Mechanical and hydraulic properties of residual dolomite and wad

D. Swart, M.A. Dippenaar and J.L. Van Rooy
University of Pretoria, Department of Geology, Pretoria, South Africa
e-mail: dvanswart@gmail.com; matthys.dippenaar@up.ac.za; louis.vanrooy@up.ac.za

© 2019 Geological Society of South Africa. All rights reserved.

Abstract

The properties of residual dolomite, sometimes termed wad, are variable and uncertain. It represents the insoluble residue after dissolution of dolomite and is commonly found in the Neoarchaean Malmani Subgroup of the Chuniespoort Group (South Africa). This study comprised triaxial tests, crumb tests, X-Ray diffraction and fluorescence spectroscopy, foundation indicators, stereo-microscope imagery and permeability testing of the represented formations outcropping in the northeastern portions of South Africa. Results concur that residual dolomite is not typically dispersive, has low density that can be below that of water, mostly grades in the silt fraction, has high plasticity indices with low to high liquid limits, and has hydraulic conductivities in the order of $1x10^{-6}$ m/s. This new knowledge database contributes to our understanding of the flow through these systems and to how ingress scenario subsidences and sinkholes can possibly occur.

Introduction

Residual dolomite, occasionally termed 'wad' when possessing certain qualitative attributes, forms through the enrichment by removal of soluble material during leaching of a calcium-magnesium-rich carbonate ($CaMg(CO_3)_2$) rock called dolomite (Buttrick, 1986). The Neoarchaean Malmani Subgroup in the Chuniespoort Group (±2.6 to 2.5 Ga), of the Transvaal Supergroup, hosts five formations of dolomitic rocks, namely the Oaktree (oldest), Monte Christo, Lyttleton, Eccles and Frisco Formations (youngest) (Obbes, 1995; Dippenaar et al., 2019a,b; Eriksson et al., 2006; Eriksson and Altermann, 1998). The formations form prominent exposures within the area of the preserved Transvaal Basin. These are well developed to the south of Pretroria and extend along strike to help define the western and eastern margins (limbs) of the basin.

A limited amount of literature on wad exists (Brink, 1979; Day, 1981; Wagner, 1982; De Beer, 1985; Hawkins et al., 1986; Bear Geoconsultants, 2016), however Buttrick (1986) investigated, developed and wrote a comprehensive understanding of wad, mainly focused on structured and non-structured wad. Day (1981), Wagner (1982) and Buttrick (1986) agree upon the definition that wad is a dark, fine-grained, insoluble material formed from weathering of manganese-rich dolomite and is divided into two groups assessed on the fabric, being structured or laminated and non-structured or massive wad. Day (1981) and Wagner (1982) use the term 'non-structured' to describe wad with no inherent parent structure present that might have been reworked by mechanical processes or compression from overburden that destroys the structure resulting in a powdery wad appearance. Buttrick (1986) uses the terms 'non-structured' or 'massive' to describe wad material with no distinguishing features and defines 'reworked' wad to have been mechanically reworked, destroying the relict structure of the residual massive or laminated (structured) wad material, and undergone addition of external impurities. In this paper, the term 'structured wad' will be used to describe wad with the relict parent rock structure preserved and the terms 'non-structured' and 'reworked wad' as defined by Buttrick (1986).

The formation and maximum size of sinkholes that can occur are dependent on the following factors (Buttrick et al., 2001):

- The thickness of the blanket layer;
- The size or width of the throat (gryke or fissure);
- The estimated 'angle of draw' in the various soil horizons.

Wad is usually found at the bedrock-soil interface and in grykes. These are critical areas for ground stability of a dolomite site (Buttrick, 1986), thus the mechanical, hydrological, geochemical and structural properties need to be understood. Once all the aspects and their relations are understood these can be applied when determining the inherent hazard class of dolomitic land.

This research aims to better understand the geomechanical and hydrological behaviour of wad in relation to the geochemical composition and the microstructure, and to determine the limits of geotechnical testing on this material. The structure and properties of wad are highly dependent on the parent material's stress history and the history of the soil itself. A comprehensive summary that focuses on factors that affect the wad material properties is needed as well as a summary of existing test results on wad.

Hydrological properties

When wad is non-reworked, be it structured or non-structured, it typically grades as a clayey silt or silty clay with a low density and high void ratio (Wagener, 1982; De Beer, 1985; Buttrick, 1986; Bester et al., 2017). Although wad can contain a high amount of sand especially when reworked, which may grade as a sandy, clayey silt (Day, 1981; Buttrick, 1986).

Buttrick (1986) concluded that structured wad possesses more than double the average void ratio value than non-structured wad. The high porosity, and the void ratio values that are usually greater than 1 and highest value being 16,6, are due to the leaching process that requires the residual soil to occupy the same volume as the parent rock (Buttrick, 1986). The natural moisture content usually exceeds the liquid limit of the material (Buttrick, 1986; Wagener, 1982; De Beer, 1985; Brink, 1979).

Permeability of wad depends on the fabric, void ratio, particle size and degree of saturation (Buttrick, 1986). The fabric, or primary features, of wad refer to the orientation and distribution of particles, such as laminations (Buttrick, 1986). The highly voided material generally possesses a low permeability attributable to the circuitous nature and variable radial sizes of the interconnected voids (Buttrick, 1986). The intact structured wad typically has low to very low permeability and the non-structued wad a low permeability; values for both types are generally in the order of 10^{-7}m/s (Buttrick, 1986). Other factors affecting the permeability of wad would be the presence of any secondary structures. Secondary structures like fissures or bedding planes consequently increase the permeability (Buttrick, 1986). As water flows through the preferred open pathways, reaching a high flow rate, erosion is expected to take place and remove wad material. The erosion may increase with the further opening of the fissure, or the material may lodge in a narrow opening and result in a decrease in flow, therefore, terminating the erosion process. Secondary cementing of silica or calcite and clay or wad infill in the open fissures will work to decrease the permeability (Buttrick, 1986). Thus, the water percolating through the wad material cannot reach the required seepage for piping or erosion to occur, therefore making it hydrodynamically stable, notably in structured wad (Buttrick, 1986).

