GhIE

The collapsible nature of reworked residual granites in the Stellenbosch Municipality, South Africa

Samuel Y. Asante*,[1], Nanine Fouché[2], Augustine. K. Lawer[1]

Abstract
In South Africa, residual granite is associated with the collapse phenomenon, a geotechnical hazard that was first identified in the 1950s. Residual granite is a product of chemical weathering (in-situ decomposition) or physical weathering of the parent rock (granite) whilst reworked residual granites is defined as residual granite reworked in-situ by termites. Residual granite usually consists of bulky-sized quartz particles, with silts, and bridged by colloidal matter. Extreme leaching of the colloidal matter creates a structure like a honeycomb. It, however, leaves voids within the structure, which affects the mechanical behaviour of the soil. The soil collapses upon wetting under additional loading. Construction on soils with a collapsible fabric has led to many documented problems. This paper, therefore, reports on the examination of mineral composition and particle shape examination and its effect on behavioural changes of potentially collapsible soil. The soil used for this study includes reworked residual granite obtained from the Stellenbosch area in the Western Cape of South Africa. A multi-element analysis and morphological studies were performed on mounts using the ZEISS EVO MA15 scanning electron microscope at the Centre for Analytical Facility at Stellenbosch University. Shape analysis confirmed that the severity of collapse increased with increasing angularity. In addition, the type and amount of clay present at particle contacts influenced the swell and collapse behaviour of reworked residual granite.

Introduction

Collapsible soils are known to be one of the problematic soils in some areas of the world, including South Africa. Many recorded and unrecorded problems which are associated with the collapse phenomenon have occurred in the foundations of buildings, roads, earth dams, and railways. Documented case histories of the adverse effects of collapsible soils include a tilting water tower near Nelspruit (Brink 1979, in Schwartz 1985); and the case where an individual column settled to 300 mm of the three-story Industrial Development Corporation (IDC) building founded on deeply weathered residual granite, (Terblanche, 1989). In the study conducted by Sun *et al*. (2013), it was found that from 1974 to 1975 in China, a significant number of buildings were damaged and an underground pipeline measuring 80 km in length ruptured. These incidents were attributed to the volumetric changes in collapsible soils. According to Schwartz (1985), collapsible soil exhibits a collapsible grain structure that can withstand relatively large imposed stresses with small settlements at a low in-situ moisture content but will display a decrease in volume upon wetting. The first requirement for collapse to occur is the presence of a collapse fabric (Schwartz, 1985). Brink and colleagues (1982) additionally suggested that a collapsible fabric might manifest in a loosely textured silty or sandy soil characterized by a high void ratio (low dry density). Despite this, the soil can exhibit relatively high shear strength at low moisture content, attributed to colloidal or other coatings around individual grains. Within the South African context, this phenomenon is prevalent in numerous transported soils (Schwartz, 1985; Stapelberg, 2021) and in regions where quartz-rich rocks, such as granite or feldspathic sandstone, have experienced chemical weathering, resulting in the formation of intensely leached residual soils (Asante, 2015; Gildenhuys, 2010). It is evident from the definition of Schwartz (1985) and Brink *et al*. (1982) that the formation of a collapse fabric is highly reliant on the distribution of particle sizes in the soil, particle shape and mineralogy.

Soils are made up of mineral grains and the mechanical behaviour is greatly affected by the particle morphology, porosity, particle size, pore size, and pore distribution. According to Santamarina and Cho (2004), the distribution of particle sizes in the soil governs the particle-level forces, the inter-particle packing and the ensuing macroscale behaviour, thus having a significant effect on the formation of soil with a collapse fabric.

On the other hand, studies have been conducted on the global form, the scale of major surface features and the scale of surface roughness in analyzing grain shape. This has led to an increased realization of the relevance of particle shape in soil behaviour and particulate materials (Cho *et al*., 2006). According to Cho *et al*. (2006), each scale helps in determining the global behaviour of the soil mass, hence showcasing the need to investigate the role of particle shape in the collapse phenomenon on a microscale level. Moreover, a study on laboratory test tailings from the Aitik mine utilized triaxial testing, and an examination of particle shape (employing two-dimensional image analysis) revealed recent advancements in image analysis processing. This progress has paved the way for classifying particles based on shape, indicating that image analysis holds promise as a methodology for classifying particle shapes and assessing their impact on the mechanical properties of soil materials (Rodriguez, 2013).

