*Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)*


# Testing of hydromechanical properties of the variably saturated residual dolomite (wad)

## Test des propriétés hydromécaniques de la dolomie résiduelle à saturation variable (wad)

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ABSTRACT: In previous studies investigating the formation of sinkholes, the importance of the structure of wad to dictate the material's hydromechanical behaviour has been well documented. These studies have however, largely considered saturated soil testing. Considering the tendency of wad to occur in an unsaturated state in South Africa, it is vital to investigate the unsaturated properties of this soil. This study presents the results of soil water retention curves (SWRCs) measured on remoulded and undisturbed (structured) samples. These results have then been used to derive hydraulic conductivity functions for the two samples. The results of this study illustrate that the implications of soil structure on the hydraulic conductivity of wad becomes significantly more pronounced at partially saturated states. It is therefore emphasised that unsaturated soil properties should be considered when assessing the hydro-mechanical properties of this soil.

RÉSUMÉ : Dans des études antérieures sur la formation de dolines, l'importance de la structure de la bourre pour dicter le comportement hydromécanique du matériau a été bien documentée. Cependant, ces études ont largement pris en compte l'analyse des sols saturés. Compte tenu de la tendance de la bourre à se produire dans un état non saturé en Afrique du Sud, il est essentiel d'étudier les propriétés non saturées de ce sol. Cette étude présente les résultats des courbes de rétention d'eau du sol (SWRC) mesurées sur des échantillons remaniés et non remaniés (structurés). Ces résultats ont ensuite été utilisés pour dériver des fonctions de conductivité hydraulique pour les deux échantillons. Les résultats de cette étude montrent que les implications de la structure du sol sur la conductivité hydraulique de la bourre deviennent significativement plus prononcées aux états partiellement saturés. Il est donc souligné que les propriétés des sols non saturés doivent être prises en compte lors de l'évaluation des propriétés hydromécaniques de ce sol.

KEYWORDS: Dolomite, Wad, SWRC, Hydraulic conductivity

## 1 INTRODUCTION

Dolomite rock ($CaMg(CO_3)_2$) of the Proterozoic Malmani Subgroup found in the Chuniespoort Group (±2.6 to 2.4 Ga), forming part of the Transvaal Supergroup, underlay large portions of the densely-populated Gauteng province in South Africa (Eriksson & Altermann 1998; Eriksson et al. 2006; Dippenaar et al 2019). Dolomite, well-known for the formation of sinkholes in South Africa, weathers in slightly acidic and oxidizing conditions where soluble calcium-magnesium-rich carbonate is removed during the leaching process resulting in a low-density enrichment of insoluble minerals occupying the original rock mass volume (Buttrick 1986). The insoluble material is termed residual dolomite or occasionally wad when possessing certain qualitative attributes (Buttrick 1986). Wad is dark, generally grades in the silt fraction, enriched in Mn-oxides and is divided into two groups distinguished by differences in fabric. The two groups are generally referred to as being either structured or non-structured (Day 1981; Wagener 1982; Buttrick 1986). 'Structured wad' occupies the same volume as the parent rock after leaching has occurred and possesses relict parent rock structure. This results in a low dry density that can be below that of water, with a void ratio usually greater than one and as high as sixteen (Buttrick 1986; Swart et al 2019).

The typical location of the material in the ground profile, the low dry density and structured nature of in-situ structured wad typically leads to difficulties during sampling in the field and preparation of samples in the laboratory. This has given rise to limited research available on the properties of the material, especially work contributing to the unsaturated properties of residual dolomite and wad (Dippenaar et al. 2019). Swart et al. (2019) recently contributed to the knowledge database of the material, mainly focusing on the chemical constituents and microscopic grain structure, and the impacts of these properties on the hydromechanical behaviour on this unique material. This study will aim to improve the understanding of the material at partial saturation. Furthermore, this study will show the common difficulties faced when preparing and testing this unique material in the laboratory and how the in-situ structure influences the void ratio, soil water retention curve (SWRC) and, consequentially, the unsaturated soil property functions (USPFs).

