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Collapse settlement behaviour of remoulded and undisturbed weathered quartzite

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The behaviour of semi arid residual soils derived from the weathering of Johannesburg quartzite are difficult to predict because of their heterogeneous particle constitution and weakly bonded structure. The collapse behaviour of undisturbed and remoulded weathered Johannesburg quartzite was investigated; and the reliability of the collapse settlement data was also evaluated. The results showed that a combination of low initial saturation of 13% and consolidation stress of 200 kPa result in the greatest collapse and that in order to avoid collapse, at any stress range, the soil must be compacted at a degree of saturation higher than 26%. The effect of desiccation on the magnitude of collapse settlement is dependent on the fines content and clay minerals. The collapse settlement of the undisturbed and remoulded quartzite was more sensitive to changes in dry density than changes in moisture content. Statistical analysis of collapse settlement test data of 15 undisturbed and remolded samples inundated at consolidation stress of 200 kPa revealed a mean, covariance and 95.5% reliability of 4.75%, 13.65±1.477% for undisturbed samples and 6.82%, 7.57±1.17% for remolded samples. The implications are that the higher values of collapse settlement associated with remolded samples should be recommended for geotechnical design.

Key words: Collapse settlement, desiccation, weathered quartzite, soil structure.

INTRODUCTION

Different mechanisms of collapse have been postulated on the basis of soil structural matrix, initial stress state and parametric stress variables. One of the earliest submissions presented by Knight (1961), postulates that collapse is due to wetting induced reduction in strength of clay bridges existing between unweathered grains in an open structure below existing applied stress. Extensive investigation by Bishop and Blight (1963), Barden and Sides (1970), Blight (1983), Barden, (1974), Maswoswe (1985) and TRL (1990) on measurement of matric suction, examination of soil micro structure by scanning electron microscopy (SEM) and evaluation of soil particle distribution by mercury intrusion porosimetry (MIP) have facilitated our understanding of the role of structure and matric suction on collapse potential. It is now understood that collapse produced by a system of macropeds deforming to displace air from a network of inter aggregate pores, and is strongly related to the relative abundance of the different pore sizes within a soil matrix (Rao and Revanasiddappa, 2006).

Laboratory measurement of matric suction by the concept of axis translation in which high air entry porous ceramics are used for the independent measurement of pore air pressure and pore water pressures by the use of pressure plates was first demonstrated by Hilf (1956). The axis translation method formed the basis of unsaturated soil mechanics (Bishop and Blight, 1963), and was extended to the reformulation of unsaturated shear strength model in terms of stress state variables (Bocking and Fredlund, 1980). However comprehensive review by Schreiner and Gourley (1993) revealed that although the pressure plate method is the most direct procedure for measuring suction in the laboratory and should be the preferred routine or standard procedure to be used in the laboratory, the equipment required is moderately complicated and expensive, and in general only one measurement can be made per day per pressure plate cell. The report revealed that although the filter paper method is an indirect technique of measuring suction, it provides good measurement of matrix suction

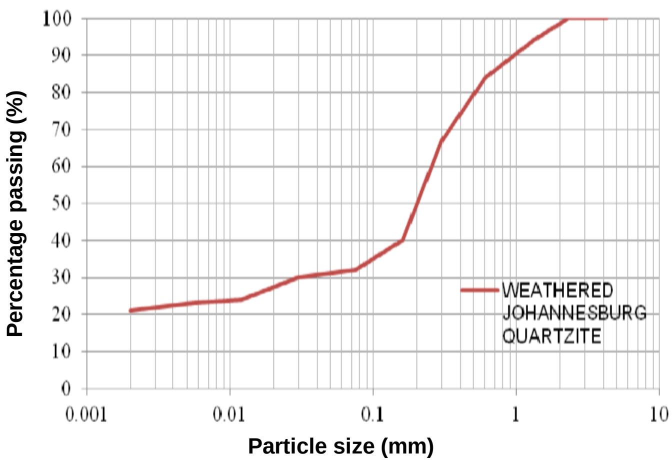

Figure 1. Particle size distribution curve of weathered Johannesburg quartzite.

using the Chandler and Guiterrez (1986) calibration. Due to its low cost and simple procedure it can be used on many samples. Schreiner and Gourley (1993) show the filter paper techniques to be somewhat sensitive to the quantity of moisture pulled out of the sample by the filter paper mass, emphasizing that difficulties may be encountered in matrix suction measurement at suctions above 1000 kPa. It is believed that at such high suctions there may be inadequate liquid to liquid contact between the water phases, implying that it is highly probable that the contact procedure is measuring total suction instead of matric suction.