The resultant chemical make-up of residual dolomite is the consequence of enrichment of insoluble particles through removal of soluble material. Buttrick (1986) theorised the high liquid and plastic limits, as well as the high water holding capacity, exhibited by certain wad materials are related to the porous nature and the high specific surface area of the fine grained material allowing for large quantities of hydroscopic water. Adsorption of water onto metal (Fe and Mn) oxide surfaces may be the governing factor in some wad materials rather than the fine grading (Bear Geoconsultants, 2016). Birnessite, an amorphous, silt size Mn-oxide that is common in wad, can hold up to 25% of its weight as water (Post, 1999; Dowding, 2007).

Wagener (1982) and Day (1981) found that the wad structure breaks down because of high pore pressures or shock loading that liquefies the material. The fabric of the wad can be completely destroyed through mechanical process such as slumping or compression from overburden. The reworking process changes the chemical composition and grading of the material by either increasing the fines content as infill in fissures or interconnected pores from water flowing through the soil profile or by increasing the sand and gravel components through mechanical processes whereby breaking down the chert layers (Buttrick, 1986). Therefore, the surrounding environment and the type and degree of reworking consequentially alters the hydrological properties. Buttrick (1986) concluded that destroying the relic structure and the secondary cementing would increase the permeability as well as allow the material to be more readily and easily eroded away. This is only true if a coarser grading or better-interconnected pores are attained from the reworking process.

Methodology

The residual dolomite samples used in this study are from dolomite outcrops in the area south of Pretoria and the western and eastern limbs, of the Transvaal Supergroup. Five undisturbed, Shelby or block samples, and eight disturbed samples at each locality, were taken from accessible areas at various excavations, sinkholes, road cuts, and abandoned and active mines. The vast sampling area (Figure 1) allows for comparing structured, non-structured and reworked wad as well as material from slightly different climates. A summary of the samples is provided in Table 1. A number of tests were conducted to expand the understanding of residual dolomite, these included dispersion, grading, Atterberg limits, chemical analyses, triaxial shear and permeability, and field and lab permeability tests, along with photographs of the soil taken at various magnitudes.

Triaxial test

60 mm diameter thin wall Shelby tubes were pushed into various soil faces and excavations by hand to retrieve the undisturbed Bokkraal, Mooiplaas and Doornhoek wad samples. The Shelby tube samples were carefully extruded and cut into 50 mm diameter and roughly 100 mm to 150 mm high cylindrical samples at the University of Pretoria Civil Engineering Laboratory.

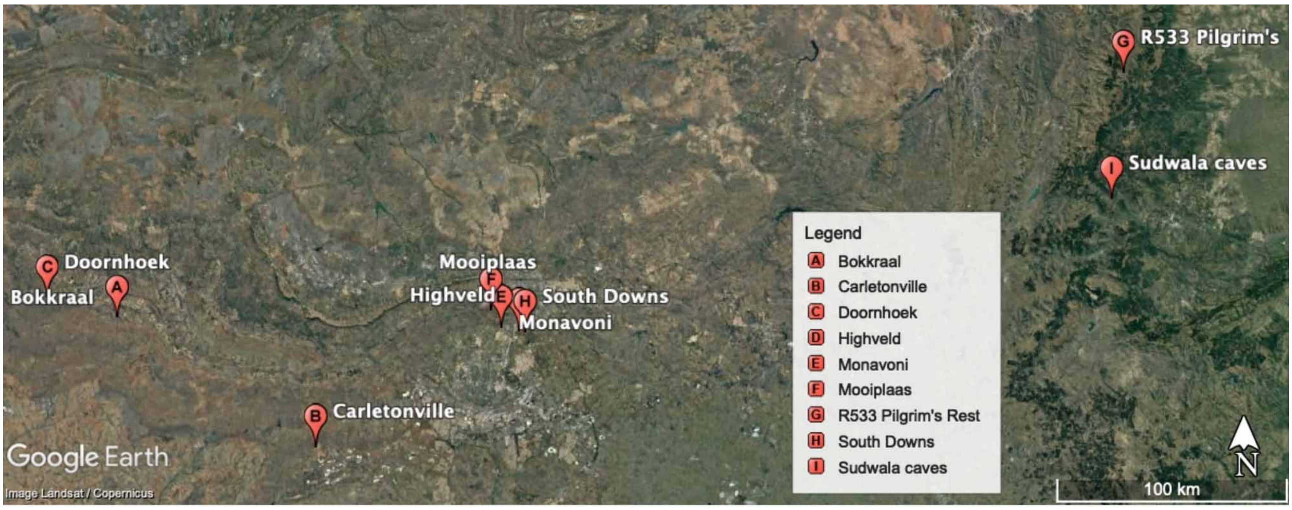

Figure 1. *Approximate sampling localities related to the distribution of the Malmani Subgroup in South Africa.*

The ASTM D4767 report is the standard used for the triaxial tests. The samples were encased in a thin rubber sheath with porous disks on either end and placed into the triaxial cell and secured by two rigid plates. The cell was then filled with water, and the fluid exerted a hydrostatic static compressive stress around the sample. Side drains were placed on the Mooiplaas sample to establish better flow paths for the water and accelerate the consolidation process, whereas the rest of the samples had no side drains. Three triaxial consolidation and permeability tests were conducted on the Mooiplaas, Bokkraal and Doornhoek samples at 100 kPa confining pressure.

