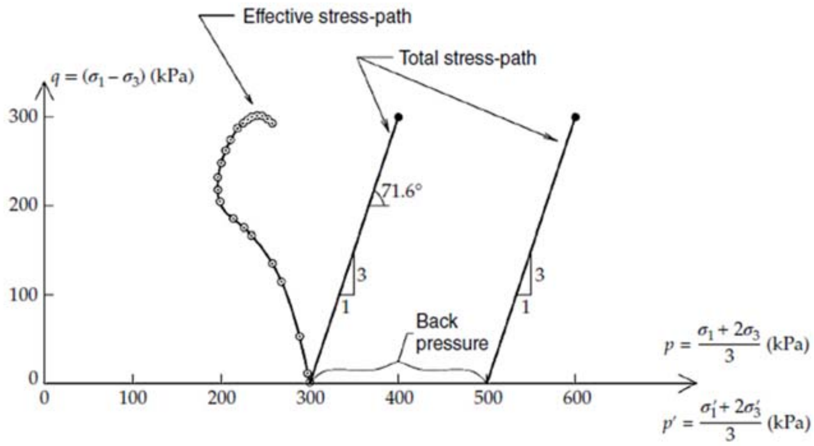

Fig. 2 Example CU and CD triaxial test stress paths in p':q space, figure by [6]

III. Test Work

A. Soil Identification and Sample Selection

For each of the soil samples, the Particle Size Distribution (PSD) and Atterberg limits were measured to classify the soils according to the Unified Soil Classification System (USCS) [5]. The dataset, presented in Table I, comprised 144 entries which were grouped into the following soil categories: sand, silt, clay, and tailings. The tailings category comprised both copper and cobalt tailings due to the restricted number of samples.

The lack of gravel samples can be attributed to the limitation of the triaxial test apparatus, where it is recommended that the specimen diameter be at least equal to six and eight times the largest particle size for uniformly graded and well-graded material [6], respectively; the availability of large-scale triaxial test apparatuses, and that gravel soils are not usually the area of interest in site investigations. Gravels tend to have favourable shear strength parameters when compared to other soils [7] and require less scrutiny. The gravels have been excluded from further analyses since their sample size is too small to make meaningful inferences about the statistical distribution of the engineering parameters discussed in this paper.

TABLE I
Number of Samples per Soil Category

Symbol	Permeability	Φ'	c'
Tailings	9	19	19
Gravel	5	5	5
Sand	28	34	34
Silt	10	23	23
Clay	39	53	53

B. Triaxial Tests

Consolidated Undrained (CU) triaxial tests were conducted on 130 of the samples collected from the TSF sites. Undrained tests were completed due to the reduced time required to perform the test and to obtain the undrained effective stress

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path. An example is shown in Fig. 2. The rate of shear, in a CU test, should be slow enough for the pore pressure to equalise throughout the specimen during the shear phase.

A Consolidated Drained (CD) triaxial test provides the drained stress path as shown in Fig. 2, where the effective stress is equal to total stress and the resulting stress path follows a constant slope of 1V:3H in p':q space. Care must be taken during the testing of fine-grained soil; the shear rate must be low enough to ensure excess porewater pressure is not induced during the shear phase.

C. Shear Box Tests

Shear box tests were conducted on 5 samples of one TSF site. Where the principle stresses are known in a triaxial, only the normal stress, perpendicular to the shear plane, can be measured in a shearbox test.

The reduced size of the shearbox specimen prevents the retention of the soil fabric. Castellanos and Brandon [8] demonstrated that friction angles of undisturbed alluvial soils from the shear box test were 2 to 5 degrees lower than those determined using a triaxial tests apparatus. However, remoulded samples performed similarly in both tests as the fabric of the soil was disturbed during sample preparation. The samples tested in the shearbox were remoulded to 95 % of their standard proctor density at optimum moisture content.