Collapse potential criteria established by for Southern African formations recommended that about 80% of aeolian sands with dry densities greater than 1670 kg/m^3 and mixed origin soils with dry densities greater than 1650 kg/m^3 are generally not collapsible (Brink et al., 1982; Rust et al., 2005). While failure of roads, embankments and slopes that can be directly linked to rainfall induced soil collapse are wide spread in rural areas as noted by Paige-Green and Gerryt (1998) renewed interest on the stability of structures in collapsible formation was associated mainly with failure of test piles and subsequent revision of the foundation design of the Mozal Aluminum Complex in Southern Mozambique. Data accumulated from extensive site investigation of the mozal formation presented by McKnight (1999a, b) revealed no relationship between *in situ* moisture content and dry density with depth, established collapse potential of above 6% from single oedometer collapse tests for soaking stresses up to 1000 kPa, and reported the occurrence of deep seated desiccation. These results together with soaked pile load tests results led to the conclusion that piling through the Mozal sand to the underlying stratum was essential considering the extreme sensitivity of the structures to differential settlement.

Series of heavily instrumented triaxial collapse tests, one dimensional incremental tests and matric suction tests on the Mozal sands by Rust et al. (2005) however revealed a potential for moderate collapse of 1 to 5%. In addition the collapse potential data showed spread and deviation of the triaxial test results (75 mm by 38 mm sample size) to be approximately three times less than the oedometer test results on sample of (75 mm × 20 mm sample size). Rust et al. (2005) reported that the large scatter observed in the oedometer test data was due to end effects associated with the trimming of undisturbed samples as well as friction between the pressure pads and the inner walls of the oedometer ring and suggested that soil collapse potential should be assessed by *in situ* element as oedometer collapse tests are unreliable.

A study was undertaken to examine the collapse behaviour of a weathered mainland Johannesburg quartzite. The study aim to provide insight to the understanding and prediction of *in situ* collapse behaviour of undisturbed formations, collapse behaviour of compacted residual soil fills and recurring failure of subgrade and prepared layers of low level pavements. The work was undertaken to evaluate the effect of dry density, matric suction and residual fines on collapse settlement behaviour. The conventional one dimensional oedometer is one of the most common and widely used devices to determine soil collapse settlement in the laboratory because it is relatively cheap and operationally simple. However since concerns related to the reproducibility of collapse settlement results in tests conducted with the conventional oedometer device has been raised by some researchers, statistical analysis of collapse settlement test data for undisturbed and remoulded Johannesburg samples was undertaken to evaluate the reproducibility of oedometer collapse settlement data.

MATERIALS AND TEST METHODS

Residual hospital hill quartzite

Reddish residual sandy soil was obtained from a road construction site in Brixton, near the University of Johannesburg's APK campus at a depth of 2 m. The site is opposite the Carlton Centre which is one of the tallest buildings in Johannesburg that was founded on residual quartzite (Brink, 1984). The soil underling eastern Johannesburg area is the local Brixton formation which consists of the Hospital Hill quartzite and the Hospital Hill shales. The Brixton formation is part of the West Rand Group. The West Rand Group is made up of a thick sequence of shales, quartzites and conglomerates with two intercalated lava flows, the Crown lava and the Bird Amygdaloidal (Brink, 1984).

The soil sample had a reddish brown color, probably due to the presence of iron oxide, and was partially saturated with an *in-situ* moisture content of approximately 10%.

The particle size constitution shown in Figure 1 are %gravel = 0%, %sand = 62.51%, %fines = 32.7%. The D10 = 0, D_{30} = 0.0314 and D_{60} = 0.151. The % sand > % gravel and also %sand >12% fines. The fines plot as CL on plasticity chart, so the group symbol is SC or clayey sand. The soil is slightly plastic with liquid limit of36% and plastic index of 11%. The specific gravity is 2.73 which is to due to the partial presence of iron oxide. The maximum dry