Crumb test

The crumb test procedure is described in Maharaj (2013) and was used due to its simplicity and reliability for unique soils. Undisturbed 'crumbs', 40 mm in diameter, were taken from each sampling locality and each one was dropped gently into a jar of distilled water as not to disturb the water. Readings were taken at 10 minutes, one hour and two hours to confirm if the material was either dispersive or non-dispersive.

XRF and XRD

The geochemical make-up of the Bokkraal, Mooiplaas and Doornhoek samples were at the University of Pretoria and the Highveld sample at UIS Analytical Services. The samples from each locality were milled and prepared in the lab. The former XRF samples were analysed using the ARL Perform'X Sequntial, and the latter using the ARL ADVANT'X Series, XRF instruments and Quantas software. The XRD samples were prepared according to the standardized Panalytical back loading system, which provides nearly random distribution of the particles. The samples were analysed using a PANalytical X'Pert Pro powder diffractometer in θ–θ configuration with an X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-Kα radiation (λ=1.789Å). The phases were identified using X'Pert Highscore plus software. The relative phase amounts (weight %) were estimated using the Rietveld method.

Foundation indicators

Eight disturbed samples were sent to BM du Plessis Civil Engineering labs for grading and Atterberg limits analyses

Table 1. Summary of wad samples retrieved.

Name	Fabric	Sample type	General locality	Province
Highveld	Structured	Block	Excavation south of Pretoria	Gauteng
Sudwala caves	Non-Structured	Disturbed	Excavation at Sudwala caves	Mpumalanga
R533	Non-structured	Disturbed	Road cut near Pilgram's Rest	Mpumalanga
Doornhoek	Non-structured	Shelby	Old mine south of Zeerust	North West
Mooiplaas	Reworked	Shelby	Active mine near Laudium	Gauteng
Bokkraal	Reworked	Shelby	Old mine south of Zeerust	North West
Carltonville	Reworked	Block	Sinkhole at Khutsong	Gauteng
South Downs	Reworked	Disturbed	Sinkhole at South Downs College	Gauteng

following SANS 3001 series as the standard proceed. Cone penetrometer test method, following the procedure stated in the BS: Part2: 1990, was used to determine the liquid limit of the wad.

Stereomicroscope

A stereomicroscope is an optical microscope (model: Ziess Stereo Discovery V20) designed for low magnification for observation of a sample's microstructure, typically using reflected light from the surface. Undisturbed wad samples and samples post shearing and consolidation were analysed at x20, x45, x70, x94 magnification and photographs of the most representative sections of the samples were also taken at these magnifications.

Scanning Electron Microscope (SEM)

The morphology of undisturbed samples was observed using a Ziess Gemini SEM under different magnifications best suited for the material. Investigating the microscopic structure of the soil grain may build an understanding as to where certain minerals are present and to better establish the governing factors of the high and variable liquid limits.

Permeability columns

Falling head tests were conducted on several samples in order to establish the hydraulic conductivity (K), or permeability, of the soil. Disturbed fine-grained samples were packed in a Perspex column, sandwiched between two coarse-grained, 30 mm in length, quartz filters. The coarse quartz filters are used to ensure material is not entrained when water is introduced and will not inhibit flow. After placing the sample between the filters, the column is gently tapped to achieve denser packing. The samples averaged in length between 130 mm and 150 mm, with a diameter of 60 mm. The initial stage entails introducing an influx of water large enough to create a significant head, which is allowed to flow through the sample with the intent of creating uniform conditions, partial consolidation and partial saturation throughout the length of the sample. Once all the initial gravitational water has drained, the test is started by adding water, increasing the head to that of the initial water influx, and allowing the water to drain through the material. The drop in head is measured every 15 minutes until all the gravitational water has flowed through. The drop in head is placed against time to ensure steady state has been reached and to determine the hydraulic conductivity of the remolded material.

Specific gravity

The specific gravity of each sample was obtained by relating the weight of oven dry soil to the weight of water as stipulated by the ASTM D5550-14 using Micromeritics AccuPyc II 1340 Pycnometer. This method uses Helium gas to create a vacuum to measure the particle density.

Results

Triaxial test

Triaxial consolidation and triaxial permeability tests were done on the Mooiplaas and Doornhoek wad and the Bokkraal road-cut wad samples. The triaxial test results are summarised in Table 2.

Table 2. Summary of triaxial permeability test results.

Samples	**Dry density (kg/m^3)**	**Permeability (m/s)**
Mooiplaas	1034-1751	9.00x10^{-7}
Bokkraal	1237	2.80x10^{-6}
Doornhoek	539	2.70x10^{-6}

Crumb test

The crumb test performed on the wad material from the eight localities rendered the samples to be non-dispersive.

XRD and XRF

The summarised results of the XRF and XRD analysis of the wad samples are shown in Table 3.

Table 3. XRF results of material from four localities.