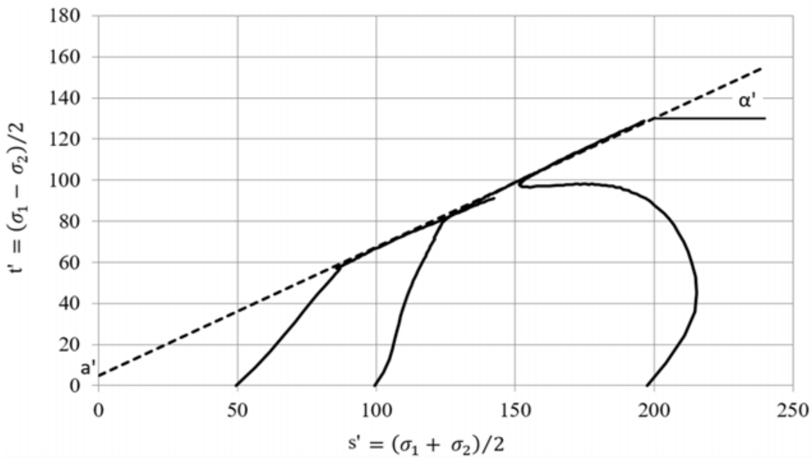

Fig. 3 Determining Φ' and c' from s': t space

D. Determination of the Effective Shear Strength Parameters

For this study, the standard result sheets were obtained in PDF format. The authors determined Φ' and c' from the stress paths in s':t space, as defined by Atkinson & Bransby [9]. Since the stress paths in s':t space represent the top of the Mohr circles, the parameters had to be transformed to represent Φ' and c' as shown in Fig. 3, along with (1) and (2).

$$\Phi' = \sin^{-1}(\tan \alpha') \quad (1)$$

$$c' = a'/\cos \Phi' \quad (2)$$

where *α'* is the slope of the failure envelope and *a'* is the y-axis intercept at s' equal to zero in s': t space.

It should be noted that the interpretation of stress paths is not a process that results in an exact outcome. It has been demonstrated by various studies [10], [11] that the experience and adversity to risk of geotechnical practitioners greatly impact the interpretation and selection of engineering parameters used in the TSF design [10].

As part of validating the data, the reported B values, defined as the ratio between the change in pore pressure for a given change in the isotropic cell pressure of the triaxial apparatus, were inspected to ensure that they are above 0.95 which signifies sufficient saturation of the samples. Furthermore, the shear rate of each specimen was evaluated to ensure that it was compatible with the time to failure.

IV. Test Results

A. Friction Angle

Fig. 4 displays the distribution of Φ' across various soil categories, presenting the findings through a box and whisker plot delineating the minimum, 1st quartile (represented by the dotted area), median, 3rd quartile (depicted by the blank area), and maximum values. Surprisingly, approximately half of the tested samples from all categorised material exhibit a Φ' ranging between 30° to 35°. The median Φ' for tailings is shown to be the highest at 32.5°, only marginally surpassing that of sand, silt, and clay at 32°. Notably, the median Φ' for clay is 4° higher than the value reported for clay samples from South Africa by Heymann [7].

Within the dataset encompassing sand, silt, and clay materials, there were 2 instances for sand, 3 for silt, and 5 for clay where the Φ' measured less than 25°.

As discussed previously, the region falls within a single geological group, namely the Katanga Supergroup, of which a large portion of the surface material is characterized by transported soils.

B. Cohesion

The median c' values for tailings and sands is zero with a slight increase for silts and clays to 3 kPa, as shown in Fig. 5.

As depicted, the majority of the interpreted c' values were lower than 9 kPa with three samples of sand and clay each, and two samples of silt with interpreted c' values larger than 15 kPa. The 25th percentile for all categories is shown to be equal to zero, with the exception of silts.