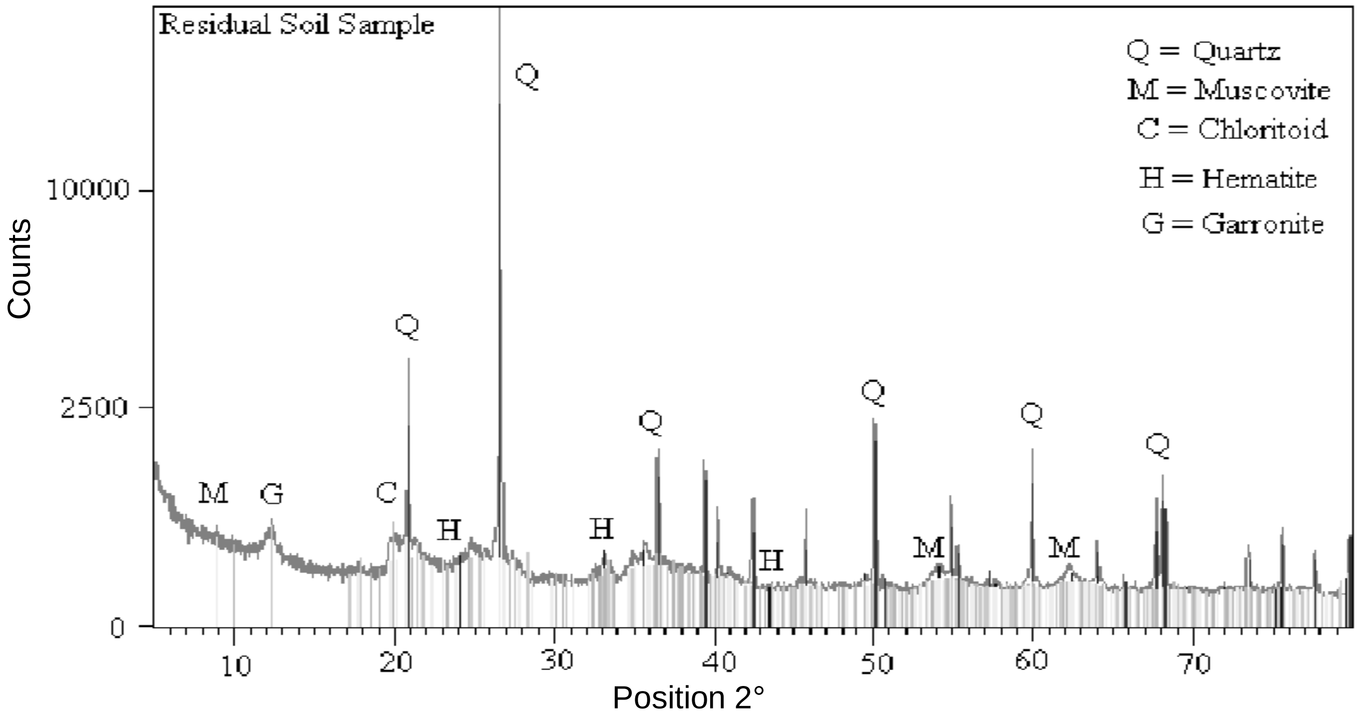

Figure 2. X-ray diffractograph of Johannesburg quartzite.

density is 1725 kg/m^3 and the optimum moisture content is 13.5%.

X - ray diffractometer analysis of the mineral constitution of the soil shown in Figure 2, reveal the presence of quartz, hematite (Fe_2O_3), muscovite, $KAl_2(AlSi_3O_{10})(F,OH)_2$), garronite ($Na_2Ca_5Al_{12}Si_20O_{64}\bullet 27(H_2O)$) and chloritoid (($Fe^{++}$, Mg, Mn)$2Al_4Si_2O10(OH)_4$). Quartz occurred at a relatively higher percentage in the soil followed by hematite, muscovite, garronite and chloritoid respectively. The high proportion of quartz is consistent with the findings on the geology of the area, which is made up of the Brixton quartzites of the Hospital Hill Subgroup. The reddish color of the soil is attributed to the presence of hematite. The aluminum and silicate compounds in the chloritoid, garronite and muscovite minerals are cementing agents that create inter-particle bonds and impact some plasticity to the soil. Kaoline clay minerals was not identified, however muscovite breaks down to form chlorite (chloritiod) which in turn breaks down to form kaolin (Blight, 1997).

Sampling and sample preparation methods

Weathering of *in situ* tropical deposits results in significant variation in void ratio and dry density implying that it is difficult to obtain undisturbed identical sets of soil samples for the series of laboratory tests often required for the study of the moisture induced collapse behavior. The weak bonds of most residual sandy soils present a structure that is highly brittle and for which sampling and trimming often lead to significant disturbance of the *in situ* structural state of the sampled soil. The major advantage of using compacted samples was that trimming to specific testing sizes was no longer necessary as the samples were compacted inside the respective testing instruments. It is possible to prepare carefully and test sets of samples at selected values of moisture contents and densities. Thus the soil under study was air dried at open laboratory room temperature and compacted into proctor mould blocks of 100 mm diameter by 120 mm height. The proctor moulds contain the oedometer rings of 75 mm diameter by 20 mm height. The samples were statically compacted or pressed down with a small pestle in small layers into the proctor moulds containing the oedometer rings to the required dry densities at moisture content and then slowly dried down to the target moisture value in the curing room were the humidity and temperature were kept at 65% and 25°C, respectively. The dry densities were values lower than the maximum dry density, moisture contents wet and dry of the optimum was investigated as well as sample compacted wet of the optimum below the saturation moisture content, dried and tested at moisture contents less than the optimum. The drying process lasted up to four days depending on the target moisture content.