XRF	**Bokkraal (%)**	**Doornhoek (%)**	**Mooiplaas (%)**	**Highveld (%)**
SiO_2	62.00	45.90	82.00	5.78
Fe_2O_3	16.50	25.50	5.61	33.85
MnO_2	10.76	11.46	3.19	45.79
Al_2O_3	3.57	2.67	5.09	0.76
MgO	0.35	0.73	0.28	0.52
CaO	0.13	0.08	0.20	2.13

XRD	**Bokkraal (wt %)**	**Doornhoek (wt %)**	**Mooiplaas (wt %)**	**Highveld (wt %)**
Goethite	11.79	12.82	1.9	19.03
Kaolinite	2.48	4.4	6.99	11.91
Muscovite	5.2	2.46	86.22	29.35
Quartz	80.54	80.32	nd	36.99
Talc	nd	nd	4.9	nd

Foundation indicators

Grading and Atterberg limits were successfully analysed on all wad samples. The results are summarized in Table 4.

Table 4. Summary of results from foundation indicators.

Sample	Grading clay (%)	Silt (%)	Sand (%)	Gravel (%)	PI (%)	LL (%)	USCS
Highveld	9	89	2	0	8	229	MH
Sudwala Caves	19	56	4	21	20	67	MH
R533	28	53	11	8	33	145	MH
Doornhoek	4	68	23	5	33	121	MH
Mooiplaas	12	50	20	18	12	29	SC
Bokkraal	11	33	45	11	16	49	SL
Carltonville	11	39	27	23	17	94	MH
South Downs	18	46	26	10	17	65	MH

* PI - Plasticity index; LL - Liquid limit; USCS - Unified Soil Classification System.

Stereomicroscope and SEM

Images were taken of majority of the samples using the stereomicroscope and SEM. Figures 2 and 3 are images taken of the undisturbed Mooiplaas samples pre- and post-consolidation and of an undisturbed Doornhoek sample at various magnifications.

Permeability columns

Six of the eight samples successfully underwent permeability tests using Perspex columns. The hydraulic conductivities (K) are summarized in Table 5. The table includes the triaxial permeability test results and falling head infiltration and percolation field test results conducted at the Mooiplaas sample locality by Heuer (2017) for ease of comparison.

Specific gravity, void ratio and density

Table 6 summaries results from the specific gravity tests and includes values of dry density and void ratio, determined from weighing saturated and dried undisturbed samples at a constant volume.

Discussion of test

Triaxial Tests

The Bokkraal Shelby samples contained two localities on the mining area; a underground shaft and a road cut on surface. The sample obtained from the abandoned underground mine shaft was successfully extruded; however when the sample was being prepared for the triaxial cell, problems were encountered when attempting to cut the sample. The Bokkraal sample from

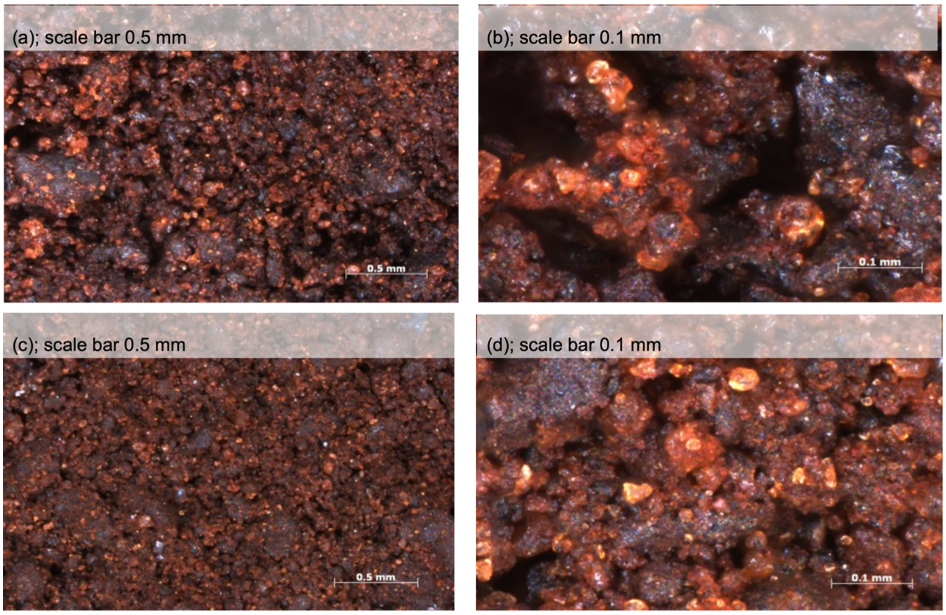

Figure 2. *Stereomicroscope images of the Mooiplaas samples pre- and post-triaxial undrained testing. (**a**) Photo taken of undisturbed sample at x20 magnification. (**b**) Photo taken of undisturbed sample at x94 magnification. (**c**) Photo taken post testing at x20 magnification. (**d**) Photo taken post testing at x94 magnification.*