In broad terms, Cape Granite Suite rocks are predominantly found in the South Western Cape, encompassing areas such as the Cape Peninsula, Stellenbosch, Paarl, Darling, Greyton, and Swellendam (Brink 1981). The widespread occurrence of Cape granites indicates the possible extent of the collapse problem in the South Western Cape. Extensive research has been carried out on the collapse nature of residual granites of the Cape Granite Suite (Fouche and Asante, 2019); and the occurrence and extent of collapse settlement in residual granite in the Stellenbosch area (Gildenhuys, 2010). However, less attention has been paid to the reworked residual granite (defined as residual granite reworked in-situ by termites) also of the Cape Granite Suite.

Considering this deficiency, the investigation of microstructural properties and the collapse potential of the reworked residual granite within the Stellenbosch vicinity is the main purpose of the study. Although some methods used for the deter-

*Corresponding author: samuelasanteyaw@gmail.com

[1]Koforidua Technical University, Koforidua, Ghana.

[2]University of Stellenbosch, Western Cape, South Africa.

mination of collapse settlement properties and mechanism of reworked residual granite are traditional tests and field survey procedures, applications of image analysis and mineral identification using a scanning electron microscope introduced in this study are new approaches, examples of which have not been encountered. The data obtained from both image and mineral compositing analysis provides an important contribution to the characterization of microstructural properties of reworked residual granite as a potential collapsible material.

The main objective of this paper is to determine the collapse settlement of reworked residual granites of the Cape Granite suite in the Stellenbosch municipality using traditional geotechnical laboratory methods as well as alternate methods such as scanning electron microscopy (SEM) and the particle shape.

General properties of the study area

A wine farm situated on the outskirts of Stellenbosch University was demarcated for this study. The selection of the specified site by the researcher was driven by various factors, including its convenient proximity to the University of Stellenbosch and previous studies conducted in the area that demonstrated the presence of collapsible soils.

The presence of coarse-grain porphyritic granite beneath the farm implies a potentially elevated susceptibility to collapsibility. Additionally, Malmesbury shales are situated in the western region of the farm, and granite outcrops are located 50 meters to the west of the test pitting area. The reworked residual granite samples collected from the area were mostly moist had a light brown to reddish-brown colour and were composed of sandy silt with clay fractions. The mineral composition analysis using SEM revealed that the coarse-grained material consisted of angular to subangular quartz sand. The clayey portion of the samples was composed of Kaolin.

The reworked residual granite, although formed by biotic action, forms part of the Cape granites which intrudes into the Malmesbury Group. According to Leygonie (1977), the radiometric dating age range is 632 ±10 Ma for the earliest phase to 530 ±15 Ma for the youngest phase. Rocks ranging in composition from coarse-grained porphyritic biotite granites to finer-grained quartz porphyries, and even including some syenites and some quartz diorites make up the lithology of the suite complex (Brink, 1981). Except for isolated occurrences in Namaqualand and the Southern Cape, near George, exposures of Cape Granite are restricted to the South Western Cape which includes the study area.

Materials and Methods
Materials

Disturbed and undisturbed soil samples of reworked residual granite from three (3) test pits were used to examine the mechanical and microstructural properties. The disturbed soil samples were used for particle size distribution (PSD), Atterberg limit, and particle morphology. However, the undisturbed soil samples were used for collapse potential tests and mineral composition analysis.

Mechanical sieving and hydrometer analysis

Disturbed soil samples were collected from three test pits within the demarcated study area. The particle size distribution of these materials was determined following ASTM D421-85 (2012). The clay fraction within the soil samples was determined by hydrometer analysis in accordance with ASTM D422 -63 (2012). Fifty grams (50 g) of the material passing through the number two hundred sieve (No. 200) was dispersed in one hundred and twenty-five millilitres (125 ml) solution of sodium hexametaphosphate and deionized water for twenty-four hours

(24 hrs). The resulting solution was then thoroughly mixed and poured into a jar up to the one thousand millilitres (1000 ml) mark.