## 2 HYDROMECHANICAL BEHAVIOUR OF UNSATURATED DOLOMITE RESIDUUM

The flow and permeability in unsaturated soils has been thoroughly investigated by numerous authors who have described various flow mechanisms applicable to partially saturated soils (Lu & Likos 2004; Toll 2012; Fredlund et al 2012; Dippenaar et al. 2014; Dippenaar & Van Rooy 2019). The flow mechanisms of a soil profile are important parameters to consider when assessing the vulnerability of ground water to pollution and movement of moisture around infrastructure. This seepage through a soil profile is primarily dependent on the hydraulic conductivity (k), which is dependent on the sum of the interconnected pore spaces, referred to as the effective porosity. However, when a soil becomes partially saturated (i.e., void spaces are occupied by both air and water), the influence of grading, porosity and subsequently the surface area available for wetting become increasingly important in dictating imbibition and drainage. This becomes vital when dealing with residual dolomite and wad which is usually crucially located at the soil-rock interface or above a cavity or receptacle during the ingress scenario of sinkhole formation.

Jennings et al. (1965) proposed the conditions needed for sinkholes to form. An open cavity in the soil material, usually found in the vadose zone, must exist above a receptacle, as this will receive and remove the material as the cavity grows above. The stability within the arch is generated due to the suction pressures in the soil, thereby creating a bonding agent between the coarser chert material and finer material (Jacobsz, 2016). A disturbance is required to disrupt the equilibrium in the arch, such as an increase in water content that results in loss of strength and causes the material to collapse. Wagener (1985) described two such scenarios, dewatering (lowering of water table) and water ingress (static water table beneath the crest of the arch). Water ingress scenarios accounts for majority of the sinkholes that form in dolomite areas within South Africa (Richardson, 2013; Constantinou & Van Rooy, 2018). Water ingress results in transient pore pressure gradients in the arch material and is the most common cause of failure of cover-collapse sinkholes (Tharp, 1999).

Structured wad typically has a high porosity, a large water holding capacity and a permeability in the order of $10^{-6}$ to $10^{-7}$ m/s (Buttrick 1986; Swart et al 2019). Thus, water percolating through wad will not exceed the required seepage velocity for erosion to occur (Buttrick 1986). Kleinhans & Van Rooy (2016) explained for the blanket material to mobilize, a competent component such as a dolomite pinnacle is needed. During high levels of water ingress, moisture will accumulate and flow against the dolomite pinnacle, causing a rapid increase in soil saturation, and a loss in suctions. This results in a loss of strength and increase in hydraulic conductivity, significant enough to trigger movement within the material. As can be seen from previous case studies and research, a good understanding of unsaturated soil behaviour of structured wad is important for the geological model of sinkhole formation.

## 3 METHODOLOGY

The material tested in this study was retrieved from trenches excavated by means of a 10-tonne excavator in the Highveld, an area approximately 14 km south of Pretoria, South Africa. The Highveld sample was logged as gun blue to purple, slightly clayey silt, structured wad. Work done, such as dispersion testing, triaxial shear and permeability testing, and laboratory permeability testing on the wad sample in this study has been previously published in Swart et al (2019). This study focused on the unsaturated behaviour of the soil through the measurement of soil water retention curves (SWRCs) which have subsequently been used to infer hydraulic conductivity functions (HCFs). Other soil characterisations performed, include grading and Atterberg limit testing, chemical analyses and microscopy.

### 3.1 *Grading and Atterberg limits*

Atterberg limits were measured according to the testing procedure outlined in the SANS 3001 series. The liquid limit of the material was tested using the cone penetrometer test method, following the procedure stated in BS: Part2: 1990.

### 3.2 *XRF analysis*

One (1No.) x-ray fluorescence (XRF) analysis was conducted on the Highveld sample. The Highveld sample was analysed using the ARL ADVANT'X Series XRF instrument and Quantas software. The XRF technique allows the quantitative determination of the chemical composition of the sample material.

### 3.3 *Scanning Electron Microscope (SEM)*

The morphology of undisturbed samples and single grains were observed using a Zeiss Gemini SEM under different magnifications best suited for the material. The SEM scans the material surface with the use of a focused beam of electrons, producing an image revealing the grain surface topography, inter-grain relations and packing of grains.