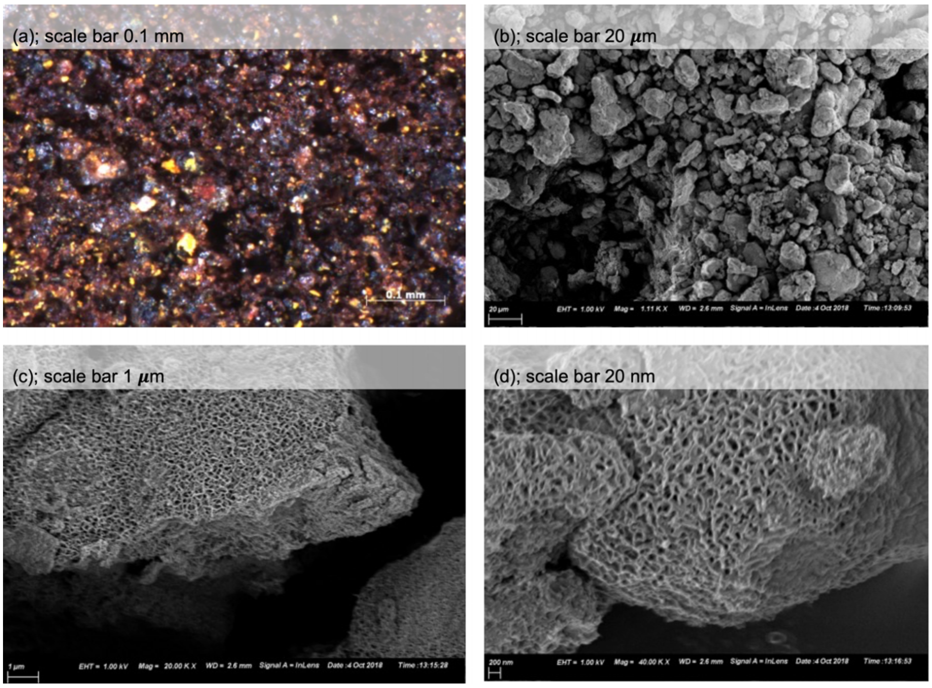

Figure 3. *(**a**) Stereomicroscope image of the Doornhoek sample taken at x94 magnification. (**b**) SEM image taken of Doornhoek silt size aggregates at x1000 magnification. (**c**) SEM image taken of a single Doornhoek sample grain at x20000 magnification. (**d**) SEM image taken of a single grain at x40000 magnification.*

Table 5. Hydraulic conductivities results from field, triaxial and column tests.

Sample	Fabric	Hydraulic conductivity (m/s)		
		Undisturbed		Remolded
		Field (Heuer, 2017)	Triaxial	Columns
Highveld	Structured	-	-	-
Sudwala caves	Non-structured	-	-	3.0 x 10-5
R533		-	-	2.3 x 10-5
Doornhoek		-	2.7 x 10-6	4.0 x 10-6
Mooiplaas	Reworked	2.81 x 10-4 - 9.52 x 10-4	9.0 x 10-7	2.0 x 10-5
Bokkraal		-	2.8 x 10-6	-
Carltonville		-	-	2.0 x 10-5
South downs		-	-	2.0 x 10-5

Table 6. Summary of dry density, void ratio and specific gravity tests conducted on wad.

Sample	Fabric	Dry density (kg/m³)	Void ratio	Specific gravity (kg/m³)
Highveld	Structured	309	8.32	2886
Sudwala Caves	Non-structured	-	-	2860
R533		-	-	2050
Doornhoek		593	3.87	2896
Mooiplaas	Reworked	1034-1751	0.55	2727
Bokkraal		1237	1.34	2897
Carltonville		898	2.07	2760
South Downs		-	-	2934

within the underground mine was highly fissured with galena (PbS) being present in the fissures. Therefore the soil is not a representative sample, as the lead sulphide mineral would act as a preferred pathway for water to travel, and permeability tests were not conducted. The samples taken from the road cut at Bokkraal was sampled at a very shallow depth (+/- 50 cm) to surface. It was observed when extruding the three Shelby samples that the soil was desiccated and highly reworked.

The soil excavation face at Doornhoek was slightly moist and stiff to very stiff in some places due to the fabric of the wad and presence of lead ore. Thus, a Shelby tube could not be pushed in by hand any further than a few centimetres. The soil sample extruded out of the Shelby tube was of sufficient height for permeability testing.

The Mooiplaas, Bokkraal and Doornhoek samples underwent isotropic consolidation at 100 kPa confining pressure and experienced full primary consolidation under two minutes, verifying that the sufficient permeability makes the side drains placed on Mooiplaas sample unnecessary for the material.

The Mooiplaas samples' dry density values are higher than any other values previously found on wad. The wad was retrieved from a narrow gryk, about 1.5 m wide, and is highly reworked. This is evidential in the microstructure photos in Figure 2, the grading and chemical composition of the wad as it contains a high amount of chert grains that contribute to the higher density.

Dispersivity

Majority of samples completely disintegrated when placed into the distilled water, suggesting all strength and cohesion lost when saturated. The Doornhoek sample only partly crumbled with a few pieces staying intact at the beginning of the test. However, most of the sample disintegrated after an hour of being placed in the water.

XRF, XRD and Foundation Indicators

The grading of the reworked wad samples is dependent on the parent rock composition but more importantly on the mechanical processes experienced by the wad material, if any. The Mooiplaas and Bokkraal samples have been highly reworked, consequently losing the inherent parent structure as well as an increase the amount of sand size chert grains, therefore affecting the grading and the chemical composition of the material. The XRF results show the Bokkraal and Mooiplaas samples have very high SiO_2 content. These reworking processes have affected the Atterberg limits of the material, in this case lowering the liquid limit, which is expected of soil that contains more inert, coarse material. The Carltonville and South Downs samples were retrieved several meters below the ground surface in an existing open sinkhole. The samples seem to be reworked to a lesser degree than the Bokkraal and Mooiplaas samples and consequentially have higher liquid limits. This variation in 'degree' of reworking leads to problems in classifying the wad material and building the geological model of the material.