The percentage passing is then calculated by subtracting the cumulative percent retained from one hundred percent (100 %). The data are plotted on a semi-log plot of percent finer versus grain diameters to represent the particle size distribution.

Collapse potential test

Collapse potential tests were carried out on six (6) undisturbed soil samples in an oedometer (one-dimensional consolidation apparatus). The undisturbed samples were obtained from three different locations within the Stellenbosch municipality in South Africa. Using the oedometer ring, a soil sample was carefully cut to avoid disturbance of the sample. Consolidation tests were carried out on these samples at their natural moisture content. Loads were applied incrementally from 25 kPa, 50 kPa, and 100 kPa up to 200 kPa via a lever arm. When no further compression occurred at 200 kPa, the soil specimen was inundated by water (fully submerged) and allowed to stand for twenty-four hours (24 hrs). Additional stresses of 400 kPa and then 800 kPa were applied to the flooded samples. A logarithmic graph of the void ratio against pressure (in kPa) was plotted.

The collapse potential of the soils was computed following ASTM D 5333 using the Equation (1):

$$CP = \left(\frac{\pm \Delta e}{1 + e_0} \right) \times 100\% \qquad (1)$$

Where $\pm \Delta e$ is the difference in void ratio between unsaturated and saturated conditions, with the positive and negative signs indicating swelling and collapse respectively, and e_0 is the initial void ratio. The interpretation was done in accordance with Jennings and Knight (1975) guiding values of collapse potential as depicted in Table 1.

Characterization, morphology and elemental composition

The ZEISS EVO MA15 scanning electron microscope at the Central Analytical Facility at Stellenbosch University was used for the morphological and mineral composition determination using a high vacuum mode. This is depicted in Figure 1.

The polished and carbon-plated soil samples were prepared for further analysis of their particle morphology. To do this, three grams (3 g) of each soil sample were taken and subjected to sample preparation techniques.

The first step in the sample preparation process involved polishing the soil samples. This was done to create a smooth and flat surface on the samples, which would allow for a better examination of the particles' morphology. The carbon coating helps to enhance the contrast and visibility of the particles during microscopy analysis. Figure 1b shows an illustration or image of the prepared soil samples on the glass slide, demonstrating the improved visibility and clarity of the particles' surface morphology.

Images were obtained by scanning the mounted sample with a focused beam. Imaging of coarse and fine particles is done separately to reduce background noise resulting from volume interaction in SEM images. In Figure 2, we can observe secondary electron images of particles of different sizes. These images were taken at varying magnifications and spot sizes. By imaging coarse and fine particles separately, we aim to reduce the effect caused by their different sizes. The imaging process was carried out using an acceleration voltage of twenty kilovolts (20 kV). The choice of magnification and spot size varied

depending on the size of the particles being imaged. After all the images were processed; they were then exported to examine the shape of the soil particles.

Table 1 Guiding values of collapse potential

Collapse potential	Severity of problem
0% - 1%	No problem
1% - 5%	Moderate trouble
5% - 10%	Trouble
10% - 20%	Severe trouble
> 20%	Very severe trouble

The particle shape analysis was done with the rapid measurement method proposed by Krumbein (1941) together with the printed 2D images from the SEM. The interpretation was based on the "sphericity and roundness chart" (Cho *et al.*, 2006). Fifty-five (55) two-dimensional images of the different particle sizes retained (> 4.75 - < 0.075) were analyzed for each of the three test pits.

Multi-element analysis was performed on mounts using the ZEISS EVO MA15 microscope to ascertain the mineralogical composition using the backscattered electrons of the SEM. A well-polished and carbon-coated specimen was subjected to the beam from the x-ray source in the microscope chamber, monitored by the backscattered detector to produce a backscattered image. For quantitative element analyses, energy dispersive x-ray (EDX) spectrograms were recorded and analyzed using Oxford INCA Version 4.02. An example spectrogram is shown in Figure 3a.