### 3.4 *Suction testing*

The pore pressure tensiometer (PPT), as described by Jacobsz (2018), was used to record the suction pressures in an undisturbed and remoulded Highveld samples. The undisturbed sample is referred to as the 'structured' sample. Measurement of the soil water retention curve (SWRC) took place along a drying path, starting at full saturation, and ending at the point of cavitation of the PPT. The spoil after cutting the structured sample was taken and the macro-structure was further broken down with a rubber spoon. The spoil was air dried and remoulded to fit the testing ring, brought to full saturation, and the test was repeated. A description of the tensiometer design is provided by Jacobsz (2018). The testing procedure implemented, referred to as the continuous tensiometer approach has been described by Gaspar et al. (2019). The PPT has been proven to accurately measure suctions in excess of 500 kPa (Jacbosz 2018). A datalogger and an electronic scale was used to record the change in suction and mass of the samples at a logging rate of 5 and 1 second intervals, respectively.

## 4 RESULTS AND ANALYSES

### 4.1 *Grading and Atterberg limits*

The results of the grading and Atterberg limit tests of the material tested are summarised in Table 1.

Table 1. Summary of grading and Atterberg limits.

| Sample | Grading (%) | | | | PI (%) | LL (%) | USCS |
|---|---|---|---|---|---|---|---|
| | Clay | Silt | Sand | Gravel | | | |
| Highveld | 9 | 89 | 2 | 0 | 8 | 229 | MH |

Notes: LL- Liquid Limit; PI – Plasticity Index; USCS – Unified Soil Classification System

### 4.2 *XRF analysis*

The summarized XRF test results are shown in Table 2.

## 4.3 *Scanning Electron Microscope (SEM)*

The images obtained from the SEM analyses are presented in Figure 1, Figure 2, and Figure 3 at increasing magnifications.

Table 2. XRF test analyses results.

| Chemical Component | Highveld (%) |
|---|---|
| $MnO_2$ | 45.8 |
| $Fe_2O_3$ | 33.9 |
| $SiO_2$ | 5.78 |
| CaO | 2.13 |
| $Al_2O_3$ | 0.76 |
| MgO | 0.52 |

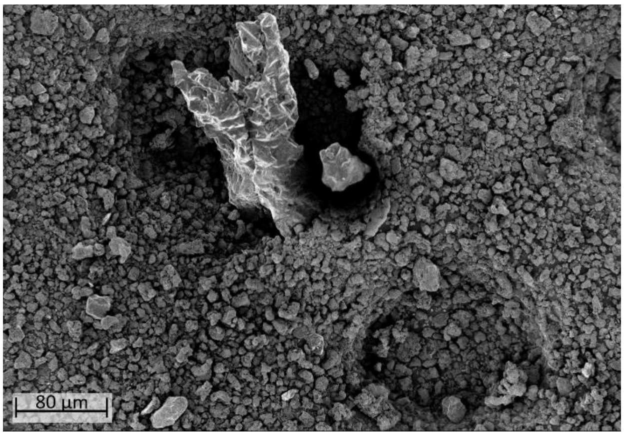

Figure 1. Image of wad from SEM at x500 magnification.

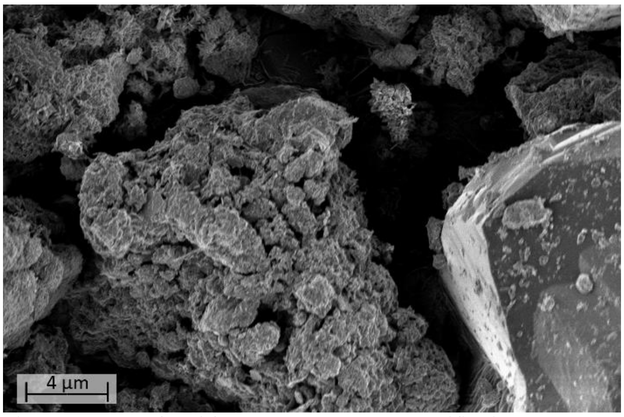

Figure 2. Image of wad from SEM at x10 000 magnification.