Series of tests were conducted to investigate the effect of different parameters on magnitude of collapse settlement of weathered Johannesburg quartzite. Single oedometer collapse test method employed by knight was used was used to determine the moisture induced collapse settlement of weathered Johannesburg quartzite. This method entails increasing the consolidation stress on a sample up to a desired value, at the end of consolidation, the sample is inundation and left for a day at that specified stress. The advantage of this method is that field compression stress paths can be approximately simulated. The samples used for these tests were statically compacted into lubricated oedometer rings of 20 mm height and 75 mm diameter to minimized end effects. Load increments were controlled by time to 90% consolidation (t_{90}). The collapse settlement potential (CSP) is defined as:

$$CSP = \frac{\Delta e_o}{1+e_o} = \frac{\Delta H}{H_o} \qquad (1)$$

Δe_o = change in void ratio upon wetting

e_o = natural void ratio
ΔH = Change in sample height upon wetting
H_o = Initial height of sample

According to the severity rating for the different values of collapse settlement potential suggested by Jennings and Knight (1957), CSP of 0 to 1% implies no problem, 1 to 5% implies moderate trouble while 5 to 10% implies trouble, greater than 10 implies severe trouble.

Test series I: Effect of dry density and moisture content on collapse settlement

For the study of the effect of dry density and moisture content on collapse settlement, the dried soil was molded at water content close to saturation water content (15 to 17%), and slowly dried to lower water contents. Five sets of ten speciemens were soaked under applied stresses of 50, 100, 200, 400 and 800 kPa. The specimens were compacted into the oedometer rings at average moisture content of 15.7 to 16.6% to dry densities of 1545 to 1567 kg/m^3 and tested at moisture content range of 4.4 to 4.6%, 5.9 to 6.2% and 8.4 to 8.8%. Thus the specimens were tested at dry densities close to 90% relative compaction and moisture content on the dry side of the optimum moisture content.

The structure of a compacted fine soil is greatly influenced by the molding water content and that there are very different volume change characteristics for fine soils compacted wet and dry of the optimum moisture content. Laboratory studies detailed by Brewer (1964), Barden and Sides (1970) and Vaughan et al. (1988), related the above behavior to the different fabric alignment of the soil grains. Compacting the soil samples at high moisture content essentially creates soils of similar initial fabric and structure (Maccarini, 1987).

Test series 2: Effect of desiccation on collapse settlement

Series of oedometer collapse tests were also conducted on artificially desiccated and remolded partially reconstituted samples. The weathered Johannesburg quartzite was made up of 62.51% sand and 32.7% fines soil materials passing the 0.075 mm. The soil was reconstituted by adding five different proportions of the fines that is 15 to 75% to the coarse grain fractions. Two sets of samples were compacted to dry densities of 1450 and 1580 kg/m^3. The selected dry densities below the values are between 85 to 90% of the maximum dry density and within the range of *in situ* dry density of weathered Johannesburg quartzite. One set of samples were compacted to moisture content of 7.0%, which is slightly lower than the *in situ* moisture content of 10% and on the dry side of the optimum moisture content while the second set was compacted at moisture content of 20% which is on the wet side of the optimum moisture content and then dried down to target moisture content of 7% in a curing room at temperature of 25°C. The wetting and drying process was repeated three times as preliminary investigation had revealed that shrinkage of the samples was very minimal and insignificant after 3 to 4 cycles. Each drying path took about 24 h. Although the target moisture content was 7%, the final average moisture content after desiccation was found to be in the range of 6.2 to 6.5%. Thus, the first set of samples was tested in the oedometer as desiccated. The second set of samples was produced by breaking up and recompacting the desiccated samples to thesame density and water content before testing in the oedometer. In this test series, all the samples tested were loaded step wise to pressure of 200 kPa before inundation. This value is higher than the average *in situ* preconsolidation pressure of the weathered quartzite at 40 to 70 kPa, in addition consolidation pressure of 200 kPa was also used to define soil collapse potential by Knight (1961) and within the range of foundation pressure of buildings in central Johannesburg. The collapse settlement at any given soaking pressure is based on the average of three tests.

Test series 3: Relationship between matric suction and collapse settlement

The matric suction of remolded and desiccated samples that were compacted at 1450 kN/m^3 and inundated at 200 and 400 kPa were determined at different moisture content. The matric suctions of desiccated and remolded samples were determined with Whatman 42 filter papers of samples with moisture content range of 4.1 to 8.4%. The matric suction of very dry samples with the lowest moisture content was not evaluated.

Matric suction was measured using the Laboratory filter paper techniques of Chandler and Gutierrez (1986). Relatively small piece of Whatman No. 42 filter papers were placed in between compacted layers of soils in a 100 mm diameter and 50 mm thick matric suction containers, which are then sealed thus creating an air tight chamber so that stable equilibrium can be established. The tests were conducted in a temperature controlled room where temperature is maintained at 20°C. The equilibrium times has been found to be dependent on the mass of filter paper and the temperature (Schreiner and Gourley, 1993).