Results and Discussion
Particle size distribution
The particle size distribution (PSD) determined by mechanical sieving and hydrometer analysis is shown in Figure 4 whilst Table 2 provides a summary of the soil characteristics. It can be deduced from Table 2 that, the soil from all three test pits constituted an average of 70.17 % sand and 2.33 % silt with a significant proportion of gravel, 27.5 %. Using the grading curve (Figure 4) together with the mechanical properties in Table 2,
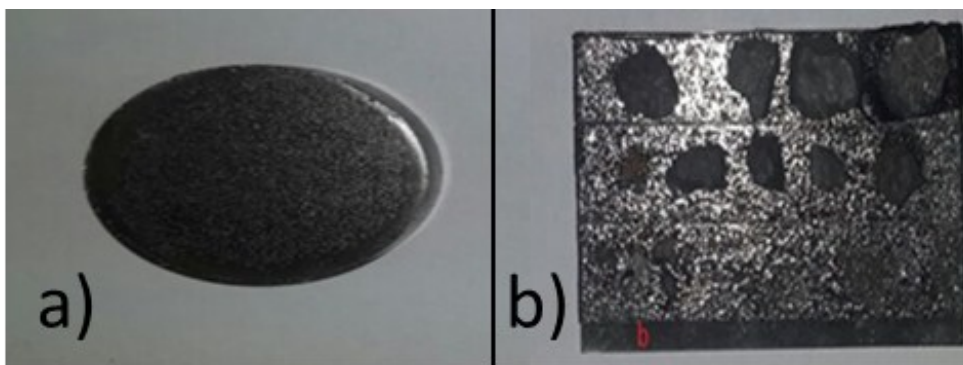

Figure 1 Carbon-plated mounts of the soil samples for a) mineral identification, and b) particle morphology
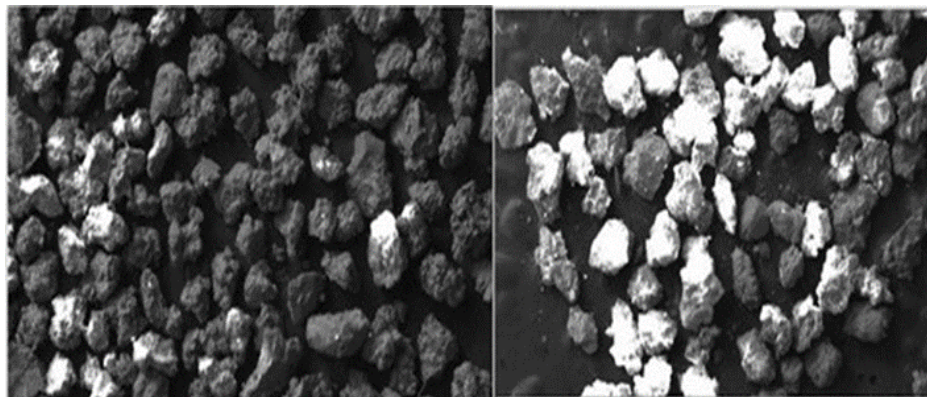

Figure 2 The (a) 0.15 mm particle size at 38x magnification, and (b) 0.075 mm size at 22x magnification

Figure 3 The (a) energy dispersive x-ray spectrogram of reworked residual granite, and (b) imaging using ZEISS EVO MA15

Table 2 Mechanical properties of reworked residual granite

| Sample Properties	Pit 1	Pit 2	Pit 3
Depth (m)	0.5	0.7	1
Gravel (%)	26	29.5	27
Sand (%)	71	68.5	71
Silt (%)	3	2	2
Clay (%)	0*	0*	0*
Liquid Limit (LL)	43.53	35.87	43.66
Plastic Limit (PL)	28.04	31.57	27.77
Plasticity Index (PI)	15.49	4.3	15.89
Difference in sand and clay (%)	71	68.5	71
Unified soil classification	SW	SW	SW

*A very low clay content in soil rounded to 0%.

the soil from the three test pits can be classified as well-graded sands, gravelly sands, little or no fines with low plasticity as per the Unified Soil Classification System (USCS).