The Doornhoek and Highveld samples have not been reworked, consequently, preserving the fabric inherent to the parent rock and maintaining the fine grading with no added impurities. The Doornhoek and Highveld samples contain only 4% and 9% clay, respectively. These two samples represent the lowest clay content all the samples tested but exhibit some of the highest liquid limits 121% and 229%. The Doornhoek and Highveld samples have significant content of Fe and Mn oxides at 36.96% and 79.64%. Mn-oxides commonly form coatings on other minerals and form reactive surfaces (Post, 1999), such as on inert chert or quartz grains. The high liquid limits may result from adsorption of water onto metal (Fe and Mn) oxide surfaces rather than the adsorption of the clay structure (Bear Geoconsultants, 2016). Post (1999) found that Mn-oxides could readily take up water molecules, the amount of which is dependent on the structure of the Mn-oxide. McKenzie (1972) found that a fine-grained birnessite could have a surface area of up to 300 m^2/g, allowing for the material to carry 15% to 25% of its weight in water (Post, 1999). Jenne (1968) stated that the chemical influences that Mn-oxides have on the surrounding environment and aqueous solutions far outweighs their concentrations. Dowding (2007) studied the Mn-rich soils in the Graskop, Mpumalanga, area and identified lithiophorite, birnessite and todorokite and goethite, hematite and maghemite as the common Mn and Fe minerals found in wad, respectively. Mn-oxides are typically poorly crystalline (i.e. amorphous) and generally no attempt is made to distinguish the exact Mn mineral (Post, 1999). When a large quantity of Fe-ions are present in the soil, an extensive amount of substitution with the Mn-oxides will occur, resulting in the crystal structure to morph and the infrared (IR) spectra, or XRD 'peaks' used to identify the minerals, to broaden and shift (Hawkins and Thompson, 1988). This change in morphology may result in an alteration of the large surface area that may affect the water holding capacity of the oxides. Further difficulty is experienced as many of the common Mn-oxides found in wad share similar IR spectra to other common minerals found in soil. Referring to the XRD results (Table 3), none of the samples contain any aforementioned Mn-oxide minerals. Birnessite, the most common mineral in wad, has the same IR peak as kaolinite, a common clay mineral. This is the same for Mn-oxides manganite and todorokite with respect to goethite and mica or gibbsite. Therefore, the minerals identified in Table 4 may not be the only constituents of the soil and a more detailed approach to identifying the minerals is needed.

The R533 sample was retrieved in the greater area of Pilgrim's Rest. The soils are very similar to the soils studied by Dowding (2007). The higher clay content of this soil is expected due to the relatively wetter climate of the area.

Stereomicroscope and SEM

The Mooiplaas samples, when looking at the microstructure, are mainly made up of fine to medium sand size chert grains and very fine to sand size clumps of wad with Fe-oxides on the surface of the chert grains and wad. The undisturbed sample (Figure 2a and 2b) is highly reworked, thus has no structure and is highly voided, some voids are 0,1 mm across. The post shear testing sample (Figure 2c and 2d) has a reduced void ratio; however many voids are still present after consolidation and shearing. The voids are still present due to the load applied being insufficient to overcome the clay bridges and inter-granular shear strength.

Examining the Doornhoek sample through the stereomicroscope and SEM reveals explanations for the extremely high liquid limit of a material with only 4% clay. Figure 3a exhibits relatively large voids between the indefinable individual grains that make up the soil. At x1000 magnification, Figure 3b, the individual grains are defined with open voids visible between the various grains. Figure 3c and 3d, magnification at x20 000 and x40 000, respectively, divulges some key aspects of wad. The single grain appears to be highly voided and exhibits a coral or sponge type structure. Referring to Figure 4a and 4b below, the appearance of black birnessite at x9000 and x25000 from Cheney et al., (2008) is very similar to Figure 3c and 3d. Day (1981), Wagener (1982) and Buttrick (1986) discovered a similar material, as in Figure 3a, 3b and 3c, in massive or non-structured wad and it was famously described by Wagener to have the appearance of "Rice Crispies". This structure is typical of physico-chemically formed birnessite (Jiang et al., 2010; Bruins, 2016). The presence of this highly voided metal oxide birnessite that can carry up to 25% of its weight as water, will have a major influence on the high liquid limit (125%) of this clay-poor material.

Permeability

Very limited permeability field-testing has been conducted on wad, with expectation to Heuer (2017). Heuer (2017) preformed falling head infiltration and percolation tests at Mooiplaas mine in Laudium, in close proximity to the Mooiplaas sample location. An undisturbed Mooiplaas sample underwent a triaxial permeability test post 100 kPa consolidation. Referring to Table 5, the triaxial results have a much lower permeability value than the field tests. Heuer (2017) states this may be due to lateral dispersion and the soil not being fully saturated at the time of measurement readings. Other possible reasons may be sample disturbance when retrieving, transporting and cutting of the sample, the isotropic consolidation caused a much more denser packing of grains or the sample tested had greater clay content. When the samples were cut for triaxial, many samples disintegrated due to the friable nature of the soil. The samples that maintained structure, and ultimately used, may have been from pockets of the reworked material with greater clay content.

Majority of the other samples tested had hydraulic conductivity values in the order of 10^{-5} m/s, typical of a silty soil. The Doornhoek sample had undisturbed triaxial and remoulded column K values in the same order of magnitude (x10-6). The fabric didn't influence the K value for this particular sample and suggests the grading, and added impurities when reworked, influences the change in permeability for non-structured wad.

General discussion

Wad is regarded as a complex material to test for its geotechnical properties. Firstly, retrieving a representative sample is difficult due to the variation of wad. Secondly, preparing an undisturbed sample for testing, be it cutting a block sample or extruding a Shelby tube, the wad tends to disintegrate and crumble along primary and secondary features. The Galena present in the fissures of the Bokkraal sample caused difficulties during the preparation of the sample for the triaxial cell. The competent lead ores will create preferred flow paths for water and may result in flow rates high enough to cause erosion. Lead deposits found in dolomite series of the Transvaal system can be divided into four main groups: Southern lead-zinc belt in the south-western Groot Marico lead deposit (Bokkraal and Doornhoek mines are part of this group), Hennops-Crocodile River Area southwest of Pretoria, Northern lead belt and Crocodile river fragment (Hammerbeck, 1976). It should be noted when sampling in these locations that the wad may be highly fissured with galena, and possibly other ore, therefore special care must be taken to avoid the ore stringers and inclusions.