Following equilibration, the filter paper is removed from the sealed chamber and weighed wet inside a small plastic bag, and then oven dried and finally reweighed in the dry condition. The moisture content of the filter paper is substituted into the calibration equation of Chandler et al. (1992) to determine the value of the suction. Changes in moisture content of the filter paper disc are measured using a 0.0005 g precision Denver balance. The precision of the filter paper method is dependent on the precision with which the filter paper moisture content can be determined. For a balance with a precision of 0.0005 g and dry filter paper mass of about 0.35 g, error in the opposite direction of the dry mass and wet mass gives an error in the moisture content of ± 0.14% points (Schreiner and Gourley, 1993).

Test series 4: Reproducibility of collapse settlement

Series of tests were conducted to study the reproducibility of collapse settlement results determined by the single oedometer collapse test method in a conventional lever arch oedometer assembly with sample rings of 75 mm diameter and 20 mm thickness.

15 oedometer rings were hammered into the base and lower sides of the soil pit in the site that was dug to average depth of 2 m depth. The rings were excavated trimmed and kept in sealed bags. In addition, 15 remolded samples were also prepared from the leftover trimmings as well for the determination of *in situ* moisture content. The average moisture content and dry density of the undisturbed samples was the target values used in the preparation of the remolded samples. The two types of samples were loaded to consolidation stress of 200 kPa and inundated.

RESULTS AND DISCUSSION

For the range of applied normal stress at which the specimens were soaked, the general trend shown in Figure 3 was that the amount of collapse increases with the normal stress, however as the applied normal increases even more, the soil void will be reduced to such an extent that the amount of collapse would start to

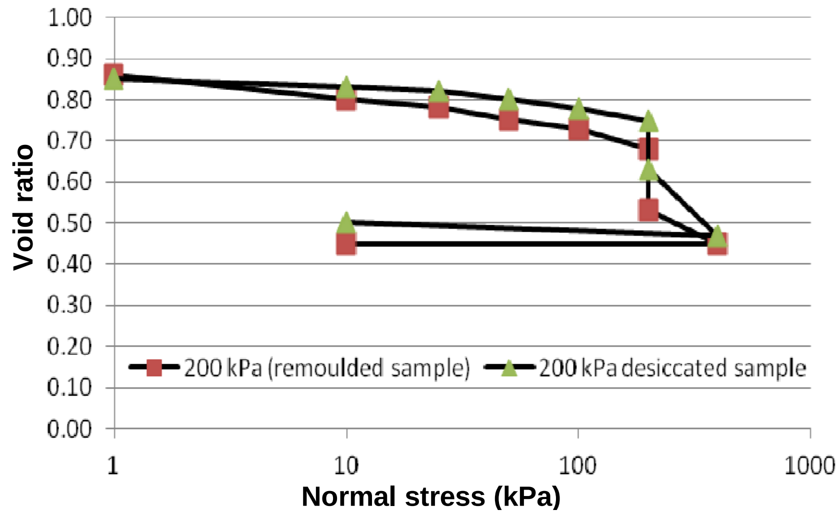

Figure 3. $_eLog_p$ graphs of dessicated and remoulded samples of Johannesburg quartzite at normal stress of 200 kPa and moisture content of 7% and dry density of 1580 kN/m^3.

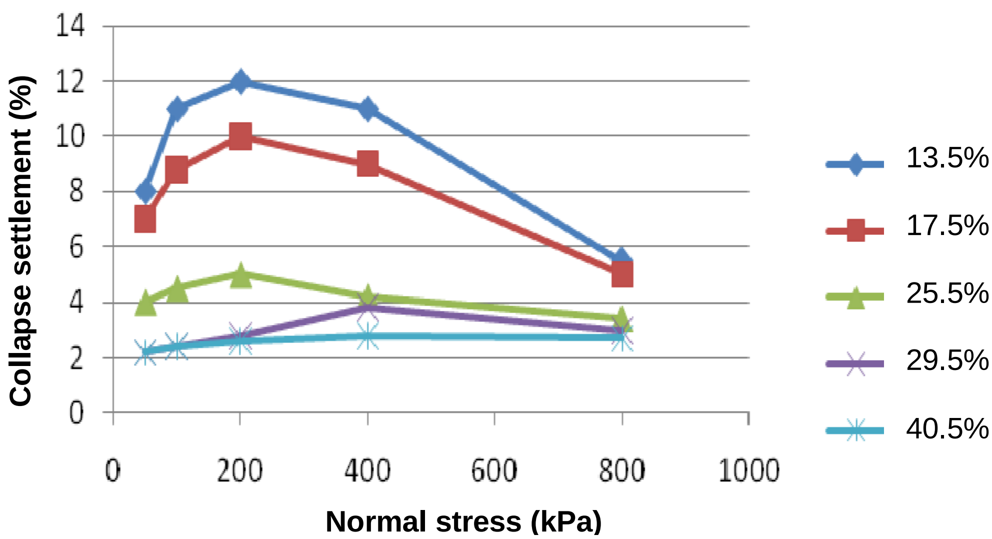

Figure 4. Collapse settlement of remoulded Johannesburg quatzite sand related to moulding moisture content.