The problems with collapse are generally associated with silty or sandy soils with low clay content (Brink *et al*., 1982). This texture was observed in the analysed soils. The different grain sizes of the reworked residual granite were bridged together by clay which created a honeycomb structure (a porous structure within the soil matrix). Upon saturation and loading, the clay and very fine silt are washed out leading to particle rearrangement and collapse.
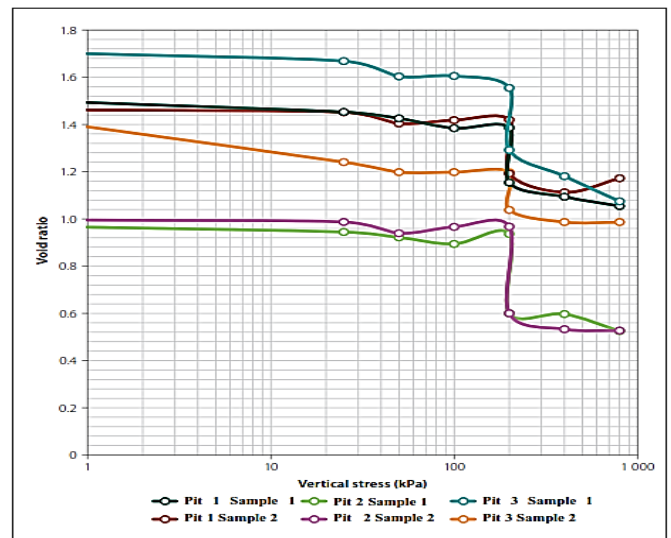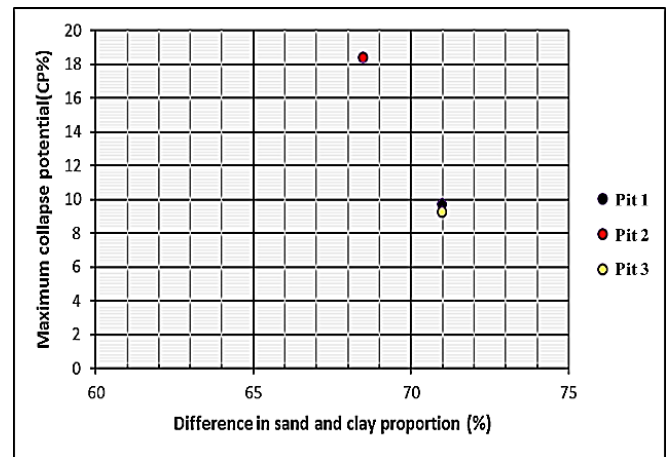
Collapse potential

The collapse potential test was used as an index test as suggested by Schwartz (1985) to determine the susceptibility of the soils to collapse. Moreover, the results from the collapse potential test together with the multi-element analysis, the particle shape, and PSD provided a clearer picture of the behaviour of
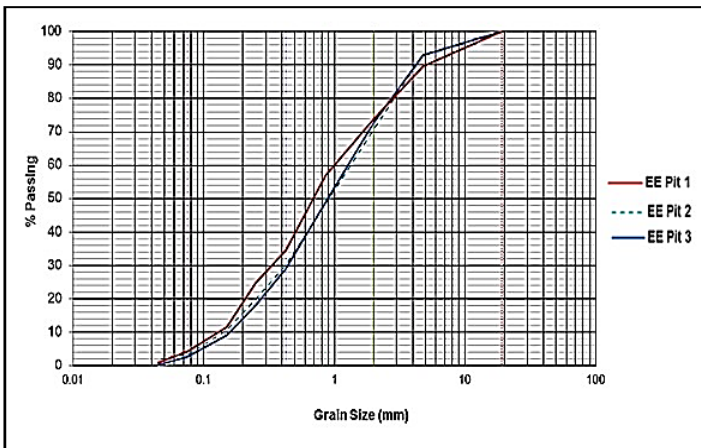
Figure 4 Particle size distribution of reworked residual granite

the soil type under study.

It can be deduced from Figure 5 that all six samples started to yield at 25 kPa. The results were anticipated because collapse settlement is generally associated with silty or sandy soils with low clay content (Brink *et al*., 1982). According to Dippenaar *et al*. (2006), the constituents of residual granite, i.e., kaolin clay, feldspar, and quartz sand formed by weathering, are easily leached and eroded. The presence of a collapse grain structure is confirmed by the collapse potential tests.