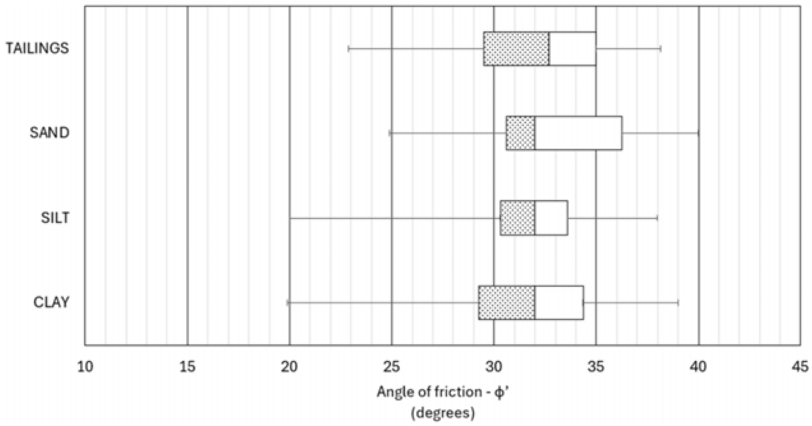

Fig. 4 Friction Angle (φ') test results

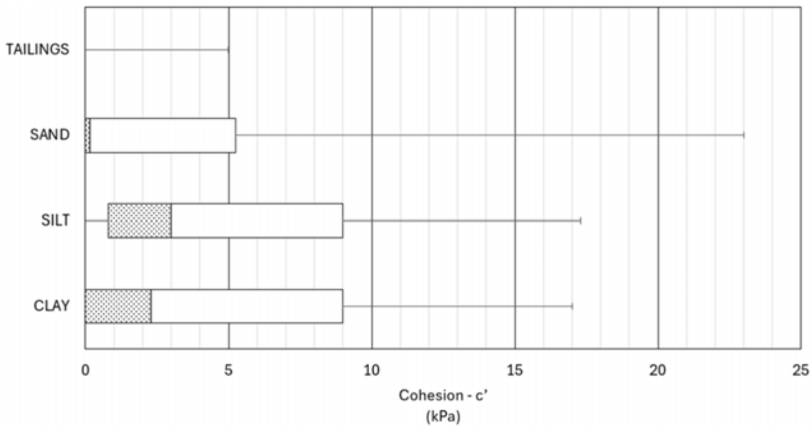

Fig. 5 Cohesion (c') test results

C. Permeability

The saturated permeabilities measured in flexible wall tests and falling head permeability tests are presented in Fig. 6 for each soil category.

The consolidation process in soils involves the expulsion of pore water, dictated by a nonlinear finite strain consolidation theory, necessitating the determination of material parameters through laboratory testing consistent with this theoretical framework. Both compressibility and permeability characteristics are pivotal, often described by power functions fitted to experimental data, as shown in (3) and (4):

Compressibility:

$$e = A \cdot \sigma'^{B} \tag{3}$$

Hydraulic conductivity:

$$k = C \cdot e^{D} \tag{4}$$

where e represents the void ratio, k is hydraulic conductivity, σ' is the effective stress, and A, B, C, and D are material parameters determined through laboratory testing. Challenges emerge in reliably measuring low effective stress data and hydraulic conductivity, particularly in highly compressible, low permeability soils, necessitating specialised procedures such as the Slurry Consolidation Test (SCT) or the Seepage-Induced Consolidation Testing and Analysis (SICTA) to address these issues [11].

The reasons for the lower hydraulic conductivity (k) observed in sand compared to clay are multifaceted. One contributing factor may be the grading analysis, which revealed that clays consist, on average, of 34% of particles greater than 75 µm, while the fraction of sand material smaller than 75 µm averages 38%.

Additionally, from (4), k is a function of void ratio. The same soil shall have a different saturated k if tested at a different void ratio. Other factors, such as particle shape, surface area, and soil structure can significantly influence the saturated permeability of a given sample [12]. It is recommended that further testing is required to evaluate the cause of the unexpected results.

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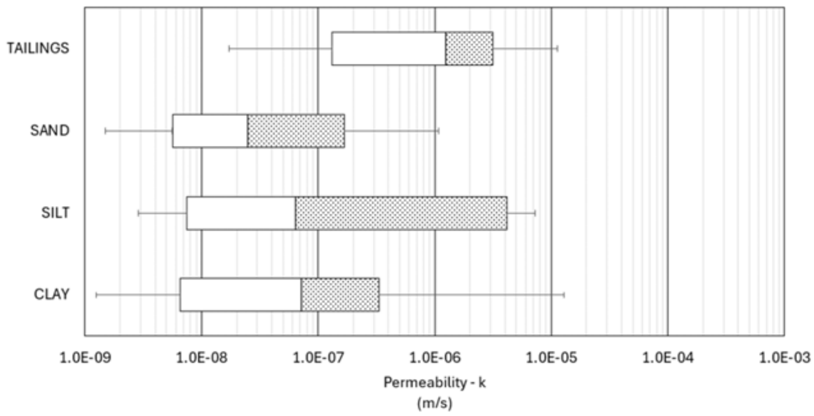

Fig. 6 Permeability (k) test results

V. Discussion

The study revealed similarities of engineering parameters Φ', c', and k of the sands, clays, and silts in the region, which is dominated by the Ferrallitic and Ferruginous soils present in the region.

From the test data, the following points are noted:

- The saturated permeability of the sand and clay has similar median values and comparable interquartile ranges, with the sand having a lower median value.
- The effective cohesion values generally increased with the fine soil fractions. The sand dataset included an outlier of 23 kPa, which is 5.8 kPa higher than the maximum of the silt samples.
- The effective friction angles for all categorised materials were remarkably similar, with about 50% of the recorded angles falling between 30° and 35°. The median friction angle across all soil types varied narrowly from 32° to 32.5°. However, the lack of tailings samples sufficient for categorisation, based on commodity type, underscores the need for awareness regarding the sample size necessary for drawing meaningful conclusions about soil parameter distribution.

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