The Mooiplaas sample has been reworked to an abundant coarse material having the highest SiO_2 content and density, and lowest Fe- and Mn-oxide weight % value of the samples in this research. The Doornhoek sample is non-structured and Highveld sample is structured therefore has not been reworked, and both represent low dry densities and the highest Fe- and Mn-oxide contents and lowest SiO_2 weight % values. The reworking process clearly plays a major role in the geomechanical properties and geochemical content of wad.

Table 7 is a summary of test results conducted on wad from pervious authors and a summary of results from this study. Referring to Table 7, the Mooiplaas sample has the highest dry density than results of work previously done on reworked wad. Wad generally has a void ratio greater than one with the reworked wad usually having the lower void ratios than non-reworked wad. The properties of the reworked wad are highly dependent on the process and degree of reworking and the surrounding environment. Classifying wad into a single group

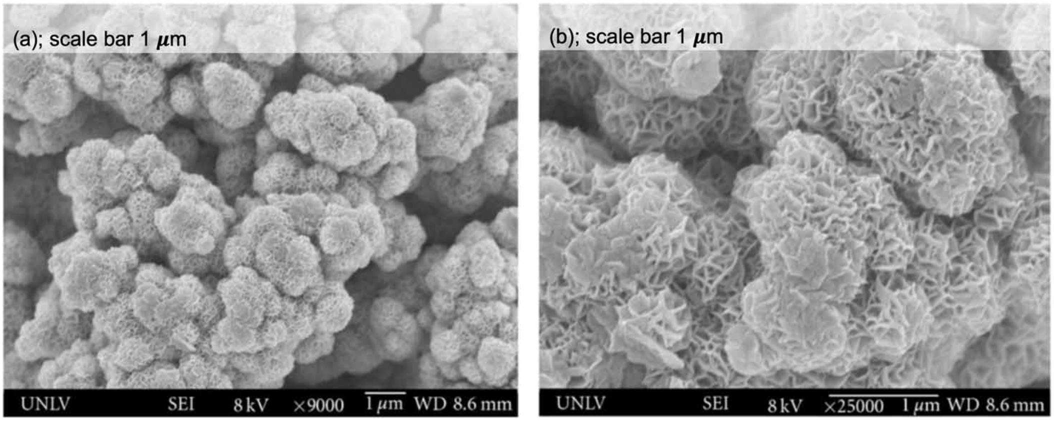

Figure 4. *SEM images of black birnessite at (a) x9000 and (b) x25000 magnification (Cheney et al., 2008).*

Table 7. Summary of test results conducted on wad.

Author/Report	Fabric	Grading (%)				Dry density	Dispersiveness	PI	LL	e	SG	Permeability
		Clay	Silt	Sand	Gravel	(kg/m³)		(%)	(%)			(m/s)
Brink (1979)	-	<29	-	-	-	285 - 722	-	5-28	47-96	2.7-9.6	1.63-3.47	-
Day (1981)	Structured or Intact and; non-structured or Reworked	30 Clayey silt to silty clay	50	22	-	225 - 1327	-	14-27	61-125	-	-	-
Jones and Wagener (1981)	-	29 Clayey silt	49	21	1	225 - 1327	-	10-29	61-125	1.1-11.2	2.9	-
Jones and Wagener (1982)	-	Clayey silt to sandy silt				253 - 1481	-	15-23	40-135	-	-	-
Wagener (1982)	Intact (structured) Powdery (non-structured)	Clayey silt				225 - 1481	Not dispersive	-	-	0.9-11.2	-	High
De Beer (1985)	-	11-60 Clayey silt	-	-	-	273 - 1558	-	5-27	49-126	0.3-8.9	-	-
Hawkins et al. (1986)	Laminated	-				500 - 600	-	18	71	-	-	-
Buttrick (1986)	Laminated or Structured	48 Clayey silt to sandy silty clay	-	-	-	220 - 1221	Not to slightly dispersive	3-26	28-113	1.3-16.6	2.2-3.1	Very low to intermediate
	Massive or Non-Structured	Sandy clayey silt				406 - 1516		11-27	27-136	0.9- 6.2	1.94-3.0	Very low to Low
Bear Geoconsultants (2016)	"pure" wad (Non-structured or Structured)	-				576 - 1075	Not dispersive	10-40	57-93	2-12	-	1.5x10^{-6}-1.2x10^{-8}
Swart	Structured	9	89	2	0	309	Not dispersive (but erodible)	8	229	8.32	2.28-2.86	-
	Non-Structured	4-28	53-68	11-23	5-8	593		33	121-145	3.87	1.79-2.89	2.7x10^{-6}
	Reworked wad	11-12 Dependent on origin, type and degree of reworking, and environment	33-50	20-45	11-18	898 - 1751		12-17	29-94	0.55-2.07	2.72-2.93	9.0x10^{-7} - 2.0x10^{-5}

PI - Plasticity Index; LL - Liquid Limit; e - void ratio; SG - specific gravity.

based on the reworked fabric alone would be redundant because of the broad behavioural characteristics and properties possible. To reduce some of the ambiguity of the classification, evaluation of the wad fabric must include the type of reworking process, the degree of reworking and resulting geochemical content and grading.