The average collapse potential (CP %) for Pit 1, Pit 2, and Pit 3 are 9.29, 17.76, and 8.23, respectively. According to Basma and Tuncer (1992), a higher coefficient of uniformity (Cu) typically gives a higher collapse potential (CP %). Similarly, at specific stress levels, the collapse potential is directly proportional to the difference in the percentage of sand and clay in the

Figure 5 Void ratio versus vertical stress of reworked residual granite (Asante, 2015)

Figure 6 Maximum collapse potential versus percentage difference between sand and clay for reworked residual granite

soil. The soil sampled from pit 2 had the highest value of Cu (9.4) compared to the lower values obtained for the soils from pit 1 and pit 3 (7.1 and 7.8, respectively). The influence of particle size distribution on collapse potential was supported by the collapse potential results. The percentage difference between sand and clay was found to be the highest for the soils from Pit 1 and Pit 3, with lower values of collapse potential. This is illustrated in Figure 6.

Particle shape analysis

The results of the particle shape analysis, providing the number of studied particles, the mean roundness and the shape description, are shown in Table 3. According to Ashmawy (2003), the particle shape has a direct influence on the void ratio, particle arrangement, and inter-particle contacts of soil fabric. In the case of pit 2, the soil sampled may have contained a higher proportion of angular particles compared to pits 1 and 3. This would have increased the likelihood of the formation of a collapse fabric and ultimately led to a higher collapse settlement. It is important to consider the particle shapes when analyzing the collapse potential of soil, as it can greatly influence the behaviour and stability of the soil mass. An arching phenomenon occurs when angular particles interlock and create a stable structure that resists collapse (Ashmawy, 2003).
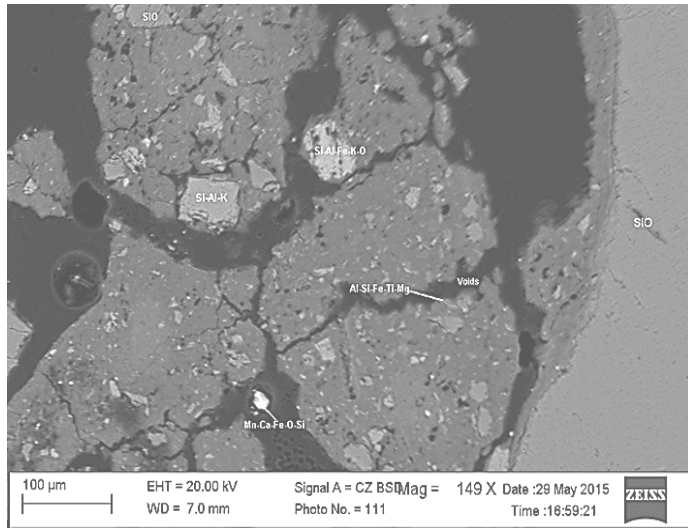
Figure 7 Backscattered electron image of a soil specimen with various minerals

The sub-angular to sub-rounded particles from pit 2 formed an arching phenomenon, creating well-connected voids, hence producing the highest collapse settlement (18.40 %), as suggested by Ashmawy (2003). The sub-rounded particles formed a collapsible fabric but with narrowed voids. Although the shapes of particles from pit 3 and pit 1 had similar attributes, the collapse settlement in soils from pit 3 (9.73) was higher than that of pit 1 (9.31), this being attributed to the greater amount of sub-rounded particles in pit 3. This can also be ascribed to the higher percentage of gravel in pit 3 (27 %) com-

pared to that of pit 1 (26 %), with pit 2 having the highest percentage of gravel (29.5 %).

Mineral composition

A soil with a collapse grain structure usually consists of a mixture of coarser soil particles cemented together by finer particles (Schwartz, 1985). This is evident from the PSD with the most dominant primary mineral being quartz (SiO_2), which is very typical of granites (refer to Figure 7 and Table 4). The finer particles (clay) consist of secondary minerals such as kaolinite and smectite, which, according to Koerner (1984), are cementing materials as shown in Table 4. The presence of smectite induces swelling. Smectite is an expansive clay mineral which bridged the particles of the soil under study together.