decrease. Thus the normal stress at which percentage collapse was a maximum was influenced by the change in dry density and degree of saturation. For the range of degree of saturation considered, the maximum collapse settlement was induced by normal stress of 200 kPa on specimens prepared with least degree of saturation of 13.5%. Figure 3 indicated that for the same soaking stress, the lower the initial saturation, the greater the collapse, and for samples with initial saturation lower than 30%, there is a tendency for the amount of collapse, at a specific initial saturation, to decrease with increasing soaking stress. This is due to the higher applied stress reducing the collapse potential of an initially very loosely compacted sample by reducing the available void.

For the weathered quartzite tested, the critical degree of saturation was not influenced by desiccation, because the difference in collapse settlement due to the different methods of sample preparation is marginal. Figure 4 showed that a combination of low initial saturation of 13% and applied stress of 200 kPa result in the greatest collapse. For samples soaked at an applied stress less than 200 kPa, they only show significant collapse settlement of greater than 5% if the initial saturation was less than 26%. The general picture is that in order to

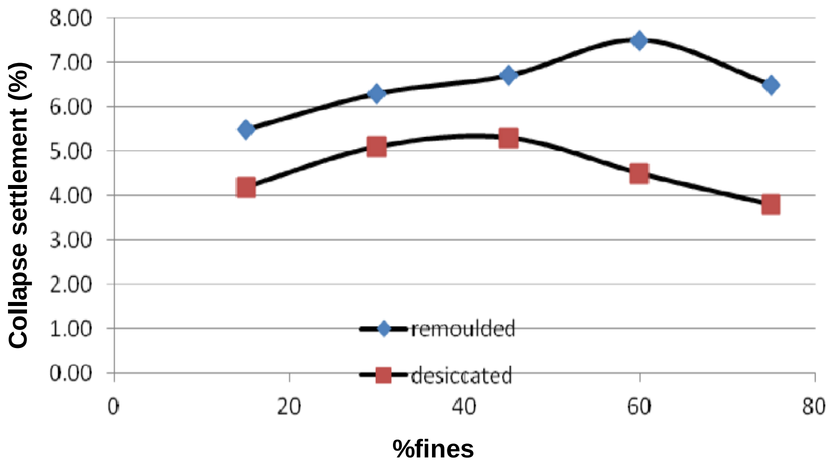

Figure 5. Colapse settlement curve of dessicated and remoulded samples of resudual quartzite at at normal stress of 200 kPa, moisture content of 7 % and dry density of 1450 kN/m^3.

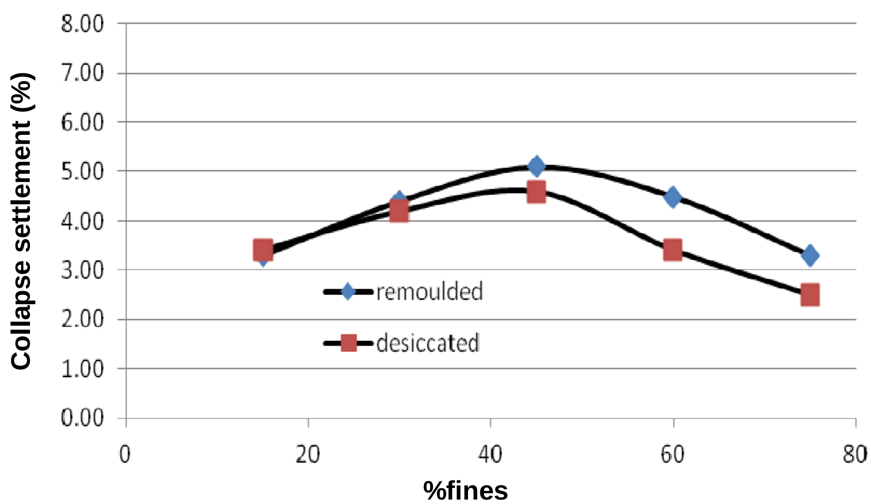

Figure 6. Colapse settlement curve of dessicated and remoulded samples of Johannesburg quartzite at at normal stress of 200 kPa, moisture content of 7% and dry density of 1580 kN/m^3.

avoid collapse, at any stress range, the soil most be compacted at a degree of saturation higher than 26%.