## 4.4 *Suction testing*

The drying soil water retention curves (SWRCs) for the structured and remoulded samples are shown by plotting the measured suction values from the PPT against calculated degree of saturation (Sr – SWRC) in Figure 4 and Figure 5, respectively. The two fitted curves of the Sr – SWRC are plotted in Figure 6. The Fredlund and Xing (1994) best-fit curves, are plotted to fit the SWRCs through the measured data points in Figure 4 and Figure 5. Table 3 summarises the fitting parameters, as discussed in Fredlund and Xing (1994) along with the initial void ratios of the samples.

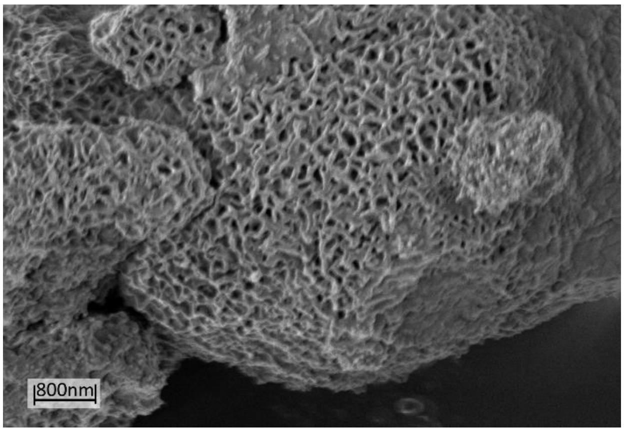

Figure 3. Image of single wad grain from SEM at x40 000 magnification.

Table 3. Summary of fitting parameters and test sample void ratio.

| Parameters and void ratio | Structured | Remoulded |
|---|---|---|
| a | 35.7 | 5 |
| n | 5.13 | 1,00 |
| m | 0.46 | 0,92 |
| Void ratio, e | 8.32 | 2.18 |

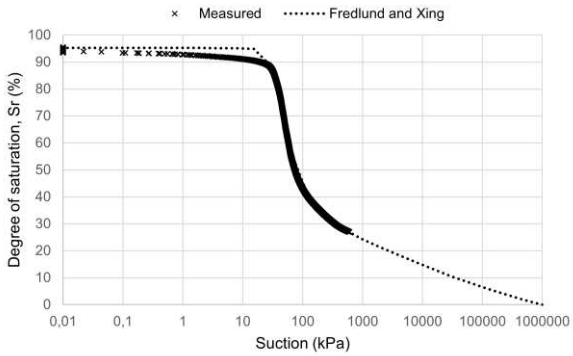

Figure 4. Suction values measured using PPT of structured sample with the fitted curve using equation presented by Fredlund and Xing (1994)

### 4.4.1 *Comparison of SWCC*

The curves for the structured and remoulded samples are plotted as suction versus volumetric water content (θ – SWRC) in Figure 7. In Figure 6, the difference in slope of the SWRCs in the mid suction range is apparent. This is indicative of the distinct differences in pore size distribution of the two samples, with the steeper gradient of the structured material being indicative of a more uniform pore size distribution. From Figure 7, the difference in initial volumetric water content can’t be attributed to the large differences in initial void ratio of the two samples. The curves are fitted to the measured values using the equation presented by Fredlund and Xing (1994).

# 5 DISCUSSION

Wad is regarded as a complex material to sample and test for its geotechnical properties. Preparation of samples for s pecialized testing usually means cutting block samples into various shapes to suit testing apparatus. The structured mat erial is friable and tends to crumble along secondary and primary features when preparing the sample.

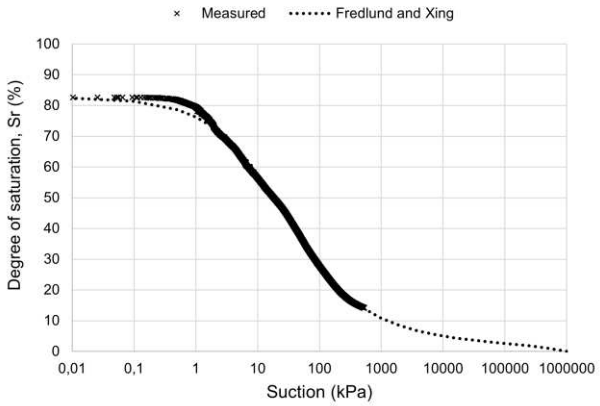


Figure 5. Suction values measured using PPT of remoulded sample with the fitted curve using equation presented by Fredlund and Xing (1994)