This observation suggests that the presence of clay and smectite minerals in residual granites plays a crucial role in controlling the collapse behaviour of soils (Mong, 2022). When the clay content is higher, there is a greater amount of smectite present. Smectite is known for its expansive nature, meaning it can absorb water and swell, exerting pressure on the surrounding soil particles. This expansion and pressure distribution mechanism is beneficial in potentially collapsible soils. Instead of experiencing sudden and localized collapse, the presence of smectite allows the soil to distribute the stresses caused by loading and saturation over a larger area. This helps to mitigate the severity of collapse and prevent catastrophic failure

To conclude, the rounded and sub-rounded coarse quartz within the soils is coated and bridged together by clays which are easily eroded and leached out. The morphology of the soil

Table 3 Mean roundness and shape description of particles

Particle Size Retained (mm)	Number of particles (f)			Arithmetic mean roundness			Description		
	Pit1	Pit2	Pit3	Pit1	Pit2	Pit3	Pit1	Pit2	Pit3
> 4.75	8	4	7	0.3	0.3	0.4	SR	SR	R
2	6	5	3	0.3	0.3	0.4	SR	SR	R
0.85	7	8	5	0.4	0.2	0.3	R	SA	SR
0.425	5	7	8	0.4	0.3	0.3	R	SR	SR
0.25	7	10	9	0.3	0.3	0.3	SR	SR	SR
0.15	9	9	8	0.4	0.3	0.3	R	SR	SR
0.075	8	9	9	0.3	0.3	0.3	SR	SR	SR
< 0.075	8	8	8	0.3	0.2	0.3	SR	SA	SR

*SR: Sub-rounded; SA: Sub-angular; R-Round

Table 4 Reworked residual granite mineral composition.

Primary minerals	Mineral composition	Wt % (Si)	Wt % (O)	Wt % (K)	Wt % (Al)	Wt % (Ca)	Wt % (Na)	Wt % (Fe)	Wt % (Ti)	Wt % (Mg)	Wt % (Mn)
Quartz	SiO_2	46.24	52.95								
Orthoclase feldspar	$KAlSi_3O_8$	30.30	46.19	13.27	9.93						
Plagioclase feldspar	$(Ca, Na)AlSi_3O_8$	31.54	48.57	0.09	1.56	0.13	9.11				
Secondary minerals											
Kaolinite	$(Si_4)Al_4O_{10}(OH)_8$	46.54	52.20		0.33						
Smectite	$(Ca, Na)(Al, Mg)(Si_4O_{10})_3(OH)_6$	27.29	45.47	0.30	10.20			15.53		1.12	
Other minerals											
Astrophyllite	$(K, Na)(Fe, Mn)_7Ti_2(SiO_3)_8(OH)_7$	8.72	40.86	2.42	3.80		0.11	4.67	37.70		1.55

particles influences the porosity, with increasing angularity leading to increased porosity and collapse settlement. The extent of collapse is also influenced by the presence and quantity of smectite clay. Table 4 depicts the elemental composition of reworked residual granite.

Conclusions

The main objective of this paper is to determine the collapse settlement of reworked residual granites of the Cape Granite suite in the Stellenbosch municipality using traditional geotechnical laboratory methods as well as alternate methods such as scanning electron microscopy (SEM) and the particle shape. The soil sample types used for this study included reworked residual granites from Stellenbosch in the Western Cape, South Africa. SEM/EDX proved to be a powerful tool for the investigation of the morphology and elemental/mineral composition of reworked residual granite soil of the Cape granite suite with the Stellenbosch municipality.

The study found that the type and amount of clay mineral present in reworked residual granite soil determine the severity of collapse. Additionally, these advanced imaging techniques will allow for a more accurate analysis of the internal structure and pore characteristics of expansive clay minerals, which can greatly contribute to understanding their mechanical behaviour and potential for collapse settlement. By gaining a better understanding of the particle shape and internal structure, engineers and geologists can develop more effective strategies for mitigating collapse settlement in areas with expansive clay minerals.

Acknowledgements

Conflict of Interest Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Reference

American Society for Testing and Materials (2012). Annual book of ASTM standards – ASTM D421/422 – dry preparation of soil samples for particle-size analysis and determination of soil constants/particle-size analysis of soil, ASTM International, West Conshohocken, PA

Asante, S. Y. (2015). Alternate methods to determine the microstructure of potentially collapsible soils, M.Sc. Thesis, Department of Civil Engineering, University of Stellenbosch, South Africa, available online at www.sunscholar.sun.ac.za. (assessed online: April 10, 2022)

Ashmawy, A. (2003). Evaluating the influence of particle shape on liquefaction behaviour using discrete element modelling. Proceedings of Offshore and Polar, pp. 1–8. Retrieved from http://e-book.lib.sjtu.edu.cn/isope2003/pdffiles/volume2/2079p542.pdf.