The results shown in Figure 5 revealed that desiccation reduced the magnitude of collapse. This was due to the realignment of the fabrics of the fine particles as a result of cycles of wetting and drying and thus increased resistance to applied stress upon inundation. Figure 6 show that collapse settlement increased with increase in fine content up to a limiting value beyond which it started to decrease. The increase in collapse indicated was not proportional to increase in the amount of fines. It was also shown that the effect of desiccation also increased with increase in fine content. In relation to Figures 5 and 6 showed that increasing the dry density reduced the magnitude of collapse settlement. It was also observed that for samples with high fines constitution, the effect of desiccation was reduced by increase in dry density.

The matric suction at the different molding water content at which the soil was inundated for samples that were compacted at 1450 kN/m^3 and inundated at 200 and 400 kPa were presented in Figures 7 and 8. The matric suction determined in the remolded samples were higher than the values in desiccated samples. The difference in matric suction was due to surface tension equilibration, surface distribution of menisci and fines distribution within aggregate pore spaces (Maswoswe, 1985; Toll, 1988). For samples inundated at normal stress of 400 kPa, the difference in collapse settlement of desiccated and

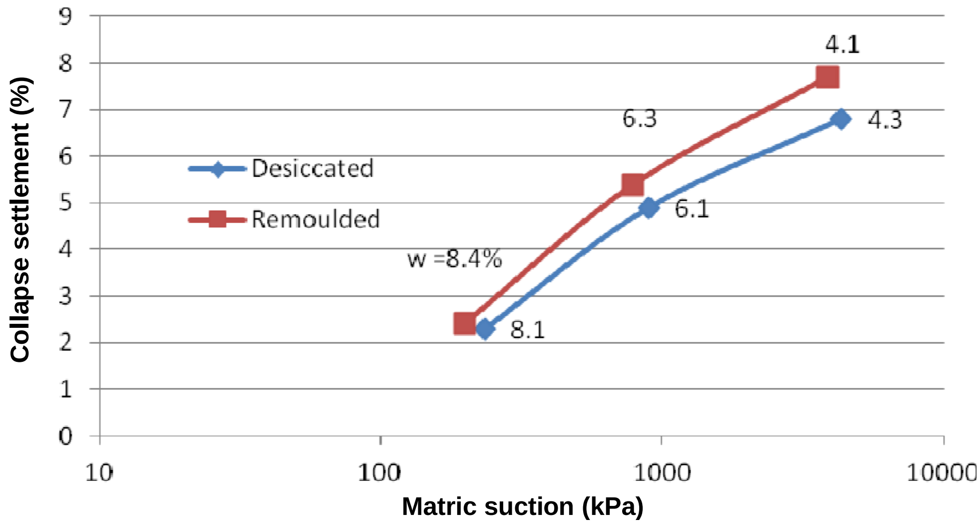

Figure 7. Collapse settlement – matric suction curves of Johannesburg quatazite compacted to dry density of 1450 kN/m^3 and inundated at normal stress of 400 kPa.

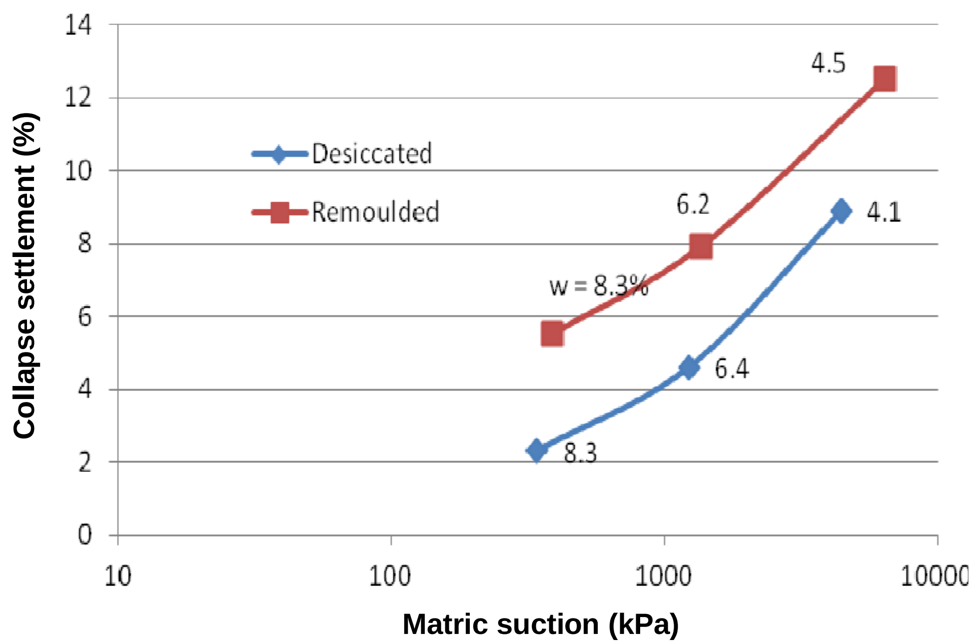

Figure 8. Collapse settlement – matric suction curves of Johannesburg quatazite compacted to dry density of 1450 kN/m^3 and inundated at normal stress of 200 kPa.

remouded samples were not significant because of the increased degree of saturation associated with the increased volume compression before inundation. However for samples inundated at the relatively lower normal stress of 200 kPa, the influence of desiccation was significant, the desiccated samples were stiffer and the volume compression due to normal stress of 200 kPa was not significant, thus the degree of saturation was low resulting in increased matric suction and collapse settlement.