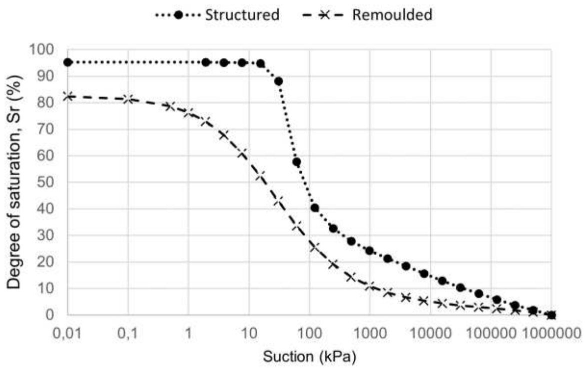


Figure 6. The fitted curves plotted on same graph.

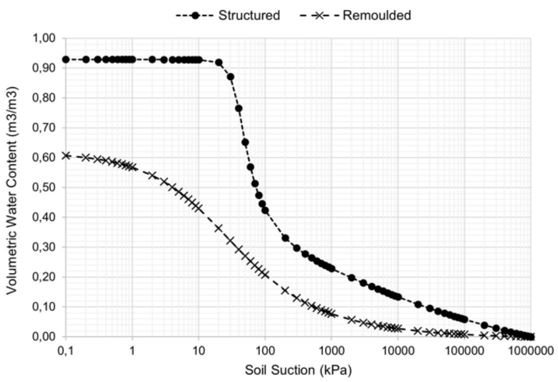


Figure 7. SWCC-θ of structured and remoulded samples. The data fitted using equation presented by Fredlund and Xing (1994).

Furthermore, hydro-thermal veins that deposited in joints of the parent rock tend to exist in the secondary features of the residual material after leaching of dolomite has occurred (Swart et al 2019). These difficulties typically result in geotechnical testing of remoulded samples. However, Day (1981) emphasised how the structure of wad is essential when assessing the material's compressibility. In this publication, Day (1981) cited soil structure as the most critical aspect governing the soil's compressibility. Buttrick (1986) highlights the importance of preserving the inherent structure when testing the permeability of the material. Considering the importance of soil structure in the testing of this material, it may be desirable to conduct full-scale testing (Jacobsz 2013). However, as such tests are often not financially feasible, an in-depth understanding of the implications of element testing of wad is crucial.

The test results reveal the Highveld sample possesses a high liquid limit, a low plasticity index and occurs as a mass of silt-sized grains with very little to no cementation between the grains. The material is predominately made up of Mn- and Fe-oxides, accompanied by silica, in the form of quartz or chert and, to a lesser extent Ca-oxide. Figure 3 reveals that the Mn-oxides existing as silt-sized grains are highly voided and exhibits a coral or sponge type structure (Swart et al 2019). The presence of the Mn-oxides and the inherent relict fabric of the parent rock results in the structured sample having a void ratio of 8.32. The breaking down of the relict fabric reduced the void ratio of the remoulded sample, however a void ratio greater than one is still achieved, as the Mn-oxides' microstructure is retained. The most common Mn-oxide found in wad is birnessite which has been found to have a surface area of up to 300 $m^2/g$ (McKenzie 1972; Swart et al 2019). This micro-structure of the metal oxide grains allows for large surface areas for adsorption of water, resulting in a high liquid limit.

Figure 6 shows the difference in the SWRCs of the structured and remoulded samples of the same material. The higher volumetric water content (θ) of the structured wad is due the porous nature of the relict parent structure, the fine grading and the presence of the Mn-oxides that allows for large quantities of hydroscopic water in the material. The structured sample recorded an initial void ratio (e) of approximately 8.32 and a saturated moisture content of 300%. The remoulded sample had a lower saturated volumetric water content due to the loss of relict parent structure. The remoulded sample still retained a high void ratio (e = 2.18) due to the presence of the fine graining and metal oxides.