Basma, A. A and Tuncer, E. R. (1992). Evaluation and control of collapsible soils. Journal of Geotechnical Engineering, 118 (10), pp. 1491-1504. https://doi.org/10.1061/(ASCE)0733-9410(1992)118:10(1491)

Brink, A.B.A. (1981). Engineering geology of Southern Africa: Volume 2. South Africa: Building Publications.

Brink, A.B.A., Partridge, T.C. and Williams, A.A.B. (1982). Soil survey for engineering. Oxford: Oxford University Press.

Cho, G.C., Dodds, J. & Santamarina, J.C. (2006) Particle shape effect on packing density, stiffness, and strength: Natural and crushed sands. Journal of American Society of Civil Engineers, 132, pp. 591-602. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:5(591)

Dippenaar, M., Van Rooy, L. and Croukamp, L. (2006). The use of index laboratory testing to determine the engineering behaviour of granitic saprolite. Proc.: International Association of Engineering and Environmental Geologists. 466, pp. 1-4.

Fouche, N and Asante, S Y. (2019). The collapsible nature of residual granite soils of the Cape Granite Suite. J. S. Afr. Inst. Civ. Eng. 61, pp. 57-63. http://dx.doi.org/10.17159/2309-8775/2019/v61n2a6

Gildenhuys N, (2010). The occurrence and extent of collapse settlement in residual granite in the Stellenbosch area. MSc. Eng. Thesis, University of Stellenbosch, South Africa.

Koerner, R.M. (1984). Construction and geotechnical methods in foundation engineering. USA: McGraw-Hill, Inc.

Krumbein, W.C. (1941). Measurement and geological significance of shape and roundness of sedimentary particles. Journal of Sedimentary Research, 11(2), pp. 64 -72. https://api.semanticscholar.org/CorpusID:129176838

Leygonie, F.E. (1977). Die graniete van Langebaan, Kaapprovinsie. Annals University of Stellenbosch. A1(2), pp. 33 -105.

Mong, D. (2022). The disintegration characteristics of residual granite soil. MSc Thesis, Faculty of Engineering (meng) at the University of Stellenbosch, South Africa. https://scholar.sun.ac.za (assessed online: November 15, 2023)

Paige-Green, P. (2008). Dealing with road subgrade problems in Southern Africa. 12th International Conference on Computer Methods and Advances in Geomechanics.

Rodriguez, J. (2013). Importance of the particle shape on mechanical properties of soil materials (Licentiate dissertation, Luleå tekniska universitet). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-26434

Santamarina, J.C. and Cho, G.C. (2004). Soil Behaviour: The role of particle shape. Proc. Skempton Conf., March, London. pp. 604-617. https://doi.org/10.1061/40659(2003)2

Schwartz, K. (1985). Problem soils in South Africa - state of the art: collapsible soils. The Civil Engineer in South Africa, 27 (7), pp.379-393. https://hdl.handle.net/10520/EJC24997

Smalley, I. (1992), The Teton Dam: rhyolite foundation loess core disaster. Geology Today, 8, pp. 19-22. https://doi.org/10.1111/j.1365-2451.1992.tb00347.x

Stapelberg, F. D. J. (2021). Case study in The Northern Cape (Loopeng Area), South Africa, confirming occurrence of a collapsible soil structure in transported soils. [https://doi.org/10.21203/rs.3.rs-317200/v1

Sun, P. P., Zhang M. S., & Zhu, L. F. (2013). Typical case study of loess collapse and discussion on related problems. Geological Bulletin of China. 32(6): pp. 847-851 (in Chinese). http://dzhtb.cgs.cn/en/article/id/20130604

Terblanche E.H. (1989). Settlement and underpinning of a building founded on residual granite. A case history. The civil engineer in South Africa. 31(3), pp. 77-80,99. https://hdl.handle.net/10520/AJA10212019_18969

GhIE