Figures 7 and 8 show that the collapse settlement greater than 5% was associated with matric suction greater than 1000 kPa for samples inundated at 400 kPa irrespective of the sample state. For samples inundated at 200 kPa, collapse settlement greater than 5% was associated with matric suction values greater or less than 1000 kPa depending on whether the samples were remolded or desiccated.

Table 1. Collapse settlement of undisturbed and disturbed Johannesburg quartzite.

Number	Undisturbed sample			Remoulded sample		
	MC (%)	DD (MG/M^3)	% collapse	MC (%)	DD (MG/M^3)	% collapse
1	7	15.23	4.7	6.7	15.83	6.5
2	6.7	15.73	3.9	7.7	15.53	6.9
3	8.17	15.64	4.7	6.17	16.04	6.3
4	7.5	16.12	5.5	6.5	15.92	6.5
5	7	15.83	4.7	7.1	15.83	7.7
6	6.5	15.47	4.5	7.1	15.77	6.4
7	7.5	15.73	3.5	6.7	15.73	7.3
8	6.5	15.77	5.5	7.2	15.77	6.4
9	7.6	15.99	4.6	6.6	15.99	5.9
10	7.3	16.04	5.3	6.3	15.74	6.5
11	6.8	16.04	4.8	7.8	15.84	7.5
12	7.4	16.18	4.4	6.4	16.03	6.9
13	6.8	16.14	5.8	7.8	15.89	6.8
14	7.2	16.32	3.9	6.2	15.67	7.6
15	6.5	15.66	5.5	7.5	15.96	7.2
	106.47	237.89	71.3	103.77	237.54	102.4
Mean	7.098	15.8593333	4.75333333	6.918	15.836	6.82666667
Variance	0.219656	0.08145956	0.42115556	0.31653	0.018584	0.26728889
Covariance	6.602912	1.79964188	13.6528399	8.13262	0.8608433	7.57324061
STD	0.468674	0.2854112	0.64896499	0.56261	0.13632315	0.51699989
95.50%	1.067273	0.64994306	1.47783368	1.28119	0.3104373	1.17732061

The collapse settlement data determined by oedometer device with the standard ring of 75 mm diameter by 20 mm height was found be constant due to end effects. End effects in oedometer tests are due settlement resulting from poorly trimmed samples or samples with rough surfaces. Poorly trimmed samples result in error in estimated collapse settlement because of the aspect ratio. Friction between the pressure pad and the inner walls of the oedometer ring can also result in inaccurate value of collapse settlement due to the wrong effective value of consolidation stress. Instrumented methods like the *in situ* pile element and the triaxial method with embedded sensors have been proposed as these methods are associated with minimal end effects. The reproducibility of the collapse settlement of 15 remolded and undisturbed specimens of Johannesburg quartzite was investigated. The variation in back calculated moisture content, dry densities and magnitude of collapse settlement were statistically analyzed. The results are presented in Table 1. The covariance and 95.5% reliability of the collapse settlement of undisturbed samples of Johannesburg quartzite are 13.65 and 4.75±1.47% and for the remolded samples are 7.57% and 6.82±1.17%. The lower reliability of the undisturbed samples may be due to the effect of sampling on the weakly bonded structure of the soil. The bonds also resulted in the relatively lower average value of collapse settlement.

Conclusion

For remolded Johannesburg quartzite, a combination of low initial saturation of 13% and applied stress of 200 kPa result in the greatest collapse. For samples soaked at an applied stress less than 200 kPa, they only show significant collapse settlement of greater than 5% if the initial saturation was less than 26%. The general picture is that in order to avoid collapse, at any stress range, the soil must be compacted at a degree of saturation higher than 26%.

The magnitude of collapse settlement indicated by desiccated soil was lower than the settlement observed in the same soil recompacted to the same initial state due to the presence of structure. The effect of desiccation on collapse settlement is dependent on fine content and dry density.

Statistical analysis of the collapse settlement of 15 undisturbed and remolded samples of Johannesburg quartzite was implemented. The covariance and 95.5% Students t reliability of the collapse settlement of undisturbed samples are 13.65% and 4.75±1.47% and for the remolded samples are 7.57% and 6.82±1.17%. The lower reliability of the undisturbed samples can be linked to the statistical variation in the dry density values. The implication is that the higher values of collapse settlement associated with remolded samples should be recommended in site investigation for geotechnical design.

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