Referring to the fitting parameters, as discussed by Fredlund and Xing (1994), in Table 3 and the curves in Figure 6 and Figure 7, the influence in the loss of structure can be seen. The n parameter, which reflects the slope of the SWRC in mid suction range is a reflection of the pore size distribution of the sample (Fredlund et al 2012). It is hypothesized the higher n parameter value for the structured sample is a result of the relict parent structure uniform pore sizes throughout the relativity small test sample volume. The breaking down and remoulding of the sample material results in a wider pore size distribution.

As previously discussed, it is difficult to retrieve and test undisturbed samples of structured wad, therefore testing is typically conducted on remoulded samples The potential impact of remoulding a sample has been shown in the SWRC (Figure 6 and Figure 7) which is a fundamental tool when estimating USPFs (Fredlund et al 2012). The hydraulic conductivity function (HCF) is estimated by using the saturated hydraulic conductivity and the SWRC. The HCF was estimated using the equation presented by Gardner (1958). The HCF of the structured and remoulded samples are shown in Figure 8.

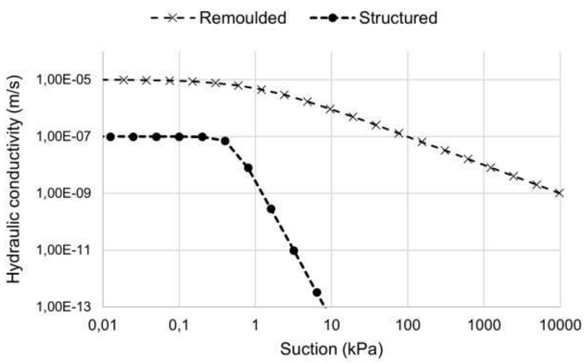


Figure 8. Hydraulic Conductivity Function (HCF) of the structured and remoulded sample. The HCF was estimated using equation presented by Gardner (1958).

The saturated permeability ($k_{sat}$) of the remoulded sample is approximately 1x10$^{-5}$ m/s (Swart et al 2019). The $k_{sat}$ of the structured sample could not be tested as the sample disintegrated during preparation for the triaxial permeability test. Buttrick (1986) and Bear Geoconsultants (2016) confirmed the $k_{sat}$ of structured wad is in the order of 1x10$^{-}$7 m/s, therefore this $k_{sat}$ value was used in estimating the HCF in Figure 8.

Figure 8 serves as an indication of the possible divergence of test results with the loss of structure in the Highveld sample. As stated above, the understanding of water seepage through unsaturated wad becomes increasingly important with a reduction in water content. Furthermore, the movement of water through the residual material is the most important factor controlling the formation of sinkholes in southern Africa.

Figure 8 highlights two important aspects when considering the hydraulic conductivity of wad. Firstly, it can be seen that while the difference in saturated hydraulic conductivity between the two samples is merely 2 orders of magnitude, if the soil is partially saturated, this discrepancy can be substantially increased. It is therefore vital to consider the unsaturated soil properties of wad, if hydro-mechanical mechanisms are to be properly understood. Furthermore, the divergence of unsaturated hydraulic conductivity with increasing suction further emphasises the role of soil structure in the testing of this material.

## 6 CONCLUSIONS

Suction testing was carried out on intact and remoulded samples of the same material. The test results of the SWRCs measured have been used to highlight the effect of soil structure on the soil properties. The differences in soil properties of each sample were influenced by the breaking down of the inherent parent structure and the remoulding of the Highveld sample. Consequently, the hydraulic conductivity functions (HCFs) estimated from the SWRCs showed notable differences. This research highlights the importance of preserving the soil structure when preforming geotechnical tests on a unique material such as wad, as its behaviour is highly dependent on its soil structure. The differences in hydraulic conductivity are shown to become significantly more pronounced as the soil is desaturated, illustrating the importance of considering unsaturated soil mechanics in the assessment of this material.

## 7 ACKNOWLEDGEMENTS

The authors wish to thank the South African Water Research Commission (www.wrc.org.za) for funding of project K5/2523 on the Karst Vadose Zone, published as Dippenaar et al. (2019)

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