The high liquid limits exhibited in certain wad materials are influenced by the fabric, the fine grain nature of the material and, as presented in this study, the presence of certain metal oxides. The magnitude to which each of these factors influences the behaviour of wad is not exactly defined and will vary considerably.

Conclusion

The fabric of wad is inherent to the structure of the parent rock, which is determined by the stress history of the rock. The fabric influences the behavioural characteristics and properties of the wad. The high void ratios are a usual consequence of the preserved structure. Wad is considered reworked when mechanical processes destroy the structured or non-structured inherent fabric or external impurities are added. The type of reworking process and degree of reworking affects the geomechanical and hydrological properties, and geochemical content of the material. The addition of coarse or fine grade material may have a bigger influence on the permeability of non-structure wad than mechanical processes alone. Wad is a complex material to sample, because of the variable nature of the material, and to test, due to the difficulties confronted during the preparation phase and possible presence of ore in certain localities. The Atterberg limits are usually high but also variable and the factors that govern these limits, especially the liquid limits, are the fabric, grading and presence of metal oxides, such as birnessite.

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. (2019b).

References

Bear Geoconsultants., 2016. Report on dolomite stability and geotechnical investigation for the proposed township of Monavoni Extension 11. Report J15-132/3. Prepared for M&T Development.

Bester, D., A'Bear, A. and Day, P., 2017. A Review of the Geotechnical Properties of Wad from the Oaktree Formation in Centurion, South Africa. 9th South African Geotechnical Engineers Conference (375-383). Salt Rock, SAYGE.

Brink, A., 1979. Engineering Geology of Southern Africa (Vol. 1). South Africa, Building Publications.

Bruins, J., 2016. Manganese removal from groundwater: Role of biological and physico-chemical autocatalytic processes. Dissertation at Delft University of Technology.

Buttrick D.B., 1986. Wad and ferroan soil developed in the dolomitic area south of Pretoria. MSc dissertation (unpublished). University of Pretoria. Pretoria.

Cheney, M., Bhowmik, P., Moriuchi, S., Villalobos, M., Qian, S. and Joo, S., 2008. The Effect of Stirring on the Morphology of Birnessite Nanoparticles. Journal of Nanomaterials.

Day, P.W., 1981. Properties of Wad. Seminar on Engineering Geology of Dolomite Areas (135-147). Pretoria, University of Pretoria.

De Beer, J., 1985. Investigation of a Site with Extensive Occurrences of Wad. Proceedings of Problem soils in South Africa.

Dippenaar, M.A., Van Rooy, J.L. and Diamond, R.E., 2019a. Engineering, hydrogeological and vadose zone hydrological aspects of Proterozoic dolomites (South Africa). Journal of African Earth Science. 150, 511-521.

Dippenaar M.A., Swart D., Van Rooy J.L. and Diamond R.E., 2019b; in print. The karst vadose zone: Influence on recharge, vulnerability and surface stability. Water Research Commission. WRC Report No. TT 779/19. Pretoria.

Dowding, C. and Fey, M., 2007. Morphology, mineralogy and surface chemistry of mangaiferous oxisols near Graskop, Mpumalanga Province, South Africa. Geoderma, 141, 23-33.

Eriksson, P. and Altermann, W., 1998. An overview of the geology of the Transvaal Supergroup dolomites (South Africa). Environmental Geology , 36, 179-188.

Eriksson, P., Altermann, W. and Hartzer, F., 2006. The Transvaal Supergroup and its precursors. In Geology of South Africa 237-260. Pretoria, Geological Society of South Africa.

Hawkins, Hawkins and Osborn., 1986. A Geological Investigation and Geotechnical Appraisal of Subsurface Conditions in Tokoza.

Heuer, S., 2017. Vadose Zone hydrological characterisation of resdiual dolomite (Malmani Subgroup, Gauteng). (Unpublished Honours Project at the University of Pretoria).

Jenne, E., 1968. Trace Inorganics in Water. ACS Advances in Chemistry Series, 73, 337-387.

Jiang, S., Kim, D., Kim, J. and Ko, S., 2010. Characterization of the Biogenic Manganese Oxides Produced by Pseudomonas Putida strain MnB1. Environmental Engineering Research, 15, 183-190.

Jones and Wagener., 1981. Geotechnical Assessment of Proposed Township on Dolomite. Rooihuiskraal Extension, Verwoerdburg.

Jones and Wagener., 1982. Geotechnical Investigation for Township Development North of Krugersdorp/Pretoria Freeway on Farm Brakfontein.

Knappett, J.A. and Craig, R.F., 2012. Craig's Soil Mechanics (8th Editon ed.). London, Spon Press.

Maharaj, A., 2013, May. The Evaulation of Test Protocols for Dispersive Soil Identification in Southern Africa. Master Dissertation, University of Pretoria.

McKenzie, R., 1972. The Manganese Oxides in Soils - A Review. Journal of Plant Nutrition and Soil Science, 131, 221-242.

Obbes, A., 1995. The Structure, Stratigraphy and Sedimentology of the Black Reef-Malmani-Rooihoogte Succession of the Transvaal Supergroup South-West of Pretroia. Master Thesis, Rand Afrikaans University.

Post, J., 1999. Manganese oxide minerals: Crystal structures and economic and environmental significance. Proc. Natl. Acad. Sci., 96, 3447-3454.

Wagener, F., 1982, November. Engineering Construction on Dolomite. PhD thesis (unpublished). University of Natal.

Editorial handling: S. Adams.

Copyright of South African Journal of Geology is the property of Geological Society of South Africa and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.